Provision of IR-UWB wireless and baseband wired services over a WDM-PON

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Abstract: A simple scheme to simultaneously generate an on-off keying or bi-phase modulation (BPM) impulse radio ultra wideband (IR-UWB) signal and a baseband wired signal in the optical domain using a dual-drive modulator is proposed and demonstrated. Although the two signals have spectral overlap in the optical spectrum, they are located at different frequency bands when converted to electrical signals at a photodetector (PD), which can be well separated by an electrical filter. An experiment is carried out. Eye diagrams, electrical spectra and BER measurements show that the co-channel interference between the UWB and the wired signals is small for a single-channel 36-km fiber link to provide 1.25-Gb/s UWB wireless and 1.25-Gb/s baseband wired services. The inter-channel interference is also small and negligible when the link is operated together with two other 1.25 Gb/s baseband wired links, which demonstrates that a conventional WDM-PON can be upgraded to provide additional UWB services without affecting the existing services by modifying the modulators in the center office and inserting UWB antennas in the optical network units.

OCIS codes: (060.2330) Fiber optics communications; (060.4510) Optical communications.

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1. Introduction

Recently, wavelength-division multiplexed passive optical networks (WDM-PONs) have drawn considerable interest because of their advantages in terms of capacity, scalability, service transparency, and enhanced security. For future WDM-PONs, the ability to provide services to both wired and mobile users is needed [1]. Previously, several proposals were reported to distribute ultrawideband (UWB) signals over WDM-PONs since UWB is a power-saving technology to provide high data-rate wireless services for the future wireless local area networks (WLANs) and wireless personal-area networks (WPANs) [2–7]. Prince *et al.* demonstrated that a UWB service can be provided in a WDM-PON network [3], but the UWB service is provided at the cost of sacrificing the wired service in the same wavelength channel. We have proposed a UWB over fiber (UWBoF) system that is compatible with WDM-PON architecture using a Fabry-Perot laser diode, which is served as a multiwavelength UWB pulse shaper in the center office or alternately work as a pulse shaper for the downstream signal and a signal generator for the upstream signal [4]. But again, the system can only provide wireless service.

Recently, we have demonstrated an optical system that can simultaneously provide UWB wireless and baseband wired services using a centralized light source [5]. This system might reduce greatly the cost while improving significantly the spectrum efficiency of a WDM-PON network incorporating UWBoF systems for broadband wireless access. The idea was further developed by Pham et al. to simultaneously provide gigabit baseband service and gigabit IR-UWB service on a single wavelength [6, 7]. In [5], the UWB signals are generated in the electrical domain, and double-sideband (DSB) modulation is used to convert the UWB signal from the electrical domain to the optical domain. The UWB signal (3.1-10.6 GHz) and the wired signal (DC-3.1 GHz) are well separated due to the spectral nature of the UWB and wired signals. To avoid performing large bandwidth electrical to optical conversion, it would be highly desirable that the UWB signal is generated directly in the optical domain [2].

In this paper, we propose and demonstrate a novel system to provide impulse radio (IR) UWB wireless services in a WDM-PON without affecting the existing wired services. In each wavelength channel of the system, a dual-drive Mach-Zehnder modulator (MZM) placed at the center office is used to simultaneously shape an electrical return-to-zero (RZ) or dark RZ signal to an optical UWB signal and convert an electrical non-return-to-zero (NRZ) signal to an optical wired signal. An analysis of the system is performed. Although the two signals have spectral overlap in the optical spectrum, they are located at different frequency bands when converted to electrical signals at a photodetector (PD) in the optical network unit (ONU), which can still be separated by an electrical filter. Therefore, the optically generated UWB signal and the wired signal can be used to provide wireless and wired services on a single wavelength in the proposed network. A proof-of-concept experiment is also carried out. Optical UWB signals with on-off keying (OOK) and bi-phase modulation (BPM) are successfully generated and distributed in the WDM-PON. Eye diagram and bit error rate (BER) measurement shows that the interference between the UWB and wired signals is very small, which has negligible impact on the system performance.

2. Principle

2.1 Simultaneous Generation of an Optical UWB Signal and an Optical Wired Signal Using a Dual- Drive MZM

Fig. 1(a) shows the proposed scheme for the simultaneous generation of an optical UWB signal and an optical wired signal. A light wave from a laser source is fiber coupled to a dual-drive MZM. An electrical RZ or dark RZ signal is split into two equal parts. One part together with an electrical NRZ signal is introduced to one RF port of the dual-drive MZM. The other part is lead to the other port of the MZM via an electrical delay line.

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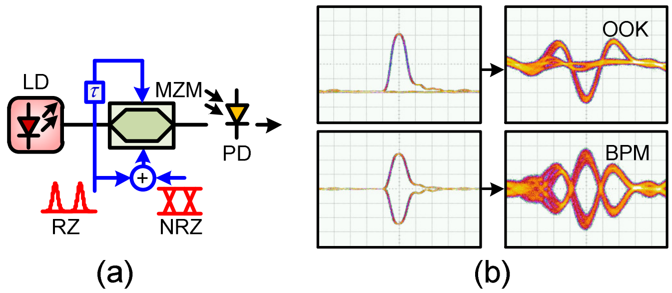

Fig. 1. (a) The proposed scheme for the simultaneous generation of optical UWB signal and optical wired signal. (b) The generation of UWB signals with different modulation formats. LD: laser diode; MZM: Mach-Zehnder modulator; PD: photodetector; RZ: return-to-zero; NRZ: non-return-to-zero; OOK: on-off keying; BPM: bi-phase modulation.

Assume the electrical drive signals applied to the dual-drive MZM via the two ports are $v_1(t) = V_0 \cdot r(t) + V_1 \cdot z(t)$ and $v_2(t) = V_0 \cdot r(t + \tau)$, where $r(t)$ is the normalized RZ or dark RZ signal, $z(t)$ is the normalized NRZ signal, V_0 and V_1 are the amplitudes of the two signals, and τ is the time delay introduced by the electrical delay line. With an optical field of $e_i(t) = \exp(j\omega_c t)$ injected, where ω_c is the angular frequency of the optical carrier, the output optical field can be expressed as [8]

$$e_o(t) = \frac{\sqrt{2}e_i(t)}{2}\left[\exp\left(j\kappa_1 r(t) + j\kappa_2 z(t) + j\frac{\pi}{2}\right) + \exp\left(j\kappa_1 r(t+\tau)\right)\right] \quad (1)$$

where $\kappa_1 = \pi V_0/V_\pi$ and $\kappa_2 = \pi V_0/V_\pi$ are the phase modulation indices, V_π is the half-wave voltage of the MZM. In writing Eq. (1), the MZM is assumed to be biased at the quadrature transmission point.

To shape the RZ or dark RZ signal to a UWB signal and to avoid the nonlinear distortion in the MZM, small-signal modulation ($\kappa_1, \kappa_2 \le \pi/6$) is assumed. Applying the small-signal modulation assumption and converting Eq. (1) to the frequency domain, we have

$$E(\omega) = 2\pi(1+j)\delta(\omega-\omega_c) + \frac{\kappa_1}{2}\left[je^{-j(\omega-\omega_c)\tau} - 1\right]\cdot R(\omega-\omega_c) - \kappa_2 Z(\omega-\omega_c) \quad (2)$$

where $R(\omega) = \tilde{\mathcal{F}}\{r(t)\}$ and $Z(\omega) = \tilde{\mathcal{F}}\{z(t)\}$ are the Fourier transforms of the input RZ or dark RZ signal and NRZ signal, respectively. Since both $R(\omega)$ and $Z(\omega)$ would have large spectral components around the optical carrier, the two signals would have spectral overlap in the optical spectrum.

On the other hand, if the optical signal expressed in Eq. (1) is sent to a PD for square-law detection, we have the photocurrent given by

$$i(t) \propto |e_o(t)|^2 \approx 2 - 2\sin\{\kappa_1[r(t) - r(t+\tau)]\}\cos[\kappa_2 z(t)] - 2\cos\{\kappa_1[r(t) - r(t+\tau)]\}\sin[\kappa_2 z(t)] \quad (3)$$

Applying again the small-signal modulation assumption, Eq. (3) can be rewritten as

$$i(t) \propto 1 - \kappa_1[r(t) - r(t+\tau)] - \kappa_2 z(t) \quad (4)$$

If τ is sufficiently small, $r(t)$-$r(t + \tau)$ can be approximated as the first-order derivative. As a result, if 1s in $r(t)$ are represented by a Gaussian-like pulse, and 0s are represented by DC, the system can shape the signal to a UWB signal with OOK format [2]. In addition, if 0s in $r(t)$ are represented by a dark pulse other than DC, the signal will be converted to a UWB signal with BPM format, as shown in Fig. 1(b). Since the UWB signal, based on the

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requirement regulated by the FCC, would have a spectrum in the range of 3.1-10.6 GHz, if the NRZ wired signal is controlled to have a spectrum in the range of 0-3.1 GHz, the two signals has no spectral overlap in the electrical spectrum, which could be separated by an electrical filter in the receiver site.

It should be noted that Eq. (4) is no longer valid if large signal modulation is assumed. An analysis on the impact of large signal modulation on the system performance was reported in [9].

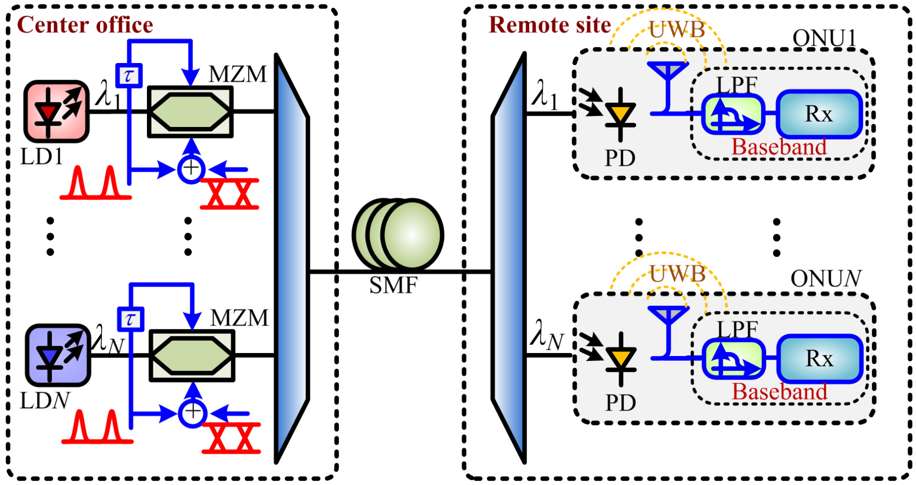

Fig. 2. Schematic diagram of the proposed UWB over WDM-PON system. LPF: lowpass filter; Amp: electrical amplifier; Rx: receiver; ONU: optical network unit; SMF: single-mode fiber; LO: local oscillator.

2.2 UWB over WDM-PON Architecture

Based on the above principle, a UWB over WDM-PON system can be constructed to provide both UWB wireless and baseband wired services. Fig. 2 shows the schematic of the proposed UWB over WDM-PON system. The optical UWB wireless and baseband wired signals generated by the dual-drive MZMs in the center office are multiplexed via a wavelength-division multiplexer. After transmission over a length of single-mode fiber (SMF), they are demultiplexed and sent to different optical network units (ONUs). In each ONU, the optical signal is sent to a PD. The converted signal that consists of a UWB signal and a wired signal is split into two portions. One portion is directly emitted to the free space through a UWB antenna. Due to the bandpass nature of the UWB antenna, the wired signal is filtered out by the antenna. Thus, the UWB wireless service is provided. The other portion of the signal is sent to a lowpass filter to filter out the UWB signal. The remaining wired baseband signal is then received by a NRZ receiver, and the baseband wired service is thus provided.

The key advantage of the proposed system is that both the UWB and wired services are provided in a wavelength channel using a centralized light source. The network can be simply upgraded from a conventional WDM-PON to provide simultaneously two services by modifying the modulators in the center office and inserting UWB antennas in the ONUs. Since the presence of the UWB services does not involve any wavelength selective devices, the technique to implement wavelength-independent ONUs based on reflected semiconductor optical amplifiers (RSOAs) can also be applied in the proposed architecture to provide upstream services [1].

2.3 UWB Receiver

To study the transmission performance of the UWB signals, the electrical spectra and eye diagrams would provide insufficient information, and a bit-error-rate measurement is highly desirable. Since a correlation receiver covering the full range of 3.1-10.6 GHz is currently not

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available, an indirect BER measurement technique should be applied. Previously, Abtahi *et al.* reported a technique to convert the UWB signal to a RZ signal using an optical full or half wave rectifier based on MZMs or electroabsorption modulators (EAMs) [10]. BER performance is obtained by measuring the BER of the RZ signal. However, a reference optical rectangular pulse synchronized to the UWB pulse generator is required, making the method complex. Recently, Gibbon *et al.* proposed a method to convert the analog UWB signal to a digital signal and then calculate the BER using a digital signal processor (DSP) by bit-for-bit comparison between the transmitted and received bits [11]. This method is flexible but requires broadband and high resolution analog-to-digital converters (ADCs). In addition, due to the limited sequence length that can be stored in the memories, it is very hard to measure a BER smaller than 1×10^{-5}.

To overcome the above problem, we propose another indirect method to evaluate the transmission performance of the UWB signals. Generally, when observed in the spectral domain, a pulse train comprises a series of discrete spectral components whose frequencies are an integer times of the repetition rate. The modulation of a signal on the pulse train results in two sidebands around all the discrete spectral components [12]. Therefore, one can down-convert the signal from these center frequencies to see if the information around these frequencies is degraded. If an error-free operation is achieved for the signals around all the spectral components, we can conclude that the information carried by the pulse train can be fully recovered in the receiver. Since IR-UWB is a type of pulse communication, the performance of the system can also be evaluated by down-converting the UWB signals from each frequency that is an integer times the repetition rate. Based on the above principle, a UWB receiver can be implemented by a UWB antenna, a low-noise amplifier, a mixer and a tunable microwave source. The UWB signal is collected by the UWB antenna, and then amplified by the low-noise electrical amplifier. The amplified signal is mixed at the electrical mixer with a local oscillator (LO) signal having a frequency that is an integer times the repetition rate, followed by a lowpass filter. This operation is equivalent to performing frequency down-conversion, to convert the UWB signal to the baseband. By measuring the BER of the resulted signal from the transmitted and received UWB signals at all the center frequencies in the range of 3.1-10.6 GHz, the transmission performance of the UWB signal can be obtained.

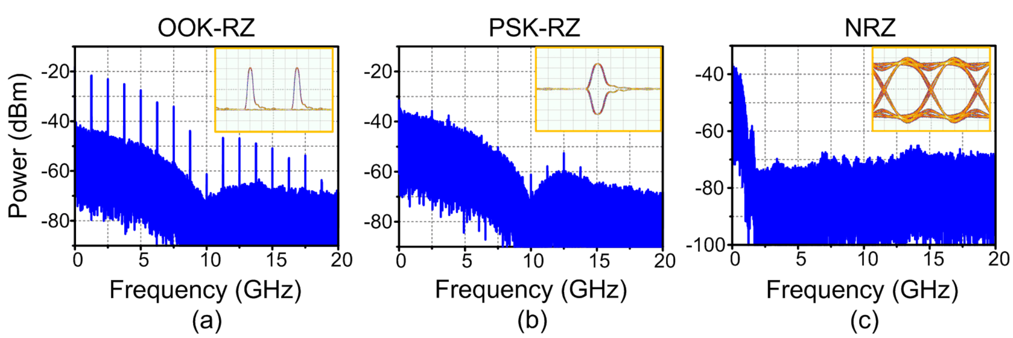

Fig. 3. Eye diagrams and electrical spectra of the electrical drive (a) RZ and (b) dark RZ signals and (c) NRZ signals. RBW = 1 MHz.

3. Experimental demonstration

3.1 Experimental setup

One key consideration of the system is that the introduction of the UWB service should not affect the provision of the wired service in the same channel and in other channels. To evaluate the interference between the UWB and co-channel or inter-channel wired signals, an experiment based on the setup shown in Fig. 2 is performed. Three channels at wavelengths of 1544.91, 1545.72 and 1546.53 nm are employed. In the 1544.91-nm channel, the light

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wave is sent to a 10-GHz $LiNbO_3$ dual-drive MZM. A 1.25-Gb/s electrical RZ or dark RZ pseudo random bit sequence (PRBS) with a word length of 2^{15}-1 and a duty cycle of about 1/8, generated by an arbitrary wave generator (AWG, Tektronix AWG7102) is split into two parts. One part together with a 1.25-Gb/s electrical NRZ PRBS with a word length of 2^{31}-1 generated by a bit-error-rate tester (BERT, Agilent 4901B) is applied to the MZM via one of the two RF ports. The other part of the RZ or dark RZ signal is delayed by ~20 ps and then applied to the other RF port of the MZM. To prevent the high-order sidebands of the NRZ signal from interfering with the generated UWB signal, the NRZ signal is filtered by a 1.2-GHz lowpass filter. The eye diagrams and electrical spectra of the electrical RZ or dark RZ and NRZ signals are shown in Fig. 3. In the 1554.72- and 1546.53-nm channels, only the 1.25 Gb/s optical NRZ signals are generated. The length of the SMF used to distribute the optical signals is 36 km. In the ONUs, the 10-dB bandwidth of the UWB antenna (Skycross SMT-3TO10M-A) is 8.35 GHz (2.25-10.6 GHz) and the lowpass electrical filter has a cut-off frequency of 1.2 GHz. To evaluate the BER performance of the UWBoF system, a UWB receiver is constructed. The wideband electrical amplifier can provide a flat gain of 25 dB from DC to 12.5 GHz, the electrical mixer supports operation in the frequency range of 2-18 GHz, the local oscillator (LO) generates a microwave signal with a frequency of 3.75, 5 or 6.25 GHz, and the lowpass filter has a cut-off frequency of 1.2 GHz.

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).

3.2 Single Channel Operation

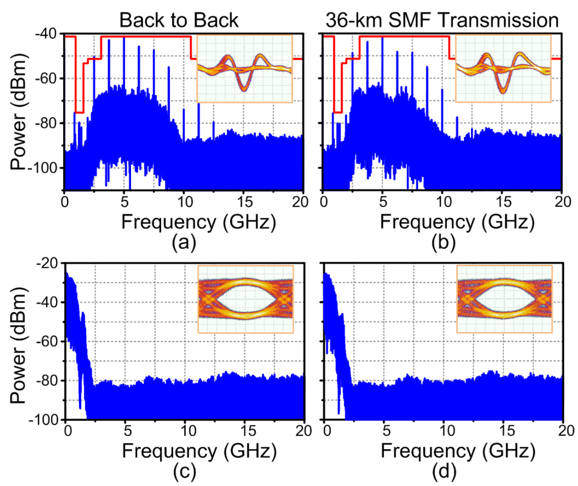

Fig. 4. Eye diagrams and electrical spectra of the received signals in the remote site when a single input signal is introduced to the MZM. (a), (b) The RZ signal is enabled; (c), (d) the NRZ signal is enabled. RBW = 1 MHz.

To evaluate the impact of the interference between the UWB and the wired signals in the same channel on the system performance, only the 1544.91-nm channel is enabled.

Fig. 4 shows the eye diagrams and electrical spectra of the received signals when either the RZ signal or the NRZ signal is introduced to the MZM. When the RZ signal is enabled, a UWB signal that has a spectrum fitting the FCC-specified spectral mask is obtained at the UWB receiver. The optical UWB signal is transmitted over a 36-km SMF. The eye diagram of the received UWB signal does not show any evident distortion. Because the optical UWB signal generated by the dual-drive MZM is chirped [8], the phase variation in the UWB pulses would be converted into intensity variation in the optical fiber. As a result, the high frequency components of the UWB signal are enhanced, as shown in Fig. 4(b). When the NRZ signal is enabled, an eye diagram with a widely opened eye is obtained at the remote site. The eye

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diagram and electrical spectrum of the signal after 36-km SMF transmission are almost the same as those without fiber transmission.

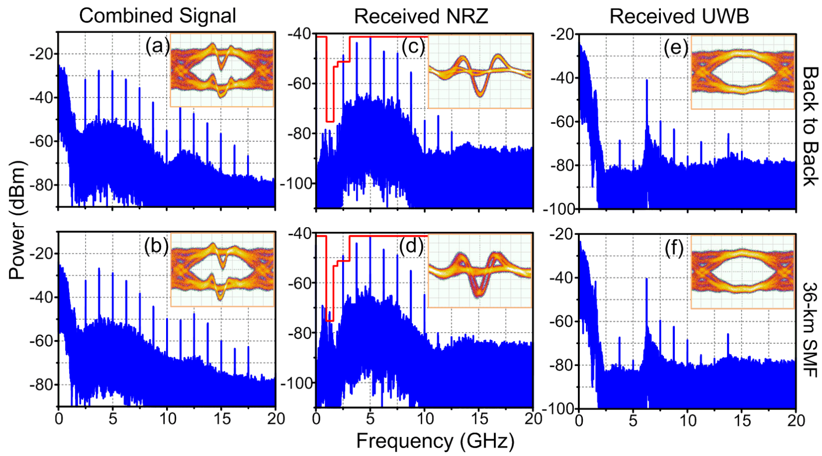

Fig. 5. Eye diagrams and electrical spectra of the back-to-back signals and the signals after transmission over a 36-km SMF when both signals are enabled. (a), (b) the OOK UWB and wired combined signal; (c), (d) the received OOK UWB signal; (e), (f) the received NRZ signal. RBW = 1 MHz.

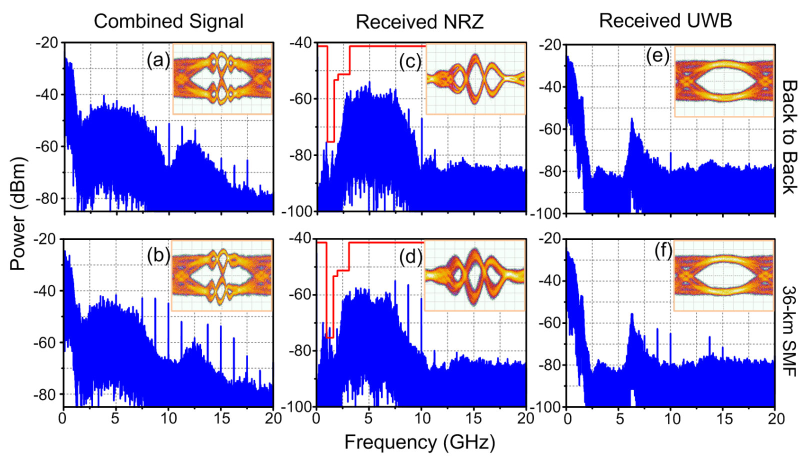

Fig. 6. Eye diagrams and electrical spectra of the back-to-back signals and the signals after transmission over a 36-km SMF when both signals are enabled. (a), (b), the BPM UWB and wired combined signal; (c), (d), the received BPM UWB signal; (e), (f), the received NRZ signal. RBW = 1 MHz.

Fig. 5 shows the experimental results when both the RZ and NRZ signals are enabled. In this case, the MZM outputs an OOK UWB and a wired combined optical signal, as shown in Fig. 5(a). From the electrical spectrum of the combined optical signal we can see that the UWB signal and the wired signal coexist with small overlap in spectrum. In the remote site, the optical signal is detected by the PD, and then divided into two paths. In one path, the converted electrical 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. 5(c), both the eye diagram and the electrical spectrum are almost the same as those when the NRZ signal is disabled (Fig. 4), which indicates that the coexistence with the NRZ signal would introduce negligible interference to the UWB signal. In the other path, the UWB signal is removed by the lowpass filter. As can be seen from Fig. 5(e), the eye of the NRZ signal is widely open. Small distortions can be found at the top and

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bottom of the eye diagram, which are due to the residual spectral components around 6 GHz from the UWB signal because of the imperfect lowpass filtering. These residual spectral components can be eliminated by an additional lowpass filter in the 1.25-Gb/s NRZ receiver. Therefore, the UWB signal also has negligible influence on the NRZ signal. The combined signal is transmitted in the 36-km SMF. The signal degradation due to the fiber dispersion is very small except that a small time shift is observed in the UWB signal. The time shift is originated from the chirp of the optical NRZ signal. Since the NRZ drive signal is only introduced to one arm of the dual-drive MZM, phase variation representing a 1 bit is contained in the optical signal. This phase variation will introduce a small time shift between a 0 bit and a 1 bit when the signal is transmitted in a dispersive element [8]. Therefore, the UWB signal embedded in a 0 bit and a 1 bit of the NRZ signal would undergo the different time shift. Fig. 6 shows the eye diagrams and electrical spectra of the back-to-back signals and the signals after transmission over a 36-km SMF when the system is configured to provide BPM UWB wireless and baseband wired services. Again, the interference between the BPM UWB signal and the wired signal is very small. In the experiment, the wavelength of the light wave from the LD is tuned from 1535 to 1570 nm. No significant changes in the eye diagrams and the electrical spectra are observed. The independence of the operations on the optical wavelength makes the system particularly suitable for WDM applications.

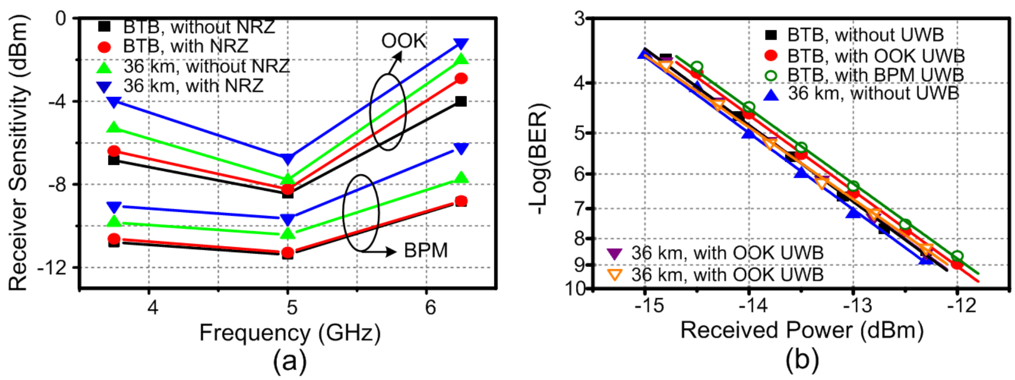

Fig. 7. (a) Receiver sensitivity for the transmission of the UWB signals, and (b) BER measurements for the transmission of the NRZ signals when only the 1544.91-nm channel is enabled. BTB: back to back.

Fig. 7(a) shows the receiver sensitivities for the received UWB signals. The receiver sensitivity is defined as the optical power required to ensure a bit error rate (BER) of 10^{-9} at the UWB receiver. As can be seen from Fig. 7(a), without and with the wired signal, the difference between the receiver sensitivities is less than 2 dB for both OOK and BPM UWB signals, which confirms that the 1.25 Gb/s wired signal has very small impact on the UWB signal. Since the signal around 6.25 GHz has a lower power, its receiver sensitivity is generally poorer than that of the signal around 5 GHz. After 36-km SMF transmission, an error-free operation is still achieved. The power penalty is less than 3 dB. The BER curves of the wired signals are shown in Fig. 7(b). The 36-km SMF transmission introduces a negative power penalty to the NRZ signal. This is because the initial NRZ signal generated by the dual-drive MZM is chirped. The wired signal in the case with a UWB signal has a power penalty of less than 0.2 dB as compared to that without a UWB signal. These results demonstrate that the co-channel interference is very small.

Although the data rate of the baseband signal is only 1.25 Gb/s in this experiment, the system can principally provide wired services as high as tens of Gb/s, since a bandwidth of 3.1 GHz is available for the baseband signal and the use of advanced modulation formats, e.g., quadrature amplitude modulation (QAM), can improve the efficiency of the spectrum usage.

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3.3 Multi-channel Operation

To investigate the impact of adding a UWB wireless service in one channel on other existing wired services, all the three channels are enabled, in which the 1544.91-nm channel provides both UWB wireless and baseband wired services, and the 1545.72 and 1546.53 nm channels provide the baseband wired service only. Fig. 8(a) and (b) shows the BER performance of the UWB and wired signals. As can be seen from Fig. 8(a), the existence of wired signals in the other channels has no impact on the receiver sensitivities for the UWB signals with OOK or BPM formats. Meanwhile, it can be seen from Fig. 8(b) that the presence of UWB signals with OOK and BPM would lead to a power penalty of less than 0.1 dB to the wired signals in the 1545.72- and 1546.53-nm channels, which indicates that the inter-channel interference is small and negligible.

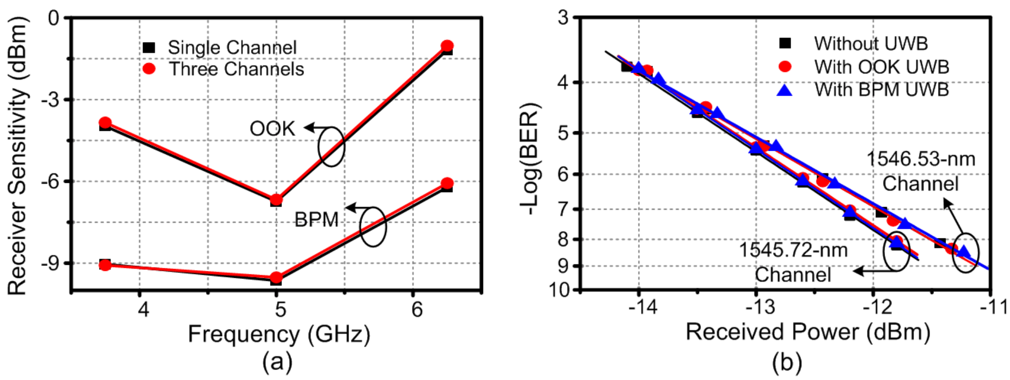

Fig. 8. (a) Receiver sensitivity for the transmission of the UWB signals, and (b) BER measurements for the transmission of the NRZ signals when all the three channels are enabled.

4. Conclusion

A novel method to simultaneously generate a UWB signal and a wired signal in the optical domain using a dual-drive MZM was proposed and demonstrated. The performance of the generated 1.25-Gb/s UWB signals with OOK or BPM format and 1.25-Gb/s wired signals was evaluated by transmission of the signals over a 36-km SMF in a WDM-PON. The eye diagrams, electrical spectra and BER measurement showed that the provision of UWB wireless service had negligible impact on transmission of the co-channel and inter-channel baseband wired signals. In addition, the 36-km SMF transmission introduced less than 2 dB power penalty to both the UWB and wired signals. These results demonstrated that a conventional WDM-PON can be upgraded to provide additional UWB services without affecting the existing services by modifying the modulators in the center office and inserting UWB antennas in the ONUs. The proposed technique may find application in the future wired and wireless converged networks.

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