Technologies for DWDM Millimetre-Wave Fibre-Radio Networks

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To my parents
Abstract

The phenomenal growth in global telecommunication networks is continually expanding with the advent of new services and applications. These services and applications are placing increasing demands for more bandwidth allocation via wireless access networks. This requirement of more bandwidth causes spectral congestion at lower microwave frequencies, which currently being used in wireless access networks. The millimetre-wave (mm-wave) fibre-radio system with its inherent advantages of large bandwidth characteristics is considered as one of the potential wireless access technologies for the provision of future broadband services and applications.

At mm-wave frequencies, propagation effects through the air limit the radio cell sizes to microcell and picocell. Therefore, the implementation of mm-wave fibre-radio network would require large numbers of simple, compact and low-cost base stations (BSs). Also this large numbers of BSs must be supported by the fibre optic feeder network, which connects each of the BSs to the central office.

The capacity of the fibre optic feeder networks in mm-wave fibre-radio systems can be increased by applying wavelength-division-multiplexing (WDM) technology, which is an elegant and effective way to increase the useable bandwidth of the fibre. The effective WDM channel separations in current fibre optic networks in the access and metro domain are gradually replaced with dense-wavelength-division-multiplexed (DWDM) channel separations of 50 GHz and 25 GHz. The benefits of such DWDM channel separations in mm-wave fibre-radio systems can be realised by applying wavelength interleaving technique.

This thesis explores the design and development of new system technologies for the implementation of DWDM mm-wave fibre-radio systems. Multifunctional WDM optical interface is proposed that offers simplified and consolidated BS architectures, while enabling the BSs to wavelength-interleaved DWDM (WI-DWDM) fibre feeder networks. The device is realised by using multiport optical circulator and fibre-Bragg gratings filters. The performance of the interface is characterised both in single as well as in cascaded configuration. The viability of the interface is confirmed by
network modelling. The performance of the mm-wave fibre-radio links incorporating such device is significantly enhanced with the inclusion of minor modification to the proposed interface.

Wavelength-interleaved multiplexers, with the capacity to multiplex optical mm-wave signals for WI-DWDM networks, are proposed. In addition to multiplexing, these devices also improve the overall performance of the links by enhancing the modulation depth indices of the multiplexed signals. A wavelength-interleaved demultiplexer, with the capacity to demultiplex WI-DWDM signals in such networks, is also proposed. Moreover, a simultaneous multiplexer and demultiplexer is proposed, which offers a route towards the realisation of simplified network architectures. These devices are realised by using a narrow-band cyclic arrayed waveguide grating with optimum selection of loop-back paths.

This thesis also investigates hybrid technologies towards the integration of mm-wave fibre-radio systems in WDM optical access infrastructure. Hybrid multiplexing and demultiplexing schemes are proposed. These schemes enable multiple baseband, narrowband and broadband optical access technologies to co-exist together, leading to an integrated optical network in the access and metro domain.
Declaration

This thesis is the result of my own work and, except where acknowledged, includes no material previously published by any other person. I declare that none of the work presented in this thesis has been submitted for any other degree or diploma at any University and that this thesis is less than 100,000 words in length, excluding figures, tables, bibliographies, appendices and footnotes.

__________________________________________
Masuduzzaman Bakaul
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Chapter 1: Introduction

1 INTRODUCTION

1.1 Broadband Wireless Access

In the recent years, the phenomenal growth in global mobile and wireless access technologies is driven mostly by the modern information age, principally by the Internet, which is continually expanding with the advent of new services and applications. Next generation mobile and wireless access systems are expected to offer wide range of broadband services such as video on demand, video conferencing, interactive multimedia, e-commerce, intelligent transport & traffic information, mobile computing in addition to the narrowband traditional voice and data services. These services and applications are placing increasing demands for more bandwidth allocation via wireless access networks [1-6].

This requirement of more bandwidth allocation for the provision of broadband services via wireless access networks places heavy burden on the current operating radio spectrum and causes spectral congestion at lower microwave frequencies which are currently being used to offer fixed and mobile wireless services [4-8]. To overcome this problem millimetre-wave (mm-wave) frequencies (25 GHz to 100
GHz), having the potential to resolve the spectral congestion and the scarcity of transmission bandwidth at lower microwave frequencies, are being considered for the delivery of a variety of broadband fixed radio access and mobile services with the frequency bands allocation of 28 GHz for the Local Multipoint Distribution Services (LMDS), 40 GHz for fixed wireless access, and 60 GHz for indoor picocellular networks and automotive radar [5-9]. Wireless access network operating at these frequencies will have a central office (CO) where all switching functions are performed with a backbone network interconnecting a large number of antenna base stations (BSs), which provides the wireless access point functionality with low complexity [9-12]. A typical mm-wave radio network architecture is illustrated in Fig. 1.1, which incorporates multiple BSs, each serving the customer units (CU) of a microcell or picocell, connected to a CO though wireless links. The BS contains transmitter and receiver (TX/RX), modulator and demodulator (MOD/DEMOD), multiplexer and demultiplexer (MUX/DEMUX), and necessary controlling devices

Fig. 1.1: Schematic diagram of a millimetre-wave radio network
that effectively enable bidirectional wireless links between the BS to CO, as well as BS to CU [12-14].

The major difficulty for a signal in mm-wave band is the limited radio propagation distance due to high attenuation caused by atmospheric absorption by (OH) ion of H₂O, phase dispersion by oxygen (O₂), water vapour and raindrops, in addition to high obstruction loss [15-18]. Depending on the applications and system architectures the propagation distance is usually limited to few ten’s to few 100’s metres with line of sight communication (point-to-point links). Consequently, the broadband wireless access (BWA) network architecture incorporating mm-wave radio transmission requires a microcell or picocell which brings forth the needs for a large number of remote antenna BSs within a small geographical area [19-21]. Therefore, to make it economically viable, the BS architecture incorporating mm-wave radio transmission has to be simplified, consolidated and cost effective. Moreover, in these systems (shown in Fig. 1.1), the high atmospheric attenuation in transporting such high frequency radio signals to longer distances can be overcome by connecting the BSs to the CO via an wired backbone instead of wireless transportation. The optical fibre with its inherent advantages of low loss, large bandwidth, and immune to electromagnetic interference serves as an ideal medium to transmit the mm-wave radio signal to the antenna BSs, which increases the transmission distance by reducing the loss incurred by the propagating data signal. The introduction of optical transport of mm-wave signals to BSs in BWA systems then leads to a hybrid optical and wireless technology termed as “MM-Wave Fibre-Radio Systems”, which is described in details in the next section [19-23]. While the high atmospheric attenuation exerts lots of restrictions in realising BWA networks incorporating mm-wave radio transmission, the presence of high attenuation aids in minimising the interferences between neighboring cellular channels and helps in preventing unauthorised users from intercepting a transmission [24-26]. Also due to well-defined small radio sizes (microcell or picocell), considerable frequency reuse becomes possible between the neighboring cellular cites that helps in realising spectrally efficient BWA networks by delivering services simultaneously to a larger number of subscribers [24-26].
1.2 Millimetre-Wave Fibre-Radio Networks

Fig. 1.2 shows the generic mm-wave fibre-radio architecture where the benefits of optical fibre and mm-wave radio technologies are combined to provide an alternative methodology for broadband wireless access to customers. An optical fibre feeder network is used to interconnect a large number of remote antenna BSs with a CO, where all the switching and signal processing equipment can be located for centralised control and monitoring [19-23, 27, 28]. The typical distances between the CO and the BSs are 5-50 km, where each of the BS serves a microcell or picocell covering the distances of few ten’s to few 100’s metres. Depending on the applications, the fibre feeder network can be either active or passive. If the mm-wave systems are installed for ‘last mile’ wireless access, all the active devices are usually...
located either at the CO or at the BSs, by which a passive feeder network can be easily realised. However, if the mm-wave fibre-radio systems are implemented as a metro infrastructure, the feeder network may contain multiple active devices, such as optical amplifier. The provision for centralised network arrangement allows to simplify the BSs to having transmitter and receiver with additional optoelectronic & electrooptic (O/E) interface to detect and transmit optical mm-wave signals. It also allows securing the sensitive and delicate equipment in a central location, in addition to enabling them to be shared between a larger numbers of customers. Moreover, the centralised control enables dynamic as well as reconfigurable channel assignment schemes, which improves the network performance significantly [29-31]. These channel assignment schemes allows the BSs to be assigned literally to any frequency and can dynamically control the frequency of the radio cells heavily loaded with users in order to reduce the blocking probability from the lack of frequency capacity [32].

The capacity of the mm-wave fibre-radio systems can be increased by applying wavelength division multiplexing (WDM) technology in fibre optic feeder network, which is an elegant and effective way to increase the useable bandwidth of the fibre. In this method a large number of mm-wave channels, each carried by a separate wavelength, are transmitted to/from the BSs via the CO through a single fibre that provides quantum increase in network capacity without the need for laying new fibre [33-39]. Optical mm-wave signals spaced with an effective WDM separation are passed through a multiplexer that aggregates them onto a single optical fibre before transported to the destination. The transmission path may contain optical add-drop-multiplexers (OADMs), or optical crossconnects (OXC)s that effectively adds/drops/routes the desired channel to/from the WDM feeder network, or demultiplexers, where the original signals are extracted depending on network topologies and architectures. Since each of mm-wave WDM channels are effectively separated from others, they can be independent in protocol, speed, and direction of communication. As a result, mm-wave fibre radio network incorporating the WDM technology is potentially faster and more flexible, and can be less costly to maintain when compared to other methods. Moreover, the use of WDM in the fibre feeder
network allows a fast route for these systems to be developed by accessing the existing optical network infrastructure in the access and metro network domains, where due to cost effectiveness, the unused capacity will be used as the means of communication between the CO and the BSs, by which the need for implementing separate fibre-radio backbone can be avoided [33-39]. As discussed throughout this thesis, it is envisaged that future wireless bandwidth will be met by WDM mm-wave fibre-radio systems, where each of the remote antenna BS will be allocated a WDM optical carrier to transport the optically modulated mm-wave signals to/from the CO through the fibre optic feeder network, irrespective of direction of communication. However, using the same wavelength for both downlink and uplink communication is not any requirement, since channel offset scheme as well as interleaved downlink and uplink channels can also be used.

There are a number of challenges associated with the design and implement of future WDM fibre-radio network accessing the existing WDM infrastructure in the access and metro domain. The effective WDM channel separations in the access and metro domain are gradually replaced with dense-wavelength-division-multiplexing (DWDM) channel separations of 50 GHz and 25 GHz. The benefits of DWDM technologies in mm-wave fibre-radio systems can be realised by applying DWDM compatible wavelength interleaving (WI) technique. However, to exploit the benefits of WI, suitable system technologies such as multiplexer, demultiplexer, and OADM need to be explored and developed.

The development and implement of simple, compact, low-cost, and light-weight remote antenna BSs is essential. BSs with such architectures reduce the customer cost and accelerates the deployment of the mm-wave fibre-radio systems, while offers transparent OADM functionality to the wavelength-interleaved-DWDM (WI-DWDM) feeder networks. At the antenna BS, the integration of optics and opto-electronic components will enable the development of such BSs, which need to be explored and investigated.

The OADM interfaces of the BSs in a WI-DWDM feeder network are expected to be used in cascade, where due to narrow band spectral responses, the required wavelength stability and accuracy becomes more stringent with the number of
cascaded stages and the accumulated effects of the impairments may lead to the distortion of signal waveforms and degradation in the network performance. This may limit the cascadability of the interfaces and impose limitations in network dimensioning. The effects of network impairments in single as well as in cascaded OADMs, which enable the BSs to the WI-DWDM fibre feeder network, need to be explored and characterised.

Moreover, in mm-wave fibre-radio systems, external modulators are used to superimpose the mm-wave signals onto optical carriers, which often exhibit smaller modulation depth indices, and lead to poor overall link performances. To overcome this problem, modulation depth enhancing techniques need to be explored and developed.

1.3 Integrated Access Networks

The explosive growth in traffic and demand for more bandwidth continues universally at an increasing rate both in fixed and mobile access networks. To meet such massive growth in bandwidth demand, a variety of access technologies are being introduced in the last mile access network, incorporating both wireless and wireline media. Among these last mile access solutions, passive optical network (PON) and its specific implementations such as fibre-to-the-home (FTTH), and fibre-to-the-curb (FTTC) remains as the most future proof technology for the delivery of broadband to the users [2-3, 40-43]. Radio-over-fibre (RoF) network, which broadly can be categorised as the networking of wireless access points are also very attractive for the delivery of broadband via wireless last mile solutions [5, 6, 11, 16, 20, 27-29]. The various access technologies, based on their electrical spectral bands, can be re-grouped as baseband (BB), intermediate frequency (IF), and mm-wave radio frequency (RF) transport over fibre.

Carriers and service providers are actively seeking a convergent network architecture that can facilitate a rich mix of value added and clearly differentiated services via a mix of wireless and wireline solutions to meet the demand for
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mobility, bandwidth and range of connectivity options from the customer [44, 45]. All these requirements can be met by offering an integrated telecommunication package, for which an integrated access network is essential. Given the wide bandwidth offered by fibre, an integrated optical access network that can support appropriate integration of wired and wireless last mile solutions seems very plausible; and to enable such a network, co-existence of the optical access technologies in the same fibre is essential.

Fig. 1.3 shows the generic architecture of an integrated access network where broadband wireless, such as RoF via BS_{RF} and wireline, such as, WDM PON based BB and IF transport via respective optical network unit (ONU), ONU_{BB} and ONU_{IF}, technologies co-exist in the same optical access infrastructure. The integration of these technologies will reduce the cost of the services via broadband access and ensure effective utilisation of the abundant capacity of the optical infrastructure in the access/metro domain [44-47]. However, the realisation of such as an integrated network requires suitable hybrid system technologies for the CO and the remote access nodes (RANs), which need to be explored and investigated.

![Fig. 1.3: Architecture of integrated access network that supports mm-wave fibre-radio systems as well as conventional access technologies together.](image-url)
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1.4 Thesis Outline

The objective of this thesis is to investigate and develop a variety of system technologies and architectures for the implementation of future DWDM mm-wave fibre-radio systems. In particular, the thesis investigates and develops novel system technologies in multiplexing, demultiplexing and, add-drop-multiplexing (ADM) of optical mm-wave signals, which enable DWDM compatible WI technique for mm-wave fibre-radio systems. Novel WDM optical interface is proposed that offers a simplified and consolidated BS architecture, while enabling OADM functionality for the BSs in WI-DWDM fibre feeder network. A significant part of the thesis is devoted in characterising the performance of single and cascaded WDM optical interfaces and exploring modulation depth enhancing techniques for mm-wave fibre-radio networks. The thesis also investigates hybrid system technologies, by which an integrated optical access network can be realised.

The thesis is organised as follows:

CHAPTER TWO: Literature Review

This chapter reviews the extensive research, which has been carried out in data transport schemes of mm-wave fibre radio systems in realising simplified BS architectures, highlighting the key issues and experimental investigations. The literatures on efficient fibre-radio networks towards the realisation of DWDM compatible wavelength-interleaved feeder network is explored and presented. Potential sources of networks impairments and their possible impacts in mm-wave fibre-radio systems are reviewed and discussed. Also, the literatures on the enhancement of the modulation depth indices of mm-wave fibre-radio links, as well as, the integration of access technologies in unique optical network are reviewed and investigated.
CHAPTER THREE: WDM Optical Interface for Simplified Antenna Base Stations

In this chapter, we propose a multifunctional WDM optical interface for 37.5-GHz-band WI-DWDM fibre-radio signals spaced at 25 GHz, which enables a wavelength reuse technique in the BS, eliminating the need for a light-source in the uplink direction. The functionality of the proposed interface is verified both by experiment and simulation. The use of the demonstrated interface in WI-DWDM fibre-radio networks enables transparent wavelength routing, improves the spectral efficiency, and ensures efficient wavelength utilisation, while realises a simple, compact and low-cost BS. Also, the effects of the performance of O/E devices on the overall performance of the link incorporating the proposed interface are investigated by simulation models. Moreover, a comparison is carried out to investigate the effects of reusing optical carriers over independent light-sources in the uplink path.

CHAPTER FOUR: Characterisation and Enhancement of Links Performance Incorporating WDM Optical Interface

The performance of the WDM optical interface (proposed in Chapter 3), in single as well as in cascaded configuration, is characterised both by simulation as well as by experiment. Numerical models are developed for both star-tree and ring/bus network configurations, from which the prospect as well as the boundaries of the cascaded interfaces are predicted. To enhance the performance of the link, a minor modification is incorporated to the proposed WDM optical interface. The functionality of the modified WDM optical interface is also verified with another experiment. Moreover, the impact of the incorporation of the modification on the cascadability of the interfaces was quantified through another numerical model.

CHAPTER FIVE: Enabling Wavelength Interleaving in Millimetre-Wave Fibre-Radio Networks

Wavelength interleaved multiplexers, with the capacity to multiplex optical mm-wave signals for WI-DWDM networks, are proposed, which also improves the link performance by enhancing the modulation depth indices of the multiplexed signals.
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A wavelength interleaved demultiplexer, with the capacity to demultiplex wavelength interleaved signals from WI-DWDM networks, is also proposed. Moreover, a simultaneous multiplexing and demultiplexing scheme is proposed that offers a route towards simple network architecture by realising simplified and cost-effective CO and remote nodes. These schemes, incorporating a commercial $8 \times 8$ arrayed waveguide grating (AWG), are demonstrated experimentally using three optical mm-wave signals spaced at 25 GHz, each of them carrying 37.5 GHz RF signal with 155 Mb/s data. The AWG characteristics affecting the performance of the demonstrated schemes have been experimentally investigated.

CHAPTER SIX: Integration of Millimetre-Wave Fibre-Radio Networks in WDM Optical Access Infrastructure

In this chapter, hybrid multiplexers and demultiplexers for simultaneous transmission of optically modulated BB, IF and RF signals are proposed, which realises an integrated optical network in the access and metro domain. In order to realise such networks with DWDM channel spacing smaller than the mm-wave RF carrier frequency, a hybrid WI technique is proposed. The functionality of the wavelength-interleaved hybrid multiplexer and demultiplexer are verified experimentally with three DWDM signals consisted of a BB signal with 1 Gb/s data, a 2.5 GHz IF signal with 155Mb/s data and a 37.5 GHz RF signal with 155Mb/s data, spaced at 12.5 GHz.

CHAPTER SEVEN: Conclusion and Future Work

This chapter summarises the important conclusions derived from this research project. Suggestions for future work based on the finding of this thesis are also included.
1.5 Original Contributions

The major contributions of this thesis are stemmed from the proposed system technologies and architectures and their experimental demonstrations in implementing WI-DWDM mm-wave fibre-radio network, integrated optical access network as well as the realisation of a simplified and consolidated BS architecture. Following are the original contributions originated from the research undertaken for this thesis. Publications arising from this work are listed in Section 1.6 and also in Appendix B, for convenience.

Chapter 3

- Proposal of a multifunctional WDM optical interface that enables OADM functionality to the BS, and offers a simplified BS by eliminating the need for a light-source in the uplink direction [Publication Ref: 1, 10, 11, Section 1.6].

- Experimental demonstration of the proposed WDM optical interface with three wavelength-interleaved DWDM signals spaced at 25 GHz, each of them carrying 37.5 GHz RF signal with 155 Mb/s BPSK data [Publication Ref: 1, 10, 11, Section 1.6].

- Introduction of new scheme to enhance the modulation depths of optical mm-wave signals and verification of its functionality by simulation.

Chapter 4

- Experimental characterisation of the performance of single and cascaded WDM optical interfaces [Publication Ref: 3, 12, Section 1.6].

- Simulation characterisation of the performance of single and cascaded WDM optical interfaces [Publication Ref: 1, Section 1.6].
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- Development of analytical models to predict the cascadability of WDM optical interfaces for more than two interfaces in cascade [Publication Ref: 3, Section 1.6].

- Incorporation of modification to the proposed WDM optical interface that improves the link performance, both in uplink and downlink directions [Publication Ref: 6, 13, 21, Section 1.6].

- Demonstration of the modified WDM optical interface in experiment [Publication Ref: 6, 21, Section 1.6].

- Development of analytical models to predict the impacts on the cascadability of WDM optical interfaces due to the incorporation of the modification.

Chapter 5

- Proposals of novel multiplexing schemes to multiplex WI-DWDM signals, which also improve the overall link performance by enhancing the modulation depth indices, while multiplexing [Publication Ref: 2, 4, 14, 18, 19, Section 1.6].

- Experimental demonstration of the proposed multiplexing schemes with 37.5 GHz-band optical mm-wave signals, spaced at 25 GHz [Publication Ref: 2, 4, 14, Section 1.6].

- Proposal of a demultiplexing scheme to demultiplex WI-DWDM signals and its experimental demonstration [Publication Ref: 4, 15, Section 1.6].

- Proposal of a simultaneous multiplexing and demultiplexing scheme that offers simple, compact and low-cost CO and remote nodes for mm-wave fiber-radio networks, which also improves the overall link performance by
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enhancing the modulation depth indices of the multiplexed signals [Publication Ref: 4, 15, 18, 19, Section 1.6].

- Experimental demonstration of the proposed simultaneous multiplexing and demultiplexing scheme with 37.5 GHz-band 25 GHz spaced WI-DWDM downlink signals and the uplink signal separated from the desired downlink signal by multiples of FSR of AWG [Publication Ref: 4, 15, Section 1.6].

- Experimental demonstration of the proposed simultaneous multiplexing and demultiplexing scheme with 37.5 GHz-band 25 GHz spaced WI-DWDM downlink signals and the uplink signal from reuse of the optical carrier of the desired downlink signal [Publication Ref: 4, 9, 15, 20, Section 1.6].

- Experimental characterisation of the effects of optical crosstalk on the demonstrated system technologies for WI-DWDM network [Publication Ref: 4, Section 1.6].

- Experimental characterisation of the performance of the AWG used in demonstrating the proposed system technologies and architectures [Publication Ref: 4, Section 1.6].

Chapter 6

- Proposals of hybrid multiplexing and demultiplexing schemes, which realises integrated optical network in the access and metro domain [Publication Ref: 7, 8, 16, 22, Section 1.6].

- Introduction of a novel hybrid wavelength interleaving technique, by which integrated DWDM network with a channel spacing smaller than them-wave RF carrier frequency can be realized [Publication Ref: 7, 8, 16, 22, Section 1.6].
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- Design of hybrid multiplexer for WI-DWDM integrated access network [Publication Ref: 8, 16, Section 1.6].

- Experimental demonstration of hybrid wavelength-interleaved multiplexing scheme incorporating 37.5 GHz RF, 2.5 GHz IF and BB signals for a DWDM integrated access network, spaced at 12.5 GHz [Publication Ref: 8, 16, Section 1.6].

- Proposals of hybrid demultiplexing schemes for WI-DWDM integrated access network [Publication Ref: 7, 22, Section 1.6].

- Experimental demonstration of a hybrid wavelength-interleaved demultiplexing scheme incorporating 37.5 GHz RF, 2.5 GHz IF and baseband signals for a DWDM integrated access network, spaced at 12.5 GHz [Publication Ref: 7, 22, Section 1.6].

1.6 Publications Originated from This Work

JOURNAL PUBLICATIONS


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CONFERENCE PUBLICATIONS


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1.7 References


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2 LITERATURE REVIEW

2.1 Introduction

Chapter 1 has outlined how millimetre-wave (mm-wave) fibre-radio systems are developed to meet the future bandwidth requirements for broadband wireless access (BWA) in ‘last mile’ communication. A generic architecture of mm-wave fibre-radio network is shown in Fig. 1.3. In these networks multiple remote antenna base stations (BSs), suitable for untethered connectivity for the BWA services, are directly interconnected to a central office (CO) via an optical fibre feeder network [1-4]. Due to the high propagation losses of mm-wave signals, the radio coverage of these BSs shrink to microcells and picocells, which implies the need for a large number of antenna BSs to cover a certain geographical area [4-12]. Therefore, the BS architecture has to be simplified and cost effective, whereas, the fibre feeder network has to be able to support the large number of BSs required to service a certain geographical area. This chapter presents a comprehensive review of the research in mm-wave fibre radio systems and the associated technologies, providing a motivation for the topics covered in the rest of the thesis.

Section 2.2 presents a comprehensive review of the research towards the simplification of BS architectures. The literature on spectrally efficient fibre feeder networks that support a large number of BSs required to service a certain geographical area is reviewed in Section 2.3. Also, the literature involving the
network impairments in wavelength-division-multiplexed (WDM mm-wave fibre-radio networks and the modulation depth enhancement of mm-wave fibre-radio links are summarised in Sections 2.4 and 2.5 respectively. The literature towards the realisation of an integrated optical access network incorporating mm-wave fibre-radio systems are reviewed in Section 2.6.

2.2 Base Station Architecture

As mentioned earlier, the successful deployment of mm-wave fibre-radio systems is largely dependent on the development of simple, compact, light-weight and low-cost BS. The possible strategy to realise such a BS is a highly centralised CO along with less-equipped BSs, in which optical as well as mm-wave components and equipment are expected to be shared with a large number of BSs [13]. The centralised network arrangement allows to simplify the BSs to having transmitter and receiver with additional optoelectronic & electrooptic (O/E) interface to detect and transmit optical mm-wave signals [1,14]. The introduction of WDM in fibre feeder network enable these systems to interconnect multiple BSs to the CO through a

![Fig. 2.1: Generic BS architecture incorporating 3 integrated interfaces: OADM interface adds and drops the desired channels to and from the feeder network, O/E interface converts signals from optical-to-electrical and electrical-to-optical form and rf interface having RF signal processing and conditioning circuits, diplexer and radiating antenna.](image-url)
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single fibre (both in the star-tree and ring/bus network configuration), where each of the BSs will be needed an optical-add-drop-multiplexed (OADM) interface to add and drop the desired channels to and from the feeder network [15-17]. Fig. 2.1 shows the generic BS architecture consisting of 3 integrated interfaces: the OADM interface adds and drops the desired channels to and from the feeder network; O/E interface, consisted of optical modulator, photodetector (PD) and uplink light-source, converts signals from optical-to-electrical and electrical-to-optical form; and radio-frequency (rf) interface, consisted of mm-wave radio-frequency (RF) signal processing circuits, diplexer and radiating antenna, does the required conditioning/modification on the RF signals and before sending it to the next hop. Among these 3 interfaces, the complexity of the rf interface is largely dependent on the data transport schemes that distributes the radio signal over fibre from the CO to the BSs, where by optimum selection of the data transport scheme, the complexity of the BSs can be greatly reduced. The following section reviews the complexity of the BSs based on the data transport schemes currently proposed for the implementation of mm-wave fibre-radio systems.

### 2.2.1 Data Transport Schemes

There are three possible data transportation methods, which have been considered in distributing the radio signals over fibre from the CO to the BSs with their relative merits and demerits [18-20]. These methods can be termed as baseband(BB)-over-fibre, intermediate frequency (IF)-over-fibre, and RF-over-fibre.

In baseband-over-fibre scheme, signal will be transported over fibre as optically modulated BB signal and will be up/down converted at the BS, by which additional signal management in the optical domain can be avoided. This scheme enables the use of matured, proven and industry driven digital and microwave technologies; in addition to minimum chromatic dispersion effect on the delivery of sub-Gb/s data stream over fibre [21-26], which enables distribution of mm-wave signal over longer distances without regeneration. Also, this scheme has the potential to merge mm-wave fibre-radio systems to the internet protocol (IP) based gigabit ethernet (GbE), asynchronous transfer mode (ATM) etc. access technologies, by which an integrated
optical access network can be easily realised [27-28]. However, those benefits are offered at the expense of a complicated BS architecture, as additional hardware and signal processing circuits are required at the BS to process the received and transmitted radio signals. Fig. 2.2 shows the generic BS architecture that enables BB-over-fibre transport scheme for mm-wave fibre-radio systems. As shown in the Fig. 2.2, the radio signal in the rf interface needs to pass through multistage up/down conversion and multiple radio channel enabling hardware, in addition to RF signal conditioning circuits, diplexer and radiating antenna, which make the BS complex, bulky and expensive. In addition to the system complexity, the requirement of up and down conversion devices decreases the systems’ flexibility in reconfiguring the channel assignment scheme by centralised control and monitoring, since each of the remotely located local oscillators (LOs) in the BSs needs to be detuned separately [14, 21-24].

In IF-over-fibre scheme, signal will be transported over fibre at IF and will be up/down converted to/from mm-wave signal at the BS. This scheme also provides similar advantages of using matured, proven and industry driven digital and
microwave technologies; while experiences lower chromatic dispersion effect on the delivery of sub-Gb/s data stream over fibre [29-30]. Similar to BB-over-fibre scheme, those benefits also can be realised at the expense of a complicated BS architecture, as additional components and equipment, such as LO and mixer are needed at the BS to up/down convert the radio signals before it is radiated by the antenna or converted to optical signal by O/E interface. The generic architecture of the BS in IF-over-fibre transport scheme can be seen from Fig. 2.3. Like before, due to having LOs and mixers, this scheme also is not flexible for centralised control and monitoring [1, 14, 31-32]. However, this scheme is suitable for implementing multiple channel transmission by using subcarrier multiplexing (SCM), where different radio channels can be superimposed onto different subcarrier frequencies before the combined signal is modulated by an optical carrier and is transported over fibre [6, 15, 33-37]. Moreover, the remote delivery of LO from the CO can eliminate the physical LO from the BS, by which the benefits of centralised network arrangement can be realised [38-44].

In RF-over-fibre scheme, signal will be transported over fibre as optically modulated mm-wave RF signal, which eliminates all the up/down conversion as well as multiple channel transmission hardware from the BS leading to a simple, compact,
low-cost and light-weight BS architecture [45-54]. The schematic depicting such a BS is shown in Fig. 2.4. The BS architecture in this scheme trades off complexities in rf interface with that of OADM and O/E interfaces. In this scheme, the optical link is transparent to the radio signal transmission, as the mm-wave radio signals do not undergo any frequency translation during transmission over fibre. The use RF antenna remoting in such scheme allows dynamic and reconfigurable channel allocation, in addition to simplifying the provision of rapid handover (reduce the number of handovers) and diversity combining from a central location [14, 31-32, 55]. Similar to IF-over-fibre scheme, this scheme is also suitable for implementing multiple channel transmission by using SCM, by which integrated radio frequency services can be easily realised [35-37, 43-44]. However, RF-over-fibre transport is susceptible to the adverse effects of fibre chromatic dispersion (CD), which limits the fibre transmission distance severely [22, 25-26, 56-58]. This can be overcome by using a suitable chromatic dispersion mitigation technique, although some of which require additional hardware to be employed in the BS [59-66]. Also, this scheme is based on high frequency optoelectronic devices most of which are still expensive and yet to mature. Furthermore, this scheme gives more emphasis on the optical domain rather than taking the benefits of more matured electrical technologies, which
requires special attention in realising mm-wave fibre-radio systems through optical infrastructure in the access and metro domain.

Despite the relative merits and demerits of all the three transport schemes, RF-over-fibre scheme resolves the fundamental requirement of dynamic and reconfigurable channel allocation in mm-wave fibre-radio systems by enabling centralised control and monitoring, while realising simplified and consolidated BS architecture by eliminating all the up/down conversion devices from the rf interface. Therefore, RF-over-fibre based BSs have been considered for the future delivery of mm-wave signals to customers, and have attracted much research in the recent past.

Shown in Fig. 2.4, RF-over-fibre scheme enabled remote antenna BS consists of three interfaces (OADM, O/E and rf interface) containing a light-source, photodetector, optical modulator, RF amplifiers and signal conditioning circuits, diplexer, and radiating antenna, in addition to an OADM, as described in the previous sections. Although these can be housed in a quite small module, they are reasonably complex and expensive. To further simplify the BS architecture, research has been focused on ways to reduce the complexity of OADM as well as O/E interface, as the BS architecture in this scheme trades off complexities in rf interface with that of OADM and O/E interfaces. Two different modulation building blocks are the inherent core technologies which stimulated two different research directions in achieving the goal of simplified BS [67-70]. These are multiple quantum wells (MQW) based electroabsorption modulator (EAM) and travelling wave structure based electrooptic modulator (EOM).

### 2.2.2 Simplified BS Based on EAM

To simplify the BS by reducing the component counts, a multifunctional electroabsorption transceiver (EAT) based on EAM technologies has been introduced [71-87], which replaces uplink modulator as well as downlink PD in the BS and simplifies the O/E interface of the BS to a single component configuration. EAT is a MQW active waveguide in III-V compound semiconductor which exploits the quantum confined Stark Effect (QCSE). In a quantum well (QW), electrons and holes are confined in the same physical QW, where they form a bond similar to a
hydrogen atom. This bonded particle, termed as ‘exciton’, has a strong absorption somewhat similar to an atomic absorption, and is localised in the vicinity of wavelengths corresponding to the band-gap of the QW. When an external electric field is applied, electron and hole are forced to be physically separated to the opposite ends of the QW and the interaction of the electron and the hole is reduced and the absorption due to the bonded exciton is decreased and broadened. This property of the QW enables the modulation of the absorption very strongly with external fields around a narrow wavelength range and known as the QCSE [69]. Above absorption edge wavelengths, EAT yields a large extinction ratio and below absorption edge, the wavelength is strongly absorbed. Therefore, a single EAT can simultaneously serve as the optoelectronic and electrooptic converter for the uplink and downlink communication. The optimum performance of an EAM is generally achieved at optical wavelengths approximately 40-60 nm above the excitonic resonance wavelength of the MQW structure. The reason behind this is the small fundamental absorption of the unbiased modulator within this wavelength region, which, due to the QCSE, can be increased drastically by applying a reverse bias. In order to use the same MQW structure for both modulation as well as photodetection at the same wavelength, a large fundamental absorption is required that achieves high responsivity. This can be accomplished by adjusting the biasing voltage (reverse bias) of the MQW structure for either efficient modulation or efficient photodetection. The EAT introduced by Moodie (D.), Wake (D.) et. al. [71-75] accomplishes such an EAT that removes the light-source from the uplink path by remodulating the unabsorbed downlink optical power from the photodetection, in addition to enabling modulation and photodetection functionality. The main drawback of this approach is that the reverse biasing of the MQW structure needs to be switched and optimised separately in order to distinguish between modulation and detection performance and, therefore, EAT of this kind effectively allows only half duplex transmission, instead of full duplex transmission [76-77]. However, full-duplex transmission can be achieved by providing an intermediate bias, where the performance of the EAT is a trade off between the modulation and detection performance [78]. In order to realise efficient modulation and photodetection together through a single EAT, dual light-wave enabled MQW structure was
introduced [79-87]. In this approach, the EAT is operated with two different wavelengths simultaneously, the first wavelength is adjusted for optimum modulation while the second wavelength for optimum detection performance. The dual light-wave technique enables full-duplex transmission with optimum device performance. The schematic diagram of the dual light-wave enabling EAT is shown in Fig. 2.5, which is comprised of three characteristic regions: a photodetection, a passive waveguide and a modulation region serving all the three fundamental functionality in the O/E interface of a BS for upstream and downstream

Fig. 2.5: Multifunctional electroabsorption transceiver based on MQW III–V semiconductor active waveguide, which performs photodetection and modulation functionality together and offers the provision for remote delivery of uplink optical carrier: (a): the generic architecture, (b): the exciton absorption vs. wavelength curve, where the absorption edge of the structure changes with the applied reverse-bias voltage due to the quantum-confined Stark effect.
communication. The uplink optical carrier requirement is met by remotely delivered optical pilot tone as the consequence of dual light-wave technique. The downlink optical mm-wave signal along with the uplink optical pilot tone are recovered from the fibre feeder network by using the OADM interface of the BS (as shown in Fig. 2.4), and are fed to the EAT. The downlink optical mm-wave signal and the uplink optical pilot tone are assigned wavelengths from C-band (1530-1560 nm) and L-band (1560-1600 nm) respectively. The EAT then simultaneously enables the detection of the downlink optical mm-wave signal as well as the modulation of the uplink optical pilot tone with the uplink mm-wave signal, which is looped back to the CO via the OADM interface of the BS.

Although the multifunctional EAT simplifies the O/E interface of the BS to a single component configuration, it exhibits poor performance in propagation loss due to free carrier as well as band-to-band absorption, and poor power handling capability due to carrier pile up. The characteristics of EAT are also very sensitive to wavelength and temperature changes and therefore strict bias control in necessary during operation. This dependency can be detrimental in WDM fibre-radio systems while routing the signals to the destination [69-70, 88]. Moreover, EAT is inherently designed to generate optical mm-wave signal in double sideband with carrier (ODSB+C) modulation format, which is susceptible to the adverse effects of fibre chromatic dispersion, and requires additional dispersion compensation before transporting over fibre [56-60, 89-90]. Moreover, due to the dual light-wave technique, EAT based systems require separate wavelengths both in uplink and downlink directions and unable to exploit the benefits of wavelength reuse technique [91-92], which limits the number of supportable BSs within the flat gain-region of erbium-doped-fibre-amplifier (EDFA). In addition, the remote delivery of uplink optical carrier still requires the light-source to be located at the CO, which increases its cost and complexity.

The following section reviews the simplification of BSs, where travelling wave structure based electro optic modulator is used as the inherent core technology.
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2.2.3 Simplified BS Based on EOM

To overcome the difficulties of EAT based BSs, an alternative approach is the introduction of wavelength reuse technique in the OADM interface, which simplifies the O/E interface by removing the light-source from the uplink path [92-94]. This technique uses EOM instead of EAM, which is also suitable for the dispersion tolerant generation of the optical mm-wave signals in optical single sideband with carrier (OSSB+C) modulation scheme [57, 59-61].

In EOM, travelling wave electrodes are designed as the transmission medium, which exhibits distributed capacitance. Therefore, unlike the EAM, modulation speed of the EOM is not affected by the RC time constant. Also in a EOM, the modulating mm-wave signals on the electrode travel in the same direction of the optical carrier. If mm-wave signals in both the electrode travel at the same velocity, the phase change induced by the mm-wave signal is integrated along the length of the electrode. Since the electrode capacitance does not limit the bandwidth of the modulator, the electrode can be made very long, which allows even a very small phase change over a wavelength to be accumulated to an appreciable value. Thus the driving voltages for such devices can be significantly reduced without reducing the bandwidth. However, to reduce the drive voltage of the modulator, it is important that the electrode is able to generate strong directional electric field dictated by the electrooptic material of the device, overlapping the optical modes. All these requirements on the electrode are often conflicting, which requires compromises to certain extend. Moreover, the properties of the electrode are dependant on the materials used. The main properties of the EOMs such as bandwidth and drive voltage are mostly determined by the properties of the electrode, which will be most efficient if the group velocities of the electrical and optical signals are matched [67-69, 88, 95-97]. Among different designs of EOMs, Lithium Niobite (LiNbO₃) based Mach-Zehnder modulator (MZM) is the most popular for the generation of optically modulated mm-wave signal due to its combination of high electro-optic coefficients and high optical transparency in the near infrared wavelengths [69, 88]. LiNbO₃ is a ferroelectric crystal, commonly used in various types of commercial products, and are readily available in the market [69].
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Although LiNbO$_3$ based MZM modulator are impressive for mm-wave applications, the drive voltages required at high frequencies are still high. The high drive voltage of the modulator complicates the implementation, as it requires higher voltage sources, in addition to temperature control circuits to regulate the modulator temperature. A technique that has significantly enhanced the performance of MZM modulators is incorporation of ridge waveguides. Ridge waveguide further improves the focusing of the electric field under the hot electrode and have been used to achieve drive voltages of 3.5V for Z-cut modulators with 3 dB bandwidths of 30 GHz and 70 GHz respectively [69, 88]. In addition, bias stability, which is very good with the MZM modulators, is another issue to be noted. Under the control of automatic biasing circuit, they can operate at constant bias for thousands of hours [69].

Fig. 2.6 shows the schematic diagram of the OADM and O/E interface of the BS that simplifies the BS by removing the uplink light-source, in addition to enabling LiNbO$_3$ based MZM modulator, suitable for dispersion tolerant OSSB+C modulation.

![Fig. 2.6: Schematic diagram of wavelength reuse enabled OADM and O/E interface of the BS, where a portion of downstream optical carrier is recovered and reused for upstream transmission in addition to enabling LiNbO$_3$ based MZM modulator, suitable for dispersion tolerant OSSB+C modulation.](image-url)
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modulation. OADM interface recovers the downlink optical mm-wave signal from the fibre feeder network and uses a wavelength reuse technique to recover a portion of the downlink optical signal to provide optical carrier for the uplink path. The recovered carrier was then used by the MZM of the O/E interface, which at the presence of uplink mm-wave signal generates OSSB+C modulated uplink optical mm-wave signal and adds it back to the OADM interface in order to send it to the CO through the feeder network. The remaining portion of the downlink signal is used by the PD of the O/E interface, which recovers the downlink mm-wave signal to be sent to the rf interface of the BS as shown in Fig. 2.4.

Wavelength reuse or ‘single wavelength for single BS’ technique is a smart method that eliminates the need for a separate light-source for upstream communication. This technique enables the fibre feeder network to support additional BSs through a single CO by increasing the availability of optical carriers within the flat-gain region of EDFA, which is very important in future WDM fibre-radio networks. Moodie (D.), Wake (D.) et. al. [71-75] first introduced a wavelength reuse technique in mm-wave fibre-radio antenna BSs that removes the uplink light-source from the BS by remodulating the unabsorbed downlink optical power from the detection functionality of the MQW structured multifunctional EAT. However, this approach of reusing downlink signal exerts fundamental difficulties in the EAT, and was avoided in the consequent demonstrations, where wavelength reuse technique was replaced with a dual light-wave technique [79-87]. The effective utilisation of wavelength reuse technique in mm-wave fibre-radio systems was introduced by Nirmalathas (A.) et. al. in [92-93], which was complemented by Kuri (T.) et. al. in [94]. They have proposed two alternative methods to recover a fraction of the downlink signal in the OADM interface of the BS to be reused in the O/E interface as the optical carrier for uplink path.

In the first technique, downlink optical mm-wave signal (in OSSB+C modulation format) is equally divided into two halves by a 50:50 coupler. One half goes directly to the PD of the O/E interface, where the downlink mm-wave signal is recovered, and the other half is being transmitted through a combination of an optical isolator and a 100% reflective fibre Bragg grating (FBG), the schematic diagram of which can be seen from Fig. 2.7. As shown in the Fig. 2.7, 100% reflective FBG reflects the
modulation sideband completely from the transmitted signal, while allows the optical carrier to pass through to the OSSB+C modulator in the O/E interface to generate optically modulated uplink mm-wave signal. The main drawback of this technique is the wastage of 50% of the modulation sideband power, which weakens the downlink optical mm-wave signal to be detected by the PD. Also, the 100% reflective FBG is designed to reflect only the selective modulation sideband separated from the optical carrier by the mm-wave frequency, which limits the proposed scheme to a specific BS.

In the second technique, the drawbacks of the first technique was overcome by employing an optical circulator (OC) and a 50% reflective FBG filter, instead of using a 50:50 coupler and a 100% reflective FBG filter. The schematic diagram of the second technique can be seen in Fig. 2.8. It shows that the downlink optical mm-wave signal (in OSSB+C modulation format) enters the optical circulator through port-1, travels from port-1 to port-2, and encounters the 50% reflective FBG at port-2, which reflects 50% of the optical carrier from the downlink optical mm-wave
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signal. The reflected optical carrier is recovered at port-3 of the OC and is delivered to the OSSB+C modulator in the O/E interface to generate optically modulated uplink mm-wave signal. The remaining 50% of the optical carrier, along with the modulation sideband, passes through the 50% reflective FBG to the PD of the O/E interface, where it is detected and recovered the downlink mm-wave signal.

Despite the relative merits and demerits of both the techniques of simplifying the BSs, EOM based technique uses more impressive LiNbO₃ based MZM modulator and effectively resolves the fundamental chromatic dispersion problem by enabling OSSB+C modulation without employing additional optical hardware. Therefore, EOM based BSs are more attractive over EAM based BSs, and considered for further investigation in Chapters 3 and 4.

The following section reviews the integrated circuit approaches towards the simplification and miniaturisation of the BSs in mm-wave fibre-radio networks.

![Fig.2.8: Configuration for optical carrier recovery based on an optical circulator in conjunction with an FBG filter. [courtesy: Ref [93]: A. Nirmalathas et. al. ]](image)
2.2.4 Integration of the Components of the BS

Another approach of reducing the complexity of the BSs is the simplification and the miniaturisation of the optoelectronic, mm-wave and radiation components via fabricating integrated circuit [98-99]. Integrated circuit approach offers the advantage of low cost manufacture, since the amount of manual labour involvement decreases significantly. Also, integrated approach reduces the parasitic effects associated with packaging and interconnects [99-102].

There are two main approaches for integration and packaging of the optoelectronic, mm-wave and radiation components of the BSs. In the first approach, optoelectronic (e.g. PD) and rf (e.g. monolithic millimetre-wave integrated circuit (MMIC) amplifier) and radiation (e.g. antenna) devices, both active and passive, are grown monolithically on a single chip to perform all the functionality together. The resulting chip is termed an optoelectronic integrated circuit (OEIC) or, monolithic integrated circuit (MIC). It offers several advantages including the potential for low cost manufacture as well as the elimination of bond wire parasitic effects associated with packaging and interconnects of BS devices, ensures device uniformity, ability to test on-wafer and the use of batch processing. Therefore, OEIC/MIC has been considered as the most optimum solution in realising BSs for the mm-wave fibre-radio systems. However, there are several key issues associated with this technology that need to be addressed and resolved, which outweighed the benefits of this technology and have slowed their practical deployment. One of major shortcoming is the additional complexity of OEICs over electronic counterpart, as they involve a mix of planar and vertical structures resulting in complicated multistep growth and fabrication sequences, which reduces the achievable yields. Another fundamental problem is the lack of suitable material for OEICs that can simultaneously optimise optoelectronic and mm-wave functionality together. Although OEIC technology has the potential for low cost manufacture for large volume production, the on-chip customisation is highly expensive for small scale production. Therefore, integration of optoelectronic, mm-wave and radiation components based on OEIC is not straightforward, and still an active area for further investigation [88, 96, 100-105].
In the second approach, various devices are combined on a common substrate using surface mount methods and passive optical waveguides and electronic interconnects in a similar manner to multichip module (MCM) technology, which is termed as hybrid optoelectronic integration (HIC). Silicon is the preferred choice as the substrate, and the technology associated with the silicon substrate is known as silicon optical bench or silicon waferboard. This technology offers the designers to use the most appropriate material and device structure for each component type, instead of single material limitation of OEICs. This allows optoelectronic and mm-wave devices to be optimised individually, by which the best overall subsystem performance can be realised. The advantages of HIC technology include its flexibility and cost effectiveness, although it requires manual trimming to achieve optimum performance and therefore can be labour intensive. Hybrid optoelectronic integration offers a potential route to reducing the cost of packaging [88, 96, 100-105].

Waterhouse (R. B.) et. al. [106] has again divided the hybrid integration technique into indirect and direct integrations. In indirect integration, optoelectronic, mm-wave and radiation devices of the BSs are designed and developed preferably using planer technology on an optimised combination of materials. In this approach, each of the functional modules are developed relatively independently, and interconnected using small sections of transmission lines (typically 50Ω) and series of bond wires. As example, diplexer/filter can be designed independently of the antenna or the photodiode as long as each component has input/output ports are matched to the specified impedance. Antenna can be designed using full-wave spectral analysis, whereas, diplexer/filter can be designed using transmission line theory. However, this technique suffers from the larger size terminal (compared to direct integration) and labour-intensiveness of the integration, in addition to the loss associated with the interconnections [106].

In the direct integration approach, all the functional module utilise a common material to overcome the issues associated with the development of smaller terminal and independent transmission line sections, in addition to using separate material to develop the special aspects of each of the component. The direct integration can be considered as the bridging between the indirect integration and OEIC technologies,
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Fig. 2.9: A typical configuration for an integrated fibre-optic millimetre-wave emitter comprising of a high-power photodiode and a planar antenna. The PD chip is flip-chip mounted on the antenna made on Si substrate, where the antenna chip is bonded to the hemispherical Si-lens in order to collimate mm-wave signals in the opposite direction of the optical illumination [courtesy: Ref [99]: T. Nagatsuma et. al.]

by which some of benefits of OEIC approach is realised. The direct integration approach also experiences the drawbacks of larger wafer requirement to accommodate the foot-print of the component modules, in addition to the difficulties in design process due to various material requirements. Despite these drawbacks, the development of sophisticated micro-matching and flip-chip technologies enables the direct integration to be a cost effective solution for the integration optoelectronic, rf and radiation components for the future mm-wave fibre radio antenna BSs [106].

Based on the above-mentioned integration technologies, several demonstrations that combine different components of the O/E and rf interfaces are described in [99-101, 105-111], which realise the desired simplified, consolidated and cost-effective BSs. As example, integration of PD with antenna as well as other mm-wave signal
enabling components were demonstrated in [99, 101, 110-111], a typical architecture can be seen in Fig. 2.9.

A broadband photonic antenna interface chip combining PD, MMIC low noise amplifier (LNA), diplexer, medium power amplifier (MPA), and band pass filter (BPF) together was demonstrated in [105], which is suitable for mm-wave fibre-radio systems covering multiple service applications. The chip can be used to recover and radiate the downstream 26 - 40 GHz mm-wave radio signals, in addition to simultaneously enabling recovery of LO signal to downconvert the upstream mm-wave wireless signal while necessary before transmit over fibre [105, 106]. A photograph of the demonstrated broadband integrated mm-wave photonic-antenna BS package can be seen in Fig. 2.10.

However, due to the anisotropic nature and the high permittivity of the LiNbO₃ material of the EOM modulators, the design of printed antenna based on LiNbO₃ material becomes extremely complex and not many explorations have been reported.
As a way to overcome, *hi-lo* stacked patch antenna technology was exploited, by which the concerns of the LiNbO$_3$ material in designing printed antennas have been alleviated. A typical schematic diagram of the LiNbO$_3$ *hi-lo* stacked patch antenna can be seen in Fig. 2.11, where LiNbO$_3$ is used as the feed substrate for both z cut and x-cut crystal orientations.

### 2.3 Efficient Fibre Optic Feeder Network

In mm-wave fibre radio systems, multiple remote antenna BSs are directly interconnected to a CO via an optical fibre feeder network, as illustrated earlier in Chapter 1. Due to the reduced coverage of the BSs at such high radio frequencies, a large number of BSs are required to cover a certain geographical area. Therefore, the challenge is the realisation of a simplified, consolidated and cost-effective BS, while
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enabling the fibre feeder network to support the required large number of BSs to service a certain geographical area.

The introduction of OSSB+C modulation as well as tandem single sideband modulation enables increased spectral efficiency by reducing the required spectral-band for an optical mm-wave channel, in addition to mitigating the effect of fibre chromatic dispersion due to ODSB+C modulation format [59-61,112-122]. The tandem single sideband modulation effectively doubles the capacity of the mm-wave fibre-radio systems while compared to the conventional ODSB+C based systems [121-122]. However, the use of WDM in fibre feeder networks can resolve the challenge by enabling transport of multiple optically modulated mm-wave signals, feeding multiple antenna BSs through one fibre [15-16, 23, 36-39]. The following section reviews the literatures towards the implementation of WDM fibre feeder network in mm-wave fibre-radio systems.

2.3.1 Wavelength Division Multiplexed MM-Wave Fibre-Radio

WDM is an elegant and effective way to increase the capacity of the fibre optic feeder networks in mm-wave fibre radio systems. In the WDM incorporated feeder networks, optical mm-wave channels, each carried by a separate wavelength, are transmitted to/from the BSs via the CO through a single fibre that provides quantum increase in network capacity without the need for laying new fibre [15-16, 23, 36-39, 44, 89, 92-93, 123-129]. It also simplifies the network upgrades and the deployment of additional BSs, while support multiple interactive services for future broadband wireless access communications [15, 36-37, 125-126].

Fig. 2.12 shows the general concept of a typical mm-wave fibre-radio system incorporating WDM. In the downlink direction, optical mm-wave channels, spaced at an effective WDM separation, are generated in the CO by using WDM optical sources, and are passed through a suitable multiplexer that aggregates them to a composite signal. The multiplexed signals are then transported over optical fibre to the remote nodes (RN), where the individual optical mm-wave signals are demultiplexed and directed to antenna BSs for mm-wave wireless distribution. In the uplink direction, mm-wave signals generated at the customer sites are converted
from electrical-to-optical form at BSs and sent to the RN, where the optically modulated signals are multiplexed before directed to the CO through fibre for further processing. Such fibre-radio feeder network enables a large number of BSs remotely share the switching and signal processing hardware located at the CO, in addition to simplifying the complexity of BSs by enabling passive multiplexing and demultiplexing functionality at the RNs. Since each of the optical mm-wave channels are effectively separated from others, they can be independent in protocol, speed, and direction of communication. As mentioned in Chapter 1, it is envisaged that future wireless bandwidth will be met by mm-wave WDM fibre-radio systems, where each of the remote antenna BS will be allocated a WDM optical carrier to transport the optically modulated mm-wave signals to/from the CO through the fibre optic feeder network, irrespective of direction of communication. However, using the same wavelength for both downlink and uplink communication is not any requirement, since channel offset scheme as well as interleaved downlink and uplink channels can also be used.
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With the maturity of WDM components and system technologies, the effective WDM channel separations in the conventional optical access and metro domain are gradually replaced with dense-wavelength-division-multiplexing (DWDM) separations of 100 GHz, 50 GHz, and 25 GHz. The introduction of DWDM fibre feeder networks in mm-wave fibre-radio systems may surprisingly increase the capacity of the systems by supporting huge number of BSs required for future multiple interactive broadband wireless services. Also, it is important that mm-wave fibre-radio systems can coexist with other conventional DWDM access and metro technologies, as it is expected that mm-wave fibre-radio systems will be realised by utilising the unused capacity of the existing optical infrastructure in the access or metro domain, instead of deploying separate fibre-radio backbone. However, the inherent wideband characteristics of mm-wave signals (25-100 GHz) impose spectral restrictions in realising fibre feeder network with a channel separation $\leq$ 100 GHz.

Fig. 2.13 shows the optical spectra of OSSB+C modulated N optical mm-wave channels with a WDM channel separation and a mm-wave carrier frequency of $\Delta f_{\text{WDM}}$ and $\Delta f_{\text{mm-wave}}$ respectively, where $\Delta f_{\text{mm-wave}} < \Delta f_{\text{WDM}}$. In order to realise DWDM fibre feeder networks for mm-wave fibre-radio systems, in most of the cases, it is necessary to reduce $\Delta f_{\text{WDM}} < \Delta f_{\text{mm-wave}}$, which has been an active area for

\[\text{Fig. 2.13: Optical spectra of the N optical mm-wave channels in a WDM feeder network for mm-wave fibre-radio systems.}\]
further explorations in the recent past. To realise the DWDM feeder networks by reducing the channel separations smaller than mm-wave carrier frequencies, the data bandwidth capacity of the mm-wave carriers have been considered. The data bandwidth capacity of the mm-wave carriers is usually limited within several Gb/s, and the major portion of the wideband spectra of the optical mm-wave signals remain unused. Wavelength interleaving technique has been introduced, where these unused spectra are utilised to enable sub-GHz channel spacing of mm-wave signals, by which DWDM fibre feeder network can be realised [130-132]. The following section reviews different wavelength interleaving schemes and capacity analysis of the systems incorporating such schemes based on network architectures and BS configurations that realises DWDM fibre feeder network for mm-wave fibre-radio systems.

2.3.2 Wavelength Interleaved MM-Wave Fibre-Radio

In mm-wave fibre-radio systems, when the mm-wave rf signals are imposed on to the optical carrier, sidebands are generated at the spacings equal to the modulating mm-wave frequency. This causes the inter-channel spacing of a WDM feed network for a mm-wave fibre-radio system to rise and restricts the effective WDM channel separation $\geq 100$ GHz. A 100 GHz WDM channel separation in mm-wave fibre-radio system was first investigated in [133], and the analysis of the system was extended in [134] for measuring the crosstalk properties. The properties of a mm-wave fibre-radio system having a WDM channel separation of $<100$ GHz, were first investigated in [135-136], which demonstrates that the channel spacing is strongly dependent on the edge steepness quality of the WDM demultiplexing filter. The investigations have shown that a significant reduction of WDM channel separation even lower than the mm-wave transmission frequency can be realised provided a demultiplexing filter with sufficient edge steepness, offering very low side-lobes, is incorporated. This reduction of channel separation results in an overlap of the first order sidebands of adjacent channels and hence leading to a significant increase in channel number. This investigation in reducing the WDM channel separation in a mm-wave fibre-radio system has been exploited to introduce DWDM compatible wavelength interleaving
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(WI) techniques in the fibre-radio systems, by which 50 GHz or 25 GHz channel separated fibre optic feeder network can be easily realised [130-132]. In these techniques, OSSB+C modulated optical mm-wave channels with a channel separation smaller than the modulating mm-wave signal frequency are multiplexed in such a way that the unused spectral-bands available in between the optical carriers and the respective modulation sidebands of the optical mm-wave channels are occupied by the neighboring DWDM channels. Fig. 2.14 shows the optical spectra of N optical mm-wave channels with a DWDM channel separation and a mm-wave carrier frequency of $2\Delta f$ and $3\Delta f$, respectively. The optical carriers $C_1, C_2, \ldots C_N$ and their respective modulation sidebands $S_1, S_2, \ldots S_N$ (in OSSB+C modulation format) are interleaved in such a way that the adjacent channel spacing, irrespective of carrier or sideband, becomes $\Delta f$. The underlying principle that determines the adjacent channel spacing is the highest common multiple between the DWDM channel separation as well as the mm-wave carrier frequency. Therefore, the optimum selection of the adjacent channel spacing enables the scheme to interleave various optical mm-wave channels, generated by various mm-wave radio channels in different frequency bands. Table 2.1 demonstrates several examples of such adjacent

![Fig. 2.14: Optical spectra of the N wavelength-interleaved optical mm-wave channels in a DWDM feeder network for mm-wave fibre-radio systems.](image-url)
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channel spacings that enable both 40 GHz and 60 GHz band optical mm-wave radio channels to be interleaved with a DWDM channel separation of 20 to 30 GHz:

<table>
<thead>
<tr>
<th>Item</th>
<th>Adjacent channel spacing (GHz)</th>
<th>MM-Wave at 40 GHz-band (GHz)</th>
<th>MM-Wave at 60-GHz-band (GHz)</th>
<th>DWDM channel spacing (GHz)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>12.5</td>
<td>37.5</td>
<td>62.5</td>
<td>25</td>
</tr>
<tr>
<td>2</td>
<td>12</td>
<td>36</td>
<td>60</td>
<td>24</td>
</tr>
<tr>
<td>3</td>
<td>10</td>
<td>40</td>
<td>60</td>
<td>20, 30</td>
</tr>
</tbody>
</table>

Table 2.1: Interleaving schemes for 40 GHz and 60 GHz band optical mm-wave channels, having a DWDM channel separation of 20 to 30 GHz.

The capacity and the link budget requirements of wavelength-interleaved DWDM (WI-DWDM) mm-wave fibre-radio systems were investigated in [137-139]. In doing such, link budget calculation based network models were developed that analyse the overall capacity of the fibre-fed backbone networks, both in star-tree and ring architectures. It shows that an amplified optical link is essential for an optical transmission distance more than 10 km, irrespective of network topologies and architectures. It also demonstrates that the amplifier placement plays a crucial role in the overall capacity and performance of the networks.

The capacity analysis of the WI-DWDM mm-wave fibre-radio systems were further extended in [140], where WI-DWDM ring architectures feeding 4-sector remote antenna BSs (a typical sectorisation scheme for line-of-sight wireless distributions) were explored. This analysis included optimum channel allocations to incorporate guard bands for efficient add-drop functionality with the ability to merge/integrate with standard 100 GHz spaced WDM infrastructure in the access and metro domain. Therefore, each of the 100 GHz band of the gain bandwidth of EDFA is assumed to carry four WI-DWDM mm-wave fibre-radio channels feeding each of
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Fig. 2.15: Wavelength interleaving schemes incorporating guard bands for 4-sector antenna BSs, where scheme (b) is more efficient compared to scheme (a).

the four sectors of the antenna with separate optical mm-wave channel, and terminated with two guard bands for efficient add-drop functionality.

Two different interleaving schemes are considered here with their relative merits and demerits. The optical spectra of these schemes can be seen in Fig. 2.15. It shows that scheme (b) is more efficient compared to scheme (a). However, special attention is needed while implementing scheme (b), as, in this scheme the first and the second channels have to be generated by suppressing the lower sideband (LSB), while the third and the fourth channels have to be generated by suppressing the upper sidebands (USB).

The working principle and the benefits of WI-DWDM mm-wave fibre-radio systems are reviewed and investigated. However, the practical deployments of such systems are largely dependent on the suitable wavelength interleaved multiplexing and demultiplexing technologies, which will be explored in more detail in Chapter 5.
2.4 Impairments in WDM MM-Wave Fibre-Radio

As outlined in Chapter 1, mm-wave fibre-radio technologies, which have the potential to resolve the spectral congestion and the scarcity of transmission bandwidth at lower microwave frequencies, are considered promising technologies for the ‘last mile’ delivery of future BWA services to the customers. In these systems, multiple remote antenna BSs are directly interconnected to a CO via an optical fibre feeder network, where the complexity of the BSs are largely dependent on the data transport schemes that distributes the radio signal over fibre from the CO to the BSs. Among different data transport schemes as described in Section 2.2.1, it is worth noting that the desired simplest architecture results when the system transports the mm-wave radio signal over fibre (RF-over-Fibre scheme). In this

![Diagram](a)

![Diagram](b)

Fig. 2.16: Generation of optical millimetre-wave signal: (a): in ODSB+C modulation format, and (b): in OSSB+C modulation format.
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A scheme optically modulated mm-wave signal is generated by modulating the intensity of a laser via an external modulator, where the conventional external modulators with low modulation index create an optical signal with two modulation sidebands [47-48, 53-54]. These modulation sidebands, onto which data is subcarrier multiplexed, are separated from the optical carrier by the modulating mm-wave carrier frequency. This type of modulated signal, often referred as ODSB+C, is susceptible to the adverse effects of fibre chromatic dispersion, which limits the fibre transmission distance severely [22, 25-26, 56-58]. A typical ODSB+C modulation setup is illustrated in Fig. 2.16(a).

Considering the severity of fibre chromatic dispersion in ODSB+C based mm-wave fibre-radio systems, substantial research has been attracted in recent past. Most of the research was focused in introducing novel dispersion tolerant optical mm-wave signal generation scheme, optimum modulation format, optimum operating conditions for the lasers, in addition to the proposed several mitigation techniques by optical filtering and negative chirp characteristics [59-66, 141]. Fig. 2.16(b) illustrates a typical OSSB+C modulation setup that generates dispersion tolerant optical mm-wave signals. In our investigations throughout the whole thesis, we have generated dispersion tolerant optical mm-wave signals by using such OSSB+C modulation setup, which we will be further elaborated through the contributory chapters.

As described before mm-wave fibre-radio systems will require a large number of BSs to cover a certain geographical area, while the fibre feeder network has to be efficient enough to support the required BSs. To increase the capacity of the fibre feeder network, WDM technologies are introduced [15-16, 23, 36-39, 44, 89, 92-93, 123-129]. In these networks optical mm-wave channels with an effective WDM separation are passed through a suitable multiplexer, where the signals are aggregated before lunching on to the fibre link. The multiplexed signals are then lunched on to the fibre and transported to the other end of the link, where the individual optical mm-wave signal is recovered by using suitable OADM or demultiplexer and directed to the next hop. Therefore, from the CO to the BSs of WDM fibre-radio networks, the optical mm-wave signals pass through several wavelength-selective devices, which have the potential to cause performance
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degradation through optical crosstalk. The primary source of optical crosstalk is the imperfect isolations between WDM channels, introduced by the passive WDM devices, such as MUX, DEMUX and OADM, in addition to the electrical modulation schemes [142-145]. Although the WDM devices generally reject the adjacent wavelength channels by up to 30 dB or more, some residual signals will still be present, particularly if the WDM channels are of unequal power. This type of unwanted crosstalk is termed as inhomodyne or heterodyne or out-of-band crosstalk. The out-of-band crosstalk is relatively less severe and occurs at wavelengths, which are different from the desired signal. A much detrimental type of crosstalk is the homodyne or in-band crosstalk, which occurs at the same wavelength as the desired signal. This type of crosstalk is much more detrimental, the reason is, during photodetection it creates additional mixing terms that degrade the detected signal quality further compared to the out-of-band crosstalk. Also, since it is at same wavelength of the desired signal, it can not be filtered out. The difference between the out-of-band and in-band crosstalk is illustrated in Fig. 2.17.

The effects of in-band and out-of-band crosstalk in WDM fibre-radio networks were analysed in detail in [129, 146-149] with channel spacing around 100 GHz covering amplitude-shift-keyed (ASK) and (binary-phase-shift-keyed) BPSK modulation formats. The demonstrated results confirm the significance of in-band and out-of-band crosstalk, which need to be considered when designing WDM fibre-radio networks.

![Fig. 2.17](image-url)

Fig. 2.17: Optical spectra illustrating different optical crosstalk: (a) out-of-band crosstalk, (b) in-band crosstalk.
Another important network impairment that causes significant performance degradation is the dispersion created by the wavelength-selective optical components, such as FBG. FBGs are considered to be used as narrowband notch filters in OADM interfaces to recover the desired signals from WDM fibre-radio networks. The effect of FBG dispersion across the data bandwidth was investigated in [89,113, 150-151]. The demonstrated results show that grating dispersion can be a potential source of performance degradation, which must be considered when implementing WDM fibre-radio systems

Moreover, the significance of these network impairments is largely dependent on the network topologies and architectures. Like, in the WDM ring/bus feeder networks, multiple OADMs will be used in cascade. The accumulated effects of the impairments (more importantly, optical crosstalk and grating dispersion) in cascaded units can be severe enough to cause distortion of signal waveforms and degradation in the network performance. In Chapter 4, we will investigate the effects of optical impairments in single and cascaded OADM interfaces, both by experiment as well as by simulation models. The analysis will be further extended in Chapter 6, where crosstalk effects on the arrayed waveguide grating based demultiplexer will be quantified experimentally.

2.5 Modulation Depths of MM-Wave Fibre-Radio Links

In mm-wave fibre-radio system, wide bandwidth external modulators are used to superimpose mm-wave signals onto optical carriers. Such wideband fibre optic transmission and signal processing systems typically require a high spurious-free dynamic range (SFDR). As a result, these systems are usually operated with shot noise limited optical detection by avoiding the thermal noise contributions. Increasing the optical power either by utilising optical amplifiers or by using high powered optical sources has the potential to improve the performance of such systems quite effectively. The benefits of optical power increase include lower receiver sensitivity, improved SFDR (gain and noise figure), larger dynamic range,
and higher mm-wave output power. However, these methods increase the average optical power to the PD that causes nonlinearities to output of the PD leading to harmonic distortion to response reduction, and eventually to catastrophic failure through complete damage due to high current or thermal effects [152-156].

Concurrent with PD power limitations, the performance of wide bandwidth intensity modulators are also limited by very narrow linear characteristics. Therefore, modulation depths, which can be defined as the carrier-to-sideband-ratio (CSR) of such wideband optical mm-wave signals, are often sacrificed for less efficient modulation by manageable mm-wave input powers, although high input power of modulating mm-wave signals have the potential to enable larger modulation depths. The combination of lower modulation depth and incident power limitation of PD results in very inefficient mm-wave fibre-radio systems, despite the use of optical amplifiers and high-power lasers [152-154].

As a way to overcome, several modulation depth enhancing techniques were proposed and demonstrated. All optical wideband efficiency improvement of fibre optic systems were proposed and demonstrated in [152-153, 155], where the efficiency of fibre optic systems were improved by reducing the optical carrier,
similar to well-known double sideband suppressed carrier (DSB-SC) modulation. Stimulated Brillouin scattering (SBS) mechanisms were used in [154,156], that depletes the stronger optical carrier (which carries no information) and leaving the weak modulation sidebands (which carry information) unchanged. In multiplexing OSSB+C modulated signals, a variable optical coupler was employed to combine the optical carriers and the respective modulation sidebands, where modulation depth indices of the multiplexed signals can be controlled simply by changing the coupling ratio of the coupler [157]. An FBG filtering based technique was demonstrated in [158], that has the potential to filter the additional optical carrier even for lower optically modulated microwave signals (3 GHz microwave), irrespective of optical modulation formats. The difference in a typical OSSB+C modulated optical mm-wave signal before and after modulation depth enhancement is illustrated in Fig. 2.18.

However, most of these techniques require additional signal processing devices, which unfortunately are inherently susceptible to performance degradation in addition to adding up new complexities to the systems. If the modulation depth enhancement can be combined with the other system technologies by avoiding the additional devices, an effective modulation depth enhancement can be easily realised. In Chapter 4, we propose and demonstrate such a technique where modulation depth enhancement is combined with multifunctional OADM interface of the BS that substantially improves the overall link performance, both in uplink and downlink transportation, in addition to enabling OADM functionality to the BS. This approach is further extended in Chapter 5, where a multiplexing scheme is proposed and demonstrated with the capability to interleave optically modulated mm-wave radio channels in a DWDM fibre-radio system, in addition to enabling a carrier subtraction technique that improves the overall link performance by reducing the CSR of the multiplexed channels. Moreover, in Chapter 6 hybrid multiplexing and demultiplexing of schemes for integrated optical access networks are proposed, which also reduces the CSRs of the optical mm-wave signals via the proposed multiplexers and demultiplexers.
2.6 Integrated Optical Access Infrastructure

The demand for broadband services both in fixed and mobile access networks are gradually increasing. To meet these incremental demands in next generation broadband multimedia and real-time applications, a variety of emerging optical access technologies are introduced in the last mile access network, both in wireless and wireline medium. These include passive optical network (PON)-based implementations such as fibre-to-the-home (FTTH) and fibre-to-the-curve (FTTC), radio-over-fibre (RoF) for BWA applications, etc. just to mention a few. Based on the data transport method over fibre, these technologies can be re-grouped into three heads: (i) BB-over-fibre, where data is directly imposed onto the optical carrier (e.g. GbE, ATM), microwave carrier based IF-over-fibre, where data is imposed onto narrow band microwave subcarrier (e.g. wireless local area network (LAN), broadcast video), and mm-wave carrier based RF-over-fibre, where data is imposed onto broadband mm-wave subcarrier (e.g. LMDS) [159-167]. The optical spectra of these technologies are illustrated in Fig. 2.19.

![Fig. 2.19: Optical spectra illustrating different optical access technologies: (a): baseband-over-fibre, (b): IF-over-fibre, and (c): RF-over-fibre.](image-url)
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The evolution of these access technologies are driven by the need to bring advance services to customers in an efficient way, which may differ with respect to bandwidth, quality of service (QoS), and mobility aspects. Carriers and service providers are actively seeking a convergent network architecture that can facilitate a rich mix of value added and clearly differentiated services via a mix of wireless and wireline solutions to meet the demand for mobility, bandwidth and range of connectivity options from the customer [27-28]. All these requirements can be met by offering an integrated telecommunication package, for which an integrated access network is essential. The integrated access network will enable BB, IF and RF (also termed as ‘multiband’ for clarity) optical technologies to coexist together in the same fibre, thereby offering a cost-effective integrated optical infrastructure in the access domain [27-28, 163-167]. A generic architecture of such integrated network in ring configuration is shown in Fig. 2.20. In the downlink direction, optically modulated BB, IF and RF signals are transported over fibre from the CO to the remote access node.
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nodes (RANs), where the composite signal is demultiplexed to its components and distributed to the specific destinations, either to the remote antenna BS or to the optical network units (ONUs). Similarly, in the uplink direction, optically modulated BB, IF and RF signals from the ONU s and the BSs come across the RAN, where they are multiplexed to a composite signal and transported over fibre to the CO. The integration of these technologies will reduce the cost of the services via broadband access and ensure effective utilisation of the abundant capacity of the optical infrastructure in the access/metro domain.

A novel transmitter architecture based on a differentially driven integrated-optic Mach–Zehnder interferometer that enables optoelectronic combination of 10-Gb/s BB and 60-GHz-band signals has been demonstrated in [163]; A DE-MZM modulator based configurations of novel optical modulation scheme for simultaneous generation of optically modulated BB and RF signals were proposed in [28, 164]; and an EAM based simultaneous multiband modulation of 2.5-Gb/s BB, microwave-band, and 60-GHz-band signals were experimentally demonstrated in [165-166]. However, the performance of these methods has been limited by the nonlinearity as well as the optimum operating conditions of the modulators. Also, these techniques require significant changes both in the existing mini switching centres (MSCs) and the RANs. An alternative approach to realising an integrated DWDM network in the metro and higher network domains, is to incorporate a number of MSCs suitable for the role of a CO feeding clusters of BSs, to service the RF fibre-radio system [167]. This technique has the limitation of requiring a dedicated optical network in the access domain. Instead, if the passive WDM components (e.g. multiplexers, demultiplexers, OADMs) in the existing MSCs and RANs can be provisioned to support RF as well as other conventional BB and IF access technologies thereby avoiding significant changes in the existing setup, an effective integrated optical access network can be easily realised. In Chapter 7, we will introduce such hybrid multiplexing and demultiplexing schemes that enable integration of multiband signals and offers integrated optical infrastructure in the access domain.
2.7 Conclusion

In this chapter, various aspects of mm-wave fibre-radio systems are reviewed comprehensively. The potentials as well as the challenges of the system are identified and discussed. Section 2.2 presented an overview of BS architectures and discussed its importance towards the successful deployment of the system. This section also presented a comparison among different data transport schemes enabled BS architectures with their relative merits and demerits, concluding the essence of realising simple, compact, low-cost, and light-weight BS architectures. Research towards the simplification of BS architectures are explored and analysed, particularly with the highlight of limited research towards the simplification of OADM interface of the BS that has the potential to realise a consolidated and cost-effective BS architecture. This thesis explores multifunctional WDM optical interface for BSs, which simplifies the BS by providing optical carrier in the uplink path. Moreover, this section also reviewed the integrated circuit approaches towards the integration as well as the miniaturisation of all the optoelectronic, mm-wave and radiation components in the BSs.

Section 2.3 summarises the demonstrated technologies and architectures towards the realisation of spectrally efficient fibre-radio feeder network, which is indispensable for a practical fibre-radio system. Section 2.3.1 reviewed the fibre-radio demonstrations incorporating WDM, and described the working principle of such networks, both in downlink and uplink direction. The review was further extended in realising DWDM channel separations in mm-wave fibre-radio systems, which have the potentials to be realised by accessing the DWDM infrastructure in the access domain. The challenges in realising such DWDM channel separations in fibre-radio networks are also explained. Section 2.3.2 reviews and illustrates wavelength interleaving techniques, which enable DWDM channel separations in mm-wave fibre-radio networks. The literatures explaining the capacity and the link budget requirements for a WI-DWDM mm-wave fibre-radio system are also reviewed, with particular focus towards its
practical deployment. The challenges are identified to further explore through the contributory chapters.

The network impairments in WDM mm-wave fibre-radio systems are explored and reviewed in Section 2.4. OSSB+C modulation is identified for dispersion tolerant mm-wave transport over fibre, and will be used as the basis of optical mm-wave signal generation throughout the whole thesis. Literatures characterising the effects of optical crosstalk and grating dispersion in WDM fibre-radio networks are also investigated and evaluated. Very few demonstrations are reported that characterise the composite effects of optical crosstalk and grating dispersion in OADM interfaces of BSs, particularly in the networks where OADM interfaces will be used in cascade.

Literatures reporting the modulation depth enhancement of mm-wave fibre-radio channels are also reviewed and summarised in Section 2.5. The review indicates that most of the reported demonstrations require additional wavelength-selective signal processing devices, which are inherently susceptible to performance degradation in addition to adding up new complexities to the systems. This thesis also focused on the development of new system technologies, where modulation depth enhancement is combined with the other system technologies, by which requirement of additional devices can be avoided.

Finally, Section 2.6 reviews the literatures towards the realisation of an integrated optical infrastructure in the access domain, where optically modulated BB, IF and RF signals will coexist together in the same fibre. The limitations as well as the challenges of the reported demonstrations are identified, which will be further explored in this thesis.
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2.8 References


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3.1 Introduction

In mm-wave fibre-radio systems multiple remote antenna base stations (BSs), suitable for untethered connectivity for the broadband wireless access (BWA) services, are directly interconnected to a central office (CO) via an optical fibre feeder network [1-4]. Due to the high propagation losses as well as line-of-sight requirements associated with mm-wave communication links, the radio coverage of these BSs is typically limited to microcells and picocells, which demands large number of antenna BSs to cover a certain geographical area [4-12]. The successful deployment of these systems, therefore, is largely dependent on the development of simple, compact and low-cost BSs, which has been received much interest in the recent past and were reviewed in details in Chapter 1 and 2.

Another challenge in future fibre-radio system is the spectral efficiency of the fibre feeder network that has to be able to support the required large number of BSs servicing a certain geographical area. The introduction of wavelength interleaving
(WI) in fibre feeder network can help to meet the challenge by enabling transport of optically modulated dense-wavelength-division-multiplexed (DWDM) millimetre (mm-wave) signals very effectively [13-15]. A detail review of the literature towards the realisation of DWDM channel spacing in mm-wave fibre-radio system was presented in Chapter 2. However, to accelerate the deployment of such WI in fibre-radio feeder networks, suitable optical subsystems such as optical-add-drop-multiplexers (OADMs) with specific filtering requirements will be needed.

In this chapter, we present the design and demonstration of a novel multifunctional wavelength-division-multiplexed (WDM) optical interface with the capacity to add and drop wavelength-interleaved DWDM (WI-DWDM) channels in/from the mm-wave fibre-radio networks, while offering a simplified and consolidated architecture for the BS.

Section 3.2 outlines the general concept of the simplification of the BSs and briefly describes the research directions in realizing such simplified architectures in mm-wave fibre-radio systems. The filtering requirements of the OADMs for the implementation of WI-DWDM mm-wave fibre-radio systems are described in Section 3.3. This section also reviews the demonstrations towards the realisation of suitable OADMs for WI-DWDM mm-wave fibre-radio systems. The description of the proposed multifunctional WDM optical interface is presented in Section 3.4. Section 3.5 describes the experimental demonstration of the proposed interface incorporated in a 10 km mm-wave fibre-radio link and presents the experimental results for both downlink and uplink direction. This section also includes the characterization of the optical components, which comprises the proposed interface. Section 3.6 presents the simulation model developed using VPITransmissionMaker, which preliminarily verified the functionality of the interface, prior to experimental implementation. The performances of the optoelectronic devices and their possible impact in the overall performance of the mm-wave fibre-radio links are quantified in Section 3.7, while Section 3.8 evaluates the effects of reusing the downlink optical carrier in generating uplink optical mm-wave signals, instead of using independent light-sources in the BSs; and finally, Section 3.9 summarises the overall chapter.
3.2 Simplified Base Station Architecture

As stated above, simplified and consolidated BSs are highly desirable for practical deployment of mm-wave fibre-radio systems. The possible strategy to realize such a BS is a highly centralized CO along with less-equipped BSs, in which optical as well as mm-wave components and equipment are expected to be shared with a large number of BSs [16]. Among the three possible data transport schemes, as described in Chapter 2, mm-wave RF-over-fibre scheme (shown in Fig. 3.1) resolves the fundamental requirement of dynamic and reconfigurable channel allocation in mm-wave fibre-radio systems by enabling centralised control and monitoring [17-21] and offers a simplified and consolidated BS architecture by eliminating all the up/down conversion devices from the radio frequency (rf) interface of the BS, although the BS architecture in this scheme trades off complexities in rf interface with that of OADM and optoelectronic & electroptic (O/E) interfaces [22-29]. Therefore, RF-over-fibre

Fig. 3.1: Schematic of RF-over-Fibre scheme enabled mm-wave fibre-radio system, which simplifies the BS architecture by eliminating all up/down conversions as well as multiple channels transmission hardware.
Based remote antenna BSs have been considered for the future delivery of mm-wave signals to customers via the optical fibre feeder network.

To simplify the O/E interface of the BS by reducing the component counts, a multifunctional electroabsorption transceiver (EAT) based on electroabsorption modulator (EAM) technologies has been introduced [30-46], which replaces uplink modulator as well as downlink photodetector (PD) in the BS and simplifies the O/E interface of the BS to a single component configuration. Although EAT simplifies the O/E interface of the BS to a single component configuration, it exhibits poor performance in optical propagation loss as well as in power handling capability, and very sensitive to wavelength and temperature changes for which strict bias control is necessary [47-49]. Moreover, it is inherently designed to generate optical double sideband with carrier (ODSB+C) modulated signal, which is susceptible to the adverse effects of fibre chromatic dispersion, and requires additional dispersion compensation before transporting over fibre [50-56]. Moreover, the dual light-wave technique requires separate wavelengths for both uplink and downlink paths, and unable to exploit the benefits of wavelength reuse technique [57-58] and limits the total number of BSs supported by the wavelength band within the flat gain region of erbium doped fibre amplifier (EDFA).

An alternative approach is the introduction of wavelength reuse technique in the OADM interface of the BS, which simplifies the O/E interface by removing the light-source from the uplink path [58-60]. This approach uses electrooptic modulator (EOM) instead of EAM, suitable for the generation of dispersion tolerant optical singlesideband with carrier (OSSB+C) modulated signals, thus avoiding the additional dispersion compensating devices needed for EAM based techniques [51-54, 61]. Moreover, this approach enables the fibre feeder network to support additional BSs through a single CO by increasing the availability of optical carriers within the flat-gain region of EDFA, which is very important in future WDM fibre-radio networks. This chapter thus focuses on wavelength-reuse enabled architectures, instead of EAT-enabled architectures towards the realisation of simplified and consolidated base stations.
3.3 Wavelength Interleaving Enabled OADM Interface

Chapter 2 has reviewed the concept of WDM fibre-radio networks, where mm-wave fibre-radio channels are multiplexed together and distributed by an optical fibre network from a CO to the BSs [62-65]. OADM interfaces, generally located at the base stations, are integral parts of such networks and used to filter out the required optical mm-wave signals from the feeder networks. Conventional WDM OADMs can be used quite effectively to filter out such signals without much alteration.

However, the introduction of wavelength interleaving technique [13-15], which enables these systems to be consistent with DWDM fibre-radio networks, places more stringent requirements on the required filter characteristics of the OADM interface. Since multiple transmission notches are necessary, the spectral response is of greater complexity, and in addition, the OADM interface must be able to transmit the adjacent channels unaffected by the filter profile. Fig. 3.2 highlights such a filter profile required to recover the desired signals from mm-wave fibre-radio systems.

![Required OADM filter profile](image_url)

**Fig. 3.2:** Schematic diagram illustrating the filtering profile of an OADM interface that filters out the desired signal from WI-DWDM fibre-radio networks.
incorporating WI. The implementation of an OADM interface with such filter profile can be quite challenging. Several implementations have been demonstrated to realise such OADM interfaces. Marra et al. [66-67] has proposed multiple OADM interfaces incorporating phase-shifted fibre-Bragg-grating (FBGs), both apodised and nonapodised, and compared their relative advantages and disadvantages. Toda et al. [68-69] utilises the cyclic characteristics of arrayed waveguide grating (AWG), in conjunction with a Fabry-Perot (FP) etalon and a 3-port optical circulator (OC) to demonstrate demultiplexing/OADM of optical mm-wave signals from WI-DWDM fibre-radio networks.

Although these OADM interfaces/demultiplexers can effectively add and drop the desired signals to and from the WI-DWDM fibre-radio networks, they contribute very little towards the simplification of the BS architecture, which is highly desirable for the practical deployment of such systems. If the OADM interface in the BS can be provisioned to provide optical carrier for the generation of uplink optical mm-

Fig. 3.3: BS architecture incorporating multifunctional OADM interface in mm-wave fibre-radio systems that enables WI-DWDM fibre feeder network to the BSs in additional to removing the uplink light-source by providing optical carrier for the uplink communication.
wave signals, in addition to the OADM functionality, simplified and consolidated BS architecture can be easily realised. The schematic of a BS incorporating such OADM interface is shown in Fig. 3.3.

Following section presents a multifunctional WDM optical interface with the capacity of adding and dropping optical mm-wave signals to and from the WI-DWDM fibre-radio networks with a DWDM channel separation of 25 GHz, and also enabling wavelength reuse which eliminates the need for a light-source at the BS [70-73].

3.4 Proposed WDM Optical Interface

Fig. 3.4 shows the schematic of the proposed WDM optical interface with the optical spectra obtained from corresponding input, output, drop and add ports of the interface shown as insets. The input spectrum shows three 37.5 GHz-band wavelength-interleaved signals with a DWDM channel separation of 25 GHz, generated in OSSB+C modulation format. The optical carriers namely $\lambda_1$, $\lambda_2$, $\lambda_3$ and their respective modulation sidebands at $S_1$, $S_2$, $S_3$ of the optical mm-wave channels are interleaved in such a way that after interleaving the adjacent channel spacing, irrespective of carrier or sideband, becomes 12.5 GHz.

The interface consists of a 7-port OC connected to a two-notch FBG (FBG1) between port-2 and port-6 and a single-notch FBG (FBG2) at port-3 of the OC with a notch bandwidth of $\leq$ 12.5 GHz each. The FBG1 is designed in such a way that it reflects 100% of a specific downlink optical carrier (for instance, $\lambda_2$) with its modulation sideband ($S_2$), from the input WI-DWDM mm-wave fibre-radio signals. The reflected signal is received at port-3 while the transmitted signals (the through channels) are routed to port-6 of the OC where they will exit the interface via port-7 (OUT). FBG2 at port-3 was designed to reflect only 50% of the carrier at $\lambda_2$ while the remaining 50% of the carrier and the corresponding sideband, $S_2$ of the downlink signal will be dropped at port-3 (DL Drop) that can be detected using a high-speed
photodetector (PD). The reflected 50% carrier at $\lambda_2$ is recovered at port-4 ($\lambda$-Re-Use) of the OC and will be reused at the BS as the optical carrier for the uplink path.

In the uplink direction, a dispersion-tolerant OSSB+C formatted optical signal is generated using the recovered optical carrier and the uplink radio signal at the same RF frequency as the downlink mm-wave signal. The optically modulated uplink signal is then added to the interface via port-5 of the OC. The added signal will be routed to port-6 where it will be reflected by FBG1 and combines with the remaining wavelength-interleaved channels (the through channels) before being routed out of
the interface via port-7 (OUT). The output spectrum along with the spectra of the
downlink drop, the recovered wavelength reuse carrier and the uplink signal
generated by using the recovered optical carrier are shown in the inset of Fig. 3.4.
The proposed interface thus enables the BSs of fibre-radio systems to the
WI-DWDM fibre-feeder networks by dropping and adding the desired signals, in
addition to providing the optical carrier for the uplink path, which simplifies the
systems by removing the uplink light-source completely.

The following section demonstrates the proposed interface experimentally and
presents the experimental results both in the downlink and uplink directions. This
section also includes the characterization of the optical components, which comprises
the proposed interface under investigation.

3.5 Demonstration of the Proposed WDM Optical
Interface

In this section, the performance of the proposed interface is quantified
experimentally. As described in the previous section, the WDM optical interface is
comprised of a multiport OC connected to single-notch as well as double-notch
FBGs. The characteristics of the constituent FBGs as well as the multiport OC will
be described in Section 3.5.1 and 3.5.2 respectively. Section 3.5.3 describes the
experimental setup used to demonstrate the functionality of the proposed interface
with experimental results for both up and downlink directions and in Section 3.5.4,
the overall performance of the proposed interface will be discussed.

3.5.1 Fibre Bragg GRATINGS

Single-notch and double-notch FBGs are essential elements in the proposed
WDM optical interface. However, to successfully utilised these FBGs, some specific
filtering requirements have to be satisfied. As mentioned in the previous section, to
achieve close to perfect recovery of the desired signal from the WI-DWDM
channels, the double-notch FBG needs to have a transmission strength such that the reflectivity for each of the notch is as close as possible to 100%, with a separation between the notches is 37.5 GHz (~0.3 nm), and a 3-dB notch bandwidth of ≤ 12.5 GHz (0.1 nm), in addition to having minimal sidelobe ripples to avoid additional loss in the transmitted WI-DWDM channels. Apart from that, a sharp roll-off filtering profile is essential to minimise the filtering of the adjacent channel, irrespective of the carrier or modulation sideband. On the other hand, the single-notch FBG is required to have a transmission strength with a reflectivity as close as possible to 50%, enabling the interface to recover 50% of the optical carrier from the downlink optical mm-wave signal to be reused as the uplink optical carrier, as illustrated in section 3.4. The schematic diagrams of the reflection responses of the FBGs are shown in Fig. 3.5(a) - (b).

Fig. 3.5: Schematic diagram illustrating the reflection responses of the FBGs used in the proposed WDM optical interface: (a): for double-notch FBG (FBG1), and (b): for single-notch FBG (FBG2).
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The FBGs used in experimental demonstration of the proposed interface are characterised by an experiment shown in Figs. 3.6(a) - (d). A wideband noise source (e.g. asynchronous spontaneous emission (ASE)) is connected to port-1 of a 3-port OC, and the FBG to be characterised was connected to port-2 of the OC. The transmission spectrum was measured with an optical spectrum analyser (OSA) connected to the other end of the FBG (Figs. 3.6a and 3.6c). The reflection spectrum was measured by moving the OSA from port-2 to port-3 of the OC (Figs. 3.6b and 3.6d). To prevent the reflection from other source coming back to the OC, the other end of the FBG under investigation was terminated with an optical isolator (OI). The measured transmission and reflection responses for the FBGs are shown in Figs. 3.7(a) - (d). The FBGs were designed with a tunability of approximately 0.5 nm, to be controlled by mechanical stretching. For instance, the characteristic curves for
FBG1 show the nominal Bragg wavelengths for the notches are 1556.305 nm and 1556.624 nm with a 3-dB notch-bandwidth of approximately 0.1 nm each. The transmission spectrum (Fig. 3.7a) shows that the notches have a leakage of approximately -30 dB at the Bragg wavelengths from which the reflectivity of FBG1 can be calculated as follows:

$$\text{Reflectivity}_{\text{FBG1}} = 100\% - 10^{\frac{\text{Leakage at the Bragg wavelengths}}{10}} = 99.9\%$$
Also, the reflection spectrum of FBG1 (shown in Fig. 3.7b) confirms its sharp roll-off profile having minimal side-lobe ripples (>25 dB). The measured insertion loss of the grating was 0.2 dB.

The characteristic curves of FBG2 show a 3-dB bandwidth of approximately 0.1 nm with a nominal Bragg wavelength of 1556.0 nm, which can be tuned to the desired wavelength by mechanical stretching. The transmission spectrum (Fig. 3.7c) shows that 47% (approximately -3.25 dB) of the incident power was transmitted, while the rest 53% was reflected, which will be recovered by the proposed interface to be reused as optical carrier for the uplink transmission. Also, the sharp roll-off profile with minimal side-lobe ripples of the reflection spectrum (shown in Fig. 3.7d) confirms its suitability for recovery of the optical carrier. The measured insertion loss of the grating was 0.1 dB which is quite low.

### 3.5.2 8-port Optical Circulator

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</thead>
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</tr>
<tr>
<td>2 to 3</td>
<td>1.13</td>
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<td>1.93</td>
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<tr>
<td>7 to 8</td>
<td>2.1</td>
</tr>
</tbody>
</table>

Table 3.1: Port-to-port insertion losses of 8-port optical circulator

Optical circulators are non-reciprocal devices that redirect light from one port to another in a sequential manner, and in one direction only. The directions are generally termed as clockwise or counter-clockwise. The general specified characteristics of an OC include parameters such as port to port insertion loss,
isolations, directivity etc.. The isolation between ports 1 and 2 is defined as the loss experienced by a signal launched into port-2 and measured at port-1. The directivity for an 8-port OC is defined as the loss experienced by a signal launched into port-1 and recovered at port-8, and, the insertion loss is defined as the loss experienced by a signal launched into port-1 and measured at port-2. The OC measured isolations and directivity were below -50 and -65 dB, respectively. The measured port-to-port insertion losses are listed in Table 3.1. The variations of port-to-port insertion losses can be attributed to fabrication errors.

3.5.3 Experimental Demonstration and Results

The experiment to demonstrate the downlink/uplink transmission incorporating the proposed multifunctional WDM optical interface at the BS is shown in Fig. 3.8. In this experiment, three narrow line-width tunable light sources LS$_1$, LS$_2$, and LS$_3$ at the corresponding wavelengths $\lambda_1$ (1556.0 nm), $\lambda_2$ (1556.2 nm) and $\lambda_3$ (1556.4 nm) were used as the optical sources. The three optical carriers, followed by separate

![Experimental setup for the demonstration of the proposed WDM optical interface, which enables wavelength reuse in a wavelength-interleaved DWDM mm-wave fibre-radio system.](image)

Fig. 3.8: Experimental setup for the demonstration of the proposed WDM optical interface, which enables wavelength reuse in a wavelength-interleaved DWDM mm-wave fibre-radio system.
polarization controllers (PCs) were multiplexed together using two 3-dB optical couplers. The multiplexed optical carriers were then launched into a dual-electrode Mach-Zehnder modulator (DE-MZM). A 37.5 GHz mm-wave signal with binary-phase-shift-keyed (BPSK) format was generated by mixing a 37.5 GHz local oscillator (LO) signal with a 155 Mb/s pseudo-random-bit-sequence (PRBS) data. The DE-MZM was biased at quadrature bias (QB) point and the amplified mm-wave signal was used to drive the two RF ports of the DE-MZM with a 90° phase shift maintained between the two drive signals. The resultant output of the modulator was an OSSB+C modulated signal with the three optical carriers and their respective sidebands interleaved, the spectrum of which can be seen in Fig. 3.9. Fig 3.9 also shows that the undesired (i.e. lower sideband in this case) sideband suppression and the carrier-to-sideband ratio (CSR) of approximately 14 dB (in comparison to the upper sideband) and 28 dB respectively were attained. The poor modulation depth can be attributed to the bandwidth limitation of the DE-MZM (18 GHz) used in generating signals in the CO, which is well below the downlink mm-wave subcarrier frequency (37.5 GHz) under investigation. The other possible factors such as the rf frequency dependency of the OSSB+C generator, and the departure of magnitude and phase ratios of the RF inputs from the necessary 0 dB and 90° respectively [74-76] could also contribute to lower modulation depths.

![Figure 3.9](image)

**Fig. 3.9:** Measured optical spectrum of the wavelength interleaved signals generated in CO by using a DE-MZM in OSSB+C modulation format to be used to demonstrate the proposed interface experimentally.
The interleaved optical mm-wave signal was then amplified by using an EDFA followed by an optical band pass filter (BPF) that minimises the out-of-band ASE noise prior to being transported over 10 km single-mode fibre (SMF) to the remote antenna BS. The remote antenna BS comprises the proposed WDM optical interface, the optoelectronic & electrooptic devices (O/E interface) and the rf electronics (rf interface). An 8-port OC (as described in Section 3.5.2) was used to construct the proposed WDM optical interface in conjunction with the FBGs, the characteristics of which were also described in Section 3.5.1. The Bragg wavelengths of the notches of FBG1 were tuned to wavelengths 1556.2 nm and 1556.5 nm, having 3 dB notch-bandwidths of approximately 0.1 nm and reflectivity of 99.9%. Also, the Bragg wavelength of FBG2 was tuned to a wavelength 1556.2 nm, having a 3-dB bandwidth of approximately 0.1 nm and reflectivity of 53%. The desired downlink signal for the specific BS, which was comprised 47% of the carrier at 1556.2 nm with its corresponding modulation sideband at 1556.5 nm, was recovered from the WDM optical interface through the DL Drop port.

Fig. 3.10: Measured optical spectra of the proposed WDM optical interface while demonstrating experimentally using three W1-DWDM channels: (a): the input signal at port IN, and (b): the downlink signal at port DL Drop.
Fig. 3.10(a) shows the spectrum of the WI-DWDM signals entering the proposed interface via port IN, while Fig. 3.10(b) is the desired downlink signal recovered at the port, DL Drop. Comparing the spectra, it can be seen that the optical carrier of the downlink signal recovered via the DL Drop port is reduced by more than 5-dB. This can be ascribed to the reflection of 53% optical carrier by FBG2, in addition to the port-to-port insertion losses of the 8-port OC, which was described in Section 3.5.2. The spectra also show that due to the reflection of 53% optical carrier, the modulation depth of desired downlink signal is enhanced by more than 3-dB, which

![Fig. 3.10(a) and (b)](image)

**Fig. 3.11**: Measured rf spectra of the downlink mm-wave signal: (a): generated in the CO before modulated optically, (b): in the BS after photodetection by a 45 GHz PD, and (c): in the BS after down-conversion to 2.5 GHz IF signal to recover data by using 2.5 GHz PLL.
have significant impact in overall link performance [77-78], and will be further characterised in Section 3.7.

To quantify the link performance, the recovered downlink signal was then directed to the O/E interface of the BS where it was detected using a 45 GHz PD. After photodetection, the downlink signal was amplified using an amplifier chain of low noise amplifier (LNA) and medium power amplifier (MPA) and then down-converted to an intermediate frequency (IF) of 2.5 GHz where the desired baseband data can then be recovered using a 2.5 GHz electronic phase-locked loop (PLL) based on “Costas Loop” configuration.

Fig. 3.11 illustrates the recovered rf spectra of the downlink mm-wave signal at different positions of the link. Fig. 3.11(a) shows the rf spectrum of the 155 Mb/s BPSK data centred at 37.5 GHz, measured at the CO before optical modulation. The spectrum is fully symmetrical with respect to the centre mm-wave frequency and indicates a carrier-to-noise ratio (CNR) of more than 30 dB. Fig. 3.11(b) shows the measured rf spectrum of the detected 37.5 GHz carrier with 155Mb/s BPSK data at the BS after recovery of downlink optical signal from the DL Drop port of the interface. It can be seen that the received signal is not fully symmetrical around the centre frequency. Also, the CNR is reduced to approximately 20 dB. This can be attributed to the degradation of signal quality in the optical domain, in addition to the optoelectronic and rf devices both in the CO and the BS before recovery of the spectrum at the BS. The spectrum of the detected rf signal down-converted at the BS to an IF of 2.5 GHz is shown in Fig. 3.11(c). In comparison to the spectrum in Fig. 3.11(b), the signal quality is further degraded both in symmetry as well as in CNR level. This also can be ascribed to the effects of multistage rf amplification, rf mixer and other rf signal conditioning devices (e.g. rf attenuator, connector, filter etc.) in the rf interface of the BS.

Fig. 3.12(a) shows the measured bit-error-rate (BER) curves as a function of received optical power for the recovered downlink data at the BS with the back to back curve (0.0 km SMF) as a reference, while Fig. 3.12(b) shows the measured eye-diagram at a BER less than of $10^{-9}$. The measured BER curves show a transmission power penalty of 0.90 dB with receiver sensitivity of $-5.2$ dBm at a BER of $10^{-9}$ for transmission over 10 km of SMF. The incurred power penalty in the downlink path
can be attributed to the effects of crosstalk from the neighboring WI-DWDM channels, in addition to the dispersion induced penalties due to lower suppression of the unwanted sidebands while generating OSSB+C modulated downlink signals in the CO [51-55]. A detail characterisation of the effects of these impairments will be presented in Chapter 4.

To demonstrate the functionality of the proposed interface in the uplink direction, the 53% optical carrier at 1556.2 nm reflected by the FBG2 was recovered from λ-Re-Use port of the interface. The recovered carrier was reused to drive the uplink DE-MZM, part of the O/E interface of the BS. A 37.5 GHz mm-wave signal was generated by mixing a 37.5 GHz local oscillator (LO) signal with a 155 Mb/s BPSK data, the similar way it was generated in the downlink direction. The mixer output was amplified by an amplifier chain before being applied to the DE-MZM. The biasing voltages and the RF inputs of the DE-MZM were controlled in such a way that the resulting output of the modulator was an optical mm-wave signal modulated in OSSB+C modulation format. The spectra of the recovered 53% optical carrier and

Fig. 3.12: Measured experimental results that quantify the degradation of downlink WI-DWDM mm-wave fibre-radio signals while recovered via the DL Drop port of the proposed interface: (a): the BER curves (b): the eye-diagram.
uplink optical mm-wave signal generated by reusing the recovered optical carrier are shown in Fig. 3.13(a) – (b).

The spectrum of the generated uplink optical mm-wave signal (Fig. 3.13b) demonstrates an attained lower sideband suppression and CSR of approximately 18 dB (in comparison to the upper sideband) and 22 dB, which indicates that the uplink DE-MZM performed much better than the downlink DE-MZM. These two spectra also confirm that the uplink DE-MZM experienced an insertion loss of approximately 9 dB, which also can be termed as ‘drop-add’ insertion loss of the proposed interface.

The uplink optical mm-wave signal was then routed to the interface via the ADD port, where it is combined with the through downlink signals at port-6 and left the interface as a composite signal via the OUT port. The spectra of the through downlink signals obtained at the through port as well as the composite signal leaving the interface via port OUT can be seen in Fig. 3.14(a) – (b).
The spectrum of the through signals (Fig. 3.14a), recovered as the transmission spectrum of FBG1, demonstrates a leakage of the dropped channels lower by more than 30 dB, which is a good compromise with the characteristic spectra of the FBG1, as described in Section 3.5.1. In comparison to the spectrum of the input WI-DWDM signals (shown in Fig. 3.10a), due to the lossy OC, the through channels experience a relatively large insertion loss of around 3.5 dB, although the typical loss is approximately 1 dB. The spectrum of the composite signal leaving the interface (Fig. 3.14b) indicates a much weaker uplink optical mm-wave signal compared to the neighboring downlink through signals. This is due to the higher insertion loss experience by the ‘drop-add’ signal in the demonstrated interface, which can be minimised using a better quality DE-MZM with lower insertion loss.

To measure the link performance for the uplink communication, the experimental setup shown in Fig. 3.8 was modified and shown in Fig. 3.15, where due to unavailability of suitable optical filter (i.e. another FBG1 could serve the purpose), the generated uplink optical mm-wave signal, instead of routing to the interface via
the add port, was transmitted through another 10 km of SMF to the CO. However in
Chapter 4, uplink optical mm-wave signals are recovered at the OUT ports of the
interfaces, and the effects of residual in-band interferences are evaluated, which are
very important in real applications. The uplink optical mm-wave signal was then
optically amplified by an EDFA and filtered by an optical BPF that minimises the
out-of-band ASE noise prior to being detected by a 45 GHz PD. After
photodetection, the uplink mm-wave signal was amplified by using an amplifier
chain of LNA and MPA and down-converted to an IF of 2.5 GHz from which
baseband data was recovered using a 2.5 GHz electronic PLL circuit. To make the
results comparable, the same PD, rf and data recovery devices were used in both
downlink and uplink directions.

Fig. 3.16 illustrates the recovered rf spectra of the uplink mm-wave signal before
and after down-conversion at the CO, while the spectrum of the uplink mm-wave
signal before modulated optically is described in Fig. 3.11(a). Fig. 3.16(a) shows the rf spectrum of the detected 37.5 GHz carrier with 155Mb/s uplink BPSK data at the CO after transmission of the uplink optical mm-wave signal over 10 km of SMF. The spectrum is almost symmetrical with respect to the centre mm-wave frequency and indicates a CNR of approximately 25 dB. The rf spectrum of the down-converted uplink mm-wave signal is shown in Fig. 3.16(b). In comparison to the previous spectrum (Fig. 3.16a), the signal quality is degraded both in symmetry as well as CNR level. Similar to the downlink measurements, this also can be ascribed to the effects of multistage rf amplification, rf mixer and other rf signal conditioning components in the CO, used in the data recovery process.

Fig. 3.17(a) shows the measured BER curves as a function of received optical power for the recovered uplink data at the CO with the back-to-back curve (0.0 km SMF) as a reference. Fig. 3.17(b) shows the eye-diagram for the recovered uplink data measured at a BER less than of $10^{-9}$. The BER curves exhibit a negligible power
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Fig. 3.17: Measured experimental results that quantify the degradation of uplink optical mm-wave signal, generated by reusing the optical carrier recovered by the proposed interface: (a): the BER curves (b): the eye-diagram.

penalty of 0.60 dB with receiver sensitivity of $-7.7 \text{ dBm}$ (at BER of $10^{-9}$) for a transmission distance of 10 km SMF. The incurred power penalty can be attributed to experimental errors.

However, in comparison to the BER curves of Fig. 3.12(a), for the same transmission distance, the uplink signal demonstrates a 0.3 dB improvement in penalty than the downlink signal, which is due to the absence of optical crosstalk in the uplink path and the higher suppression of unwanted sidebands in the OSSB+C modulated uplink signal. Also, the receiver sensitivity in the uplink direction is 2.5 dB higher compared to the downlink direction, which can be attributed to the higher modulation depth (reduced CSR) of the uplink DE-MZM, which is more than 4 dB even after 53% optical carrier of the downlink optical mm-wave signal is removed at the interface for carrier reuse.

Therefore, the experimental results, both in downlink and uplink direction, clearly demonstrate the functionality of the proposed multifunctional WDM optical interface that offers a practical solution for future high capacity BWA networks incorporating wavelength interleaving and wavelength reuse techniques.
3.5.4 Discussions

In general, mm-wave fibre-radio system is a last mile optical access technology, where the customers are connected to the BSs via mm-wave wireless links. Therefore, to make the system economically viable, passive fibre feeder network is highly desirable. As inclusion of EDFA in the BS will make the system more complex and expensive, the demonstration placed all the optical amplifiers (irrespective of downlink or uplink) in the CO where it is expected to be used in a shared environment, rather than in individual BS. In such situation, significantly large optical power is needed to be launched into the optical fibre in the downlink direction to achieve adequate link budgets, where optical attenuation of WDM components as well as the optical fibre span is compensated by the boost-amplifier located in the CO. However, unlike the baseband-based conventional optical access technologies, the OSSB+C modulated WI-DWDM optical mm-wave signals are comprised of strong ultra-narrow line-width optical carriers along with weakly modulated data sidebands. As a result, the effect of fibre nonlinearities, particularly SBS will place an upper limit in achieving large optical output power through amplification, and restrict the optical signal-to-noise ratios (OSNR) in the link [79-80].

In the uplink direction, optical mm-wave signals are generated by reusing the recovered optical carriers in the BSs, and are transported to the CO, where it is amplified by a pre-amplifier before photodetection. However, the generated weaker uplink signals are further weakened in the link by the optical attenuation of WDM components as well as the span of optical fibre before entering the pre-amplifier in the CO. As a result, the performances of the uplink paths are often limited by poor OSNRs due to insufficient input power to the optical pre-amplifier. Also in WDM ring/bus network configurations, same fibre will be shared in both downlink and uplink communications. Due to the amplification in the CO before transmission over fibre, the downlink signal will be contaminated by ASE noise. If the uplink signals are too weak, then the ASE noise originated from the CO will further deteriorate the OSNR of the uplink signals. Therefore further explorations are necessary in terms of optimum recovery of uplink optical carrier and amplification in the CO, in addition
to performance enhancement of the links. Chapter 4 will incorporate some modifications to the proposed interface addressing these issues, which enhances the performance of the link both in and uplink and downlink direction quite significantly.

The downlink and uplink DE-MZMs (older implementations) used in the demonstration had insertion losses of 13 dB and 7 dB respectively which are relatively high. DE-MZMs exhibiting lower insertion losses (3-4 dB) are now commercially available and may ease the high power launch requirements. In addition, the high launch power requirement can be relaxed by replacing the 8-port OC used in the WDM interface that had insertion losses from 1 to 2.1 dB between ports with a standard OC with losses < 1 dB. Moreover, the ultra-narrow band FBGs used in the interface were experiencing a slow Bragg frequency drift with time and was showing a power fluctuation of 0.5 to 1.5 dB. These had an overall impact on achieving the targeted BER with optimum power penalty and sensitivity. Perfection in designing such FBGs may assist in improving the performance further.

In the proof-of-concept demonstration, a typical 10 km SMF link with a single unit of the proposed WDM optical interface at the RN was used. However, if the optical link is much longer with multiple units of the interface in cascade, additional losses will be added into the link that may not be sufficiently compensated by purely amplification. To quantify the penalties introduced by different segments of the interface while simultaneously transmitting multiple channels in the link, further characterization is needed to optimise the system in terms of both signal-to-noise ratio (SNR) and the overall power budget. The next chapter will investigate the effects of the network impairments on the performance of the proposed interface while used in single as well as cascaded form, which will be extended to the modelling of the system based on link’s budget estimation.
3.6 Simulation Model

Before implementing setup for experimental demonstration, the proposed WDM optical interface was modelled by using VPI simulation platform, where the functionality of the proposed interface was verified preliminarily. The schematic of the simulation model is shown in Fig. 3.18. The module parameters used in the simulation are illustrated in Table 3.2.

Similar to the experiment, the simulation model also used three OSSB+C modulated 37.5 GHz-band WI-DWDM fibre radio signals spaced at 25 GHz and each carrying 155 Mb/s BPSK data. The interleaved signals were then amplified by an EDFA and transported over 10 km of SMF to the proposed interface. The optical
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<th>Module</th>
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<td>RF Carrier Amplitude</td>
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<td>DE-MZM Biasing Voltage</td>
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</tr>
<tr>
<td>Notch Bandwidths of FBGs</td>
<td>12.5 GHz</td>
</tr>
<tr>
<td>PD Responsitivity</td>
<td>0.2 (A/W)</td>
</tr>
</tbody>
</table>

Table 3.2: Module Parameters used to verify the functionality of the proposed WDM optical interface via simulation

The spectrum of the signals entering the interface is shown in Fig. 3.19(a), while the spectra of the downlink drop (DL Drop), the wavelength reuse drop (λ-Re-Use) and add (ADD) signals can be seen from Figs. 3.19 (b) – (d) respectively. The optical spectra recovered from the simulation model are very similar to the spectra recovered from the experiment (Figs. 3.10 and 3.13). The BER performances of the downlink
signal at DL Drop port and the uplink signal at ADD port, generated by reusing the recovered optical carrier, were also quantified, which are shown in Fig. 3.20. The error-free (at a BER of $10^{-9}$) data recovery and the recovered optical spectra verified
3.7 Effects of the Performance of O/E Devices

The overall receiver sensitivity of the experimentally demonstrated system incorporating the proposed interface, irrespective of direction of communication, is less than or equal to -7.7 dBm at a BER of $10^{-9}$, which is very poor and needs to be improved through further investigation. The performance of the optoelectronic and electrooptic devices such as DE-MZMs and the PD play a very important role in limiting the overall performance of the link. The DE-MZMs used in the experiment exhibit a CSR from 22 to 28 dB. Also, the PD used in the experiment had a responsitivity of less than 0.4. If the performance of O/E devices can be improved either by replacing it with better performing devices or by applying some external

---

**Fig. 3.20:** Simulation BER curves that quantify the degradation of the signals due to traversing the proposed interface: (a): the recovered downlink signal at DL Drop port, and (b): the uplink signal, generated by reusing the recovered optical carrier, at ADD port.

---

the functionality of the proposed interface, which was later demonstrated in experiment, as described in Section 3.5.3
performance enhancing techniques (such as CSR reduction by external means), the sensitivity limitation can be resolved quite easily.

Fig. 3.21 shows a simulation model developed by using VPI platform, which quantifies the performance enhancement of the system at different values of CSR at the output of the DE-MZMs and the responsivity of the PD. To make the results comparable, the properties of the modules in the model follow the experimental parameters very closely. To enable variable CSRs in the generated WI-DWDM signals, the sidebands of the OSSB+C signal are separated from the optical carriers using a Fabry Perot filter in conjunction with a 3 port optical circulator, where the intensities of the sidebands were varied by another EDFA (keeping the noise figure unchanged) before combining them back with the separated optical carriers. Fig. 3.22(a) shows the sensitivity at BER = $10^{-9}$ vs. reduction in CSR curve obtained from simulation model, which clearly indicates that, the sensitivity of the system increases almost linearly with reduction in CSR.
To verify the impact of the PD on the overall system performance, the responsivity of the PD module in the simulation model were increased gradually from 20% up to 100% and plotted against the sensitivity of the system at BER = 10^{-9}, which is shown in Fig. 3.22(b). This curve also confirms that the sensitivity of the system increases almost linearly with responsivity of the PD and saturates when the responsivity > 0.9 A/W. Therefore, both curves (Fig. 3.22a-3.22b) demonstrate that with proper selection of the O/E devices, the overall performance of the link can be enhanced significantly.

**Fig. 3.22:** Simulation graphs that quantify the performance enhancement of the system at different values of the CSR of the DE-MZMs as well as the responsivity of the photodetector: (a): sensitivity vs. reduction in CSR, and (b): sensitivity vs. PD responsivity.
3.8 Carrier Reuse over Independent Uplink Light Source

As described in the previous sections, the proposed interface enables a carrier extraction technique that provides optical carrier to modulate the uplink mm-wave signals. The downlink optical carrier traverses a series of optical devices, in addition to propagating through a span of optical fibre before being recovered at the interface. This transportation of the optical carrier to the interface may potentially cause broadening of the linewidth of the carrier-pulse due to the Group-Velocity Dispersion (GVD), which can be expressed mathematically [81] as follows:

\[
\Delta T = \frac{dT}{d\omega} \Delta \omega = \frac{d}{d\omega} \left( \frac{L}{\nu_g} \right) \Delta \omega = L \frac{d^2 \beta}{d\omega^2} \Delta \omega = L \beta_2 \Delta \omega \quad \text{(1)}
\]

where,
\[\nu_g\] is the group velocity,
\[\beta\] is the propagation constant
\[L\] is the length of SMF,
\[\Delta T\] is the amount of pulse broadening,
\[\Delta \omega\] spectral width of the carrier pulse, and
\[\beta_2 = \frac{d^2 \beta}{d\omega^2}\] is the GVD parameter that determines the amount of broadening

In terms of range of wavelengths \[\Delta \lambda\], rather than frequency spread \[\Delta \omega\], the extent of pulse broadening \[\Delta T\] can be expressed as:

\[
\Delta T = \frac{dT}{d\omega} \Delta \omega = \frac{d}{d\lambda} \left( \frac{1}{\nu_g} \right) \Delta \lambda = DL \Delta \lambda \quad \text{(2)}
\]

where,
\[D = \frac{d}{d\lambda} \left( \frac{1}{\nu_g} \right) = \left( \frac{2\pi c}{\lambda^2} \right) \beta_2\]
\( \beta_2 \) is the dispersion parameter expressed in unit of ps/(km-nm)

The above two expressions of pulse broadening demonstrates that there is a definite broadening of downlink carriers before being recovered in the proposed interface to be reused for uplink communication. This dispersion induced pulse broadening contaminates the receiver performance by introducing Intersymbol Interference (ISI) and by reducing the SNR at the decision circuit.

To quantify the effects of pulse broadening in a system incorporating the proposed interface, a simulation was carried out using VPITransmissionMaker5.5. The simulation model was very similar to the experiment, where uplink optical mm-wave signal was generated in two different ways: (i) by reusing the recovered downlink carrier, and (ii) by using an independent optical source. In both cases, the BER curves were measured in the CO. The simulation BER curves are presented in Fig. 3.23. It shows that due to pulse broadening, the uplink signal experiences a 0.1 dB
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additional penalty, which is very negligible, and can be ignored. Therefore, the effect of recovered carrier pulse broadening on the overall uplink performance is minimal and hence can be neglected while designing the mm-wave fibre-radio systems incorporating the proposed WDM optical interfaces.

3.9 Conclusion

This chapter presented a multifunctional WDM optical interface for future DWDM fibre-radio system that enables dispersion tolerant OSSB+C modulation based wavelength-interleaved networks and capable of providing the optical carrier for the uplink transmission by exploiting a wavelength reuse technique. The functionality of the proposed interface was verified experimentally as well as via simulation for three wavelength-interleaved DWDM channels with a channel spacing of 25 GHz, each carrying 37.5 GHz RF signal with 155 Mb/s BPSK data transported over 10 km of fibre link. The use of the demonstrated interface in the future DWDM fibre-radio networks can improve spectral efficiency and ensure efficient wavelength utilisation, while offers a simplified and consolidated BS architecture by eliminating the need for separate optical source for uplink. In the design process we have taken the benefits of matured and standard component technologies that enhance the possibility of merging the mm-wave fibre-radio based BWA systems with existing optical network infrastructure in the access and metro domains.

The effects of the performance of optoelectronic devices (DE-MZM and PD) in the overall performance of the link incorporating the proposed interface were investigated. A simulation model was developed to investigate the impairments contributed by imperfect optical devices such as the DE-MZM and PD. The CSR of the DE-MZM and the responsitivity of the PD were varied and the respective sensitivities were measured. The results indicated that the performance of the links incorporating the proposed interface were largely dependent on the performance of the optoelectronic devices, and by proper selection of these devices, the performance of the link can be significantly enhanced.
A comparison was carried out to investigate the effects of pulse-broadening due to dispersion on the optical carriers recovered using wavelength reuse scheme and independent light-sources in the uplink path. The mathematical expressions showed that there was a definite broadening of the optical carrier recovered by the proposed interface to be reused in the uplink path. However, the simulation results demonstrated that the effects have minimal impact on the overall system performance and can be ignored while designing the mm-wave fibre radio systems incorporating the proposed WDM optical interface.
3.10 References


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Chapter 4: Characterisation and Enhancement of Links Performance Incorporating WDM Optical Interface

4 Characterisation and Enhancement of Links Performance Incorporating WDM Optical Interface

4.1 Introduction

Chapter 3 presented a multifunctional wavelength-division-multiplexed (WDM) optical interface with the capacity to add and drop optical millimetre-wave (mm-wave) signals to and from the wavelength-interleaved dense-wavelength-division-multiplexed (WI-DWDM) fibre-radio networks with a DWDM channel separation of 25 GHz, which also enables wavelength reuse in the uplink direction by eliminating the need for a light-source at the base station (BS) [1-3]. The use of such interface in future DWDM fibre-radio networks will offer higher spectral efficiency, efficient wavelength utilisation and transparent wavelength routing, while realising simple, compact and low-cost BSs [2]. The interface, which is comprised of narrow band fibre Bragg gratings (FBGs) and multiport optical circulator (OC), exploits the
benefits of matured WDM component technologies that enhance the possibility of merging the mm-wave fibre-radio based broadband wireless access (BWA) systems with existing optical network infrastructure in the access and metro domains [4-8]. However, the constituent elements of the interface have the potential to degrade the performance of systems by introducing additional network impairments, such as, optical crosstalk and chromatic dispersion [9-14]. Moreover, the concatenation of the interfaces in a practical network will make the effective passband narrower due to the variations in the passband roll-off and ripple in each individual FBG transfer functions [15-17]. The required accuracy in these systems therefore, becomes more stringent with the number of stages in cascade [18-19].

As discussed in Chapter 3, the overall performance of a mm-wave fibre-radio system is largely dependent on the achieved modulation depths with the wideband electrooptic intensity modulators, such as dual-electrode Mach-Zehnder modulators (DE-MZMs). In the case of the optical single sideband with carrier (OSSB+C) modulated optical mm-wave signal [20-22] transmission, carrier-to-sideband ratio (CSR), which is inversely proportional to the modulation depth, were found to be better measure of predicting the performance. A simulation was carried in section 3.7 where the modulation sidebands, which were separated from the respective optical carriers using a Fabry-Perot (FP) filter and a 3-port OC, were amplified by an erbium doped fibre amplifier (EDFA) before recombining them using a 3-dB coupler. The demonstrated results confirm the effectiveness of the reduction of CSRs by the external means in increasing the performance of analogue fibre optic links. Similar to the others [20, 22], this external technique however, adds up in cost and complexity of the systems, and may turn the systems impracticable. Instead, if the proposed WDM optical interface, in addition to its routine functionality, can be enabled to reduce the CSRs by avoiding additional hardware, efficient and effective fibre-radio network architecture can be easily realised.

This chapter thus focuses on the characterisation as well as the enhancement of the performance of the fibre-radio links incorporating the proposed WDM optical interface. Both simulations as well as experimental approaches have been taken in order to achieve this. Section 4.2 gives a brief description about the possible impairments in a fibre-radio link incorporating the proposed WDM optical interface.
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Section 4.3 presents a simulation that study and characterise the effects of optical impairments on the optical mm-wave signals, while traversing through single as well as cascaded interfaces. Experimental investigations of the performance of single and cascaded interfaces are demonstrated in Section 4.4. MM-wave fibre-radio links (incorporating WDM optical interface) in star-tree and ring/bus network architectures are modelled in Section 4.5, from which number of allowable interfaces in cascade can be predicted. Section 4.6 incorporates modification in the proposed WDM optical interface that enables significant improvement in link’s performance, both in uplink and downlink direction. The improvements in performances are quantified by another experiment presented in Section 4.7. The impact of the incorporation of modification on the overall network performance is quantified in Section 4.8.

4.2 Optical Impairments Introduced by the WDM Optical Interface

Practical WDM networks (e.g. ring/bus networks) are promising technologies to achieve high capacity transparent optical networks that offer advanced routing functionality through optical add-drop-multiplexers (OADMs) [23-26]. DWDM compatible wavelength interleaving (WI) technique has been introduced in mm-wave fibre-radio networks [27-29], where a large number of BSs, required to cover a certain geographical area, are supported via a single central office (CO). In these networks the downlink optical mm-wave signals with an effective DWDM channel separation are passed through a suitable multiplexer in CO and are aggregated before being launched on to the fibre network. The multiplexed signals are then launched on to the fibre network and transported to the BSs, where each of the BS recovers the desired downlink signal by using a suitable OADM. The uplink optical mm-wave signals generated in the BSs are also added to the network via the same OADM and being transported to the CO. Therefore, in WI-DWDM fibre-radio networks, the optical mm-wave signals encounter wavelength-selective OADMs on the way to its
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destination, which have the potential to cause performance degradation through both in-band and out-of-band optical crosstalk [11-14, 30, 31].

Another potential source of performance degradation via an OADM is the dispersion penalty introduced by the FBGs [9, 10, 32, 33], which are widely used as narrow-band notch filters in the OADMs in recovering the desired signals. Moreover, the various architectures of the optical networks (e.g. ring/bus) result in concatenated OADMs, which makes the effective passband of the cascade narrower due to the passband curvature and ripple of the FBG transfer functions. The required wavelength stability and accuracy in networks therefore goes up with the number of cascaded stages. The accumulated effects of all the above will give rise to signal waveform distortion leading to significant network performance degradation [15-17].

Similar to a conventional OADM, WDM optical interface (shown again in Fig. 4.1 for convenience) is also comprised of multiple FBGs and multiport OC and has the capacity of adding and dropping optical mm-wave signals to and from the WI-DWDM fibre-radio networks, in addition to enabling wavelength reuse in the uplink.

![WDM optical interface diagram]

Fig. 4.1: WDM optical interface, to be characterised in single as well as cascaded configuration, enables wavelength recovery and optical add-drop functionality for a WI-DWDM fibre-radio system.
direction. Therefore, the optical mm-wave signals in a WI-DWDM network incorporating the WDM optical interface will be contaminated by the optical crosstalk as well as the grating dispersion, which will be accumulated for cascaded setup [2, 34, 35]. Moreover, the interface itself contains a double-notch FBG for which the wavelength stability and accuracy becomes more stringent than a conventional OADM. The following section develops a simulation model by which the effects of such impairments on the optical mm-wave signals are characterised while traversing single as well as cascaded interfaces.

4.3 Simulation Characterisation of the Performance of Single and Cascaded WDM Optical Interfaces

4.3.1 Simulation Model

The simulation model that study and characterise the effects of optical impairments introduced by single as well as cascaded WDM optical interfaces was developed by using VPITransmissionMaker, a commercially available platform for photonic simulations. The schematic diagram of the model is shown in Fig. 4.2. In the downlink direction, three OSSB+C generators are combined and interleaved by using a 4x1 combiner, amplified by an EDFA and followed by an optical band pass filter (BPF) to minimise the out-of-band asynchronous spontaneous emission (ASE). The filtered output was then transported over 10 km of singlemode fibre (SMF) to the two concatenated WDM optical interfaces, WDM Optical Interface 1 and WDM Optical Interface 2. Each interface is shown as a block with five ports, namely, the input (IN), downlink drop (DL Drop), wavelength reuse drop (λ-Re-Use), add (ADD) and output (OUT). The OSSB+C generators consist of three narrow linewidth optical carriers spaced at 25 GHz, where each of the carrier is modulated by a 37.5 GHz mm-wave signal carrying 155 Mb/s binary-phase-shift-keyed (BPSK) data. The optical spectrum of the wavelength-interleaved signals entering the interfaces can be seen in the inset of Fig. 4.2, where for simplicity, the three interleaved downlink
signals with their modulation sidebands are denoted as Ch\(_1\), Ch\(_2\) and Ch\(_3\). The simulation model assigns WDM Optical Interface\(_1\) and WDM Optical Interface\(_2\) to drop and add Ch\(_2\) and Ch\(_1\) respectively.

In the uplink (UL) direction, the OSSB+C formatted UL Ch\(_2\) and Ch\(_1\) were generated by modulating the recovered \(\lambda\)-Re-Use carriers of the interfaces with 37.5 GHz-band UL mm-wave signals, each carrying 155 Mb/s BPSK data. The uplink signals were then routed to interfaces via the ADD ports. The effects of impairments on the WI-DWDM signals due to traversing the concatenated interfaces were characterised by recovering the transmitted signals at positions A, B, C, D, E, and F as indicated in Fig. 4.2. The simulation model incorporated the observed parameters of the experiment demonstrated in Section 3.5 of Chapter 3 such that the simulation study closely follows the experimental setup as far as possible. A tunable double-notch FBG module alongwith a 3–port OC module were used to recover the desired signals at points A, D and F. The bit error rate (BER) curves for different channels at
different positions were obtained by changing the Centre frequencies of the FBGs while keeping all other properties and parameters unchanged.

### 4.3.2 Simulation Results and Discussion

Fig. 4.3 shows the BER curves for downlink Ch\(_2\) at point A with other two channels (Ch\(_1\) and Ch\(_3\)) ON and OFF, respectively. Recovered downlink Ch\(_2\) at point A experiences a negligible 0.15 dB power penalty that can be attributed to the effects of out-of-band crosstalk caused by the neighboring Ch\(_1\) and Ch\(_3\).

Wavelength-interleaved downlink signals (Ch\(_1\), Ch\(_2\), and Ch\(_3\)), immediately after entering to the WDM Optical Interface, encounters the FBG1 at port 2 of the multiport OC. This results in a fraction of neighboring interleaved signals (Ch\(_1\) and Ch\(_3\)) to be reflected and passed through the DL Drop port of the interface along with the desired downlink Ch\(_2\) that contaminates the recovered downlink signal at DL Drop port of the interface by out-of-band crosstalk. Also, the UL Ch\(_2\) added to the

![Fig. 4.3: Simulation BER curves as a function of received optical power at point A showing downlink Ch\(_2\) with Ch\(_1\) and Ch\(_3\) ON and OFF respectively.](image-url)
interface encounters FBG1 while traversing from the ADD port to the OUT port that allows a fraction of the UL Ch2 to be transmitted to the DL Drop port, causing in-band crosstalk to affect the desired downlink Ch2. The interface therefore, causes both out-of-band and in-band crosstalk, in addition to the effects of grating dispersion as well as the concatenated FBG-notches that contaminate the desired downlink signals while recovered via DL Drop port. To quantify the effects of these impairments, a set of BER curves for downlink Ch2 were measured at point B (the

![Fig. 4.4: Simulation BER curves as a function of received optical power at point B for downlink Ch2 with: (i) none of the downlink Ch1, Ch3 or uplink Ch2 present, (ii) downlink Ch1 and Ch3 present, but no uplink Ch2, and (iii) all the downlink as well as uplink channels present.](image)

DL Drop port of WDM Optical Interface1) under three different conditions: (i) removing Ch1 and Ch3 from the downlink interleaved channels along with the uplink Ch2 from the ADD port, (ii) removing only the uplink Ch2 from the ADD port, but Ch1 and Ch3 are present, and, (iii) all the three interleaved channels along with the added uplink Ch2 are present. The measured BER curves are shown in Fig. 4.4. Similar to the BER curves at point A, it again shows that the downlink Ch2 experiences a negligible ~0.15 dB power penalty due to the presence of out-of-band
crosstalk from the neighboring Ch₁ and Ch₃, which however, increases to ~0.30 dB when the uplink signal is added to the interface contaminating the downlink Ch₂ by in-band crosstalk.

To see the overall effects of encountering WDM Optical Interface1, BER curves for downlink Ch₂ measured at point B (having Ch₁, Ch₃ and uplink Ch₂ present) and A (having Ch₁ and Ch₃ present) are compared in Fig. 4.5. It shows that, instead of exhibiting additional power penalty, downlink Ch₂ at B demonstrates an improvement of power penalty (negative power penalty) by approximately 0.3 dB. This can be attributed to the suppression of optical carrier of DL Ch₂ by as much as 50% (as a result of wavelength reuse for the uplink path via FBG2) that in turn increases the CSR of the downlink Ch₂ by 3-dB before being recovered via DL Drop port.

![Fig. 4.5: Comparison of the BER curves for downlink Ch₂ measured at points B (with downlink Ch₁ and Ch₃, as well as uplink Ch₂ present) and A (with all the three downlink channels present).](image-url)
In the uplink direction, the uplink Ch\textsubscript{2} being reflected by FBG1 combines with the through channels and is contaminated by the in-band crosstalk due to the leakage of downlink Ch\textsubscript{2}, in addition to the effects of grating dispersion as well as the concatenated FBG-notches before leaving WDM Optical Interface\textsubscript{1} via the OUT

**Fig. 4.6:** Simulation BER curves as a function of received optical power showing: (a): uplink Ch\textsubscript{2} at point C and D with all the three downlink channels ON, (b): downlink Ch\textsubscript{3} at point D with (i) none of the downlink Ch\textsubscript{1}, downlink Ch\textsubscript{2} or uplink Ch\textsubscript{2} present (ii) downlink Ch\textsubscript{1} and Ch\textsubscript{2} present but no uplink Ch\textsubscript{2} and (iii) all the downlink as well as uplink channels present.
port. In order to quantify the effects of these impairments, BER curves for uplink Ch$_2$ were measured at points C and D (keeping all the other channels ON), which are shown in Fig. 4.6(a). It shows that the uplink Ch$_2$ experiences approximately 0.4 dB additional power penalty potentially due to the impairments in the uplink direction, in addition to the out-of-band crosstalk caused by the filter characteristics used to recover the uplink Ch$_2$ at D.

The effects of impairments on the through channels due to traversing the interface were investigated by measuring the BER curves for Ch$_3$ at point D under three different conditions: (i) removing Ch$_1$ and Ch$_2$ from the downlink interleaved channels along with the uplink Ch$_2$ from the ADD port of WDM Optical Interface1, (ii) removing only the uplink Ch$_2$ from the ADD port of WDM Optical Interface1, but Ch$_1$ and Ch$_2$ are present, and (iii) all the three interleaved channels along with the added uplink Ch$_2$ are present. The measured BER curves can be seen from Fig. 4.6(b). It shows that the downlink channels or the added uplink channel do not have much effect on the through channels.

![Graph showing simulation BER curves as a function of received optical power at points B and E showing downlink Ch$_2$ and Ch$_1$ respectively with all the downlink as well as uplink channels present.](image)

**Fig. 4.7:** Simulation BER curves as a function of received optical power at points B and E showing downlink Ch$_2$ and Ch$_1$ respectively with all the downlink as well as uplink channels present.
In the cascaded configuration, downlink Ch₂ and Ch₁ were recovered at points B and E, respectively; having all the three interleaved channels along with the uplink Ch₂ and Ch₁ were present. Shown in Fig. 4.7, BER of the order of $10^{-9}$ confirms the functionality of the proposed interfaces in cascade. The difference in sensitivities of channels can be attributed to the difference in CSR as well as the performance degradation due to traversing WDM Optical Interface₁ before entering to WDM Optical Interface₂.

The cascading effects on the through channels were quantified by recovering downlink Ch₃ at points A, D and F with simultaneous drop and add of Ch₂ and Ch₁ from and to the respective interfaces. The recovered BER curves can be seen from Fig. 4.8. It shows that, at each stage of cascade, the through channels observe approximately 0.20 dB additional power penalty. This can be again attributed to the filtering effects as well as the grating dispersion of FBGs constituting the interfaces in cascaded setup. The accumulated effects of impairments, due to traversing WDM
Optical Interface1 and IN-DROP part of WDM Optical Interface2, were quantified by recovering downlink Ch₁ at points A, D and E. The recovered BER curves are shown in Fig. 4.9. It shows that downlink Ch₁ (at point E) even after traversing WDM Optical Interface1 and IN-DROP part of WDM Optical Interface2 demonstrates an improvement of power penalty by approximately 0.15 dB, although it undergoes several optical components that have the potential to degrade the signal quality significantly. This improvement of performance is due to the reduction in CSR at WDM Optical Interface2, as 50% optical carrier of Ch₁ was extracted by FBG2 before recovered via DL Drop port. Despite this improvement, Ch₁ experiences 0.2 dB power penalty in WDM Optical Interface1, as described before for the through channels.

Therefore, the characterised results of the simulation confirm the operation of the proposed WDM optical interface for WI-DWDM mm-wave over fibre radio systems, both in single as well as cascaded configurations. The simulation results also indicate

---

**Fig. 4.9:** Simulation BER curves as a function of received optical power at points A, D and E showing downlink Ch₁ with all the downlink as well as uplink channels present.
that the effect of impairments introduced by the proposed interface is very negligible and can be used in cascade with an additional power penalty no more than 0.5 dB per stage of cascade.

4.4 Experimental Characterisation of the Performance of Single and Cascaded WDM Optical Interfaces

Previous section has described the effects of optical impairments on WI-DWDM mm-wave fibre-radio signals while traversing single as well as cascaded WDM optical interfaces. These effects were characterised by developing a simulation model based on VPITransmissionMaker platform. This section extends the simulation characterisation to experimental investigations. Similar to the simulation, the experiment also uses two WDM optical interfaces in cascade located at 10 km from the CO. Section 4.4.1 describes the characteristics of the components used in the experimental investigations. Experimental setup incorporating single and cascaded WDM optical interfaces is illustrated in Section 4.4.2. Also, the results from the experiment and a discussion are presented in Section 4.4.3 and 4.4.4 respectively.

4.4.1 Characteristics of Optical Components

4.4.1.1 Fibre Bragg Grating

The FBGs used in the investigation of the cascaded interfaces are characterised by another experiment already described in Section 3.5.1. All the FBGs were obtained from a commercial vendor, located in Sydney, Australia. These FBGs work at room temperature without any temperature control. They were provisioned to be tuned (stretch tuning) by approximately 0.5 nm. All the FBGs have a notch bandwidth of approximately 0.08 nm.
Fig. 4.10 shows the transmission and reflection responses for the double-notch FBGs used in the demonstration. The characteristic curves at Fig. 4.10(a) show that the nominal Bragg wavelengths for the notches are 1556.207 nm and 1556.509 nm with a separation of 0.302 nm between the notches. The Bragg wavelengths can be tuned to the desired experimental wavelengths by employing suitable mechanical stretchers. The transmission spectrum shows that the notches have leakages of approximately -26 and -27 dB at the Bragg wavelengths from which the reflectivity can be calculated as 99.7% and 99.8% respectively. The characteristic curves at Fig.
4.10(b) show that the nominal Bragg wavelengths for the notches are 1556.157 nm and 1556.459 nm with a separation of 0.302 nm between the notches. The transmission spectrum shows that the notches have leakages of approximately -22 and -22.5 dB at the Bragg wavelengths from which the reflectivity can be calculated as 99.3% and 99.4% respectively. Also, the reflection spectra demonstrate its sharp roll-off profiles with minimum side-lobe ripples. The measured insertion losses of the gratings were approximately 0.3 dB each.

The characteristic curves for 50% reflective FBGs with nominal Bragg wavelengths of 1556.109 nm and 1556.129 nm are shown in Fig. 4.11. Like before, these Bragg wavelengths also can be tuned to the desired experimental wavelengths.
by employing suitable mechanical stretchers. The transmission spectra show that 46% and 47% of the optical power entering to these FBGs will be transmitted, while the respective remaining 54% and 53% will be reflected and recovered by the proposed interface, and eventually, will be reused as optical carriers in the uplink path. These reflection spectra also indicate its sharp roll-off profiles with minimum side-lobe ripples. The measured insertion losses of these grating were approximately 0.3 dB each.

### 4.4.1.2 8-Port Optical Circulators

Two 8-port OCs are required for this experiment. The 8-port OC described in the previous chapter (Chapter 3) will also be used here. However, due to aging and multiple uses, the characteristics of the OC have been changed slightly, especially in port to port insertion losses. The new measurements for the port-to-port insertion losses are shown in the 2\textsuperscript{nd} column of Table 4.1. Due to the unavailability of another 8-port OC, a combination of one 4-port and one 3-port OCs will be used. The port to port insertion losses of the cascaded OCs are also shown in the 3\textsuperscript{rd} column of Table 4.1. The other characteristics of the cascaded OCs (e.g. isolation, directivity etc.) are very similar to that of the 8-port OC, illustrated in the previous chapter.

<table>
<thead>
<tr>
<th>Port to Port</th>
<th>Insertion Losses of 8-port OC (dB)</th>
<th>Insertion Losses of Cascaded 7-port OCs (dB)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1 to 2</td>
<td>0.7</td>
<td>0.9</td>
</tr>
<tr>
<td>2 to 3</td>
<td>1.21</td>
<td>1.21</td>
</tr>
<tr>
<td>3 to 4</td>
<td>0.94</td>
<td>1.4</td>
</tr>
<tr>
<td>4 to 5</td>
<td>2.56</td>
<td>n/a</td>
</tr>
<tr>
<td>5 to 6</td>
<td>3.25</td>
<td>1.35</td>
</tr>
<tr>
<td>6 to 7</td>
<td>1.14</td>
<td>1.55</td>
</tr>
<tr>
<td>7 to 8</td>
<td>1.13</td>
<td>n/a</td>
</tr>
</tbody>
</table>

Table 4.1: Port-to-port insertion losses of the optical circulators
4.4.2 Experimental Setup

Fig. 4.12 shows the experimental set up. In the downlink direction, three narrow-linewidth lasers $\lambda_1$ (1556.2 nm), $\lambda_2$ (1556.4 nm) and $\lambda_3$ (1556.6 nm) were combined and applied to a DE-MZM. A 37.5-GHz mm-wave signal was generated by mixing a 37.5-GHz local oscillator (LO) signal with 155 Mb/s data in BPSK format. The mixer output was then amplified and applied to the DE-MZM that generates OSSB+C modulated optical mm-wave signals, with three optical carriers and their respective sidebands interleaved, similar to the interleaved signal generated in simulation characterisation. The interleaved signal was again amplified by an EDFA and passed through an optical BPF prior to being transported over 10 km of SMF to the two concatenated WDM optical interfaces (WDM Optical Interface1 and WDM Optical Interface2).
Optical Interface2). The signal entering concatenated interfaces is shown in the inset of Fig. 4.12, where the three interleaved carriers with their respective sidebands are denoted as Ch$_1$, Ch$_2$ and Ch$_3$ for simplicity. Like before, each interface in Fig. 4.12 is shown as a block with five ports, namely, the input (IN), the downlink drop (DL Drop), the wavelength reuse drop (λ-Re-Use), the add (ADD) and the output (OUT) port. During the experiment WDM Optical Interface1 was assigned to drop and add Ch$_2$ while WDM Optical Interface2 was to drop and add Ch$_3$. In the uplink direction, the OSSB+C formatted UL Ch$_2$ was generated by modulating the recovered λ-Re-Use carrier with another 37.5 GHz-band UL mm-wave signal carrying 155 Mb/s BPSK data. The UL Ch$_2$ was then routed to WDM Optical Interface1 via the ADD port.

The effects of impairments on the WI-DWDM channels due to traversing the cascaded interfaces were characterised by recovering the transmitted channels at positions A, B, C, D, E, and F indicated in Fig. 4.12. To make the measurements comparable, the same photodetection and data recovery circuit was used for the different channels at different positions with the characteristic parameters unchanged. The desired channels at points A, D and F were recovered by using a tunable double-notch FBG alongwith a 3–port OC, which are shown in Fig. 4.13.
4.4.3 Experimental Results

Fig. 4.14 shows the recovered BER curves for downlink Ch₂ at point A with the other two channels ON and OFF, respectively. The recovered downlink Ch₂ experiences a negligible ~ 0.15 dB power penalty due to out-of-band crosstalk from the neighboring WI-DWDM channels.

The interface causing the impairments to the downlink as well as uplink Ch₂ were described in Section 4.3.2. To quantify the effects of those impairments experimentally, downlink Ch₂ was measured at point B under three different conditions: (i) removing downlink Ch₁ and Ch₃ from the WI-DWDM channels along with the uplink Ch₂ from the ADD port of WDM Optical Interface₁; (ii) removing only the uplink Ch₂ from the ADD port of WDM Optical Interface₁, but having downlink Ch₁ and Ch₃ present; and (iii) having all the downlink WI-DWDM channels along with the added uplink Ch₂ present. The recovered BER curves can be seen in Fig. 4.15. It again shows that the downlink Ch₂ at the DL Drop port
experiences a negligible ~0.15 dB power penalty due to the presence of out-of-band crosstalk, which increases to ~0.30 dB at the presence of in-band crosstalk from uplink Ch$_2$. However, compared to the BER curves at A (again shown in Fig. 4.15 for clarity), downlink Ch$_2$ at B exhibits a negative power penalty of ~ 0.30 dB which is due to the reduction of the CSR of downlink Ch$_2$ by approximately 3 dB while 54% of the carrier is recovered with FBG2, which is explored in detail in the following sections.

Fig. 4.15: Measured BER curves as a function of received optical power at point B for downlink Ch$_2$ with: (i) none of the downlink Ch$_1$, Ch$_3$ or uplink Ch$_2$ present, (ii) downlink Ch$_1$ and Ch$_3$ present, but no uplink Ch$_2$ and (iii) all the downlink as well as uplink channels present, in addition to downlink Ch$_2$ at point A for comparison.

In the uplink direction, the composite spectrum of the downlink through channels as well as the uplink Ch$_2$ after added to the interface is recovered at point D, which can be seen from Fig. 4.16 (a). It shows that, as expected, uplink Ch$_2$ is much weaker than the neighboring downlink channels due to the carrier reuse, the higher insertion loss in OSSB+C generation, as well as the removal of EDFA from the BSs. This weaker uplink signal may cause greater out-of-band crosstalk while recovered, and may limit the link performance immensely.
Incorporating WDM Optical Interface

Shown in Fig. 4.16(b), the effects of the impairments in uplink direction are quantified by measuring BER curves for uplink Ch2 at the points C and D. The uplink Ch2 exhibits a ~0.65 dB additional power penalty at point D which can be potentially ascribed to the in-band and out-of-band crosstalk as explained earlier.

In the cascaded configuration, downlink Ch2 and Ch3 were recovered at points B and E, respectively. The measured optical spectra and the respective BER curves are

Fig. 4.16: (a): Optical spectrum at point D with uplink Ch2 added to the WDM Optical Interface1, (b): BER curves for uplink Ch2 recovered at points C and D respectively.
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Incorporating WDM Optical Interface

The measured BER is of the order of $10^{-9}$ which confirms the functionality of the proposed interfaces in cascade. The difference in sensitivity of downlink Ch3 (~0.25 dB) is mainly due to the difference in CSR as well as the performance degradation due to traversing WDM Optical Interface1 before entering to WDM Optical Interface2.
The cascading effects on the through channels were quantified by recovering downlink Ch$_1$ at points A, D and F with simultaneous drops of downlink Ch$_2$ and Ch$_3$ from the respective interfaces. The recovered optical spectra at points D and F are shown in Fig. 4.18, while optical spectrum at point A has already been shown in the inset of Fig. 4.12. The measured optical spectra at A, D and F show that, due to lossy OCs, the through downlink Ch$_1$ experiences unusual losses of 3.1 and 3.3 dB in WDM Optical Interface1 and WDM Optical Interface2 [typical loss = 1 dB].

![Recovered optical spectra of downlink Ch$_1$ at points: (a) D and (b) F respectively.](image-url)
respective BER curves shown in Fig. 4.19 confirm that, at each stage of cascade, the through channels experience approximately 0.4 dB additional power penalty, which can be attributed to the unusual losses of the through channels as well as the characteristics of the double-notch FBGs used as bidirectional reflective components within the interfaces.

The effects of using additional filtering arrangement at points A, D, and F are quantified by recovering downlink Ch₁ at D with and without filtering arrangement.

![Fig. 4.19: Measured BER curves as a function of received optical power at points A, D, and F for downlink Ch₂.](image)

The recovered BER curves (shown in Fig. 4.20) indicate very negligible effects for using such additional filtering arrangements.

Therefore, similar to the simulation results, the experimentally characterised results also confirm the operation of the proposed WDM optical interface for WI-DWDM mm-wave fibre radio systems, both in single as well as cascaded configurations. The experimental results also indicate the viability of the proposed interface to be used in
Chapter 4: Characterisation and Enhancement of Links Performance
Incorporating WDM Optical Interface

Fig. 4.20: Measured BER curves as a function of received optical power for downlink Ch1 at point D with and without recovering filtering arrangement.

networks with additional power penalty no more than 0.5 dB for each stage of cascade.

4.4.4 Discussion

The ability of the WDM optical interface to be used in both single as well as cascaded configurations indicate that, WDM optical interface is a promising scheme in future DWDM mm-wave fibre-radio networks which enables spectrally efficient WI, efficient wavelength utilisation and transparent wavelength routing to the BSs, while simplifying the BSs by removing the uplink light source completely.

The one drawback of the scheme is the generation of weaker uplink channels that may cause greater out-of-band crosstalk while recovered in the CO, and may limit the link performance immensely. This can be avoided by using optical filters with stringent characteristics of having very sharp roll-off and ultra-narrow notch-bandwidths. Also, the large differences between the interleaved uplink and downlink
channels may stimulate the effects of nonlinearity in the link, which may limit the
network dimensioning. Therefore, in order to maximise the greater uplink channels,
proper link budget as well maximizing the delivery of reuse carrier is essential.
Sections 4.6 to 4.9 will explore such techniques that resolve this limitation to a
remarkable extent.

The setup used in experimental demonstration (shown in Fig. 4.12) is also having
some limitations. The demonstrated setup is the worst case scenario in performance
degradation potential and data on various modulated channels are partially
correlated. Therefore, the exhibited penalties may contain contributions from the data
correlation in addition to other network impairments. In order to quantify data
correlation, the delay between data on various modulated channels at the cascaded
interfaces end can be calculated as follows:

\[ T = D \Delta \lambda L = 17 \text{ psec/nm/km} \times 0.2 \text{ nm} \times 10 \text{ km} = 34 \text{ psec} \]

where, \( T \) = Delay (psec),
\( D \) = dispersion = 17 ps/nm/km
\( \Delta \lambda \) = channel separation = 0.2 nm, and
\( L \) = length of fibre = 10 km

On the other hand, the time duration of 155 Mb/s data is 6.45 nsec = 6450 psec.
These mean that the group-delay difference of data transmitted on 0.2-nm-separated
optical carriers is very small and correlation effects are present. This is however, can
be easily overcome by generating each of the channels independently, which we
were unable to do due to resource limitation.
4.5 Modelling of Fibre-Radio Networks Incorporating Cascaded WDM Optical Interfaces

Sections 4.3 and 4.4 characterised the effects of optical impairments caused by single as well as cascaded WDM optical interfaces in a WI-DWDM mm-wave fibre-radio network. The cascade was comprised of two WDM optical interfaces connected by a small piece of patchcord, having no ‘in between’ fibre span. These analyses are particularly important in quantifying the power penalties introduced by each stage of cascade, in addition to the impacts on the performance of drops and adds channels, while deployed in a practical network.

However, a typical fibre-radio network configured in star-tree architecture [36-39], is expected to contain more than two WDM optical interfaces in cascade in the remote nodes (RNPs). Also, the networks configured in ring/bus architecture [40-43], will be having multiple WDM optical interfaces in cascade, along with a span of fibre within each pair of cascaded interfaces. Therefore, from architectural considerations of the networks, the performance of the WDM optical interface needs to be further analysed. This section thus focuses in modelling of mm-wave fibre-radio networks (based on power budget calculation) incorporating the WDM optical
interface, from which number of allowable units in cascade can be predicted.

The WDM optical interface (WOI) parameters used in the analysis are illustrated in Fig. 4.21 and Table 4.2. The parameters are obtained from the experimental results presented in Section 4.4.

<table>
<thead>
<tr>
<th>Symbol</th>
<th>Description</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>$L_{\text{ThroughWOI}}$</td>
<td>Insertion loss experienced by the through channels in a WDM optical interface</td>
<td>3.2 (dB)</td>
</tr>
<tr>
<td>$L_{\text{DropWOI}}$</td>
<td>Insertion loss experienced by the downlink drop channel in a WDM optical interface. It also includes the 3-dB recovery of the carrier for uplink communication</td>
<td>5.8 (dB)</td>
</tr>
<tr>
<td>$L_{\text{ADDWOI}}$</td>
<td>Insertion loss experienced by the uplink add channel in a WDM optical interface</td>
<td>1.3 (dB)</td>
</tr>
<tr>
<td>$PP_{\text{Through}}$</td>
<td>Power penalty experienced by the through channels for traversing each stage of WDM optical interface</td>
<td>0.4 (dB)</td>
</tr>
<tr>
<td>$PP_{\text{IN-DL Drop}}$</td>
<td>Power penalty experienced by the downlink drop channel for traversing IN-DL Drop part of WDM optical interface</td>
<td>-0.3 (dB)</td>
</tr>
<tr>
<td>$PP_{\text{ADD-OUT}}$</td>
<td>Power penalty experienced by the uplink add channel for traversing ADD-OUT part of WDM optical interface</td>
<td>0.65 (dB)</td>
</tr>
<tr>
<td>$L_{\text{MOD}}$</td>
<td>Insertion Loss of OSSB+C modulator in CO</td>
<td>15.9 (dB)</td>
</tr>
<tr>
<td>$G_{\text{BAMP}}$</td>
<td>Amplification by boost EDFA in CO</td>
<td>22.5 (dB)</td>
</tr>
<tr>
<td>$L_{\text{SMF}}$</td>
<td>Attenuation of signal in 10 km SMF</td>
<td>2.2 (dB)</td>
</tr>
<tr>
<td>$T_{\text{LSCO}}$</td>
<td>Power launched from the light-source</td>
<td>0.3 (dBm)</td>
</tr>
<tr>
<td>$L_{\text{MUX}}$</td>
<td>Insertion loss of the optical combiner</td>
<td>4.9 (dB)</td>
</tr>
</tbody>
</table>

Table 4.2: WDM Optical Interface parameters to be used in performance analysis in networks considerations.
The interface parameters include the insertion losses as well as the power penalties of the through and add/drop channels, while traversing single and cascaded WDM optical interfaces. Other parameters included in the Table 4.2 are the insertion losses of the OSSB+C generator and optical combiner in the CO, the power launched from the light-source at the CO, the amplification of signals by boost EDFA, and the attenuation of signal in 10 km SMF. Most of the values shown in Table 4.2 are related to the transmission and detection of downlink and uplink Ch2 by the experiment in Section 4.4. The calculation of the loss/gain parameters are based on the peak powers of the measured optical spectra.

4.5.1 Network Architectures and Optical Power Budget

The performance of WDM fibre-radio systems were investigated based on different network topologies and architectures with their relative merits and demerit [36-48]. Among these architectures, star-tree and rings/bus architectures are considered very effective in delivering future broadband wireless services to customers via fibre-radio networks. This section thus considers both star-tree and rings/bus networks in analysing the performance of links incorporating WDM optical interfaces.

4.5.1.1 Star-Tree Networks

A generic start-tree configured WI-DWDM fibre-radio network incorporating WDM optical interfaces is shown in Fig. 4.22. fibre links from the CO form the ‘star’ part of the architecture, while the ‘tree’ part is at the RNs with each branch feeding different BSs through the respective WOIs. A unique wavelength is used to feed each BS connected by a common arm of star, with wavelengths being reused within different arms. WOIs can be used in cascade in the RNs to enable OADM functionality to the BSs, in addition to provide optical carrier in the uplink path. A single DWDM optical carrier will be used for both upstream and downstream transmission from and to a BS, and the rf signals on any DWDM carrier are those transmitted and received by the specific BS.

In the CO, a large number DWDM optical carriers are used to generate OSSB+C modulated optical mm-wave signals, combined using a suitable multiplexer and
amplified before launching onto the fibre. The amplified signals will be then transported to the RNs where the composite signal will be demultiplexed by using concatenated WOIs and drop the desired downlink signals as well as the uplink optical carriers to the respective BSs. In the uplink direction, each BS will generate OSSB+C modulated optical mm-wave signal by reusing the recovered optical carrier and route it to the fibre network through the respective WOI in the RN. The fibre network then enable the uplink signals to be transported to the CO for further processing. One of the main benefits of this architecture is the possibility of sharing the optical carriers between different feeder networks of the RNs [36-37].

To calculate the power budget of an optical link in star-tree network architecture, one branch of the star (shown in Fig. 4.22) is simplified as Fig. 4.23, where the components and subsystems contributing in power budget calculation are clearly shown. Shown in Fig. 4.23, the link is assumed to support N BSs through a single
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RN, where each of the BS is represented by the relevant WOI. Throughout this section, ‘BS’ and ‘WOI’ terms will be used for similar meanings. The power budget and the power margin in the downlink direction for the Mth BS (1 ≤ M ≤ N), can be calculated by:

\[ PR_{BSM} = T_{LSCO} - L_{MUX} - L_{MOD} + G_{BAMP} - L_{SMF} - (M-1)L_{ThroughWOI} - L_{DropWOI} \]

\[ PM_{BSM} = PR_{BSM} - Sensitivity_{BSM} \]

where \( PR_{BSM} \) and \( PM_{BSM} \) are the received optical power and the power margin at photodetector (PD) of Mth BS (BSM), \( Sensitivity_{BSM} \) is the sensitivity at the PD of BSM, \( T_{LSCO} \) is the optical power from the respective light-source in the CO, \( L_{MOD} \) is the loss in OSSB+C modulator, \( G_{BAMP} \) is the gain from the boost-amplifier in the downlink path, \( L_{SMF} \) is the loss in fibre span between the CO and the RN, \( L_{ThroughWOI} \) is the through channel loss of WOI, and \( L_{DropWOI} \) is the drop-channel loss of WOI while recovering the desired downlink by the respective WOI. In this calculation, the losses in the connecting patchcords between the WOIs and the BSs are ignored due to very shorter distances.

By using the values noted in Table 4.2, Equation (1) can be simplified as:

Fig. 4.23: Simplified optical link in star-tree architecture showing the relevant components and subsystems in the CO and RN.
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Incorporating WDM Optical Interface

\[ PR_{BSM} = -6.0 - (M-1)3.2 \] \hspace{1cm} \text{……… (3)}

Therefore, received optical power at the PD of BS_1 (where \( M = 1 \)),

\[ PR_{BS1} = -6.0 \text{ (dBm)} \]

The power margin at the PD of BS_1 can be calculated by using the sensitivity of the recovered signal (shown in Fig. 4.15), which is -14.2 dBm. Therefore, power margin at the PD of BS_1,

\[ PM_{BS1} = 8.2 \text{ (dB)} \]

If the power penalty is considered to add up linearly with increasing number of BSs and the BSs (or WOIs) are considered to be identical, then the number BSs supported by the link can be calculated by:

\[ PM_{BSN} = (N - 1)(PP_{Through} + L_{ThroughWOI}) \] \hspace{1cm} \text{……… (4)}

where \( N \) is the number of WOIs in cascade in the RN, \( PM_{BS1} \) is the power margin at the PD of BS_1, \( PP_{Through} \) is the power penalty experienced by the through channels for traversing each stage of WOI, and \( L_{ThroughWOI} \) is the insertion loss experienced by the through channels in a WOI.

By using the values of the parameters noted in Table 4.2, and Equation (4), number of WOIs in cascade can be calculated by:

\[ N = 1 + \frac{PM_{BS1}}{(PP_{Through} + L_{ThroughWOI})} = 1 + \frac{8.2}{0.4+3.2} = 3.28 \approx 3 \text{ units} \]

However, if the lossy multiport OCs in the WOIs in the experiment (described in Section 4.4) are replaced with standard OCs having typical through channel insertion loss (typical through loss 1dB/WOI), and typical drop channel insertion loss
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(typical loss 1dB/WOI), the number of units in cascade will increase to 8. Also, if the insertion of the OSSB+C generator in CO can reduced to 9 dB, the number of units in cascade will increase to 13.

Therefore WOI proposed in Section 3.4 can be a suitable candidate in future WI-DWDM mm-wave fibre-radio networks, configured in star-tree architecture, where cascaded interfaces will be used in the RNs to enable OADM functionality to the BSs, in addition to provide optical carriers for the upstream transmission.

4.5.1.2 Ring/Bus Networks

A generic ring/bus configured WI-DWDM fibre-radio network incorporating WOIs is shown in Fig. 4.24. This architecture allows the CO to distribute wavelengths to remote antenna BSs that are placed along the ring, with a WOI enabling OADM functionality to the relevant BS, in addition to delivering the optical carrier for upstream transmission. Each of the BSs fed from the CO have their own unique wavelength to be used for both uplink and downlink communication. In the CO, a large number optical carriers are used to generate OSSB+C modulated optical mm-wave signals, combined using a suitable multiplexer and amplified before launching onto the fibre ring. The amplified signals will be then transported along the ring where the relevant WOI will recover the downlink signal relevant to the BS and enables the through channels to be routed to the next BSs. The WOI also provides uplink optical carrier to the respective BS by recovering 50% of the optical carrier from the recovered downlink signal. In the uplink direction, each BS generates OSSB+C modulated optical mm-wave signal by reusing the recovered optical carrier and routes it to the fibre ring via the relevant WOI. The uplink signal then passes through the remaining BSs with the through channels along the ring and transported to the CO for further processing.

This architecture is typically unidirectional and the BSs in the ring are separated typically by equal distances. It has the potential for fault restoration using second protection ring allowing a fibre break between nodes or a failure of node to be bypassed [49-52]. It also enables easy implementation of rf carrier reuse between the BSs, in addition to allowing dynamic frequency allocation, since frequency
assignment schemes can be controlled from the CO [53-55]. The main problem with a passive ring network is the non-uniform signal quality provided to different BSs, along with cumulative component loss along the ring.

To calculate the power budget of an optical link in ring/bus network architecture, the generic architecture shown in Fig. 4.24 can be redrawn as Fig. 4.25, where the components and subsystems contributing in power budget calculation are clearly shown. Similar to star-tree network, the ring is assumed to support N BSs through a single CO, where each of the BS is represented by the relevant WOI. Shown in Fig. 4.25, each of the WOIs is followed by a span of fibre to be connected with the neighboring WOI, which forms the ring under investigation. This section also uses the terms ‘BS’ and ‘WOI’ for similar meaning. For simplicity, all the fibre spans are considered to be equal having a transmission attenuation of 0.2 dB/km.

The power budget and the power margin in the downlink direction for the Mth BS (1 ≤ M ≤ N), can be calculated by:

\[
PR_{BSM} = T_{LSCO} - L_{MUX} - L_{MOD} + G_{BAMP} - M*L_{SMF} - (M-1)L_{ThroughWOI} - L_{DropWOI}
\]

\[
\text{……………………………..(5)}
\]
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\[ PM_{BSM} = PR_{BSM} - Sensitivity_{BSM} \]

where \( PR_{BSM} \) and \( PM_{BSM} \) are the received optical power and the power margin at the PD of Mth BS (BS\(_M\)), \( Sensitivity_{BSM} \) is the sensitivity at the PD of BS\(_M\), \( T_{LSCO} \) is the optical power from the respective light-source in the CO, \( L_{MOD} \) is the loss in OSSB+C modulator, \( G_{BAMP} \) is the gain from the boost-amplifier in the downlink path, \( L_{SMF} \) is the attenuation in each of the fibre span between two consecutive WOIs, \( L_{ThroughWOI} \) is the through channel loss of WOI, and \( L_{DropWOI} \) is the drop-channel loss of WOI while recovering the desired downlink by the respective WOI.

Equation (5) can be simplified by using the values of the parameters from the experiment (described in Section 4.4) as well as the Table 4.2. The experiment uses 10 km SMF between to CO and the BS. To use the results from the experiment for this analysis, we consider the first span of fibre 10 km, while the others are 1 km each. After such considerations, Equation (5) can be simplified as:

\[ PR_{BSM} = -6.0 - (M-1)3.4 \]

... (7)
Therefore, received optical power at the PD of BS$_1$ (where $M = 1$):

$$PR_{BS1} = -6.0 \text{ (dBm)}.$$ 

The power margin at the PD of BS$_1$ can be calculated by using the sensitivity of the recovered signal (shown in Fig. 4.15), which is -14.2 dBm. Therefore, power margin at the PD of BS$_1$,

$$PM_{BS1} = 8.2 \text{ (dB)}$$

If the power penalty is considered to add up linearly with increasing number of BSs and the BSs (WOIs) are considered to be identical, then the number BSs supported by the link can be calculated by:

$$PM_{BSN} = (N - 1)(PP_{Through} + L_{ThroughWOI}) + N \times (1 \text{ km} \times 0.2 \text{ dB/km}) \quad \ldots \quad (8)$$

where $N$ is the number of WOIs in cascade spaced by 1 km of SMF, $PM_{BS1}$ is the power margin at the PD of BS$_1$, $PP_{Through}$ is the power penalty experienced by the through channels for traversing each stage of WOI, and $L_{ThroughWOI}$ is the insertion loss experienced by the through channels in a WOI.

By using the values noted in Table 4.2, number of units in cascade can be calculated by:

$$8.2 = (N-1) \times 3.6 + 0.2N$$

$$\Rightarrow \quad N = \frac{11.8}{3.8} = 3.1 \approx 3 \text{ units}$$

However, if the lossy multiport OCs in the WOIs in the experiment (described in Section 4.4) are replaced with standard OCs having typical through channel insertion loss (typical through loss 1dB/WOI) and typical drop channel insertion loss (typical loss 1dB/WOI), the number of units in cascade will increase to 7. Also, if the insertion of the OSSB+C generator in CO can be reduced to 9 dB, the number of
units in cascade will increase to 11. The cascadability of the WOI with different conditions can be tabulated as follows:

<table>
<thead>
<tr>
<th>Actual Configurations</th>
<th>Star/Tree</th>
<th>Ring/Bus</th>
</tr>
</thead>
<tbody>
<tr>
<td>WOI Through &amp; Drop Loss Improved to 1 dB</td>
<td>8</td>
<td>7</td>
</tr>
<tr>
<td>OSSB+C Modulator Insertion Loss Improved to 9 dB</td>
<td>13</td>
<td>11</td>
</tr>
</tbody>
</table>

Table 4.3: Number of WOIs in cascade

Therefore WDM optical interface proposed in Section 3.4 can be a suitable candidate in future WI-DWDM mm-wave fibre-radio networks, configured in ring/bus architecture, where the interfaces will be used along the fibre ring to enable OADM functionality to the BSs, in addition to provide optical carriers for the upstream transmission.

4.6 Performance Improvement of Fibre-Radio Links
Incorporating Modification in WDM Optical Interface

Millimetre-wave fibre-radio system, a wideband transmission medium, typically requires a high spurious free dynamic range (SFDR). Increase of optical power in the link can potentially resolve this problem; however, this method increases the average optical power to the PD and causes nonlinearities to output of the PD, leading to harmonic distortion to response reduction, and eventually to catastrophic failure through complete damage due to high current or thermal effects [20, 21, 56, 57]. Concurrent with PD power limitations, the performance of wide bandwidth intensity modulators, used in superimposing mm-wave signals onto optical carriers, are also limited by very narrow linear characteristics. Therefore, modulation depths of such
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Incorporating WDM Optical Interface

Wideband optical mm-wave signals are often sacrificed for less efficient modulation by manageable mm-wave input powers, although high input power of modulating mm-wave signals have the potential to enable larger modulation depths [20, 56]. These shortcomings in mm-wave fibre-radio systems result in very poor sensitivities for the detected mm-wave fibre-radio signals, which need to be overcome by further explorations.

To enable larger modulation depths without increasing input mm-wave powers, several techniques based on active and passive means were introduced [20 - 22, 57-60]. A similar technique has been proposed in Section 3.7 that also confirms the significance of modulation depth enhancement by external means. However, all these techniques require additional signal processing hardware, which are inherently susceptible to further performance degradation and adding up new complexities to the systems. Instead, if the modulation depth enhancement, which can be defined as the reduction of the CSR, can be combined with the other system technologies by avoiding additional devices, an effective modulation depth enhancement can be realised.

Another drawback of carrier reused mm-wave fibre-radio systems incorporating WDM optical interfaces is the generation of weaker uplink signals due to weaker reuse carrier, higher insertion loss in OSSB+C generation, and the removal of EDFA from the BSs. These weaker uplink signals may cause greater out-of-band crosstalk while recovered and may stimulate the effects of nonlinearity in the link, and as a result, may limit the link performance immensely. In order to realise greater uplink signals, proper link budget as well maximizing the delivery of reuse carrier is essential.

In the next section, we have modified the WDM optical interface proposed in Chapter 3 that enables larger modulation depth in the downlink direction without employing additional hardware. This scheme also allows the interface to deliver greater reuse optical carrier for uplink communication that simultaneously enhances the performance of the system in uplink direction.
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4.6.1 Modification in WDM Optical Interface

Chapter 3 describes the proposed WDM optical interface, which contains a 50% reflective FBG2 to recover 50% optical carrier from the OSSB+C modulated downlink signal for reuse in the uplink path. The recovery of 50% optical carrier reduces the CSR of the downlink signal by 3 dB (consequently, improves modulation depth by 3 dB), while delivers the recovered carrier for reuse as uplink optical carrier. If the 50% reflective FBG is replaced with an FBG having higher reflectivity, further reduction in CSR in the downlink direction, as well as greater reuse carrier for the uplink path can be realised. Table 4.4 shows how the CSR of the downlink signal and the intensity of reuse optical carrier change with the increase of reflectivity of FBG2. It shows that the increase of reflectivity of FBG2 from 50% to 99.9% will enable a reduction in CSR from 3 dB to 30 dB, while will increase the reuse optical carrier from -3 dB to 0 dB. In order to decide about the optimum reflectivity of FBG2, information regarding the CSR of the downlink signals before entering to the WDM optical interface is required, as optimum modulation depth is achieved while CSR is 0 dB [22].

<table>
<thead>
<tr>
<th>FBG2 Reflection (%)</th>
<th>Downlink Optical Carrier (dBm)</th>
<th>Reduction in Downlink CSR (dB)</th>
<th>Recovered Uplink Optical Carrier (dBm)</th>
<th>Increase in Uplink Carrier (dB)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>0.0</td>
<td>n/a</td>
<td>n/a</td>
<td>n/a</td>
</tr>
<tr>
<td>50</td>
<td>-3.0</td>
<td>3.0</td>
<td>-3.0</td>
<td>n/a</td>
</tr>
<tr>
<td>60</td>
<td>-3.98</td>
<td>3.98</td>
<td>-2.2</td>
<td>0.8</td>
</tr>
<tr>
<td>70</td>
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<td>95</td>
<td>-13.0</td>
<td>13.0</td>
<td>-0.22</td>
<td>2.78</td>
</tr>
<tr>
<td>99</td>
<td>-20.0</td>
<td>20.0</td>
<td>-0.04</td>
<td>2.96</td>
</tr>
<tr>
<td>99.9</td>
<td>-30.0</td>
<td>30</td>
<td>-0.004</td>
<td>3</td>
</tr>
</tbody>
</table>

Table 4.4: Effects of increasing the reflectivity of FBG2 of WDM Optical Interface, both in uplink and downlink direction
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Fig. 4.26: Modified WDM optical interface enabling modulation depth enhancement of the downlink signal and recovering greater optical carrier for the uplink path, while performing optical add-drop functionality for a wavelength-interleaved DWDM fibre-radio system.

This problem can be resolved by replacing FBG2 having fixed reflectivity with an FBG having a variable reflectivity from 50% to 99.9%. The variable FBG2 can be tuned and adjusted as per the CSR of the downlink signals.

Fig. 4.26 shows such a modified WDM optical interface with an enlarged view of the variable FBG2 as shown in the inset. As described in Section 3.4, the desired downlink signal at port 2 of the OC is reflected from the WI-DWDM signals by the FBG1, which then encounters FBG2 at port 3. FBG2 enables a variable reflection of downlink optical carrier depending on the CSR of the signal. The reflectivity of FBG2 is tuned and adjusted in such a way that the CSR of the signal at DL Drop port is 0 dB. A typical CSR for an optical mm-wave signal is more than 10 dB. Therefore, FBG2 will be required to be tuned to more than 90% reflectivity, for which the recovery of uplink optical carrier is also almost maximised. The remaining functionality of the interface is as similar as the original interface, described in Section 3.4. The modification in the WDM optical interface thus offers optimum modulation depth for the downlink signals and maximises the recovery of the reuse
optical carriers, while enables the BSs of fibre-radio systems to the WI-DWDM fibre-feeder networks by dropping and adding the desired signals.

### 4.7 Experimental Demonstration

The experiment to evaluate the performance of downlink/uplink transmission incorporating the modified WDM optical interface is shown in Fig. 4.27. Three OSSB+C modulated optical mm-wave signals were generated using three narrow linewidth light sources $LS_1$, $LS_2$, and $LS_3$ at the corresponding wavelengths $\lambda_1$ (1556.2 nm), $\lambda_2$ (1556.4 nm) and $\lambda_3$ (1556.6 nm) and a 37.5 GHz-band mm-wave signal. The binary-phase-shift-keyed (BPSK) formatted mm-wave signals were generated by mixing a 37.5 GHz local oscillator (LO) signal with a 155 Mb/s pseudo-random bit sequence (PRBS) data stream. The mm-wave modulated optical

![Experimental setup](image)

**Fig. 4.27:** Experimental setup for the evaluation of the performance of modified WDM optical interface enabling performance improvement of the link, both in downlink and uplink direction, for a WI-DWDM fibre-radio system.
signals were then combined using 3 dB couplers, amplified by using an EDFA followed by an optical BPF that minimises the out-of-band ASE noise prior to being transported over 10 km SMF to the modified WDM optical interface. The spectrum of the interleaved signals entering to the modified interface is shown in Fig. 4.28. The spectrum exhibits a ratio of the optical carriers ($\lambda_1$, $\lambda_2$, and $\lambda_3$) to the corresponding sidebands (S1, S2, and S3), CSR of 12.2 dB, which indicates that optimum modulation depth will be achieved if the CSR is reduced by 12.2 dB.

The modified WDM optical interface is comprised of an 8-port OC (as described in Section 4.4.1.2) and a FBG1, the characteristics of which was also described in Section 4.4.1.1, in addition to the modified FBG2, as describe in previous section. Due to commercial unavailability of such FBG2 with variable reflectivity, a bank of FBGs with various fixed reflectivity is used in the experiment. The bank of FBGs consists of four separate FBGs with reflectivity of 54%, 70%, 85% and 93%, and a 3 dB bandwidth of 0.08 nm (~10 GHz) each. The 93% reflective FBG enables almost the optimum modulation depth in the link, as the CSR needs to be reduced only by 12.2 dB, as mentioned above. The other FBGs are used to demonstrate the gradual
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Incorporating WDM Optical Interface improvement in performance, both in downlink and uplink direction while reflectivity of FBG2 is adjusted from 54% to 93%.

With various reflectivity of FBG2 mentioned above, the optical spectra of the desired downlink signals ($\lambda_{2}, S_{2}$) are recovered at DL drop port of the interface, which are shown in Fig. 4.29. Also, the characteristic parameters of the recovered spectra are illustrated in Table 4.5. Fig. 4.29 and Table 4.5 show that the insertion of

<table>
<thead>
<tr>
<th>FBG2 Reflection (%)</th>
<th>DL Carrier (dBm)</th>
<th>Sideband (dB)</th>
<th>CSR (dB)</th>
<th>Recovered UL Carrier (dBm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>No FBG2</td>
<td>-3.2</td>
<td>-15.4</td>
<td>12.2</td>
<td>No UL Carrier</td>
</tr>
<tr>
<td>54</td>
<td>-6.6</td>
<td>-15.7</td>
<td>9.1</td>
<td>-7.6</td>
</tr>
<tr>
<td>70</td>
<td>-8.4</td>
<td>-15.5</td>
<td>7.1</td>
<td>-7.3</td>
</tr>
<tr>
<td>85</td>
<td>-11.4</td>
<td>-16.4</td>
<td>5</td>
<td>-6.7</td>
</tr>
<tr>
<td>93</td>
<td>-15</td>
<td>-16.7</td>
<td>1.7</td>
<td>-5.8</td>
</tr>
</tbody>
</table>

**Table 4.5**: Characteristic parameters of the optical spectra of the downlink signals as well as the uplink reuse carriers recovered with various reflectivity of FBG2 in modified WDM Optical Interface.
FBG2 with reflectivity 54%, 70%, 85% and 93% reduces the CSRs of the downlink spectra from 12.2 dB to 9.1, 7.1, 5 and 1.7 dB respectively. Therefore, by replacing the 54% (~50%) reflective FBG in the interface with an FBG of 93% reflectivity, a reduction in CSR by as much as 7.4 dB can be achieved. The 3rd column of the Table 4.5 shows, the sidebands of the downlink signals vary by 1.3 dB; this is due to the presence of fluctuations in the recovered spectra caused by the imperfect filtering characteristics of the FBGs used in the experiment.

![Fig. 4.30: Measured optical spectra of the uplink reuse carriers with various reflectivity of FBG2, recovered at λ- Re-Use port of the modified WDM optical interface.](image)

The optical spectra of the respective reuse carriers while inserted 54%, 70%, 85% and 93% reflective FBG2 in the interface are recovered via λ- Re-Use port, and shown in Fig. 4.30. The characteristic parameters of these curves are also illustrated in Table 4.5. Fig. 4.30 and Table 4.5 show that the insertion of FBG2 with reflectivity 54%, 70%, 85% and 93% provides optical carriers in the uplink path, which gradually increases from -7.6 dB to -7.3, -6.7 and -5.8 dB respectively. Therefore, the replacement of the 54% (~50%) reflective FBG in the interface with a 93% reflective FBG enables an increase of uplink reuse carrier by as much as 1.8 dB.
In compare with the respective downlink carriers at DL Drop port, uplink carriers are reduced by approximately 1.2 dB. This can be attributed to the insertion loss of the OC between port 2 to port 3, which has been traversed by the uplink carriers before being recovered via λ-Re-Use port.

The effects of the reduction in CSR in the downlink direction are quantified by measuring BER curves for downlink (λ2, S2) at DL Drop port with various reflectivity of FBG2 mentioned above. The measured BER curves are shown in Fig. 4.31. The curves demonstrate that due to 7.4 dB reduction in CSR (mentioned above); the overall performance of the recovered downlink (λ2, S2) improves by as much as 2.9 dB. The changes in sensitivity with respect to the CSRs, as well as the reduction of CSRs, in the downlink direction of the link are also plotted in Fig. 4.32.

In order to quantify the effects in the uplink direction, the recovered uplink carriers were reused to generate uplink OSSB+C modulated signals by using another 37.5 GHz mm-wave signal, which was generated by mixing a 37.5 GHz LO signal.
with 155 Mb/s BPSK data, the similar way it was generated in the downlink direction. Each of the uplink signals was then detected to recover data by using the PD and data recovery circuit used in recovering downlink data. The BER curves for the recovered uplink data are shown in Fig. 4.33. It shows that 1.8 dB increase in the uplink reuse carriers by the modified interface improves the performance of the link in the uplink direction by 1.2 dB. The changes in sensitivity in the uplink direction with respect to the intensity of the uplink reuse carriers are also plotted in Fig. 4.34.

The experimental results, therefore, clearly indicate that the incorporation of the variable FBG2 in the WDM optical interface will enhance the modulation depths of the downlink signals by reducing the CSRs that improves the link performance in the downlink direction significantly. Also the reduction in CSRs of the downlink signals allows the interface to maximise the recovery of the uplink reuse carriers that also exerts notable performance improvement in the uplink direction, while reducing the difference between the weaker uplink signals and the through downlink signals in the fibre feeder networks.
Fig. 4.33: Measured BER curves as a function of received optical power for uplink signals generated by the reuse carriers recovered by the modified WDM optical interface with FBG2 reflectivity of: (i) 54%, (ii) 70%, (iii) 85%, and (iv) 93% respectively.

Fig. 4.34: Changes of sensitivity in the uplink direction with respect to uplink reuse carriers.
4.8 Modified WDM Optical Interface and Network Dimensioning

Section 4.6 describes the modified WDM optical interface that enhances the modulation depths of the downlink signals without employing additional hardware, and delivers greater reuse optical carrier for uplink communications. However, the incorporation of such modification in the WDM optical interface limits the power budget of the link, which may restrict the network dimensioning. Described in Section 4.5, fibre-radio network configured in star-tree architecture [36-39], is expected to contain more than two WDM optical interfaces in cascade in the RNs. Also, the networks configured in ring/bus architecture [40-43], will be having multiple WDM optical interfaces in cascade, along with a span of fibre within each pair of cascaded interfaces. Therefore, the cascadability of the modified WDM optical interface in both star-tree and ring/bus architectures are needed to be explored.

The power budget and the power margin of the link incorporating the modified WDM optical interface can be calculated by:

\[
PR_{DL} = T_{LSCO} - L_{MUX} - L_{MOD} + G_{AMP} - L_{SMF} - L_{DropWOI} \quad \text{..........(9)}
\]

\[
PM_{DL} = PR_{DL} - \text{Sensitivity}_{DL} \quad \text{.................................(10)}
\]

where \(PR_{DL}\) and \(PM_{DL}\) are the optical power and the power margin of the desired downlink signal at DL Drop port of modified WOI, \(\text{Sensitivity}_{DL}\) is the sensitivity at the DL Drop port of modified WOI, \(T_{LSCO}\) is the optical power from the respective light-source in the CO, \(L_{MOD}\) is the loss in OSSB+C modulator, \(G_{AMP}\) is the gain from the boost-EDFA in the CO, \(L_{SMF}\) is the loss in 10 km SMF, and \(L_{DropWOI}\) is the drop-channel loss in the modified WOI, while the downlink signal traverses from IN to DL Drop port. \(L_{DropWOI}\) also includes the reflection of the carrier by the variable FBG2.
The parameters obtained from the experimental results with various reflectivity of FBG2 are presented in Table 4.6, where $L_{\text{DropWOI-54\%}}$, $L_{\text{DropWOI-70\%}}$, $L_{\text{DropWOI-85\%}}$, and $L_{\text{DropWOI-93\%}}$ are the drop-channel losses in the modified WOI with respective FBG2 reflectivity of 54%, 70%, 85% and 93%. $Sensitivity_{\text{DL-54\%}}$, $Sensitivity_{\text{DL-70\%}}$, $Sensitivity_{\text{DL-85\%}}$, and $Sensitivity_{\text{DL-93\%}}$ also refer to the sensitivity at the DL Drop while reflectivity of FBG2 are 54%, 70%, 85% and 93% respectively.

<table>
<thead>
<tr>
<th>Symbol</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>$T_{\text{LSCO}}$</td>
<td>0.4 (dBm)</td>
</tr>
<tr>
<td>$L_{\text{MUX}}$</td>
<td>4.9 (dB)</td>
</tr>
<tr>
<td>$L_{\text{MOD}}$</td>
<td>15.7 (dB)</td>
</tr>
<tr>
<td>$G_{\text{BAMP}}$</td>
<td>23.5 (dB)</td>
</tr>
<tr>
<td>$L_{\text{SMF}}$</td>
<td>2.2 (dB)</td>
</tr>
<tr>
<td>$L_{\text{DropWOI-54%}}$</td>
<td>7.8 (dB)</td>
</tr>
<tr>
<td>$L_{\text{DropWOI-70%}}$</td>
<td>9.6 (dB)</td>
</tr>
<tr>
<td>$L_{\text{DropWOI-85%}}$</td>
<td>12.5 (dB)</td>
</tr>
<tr>
<td>$L_{\text{DropWOI-93%}}$</td>
<td>16.1 (dB)</td>
</tr>
<tr>
<td>$Sensitivity_{\text{DL-54%}}$</td>
<td>-15.2 (dBm)</td>
</tr>
<tr>
<td>$Sensitivity_{\text{DL-70%}}$</td>
<td>-16.1 (dBm)</td>
</tr>
<tr>
<td>$Sensitivity_{\text{DL-85%}}$</td>
<td>-16.9 (dBm)</td>
</tr>
<tr>
<td>$Sensitivity_{\text{DL-93%}}$</td>
<td>-18.1 (dBm)</td>
</tr>
</tbody>
</table>

*Table 4.6: Modified WDM Optical Interface parameters used in performance analysis in networks considerations*

By using the Equations (9) and (10) and the values noted in Table 4.6, the optical power and the power margin at DL Drop port for various reflectivity of FBG2 can be calculated as:

$$PR_{\text{DL-54\%}} = -6.6 \text{ (dBm)}$$
Star-tree configured fibre-radio networks, described in Section 4.5, are expected to having multiple WOIs in cascade in the RNs. If the power penalty is considered to add up linearly with increasing number of WOIs in cascade, then the number WOIs supported by the link (no ‘in between’ fibre) can be calculated by:

\[ PM_{DL} = (N - 1)(PP_{Through} + L_{ThroughWOI}) \]  

where \( N \) is the number of WOIs in cascade, \( PP_{Through} \) is the power penalty experienced by the through signals for traversing each stage of WOI, and \( L_{ThroughWOI} \) is the insertion loss experienced by the through channels in a WOI.

Section 4.5 has shown that, for each stage of cascade, the through signals experience a power penalty and an insertion loss of 0.4 dB and 3.2 dB respectively. Therefore, for various reflectivity of FBG2, numbers of WOIs in cascade can be calculated as:

\[ N_{54\%} = 1 + 8.6/(0.4+3.2) = 3.39 \approx 3 \text{ units} \]
\[ N_{70\%} = 1 + 7.6/(0.4+3.2) = 3.11 \approx 3 \text{ units} \]
\[ N_{85\%} = 1 + 5.5/(0.4+3.2) = 2.53 \approx 2 \text{ units} \]
\[ N_{93\%} = 1 + 3.1/(0.4+3.2) = 1.86 \approx 1 \text{ units} \]

If the lossy multiport OCs in the WOIs in the experiment are replaced with standard OCs having typical through channel insertion loss (typical through loss...
1dB/WOI), and typical drop channel insertion loss (typical loss 1dB/WOI), the number of units in cascade will increase to:

\[ \begin{align*}
N_{54\%} &= 8 \text{ units} \\
N_{70\%} &= 8 \text{ units} \\
N_{85\%} &= 6 \text{ units} \\
N_{93\%} &= 4 \text{ units}
\end{align*} \]

Also, if the insertion loss of the OSSB+C generator in CO can reduced to 9 dB, the number of units in cascade will increase to:

\[ \begin{align*}
N_{54\%} &= 13 \text{ units} \\
N_{70\%} &= 12 \text{ units} \\
N_{85\%} &= 11 \text{ units} \\
N_{93\%} &= 9 \text{ units}
\end{align*} \]

Ring/bus configured fibre-radio networks, described in Section 4.5, will be having multiple WOIs in cascade, in addition to a span of fibre between each pair of cascaded WOIs. Like before, if the power penalty is considered to add up linearly with increasing number of WOIs in cascade, then the number WOIs supported by the link can be calculated by:

\[ PM_{DL} = (N - 1)(PP_{Through} + L_{ThroughWOI}) + N.L_{FS} \]  \hspace{1cm} \ldots \ldots \ldots \ldots \ldots \ldots (12) \]

\[ N = \frac{PM_{DL} + PP_{Through} + L_{ThroughWOI}}{PP_{Through} + L_{ThroughWOI} + L_{FS}} \ldots \ldots (13) \]

where \( N \) is the number of WOIs in cascade, \( PP_{Through} \) is the power penalty experienced by the through signals for traversing each stage of WOI, \( L_{ThroughWOI} \) is the insertion loss experienced by the through signals in a WOI, and \( L_{FS} \) is the attenuation loss in the ‘in between’ fibre span. The through signals in each stage of cascade is (shown Section 4.5) experiencing a power penalty and an insertion loss of 0.4 dB and 3.2 dB respectively. If the fibre span between the WOIs is considered to
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be 1 km with an attenuation of 0.2 dB/km, the number of WOIs supported with various reflectivity of FBG2 can be calculated as:

\[
N_{54\%} = 3.21 \approx 3 \text{ units} \\
N_{70\%} = 2.95 \approx 2 \text{ units} \\
N_{85\%} = 2.39 \approx 2 \text{ units} \\
N_{93\%} = 1.76 \approx 1 \text{ unit}
\]

If the lossy multiport OCs in the WOIs in the experiment are replaced with standard optical circulators having typical through channel insertion loss (typical through loss 1dB/WOI), and typical drop channel insertion loss (typical loss 1dB/WOI), the number of units in cascade will increase to:

\[
N_{54\%} = 7 \text{ units} \\
N_{70\%} = 7 \text{ units} \\
N_{85\%} = 5 \text{ units} \\
N_{93\%} = 4 \text{ units}
\]

Also, if the insertion loss of the OSSB+C generator in CO can reduced to 9 dB, the number of units in cascade will increase to:

\[
N_{54\%} = 11 \text{ units} \\
N_{70\%} = 11 \text{ units} \\
N_{85\%} = 9 \text{ units} \\
N_{93\%} = 8 \text{ units}
\]

The cascadability of the WOI with different reflectivity FBG2 can be tabulated as follows:
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<table>
<thead>
<tr>
<th></th>
<th>Star/Tree</th>
<th>Ring/Bus</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>54% 70% 85% 93%</td>
<td>54% 70% 85% 93%</td>
</tr>
<tr>
<td>Actual Configurations</td>
<td>3 3 2 1</td>
<td>3 2 2 1</td>
</tr>
<tr>
<td>WOI Through &amp; Drop</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Loss Improved to 1 dB</td>
<td>8 8 6 4</td>
<td>7 7 5 4</td>
</tr>
<tr>
<td>OSSB+C Mod. Insertion</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Loss Improved to 9 dB</td>
<td>13 12 11 9</td>
<td>11 11 9 8</td>
</tr>
</tbody>
</table>

Table 4.7: Cascadability of WOI with different reflectivity FBG2

Thus, the numerical evaluation of the links incorporating modified WDM optical interfaces thus confirms that the replacement of 50% reflective FBG2 with an FBG having higher reflectivity will restrict the network dimensioning both for star-tree and ring/bus configurations, although it improves the overall performances of the links, both in uplink and downlink directions.

4.9 Conclusion

The performance of the proposed WDM optical interface in a single and cascaded configuration is characterised by both simulations as well as by experiment. The results show that the 37.5 GHz-band 25 GHz-separated WI-DWDM signals can be routed via the proposed interface without significant performance degradation. The characterisations as well as the modelling results confirm the viability of the proposed interface in star-tree ring/bus network architectures with observed negligible power penalty for each stage of cascade. The incorporation of the modification in the proposed interface will enhance the overall performances of the links, both in uplink and downlink directions, although it is a trade off with the capacity of network dimensioning.
4.10 References


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Chapter 5: Enabling Wavelength Interleaving in Millimetre-Wave Fibre-Radio Networks

5 Enabling Wavelength Interleaving in Millimetre-Wave Fibre-Radio Networks

5.1 Introduction

Chapter 1 provided the description of broadband mm-wave fibre-radio systems, which have the potential to resolve the spectral congestion and the scarcity of transmission bandwidth at lower microwave frequencies. Given the pico or micro cellular architectures associated with such mm-wave fibre-radio systems, it is imperative that the fibre feeder network is capable of supporting a large number of base station (BSs), while the BS architecture is simplified and cost-effective to realise [1-11]. The use of wavelength-division-multiplexed (WDM) in fibre feeder networks in conjunction with the optical single sideband with carrier (OSSB+C) modulation formats can enable the transport of multiple optical mm-wave signals in
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a cost-effective manner [12-24]. A detail review of WDM fibre-radio networks was presented in Chapter 2.

In WDM enabled fibre-radio networks, channel separations up to 100 GHz can be realised by applying mature WDM component and system technologies. The realisation of dense-wavelength-division-multiplexed (DWDM) channel separations (50 GHz or 25 GHz) that have the potentials to multiply the capacity of such networks by supporting a large number of BSs, are however restricted by the inherent wideband characteristics of the mm-wave signals. This problem can be resolved by introducing DWDM compatible wavelength interleaving technique [25-27]. Chapter 2 also reviewed different wavelength interleaving schemes with their distinct characteristics resulting in a DWDM fibre feeder network for mm-wave fibre-radio systems [28-31]. The successful design and implementation of such networks incorporating wavelength interleaving, however, encounters a number of challenges. These include, but not limited to, the enabling system technologies both for the central office (CO) and remote nodes (RNs). This chapter thus focuses on the investigation of the enabling multiplexing and demultiplexing technologies incorporating wavelength interleaving, by which an effective wavelength-interleaved (WI-DWDM) fibre-radio feeder network can be easily realised.

Section 5.2 outlines the general concept of multiplexing optical mm-wave signals incorporating wavelength interleaving, and reviews demonstrations of suitable multiplexers for WI-DWDM mm-wave fibre-radio systems. A novel wavelength-interleaved-multiplexer (WI-MUX) with the mechanism for enhancing modulation depth indices for such systems is presented in Section 5.3. Section 5.4 describes the experimental demonstration of the proposed multiplexer incorporated in a 10 km mm-wave fibre-radio link carrying three 25 GHz spaced DWDM mm-wave fibre-radio signals, each of them modulated with 37.5 GHz 155Mb/s binary-phase-shift-keyed (BPSK) signal in OSSB+C modulation format. This section also includes the characterisation of the arrayed waveguide grating (AWG), including the experimental setup for the demonstration of the proposed scheme. Section 5.5 introduces another multiplexing scheme enabling wavelength interleaving manipulated for the systems incorporating multi-sector antenna BSs. The experimental demonstration of this scheme is also included in the same section. A
simplified wavelength-interleaved-demultiplexer (WI-DEMUX), capable of demultiplexing wavelength interleaved signals in a DWDM fibre-radio network, is proposed and demonstrated in Section 5.6. Section 5.7 presents a simultaneous multiplexing and demultiplexing scheme, that simplifies the CO and RNs of WI-DWDM fibre-radio networks combining multiplexing and demultiplexing functionality into a consolidated architecture, and the effects of optical crosstalk induced by the proposed multiplexing and demultiplexing schemes are characterised in Section 5.8.

### 5.2 Multiplexing of Wavelength-Interleaved DWDM Signals

Fig. 2.14 shows the spectra of N optical mm-wave signals with a DWDM channel separation and a mm-wave carrier frequency of $2\Delta f$ and $3\Delta f$, respectively. The optical carriers $C_1, C_2, \ldots, C_N$ and their respective modulation sidebands $S_1, S_2, \ldots, S_N$...
(in OSSB+C modulation format) are interleaved in such a way that the adjacent channel spacing, irrespective of carrier or sideband, becomes $\Delta f$. The unique features of wavelength interleaving, as described in Chapter 2, however restrict the WI-DWDM systems to be realised by accessing the proven multiplexing technologies in mature DWDM access and metro networks. Conventionally, experimental demonstrations incorporating wavelength interleaving use star couplers to multiplex multiple optical mm-wave signals together [25-27, 32-38]. A typical $8 \times 1$ star coupler enables multiplexing of optical mm-wave signals, but introduces an insertion loss of 9 dB, which gradually increases with the increasing number of multiplexed signals. The impact of the high insertion loss on the interleaved signals can be avoided by replacing the star coupler with a combination of AWG, FBGs and optical circulators (OCs) as shown in Fig. 5.2. The scheme shown in Fig. 5.2 can be used to multiplex N optical mm-wave signals with the desired interleaving scheme. The optical carriers of the optical mm-wave signals are separated from the respective modulation sidebands by using suitable FBGs and 3-port OCs. The separated carriers and modulation sidebands are then routed to a $2N+2 \times 1$ AWG multiplexer as per their frequency allocations in the interleaved spectrum. The output of the AWG is therefore, the optical carriers and modulation sidebands interleaved. This technique can successfully reduce the insertion losses to 4 to 6 dB irrespective of number of signals to be multiplexed. However, it requires additional wavelength selective as well as signal processing devices before the AWG multiplexer, which are inherently susceptible to performance degradation and add up new complexities to the system.

An alternative approach is the use two separate AWGs in conjunction with 3 dB couplers before and after the AWGs [39]. The schematic of such scheme is shown in Fig. 5.2. In this scheme each of the N optical mm-wave signals are divided by a 3 dB coupler before being routed to the N $\times 1$ AWGs. The characteristics of the AWGs are selected in such a way that the passbands of upper AWG pass through the optical carriers of the modulated mm-wave signals, while the lower AWG routes only the respective modulation sidebands. Therefore, the outputs of the AWGs are the optical carriers and the respective modulation sidebands multiplexed separately. The multiplexed outputs are then passed through via a 3 dB coupler, and the output of which is the optical carriers and the respective modulation sidebands interleaved. In
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In order to control the carrier-to-sideband ratios (CSRs) of the interleaved signals, as illustrated in Chapter 3 and 4, an optical attenuator is inserted to the coupler arm carrying the multiplexed optical carriers, as shown in Fig. 5.2. Although this technique overcomes some of the aforementioned limitations by removing the wavelength-selective FBGs, it attenuates the signals through the pre-processing and post-processing couplers, in addition to the insertion losses of the AWGs. In addition, the inclusion of additional attenuator adds new complexity to the scheme.

Following section presents a novel WI-MUX based on an AWG multiplexer addressing the aforementioned limitations quite successfully.

5.3 Proposed Wavelength-Interleaved Multiplexer

The proposed scheme schematically shown in Fig 5.3 can achieve multiplexing optical mm-wave signals to the desired interleaving scheme without the need for additional devices for pre-processing and post processing, as described in the
previous section. It also enables reductions in CSRs of the optical mm-wave signals through optical loop-backs, by which the need for CSR reducing hardware can be avoided [40-41]. Fig. 5.3 also shows the input and output spectra as insets and it can be seen that it can realise the wavelength interleaving of N optical mm-wave signals as shown earlier in Fig. 2.14. The multiplexer comprises a \((2N+2) \times (2N+2)\) AWG with a channel bandwidth, \(\leq \Delta f\) and a channel spacing, \(\Delta f\), equal to the adjacent channel spacing of the desired wavelength interleaving (WI) scheme. The input (A) and output (B) ports of the AWG are numbered from 1 to 2N+2. The characteristic matrix of the AWG that governs the allocation and distribution of different channels at different ports is illustrated in Table. 5.1.
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The OSSB+C formatted input signals (shown as insets of Fig. 5.3) enter the AWG via the odd-numbered input ports, A1 to A_{2N-1}. The AWG combines all the modulation sidebands S_1, S_2, ..., S_N at the output port B_1. Due to the cyclic characteristics of the AWG as illustrated in Table 5.1, the optical carriers C_1, C_2, ..., C_N also exit as a composite signal via the output port B_4. The composite carriers are then looped back to the AWG through the input port A_2 that redistributes the carriers to the odd-numbered output ports starting with B_3. To realise the desired interleaving, the distributed carriers are again looped back to the AWG via the even-numbered input ports starting with A_4, and the resultant output at port B_1 is the optical carriers and the modulation sidebands interleaved. Due to the loop-backs (LBs), the optical carriers are suppressed by as much as twice the insertion loss (2 × IL) of the AWG (typical IL = 4 - 5 dB) compared to the modulation sidebands. Thus the proposed WI-MUX enables a reduction in the CSR of the WI-DWDM channels by 8 to 10 dB, which significantly improves the overall link performance.

### Table 5.1: Input/output characteristic matrix of (2N+2) x (2N+2) arrayed waveguide grating.

<table>
<thead>
<tr>
<th>I/O</th>
<th>B_1</th>
<th>B_2</th>
<th>B_3</th>
<th>B_{N-1}</th>
<th>B_N</th>
<th>B_{N+1}</th>
<th>B_{2N}</th>
<th>B_{2N+1}</th>
<th>B_{2N+2}</th>
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</thead>
<tbody>
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<td>λ_1</td>
<td>λ_2</td>
<td>λ_3</td>
<td>...</td>
<td>λ_{N-1}</td>
<td>λ_N</td>
<td>...</td>
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</tr>
<tr>
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<td>λ_{2N-1}</td>
<td>λ_{2N}</td>
<td>λ_{N-3}</td>
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<tr>
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</tr>
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<td>λ_1</td>
<td>λ_{N-3}</td>
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<td>λ_{2N-1}</td>
<td>λ_{2N}</td>
<td>λ_{2N+1}</td>
</tr>
</tbody>
</table>
5.4 Demonstration of the Proposed Wavelength-Interleaved Multiplexer

In this section, the performance of the proposed WI-MUX is investigated experimentally. As stated above, the WI-MUX consists of a \((2N+2) \times (2N+2)\) AWG with a channel bandwidth, \(\leq \Delta f\) and a channel spacing, \(\Delta f\), equal to the adjacent channel spacing of the desired WI scheme. Therefore, the performance of the proposed WI-MUX is largely dependent on proper selection of suitable AWG. For clarity the section is divided into two subsections: Section 5.4.1 characterises the performance of the AWG used in the experiment, while Section 5.4.2 presents the experimental setup incorporating the AWG used in the demonstration of the proposed WI-MUX experimentally. Section 5.4.2 also includes the experimental results quantifying both of its multiplexing as well as the performance enhancing functionality.

5.4.1 Characterisation of the Arrayed Waveguide Grating

An arrayed waveguide grating is a type of planer lightwave circuit (PLC) chip that performs multiplexing and demultiplexing of optical signals in conventional DWDM networks. Moreover, in conjunction with other components, AWG can be a building block for even more complicated systems such as optical add-drop-multiplexer (OADM), optical crossconnect (OXC), variable optical attenuator (VOA), thermo-optic switch, DWDM channel monitor, dynamic gain equalizer, etc.. AWG based on PLC are compact in size, highly integrateable with essential active and passive components on a single substrate, and suitable for volume manufacturing using fabrication technologies developed through the years in the semiconductor industry. The cyclic (or periodic) property of an AWG enables it to support multiple periodic frequencies to pass through a same route and the separation between the two periodic frequencies is known as free spectral range (FSR). FSR of a periodic AWG also can be defined as the multiplication of number of input/output connections and the frequency separation between two consecutive input/output connections. If the
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separation between two consecutive connections is $\Delta f$, then for a $N \times N$ AWG, FSR = $N \Delta f$.

Section 5.3 indicates that the proposed WI-MUX, enabling interleaving of $N$ $3\Delta f$ GHz-band optical mm-wave signals spaced at $2\Delta f$ GHz, will require a $(2N+2) \times (2N+2)$ AWG, with a channel bandwidth, $\leq \Delta f$ and a channel spacing, $\Delta f$, equal to the adjacent channel spacing of the desired WI scheme. The input/output characteristics of such AWG are already listed in Table 5.1. Therefore, for experimental demonstration, interleaving of three 37.5 GHz-band optical mm-wave signals spaced at 25 GHz will require an $8 \times 8$ AWG with a 3-dB channel bandwidth, $\leq 12.5$ GHz and a channel spacing equal to 12.5 GHz. The characteristic matrix illustrated in Table 5.1 can be updated as shown in Table 5.2 for the $8 \times 8$ AWG to be used to multiplex three optical mm-wave signals in WI scheme shown in Fig. 2.14.

<table>
<thead>
<tr>
<th>I / O</th>
<th>Output Ports</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
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<tr>
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<td>A₄</td>
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<tr>
<td>A₅</td>
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</tr>
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<td>A₆</td>
<td>C₂</td>
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<tr>
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<td>X</td>
</tr>
<tr>
<td>A₈</td>
<td>C₃</td>
</tr>
</tbody>
</table>

Table 5.2: Input/output characteristic matrix of $8 \times 8$ AWG used to multiplex three optical mm-wave signals in the WI scheme shown in Fig. 2.14.

The characteristic features affecting the performance of an AWG include, but not limited to, optical crosstalk, insertion loss, polarisation dependent dispersion,
polarisation rotation, passband shape, passband position, FSR etc. Among these, insertion loss, optical crosstalk, passband shape, passband position, and FSR characteristics of the AWG under investigation are characterised due to more relevance to the planned experiments.

In order to measure the optical characteristics of the AWG, it is first necessary to establish the operating temperature. This is accomplished by a technique that involved measuring the centre wavelength at a specific port at a given temperature, changing the temperature at 2.5°C interval and calculating the temperature at which the average centre wavelength offset was smallest. The operating temperature for the AWG under investigation was found to be 72°C to suit the wavelengths used in the experiment.

5.4.1.1 Insertion Loss

<table>
<thead>
<tr>
<th>Port-to-Port</th>
<th>Insertion Loss (dB)</th>
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</thead>
<tbody>
<tr>
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</tr>
<tr>
<td>4 to 2</td>
<td>3.2</td>
</tr>
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<td>4 to 3</td>
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<tr>
<td>4 to 4</td>
<td>3.3</td>
</tr>
<tr>
<td>4 to 5</td>
<td>3.3</td>
</tr>
<tr>
<td>4 to 6</td>
<td>3.3</td>
</tr>
<tr>
<td>4 to 7</td>
<td>3.2</td>
</tr>
<tr>
<td>4 to 8</td>
<td>3.1</td>
</tr>
</tbody>
</table>

*Table 5.3: Port-to-port insertion losses of the AWG.*

The primary cause for insertion loss in the AWG is due to inefficient coupling at the input/output interfaces between the free propagation regions (FPRs) and the arrayed waveguides (AWs). Coupling efficiency, and therefore insertion loss is largely determined by the separation of the AWs at these interfaces, where smaller
separations increase the coupling efficiency, although at smaller separations coupling between the AWs become significant [42, 43]. The other areas that cause insertion loss may include material losses, scattering due to fabrication errors and waveguide roughness, defocusing of the spot on the output plane due to phase errors etc.. The insertion losses of the AWG under investigation were measured by using a tunable light-source and measuring the optical powers at the respective input/output ports by varying the input wavelength. The measured insertion losses are shown in Table 5.3 that represent the worst possible losses through the device.

5.4.1.2 Passband Shape

Passband shape of an AWG plays very important roles in overall performance of the device. A sharp passband allows very little error in laser frequency and AWG wavelength tolerance. In most circumstances it is desirable that the passband is flattened so that the device produces a similar output for small changes in laser
wavelength [44-49]. The ideal shape for the passband of an AWG is to have a flat top, with a deviation of less than 1dB, for over 70% of the channel separation, and a 3-dB bandwidth as wide as possible without increasing crosstalk [43]. The measured transmission profile of the $8 \times 8$ AWG under investigation is shown in Fig. 5.4. It demonstrates a 3-dB bandwidth of the passbands are approximately 10 GHz and a spacing between two adjacent channels is 12.5 GHz, equal to the adjacent channel spacing of the desired wavelength interleaving scheme. However, the shapes of passbands are Gaussian, instead of flat-top; also the roll-off deviations are much higher than the expected characteristics. Therefore, the AWG under investigation is sensitive to wavelength tolerances and is prone to cause errors through optical crosstalk, which have to be considered in the experimental demonstration.

5.4.1.3 Optical Crosstalk

There are various sources that cause inter-channel crosstalk in an AWG. The primary source is the overlap of the focused spot in the output FPR with adjacent output waveguides. The phase inaccuracies of AWs caused by design and fabrication anomalies can make the beam spot size to increase resulting in increased levels of optical crosstalk. Optical crosstalk is also likely to occur as a consequence of complex multimodal light propagation effects in the AWs that adversely affects the phase and amplitude distributions at the output of the AWs [50-52].

To achieve close to perfect processing of the signals through the AWG, the sources of inter-channel crosstalk need to be controlled and managed, which however, often affects the other characteristics, such as insertion loss or channel spacing. Therefore, the controlling of inter-channel crosstalk of the AWG through fabrication process is not very simple, and often lead to a trade off between the crosstalk and the other desirable characteristics [53].

The optical crosstalk for the AWG under investigation were measured by separately transporting 8 optical carriers (unmodulated) through the respective input ports, and collecting them back at the output ports1, 2 and 3 which represent the output optical carriers, adjacent channel and nonadjacent channel crosstalk respectively. Fig. 5.5(a) shows the combined transmission spectra of the optical
Fig. 5.5: Measured optical spectra when 8 unmodulated optical carriers are transported through the AWG: (a): the transmission spectra, (b): the adjacent channel crosstalk, and (c): the non-adjacent channel crosstalk.

carriers at output port 1, whereas, Figs. 5.5(b) and 5.5(c) show the optical spectra of the adjacent and nonadjacent channel crosstalk at ports 2 and 3 respectively. From the Figs. 5.5(a)-(c), it can be seen that the adjacent channel crosstalk varies from -16 dB to -25 dB while the nonadjacent channel crosstalk varies from -29 dB to -46 dB.
5.4.1.4 Passband Position

Proper positioning of passbands of an AWG is essential. Design and fabrication errors cause a phase error at the end of the input/output AWs, which may shift the focal point away from the expected position, hence affecting the passband position. This shift of the passband can be repositioned by adjusting the operating temperature of the AWG [54]. The changes of optical output with the passband position shift and the shift of passband position with the operating temperature change for the AWG under investigation are shown in Fig. 5.6(a)-(b) respectively. The curves show, due to ultra-narrow separations (~12.5 GHz) between the adjacent channels, outputs of the AWG change abruptly with smaller changes in passband positions. Therefore, for a stable operation of the AWG with such narrow channel separations, strict temperature control is essential.

Fig. 5.6: Measured properties of the AWG: (a): output optical power versus passband position shift, and (b): passband position shift versus temperature.
5.4.1.5 Free Spectral Range

As stated above, FSR of a periodic AWG is defined as the frequency separation between adjacent passband positions of a given port and it happens to be normally equal to the product of the number of input/output waveguides and the frequency separation between two adjacent channels (FSR = N.Δf). Therefore FSR of the 8 × 8 AWG under investigation is 100 GHz. FSR of any AWG can be measured by connecting a broadband light source, such as asynchronous spontaneous emission (ASE) from erbium-doped-fibre-amplifier (EDFA) to any input waveguide and measuring the output at any output waveguide. Multiple periodic peaks can be seen with a periodic channel separation of N.Δf. However, in some instances, due to design and fabrication constraints, especially while adjacent channel separations

Fig. 5.7: Measured combined optical spectra at the outputs of the AWG generated using the ASE of an EDFA, covering three FSRs of the AWG used.
between the waveguides are very low, the periodic property of the AWG is enabled to repeat after multiple of FSRs \((n \times \text{FSR})\) instead of each FSR. The device under investigation is a such type of AWG, where periodic properties were enable to repeat after 5 multiple of FSRs \((\text{FSR} = 100 \text{ GHz})\). The spectra at the output waveguides of the \(8 \times 8\) AWG with three periodic peaks are shown in Fig. 5.7. The noise level between the periodic peaks is the indication of crosstalk. Therefore, the AWG under investigation can only support periodic frequencies, which are at multiple of 500 GHz, although FSR of the device is 100 GHz.

### 5.4.2 Experimental Demonstration of the Proposed WI-MUX

This section presents the experimental demonstration of the wavelength interleaved multiplexer proposed in Section 5.4. The \(8 \times 8\) AWG characterised in

![Fig. 5.8: Experimental setup for a WI-MUX that also reduces the CSR while interleaving the DWDM mm-wave channels in a WI-DWDM fibre-radio system.](image)

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Section 5.5.1 is the basic building block here. Fig. 5.8 shows the experimental setup used to demonstrate the proposed WI-MUX. In this experiment three narrow linewidth tunable light-sources at wavelengths $C_1$ (1556.0 nm), $C_2$ (1556.2 nm) and $C_3$ (1556.4 nm) followed by separate polarization controllers were used as the input to the three dual-electrode Mach-Zehnder modulators (DE-MZMs). Three 37.5 GHz mm-wave signals with 155 Mb/s BPSK data were generated by mixing 37.5 GHz and 18.75 GHz (followed by a frequency doubler) local oscillator (LO) signals respectively with 155 Mb/s pseudo-random-bit-sequence (PRBS) data. The mixer

![Figure 5.9: Measured optical spectra for the optical mm-wave signals: (a): ($S_1$, $C_1$), (b): ($S_2$, $C_2$) and (c): ($S_3$, $C_3$) before entering the proposed multiplexer.](image)
outputs were amplified (one divided into two to provide the third mm-wave signal) and applied to the DE-MZMs. The DE-MZMs were biased at quadrature bias point and the amplified mm-wave signals were used to drive the two RF ports of the DE-MZMs with a 90° phase shift maintained between the two drive signals. The resultant outputs of the modulators were OSSB+C modulated optical mm-wave signals with suppressed unwanted modulation sidebands.

Figs. 5.9 (a) - (c) show the optical spectra of the modulated optical mm-wave signals, (S₁, C₁), (S₂, C₂) and (S₃, C₃) before multiplexing with observed CSRs of 17.8, 13.5, and 13.4 dB, respectively. In comparison to (S₂, C₂) and (S₃, C₃), (S₁, C₁) experiences 4.3 and 4.4 dB higher CSR, which is due to the inefficiency of the DE-MZM, while generating OSSB+C modulated (S₁, C₁). Also the spectra show that the unwanted modulation sidebands for all the three signals are suppressed by almost 30 dB.

The modulated signals were then applied to the 8 × 8 AWG with a channel separation of 12.5 GHz and a channel bandwidth of ≈10 GHz, which is already characterised in Section 5.4.1. The allocation of the input ports and the selection of the loop-back paths are shown in Fig. 5.8, which result in the desired WI multiplexer output. Fig. 5.10 shows the combined spectrum of the signals after multiplexing,

![Optical Spectrum Graph](image)

**Fig. 5.10:** Measured optical spectrum at the output of the WI-MUX with three DWDM optical mm-wave signals.
which confirms the functionality of the proposed WI-MUX. The spectrum also indicates that WI-MUX helps to reduce the CSRs of the interleaved signals to 9.3, 6.2, and 5.1 dB for the respective signals \((S_1, C_1)\), \((S_2, C_2)\) and \((S_3, C_3)\), attaining a reduction in the CSRs by 8.5, 7.3 and 8.3 dB respectively. The differences in the CSRs before and after multiplexing can be attributed to the various insertion losses of the AWG, unique for each pair of input-output ports.

The interleaved signals were then amplified by an EDFA and followed by a 4-nm optical band pass filter (BPF) prior to transmission over 10 km of singlemode fibre (SMF) to a BS, where the desired signal \((S_3, C_3)\) is recovered using a suitable OADM interface. The OADM interface, which is comprised of a double-notch FBG and a 3-port OC, recovers the desired \((S_3, C_3)\) from the interleaved signals and allows the remaining signals to pass through. The optical spectra of the recovered as well as the through signals can be seen from Fig. 5.11 (a)–(b).

The recovered signal \((S_3, C_3)\) was then detected using a 45 GHz photodetector (PD), amplified, down-converted to an intermediate frequency (IF) of 2.5 GHz, and filtered by using an electrical BPF with a bandwidth 400 MHz, from which the
baseband data was recovered using a 2.5 GHz electronic phase locked loop (PLL).

Fig. 5.12 shows the measured bit error ratio (BER) curves for the recovered signal for the back-to-back case (having the AWG, but no fibre) and after transmission over 10 km of SMF. The result exhibits a negligible power penalty of $\approx 0.2$ dB at a BER of $10^{-9}$ that can be attributed to experimental errors.

To characterise the effects of the reduction in CSRs due to the loop-backs, signal, $(C_3, S_3)$ was transported through the AWG as shown in Fig. 5.13; and the data was recovered under four conditions: (i) carrier $C_3$ and sideband $S_3$ at the OUT ports were combined using a 3-dB coupler and no LB was provisioned; (ii) $C_3$ was allowed one LB between ports $B_4$ & $A_8$ before combining with $S_3$; (iii) $C_3$ was allowed two LBs between ports $B_4$ & $A_2$ and $B_7$ & $A_8$ before combining with $S_3$; and (iv) $C_3$ was allowed three LBs between ports $B_4$ & $A_2$, $B_7$ & $A_1$, and $B_8$ & $A_8$ before combining with $S_3$. The measured optical spectra and the respective BER curves can be seen in Figs. 5.14(a) and 5.14(b), respectively.
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The results indicate that the increase in the number of LBs from 0 to 3 causes a reduction in CSR of 10.7 dB which improves the overall link performance by 7.2 dB. From the BER curves it can also be seen that, the sensitivity of the signal for the first LB is improved by approximately 5 dB, whereas for the third loop-back it is only 0.5 dB.

Fig. 5.13: Experimental setup characterising the reduction in CSRs due to the loop-backs in the WI-MUX.
dB, although the reductions in CSRs in both the cases are very similar. To establish a relation between the CSRs and the sensitivity of the signals, another curve is plotted at Fig. 5.15. It shows that for the third loop-back, where CSR is 1.7 dB, the sensitivity improvement has reached almost to the saturation, which would be at its
peak if the CSR would be 0 dB [55]. However, the scenario would be completely different if the initial CSR of the signal was much higher. Therefore, although the proposed scheme requires two LBs, more LBs can be provisioned to attain optimum link performance, if it is permitted by the initial CSRs before multiplexing. These increase in the number of loop-backs, however, require additional input/output ports at the AWG which in turn add cost implications to the scheme.

5.5 Interleaving Scheme for Multi-Sector Antenna Base Station

Due to line-of-sight requirements associated with mm-wave radio systems, base stations with multiple sectors are often required, for example a 3-Sector base station could provide 4 separate coverage zones with 120 degrees beam width. For such an application, another interleaving scheme is proposed, where four optical mm-wave
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signals are grouped in such a way that it can deliver unique optical mm-wave signal to each sector of the antenna BS within a 100 GHz spectral-band [56]. An overview of the previous literature in this area can be found in Section 2.3.2. The schematic of the proposed scheme is shown in Fig. 5.16. It shows the optical spectra of 4 optical mm-wave signals in OSSB+C modulation format with a DWDM channel separation and a mm-wave carrier frequency of $\Delta f$ and $4\Delta f$, respectively. The first and the second signals are generated by suppressing the lower sideband (LSB), while the third and the fourth signals are generated by suppressing the upper sideband (USB). The optical carriers $C_1$, $C_2$, $C_3$ and $C_4$ and their respective modulation sidebands $S_1$, $S_2$, $S_3$ and $S_4$ are interleaved in such a way that the adjacent channel spacing, irrespective of carrier or sideband, becomes $\Delta f$. Similar to the WI-MUX proposed in Section 5.3, the multiplexing of signals in such interleaving scheme both in the CO and the RNs can be realised by an AWG-based wavelength-interleaved multiplexer shown in Fig. 5.17. The cyclic AWG comprises $9 \times 9$ input/output waveguides enabling two loop-backs for each of the optical carriers $C_1$, $C_2$, $C_3$ and $C_4$ before combining them with their modulation sidebands. The characteristic matrix of AWG.

Fig. 5.16: Schematic depicting the optical spectra of wavelength-interleaved signals for multisector antenna base stations.
that governs the allocation and selection of loop-backs in the scheme are shown in Table 5.4. The scheme can also be realised by using an $8 \times 8$ AWG at the cost of uniformity of the carriers in the multiplexed signals. In such case, $C_1$ will undergo one loop-back, while $C_2$ and $C_3$ two loop-backs before being combined with the modulation sidebands at the output port.

For the proof-of-concept demonstration, the scheme is demonstrated with an $8 \times 8$ AWG spaced at 12.5 GHz, the characteristics of which has already been described in Section 5.4.1. Instead of 4, the $8 \times 8$ AWG supports three 37.5 GHz-band optical mm-wave signals. The interleaving scheme for three channels and the experimental setup to realise such scheme are shown in Fig. 5.18(a) and Fig. 5.18(b) respectively.
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Table 5.4: Input/output characteristic matrix of 9 x 9 AWG used to multiplex four optical mm-wave signals in the wavelength interleaving scheme shown in Fig. 5.16.

<table>
<thead>
<tr>
<th>I / O</th>
<th>Output Ports</th>
</tr>
</thead>
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<tr>
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The simplified setup shown in Fig. 5.18(b) is very similar to the setup used Section 5.4.2, with the exception that optically modulated (C₁, S₁) is generated by suppressing the lower modulation sideband, while (S₂, C₂) and (S₃, C₃) is generated by suppressing the upper modulation sidebands, keeping the CSRs as well as other parameters of the of the signals unchanged as shown in Fig. 5.9. Therefore, to avoid repetition, description of the setup is discarded here. Also for similar reasons, the experiment is limited to verify the functionality of the proposed scheme only; no data was recovered.

Fig. 5.19 shows the interleaved spectrum at the optical spectrum analyser (OSA). As expected, the interleaved spectrum is very similar to the scheme shown in Fig. 5.18(a), which confirms the functionality of the proposed multiplexing scheme enabling effective interleaving of DWDM mm-wave fibre-radio signals manipulated for multi-sector antenna BS. Also, compare to the spectra shown in Fig. 5.9, the CSRs of the interleaved signals are reduced by approximately 8 dB due to the loopbacks, which eventually enhances the performance of the links significantly.
Fig. 5.18: Experimental setup for the demonstration of interleaving scheme, manipulated to support multi-sector antenna BSs: (a) the desired interleaving scheme, (b) the setup.

Fig. 5.19:Measured optical spectrum using an OSA for the proposed multiplexing scheme, with three DWDM optical mm-wave signals.
5.6 Demultiplexing of Wavelength Interleaved Signals

Chapter 3 has introduced a multifunctional WDM optical interface enabling effective add/drop of optical mm-wave signals to/from WI-DWDM feeder network, in addition to simplifying the BS by removing the light source from the uplink path [34, 35, 57]. Chapter 4 explored the functionality of the interface in cascaded configuration that showed that the proposed interface can be used in cascade without significant performance degradation [37, 38]. However, the modelling of fibre-radio networks (described in Section 4.5, Chapter 4) incorporating such interfaces show that the performance of the networks are limited by the scarcity of the required powers, and strict power budgeting is essential to enable multiple units in cascade, both in star-tree and ring/bus network configurations. An alternative approach is the introduction of AWG-based demultiplexing scheme suitable to recover multiple signals together at both the CO and RNs.

A demultiplexing scheme for 25 GHz-separated DWDM mm-wave fibre-radio signals was proposed in [58-60], which requires additional wavelength-selective pre- and post-processing hardware, in addition to a custom-developed AWG. A simplified WI-DEMUX based on a commercially available AWG is proposed in Section 5.6.1 and the proposed WI-DEMUX also removes the aforementioned limitations by avoiding the wavelength-selective pre-processing and post-processing devices. The functionality of the proposed WI-DEMUX is demonstrated experimentally in Section 5.6.2.

5.6.1 Proposed Wavelength Interleaved Demultiplexer

The schematic of the proposed WI-DEMUX is shown in Fig. 5.20. It comprises a \((2N+2) \times (2N+2)\) AWG with a channel bandwidth, \(\Delta f\) and a channel spacing, \(\Delta f\), equal to the adjacent channel spacing of the DWDM interleaved signals shown in the inset. The characteristic matrix of the AWG that governs the allocation and distribution of different channels at different ports is already illustrated in Table. 5.1.
The OSSB+C formatted wavelength interleaved DWDM signals are divided by a 3–dB coupler before entering to the AWG via the input ports A₁ and A₄. The input ports, A₁ and A₄ are selected based on the channel separations between the optical carriers and their respective modulation sidebands, equal to the mm-wave RF frequency, 3\(\Delta f\). Input port A₁ enables the modulation sidebands \(S_1, S_2, \ldots, S_N\) to be distributed to odd-numbered output ports \(B_1 - B_{2N-1}\), respectively. Also, port A₄ routes the optical carriers \(C_1, C_2, \ldots, C_N\) to the same odd-numbered output ports \(B_1 - B_{2N-1}\), enabling them to exit the AWG with their respective modulation sidebands. Thus the proposed WI-DEMUX successfully demultiplexes the wavelength interleaved signals in a DWDM fibre-radio network, suitable to be used both in the CO and the RNs.
5.6.2 Experimental Demonstration

In order to demonstrate the proposed WI-DEMUX experimentally, two possible locations of such scheme in the networks can be considered. The scheme can be located either (i) in the CO to demultiplex the interleaved uplink signals; or, (ii) in the RNs to demultiplex the interleaved downlink signals before distributing to the base stations. This section will focus in demonstrating a WI-DEMUX located in the CO only, as demultiplexing in the RNs will be considered later in Section 5.7 as a part of a simultaneous multiplexing and demultiplexing scheme.

Fig. 5.21 shows the setup used to demonstrate the proposed scheme experimentally. Three narrow linewidth tunable light sources $C_1$, $C_2$, and $C_3$ at the corresponding wavelengths 1556.0, 1556.2 and 1556.4 nm were used as the uplink optical sources. The three optical carriers, followed by separate polarization controllers were combined together using two 3-dB optical couplers. The composite
optical carriers were then launched into a DE-MZM. A 37.5 GHz mm-wave signal with BPSK format was generated by mixing a 37.5 GHz LO signal with a 155 Mb/s PRBS data. The biasing and the RF inputs of the DE-MZM were controlled in such a way that the resultant output of the modulator was an OSSB+C modulated uplink signals with the three optical carriers and their respective modulation sidebands interleaved, the similar way the interleaved signals were generated for the demonstration of the WDM optical interfaces, described in Chapter 3 and 4. As the fibre feeder network is expected to be passive in nature, the uplink signals generated in base stations, while necessary, will be amplified in the CO only. Therefore, instead of amplification, the interleaved was directly launched on to 10 km SMF and transported to the CO where the proposed WI-DEMUX is located. The spectrum of the interleaved signals entering the WI-DEMUX is shown in Fig. 5.22.

WI-DEMUX under investigation is comprised of an $8 \times 8$ AWG with a channel separation of 12.5 GHz and a channel bandwidth of $\approx 10$ GHz, the characteristics of

Fig. 5.22: Measured optical spectrum of the wavelength interleaved signals entering the wavelength interleaved demultiplexer located in the CO of a fibre-radio network.
which has already been described in Section 5.5.1. The allocation of the input ports are shown in Fig. 5.21, which result in the desired demultiplexed signals \((S_1, C_1), (S_2, C_2)\) and \((S_3, C_3)\) at the output ports \(A_1, A_3\) and \(A_5\) respectively.

Fig. 5.23(a)-(c) show the spectra of the signals after demultiplexing, which confirm the functionality of the proposed WI-DEMUX, enabling demultiplexing of wavelength interleaved signals in a DWDM fibre-radio network. The recovered spectra indicate the presence of optical crosstalk in the demultiplexed signals, which is defined here as the ratio of the undesired optical carriers to the desired optical

![Fig. 5.23: Measured optical spectra of the demultiplexed signals: (a): \((S_1, C_1)\), (b): \((S_2, C_2)\), and (c): \((S_3, C_3)\) at the output ports \(A_1, A_3\) and \(A_5\) respectively.](image-url)
 carriers at the demultiplexed signals. Crosstalk levels of -18 to -30 dB were observed. The impact of these crosstalk on the transmission performance of the demultiplexed signals will be characterised later in Section 5.8.

To measure the BER performances, the demultiplexed signals were amplified by low-noise EDFAs and filtered by optical BPFs to minimise the out-of-band ASE noise. The filtered signals were then detected using a 45 GHz PD, amplified, down-converted to an IF of 2.5 GHz, and filtered by using electrical BPF with a bandwidth of 400 MHz, from which the baseband data were recovered using a 2.5 GHz electronic PLL. Fig. 5.24 shows the measured BER curves as a function of received optical powers for the demultiplexed signals. The error free (at a BER of $10^{-9}$) data recovery confirms the successful demonstration of demultiplexing scheme, with the receiver sensitivities more than -15 dBm. The differences in the receiver sensitivities can be attributed to the effects of optical crosstalk caused by the filtering characteristics of the AWG.

Fig. 5.24: Measured BER curves as a function of received optical power for the demultiplexed signals $(S_1, C_1)$, $(S_2, C_2)$, and $(S_3, C_3)$. 
Therefore, the recovered optical spectra and the BER curves clearly demonstrate the functionality of the proposed demultiplexing scheme that offers a practical solution for future high capacity DWDM fibre-radio networks incorporating wavelength interleaving technique.

## 5.7 Simultaneous Multiplexing and Demultiplexing of Wavelength Interleaved Signals

In practical networks, the multiplexing and demultiplexing schemes proposed in Sections 5.3 to 5.6 are expected to be located as a duo in the CO and the RNs depending on the network configurations. The use of separate multiplexer and demultiplexer in the CO and RNs however, has the potential to make the systems complex and expensive. Instead, if the multiplexing and demultiplexing functionality in the CO and the RNs can be combined into a single device or subsystem, cost-effective architectures with reduced complexity can be realised.

Chapter 3 has outlined the importance of a simple, compact and low-cost BS in a mm-wave fibre-radio system; and, as a way to resolve, has introduced a multifunctional WDM optical interface, capable of offering such a BS by enabling a wavelength reuse technique [34-38, 61, 62]. In such approach, a percentage of the downlink optical carrier is recovered via a suitable OADM interface (e.g. WDM optical interface), which is reused in the BS for uplink communication. Therefore, it is important that multiplexing and demultiplexing schemes in the CO and the RNs are transparent to the uplink signals generated by reusing the downlink optical carriers.

This section thus focuses on the realisation of a simultaneous multiplexing and demultiplexing (MUX/DEMUX) scheme, which effectively multiplexes and demultiplexes the wavelength interleaved signals in a DWDM fibre-radio network, ensures transparency to the uplink signals generated by either a unique uplink optical carrier or, reusing the downlink optical carrier, while offering a simplified,
consolidated, and cost-effective architecture for the CO and the RNs by combining both the functionality into a single device [63, 64].

Section 5.7.1 describes the architecture and the working principle of the proposed MUX/DEMUX scheme while the experimental setup used to demonstrate the proposed scheme is described in Section 5.7.2. Section 5.7.3 presents the experimental results obtained from the demultiplexing of the wavelength interleaved signals via the proposed scheme. The results obtained from the demonstration of the multiplexing functionality are presented in Section 5.7.4.

### 5.7.1 Proposed Simultaneous Multiplexing and Demultiplexing Scheme

Fig. 5.25 shows a schematic of the optical spectra of N optical mm-wave signals before and after interleaving, with a DWDM channel spacing and mm-wave carrier frequency of $2\Delta f$ and $3\Delta f$, respectively. As mentioned above, the optical carriers $C_1$, $C_2$, $\ldots$, $C_N$ and their respective modulation sidebands $S_1$, $S_2$, $\ldots$, $S_N$ (in OSSB+C modulation format) are interleaved in such a way that the adjacent channel spacing, irrespective of carrier or sideband, becomes $\Delta f$.

![Fig. 5.25: Schematic depicting the spectra of the optical mm-wave signals before and after interleaving in a DWDM mm-wave fibre-radio network.](image)

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Fig. 5.26 shows the schematic of the MUX/DEMUX scheme that simultaneously enables multiplexing and demultiplexing of the optical mm-wave signals as per the scheme shown in Fig. 5.25. The proposed MUX/DEMUX comprises a \((2N+2) \times (2N+2)\) cyclic AWG with a channel bandwidth \(\Delta f\) and a channel spacing of \(\Delta f\), in conjunction with multiple OCs and optical isolators (OIs). The characteristic matrix of the AWG that governs the distribution of different channels at various ports has already been illustrated in Table 5.1. For clarity the proposed scheme is considered to be located at a RN where the uplink signals are multiplexed and the downlink signals are demultiplexed simultaneously.

As shown in Fig. 5.26, the downlink WI-DWDM signals from the feeder network (FN) enter the RN, are split by a 3 dB coupler, and pass through circulators \(\text{OC}_{\text{D1}}\) and \(\text{OC}_{\text{D2}}\).
OC\textsubscript{D2} before entering the AWG via the ports A\textsubscript{1} and A\textsubscript{4}. The input ports, A\textsubscript{1} and A\textsubscript{4} were selected in such a way that the optical carriers C\textsubscript{D1}, C\textsubscript{D2},...,C\textsubscript{DN} and their respective modulation sidebands S\textsubscript{D1}, S\textsubscript{D2},...,S\textsubscript{DN} are demultiplexed together and exit the AWG via the odd-numbered output ports B\textsubscript{1} - B\textsubscript{2N-1} followed by OC\textsubscript{M1},...,OC\textsubscript{MN}, respectively. The circulators OC\textsubscript{D1}, OC\textsubscript{D2}, and OC\textsubscript{M1},...,OC\textsubscript{MN} are used to either combine or separate the downlink and uplink channels to/from a specific port of the AWG, and also to route them to the intended destinations accordingly.

In the uplink direction, OSSB+C modulated optical mm-wave signals (S\textsubscript{U1}, C\textsubscript{U1}), (S\textsubscript{U2}, C\textsubscript{U2}),..., (S\textsubscript{UN}, C\textsubscript{UN}), generated by either using the optical carriers that correspond to wavelengths spaced at multiples of the FSR of the AWG from the downlink optical carriers or by reusing the downlink optical carriers recovered by applying a wavelength reuse technique ($\lambda_{UL} = \lambda_{DL} \pm n \times \text{FSR}$, where $n = 0, 1, 2, 3,...$), are applied to the AWG via the ports B\textsubscript{1} - B\textsubscript{2N-1} followed by the circulators OC\textsubscript{M1},...,OC\textsubscript{MN}. Due to the reciprocal and cyclic characteristics of the AWG, the uplink optical carriers and their respective modulation sidebands combine at ports A\textsubscript{4} and A\textsubscript{1}, respectively. The composite uplink carriers at A\textsubscript{4} are then passed through OC\textsubscript{D2}, looped back to the AWG via port B\textsubscript{2} and redistributed to the odd-numbered input ports starting with A\textsubscript{3}. To realise the desired interleaving for the uplink signals, the distributed uplink carriers are again looped back to the AWG via the even-numbered output ports starting with B\textsubscript{4}, and the resulting outcome comprises the uplink carriers and their respective modulation sidebands interleaved at port A\textsubscript{1}, which are then routed to the fibre feeder network via the OC\textsubscript{D1}.

The multiple loop-backs of the uplink carriers through the AWG reduce the CSR of the interleaved uplink signals by as much as twice the insertion loss ($2 \times \text{IL}$) of the AWG (typical IL: 4 – 5 dB), which is 8 – 10 dB. To minimise the effects of the unwanted signals from the even-numbered ports, B\textsubscript{4} to B\textsubscript{2N-2}, the loop-back paths of the redistributed optical carriers were provided with directional OIs that route only the redistributed uplink carriers to the AWG and suppress the remaining unwanted signals. Thus, the proposed simultaneous multiplexing and demultiplexing scheme enables efficient multiplexing for the DWDM optical mm-wave signals in the uplink.
direction, while in the downlink direction the proposed scheme also demultiplexes the WI-DWDM signals very effectively.

5.7.2 Experimental Setup

Fig. 5.27 shows the experimental set up for the demonstration of the multiplexing and demultiplexing operations of our proposed technique. In the downlink direction, three narrow line-width tunable light sources LS<sub>1</sub>, LS<sub>2</sub>, and LS<sub>3</sub> at the corresponding wavelengths C<sub>D1</sub> (1556.0 nm), C<sub>D2</sub> (1556.2 nm) and C<sub>D3</sub> (1556.4 nm) followed by separate polarization controllers were combined using two 3-dB optical couplers and used as the input to a DE-MZM. A 37.5 GHz mm-wave signal carrying 155 Mb/s

![Diagram](image-url)

**Fig. 5.27:** Experimental setup for the demonstration of a simultaneous multiplexing and demultiplexing scheme, suitable for being used in the central office and the remote nodes of a WI-DWDM mm-wave fibre-radio network.
BPSK data was generated by mixing an 18.75 GHz LO signal, followed by a frequency doubler, with 155 Mb/s PRBS data. The mixer output was then amplified, then split by a quadrature coupler into two equal components with a relative 90° phase difference, and used to drive the two RF ports of the DE-MZM. The bias voltage for the DE-MZM was selected for quadrature operation. Therefore, the resultant output of the DE-MZM was an OSSB+C modulated signal comprise the three optical carriers and their respective modulation sidebands, interleaved together. This interleaved output signal can be seen in the measured optical spectrum shown in the inset of Fig. 5.27. Here a CSR of 13 dB has been attained with 29 dB suppression of undesired sidebands. The output spectrum also shows the 12.5 GHz adjacent channel spacing (irrespective of carrier or sideband) in addition to the DWDM channel spacing and the mm-wave carrier frequency of 25 GHz and 37.5 GHz, respectively.

The downlink interleaved signals were amplified by an EDFA and then filtered using a 4 nm optical BPF to minimise out-of-band ASE noise. The filtered signal was transported over 10 km of SMF to the proposed DEMUX/MUX located at a RN, which comprised an 8 × 8 AWG in conjunction with multiple OCs and OIs as described in the previous section. The AWG transmission profile was tuned to match the transported signals by increasing its operating temperature to 72°C. The transmission profile, as well as other characteristic features of the AWG has already been illustrated in Section 5.4.1. As mentioned before, the transmission profile demonstrates a 3 dB channel bandwidth of approximately 10 GHz and a channel spacing of 12.5 GHz, equal to the adjacent channel spacing of the desired WI scheme. The allocations of entering ports to the AWG are as shown in Fig. 5.27. Therefore, the interleaved downlink signals are demultiplexed to \((S_{D1}, C_{D1})\), \((S_{D2}, C_{D2})\), and \((S_{D3}, C_{D3})\), which can be recovered by using a suitable PD and data recovery circuit through the respective output ports, \(B_1\), \(B_3\) and \(B_5\).

The multiplexing functionality in the uplink direction, due to resource limitations, is demonstrated by transporting one uplink signal. However, multiplexing of three optical mm-wave signals using a similar scheme has already been demonstrated in Section 5.4. A narrow line-width tunable light source \(LS_{FSR}\) at operating wavelength \(C_{U3}\) (1552.4 nm) was used as the input to another DE-MZM located at the BS.
uplink 37.5 GHz mm-wave signal was generated by mixing a 37.5 GHz LO signal with 155 Mb/s BPSK data, amplified and applied to the DE-MZM. The RF inputs and biasing of the DE-MZM were controlled in a similar way as was done in the downlink direction, which results in \((S_{U3}, C_{U3})\), an optically modulated mm-wave signal in OSSB+C modulation format. The carrier \(C_{U3}\) is separated from the downlink optical carrier \(C_{D3}\) by 500 GHz \([C_{U3} = C_{D3} - 5 \times \text{FSR}, \text{where FSR} = 100 \text{GHz}]\), therefore the uplink signal \((S_{U3}, C_{U3})\) will enter the proposed scheme via port B5 of the AWG. The AWG then distributes the carrier and the sideband to ports A4 and A1, respectively. To realise the desired multiplexing the optical carrier is looped back to the AWG as per the proposed scheme and the resulting multiplexed signal (the optical carrier and the respective sideband together) exits the AWG via port A1. The multiplexed signal was then routed over 10 km SMF via the circulator \(OCD_{D1}\) and transported to the CO where it is amplified by an EDFA and filtered by an optical BPF, before being detected and the data recovered by a high-speed PD and data recovery circuit.

To demonstrate the compatibility of the proposed scheme with uplink signals

![Diagram](image.png)

**Fig. 5.28:** The modified part of the experimental setup used to generate an uplink optical mm-wave signal from a recovered a portion of the downlink optical carrier by applying a wavelength reuse technique.
generated by reusing the downlink optical carriers, a portion of the experimental setup shown in Fig. 5.27 (indicated by double dotted lines) was modified as shown in Fig. 5.28. Fig. 5.28 shows that the 3-port OC_{M3} (in Fig. 5.27) is replaced with a 4-port OC_{MR3}, in addition to a 50% reflective FBG at port 3 of OC_{MR3} that corresponds to the demultiplexed \((S_{D3}, C_{D3})\). The centre frequency and the 3-dB bandwidth of the FBG are 1556.4 nm (= C_{D3}) and 12.5 GHz, respectively. The demultiplexed signal, \((S_{D3}, C_{D3})\) exits the AWG via the output port B_5, enters OC_{MR3} via port 2, and encounters the 50% reflective FBG at port 3 where 50% of C_{D3} is reflected. The remaining part of the signal \((S_{D3}, 50\% C_{D3})\) is transmitted through the FBG from which downlink data can be easily recovered via the use of a suitable PD and data recovery circuit. The reflected 50% of C_{D3} is then recovered at port 4 of OC_{MR3} and routed to the BS to drive the uplink DE-MZM. The uplink radio signal, used in the earlier technique to generate the optically modulated uplink signal, was applied to the uplink DE-MZM which results in the wavelength reused uplink \((S_{U3}, C_{U3})\) having a OSSB+C modulation format. The uplink \((S_{U3}, C_{U3})\) then enters the AWG via port B_5, exits as a multiplexed signal through port A_1, before being transported over 10 km of SMF to the CO. At the CO the signal is amplified by an EDFA, followed by an optical BPF, and then detected and data recovered with a high-speed PD and data recovery circuit.

5.7.3 Results for Demultiplexed Downlink Signals

Fig. 5.29(a) shows the measured optical spectrum of the WI-DWDM downlink signals before entering the AWG via ports A_1 or A_4, while Figs. 5.29(b) – (d) show the optical spectra for the demultiplexed \((S_{D1}, C_{D1})\), \((S_{D2}, C_{D2})\), and \((S_{D3}, C_{D3})\), respectively. The recovered spectra show the presence of optical crosstalk in the demultiplexed signals, which was defined in Section 5.6 as the ratio of the undesired optical carriers to the desired optical carriers in the demultiplexed signals. Crosstalk levels of -19 to -25 dB are observed. The impact of the crosstalk on the transmission performance of the signals will be characterised in Section 5.8. The measured spectra also confirm that the AWG in the proposed DEMUX/MUX scheme exhibits an IL of
3.3 – 5.8 dB, while the circulators OC\textsubscript{D1} and OC\textsubscript{D2} exhibit an average IL of 1.5 dB in each of the paths in the transmission direction.

To measure the BER performances, the demultiplexed channels were detected using a 45 GHz PD, amplified, down-converted to an IF of 2.5 GHz, and electrically filtered using BPFs with a bandwidth 400 MHz, from which the baseband data were recovered using a 2.5 GHz electronic PLL. Fig. 5.30 shows the measured BER curves as a function of received optical power for the demultiplexed signals. The results confirm the successful demonstration of demultiplexing functionality of the
proposed DEMUX/MUX scheme, with the receiver sensitivity approximately equal to -15 dBm at a BER of $10^{-9}$. The differences in the receiver sensitivities can be attributed to the effects of optical crosstalk caused by the filtering characteristics of the AWG.

### 5.7.4 Results for Multiplexed Uplink Signal

The results from the demonstration of multiplexing functionality are presented in two sub-sections depending on the generation techniques of uplink optical mm-wave signals, described in Section 5.7.2: (i) uplink optical carrier spaced at multiples of the FSR of the AWG from the downlink optical carrier, (ii) uplink optical carrier recovered from the downlink optical carrier by applying a wavelength reuse technique.
5.7.4.1 Uplink Spaced at Multiples of FSR of the AWG from the Downlink

Fig. 5.31(a) shows the measured optical spectrum of the generated uplink signal \((S_{U3}, C_{U3})\) before entering the proposed DEMUX/MUX scheme, while Fig. 5.31(b) shows the optical spectrum immediately after the proposed scheme. As expected, the measured spectra exhibit a CSR of 14 dB before the proposed DEMUX/MUX scheme, which is reduced to 5 dB after the DEMUX/MUX scheme. This additional reduction in CSR, as characterised in Section 5.4.2, improves the overall link

![Optical Spectrum](image_url)

Fig. 5.31: Measured optical spectra of the uplink signal: (a): before entering the scheme, (b): immediately after the scheme, and (c): after suppression of the unwanted reflection crosstalk at the CO, after transmission through 10 km SMF.
performance significantly. In addition, the optical spectrum in Fig. 5.31(b) shows that the uplink signal is contaminated by the out-of-band reflected crosstalk from the downlink direction, which is approximately -17 dB. This unwanted power can be removed (as shown in Fig. 5.31c) by the suitable selection of an optical BPF that follows the EDFA in order to minimise the out-of-band ASE noise as shown in Fig. 5.27. Also, in a practical network each of the WI-DWDM uplink signals will be demultiplexed at the CO before detection, therefore the out-of-band crosstalk from the downlink path does not require any special attention, and will merge with the typical crosstalk caused by the filtering characteristic of the demultiplexer.

To measure the BER, the filtered uplink signal was subsequently detected and data was recovered using the data recovery circuit previously described in the downlink path. Fig. 5.32 shows the measured BER curves for the back-to-back condition (with the MUX/DEMUX scheme but no transmission fibre) and after transmission over 10 km of SMF for the signal, (S_U3, C_U3). The result exhibits a negligible 0.3 dB power penalty at a BER of \(10^{-9}\) which can be attributed to experimental errors. Therefore, the recovered optical spectra and the BER curves

![Graph](image)

**Fig. 5.32:** Measured BER curves as a function of received optical power for the multiplexed uplink signal, (S_U3, C_U3) after transmission over 10 km of SMF with the back-to-back (0.0 km SMF) curve as a reference. The uplink signal was generated using an optical carrier separated by 500 GHz from the downlink carrier.
clearly demonstrate the functionality of the proposed DEMUX/MUX scheme in multiplexing the uplink signals with optical carriers at wavelengths equal to the difference between the downlink optical carriers and $5 \times \text{FSR}$.

### 5.7.4.2 Uplink by Reusing Downlink Optical Carrier

Fig. 5.33(a) shows the measured optical spectrum of the downlink signal after recovering 50% of the carrier, while Figs. 5.33(b) – (c) present the optical spectra for the recovered optical carrier and the generated uplink ($S_{U3}$, $C_{U3}$) before entering the

![Image of optical spectra](image)

**Fig. 5.33**: Measured optical spectra of: (a): the downlink signal, ($S_{D3}$, $C_{D3}$) after recovering 50% carrier, (b): the recovered optical carrier, and (c): the uplink signal, ($S_{U3}$, $C_{U3}$) generated using the recovered carrier.
DEMUX/MUX scheme respectively. As expected, due to recovering 50% of optical carrier, the CSR of the downlink signal is reduced by 3 dB, which eventually contributes in improving the link performance, as illustrated in Section 5.4.2. Spectra of Fig. 5.33(b)-(c) show that uplink DE-MZM experiences an unusual insertion loss of 16 dB resulting in a weaker uplink signal. Such situation can be avoided by placing a suitable DE-MZM having lower OSSB+C generation loss (typical loss < 9 dB).

Fig. 3.34(a) presents the multiplexed uplink signal at the CO after transmission over 10 km of SMF, while Fig. 5.34(b) presents the unwanted crosstalk at the CO from the downlink path (in the absence of uplink signal in the link). The spectra indicate that due to traversing through the AWG, the uplink signal is contaminated by the unwanted in-band and out-of-band crosstalk by the reflections from the downlink path, which is approximately -12 dB here. As before, the out-of-band crosstalk from the downlink path does not require any special attention, and will merge with typical crosstalk caused by the filtering characteristics of the demultiplexer. However, the in-band crosstalk may need to be addressed and managed when deploying such systems in practical networks. Fig. 5.34(a) also

![ Optical spectra measured at the CO for: (a) multiplexed uplink signal, (b) unwanted crosstalk from the downlink path due to reflections.](image-url)
confirms the CSR of the multiplexed uplink \((S_{U3}, C_{U3})\) as 5 dB, although before the proposed DEMUX/MUX scheme it was shown as 14 dB (shown in Fig. 5.33c). As stated before, this reduction in CSR also improves the sensitivity of the link significantly.

To quantify the signal degradation due to transmission over 10 km of SMF, uplink \((S_{U3}, C_{U3})\) was detected and BER curves measured, both at the beginning (back-to-back) and at the end of the fibre link using the same PD and data recovery circuit described earlier. The recovered BER curves are presented in Fig. 5.35 and it can be seen that the uplink \((S_{U3}, C_{U3})\) experiences a negligible 0.4 dB power penalty at a BER of \(10^{-9}\), which can be attributed to experimental errors. The presented recovered optical spectra and the BER curves clearly demonstrate the functionality of the proposed DEMUX/MUX scheme in multiplexing uplink signals that are generated by employing a wavelength reuse technique which simplifies the BS by

![Fig. 5.35: Measured BER curves as a function of received optical power for the multiplexed uplink \((S_{U3}, C_{U3})\) after transported over 10 km SMF with the back-to-back (0.0 km SMF) curve as reference, where uplink signal was generated by reusing the downlink optical carrier.](image-url)
eliminating the light source from the uplink path while realising compact, low-cost and light-weight BSs.

5.8 Effects of Optical Crosstalk on the Proposed System Technologies

Section 5.4.1 has described the characteristics of the $8 \times 8$ AWG used in demonstrating the system technologies throughout the Sections 5.4 to 5.7. The characterised results indicate that the proposed schemes incorporating such AWG are contaminated by the adjacent and nonadjacent channels crosstalk of -16 dB to -25 dB and -29 dB to -46 dB respectively. The demultiplexed results in Sections 5.6.1 and 5.7.3 also confirm presence of crosstalk from -18 to -30 dB in the demultiplexed signals. Moreover, the multiplexed results of the simultaneous MUX/DEMUX scheme described in Section 5.7.4 demonstrate that uplink signals generated by using
optical carriers spaced at 500 GHz from the downlink signals are contaminated by as much as -17 dB optical crosstalk, which increases to -12 dB with the uplink signals generated by reusing the downlink optical carriers. Therefore, there is the potential to incur performance degradation of the proposed system technologies through optical crosstalk. Fig. 5.36 shows the simplified experimental setup developed to characterise the effects of optical crosstalk while transmitting the optical mm-wave signals through the proposed system technologies incorporating AWG. Three OSSB+C modulated optical mm-wave signals, each carrying 37.5 GHz-band 155 Mb/s BPSK data, were generated by using three optical carriers at the wavelengths \(C_1\) (1556.0 nm), \(C_2\) (1556.2 nm) and \(C_3\) (1556.4 nm). The modulated signals were then applied to the AWG as shown in Fig. 5.36, where signals \((S_1, C_1)\) and \((S_2, C_2)\) follow separate VOAs before being applied. The output at port \(B_5\) was recovered in such way that the signal \((S_3, C_3)\) is contaminated by the adjacent and the nonadjacent
channel crosstalk from the signals \((S_2, C_2)\) and \((S_1, C_1)\) respectively. The VOAs are inserted to vary the optical powers of \((S_1, C_1)\) and \((S_2, C_2)\) that result in variable optical crosstalk with the recovered signal \((S_3, C_3)\). Also carrier \(C_3\) was provisioned two loop-backs before combining with \(S_3\), as the optical mm-wave signals are expected to undergo two loop-backs while multiplexing (as described in Section 5.3). The spectrum of the recovered signal \((S_3, C_3)\) is shown in Fig. 5.37, where the respective crosstalk components are mentioned in the insets. In order to observe the effects of such crosstalk, the adjacent channel crosstalk is varied with a 3–dB interval from -9 dB to -24 dB and the respective BER curves were measured as shown in Fig. 5.38. From the Fig. 5.38, it can also be seen that another two BER curves were plotted with (i) adjacent channel crosstalk removed, but nonadjacent channel crosstalk present, and (ii) both adjacent and nonadjacent channel crosstalk removed. The BER curves indicate that the demonstrated schemes will endure noticeable

![Fig. 5.38: Measured BER curves as a function of received optical power for various crosstalk levels contaminating the recovered signal \((S_3, C_3)\).]
crosstalk induced penalties with the presence of crosstalk levels more than -21 dB, which diminishes to zero when it is less than -21 dB.

In order to quantify the gradual changes in performance due to crosstalk, power penalties incurred by the signal \((S_3, C_3)\) (at a BER of \(10^{-9}\)) at various crosstalk levels are compared and the results are plotted in Fig. 5.39. This graph shows that a power penalty of 0.5 dB is observed for an optical crosstalk level of -16 dB, which however increases to 1 dB when the crosstalk level increases to -12 dB.

![Fig. 5.39: Measured crosstalk induced power penalties, with the gradual increase of crosstalk levels in the transmitted signals by the demonstrated system technologies for WI-DWDM mm-wave fibre-radio systems.](image)

5.9 Conclusion

This chapter presented novel system technologies incorporating arrayed waveguide grating filters for future wavelength-interleaved DWDM mm-wave fibre-
radio networks. WI-MUXs with the capacity to multiplex optical mm-wave signals to the wavelength interleaving schemes for these networks are proposed, which also improves the link performance by enabling reductions in CSRs of the multiplexed signals. WI-DEMUX, capable of demultiplexing wavelength interleaved signals in these networks, is also proposed. Moreover, a single MUX-DEMUX scheme for simultaneous multiplexing and demultiplexing is proposed that offers a route towards a simple network architecture by realising simplified and cost-effective CO and RNs. The proposed schemes are based on standard AWG technology, therefore, are suitable for integration with the other conventional technologies found in the optical access or metro domain. These schemes incorporating a commercially available 8 × 8 AWG are demonstrated experimentally with three optical mm-wave signals spaced at 25 GHz, each of them carrying 37.5 GHz RF signal with 155 Mb/s BPSK data. The error-free (at a BER of \(10^{-9}\)) recovery of data confirms the functionality of the proposed schemes without significant power penalty observed while transported the signals over 10 km of SMF. The AWG characteristics affecting the performance of the demonstrated schemes have been investigated experimentally.
Chapter 5: Enabling Wavelength Interleaving in Millimetre-Wave Fibre-Radio Networks

5.10 References


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6 Integration of Millimetre-Wave Fibre-Radio Networks in WDM
Optical Access Infrastructure

6.1 Introduction

The demand for higher and higher bandwidth necessitated by multimedia and real-time applications is increasing universally across both fixed and mobile access networks. To meet such growth in bandwidth demand, a variety of access technologies are being introduced in the last mile access network, incorporating both wireless and wireline media. Among these last mile access solutions, passive optical network (PON) and its specific implementations such as fibre-to-the-home (FTTH), and fibre-to-the curb (FTTC) remains as the most future proof technology for the delivery of broadband to the users [1-4]. Radio-over-fibre(RoF) network, which broadly can be categorised as the networking of wireless access points are also very attractive for the delivery of broadband via wireless last mile solutions [5-7]. The
various access technologies, based on their spectral bands, can be re-grouped as baseband (BB), intermediate frequency (IF), and mm-wave radio frequency (RF) transport over fibre, as described in Chapter 2. Carriers and service providers are actively seeking a convergent network architecture that can facilitate a rich mix of value added and clearly differentiated services via a mix of wireless and wireline solutions to meet the demand for mobility, bandwidth and range of connectivity options from the customer [8 -10]. All these requirements can be met by offering an integrated telecommunication package, for which an integrated access network is essential. Given the wide bandwidth offered by fibre, an integrated optical access network that can support appropriate integration of wired and wireless last mile solutions seems very plausible and to enable such a network coexistence of the optical access technologies in the same fibre will be essential.

Chapter 3, 4 and 5 have explored the system technologies for spectrally efficient dense-wavelength-division-multiplexed (DWDM) RoF networks operating in mm-wave frequencies, which reduce the cost of the deployment of such networks by enabling a large number of base stations (BSs) through a single central office (CO) [11-17]. The use of wavelength-division-multiplexed (WDM) in the RoF networks allows a fast route for these systems to be developed by utilising the WDM optical infrastructure in the access and metro network domains, where due to cost effectiveness, the unused capacity will be used as the means of communication between the CO and the BSs, by which the need for implementing separate fibre-radio backbone can be avoided [18]. Therefore, it is important that RoF systems are able to merge/integrate with the WDM access and metro network infrastructures.

In order to realise an integrated optical access network, simultaneous multiband modulation techniques were previously proposed [10, 19-22], which enable BB, IF and RF technologies to co-exist together in the same fibre. However, the performance of these methods has been limited by the nonlinearity as well as the optimum operating conditions of the modulators. Also, these techniques require significant changes both in the existing mini switching centres (MSCs) and the remote access nodes (RANs). Instead, if the passive system technologies (e.g. multiplexer and demultiplexer) in the existing MSCs, equivalent to the COs and RANs can be provisioned to support RF as well as other conventional BB and IF
access technologies thereby avoiding significant changes in the existing setup, an effective integrated optical access network can be easily realised.

This Chapter thus focuses on the investigation of hybrid multiplexing and demultiplexing schemes with the capacity to multiplex and demultiplex optically modulated BB, IF and RF signals together, leading to an effective integrated optical infrastructure in the access domain. Section 6.2 outlines general concept of multiplexing multiband signals together with schemes depending on various WDM channel separations. Section 6.3 presents a hybrid wavelength interleaving (WI) technique and a hybrid multiplexer for the multiplexing of DWDM multiband signals. The proposed wavelength-interleaved hybrid multiplexer is experimentally demonstrated in Section 6.4. Section 6.5 investigates the demultiplexing techniques suitable for demultiplexing multiple multiband signals from an integrated access network and proposes several hybrid demultiplexers to support various WDM channel separations. The proposed hybrid demultiplexer enabling demultiplexing of wavelength-interleaved DWDM multiband signals are also experimentally demonstrated in Section 6.6.

6.2  Multiplexing Multiband Signals in Integrated Access Networks

Chapter 2 has described the characteristics of optically modulated BB, IF and RF signals, the three broad categories of the signals generated by different optical access technologies, which are expected to reside together in the desired integrated optical access networks. In an integrated access network, three possible spectral schemes for the multiband WDM signals may evolve: (i) WDM channel separation, $\Delta f$ is much higher than the mm-wave RF frequency, $f_{RF}$, (ii) WDM (DWDM) channel separation, $\Delta f$ is equal to the mm-wave RF frequency, $f_{RF}$, and (iii) DWDM channel separation, $\Delta f$ is much smaller than the mm-wave RF frequency, $f_{RF}$.
6.2.1 Multiplexing Scheme with WDM Channels Larger than the RF Carrier Frequency

The schematic depicting the multiplexing scheme of multiband signals with WDM channel spacing larger than the mm-wave RF carrier frequency is shown in Fig. 6.1. It shows the spectra of N channels of each of the optically modulated BB, IF and RF signals with a WDM channel separation and a mm-wave RF carrier frequency of $\Delta f$ and $f_{RF}$, respectively, where $f_{RF} \ll \Delta f$. As $f_{RF}$ is much smaller than $\Delta f$, the multiplexing of the signals in such spectral configuration can be realised by using standard multiplexing technologies using a suitable arrayed waveguide grating (AWG) multiplexer, where both the optical carrier and the modulation sideband of an optically modulated RF signal will be considered together as a single channel, same as the BB and IF signals.

Fig. 6.2 shows the schematic of the hybrid multiband multiplexer (H-MUX) that realises multiplexing of the signals in the scheme shown in Fig. 6.1. It consists of a $3N \times 1$ AWG with a channel bandwidth, $\leq \Delta f$ and a channel spacing, $\Delta f$, equal to the WDM channel spacing of the desired multiplexed multiband signals. The input ports of the AWG are numbered from 1 to $3N$. The optically modulated BB, IF and RF signals...
input signals enter the AWG via the input ports, 1 to 3N as per their respective spectral positions shown in Fig. 6.1. The output of the AWG is, therefore, the multiband signals multiplexed, the spectrum of which can be seen from the inset of Fig. 6.2. This scheme has the potential to integrate 40 GHz and 60 GHz-band optical RF signals to the WDM access and metro networks separated at 100 GHz.

6.2.2 Multiplexing Scheme with DWDM Channels Equal to the RF Carrier Frequency

The schematic depicting the multiplexing scheme of multiband signals with a DWDM channel spacing equal to the mm-wave RF carrier frequency is shown in Fig. 6.3. It shows the spectra of N channels of each of the optically modulated BB, IF and RF signals with a DWDM channel separation, $\Delta f$ equal to the mm-wave RF carrier frequency, $f_{RF}$ of the optical RF signal. Unlike the hybrid multiplexer shown

Fig. 6.2: Proposed H-MUX enabling multiplexing of multiband signals in an integrated access network with a WDM channel spacing larger than the mm-wave RF carrier frequency.
for the previous scheme, multiplexing of the optical RF signals with the BB and IF signals in this case requires the optical carriers and the respective modulation sidebands of the optical RF signals to be considered as separate channels.

Fig. 6.4 shows the schematic of the H-MUX that realises multiplexing of the signals in the spectral scheme shown in Fig. 6.3. It comprises a \((4N+1) \times (4N+1)\) AWG with a channel bandwidth, \(\leq \Delta f\) and a channel spacing, \(\Delta f\), equal to the DWDM channel spacing of the desired multiplexed multiband signals. The input (A) and output (B) ports of the AWG are numbered from 1 to 4N+1. The characteristic matrix of the AWG that governs the allocation and distribution of different channels at different ports is illustrated in Table 6.1.

The optically modulated BB, IF and RF signals enter the AWG via the input ports, \(A_2\) to \(A_{4N+1}\) as per their respective spectral positions shown in Fig. 6.3. The AWG combines all the baseband signals \(BB_1, BB_2, \ldots, BB_N\) and IF signals \(IF_1, IF_2, \ldots, IF_N\) alongwith the modulation sidebands \(S_1, S_2, \ldots, S_N\) of RF signals at the output port \(B_1\). Due to the cyclic characteristics of the AWG as illustrated in Table 6.1, the optical carriers \(C_1, C_2, \ldots, C_N\) of the RF signals also exit as a composite signal via the output
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The composite carriers $C_1, C_2, \ldots, C_N$ are then looped back to the AWG through the input port $A_1$ that redistributes the carriers to the odd-numbered output ports $B_3, B_7, \ldots, B_{4N-1}$ respectively. To realise the desired multiplexing, the distributed carriers are again looped back to the AWG via the odd numbered input ports $A_3, A_7, \ldots, A_{4N-1}$, respectively and the resultant output at port $B_1$ is the BB, IF and RF signals multiplexed together. The multiplexed spectrum can be seen in the insets of Fig. 6.4.

Due to the loop-backs (LBs), the optical carriers of the RF signals are suppressed by as much as twice the insertion loss ($2 \times \text{IL}$) of the AWG (typical IL = 4 - 5 dB) compared to the respective modulation sidebands. Thus the proposed H-MUX

Fig. 6.4: Proposed hybrid multiplexer (H-MUX) enabling multiplexing of multiband DWDM signals in an integrated access network with a DWDM channel spacing equal to the mm-wave RF carrier frequency.

\( \text{AWG Channel BW} = \Delta f \)
\( \text{MM-Wave RF} = \Delta f \)
\( \text{DWDM Separation} = \Delta f \)
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enhances the performance of the optically modulated RF signals enabling a reduction in the carrier-to-sideband ratios (CSRs) by 8 to 10 dB [23 - 27], while multiplexing them with the optically modulated baseband and IF signals, leading to an integrated optical network in the access and metro domain. This scheme is particularly suitable for integrating 25 GHz and 50 GHz-band optical RF signals in the DWDM access and metro networks spaced at 25 GHz and 50 GHz respectively.

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Table 6.1: Input/output characteristic matrix of (4N+1) x (4N+1) AWG.

6.2.3 Multiplexing Scheme with DWDM Channels Smaller than the RF Carrier Frequency

As stated before, the third possible scheme in multiplexing multiband signals in an integrated access network is the use of a DWDM channel spacing smaller than the mm-wave RF carrier frequency. The realisation of integrated networks with such channel separation, however, is not practicable; as in such case, optically modulated
RF signals will overlap the neighbouring BB and IF signals. In order to resolve this problem, the following section introduces a hybrid interleaving technique by which multiplexing of multiband signals with a DWDM channel separation smaller than the RF carrier frequency can be easily realised.

6.3 Hybrid Wavelength Interleaving

The data bandwidth capacity of a mm-wave RF signal is usually limited to several hundred MHz; and therefore, the spectral band available between the optical carrier and the respective modulation sideband of an optically modulated RF signal often remains unused [13, 15, 16, 28, 29]. In order to realise a DWDM integrated access network with a channel separation smaller than RF carrier frequency, the unused spectral band of the optical RF signal can be utilised. If the unused spectral-bands of the RF signals are sliced as per the desired DWDM channel separation, and the neighbouring optically modulated BB and IF signals are interleaved at those sliced

![Fig. 6.5](image_url)

*Fig. 6.5:* Schematic depicting the optical spectra of the wavelength interleaved multiband signals in an integrated access network with a DWDM channel spacing smaller than the mm-wave RF carrier frequency.
positions, an integrated access network with such a DWDM channel separation can be realised. The underlying principle that determines the DWDM channel separation is the sliced spectral-band of the RF carrier frequency \( f_{RF} \), which is thrice the integer multiple of the DWDM channel separation \( f_{RF} = n \times 3\Delta f \), where \( n = 1, 2, 3, \ldots \), and \( \Delta f \) the desired DWDM separation).

Fig. 6.5 shows the optical spectra of the proposed WI scheme comprising \( N \) channels of each of the RF (in optical single sideband with carrier, OSSB+C modulation format), BB and IF signals, with a DWDM channel separation, and a RF carrier frequency of \( \Delta f \) and \( 3\Delta f \) respectively. The baseband signals BB\(_1\), BB\(_2\),...,BB\(_N\) and the IF signals IF\(_1\), IF\(_2\),...,IF\(_N\) are interleaved between the optical carriers C\(_1\), C\(_2\),...,C\(_N\) and their respective modulation sidebands S\(_1\), S\(_2\),...S\(_N\) of the RF signals in

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**Fig. 6.6:** Proposed wavelength-interleaved H-MUX enabling multiplexing of multiband DWDM signals in an integrated access network with a DWDM channel spacing smaller than the mm-wave RF carrier frequency.
such a way that after interleaving, the adjacent DWDM channel spacing, irrespective of BB or IF or RF signals, becomes $\Delta f$.

Fig. 6.6 shows the schematic of the proposed wavelength-interleaved H-MUX that realises multiplexing of the signals in interleaving scheme shown in Fig. 6.5. Similar to the H-MUX shown in Fig. 6.4, it also comprises a $(4N+1) \times (4N+1)$ AWG with a channel bandwidth, $\leq \Delta f$ and a channel spacing, $\Delta f$, equal to the DWDM channel spacing of the desired interleaved multiband signals. The input (A) and output (B) ports of the AWG are numbered from 1 to $4N+1$. The characteristic matrix of the AWG that governs the allocation and distribution of different channels at different ports has already been illustrated in Table. 6.1.

The optically modulated BB, IF and RF signals (shown as insets of Fig. 6.6) enter the AWG via the input ports, $A_2$ to $A_{4N+1}$, leaving the input ports $A_5$, $A_9$, $A_{13}$, ..., $A_{4N+1}$ unused, as shown in Fig. 6.6. The AWG combines all the modulation sidebands $S_1$, $S_2$, ..., $S_N$ of the RF signals as well the baseband signals BB$_1$, BB$_2$, ..., BB$_N$ and IF signals IF$_1$, IF$_2$, ..., IF$_N$ at the output port $B_1$. Due to the cyclic characteristics of the AWG as illustrated in Table 6.1, the optical carriers $C_1$, $C_2$, ..., $C_N$ of the RF signals also exit as a composite signal via the output port $B_4$. The composite carriers $C_1$, $C_2$, ..., $C_N$ are then looped back to the AWG through the input port $A_1$ that redistributes the carriers to the odd-numbered output ports $B_5$, $B_9$, $B_{13}$, ..., $B_{4N+1}$ respectively. To realise the desired multiplexing, the distributed carriers are again looped back to the AWG via the unused input ports $A_5$, $A_9$, $A_{13}$, ..., $A_{4N+1}$ and the resultant output at port $B_1$ is the RF, BB, and IF signals multiplexed with the BB and IF signals interleaved between the optical carrier and the modulation sideband of the RF signals. The multiplexed spectrum can be seen in the insets of Fig. 6.6. Like before, due to the loop-backs, the optical carriers of the RF signals are suppressed by as much as twice the insertion loss ($2 \times IL$) of the AWG (typical IL = 4 - 5 dB) compared to its respective modulation sidebands. Thus the proposed wavelength interleaved H-MUX also enhances the performance of the optically modulated RF signals enabling a reduction in the CSRs by 8 to 10 dB, while multiplexing them with the BB and IF signals in the proposed interleaving scheme, leading to an integrated optical network in the access and metro domain.
The following section demonstrates the proposed wavelength interleaved H-MUX experimentally and presents the experimental results from which the performance of the proposed multiplexer can be quantified.

### 6.4 Demonstration of Wavelength-Interleaved H-MUX

As stated above, the proposed wavelength interleaved H-MUX is comprised of a \((4N+1) \times (4N+1)\) AWG with a channel bandwidth, \(\leq \Delta f\) and a channel spacing, \(\Delta f\), equal to the DWDM channel spacing of the desired hybrid interleaving scheme. Therefore, the performance of the proposed H-MUX is largely dependent on proper selection of suitable AWG. For this demonstration an \(8 \times 8\) AWG with a channel

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**Fig. 6.7:** Experimental setup for the demonstration of a wavelength interleaved H-MUX that interleaves the DWDM multiband signal in an integrated DWDM network in access domain.
separation of 12.5 GHz and a channel bandwidth of \(\approx 10\) GHz was used, the performance of which has already been characterised in Chapter 5.

Fig. 6.7 shows the setup used to demonstrate the proposed scheme experimentally. Three narrow linewidth tunable light sources \(LS_1\), \(LS_2\), and \(LS_3\) at the corresponding wavelengths 1556.2, 1556.3 and 1556.4 nm followed by separate polarization controllers were used as the input to two low-speed (0 - 5 GHz) Mach-Zehnder modulators (MZMs) and one high-speed (0 - 40 GHz) dual-electrode-MZM (DE-MZM) to generate optical BB, IF and RF signals, respectively. The optical BB signal

![Fig. 6.8: Measured optical spectra for the modulated multiband signals before entering to the proposed wavelength interleaved hybrid multiplexer (H-MUX): (a): RF, (b): BB and (c): IF](image)
was generated by using 1 Gb/s baseband data whereas the optical IF and RF signals were generated by using 2.5 GHz microwave and 37.5 GHz mm-wave signals respectively. The 2.5 GHz microwave and 37.5 GHz mm-wave signals were generated by mixing 2.5 and 37.5 GHz local oscillator (LO) signals respectively with 155 Mb/s pseudo-random-bit-sequence (PRBS) data. The mixer outputs were then amplified prior to applying to the respective modulators, as shown in Fig. 6.7. The BB and IF signals were generated in optical double sideband with carrier (ODSB+C) modulation format by applying standard external modulation techniques, whereas the RF signal was generated in OSSB+C modulation format, for which the necessary operating conditions of the DE-MZM can be seen from Fig. 6.7.

Figs. 6.8(a) - (c) show the optical spectra of the respective modulated RF (showing optical carrier, C and the respective modulation sideband, S), BB, and IF signals before multiplexing. Although the spectra of the optical BB and IF signals do not provide much information, the spectrum of the optical RF signal clearly indicates a CSR of 13 dB with a suppression of the unwanted modulation sidebands by almost 30 dB.

![Optical Spectrum](image.png)

**Fig. 6.9:** Measured optical spectrum at the output of the proposed wavelength-interleaved H-MUX while demonstrating experimentally with one of each optically modulated BB, IF and RF signals.
The modulated signals were then applied to the AWG, as shown in Fig. 6.7. The allocation of the input ports and the selection of the loop-back paths are maintained in such a way that the resultant output of the AWG is the desired interleaved signals. Fig. 6.9 shows the combined spectrum of the signals after multiplexing, which confirms the functionality of the proposed H-MUX, enabling wavelength interleaving for the modulated multiband signals in an integrated DWDM access network. The spectrum also indicates that the multiplexing of the signals using such

![Image](image_url)

**Fig. 6.10:** Measured optical spectra for the recovered: (a): RF, (b): BB and (c): IF signals at the OADM interface.
H-MUX reduces the CSR of optical RF signal to 5 dB, attaining an effective reduction by 8 dB.

The composite signal was then amplified by an erbium-doped-fibre-amplifier (EDFA) and followed by a 4-nm optical band pass filter (BPF) prior to transmission over 10 km of singlemode fibre (SMF) to a BS, where each of the multiplexed signals was recovered using a suitable optical add-drop-multiplexing (OADM) interface. The OADM interface, which is comprised of a double-notch tunable fibre Bragg grating (FBG) and a 3-port optical circulator, recovers each of the signals separately.
from the interleaved signals by shifting the centre frequencies of the FBG. The spectra of recovered signals can be seen from Fig. 6.10 (a) - (c).

The spectra for the signals passing through the OADM interface are also shown in Fig. 6.11 (a)-(c). The optical spectra shown in Fig. 6.10 and 6.11 indicate that the recovered signals are contaminated by unwanted -24 dB to -30 dB optical crosstalk, which however, can be further minimised by proper selection of the FBG comprising the OADM interface.

Fig. 6.12: Measured BER curves as a function of received optical power for: (a): RF, (b): BB, and (c): IF signals recovered from the three wavelengths interleaved multiband signals after transmission over 10 km SMF, with the back to back curves as the reference.
In order to quantify the signal degradation in bit error ratio (BER), each of the recovered signals was detected and data was recovered using suitable photodetector (PD) and data recovery circuits. The recovery of data from the BB and IF signals have used 1 GHz and 2.5 GHz optical receivers respectively. The PD and data recovery circuit used in recovering data from the optical RF signal is shown in the dotted line inset of Fig. 6.7. The RF signal was first detected with a 45 GHz PD, then amplified, down-converted to an IF of 2.5 GHz, and filtered with an electrical BPF with a bandwidth 400 MHz, from which the data was recovered using a 2.5 GHz phase locked loop (PLL).

Fig. 6.12 (a) – (c) shows the measured BER curves for the recovered signals both for the back-to-back case (having the H-MUX, but no fibre) and after transmission over 10 km of SMF. The results exhibit negligible power penalties of 0.2 to 0.3 dB at a BER of $10^{-9}$ that can be attributed to experimental errors.

Therefore, a simple H-MUX is proposed and demonstrated with the capacity to interleave optically modulated BB, IF and RF signals with a DWDM channel separation of 12.5 GHz, which has the potential to combine multiband optical access technologies together, leading to an integrated DWDM network in the access and metro domain. The proposed H-MUX also reduces the CSR of the interleaved RF signals that improves the overall RF transmission performance significantly.

### 6.5 Demultiplexing of Multiband Signals

Section 6.3 has introduced a wavelength interleaved hybrid multiplexing scheme for integrated optical access network, which has been demonstrated experimentally in Section 6.4. In this demonstration an OADM interface comprised of a tunable double-notch FBG and a 3-port optical circulator was used as the means of recovering the desired signals at the BS. OADM interfaces of this kind however, exhibit poor performances while used as cascaded units in star-tree and ring/bus network, as described in detail in Chapter 4. As a way to overcome, AWG-based demultiplexing schemes, suitable to recover multiple multiband signals together both
in the CO and the RANs, can be used. This section thus focuses in introducing such hybrid multiband demultiplexers (H-DEMUXs), by which the recovery of the desired multiband signals from an integrated optical access network can be easily realised.

### 6.5.1 H-DEMUX with WDM Channels Larger than the RF Carrier Frequency

The schematic depicting the multiplexing scheme of multiband signals with a WDM channel spacing larger than the mm-wave RF carrier frequency is shown in Fig. 6.1. As \( f_{RF} \) is much smaller than \( \Delta f \), similar to the multiplexing scheme, the demultiplexing of the signals also can be realised by using standard demultiplexing technologies using a suitable AWG demultiplexer, where both the optical carrier and the modulation sideband of an optical RF signal will be considered together as a single channel, same as the BB and IF signals.

Fig. 6.13 shows the schematic of a H-DEMUX that effectively demultiplexes the
multiband signals from the spectral scheme shown in Fig. 6.1. Similar to the H-MUX shown in Fig. 6.2, it is also comprised of a $1 \times 3N$ AWG with a channel bandwidth, $\leq \Delta f$ and a channel spacing, $\Delta f$, equal to the WDM channel spacing of the multiplexed multiband signals. The output ports of the AWG are numbered from 1 to $3N$. The multiplexed BB, IF and RF signals, shown in inset of Fig. 6.13, enters the AWG via the input port and is demultiplexed to the output ports, the similar way it is demultiplexed in a convention WDM network.

### 6.5.2 H-DEMUX with DWDM Channels Smaller than the RF Carrier Frequency

The schematics depicting the multiplexing schemes of multiband signals with

![Diagram](image-url)

**Fig. 6.14:** Proposed H-DEMUX enabling demultiplexing of multiband wavelength-interleaved signals in an integrated DWDM access network, which also reduces the CSR of the demultiplexed RF signals through optical loop-backs.
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DWDM channel spacings equal to or smaller than the mm-wave RF carrier frequency are shown in Figs. 6.3 and 6.5. Although both of these schemes are different in spectral configuration, the desired signals from such schemes can be recovered using similar demultiplexers. Therefore, to avoid repetition, description of a separate demultiplexer for the multiplexing scheme shown in Fig. 6.3 is ignored.

Fig. 6.14 shows the schematic of the multiband H-DEMUX that realises demultiplexing of the wavelength interleaved signals from the spectral scheme shown in Fig. 6.5. It comprises a $4N \times 4N$ AWG with a channel bandwidth, $\Delta f$, and a channel spacing, $\Delta f$, equal to the DWDM channel spacing of the interleaved multiband signals. The input (A) and output (B) ports of the AWG are numbered from 1 to $4N$. The characteristic matrix of the AWG that governs the allocation and distribution of different channels at different ports is illustrated in Table. 6.2.

<table>
<thead>
<tr>
<th>Input Ports</th>
<th>Output Ports</th>
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<tr>
<td>$A_1$</td>
<td>$B_1$, $\lambda_1$, $\lambda_2$, $\lambda_3$, $\lambda_{N-1}$, $\lambda_N$, $\lambda_{N+1}$, $\lambda_{4N}$, $\lambda_{4N-1}$, $\lambda_{4N}$</td>
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<td>$A_{N+1}$</td>
<td>$\lambda_{N+1}$, $\lambda_{N+2}$, $\lambda_{N+3}$, $\lambda_{4N-3}$, $\lambda_{4N-2}$, $\lambda_{4N-1}$, $\lambda_{4N-2}$, $\lambda_{N+1}$, $\lambda_N$</td>
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</table>

Table 6.2: Input/output characteristic matrix of $4N \times 4N$ arrayed waveguide grating.

The wavelength interleaved BB, IF and RF signals, shown in the inset of Fig. 6.14, enters the AWG via the input port, $A_1$. The AWG then distributes the optical
carriers and the respective modulation sidebands of the RF signals as well as the BB and IF signals to the output ports, $B_1 - B_{4N}$ as per their respective positions in the interleaved spectrum. To realise demultiplexing for the RF signals, the distributed optical carriers $C_1, C_2, ..., C_N$ are looped back to the AWG via the input ports $A_4, A_8, ..., A_{4N}$, respectively and the resultant outputs at ports $B_1, B_5, ..., B_{4N-3}$ are the optical carriers and the modulation sidebands of the RF signals demultiplexed together. Thus the proposed H-DEMUX successfully demultiplexes the multiband signals in an integrated DWDM access network, suitable to be used both in the CO and the RANs.

Also due to the loop-backs, the optical carriers of the demultiplexed RF signals are suppressed by as much as equal to the IL of the AWG (typical IL = 4 - 5 dB) compared to the respective modulation sidebands. Therefore, the proposed H-DEMUX also enhances the performance of the optical RF signals by reducing the CSRs by 4 to 5 dB, in addition to demultiplexing them from an integrated DWDM

Fig. 6.15: Proposed H-DEMUX enabling demultiplexing of multiband wavelength interleaved signals in an integrated DWDM access network, where 3 –dB couplers are used to combine the optical carrier and the respective modulation sideband of an optical RF signal at the output ports of the AWG.
network in the access and metro domain.

The proposed H-DEMUX shown in Fig. 6.14 can also be realised by using a 1 x 4N AWG, where additional 3-dB optical couplers are needed to be inserted for each of the RF signals that combine the optical carrier and the respective modulation sideband of an RF signal together at the output ports of the AWG. The schematic of such a scheme can be seen from Fig. 6.15. This scheme, however, causes additional 3 –dB attenuation for the optical RF signals before demultiplexing, in addition to ignoring the performance enhancement of the RF signals through optical loop-backs.

The following section demonstrates the proposed wavelength interleaved H-DEMUX (shown in Fig. 5.14) experimentally and presents the experimental results from which the performance of the proposed multiplexer can be quantified.

### 6.6 Demonstration of Wavelength-Interleaved Hybrid Demultiplexer

Fig. 6.16 shows the setup used to demonstrate the proposed scheme experimentally. Similar to the demonstration of hybrid multiplexer, three narrow linewidth tunable light sources LS1, LS2, and LS3 at the corresponding wavelengths 1556.2, 1556.3 and 1556.4 nm followed by separate polarization controllers were used as the input to two low-speed (0 - 5 GHz) MZMs and one high-speed (0 - 40 GHz) DE-MZM to generate optical BB, IF and RF signals, respectively. The optical BB signal was generated by using 1 Gb/s data, whereas the optical IF and RF signals were generated by using 2.5 GHz microwave and 37.5 GHz mm-wave signals respectively. The 2.5 GHz and 37.5 GHz signals were generated respectively by mixing 155 Mb/s PRBS data with 2.5 and 37.5 GHz LO signals in BPSK format. The mixer outputs were then amplified prior to applying to the respective modulators, as shown in Fig. 6.16. The RF inputs and biasing of the DE-MZM was controlled in such a way that the resultant output of the DE-MZM was an optical RF signal in OSSB+C modulation format. The generated optical BB, IF and RF signals were then interleaved by using two 3-dB optical couplers, the composite spectrum of which can be seen from Fig.
6.17. Like before, the optical RF signal clearly shows a CSR of 13 dB with a suppression of the unwanted modulation sidebands by almost 30 dB. The spectrum also indicates the 12.5 GHz DWDM channel spacing (irrespective of carrier or sideband) in addition to the RF carrier frequency of 37.5 GHz.

The interleaved multiband signals were amplified by an EDFA and then filtered using a 4 nm optical BPF to minimise out-of-band asynchronous spontaneous emission (ASE) noise. The filtered signal was transported over 10 km of SMF to the proposed wavelength interleaved H-DEMUX, comprised of an 8 × 8 AWG with a channel separation of 12.5 GHz and a channel bandwidth of ≈10 GHz, the characteristics of which has already been described in Chapter 5. The allocation of
Fig. 6.16: The input port and the selection of the loop-back path for the optical carrier of the RF signal are as shown in Fig. 6.16, which result in the desired demultiplexed RF, BB, and IF signals at the output ports B1, B2, and B3 respectively.

Fig. 6.17: Measured optical spectrum of the composite BB, IF and RF signals, interleaved by using 3-dB couplers.

Fig. 6.18(a)-(c) show the spectra of the signals after demultiplexing. The demultiplexed spectra confirm the functionality of the proposed H-DEMUX, enabling demultiplexing of wavelength interleaved multiband signals in an integrated DWDM access network. The recovered spectra indicate the presence of optical crosstalk in the demultiplexed signals, which was already defined before as the ratio of the undesired optical carriers to the desired optical carriers at the demultiplexed signals. Crosstalk levels of -13.6 to -14.7 dB were observed. The impacts of these crosstalk on the transmission performance of the demultiplexed signals are quantified later of the section. The spectrum in Fig. 6.18(a) also indicates that the demultiplexing of the signals using such H-DEMUX reduces the CSR of demultiplexed RF signal from 13 dB to 8.4 dB.
In order to quantify the signal degradation in bit error ratio, each of the demultiplexed signals was detected and data was recovered using the same PD and data recovery circuits, used in measuring the BER performances in Section 6.4. Fig. 6.19 (a) –(c) shows the measured BER curves for the recovered signals both for the back-to-back case (having the H-DEMUX, but no fibre) and after transmission over 10 km of SMF. The results exhibit negligible power penalties of 0.15 to 0.4 dB at a BER of $10^{-9}$ that can be attributed to experimental errors.
Also, the effects of the presence of optical crosstalk in the demultiplexed signals, caused by the neighbouring DWDM multiband signals, are quantified by measuring another set of BER curves, transmitting each of the RF, IF and BB signals separately and comparing them with the BER curves measured for the demultiplexed signals.

The new set of BER curves is shown in Fig. 6.20. It indicates that the integrated DWDM access network incorporating the proposed H-DEMUX causes crosstalk...
induced penalties of 0.5, 0.6, and 0.5 dB for the respective optical RF, IF, and BB signals, which however can be minimised by proper selection of the AWG, the main building block of the proposed demultiplexing scheme.

Therefore, the recovered optical spectra and the BER curves clearly demonstrate the functionality of the proposed demultiplexing scheme that offers a practical solution for an integrated DWDM network in the access and metro domain. The
scheme also reduces the CSR of the demultiplexed RF signals that improves the overall RF transmission performance significantly.

6.7 Conclusion

This chapter presented hybrid multiplexing and demultiplexing schemes for simultaneous transmission of multiband signals together towards the realisation of an integrated network in the access and metro domain. To reduce the WDM channel spacing smaller than the mm-wave RF carrier frequency, hybrid wavelength interleaving technique was proposed, by which integrated access network with DWDM channel spacing can be realised. The proposed schemes are based on AWG technology and are suitable to be installed in the standard optical access or metro infrastructure, irrespective of the network technologies and architectures. Moreover, the schemes incorporating hybrid wavelength interleaving reduce the CSRs of the optical RF signals while multiplexing and demultiplexing that improve the overall RF transmission performance significantly.

The functionality of the wavelength interleaved hybrid multiplexer and demultiplexer were verified experimentally with three DWDM multiband signals (BB, IF and RF), comprising a baseband signal with 1 Gb/s baseband, a 2.5 GHz IF signal with 155Mb/s BPSK data and a 37.5 GHz RF signal with 155Mb/s data, spaced at 12.5 GHz transported over 10 km of fibre link. The error free (at a BER of $10^{-9}$) data recovery confirm the functionality of the proposed schemes without any noticeable power penalty observed while transporting over 10 km of SMF.
Chapter 6: Integration of Millimetre-Wave Fibre-Radio Networks in WDM
Optical Access Infrastructure

6.8 References


7 CONCLUSIONS AND FUTURE WORK

7.1 Thesis Overview

This thesis has focused on the investigation and development of novel system technologies for the implementation of dense-wavelength-division-multiplexed (DWDM) millimetre-wave (mm-wave) fibre-radio systems, which also includes the integration of these systems to the optical access infrastructure, as well as, the realisation of simple, compact and low-cost base stations (BSs). Novel wavelength-division-multiplexed (WDM) optical interface was proposed that offers simplified and consolidated BS architectures, while enabling the BSs to the wavelength-interleaved-DWDM (WI-DWDM) feeder networks. Efficient multiplexing of optical mm-wave signals in WI-DWDM fibre-radio networks were introduced. Schemes for effective demultiplexing of optical mm-wave signals from WI-DWDM feeder networks were also proposed. Moreover, hybrid multiplexing and demultiplexing
Chapter 7: Conclusions and Future Work

schemes for the integration of mm-wave fibre-radio systems to the optical access infrastructure were developed.

Chapter 2 presented a comprehensive review of the research in mm-wave fibre-radio systems and the associated technologies, providing a motivation for the topics covered in this thesis. Research towards the simplification of BS architectures were explored and analysed, particularly with the highlight of limited research towards the simplification of the optical-add-drop-multiplexer (OADM) as well as the optoelectronic & electrooptic (O/E) interface that has the potential to realise a consolidated and cost-effective BS architecture. A summary of previous work towards the realisation of spectrally efficient fibre-radio feeder network, with particular focus on WI-DWDM systems, was presented. Literatures reporting the performance enhancement of mm-wave fibre-radio systems were reviewed and summarised. Potential network impairments in such systems were also identified through further review. Moreover, the literatures towards the realisation of an integrated optical infrastructure in the access domain were explored. The limitations as well as the challenges of the reported demonstrations are identified for further investigations.

In Chapter 3, a multifunctional WDM optical interface for WI-DWDM fibre-radio systems was proposed, which enables OADM functionality to the BSs and provides optical carrier for the uplink path. The functionality of the proposed interface was verified both in experiment as well as via simulation for 37.5 GHz-band WI-DWDM fibre-radio systems spaced at 25 GHz. The effects of the performance of O/E devices on the overall performance of the link, incorporating the proposed interface, were investigated. Simulation models were developed to investigate the impairments contributed by the O/E devices such as, duel-electrode Mach-Zehnder modulator (DE-MZM) and photodetector (PD). In addition, another simulation was carried out that quantifies the effects of reusing optical carrier in the BS, instead of independent uplink light-source.

In Chapter 4, the performance of the proposed WDM optical interface in a single and cascaded configuration, both by simulation as well as by experiment, was characterised. The results indicate that the 37.5 GHz-band 25 GHz-separated WI-DWDM signals can be routed via the proposed interface without significant
performance degradation. The characterisations as well as the modelling results confirm the viability of the proposed interface in star-tree and ring/bus network architectures with observed negligible power penalty for each stage of cascade. A modification was incorporated in the proposed WDM optical interface that enhances the overall performances of the links, both in uplink and downlink directions; although it is a trade off with the dimensioning of the networks.

Chapter 5 investigated the novel system technologies incorporating arrayed waveguide grating (AWG) filters for WI-DWDM mm-wave fibre-radio networks. Wavelength-interleaved multiplexers with the capacity to multiplex optical mm-wave signals are proposed, which also improves the link performance by enhancing the modulation depth indices of the multiplexed signals. A wavelength-interleaved demultiplexer, capable of demultiplexing WI-DWDM signals in fibre-radio networks, was also proposed. Moreover, a simultaneous multiplexing and demultiplexing scheme was proposed that offers a route towards the simple network architectures by realising simplified and cost-effective central office (CO) and remote nodes. These schemes, incorporating a commercial $8 \times 8$ AWG, were demonstrated experimentally using three optical mm-wave signals spaced at 25 GHz, each of them carrying 37.5 GHz mm-wave radio frequency (RF) signal with 155 Mb/s data. The AWG characteristics affecting the performance of the demonstrated schemes were also experimentally investigated.

In Chapter 6, hybrid multiplexers and demultiplexers for simultaneous transmission of optically modulated baseband (BB), intermediate frequency (IF) and RF signals were proposed. Such hybrid systems have the potential to realise integrated optical networks in the access and metro domain. A hybrid interleaving scheme, with the capacity to reduce the effective DWDM channel separations smaller than the RF carrier frequency, was also proposed. The proposed hybrid interleaving scheme was realised with the introduction of novel hybrid multiplexer and demultiplexer. Moreover, the functionality of these multiplexer and demultiplexer were experimentally demonstrated with three optically modulated BB, 2.5 GHz IF and 37.5 GHz RF signals spaced at 12.5 GHz.
7.2 Directions for Future Work

The work presented in this thesis consisted of detailed investigations and developments of novel system technologies towards the implementation of DWDM mm-wave fibre-radio systems, the integration of optical access technologies incorporating radio-over-fibre and the simplification of BS architectures. In carrying these works, a number of related research topics were identified that could not be pursued as part of this thesis, but which however, would be interesting to further investigate.

- The WDM optical interface proposed in Chapter 3 consists of fibre Bragg grating (FBG) filters, which are usually designed to enable the specific wavelengths only. FBG based interfaces therefore, limit the BSs to specific optical carriers. Instead, if the FBG filters are replaced with filters such as Fabry-Perot (FP) etalon and AWG, a wavelength independent BS can be achieved.

- The proposed interface supports only one downlink and one uplink signal for each BS. To use such interface in multi-sector antenna BSs, multiple cascaded interfaces will be required, which complicates the BS architecture. To enable drop and add of multiple channels simultaneously, another interface incorporating FP etalon or AWG can be proposed. Such interface will enable multiple uplink and downlink signals to each BS via a single interface, in addition to offering wavelength independent BSs.

- The characterisation of the cascaded interfaces considered two interfaces in cascade both in simulation as well as in experiment. The numerical modelling of the network considered the data derived from experimental demonstration. As the accumulation of network impairments with the increase of numbers of interfaces in cascade is not linear, more analyses on the network impairments, such as, optical crosstalk and grating dispersion...
contributed by the proposed interface, are needed before its practical deployment.

- As summarised in Chapter 2, integration of optic, optoelectronic, mm-wave and radiating devices is another active area of research towards the realisation of simplified and consolidated BSs. The proposed interface simplifies the BS by eliminating the uplink light-source. Further simplification of the BS would achieve, if the interface can be fabricated with the O/E devices (e.g. DE-MZM and PD) by applying suitable integration and packaging techniques.

- MM-wave fibre-radio links incorporating the proposed WDM optical interface are needed to be optimised considering different network topologies, more importantly, for uplink communication; as the uplink signals generated by reusing the downlink optical carriers are very week to transmit over longer fibre incorporating cascaded interfaces.

- The investigations throughout this thesis indicate that AWG based system technologies are very promising for future DWDM mm-wave fibre-radio networks. The effective use of AWG in these networks, however, largely depends on its stable operations over ultra-narrow channel separations (e.g. 12.5 GHz), which is yet to achieve. Further explorations on the device technologies are essential to confirm its suitability for DWDM mm-wave fibre-radio networks. The areas to improve: sharp roll-off spectral profile with robust geometry, polarisation independency, tolerant with room-temperature change, insertion loss, crosstalk, reflection, periodicity etc.

- The capacity of the integrated networks, incorporating the proposed hybrid multiplexers and demultiplexers, are needed to be analysed for optimum channel separation, data capacity, and network dimensioning.
Realisation of simultaneous hybrid multiplexing and demultiplexing scheme that has the potential to offer simplified and consolidated CO and remote access nodes for the integrated optical access networks can be explored.
Appendix A: Acronyms

ATM         asynchronous transfer mode
AWG         arrayed waveguide grating
ADM         add-drop-multiplexing
ASE         asynchronous spontaneous emission
ASK         amplitude-shift-keyed
AW           arrayed waveguide
BS           base station
BWA         broadband wireless access
BPSK        binary-phase-shift-keyed
BPF         band pass filter
BER         bit-error-rate
BB           baseband
CD           chromatic dispersion
CO           central office
CSR         carrier-to-sideband ratio
CNR         carrier-to-noise ratio
CU           customer unit
DL           downlink
DWDM        dense-wavelength-division-multiplexing
DSB-SC      double sideband suppressed carrier
DE-MZM      dual-electrode Mach-Zehnder modulator
EAT         electroabsorption transceiver
EAM         electroabsorption modulator
EDFA        erbium-doped-fibre-amplifier
EOM         electrooptic modulator
FN           feeder network
FBG         fiber Bragg grating
FP           Fabry-Perot
FBG1        two-notch FBG
FBG2        single-notch FBG
## Appendix

<table>
<thead>
<tr>
<th>Abbreviation</th>
<th>Description</th>
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<td>FTTH</td>
<td>fibre-to-the-home</td>
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<tr>
<td>FTTC</td>
<td>fibre-to-the-curb</td>
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<tr>
<td>FSR</td>
<td>free spectral range</td>
</tr>
<tr>
<td>FPR</td>
<td>free propagation region</td>
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<tr>
<td>GVD</td>
<td>group velocity dispersion</td>
</tr>
<tr>
<td>GbE</td>
<td>gigabit ethernet</td>
</tr>
<tr>
<td>HIC</td>
<td>hybrid optoelectronic integration</td>
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<tr>
<td>H-MUX</td>
<td>hybrid multiband multiplexer</td>
</tr>
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<td>H-DEMUX</td>
<td>hybrid multiband demultiplexer</td>
</tr>
<tr>
<td>IL</td>
<td>insertion loss</td>
</tr>
<tr>
<td>IF</td>
<td>intermediate frequency</td>
</tr>
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<td>ISI</td>
<td>inter-symbol interference</td>
</tr>
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<td>IP</td>
<td>internet protocol</td>
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<td>LNA</td>
<td>low noise amplifier</td>
</tr>
<tr>
<td>LMDS</td>
<td>local multipoint distribution service</td>
</tr>
<tr>
<td>LiNbO$_3$</td>
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</tr>
<tr>
<td>LSB</td>
<td>lower sideband</td>
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<td>LAN</td>
<td>local area network</td>
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<td>LB</td>
<td>loop-back</td>
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<td>LO</td>
<td>local oscillator</td>
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<td>mm-wave</td>
<td>millimetre-wave</td>
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<td>MSC</td>
<td>mini switching centre</td>
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<td>MMIC</td>
<td>monolithic millimetre-wave integrated circuit</td>
</tr>
<tr>
<td>MIC</td>
<td>monolithic integrated circuit</td>
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<td>MCM</td>
<td>multichip module</td>
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<tr>
<td>MPA</td>
<td>medium power amplifier</td>
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<td>MOD/DEMOD</td>
<td>modulator and demodulator</td>
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<td>MUX/DEMUX</td>
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<td>MQW</td>
<td>multiple quantum well</td>
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<td>MZM</td>
<td>Mach-Zehnder modulator</td>
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<td>ONU</td>
<td>optical network unit</td>
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<tr>
<td>OADM</td>
<td>optical add-drop-multiplexer</td>
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<td>ODSB+C</td>
<td>optical double sideband with carrier</td>
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### Appendix

<table>
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<td>OSSB+C</td>
<td>optical single sideband with carrier</td>
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<td>OEIC</td>
<td>optoelectronic integrated circuit</td>
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<td>OC</td>
<td>optical circulator</td>
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<tr>
<td>OSA</td>
<td>optical spectrum analyser</td>
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<td>OI</td>
<td>optical isolator</td>
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<td>OSNR</td>
<td>optical signal-to-noise ratio</td>
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<tr>
<td>O/E</td>
<td>optoelectronic &amp; electrooptic</td>
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<td>OXC</td>
<td>optical crossconnect</td>
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<td>PLC</td>
<td>planar lightwave circuit</td>
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<td>PD</td>
<td>photodetector</td>
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<td>PC</td>
<td>polarisation controller</td>
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<td>PRBS</td>
<td>pseudo-random-bit-sequence</td>
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<td>PLL</td>
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<td>PON</td>
<td>passive optical network</td>
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<td>QoS</td>
<td>quality of service</td>
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<td>QB</td>
<td>quadrature bias</td>
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<td>quantum confined Stark effect</td>
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<td>quantum well</td>
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<td>RoF</td>
<td>radio-over-fibre</td>
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<td>RN</td>
<td>remote node</td>
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<td>rf</td>
<td>radio frequency</td>
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<td>RF</td>
<td>mm-wave radio frequency</td>
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<td>RAN</td>
<td>remote access node</td>
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<td>SFDR</td>
<td>spurious free dynamic range</td>
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<td>SCM</td>
<td>subcarrier multiplexing</td>
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<td>SMF</td>
<td>singlemode fibre</td>
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<td>SBS</td>
<td>stimulated Brillouin scattering</td>
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<td>SNR</td>
<td>signal-to-noise ratio</td>
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<td>TX/RX</td>
<td>transmitter and receiver</td>
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<td>USB</td>
<td>upper sideband</td>
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<td>UL</td>
<td>uplink</td>
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<tr>
<td>VOA</td>
<td>variable optical attenuator</td>
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<tr>
<td>WOI</td>
<td>WDM optical interface</td>
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## Appendix

<table>
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<td>wavelength-interleaved-multiplexer</td>
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<td>WI-DEMUX</td>
<td>wavelength-interleaved-demultiplexer</td>
</tr>
<tr>
<td>WI</td>
<td>wavelength interleaving</td>
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<tr>
<td>WDM</td>
<td>wavelength-division-multiplexing</td>
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<td>WI-DWDM</td>
<td>wavelength-interleaved-DWDM</td>
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Appendix

Appendix B: Publications

JOURNAL PUBLICATIONS


5. Zhaohui Li, Ampalavanapillai Nirmalathas, Masuduzzaman Bakaul, Yang Jing Wen, Linghao Cheng, Jian Chen, Chao Lu, and Sheel Aditya,
Appendix


CONFERENCE PUBLICATIONS

Appendix


fiber-radio systems” presented at the International Topical Meeting on Microwave Photonics (MWP 2005), Seoul, South Korea, October, 2005.


19. Ampalavanapillai Nimalathas, Masuduzzaman Bakuul, Christina Lim, Manik Attygalle, Dalma Novak, Rod B. Waterhouse, “Wavelength Division Multiplexed Fiber-Radio Networks” presented at the Asia-Pacific Microwave Photonics Conference (AP-MWP 2006), Tokyo, Japan, April, 2006. [Invited paper]

Appendix

Microwave Photonics Conference (AP-MWP 2006), Tokyo, Japan, April, 2006.
