Spectrally efficient hybrid multiplexing and demultiplexing schemes toward the integration of microwave and millimeter-wave radio-over-fiber systems in a WDM-PON infrastructure

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Hybrid multiplexing and demultiplexing schemes with the capability to integrate microwave and millimeter-wave frequency radio-over-fiber signals in a wavelength division multiplexed passive optical network (WDM-PON) infrastructure are proposed. The proposed schemes exploit the benefits of a spectrally efficient wavelength-interleaving technique and enhance the performance of optical millimeter-wave signals without employing an additional device. The schemes are demonstrated experimentally with simultaneous transport of 1 Gbit/s baseband, 2.5 GHz microwave, and 37.5 GHz millimeter-wave signals that have the potential to converge last-mile optical and wireless technologies, leading to an integrated dense WDM network in the access and metro domains. © 2009 Optical Society of America

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1. Introduction

The demand for higher bandwidth necessitated by data-intensive multimedia and real-time applications is increasing in the last-mile access networks. To meet this bandwidth demand, a variety of access technologies, such as digital subscriber line (xDSL), fiber-to-the-curb (FTTC), fiber-to-the-home (FTTH), ultra mobile broadband (UMB), worldwide interoperability for microwave access (WIMAX), etc., have evolved, incorporating both wireless and wireline media. Among these solutions, wired solutions based on passive optical networks (PONs) (e.g., FTTC/FTTH) remain the most future-proof technology for the delivery of broadband to the users, because they offer higher bandwidths at longer distances. Also, due to fixed physical connections, they are more secure and reliable [1]. On the other hand, radio-over-fiber (RoF) solutions, which can be broadly categorized as the networking of wireless access points, are also very attractive due to their inherent advantage of portability and flexibility [2]. To exploit the benefits of both of these transmission media, carriers and service providers are actively seeking a convergent network architecture that can facilitate a rich mix of value-added and differentiated services via an integrated wireless and wireline network, so that the demand for mobility, bandwidth, reliability, security, and flexibility can be met [3–5]. The various wireless and wireline access technologies, based on their spectral band occupancy in the optical domain, can be grouped as baseband (BB), microwave subcarrier-based intermediate frequency (IF), and millimeter-wave (mm-wave) subcarrier-based RF transport over fiber. A generic integrated network incorporating such technologies is shown in Fig. 1. In the downlink direction, optically modulated composite wireless and wireline signals are transported from the central office (CO) to the remote access nodes (RANs), where the composite signal is divided and distributed to the antenna base stations (BSs) and the optical network units.
To enable aggregation of multiple-access technologies, simultaneous multiband modulation techniques focusing on the time division multiplexed passive optical network (TDM-PON) infrastructure have been proposed [6,7]. These techniques use one optical carrier to generate interdependent signals and require lossy optical splitters in the RANs to disseminate them to the ONUs and the BSs. They also require high-speed photodetectors (PDs) and narrowband electrical filters in all the BSs and ONUs, irrespective of the type of signal. Moreover, the performance of these methods has been limited by the optimum operating conditions as well as the nonlinear characteristics of the external modulators, which make the managing and controlling functionality quite difficult. In contrast, if the passive wavelength division multiplexing (WDM) devices (e.g., MUX, DEMUX, etc.) in the CO and RANs of a WDM-PON infrastructure can be enabled to support independent optical BB, IF, and RF signals together by avoiding interdependent multiband modulations and the associated complexities, an effective integrated optical access network will be able to be realized.

This investigation focuses on the challenges associated with aggregating and separating multiband wireless and wireline access technologies in a WDM-PON infrastructure. In this paper we address suitable multiplexing and demultiplexing schemes that enable efficient aggregation and separation of BB, IF, and RF signals in a WDM-PON infrastructure. We show that the proper selection of the input–output ports of an arrayed waveguide grating (AWG) can enable integration of dense wavelength division multiplexed (DWDM) multiband signals with a channel spacing of 12.5 GHz, although the mm-wave RF subcarrier is in the 40-GHz-band domain. In addition, the optimum selection of the input–output ports reduces the carrier-to-sideband ratios (CSRs) of the optical RF signals, which significantly enhance the performance of the links [8,9]. The paper is organized as follows. Section 2 introduces the hybrid wavelength-interleaving scheme that explains the principles of accommodating multiband access technologies simultaneously in a WDM-PON infrastructure. Section 3 explains an effective multiplexing scheme that helps realize the practical implementation of such a wavelength-interleaving scheme. The demonstration of this scheme is, however, discarded here, as it has already been reported in [10]. Section 4 proposes a novel demultiplexing scheme that effectively separates each of the interleaved signals in the RAN before they are distributed to the BSs and the ONUs. The proposed demultiplexing scheme is demonstrated experimentally in Section 5, which also includes the experimental results of the effects of optical cross talk from the neighboring signals. Finally, conclusions are given in Section 6.

2. Hybrid Wavelength-Interleaving Scheme

The coexistence of multiband wireless and wireline access technologies in a WDM-PON architecture largely depends on the effective WDM channel separation as well as the mm-wave RF subcarrier frequency. If the WDM channel separation $\Delta$ is larger than the mm-wave RF subcarrier $f_{RF}$ (i.e., $\Delta > f_{RF}$), the integration can be realized by applying standard multiplexing and demultiplexing technologies. However, if the
WDM channel separation is smaller than the mm-wave RF subcarrier (\(\Delta f < f_{RF}\)), standard multiplexing and demultiplexing technologies are no longer sufficient. To realize a dense WDM (DWDM) integrated access network with a channel separation smaller than the mm-wave RF subcarrier frequency, the spectral characteristics of an optically modulated mm-wave RF signal can be exploited, because the spectral band available between the optical carrier and the respective modulation sideband of an optically modulated RF signal often remains unused due to the lower data bandwidth capacity. If the unused spectral band of an optically modulated RF signal is partitioned as per the desired DWDM channel separation and the neighboring optically modulated BB and IF signals are interleaved in those partitioned positions, an integrated access network with such a DWDM channel separation can be realized. The underlying principle that determines the DWDM channel separation is the partitioned spectral band of the optically modulated RF signal, where the RF subcarrier is three times the integer multiple of the DWDM channel separation (\(f_{RF} = n \times 3\Delta f\), where \(n = 1, 2, 3, \ldots\), and \(\Delta f\) is the desired DWDM separation). Figure 2 shows the optical spectra that result with the proposed wavelength-interleaving scheme comprising

Fig. 2. Schematic depicting the optical spectra of the wavelength-interleaved multiband signals in an integrated WDM-PON with a DWDM channel spacing smaller than the mm-wave RF carrier frequency.

Fig. 3. Proposed H-MUX enabling multiplexing of multiband wavelength-interleaved signals in an integrated WDM-PON, which also reduces the CSR of the multiplexed RF signals through optical loop-backs.
Table 1. Input/Output Characteristic Matrix of a (4N+1)×(4N+1) AWG

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N channels of each of the optical RF [in optical single sideband with carrier (OSSB + C) modulation format], BB, and IF signals, with a DWDM channel separation, and a RF subcarrier frequency of Δf and 3Δf, respectively. The baseband signals BB₁, BB₂,..., BB₄ and the IF signals IF₁, IF₂,..., IF₄ are interleaved between the optical carriers C₁, C₂,..., C₄ and their respective modulation sidebands S₁, S₂,..., S₄ of the RF signals in such a way that, after interleaving, the adjacent DWDM channel spacing, irrespective of BB, IF, or RF signals, becomes Δf.

3. Proposed Hybrid Multiplexing Scheme

Figure 3 shows the schematic of a hybrid multiplexer (H-MUX) that realizes multiplexing of the wavelength interleaved signals shown in Fig. 2. It consists of a (4N + 1)×(4N + 1) AWG with a channel bandwidth of Δf and a channel spacing of Δf 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 + 1. The characteristic matrix of the AWG that governs the allocation and distribution of different channels at different ports is illustrated in Table 1. The optically modulated BB, IF, and RF signals (shown as insets of Fig. 3) enter the AWG via the input ports, A₂ to A₄₋₄, with the
input ports $A_5, A_9, A_{13}, \ldots, A_{N+1}$ left unused, as shown in Fig. 3. The AWG combines all the modulation sidebands $S_1, S_2, \ldots, S_N$ of the RF signals as well the baseband $BB_1, BB_2, \ldots, BB_N$ and intermediate frequency $IF_1, IF_2, \ldots, IF_N$ signals at the output port $B_1$. Due to the cyclic characteristics of the AWG as illustrated in Table 1, the optical carriers $C_1, C_2, \ldots, C_N$ of the RF signals also exit as a composite signal via the output port $B_4$. These composite carriers are then looped back to the AWG through the input port $A_1$ that redistributes the carriers $C_1, C_2, \ldots, C_N$ to the odd-numbered output ports $B_5, B_9, B_{13}, \ldots, B_{N+1}$, respectively. To realize the desired multiplexing, the distributed carriers are again looped back to the AWG via the unused input ports $A_5, A_9, A_{13}, \ldots, A_{N+1}$, and the resultant output at port $B_1$ comprises 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. 3. 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 with 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 $8–10$ dB [8,9], while mul-

Fig. 5. Experimental setup for the demonstration of the proposed H-DEMUX.

Fig. 6. Characteristic properties of the AWG: (a) the transmission profile before tuning the center frequency to transported channels, and (b) frequency drifts versus temperature curve.
tiplexing them with the BB and IF signals, leading to an integrated DWDM optical access network in WDM-PON infrastructures. The experimental demonstration of the scheme can be seen in [10].

4. Proposed Hybrid Demultiplexing Scheme

Figure 4 shows the schematic of the hybrid demultiplexer (H-DEMUX) that realizes demultiplexing of the multiplexed wavelength-interleaved signals shown in Fig. 2. It comprises a $4 \times 4$ AWG with a channel bandwidth of $\Delta f$ and a channel spacing of $\Delta f$ equal to the DWDM channel spacing of the interleaved multiband signals, similar to the AWG used for the proposed H-MUX. The input (A) and output (B) ports of the AWG are numbered from 1 to $4N$. The allocation and distribution of different channels to different ports can also be clarified by the matrix illustrated in Table 1. The multiplexed BB, IF, and RF signals, shown in the inset of Fig. 4, enter the AWG via the input port, A1. 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, B1 – B4 as per their respective positions in the interleaved spectrum. To realize demultiplexing for the RF signals, the distributed optical carriers $C_1, C_2, \ldots, C_N$ are looped back to the AWG via the input ports $A_4, A_8, \ldots, A_{4N}$, respectively, and the resultant outputs at ports $B_1, B_5, \ldots, B_{4N-3}$ are the optical carriers and the modulation sidebands of the RF signals demultiplexed together. Thus the proposed H-DEMUX successfully demultiplexes the multiband signals from an integrated DWDM network based on WDM-PON infrastructures. Similar to the H-MUX, the optical carriers of the demultiplexed RF signals are also suppressed by as much as the insertion loss of the AWG (typical IL = 4–5 dB) compared with the respective modulation sidebands through the loop-back paths. Therefore, the proposed H-DEMUX also
enhances the performance of the optical RF signals by reducing the CSRs by 4–5 dB, in addition to demultiplexing them from an integrated DWDM network in the access and metro domains.

5. Experimental Demonstration

Figure 5 shows the setup used to demonstrate the proposed H-DEMUX experimentally. Similar to the demonstration of the H-MUX reported in [10], three narrow linewidth-tunable light sources, LS1, LS2, and LS3, at the corresponding wavelengths of 1556.2, 1556.3, and 1556.4 nm followed by separate polarization controllers were used as the input to two low-speed (~5 GHz) Mach–Zehnder modulators (MZMs) and one high-speed (~40 GHz) dual-electrode Mach–Zehnder modulator (DE-MZM) to generate optical BB, IF, and RF signals, respectively. The optical BB signal was generated by using 1 Gbit/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 subcarrier signals were generated by mixing 155 Mbits/s pseudorandom binary sequence (PRBS) data with 2.5 and 37.5 GHz local oscillator (LO) signals, respectively, in binary-phase-shift-keyed (BPSK) format. The mixer outputs were then amplified before being applied to the respective modulators, as shown in Fig. 5. 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 the OSSB+C modulation format. The generated optical BB, IF, and RF signals were then multiplexed by using two 3 dB optical couplers (because another AWG with the required specifications was unavailable), the composite spectrum of which can be seen from the inset of Fig. 5. The composite spectrum the optical RF signal shows a CSR of 13 dB with a suppression of the unwanted modulation sidebands of almost 30 dB. The spectrum

![](image)

Fig. 8. Measured BER curves as a function of received optical power for (a) millimeter-wave (RF), (b) microwave (IF), and (c) baseband (BB) signals demultiplexed from the three wavelength-interleaved multiband signals after transmission over 10 km SMF with the back-to-back curves as the reference.
also indicates 12.5 GHz DWDM channel spacing (irrespective of carrier or sideband) while the RF carrier frequency is 37.5 GHz.

The interleaved multiband signals were amplified by an erbium-doped fiber amplifier (EDFA) and then filtered using a 4 nm optical bandpass filter (BPF) to minimize out-of-band asynchronous spontaneous emission (ASE) noise. The filtered signal was transported over 10 km of single-mode fiber (SMF) to the proposed wavelength-interleaved H-DEMUX, consisting of a commercially available 8×8 AWG. The AWG transmission profile was tuned to match the transported channels by increasing its operating temperature to 72 °C. The AWG transmission profile, before tuning the center frequency to the transported channels, is shown in Fig. 6(a), whereas the drift of the transmission profile with temperature is shown in Fig. 6(b). 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 multiband interleaving scheme. The drift of the transmission profile with the temperature curve shows the stability of the device within ±0.0048 nm/°C. The allocation of the input port and the selection of the loop-back path for the optical carrier of the RF signal are as shown in Fig. 5, which results in the desired demultiplexed RF, BB, and IF signals at output ports B1, B2, and B3, respectively.

Figures 7(a)–7(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 WDM-PON. The spectrum in Fig. 7(a) also indicates that the demultiplexing of the signals using such a H-DEMUX reduces the CSR of the demultiplexed RF signal from 13 to 8.4 dB.

To quantify the signal degradation in bit error ratio (BER), each of the demultiplexed signals was detected and the data recovered using suitable photodetection and data recovery circuits. Figures 8(a)–8(c) show the measured BER curves for the recovered signals for both the back-to-back case (having the H-DEMUX, but no fiber) and after transmission over 10 km of SMF. The results exhibit negligible power penalties.

Fig. 9. Measured BER curves, which quantify the effects of optical cross talk on the demultiplexed channels: (a) millimeter-wave (RF), (b) microwave (IF), and (c) baseband (BB) with BER curves of single-channel transmission as the reference.
of 0.15 to 0.4 dB at a BER of $10^{-9}$ that can be attributed to accumulated effects of experimental errors as well as unwanted fiber effects, such as reflections, chromatic dispersion, etc. The differences in sensitivities of the signals are due to the performance variations of the separate terminal devices used for each of the multiband signals.

The optical spectra in Figs. 7(a)–7(c) also show that the demultiplexed channels were contaminated by the neighboring channels with an optical cross-talk level of $-13$ to $-16$ dB, which is defined here as the ratio of the undesired optical carriers to the desired optical carriers at the demultiplexed channels. To quantify these effects, the BER curves for each of the demultiplexed channels were recovered under two different conditions: (i) with only the desired channel active and the neighboring channels removed and (ii) with all three channels active. The recovered BER curves can be seen in Figs. 9(a)–9(c). The measurements show that the demultiplexed channels have experienced a noticeable power penalty of 0.4 to 0.7 dB, which implies that optical cross talk may need to be addressed and managed when deploying such systems in practical networks. However, this could potentially be resolved by using improved AWG fabrication techniques.

6. Conclusion

We have proposed and demonstrated spectrally hybrid multiplexing and demultiplexing schemes that have the potential to integrate microwave and millimeter-wave frequency RoF signals in WDM-PON infrastructure. The proposed schemes are based on standard AWG technology and are suitable for any WDM-PON, irrespective of their topologies and architectures. The demonstrations presented in this paper use a 12.5 GHz channel-spaced AWG to aggregate and separate gigabit baseband and 2.5 GHz microwave signals to and from 40-GHz-band millimeter-wave signals. These schemes can be easily scaled to different millimeter-wave frequency bands (such as 60 GHz) or to different DWDM channel spacing (for example, 20 GHz) by simply selecting suitable AWG channel spacings and optimum loop-backs. Moreover, the schemes reduce the CSRs of the RF signals that enhance their transmission performance significantly.

References