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Converged ultra-wideband and multi-level wired signal downstream transport over single wavelength in wavelength-division multiplexing passive optical network

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Simultaneous providing services of ultra-wideband and wired signal over single wavelength can greatly decrease the complexity and reduce the costs of a wavelength-division multiplexing passive optical network. However, ultra-wideband signal occupies the spectrum range from 3.1 to 10.6 GHz, and a narrow idle frequency band (from 0 to 3.1 GHz) could be employed to transport wired signal with a limited rate. In this paper, we proposed a scheme to simultaneously provide ultra-wideband and wired services, in which the information rate of the wired signal is enhanced by employing a multi-level amplitude switch keying signal in the idle frequency band formed by ultra-wideband signal. In comparison with other advanced modulation formats used for wavelength-division multiplexing passive optical networks such as orthogonal frequency division multiplexing, multi-level amplitude switch keying signal can be easily received by using intensity modulation direct detection, which will greatly reduce the cost of end-users. Especially, if a multi-band ultra-wideband signal is substituted for the direct-sequence ultra-wideband signal, the available spectrum range to transport wired signal will be easily extended to 5 GHz as multi-band ultra-wideband signal has a narrower spectrum width and flexible center frequency, so 4-amplitude switch keying signal with a rate of 5 Gbaud will achieve an information rate of 10 Gbit/s.

Keywords: ultra-wideband (UWB), multi-level amplitude switch keying (M-ASK), wavelength-division multiplexing passive optical network (WDM-PON).

1. Introduction

Recently, wavelength-division multiplexing passive optical networks (WDM-PONs) have drawn considerable attention because of the advantages in terms of capacity, scalability, service transparency, and enhanced security [1]. Future WDM-PONs should have the ability to simultaneously provide both wired and wireless services over single wavelength, which would greatly reduce the costs of optical infrastructure. Ultra-wideband (UWB) recently attracted considerable interests for short-range high-throughput wireless communications and sensor networks due to their intrinsic properties, such as immunity to multipath fading, extremely short time duration, being carrier free, having low duty cycle, wide bandwidth, and low power spectral density (PSD) [2, 3]. U.S. Federal Communications Commission (FCC) authorized a spectrum range from 3.1 to 10.6 GHz with a PSD less than –41.3 dBm/MHz for commercial application of UWB. Because of the low PSD of the emitted signal, the typical communication distance of UWB system is restricted in a few meters to tens of meters. To increase the area of coverage, ultra-wideband over fiber (UWBoF) technology is proposed to distribute UWB signals over optical fibers. Recently, different UWBoF schemes have been reported in [4–8]. Due to the fact that UWB signal occupied the spectrum range from 3.1 to 10.6 GHz, an idle frequency band will be formed in 0–3.1 GHz, which results in an inefficient spectrum utilization. Fortunately, it is suitable for the transmission of a baseband signal. Therefore, a feasible solution is to set the wired signal into the idle frequency band and simultaneously transmitted with UWB signal over a single wavelength. This idea has been proposed and experimentally demonstrated at the earliest in [9]. However, the information rate of the wired signal was restricted below 1.25 Gbit/s as the idle frequency band is very finite. In this paper, we proposed a scheme to simultaneously provide UWB service and wired service, in which the information rate of the wired signal is enhanced by using multi-level amplitude switch keying (M-ASK) signal that keeps in the same spectrum width as non-return to zero (NRZ) signal with same baud rate. The M-ASK signal is relatively simple implemented (in comparison with other advanced modulation formats used for WDM-PONs such as orthogonal frequency division multiplexing (OFDM)), and the electronic equalization technology is matured [10]. Thus, the proposed scheme would greatly reduce the costs while significantly improve the spectrum efficiency of a WDM-PON network incorporating UWBoF systems for a broadband wireless access.

2. Principle

M-ASK as a candidate modulation format could be used to promote transport ability of communication system. Each symbol of M-ASK signal can assume any of n equally spaced levels with probability $1/n$ [11]. So, information rate of M-ASK signal can be expressed as $R = (1/T)\log_2(n)$. Here, $1/T$ is the baud rate of a signal. Obviously, information rate of M-ASK signal is closely related with the value of n. For example, a 4-ASK signal can double the transport ability by increasing the levels from 2 to 4, namely, a 4-ASK signal with a rate of 2.5 Gbaud will achieve an information rate of 5 Gbit/s.

Figure 1 shows the proposed schematic diagram of the converged transmission of UWB signal and the multi-level wired signal. In the M-ASK signal generator, an M-ASK

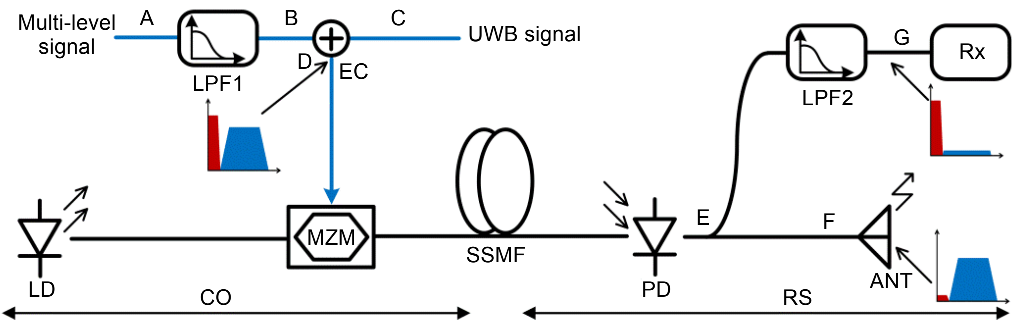

Fig. 1. Schematic diagram of the proposed system (LD – laser diode, EC – electrical combiner, MZM – Mach–Zehnder modulator, SSMF – standard single mode fiber, PD – photodetector, ANT – antenna, Rx – receivers, LPF – low-pass filter, CO – central office, RS – remote site).

signal is obtained by feeding a pseudo-random bit sequence (PRBS) into a pulse pattern generator (PPG). But the undesired high-order sidebands of the M-ASK signal will seriously interfere with the UWB signal, so a low pass filter (LPF) is cascaded with the PPG to suppress the spectrum components higher than 2.5 GHz. In a UWB signal generator, another PRBS drives an arbitrary wave generator (AWG) to obtain the UWB signal. Since the UWB signal occupies the spectrum range from 3.1 to 10.6 GHz, if the wired signal is just located in the spectrum range from 0 to 3.1 GHz, the two signals would coexist without a spectrum overlap in the frequency domain. So the two different signals are combined into a hybrid electrical signal at an electrical power combiner. Then, the continuous wave (CW) emitted from a laser diode (LD) is modulated in a Mach–Zehnder modulator (MZM) driven by that hybrid electrical signal. After that, the M-ASK signal and UWB signal are simultaneously transported over a standard single mode fiber (SSMF) to a remote site. In the remote site (RS), the hybrid optical signal is converted into a hybrid electrical signal by a photodetector (PD) and split into two equal parts. Since a UWB antenna has a –10 dB pass-band frequency response covering the frequency range of 3.1–10.6 GHz, it could work as a band-pass filter (BPF) to filter out the wired signal from the hybrid electrical signal and recover the UWB signal. Therefore, the UWB downstream route is achieved in the lower branch of RS in Fig. 1. In the upper branch of RS, the hybrid signals pass through a LPF to remove the frequency components higher than 3 GHz, and then the M-ASK signal can be recovered. Then, the downstream link for M-ASK signal is established. By this way, the simultaneous transmission of UWB signal and multi-level signal is realized.

3. Results and discussion

In the first experiment, the converged transmission of 1.25 Gbaud 4-ASK wired signal and 1.25 Gbit/s UWB doublet signal (2nd order UWB signal) is performed. The PPG is driven by a 1.25 Gbit/s PRBS generated by a bit error rate tester (BERT) to generate 4-ASK wired signal. In order to reduce the interference between the wired and doublet

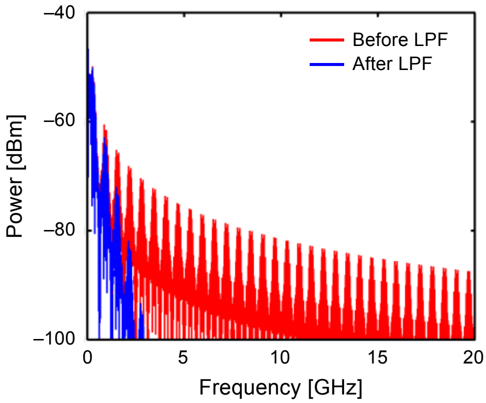

Fig. 2. Electrical spectrum of generated 4-ASK signal before and after passing through the LPF.

signal, a Gaussian LPF is cascaded with the PPG. The cut-off frequency of the LPF is 1 GHz. Figure 2 shows the electrical spectra of generated 4-ASK signal before and after passing through the LPF corresponding respectively to points A and B in Fig. 1. Obviously, after passing through the LPF, the frequency components higher than 4th order sideband are fully filtered out and the spectrum is restricted in 0– 2.5 GHz. Thus, the influence caused by 4-ASK signal would be evidently reduced.

A 1.25 Gbit/s on–off keying (OOK) electrical UWB doublet pulse train is generated by an AWG driven by a 10 Gbit/s PRBS with a fixed pattern “00000001 00000000 00000001” (“00000001” indicate a 1 and “00000000” indicate a 0). Figure 3 shows the spectrum and waveform of the electrical doublet signal corresponding to point C in Fig. 1. Evidently, the frequency components below 2.5 GHz of the electrical doublet signal will slightly interfere with that of 4-ASK wired signal. If the spectrum of 4-ASK signal is not optimized by using the LPF, the two signals would be seriously overlapped in the frequency domain, which will make it very difficult to recover the two signals.

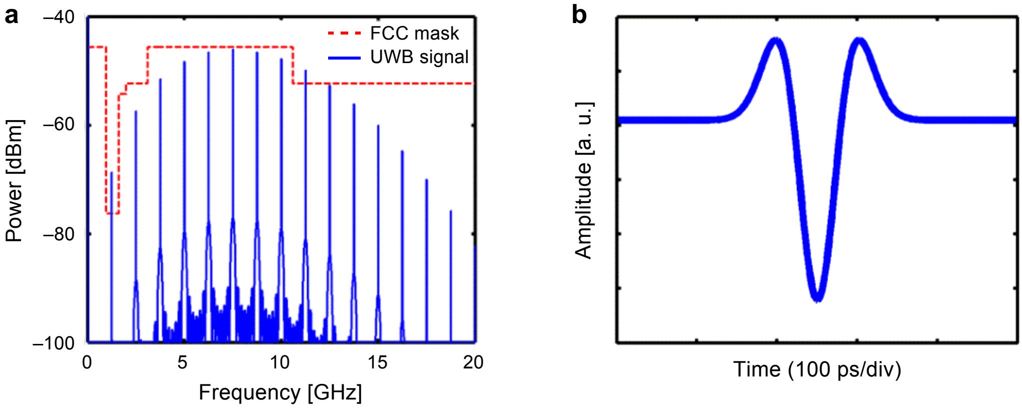

Fig. 3. Electrical spectrum (**a**) and waveform (**b**) of electrical UWB signal corresponding to point C (see Fig. 1).

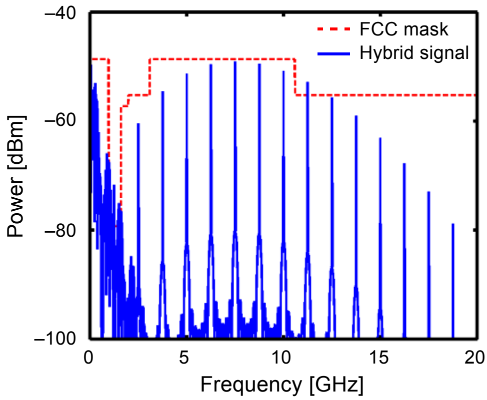

Fig. 4. Electrical spectrum of the hybrid signal corresponding to point D (see Fig. 1).

The power level of 4-ASK signal and doublet signal are adjusted by two attenuators, and then sent to an electrical power combiner to realize the combination in electric domain corresponding to point D in Fig. 1. The spectrum of the hybrid signal is shown in Fig. 4. As shown in the figure, some frequency components aliasing can be found near 3 GHz, but not serious. Then, the hybrid signal is sent to the MZM, in which the CW emitted from a LD is modulated, whose wavelength is set at 1550 nm. The optical hybrid signal is distributed by a SSMF of 20 km. At the RS, the optical–electrical conversion is performed in the PD that splits the hybrid electrical signal into two parts at the same time. One portion is sent to the UWB antenna and emitted into the air. Owing to the frequency response of the UWB antenna, it acts as a BPF, so the frequency components of wired signal are filtered out. Thus, the downstream link of UWB signal is established. The other portion of hybrid signal is sent to a Gaussian LPF, whose cut-off frequency is about 1 GHz to remove the frequency components of doublet signal. In this way, the downstream link of wired signal is also completed.

To evaluate the received signals in the RS, the spectra and eye diagrams of the recovered doublet and 4-ASK signal are analyzed. Figure 5 shows the eye diagrams and electrical spectra of the received signals in back-to-back situation and after transmission over SSMF of 20 km. The UWB antenna is equivalent to a BPF with a pass-band of about 7.2 GHz. It could be used to remove the frequency components of 4-ASK signal. The 4-ASK wired signal is recovered by a Gaussian LPF with cut-off frequency of about 1 GHz. As you see, the spectrum in Fig. 5**b** fits FCC regulation better than that in Fig. 5**a**. It is because SSMF could be used as a microwave BPF, which makes the signal after transmission over SSMF better meet the regulation of FCC [12]. The spectra and eye diagrams of the recovered 4-ASK signal in the two cases are shown in Figs. 5**c** and 5**d**, respectively. Although the frequency components of doublet signal are not removed completely, the eye diagrams of the recovered 4-ASK signals are open widely, which proved that the wired signals are not affected too much by the residual frequency components of doublet signal. Figures 5**e** and 5**f** describe the recovered doublet signals in the two cases, respectively. In the status of back-to-back, the persis-

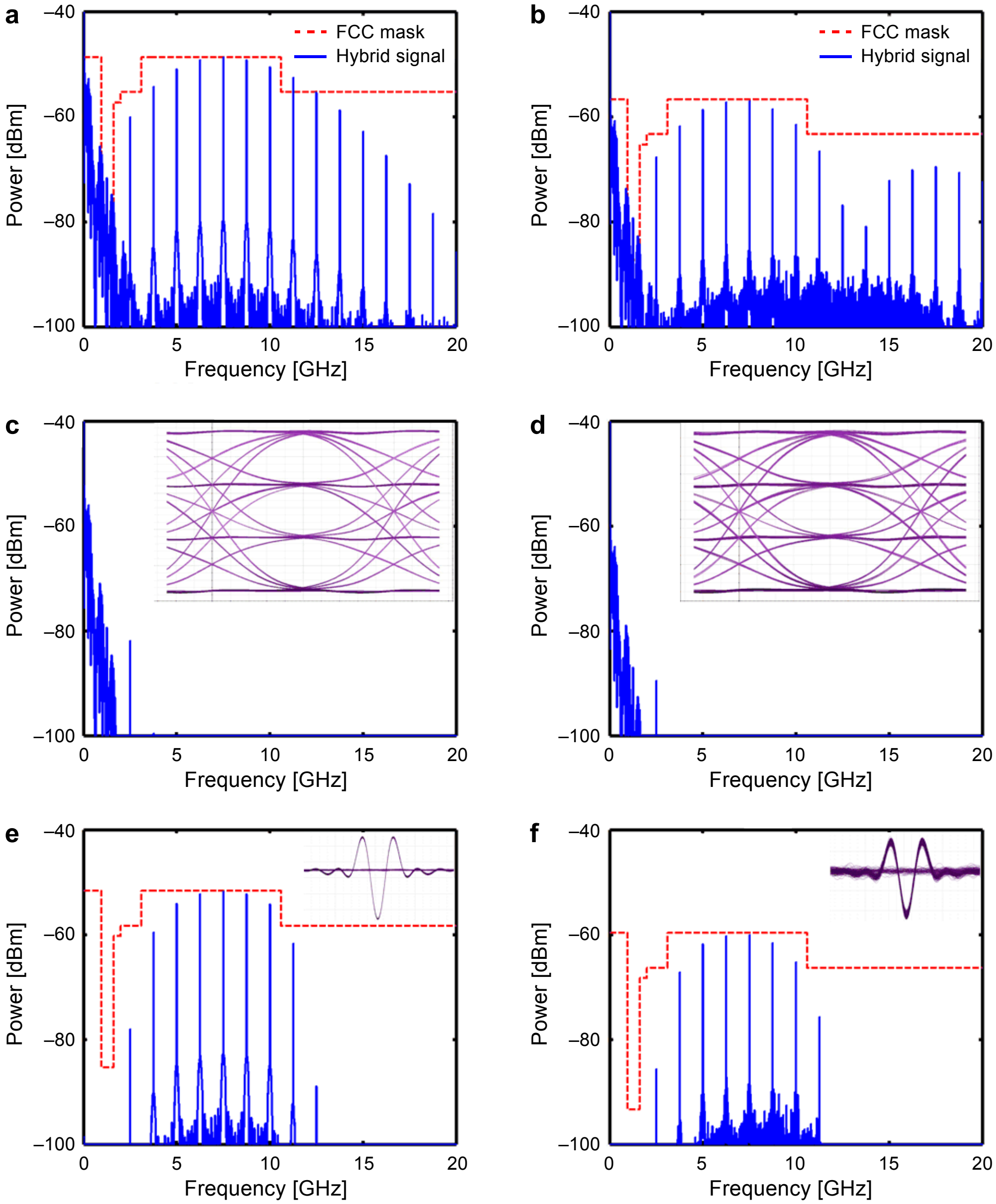

Fig. 5. Eye diagrams and electrical spectra of received doublet signal and 4-ASK signal in back-to-back situation and after transmission over a 20 km SSMF (see text for explanation).

tence trace of the eye diagram is highly overlapped. After transmission over a 20 km SSMF, the persistence trace of eye diagram is thicker than that of back-to-back situation, but the characteristic of original doublet is maintained well. Therefore, the proposed system is proved to be able to realize the converged transport of 1.25 Gbaud 4-ASK wired signal and 1.25 Gbit/s UWB signal. Due to the fact that 4-ASK is employed, the information rate of wired signal has been doubled comparing with 1.25 Gbit/s NRZ signal.

After finishing the converged transport of 1.25 Gbaud 4-ASK wired signal and 1.25 Gbit/s UWB signal, we try to promote the performance of wired signal up to a higher level. Therefore, in the second experiment, we increase the baud rate of 4-ASK signal from 1.25 to 2.5 Gbaud. To reduce the interference between wired signal and UWB signal, we employ quadruplet signal (4th order UWB signal) instead of doublet signal as the higher order UWB signal fits the UWB mask of FCC better and has weaker frequency components in the frequency range lower than 3.1 GHz. A LPF with a cut-off frequency of about 2.5 GHz is used to restrict the spectrum of the 2.5 Gbaud 4-ASK signal in the idle frequency band. The quadruplet signal is generated by using an AWG cascaded through a narrow-bandwidth band-pass filter. The AWG was driven by a 10 Gbit/s PRBS with a fixed pattern "00000001 00000000 00000001", and the narrow-bandwidth band-pass filter was employed to perform spectrum reshaping. The 2.5 Gbaud 4-ASK wired signal and quadruplet signal are shown in Fig. 6. Figures 6**a** and 6**b** represent the spectrum and waveform of quadruplet signal, respec-

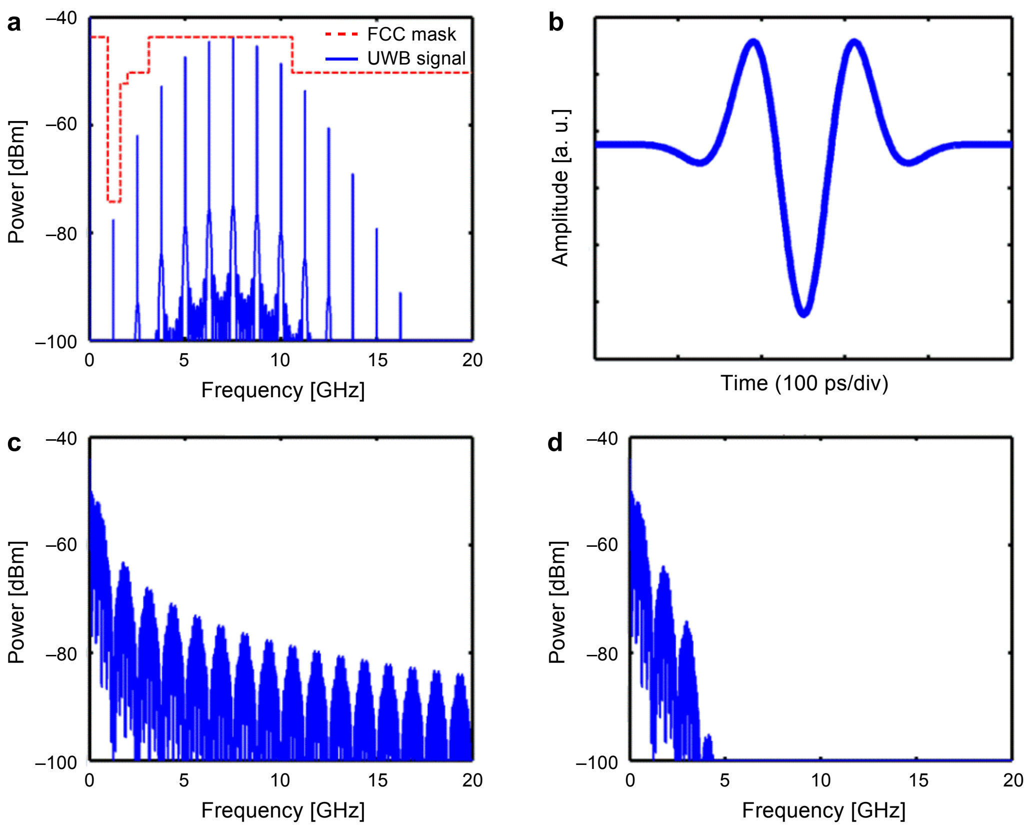

Fig. 6. Electrical spectrum (**a**) and waveform (**b**) of quadruplet. Electrical spectra of 2.5 Gbaud 4-ASK signal before (**c**) and after (**d**) passing through LPF.

tively. Figures 6**c** and 6**d** show the spectrum of 2.5 Gbaud 4-ASK signal before and after passing through LPF, respectively. Comparing with doublet signal, quadruplet signal has weaker frequency components in a low frequency range, which would reduce the interference with wired signal.

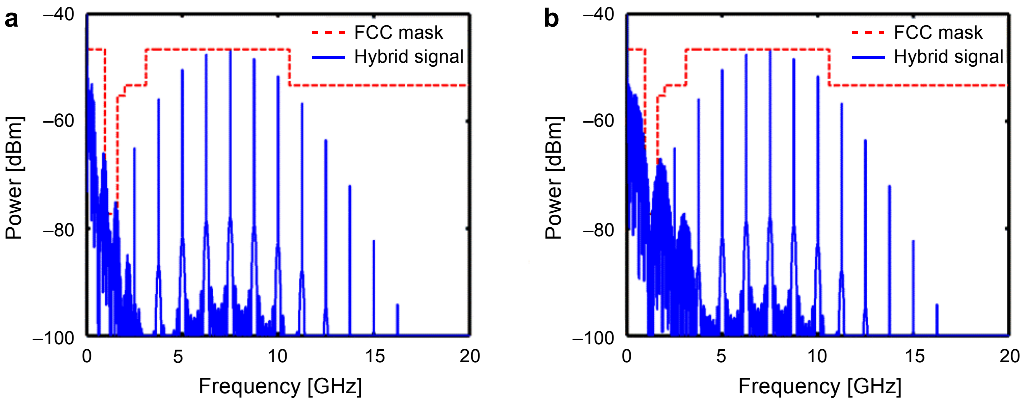

Fig. 7. Electrical spectra of hybrid signals in two different schemes (see text for explanation).

To evaluate the influence caused by the rate of 4-ASK signal, the 4-ASK signals with different rate are merged with the same 1.25 Gbit/s quadruplet signal, respectively. The spectra of the merged signals are shown in Fig. 7. Figure 7**a** shows the spectrum of the merged 1.25 Gbaud 4-ASK and 1.25 Gbit/s quadruplet signal, and Fig. 7**b** shows the spectrum of the merged 2.5 Gbaud 4-ASK and 1.25 Gbit/s quadruplet signal. Obviously, a higher rate of wire signal means more serious interference between wire and UWB signal. If the rate of wire signal is excessively high, it would make it fail to separate the two signals.

Figure 8 shows the electrical spectra and eye diagrams of the received quadruplet signal and 4-ASK signal. As shown in Figs. 8**a** and 8**b**, after being transmitted over a 20 km SSMF, the electrical spectra of the hybrid signals are reshaped due to the frequency response of the SSMF. After passing through the LPF, the recovered 1.25 and 2.5 Gbaud 4-ASK signal are shown in Figs. 8**c** and 8**d**, respectively. To recover the wired signals, LPFs with a cut-off frequency of 1 and 2 GHz are respectively used in the two schemes. Comparing with Fig. 8**c**, the eye diagram in Fig. 8**d** displays some distortion, but the eyes of 2.5 Gbaud 4-ASK signal are widely open. The spectra and eye diagrams of the recovered quadruplet signals are shown in Figs. 8**e** and 8**f**, respectively. The recovered quadruplet signals are almost not affected by the 4-ASK signals with a different rate.

Since SSMF could be used as a microwave BPF, the influence caused by the length of SSMF is investigated numerically. The results are depicted in Fig. 9. It shows the center frequency and –10 dB bandwidth of the recovered UWB signals after pass-

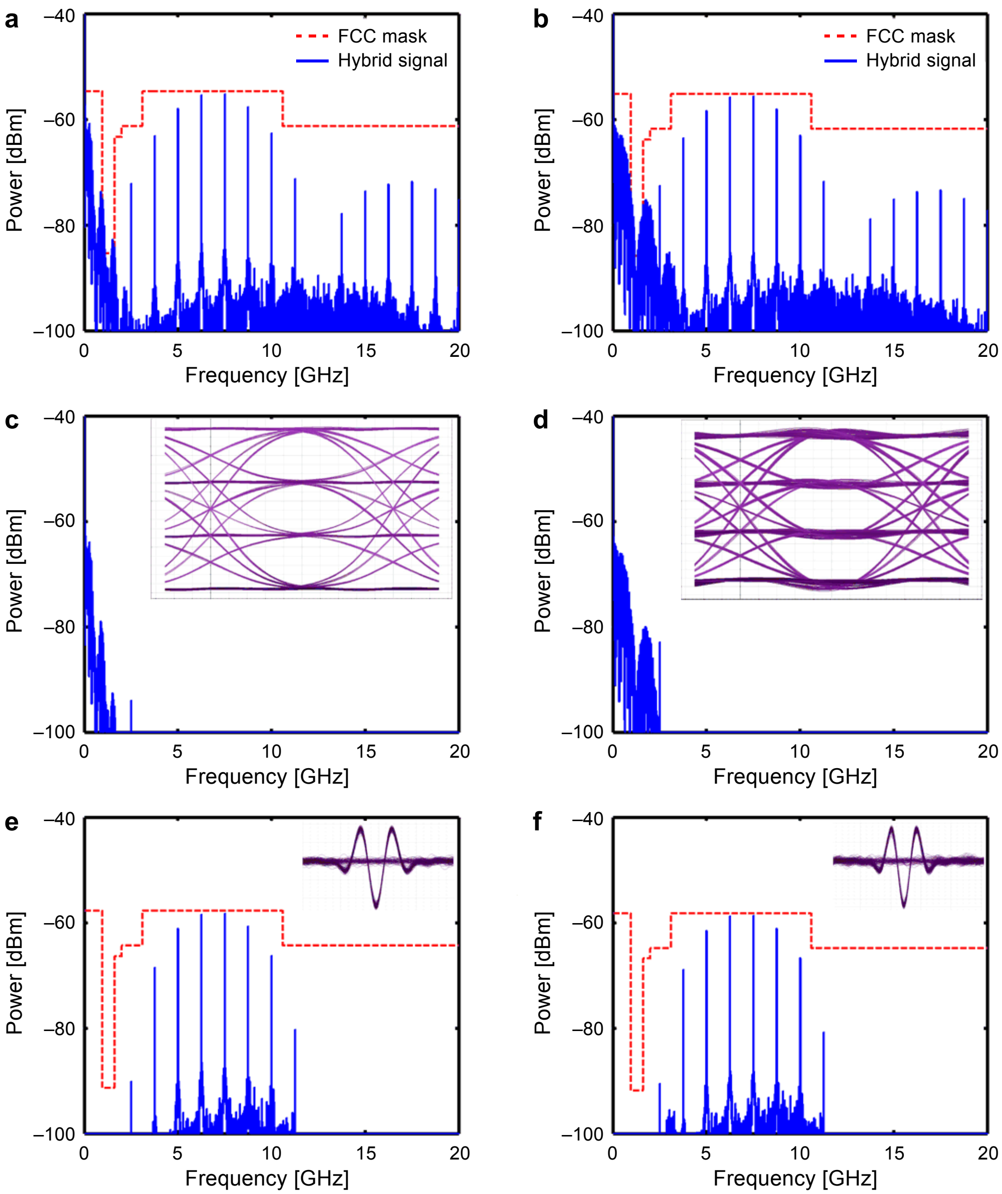

Fig. 8. Electrical spectra and eye diagrams of received UWB signal and wired signal (see text for explanation).

ing through SSMFs with different length in the three schemes. The dash lines represent the –10 dB bandwidth of the recovered UWB signals. As it can be seen, the –10 dB bandwidth of quadruplet signal is smaller than that of doublet. The solid lines represent

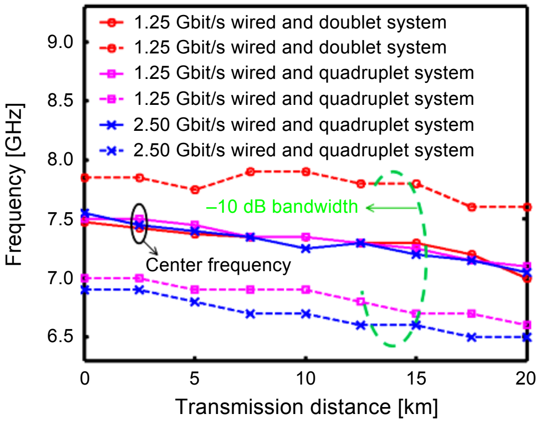

Fig. 9. Center frequency and –10 dB bandwidth of UWB signals in different transmission schemes.

the center frequency of the recovered UWB signals. Obviously, they almost centered nearby 7.5 GHz, owing to filtering process of the UWB antenna, because the frequency response of the antenna that we used is Gaussian-like and the center frequency is about 7.2 GHz.

Furthermore, we analyzed the bit error rate (BER) of recovered 4-ASK and UWB signal after being transmitted over a 20 km SSMF. The BER of the 4-ASK signal can be easily measured. However, due to the lacking of a correlation receiver, the BER of the UWB signal cannot be directly measured. So, we use a similar structure as in literature [13] to achieve the conversion from UWB signal into return-to-zero (RZ) signal. The received UWB signal is mixed at a local oscillator (LO) with a center frequency of 5 GHz, and then it passes through a LPF. This operation is equivalent to frequency down-conversion, which can be used to transform UWB signal into baseband signal. Figure 10**a** shows the result of the BER test for the demodulated UWB signal. The converged transmission of 1.25 Gbit/s quadruplet signal and 1.25 Gbaud wired signal has a lower BER, comparing with the converged transmission of 1.25 Gbit/s doublet signal and 1.25 Gbaud wired signal. When the wired signals are the same, the quadruplet signal has a narrower spectrum than that of doublet signal, which reduces the interference with the wired signal. The converged transmission of 1.25 Gbit/s quadruplet signal and 1.25 Gbaud wired signal has a lower BER, comparing with the converged transmission of 1.25 Gbit/s quadruplet signal and 2.5 Gbaud wired signal. Because when the UWB signals are the same, a lower rate wired signal can reduce the interference with UWB signal, since spectrum width of wired signal is in proportion to its rate. Besides, the BERs of the received wired signals are also analyzed, as shown in Fig. 10**b**. For a multi-level modulation format signal, forward error correction (FEC) threshold can be employed as a benchmark to evaluate the transmission performance [14, 15]. The eye diagrams are open widely, which proves the wired sig-

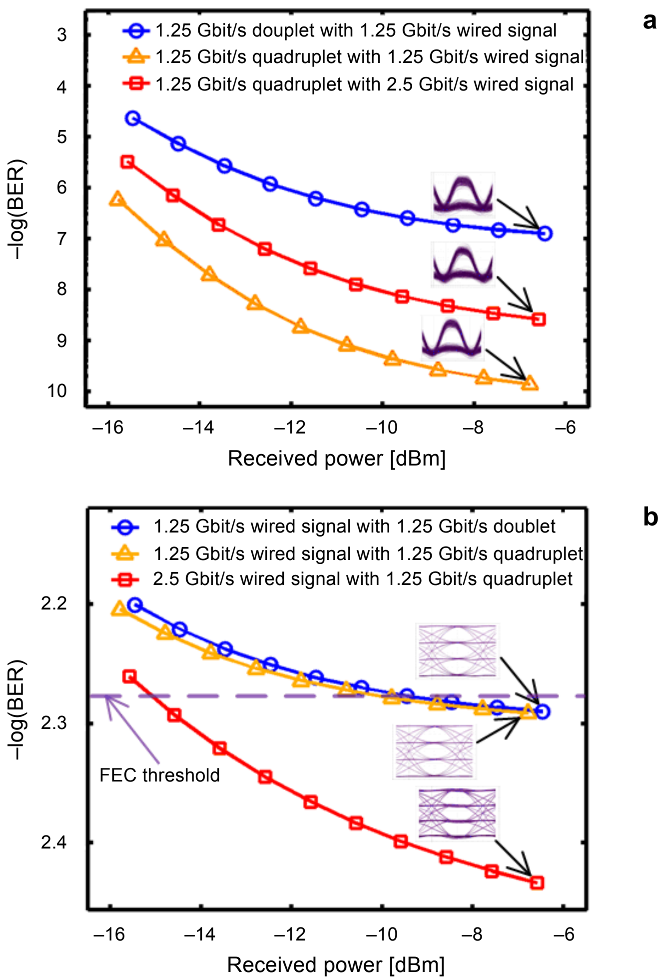

Fig. 10. Result of BER analysis (see text for explanation).

nals are recovered effectively. Because the LPF of 2.5 GHz makes the energy of the recovered 4-ASK signal higher than that of other two situations and the BER performance is proportional to the received energy of the signal, the 2.5 Gbaud wired signal shows a better BER performance. For UWB signal, it is easy to make its BER be below 10^{-6}. If the incident optical power is high enough, it even can realize an error-free transmission (BER is below 10^{-9}). However, for the M-ASK signal, the measured BER is commonly fluctuated in the level of $10^{-2.2}$. It is because the BER was measured in the worst eye of a multi-level signal. As a reference, the similar results can be found in [14, 15]. In addition, because the LPF was cascaded with the multi-level signal generator, the 4-ASK signal influence on the UWB signal was evidently reduced.

However, low frequency components of UWB signal dropped into a baseband range, which directly influenced the baseband signal. Therefore, the BER of wired signal is much worse than that of UWB signal after transmission.

4. Conclusion

In conclusion, a novel scheme is proposed and demonstrated to realize the converged transport of UWB signal and M-ASK wired signal over a single wavelength in WDM-PON. In the presented scheme, the idle frequency band of UWB signal is adequately utilized to transport a wired signal. The information rate of the wired signal is improved evidently by employing the M-ASK signal, which kept in the same spectrum width as NRZ signal with same baud rate. Furthermore, M-ASK signal is easily received compared with other advanced formats, which will cut down the costs of the system. Besides, UWB quadruplet signal is employed to reduce the interference between UWB signal and wired signal due to its narrower spectrum width comparing with UWB doublet signal. The presented approach would greatly enhance the transport ability of WDM-PON network incorporating UWBoF systems for broadband wireless access. Moreover, if a multi-band ultra-wideband (MB-UWB) signal is substituted for the direct-sequence UWB signal, the available spectrum range to transport wired signal will be easily extended to 5 GHz as MB-UWB signal has a narrower spectrum width and flexible center frequency, so 4-ASK signal with a rate of 5 Gbaud will achieve information rate of 10 Gbit/s.

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