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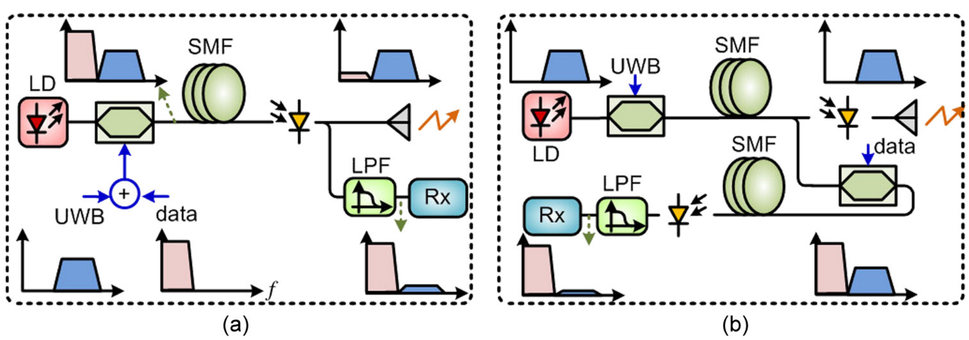

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Simultaneous Provision of UWB and Wired Services in a WDM-PON Network Using a Centralized Light Source

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Abstract: Simultaneous provision of multiple services using a centralized light source can greatly reduce the complexity and cost of a wavelength-division multiplexing passive optical network (WDM-PON). In this paper, we report two schemes to simultaneously provide an ultra-wideband (UWB) service and a wired service using a centralized light source. In one scheme, a UWB signal and a wired signal are multiplexed and modulated on a single wavelength in the center office for wireless and wired downstream services. In the other scheme, the wavelength from a UWB downstream signal is reused in the optical network unit to provide a wired upstream service. Both schemes are experimentally demonstrated with the data-transmission performance evaluated by measuring the electrical spectra, eye diagrams, and receiver sensitivities. The proposed schemes would greatly reduce the cost while significantly improving the spectrum efficiency of a WDM-PON network incorporating UWB-over-fiber (UWBoF) systems for broadband wireless access, making the WDM-PON network more attractive for practical deployment.

Index Terms: Ultra-wideband (UWB), wavelength reuse, radio over fiber, wavelength-division multiplexing (WDM), passive optical network (PON), microwave photonics.

1. Introduction

Future wireless local area networks (WLANs) and wireless personal-area networks (WPANs) would have features such as low complexity, low cost, low power consumption, and high data-rate connectivity. Ultra-wideband (UWB), which shares the spectrum resources with existing radio communications systems, is recognized as a promising solution to meet these requirements. Due to the low power spectral density regulated by the Federal Communications Commission (FCC), the typical communication distance of a UWB wireless system is limited to only a few meters to tens of meters. To increase the area of coverage and to offer the availability of undisrupted service across different networks, UWB-over-fiber (UWBoF) technology has been proposed [1]. Different UWBoF schemes have been reported recently [2]–[9]. To practically deploy UWBoF systems at a low cost, a solution is to integrate them into the current or future wired optical access networks [4], [5].

Concerning the wired optical access networks, there is a worldwide consensus that the current time-division multiple-access (TDMA) passive optical network (PON) (i.e., Ethernet PON and Gigabit PON) would evolve toward wavelength-division multiplexing PON (WDM-PON), because the TDMA-PONs cannot keep up with the requirements of future access network evolution regarding aggregated bandwidth, attainable reach, and an allowable power budget [10], [11]. However, the

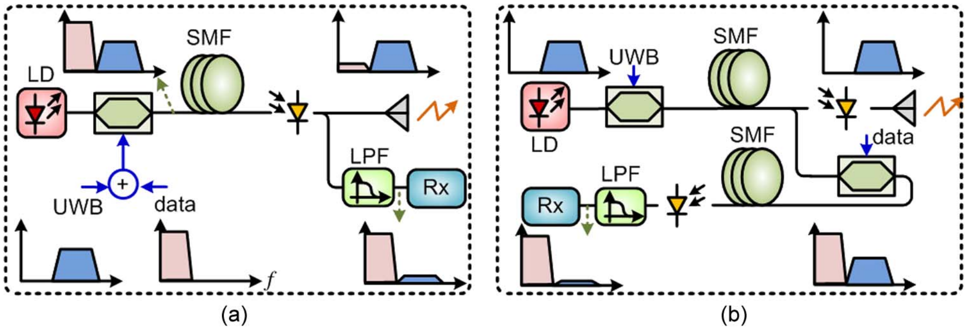

Fig. 1. Schematic diagrams of the proposed optical links with (a) signal multiplexing in the center office with wired and UWB downstream signals sharing a single wavelength and (b) wavelength reuse in an ONU with a wired upstream signal reusing the wavelength from the downstream signal. LD: laser diode; LPF: low-pass filter, ONU: optical network unit.

high cost of frequency-stable light sources and wavelength-selective optical components renders WDM-PON not yet competitive with other optical access network solutions. To reduce the cost, it is essential to simultaneously provide multiple services using signal-multiplexing or wavelength-reuse technologies based on a centralized light source. Several approaches have been reported recently, in which the optical carrier of a downstream signal was reused by remodulating it with an upstream signal [11]. To avoid interferences between the downstream and the upstream signals, the modulation format for the downstream signal is restricted to phase-shift keying (PSK), which needs special receivers in the optical network units (ONUs), hence greatly increasing the cost of the entire network. In addition, the modulation format for the upstream signal has to be on-off keying (OOK) only, which may again limit the network performance. To avoid the above limitations, one may reuse a wavelength by injecting a downstream signal into a gain-saturated reflective semiconductor optical amplifier (RSOA), but the extinction ratio (ER) of the downstream signal has to be low [12].

In this paper, we propose and demonstrate, for the first time to the best of our knowledge, two schemes that will simultaneously provide a UWB service and a wired service using a centralized light source. In the first scheme, a UWB signal and a wired signal are simultaneously modulated on a single wavelength in the center office for wireless and wired downstream services. In the second scheme, the wavelength from the downstream signal is reused in an ONU to provide a wired upstream service. For both schemes, since the spectrum of the UWB signal and that of the wired signal are located at different frequency bands, the modulation of the two signals on a single wavelength would produce no interference. In addition, it is different from the previous techniques for wavelength reuse in that there are no restrictions on the modulation format or the ER for the wired and wireless signals. These features make it possible to integrate seamlessly a UWBoF system into a WDM-PON network using centralized light sources. An experiment is performed. Signal multiplexing and wavelength reuse are experimentally verified. Error-free transmission of a UWB downstream signal and a wired downstream or upstream signal over 36-km single-mode fiber (SMF) is achieved.

2. Principle

Fig. 1 shows the schematic diagrams in which signal multiplexing and wavelength reuse schemes are employed. The signal multiplexing is performed in the center office to provide UWB and wired downstream services, as shown in Fig. 1(a), and the wavelength reuse is implemented in an ONU to provide a wired upstream service in a UWBoF system, as shown in Fig. 1(b).

For the case when the signal multiplexing is performed in the center office, an electrical UWB signal and an electrical wired signal are combined at an electrical power combiner and then modulated on a single wavelength at a $LiNbO_3$ Mach-Zehnder modulator (MZM). The wired signal should have a spectrum in the range of 0–3.1 GHz. Since a UWB signal based on the requirement regulated by the FCC would have a spectrum in the range of 3.1–10.6 GHz, the two signals could coexist without spectral overlap. The optical signal at the output of the MZM is then transmitted through a length of SMF to an ONU, where the optical signal is first detected by a photodetector (PD) and then split into two paths. In one path, the electrical signal is sent to a UWB antenna. Since the UWB antenna has a spectral response with a 10-dB passband covering a range of 3.1–10.6 GHz, it can be used to act as a bandpass filter to block the wired signal. A UWBoF link is thus established. In the other path, the UWB signal is filtered out by a low-pass filter with a cutoff frequency of 3.1 GHz, and only the wired signal is obtained. As a result, an optical link for the wired signal transmission is implemented.

For the case when the wavelength reuse is performed in an ONU, the light wave from a laser diode in the center office is modulated at a $LiNbO_3$ MZM by an electrical UWB signal, which is delivered to an ONU by a length of SMF. In the ONU, a portion of the optical signal is sent to a PD and then radiated to free space via a UWB antenna. A UWB downstream service is thus realized. The other portion of the optical signal is sent to a second $LiNbO_3$ MZM at the ONU, which is modulated by a wired upstream signal. After transmission over a length of SMF, the upstream signal is then selected by a low-pass filter and received at the center office, and a wired upstream service is established. Note that to avoid spectral overlapping with the downstream UWB signal, the data rate of the upstream signal should be controlled to ensure that the spectrum of the upstream signal is within 0–3.1 GHz. It is well known that a bidirectional optical network based on a single wavelength would suffer severely from the presence of Rayleigh scattering crosstalk, and this crosstalk can be mitigated by broadening the spectrum of the optical signal. In the proposed scheme, the residual UWB downstream signal would broaden the optical spectrum of the upstream signal and thus can reduce the signal degradation from the Rayleigh scattering crosstalk. This feature is highly desirable for a bidirectional UWBoF and WDM-PON converged network.

3. Experimental Setup and Results

An experiment based on the experimental setup shown in Fig. 1 is performed to validate the two schemes for signal multiplexing and wavelength reuse.

In the first scheme, the light wave from a laser diode is modulated at a 20-GHz $LiNbO_3$ MZM by an electrical UWB/wired combined signal. The electrical UWB signal is a 1-GHz monocycle pulse train coded with a $2^{15}-1$ PRBS pattern, generated by an arbitrary wave generator (AWG, Tektronix AWG7102), and the electrical wired signal is a 1.25-Gb/s pseudorandom bit sequence (PRBS) with a word length of $2^{31}-1$ generated by a bit error rate tester (BERT: Agilent 4901B). A SMF with a length of 36 km is used to distribute the optical UWB/wired signal to the remote site. At the remote site, the optical signal is sent to a 45-GHz PD. The converted signal that consists of a UWB signal and a wired signal is split into two portions. One portion of the signal is emitted to free space through a UWB omni-directional antenna (Skycross SMT-3TO10M-A). Due to the bandpass nature of the UWB antenna, the wired signal is filtered out by the antenna, and only the UWB signal is collected by another antenna at the UWB receiver. The UWB antenna pair has a 10-dB bandwidth of about 8.35 GHz (2.25–10.6 GHz). The other portion of the signal is sent to a low-pass filter with a cutoff frequency of 1.2 GHz to remove the UWB signal. The remaining wired baseband signal is then introduced to a 1.25-Gb/s non-return-to-zero (NRZ) signal receiver to evaluate the bit-error-rate (BER) performance.

To evaluate the BER performance of a UWBoF system, a correlation receiver should be employed. Since the correlation receiver is currently unavailable, in this work, a UWB receiver that has a similar structure as that in [7] is constructed. The UWB signal at the output of the receiver antenna is amplified by a wideband electrical amplifier (EA, 25-dB gain) and is then mixed at an electrical mixer with a local oscillator (LO) signal at 3, 4, 5, or 6 GHz, followed by a low-pass filter. This operation is equivalent to frequency down-conversion to convert the UWB signal to the baseband. Since the majority of power of the UWB signal is at around 3, 4, 5, and 6 GHz, the BER performance of these down-converted signals would reveal the transmission performance of the UWBoF system. This method, however, cannot be used to evaluate the performance of a UWB

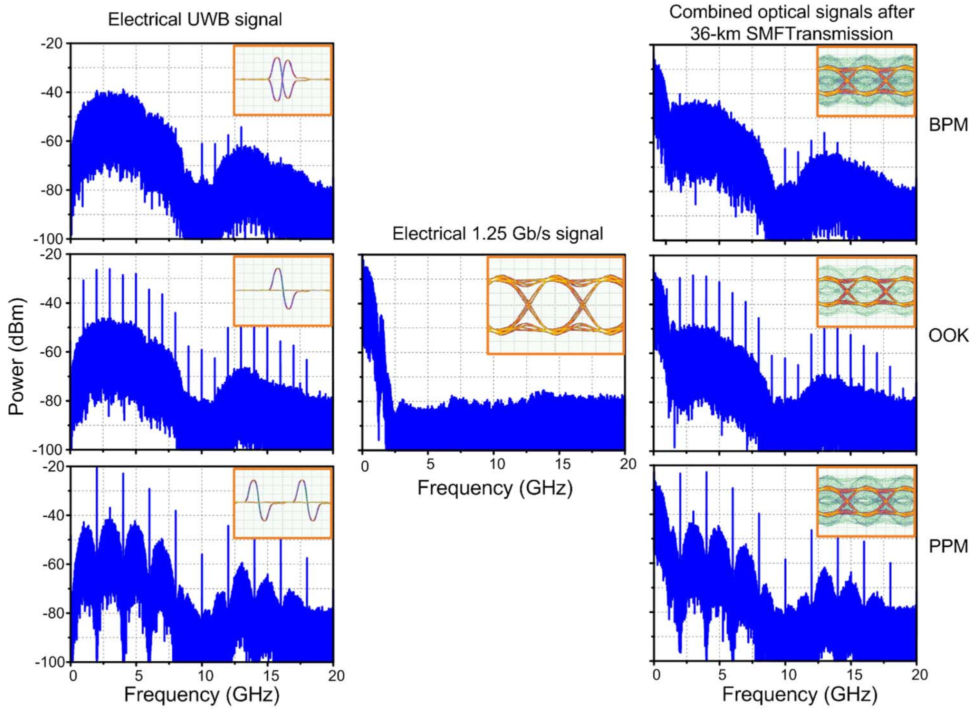

Fig. 2. Electrical spectra and eye diagrams of the 1-Gb/s electrical UWB signals with OOK, BPM, and PPM, the electrical 1.25-Gb/s wired signal, and the combined optical signals.

signal with pulse position modulation (PPM) since a time-varied signal would cause synchronization problems to the BERT.

In the second scheme, a 1-Gb/s electrical UWB signal from the AWG is converted to an optical signal at a 20-GHz MZM in the center office and then transmitted to an ONU through a 36-km SMF. In the ONU, a portion of the optical signal is sent to a PD followed by a UWB transceiver described above for UWB services. The other portion is directly modulated at a 10-GHz $LiNbO_3$ MZM by a 2.5-Gb/s PRBS with a word length of $2^{31}-1$. The signal from the output of the MZM is then sent back to the center office via a 36-km SMF, which is converted to an electrical signal at a second PD, filtered by a 2.5-GHz low-pass filter, and received by a 2.5-Gb/s NRZ signal receiver.

The waveforms (or eye diagrams) are observed by a high-speed sampling oscilloscope (Agilent 86116A), and the spectra are measured by an electrical spectrum analyzer (Agilent E4448A).

Figs. 2 and 3 show the experimental results for the signal multiplexing scheme shown in Fig. 1(a). A 1-Gb/s electrical UWB signal with bi-phase modulation (BPM), OOK, or PPM and a 1.25-Gb/s electrical NRZ signal are combined at the electrical power combiner. To prevent the high-order sidebands of the NRZ signal from interfering with the UWB signal, the NRZ signal is filtered by a 1.2-GHz low-pass filter. Since the electrical UWB signal is based on monocycle pulses, some spectral components in the range of 0-1.25 GHz are observed, but the total power of the UWB signal in this region is more than 20 dB lower than that of the NRZ wired signal; therefore, the interference with the wired signal is small and is negligible. The combined signal is converted into an optical signal at the MZM. From the electrical spectrum of the combined optical signal, we can see that the UWB signal and the wired signal coexist with negligible overlap in spectrum, as shown in Fig. 2. In the remote site, the optical signal is detected by the PD and then divided into two paths. In one path, the converted signal is sent to the UWB antenna. Since the antenna has a bandpass spectral response, the signal power in the range of 0–1.25 GHz is eliminated by the UWB antenna, as shown in Fig. 3. At the same time, the pulse shape after the antenna is also changed from a monocycle to a doublet. The FCC-specified indoor spectral mask is also plotted in Fig. 3. It can be seen that the UWB signals fit the

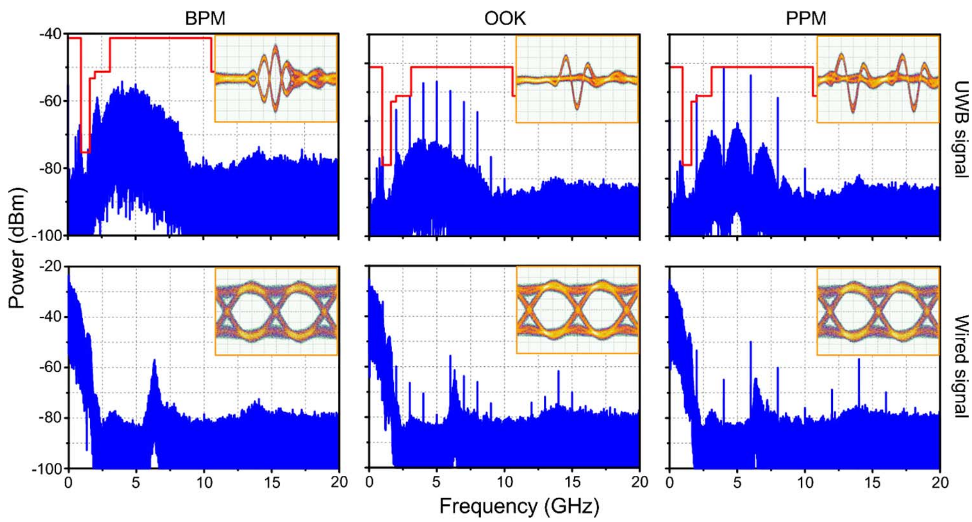

Fig. 3. Electrical spectra and eye diagrams of the received UWB signal and the wired signal when the downstream UWB signal is with BPM, OOK, and PPM.

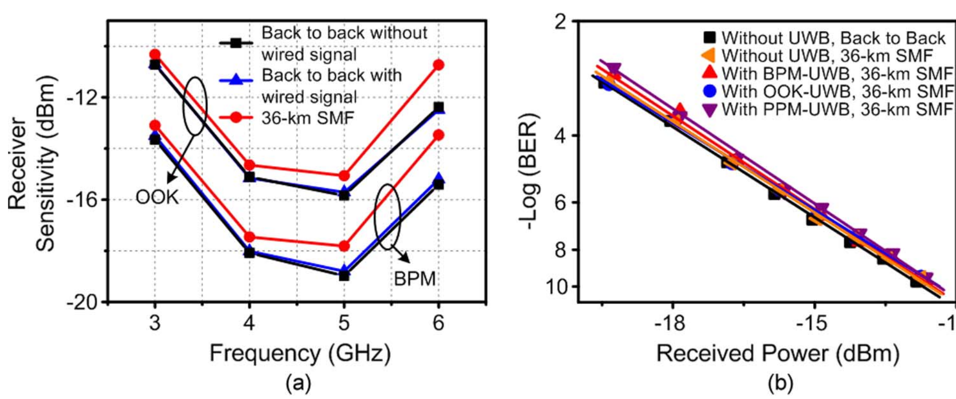

Fig. 4. (a) Receiver sensitivities for the transmission of the UWB signal with BPM and OOK and (b) BER measurements for the transmission of the wired signal.

FCC-specified spectral mask very well. In the other path, the UWB signals are removed by the low-pass filter. As can be seen from Fig. 3, the eyes of the NRZ signals are widely opened, which confirms that the continuous part of the spectra of the UWB signals in the range of 0–1.25 GHz has negligible influence on the NRZ signals. Fig. 4(a) shows the receiver sensitivities of the UWB signals with OOK and BPM. The receiver sensitivity is defined as the optical power required to ensure a bit error rate of 10^{-9} at the UWB receiver. As can be seen from Fig. 4(a), the UWB signal with BPM has a 2.8-dB receiver sensitivity improvement, as compared with the UWB signal with OOK. Without and with the wired signal, the receiver sensitivities for both signals are almost the same, which confirms that the 1.25-Gb/s wired signal has no influence on the UWB signal. After 36-km SMF transmission, an error-free operation is still achieved. The power penalty is less than 1.8 dB. The BER measurements for the wired signal are shown in Fig. 4(b). The wired signal in the case with a UWB signal has a power penalty of less than 0.2 dB as compared with that without a UWB signal. Since both the UWB signal and the wired signal achieve an error-free operation after 36-km SMF transmission, the feasibility of the signal multiplexing is confirmed.

The wavelength reuse scheme shown in Fig. 1(b) is also investigated. In this scheme, only a UWB signal is distributed in the downstream links. Thus, the UWBoF link will not be affected by the wired signal. As a result, we only investigate the performance of the system for the transmission of

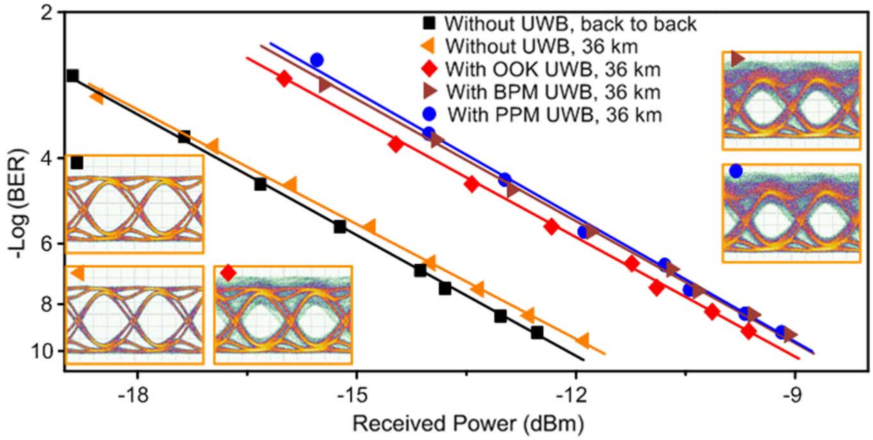

Fig. 5. BER measurements of the wired upstream signal with and without a UWB signal. Insets: Eye diagrams of the upstream signal with and without a UWB signal.

the wired upstream signal. Fig. 5 shows the BER measurements of the wired upstream signal for three different modulation schemes. Since the data rate of the wired signal is 2.5 Gb/s, and the UWB signals based on monocycle pulses have considerable spectral components in the range of 0–2.5 GHz, the existence of the UWB signal in the downstream link leads to a power penalty of more than 3 dB to the wired signal. If a UWB signal with a spectrum that strictly fits the FCC-specified spectral mask is used, the power penalty would be greatly reduced. Because the discrete lines existing in the spectrum of the UWB signal contain no data information, the interference is mainly from the continuous spectral part. As can be seen from Fig. 2, the UWB signal with OOK has the smallest continuous part in 0–2.5 GHz. Thus, for the case when the UWB signal with OOK is applied in the downstream link, the wired signal has a receiver sensitivity of about 0.5 dB better than that when the UWB signal with BPM or PPM is applied. For all the cases, the eyes of the received NRZ signals are wide opened, and error-free operations are achieved, demonstrating the successful wavelength reuse in the UWBoF system.

4. Conclusion

In conclusion, two schemes for signal multiplexing or wavelength reuse in a UWBoF system were proposed and experimentally demonstrated. The signal multiplexing was performed in the center office to provide an additional wired downstream service and the wavelength reuse was implemented in the remote site to provide a wired upstream service. When the signal multiplexing was performed in the center office, a 1-Gb/s UWB signal with BPM, OOK, or PPM and a 1.25-Gb/s wired signal could be cotransmitted over a single fiber, and negligible interference was observed. When the wavelength reuse was implemented in the ONU, the existence of a 1-Gb/s UWB signal would introduce a 3-dB power penalty to the 2.5-Gb/s wired upstream signal, but error-free operations were still maintained. The feasibility of the proposed technique was also confirmed by electrical spectra and eye diagram measurements. The proposed schemes would reduce greatly the cost while improving significantly the spectrum efficiency of a WDM-PON network incorporating UWBoF systems for broadband wireless access, making the WDM-PON network more attractive for practical deployment.

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