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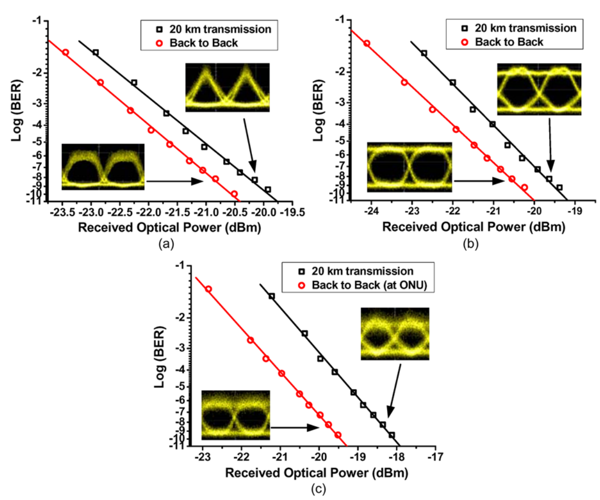

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A Wavelength-Division-Multiplexed Passive Optical Network With Simultaneous Centralized Light Source and Broadcast Capability

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Abstract: We propose and experimentally demonstrate a wavelength-division-multiplexed (WDM) passive optical network (PON) architecture with simultaneous centralized light source and broadcast capability. The proposed WDM-PON supports simultaneous delivery of 10-Gb/s broadcast on–off-keying (OOK) signals and 10-Gb/s point-to-point (P2P) differential-phase-shift-keying (DPSK) signals. The broadcast OOK signals are obtained by modulating a part of the P2P DPSK signals to enhance the wavelength utilization efficiency. Then, the two kinds of signals are transmitted to the optical network unit (ONU) through different fiber links, and this configuration guarantees the good transmission performance. At each ONU, a portion of the P2P DPSK signal provides the seeding source for remodulating the upstream 10-Gb/s OOK signal, which avoids the cost of a wavelength-specific laser at each ONU. The performance of the proposed WDM-PON with a symmetrical capacity is comprehensively investigated through both simulation and experiment. The results verify that the proposed WDM-PON scheme is a good candidate to provide broadcast service through the WDM-PON infrastructure.

Index Terms: Wavelength-division-multiplexed passive optical network (WDM-PON), wavelength reuse, centralized light source, point-to-point transmission, all-optical broadcast, differential phase-shift keying (DPSK).

1. Introduction

The passive optical network (PON) is a promising solution to satisfy the ever-increasing bandwidth demand from enterprises or households. Until now, several PON architectures have been proposed. Among them, the wavelength-division-multiplexed (WDM) PON has been recognized as an attractive solution to provide broadband services for next-generation networks due to its attractive features, such as large capacity, channel independence, format transparency, network security and per-customer-based upgrade flexibility [1]. A challenge for the wide deployment of WDM-PON is the requirement for a wavelength-specific light source in each optical network unit

(ONU), which is not cost-effective. Then, the centralized light source technique, which reuses parts of the downstream optical signal as the same carrier for upstream data remodulation, is proposed to reduce the cost and system complexity. Until now, the proposed remodulation schemes include, but are not limited to downstream differential-phase-shift-keying (DPSK) signals and upstream on–off-keying (OOK) signals [2]–[4]; downstream frequency-shift keying (FSK) signals and upstream OOK signals [5]–[7]; downstream dark-return-to-zero (DRZ) signals and upstream OOK signals [8], [9]; downstream polarization-shift-keying (PolSK) signals and upstream OOK signals [10]; OOK signals in both downstream and upstream [11]; DPSK signals in both downstream and upstream [12]; downstream OOK signals and upstream DPSK signals [13], [14]; downstream Manchester signals and upstream OOK signals [15]; and downstream orthogonal frequency-division-multiplexing (OFDM) signals and upstream OOK signals [16]. In addition, an optical subcarrier modulation technique is also proposed to realize a centralized light source in WDM-PON [17]–[19]. In those schemes, the downstream data is modulated at the optical carrier or the subcarrier, and the upstream data is remodulated at the extracted optical subcarrier or carrier at each ONU. However, narrow optical filter or interleaver is required to extract the optical subcarrier or carrier, and the subcarrier modulated data detection is complicated because a local clock is required to downconvert the subcarrier signal. Furthermore, the polarization-multiplexing technique is another possible solution to realize centralized light sources by setting the downstream data and upstream continuous-wave (CW) light sources with orthogonal polarizations [20].

To provide more network services in WDM-PON infrastructure, it is highly desired to deliver both point-to-point (P2P) data and broadcast data to the subscribers within the same WDM-PON infrastructure. Several approaches have been proposed to implement the broadcast function in WDM-PON [10], [21]–[28]. One approach is to use additional light sources for broadcast signal transmission [21], which increases the cost and complexity of the network. Another approach is to multiplex the broadcast signal with the conventional P2P data by time-division-multiplexing (TDM) technique [22], [23], which suffers from a complicated timing control and a reduced bandwidth. Subcarrier multiplexing [24], [25] is also possible to realize broadcast service, but this technique requires high-frequency electronic components at both the transmitter and receiver sides. Other schemes are proposed by using hybrid modulation format [10], [26]–[28]. The hybrid modulation format methods, including broadcast DPSK signals on P2P non-return-to-zero (NRZ) OOK signals [26], broadcast DPSK signals on P2P DRZ signals [27], [28] or broadcast PolSK signals on P2P DRZ signals [10], etc. have been demonstrated recently. Especially in [26], the broadcast DPSK signals is simultaneously modulated onto all wavelengths of the downstream P2P data. The broadcast function is realized on condition that the OOK modulated P2P data has a low extinction ration (ER). However, the P2P OOK signal will suffer from more power penalties due to its low ER.

In this paper, we propose and experimentally demonstrate a new WDM-PON architecture with a centralized light source and broadcast capability. The P2P downstream DPSK signals are first wavelength multiplexed and then split into two equal parts by a coupler. One part is used for the downstream transmission, while the other part is used for subsequent broadcast signal modulation in OOK format. Later, the downstream P2P DPSK signals and broadcast OOK signals are transmitted to the remote node (RN) through different fiber links. Thus, a good transmission performance is guaranteed. Using an array waveguide grating (AWG) router at the RN, the P2P and broadcast signals are sent to the corresponding ONU simultaneously. At each ONU, a portion of the P2P DPSK signal is used as the seeding light source for remodulating the upstream data in OOK format in order to avoid the cost of a specific laser in each ONU. The performance of the proposed WDM-PON architecture is first investigated by simulation. The system impairments cased by multiwavelength transmission and fiber nonlinearity are investigated. The proof-of-concept experiment of single-channel transmission in the proposed WDM-PON architecture is also provided.

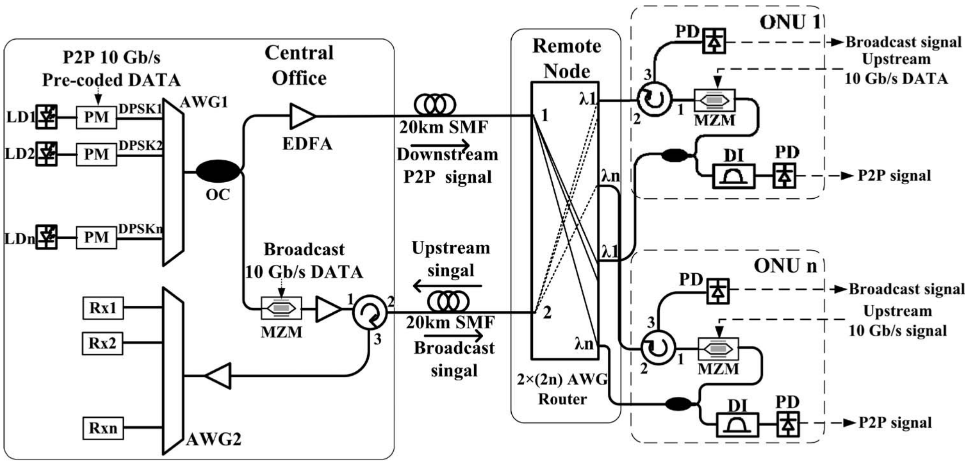

Fig. 1. Proposed WDM-PON architecture with simultaneous centralized light source and broadcast capability.

2. Architecture of Proposed WDM-PON

Fig. 1 shows our proposed WDM-PON architecture with a simultaneous centralized light source and broadcast capability. At the central office (CO), each 10-Gb/s downstream P2P DPSK signal is obtained by modulating a CW light through an electro-optic phase modulator (PM). The total n channels of P2P DPSK signals are wavelength-multiplexed by AWG 1 and then split into two equal parts by an optical coupler (OC) with a power ratio of 50:50. One part is used for downstream transmission, while the other part is used for further modulating of a 10-Gb/s broadcast signal in OOK format by a Mach–Zehnder modulator (MZM). Actually, for the broadcast data transmission, there is no need for modulation before the broadcast signal is modulated. Meanwhile, we design the WDM-PON architecture this way to achieve a low cost and reduced complexity. To prevent the interference between P2P and broadcast signals carried by the same wavelength, the P2P DPSK signals and the broadcast OOK signals are transmitted to the RN through different single-mode fiber (SMF) links after amplified by erbium-doped fiber amplifiers (EDFAs), as shown in Fig. 1. At the RN, a 2 $\times$ (2n) AWG router is used to route the input signals to different output ports. The downstream P2P DPSK signals and the broadcast OOK signals are sent to the two input ports of the AWG router, respectively. Based on the cyclic wavelength routing property, the AWG router is designed to route the 2n channels carrying P2P DPSK or broadcast OOK signals to the 2n output ports without interference. Then, the P2P DPSK and broadcast OOK signals carried by the same wavelength are sent to the corresponding ONU. The broadcast OOK signal is exported by an optical circulator and directly detected by a photodetector (PD). Meanwhile, the power of the P2P DPSK signal is split into two parts through another OC. One portion is fed into the optical delay interferometer (DI) for demodulation before direct detection, while the other portion is used as a seeding light source and completed intensity modulation for the generation of upstream 10-Gb/s OOK signal. Then, the upstream signal is sent back to the fiber link through an optical circulator and the AWG router. At the CO, the upstream OOK signals are routed to the receiver module through another optical circulator. After compensating the transmission loss by an EDFA, each upstream signal is sent to the corresponding receiver for detection after demultiplexing by AWG 2.

3. Simulation Results and Discussions

To investigate the performance of the proposed WDM-PON architecture, we have done simulation through Optiwave software (Optisystem 8.0). The simulation setup is based on the schematic setup, as shown in Fig. 1. The central wavelength of eight channels is chosen from 1546.9 nm to 1552.5 nm with a channel spacing of 0.8 nm. AWG 1, AWG 2, and the 2 $\times$ 16 AWG router have a 3-dB bandwidth of 20 GHz with a third-order Bessel filter shape for each channel. The SMF in the simulation has the

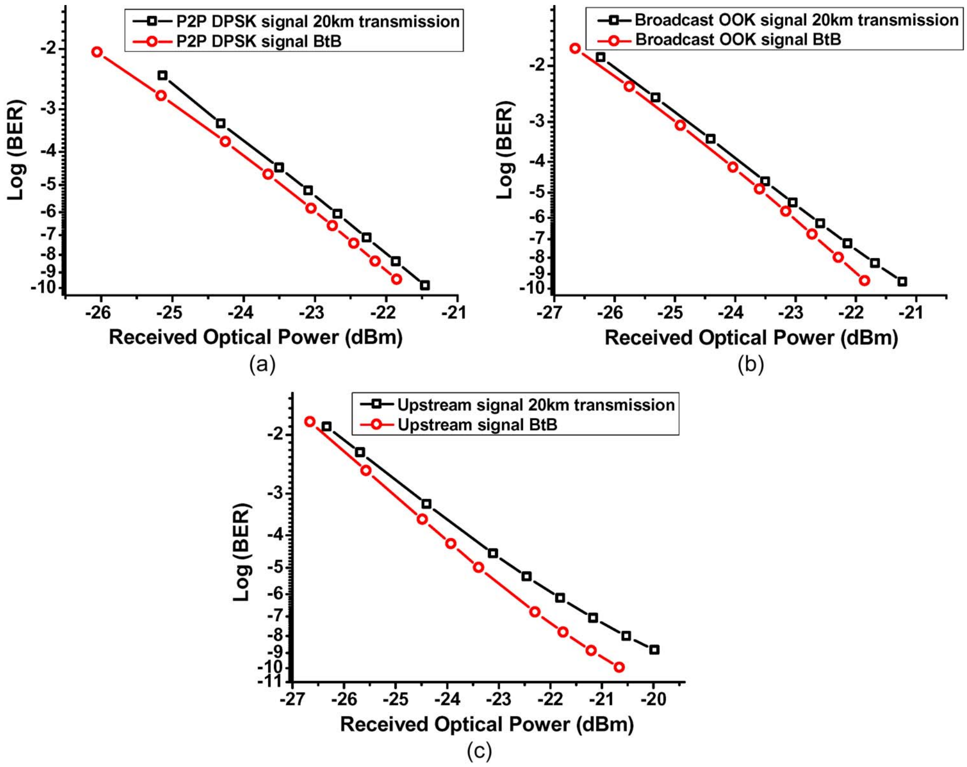

Fig. 2. Calculated BER results for single-channel transmission. (a) P2P DPSK signal, (b) broadcast OOK signal. and (c) upstream OOK signal, for both back-to-back and after 20-km transmission.

attenuation coefficient of 0.2 dB/km, the dispersion parameter of 16.75 ps/nm/km, the dispersion slope of 0.075 ps$/$nm^2$/$km, and the effective area of 80 μm^2. The nonlinear-index coefficient n_2 [29] of the SMF is 2.6×10^{-20} m^2$/$W. The effects of self-phase modulation (SPM), cross-phase modulation (XPM), four-wave mixing (FWM), and Rayleigh and Brillouin scattering are all considered when the optical signal is transmitted through the 20-km SMF. To study the impacts of multichannel transmission through the proposed WDM-PON, we investigate three cases of single-channel, four-channel, and eight-channel transmission. For the case of single-channel transmission, we choose the light wave at 1549.3 nm. Moreover, we choose the four channels from 1548.5 nm to 1550.9 nm and the eight channels from 1546.9 nm to 1552.5 nm for the cases of four-channel and eight-channel transmission, respectively. The transmission performance of the carrier at 1549.3 nm is investigated for the three cases mentioned above.

Fig. 2 shows the single-channel bit-error-rate (BER) performance of the downstream P2P DPSK signal, broadcast OOK signal, and the upstream OOK signal for both back-to-back and after 20-km transmission. The optical power of downstream signal launched into each section of SMF is about 2.3 dBm. The P2P DPSK signal, the broadcast OOK signal, and the upstream OOK signal suffer from about a 0.4-, 0.8-, and 1.1-dB power penalty after 20-km transmission, respectively. The higher power penalty of the broadcast OOK and upstream OOK signals compared with that of the P2P DPSK signal is mainly due to the Rayleigh backscattering for bidirectional transmission through a single fiber.

To investigate the impact caused by multichannel transmission in the proposed WDM-PON system, we also compare the BER performance, when single-channel, four-channel, and eight-channel signals are transmitted in the proposed WDM-PON system. Fig. 3 shows the BER performance of the P2P DPSK signal, broadcast OOK signal, and the upstream OOK signal at 1549.3 nm after 20-km transmission for the cases of single-channel transmission, four-channel transmission, and eight-channel transmission. For the P2P DPSK signal, the increment of power penalty caused by

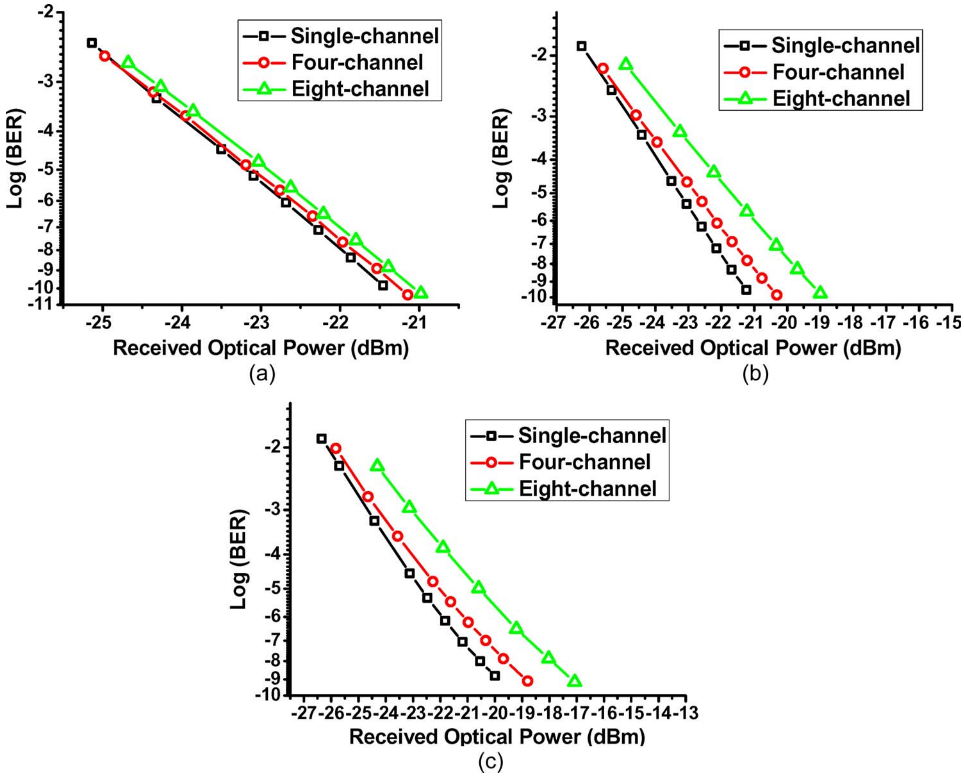

Fig. 3. Calculated BER results for signals at 1949.3 nm after 20-km transmission for three cases of single-channel, four-channel, and eight-channel transmissions. (a) P2P DPSK signal, (b) broadcast OOK signal, (c) upstream signal.

multichannel transmission is below 0.5 dB. Meanwhile, for broadcast OOK signal, the power penalty increment for four-channel transmission and eight-channel transmission compared with single-channel transmission is about 0.8 dB and 2.1 dB, respectively. The values for the upstream OOK signal are varied to 1.1 dB and 2.9 dB, respectively. In the simulation, AWG 1, AWG 2, and the 2×16 AWG router have a 3-dB bandwidth of 20 GHz with a third-order Bessel filter shape for each optical channel. The crosstalk between adjacent channels caused by nonperfect optical filtering can be further suppressed by improving the AWG filter property. Furthermore, as the channel number increases, the optical power launched into the SMF increases. The crosstalk caused by fiber nonlinearities will cause more serious impairments to the WDM-PON system.

We also investigate the system impairments caused by fiber nonlinearities when a large downstream optical power is launched into the SMF. Fig. 4 shows the receiver sensitivity at $\text{BER} = 10^{-9}$ with respect to the downstream optical power launched into each section of SMF for the downstream P2P and the broadcast signals. The case of single-channel, four-channel, and eight-channel transmissions are considered, respectively. During the simulation, the different input optical power is obtained by adjusting the output power of each LD at the CO, while keep the gain of EDFA unchanged. For the single-channel transmission, when the input optical power exceeds about 12 dBm, the receiver sensitivity degrades severely. This sharp increment of receiver sensitivity is due to the fiber nonlinearities especially the SBS effect in optical fiber. Considering the fact that the two kinds of signals are all phase modulated (the broadcast OOK signal is obtained by intensity modulating a DPSK signal), the SBS thresholds for the P2P DPSK, broadcast OOK, and upstream OOK signals are relatively high [30]. Thus, the proposed WDM-PON architecture has a relative large tolerance to the SBS effect. When the input optical power is too low, the optical-signal-to-noise ratio (OSNR) becomes bad, since EDFA is used in the system. The system sensitivity is also degraded. Therefore, there is an optimum range of input optical power in order to achieve a

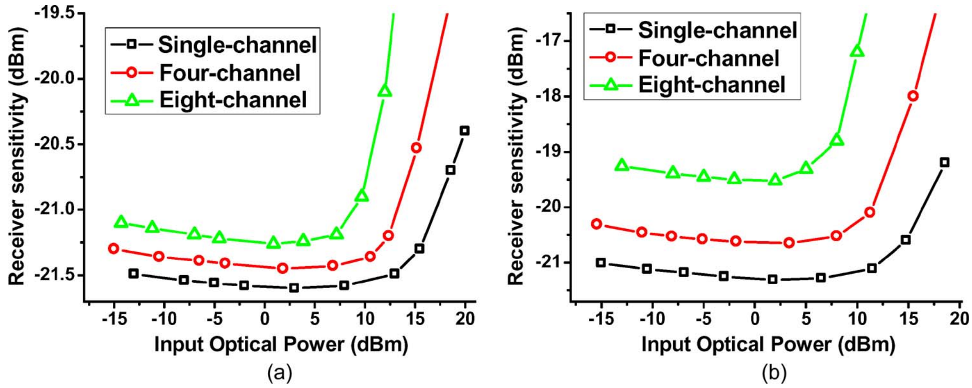

Fig. 4. Receiver sensitivity versus different downstream optical power launched into SMF for single-channel, four-channel, and eight-channel transmission. (a) P2P DPSK signal, (b) broadcast OOK signal.

high sensitivity. For multichannel transmissions, the fiber nonlinear effects such as XPM and FWM will aggravate the degradation of the system performance together with the SBS effect. The multichannel transmissions degrade severely at much lower launched optical power, compared with the single-channel transmission. It is obvious that the performance of four-channel transmission is better than that of eight-channel transmission. From Fig. 4, the extra power penalty due to multichannel transmission can also be obtained, compared with that of single-channel transmission. For the upstream OOK signals, once the downstream optical power is given, the optical power of upstream signals can be obtained, considering the power budget the WDM-PON system. Further investigation shows that the impact of fiber nonlinearity to the upstream OOK signal is similar to that of the broadcast OOK signal.

4. Experimental Demonstration

To further verify the proposed WDM-PON architecture, we experimentally demonstrate the WDM-PON with single-channel transmission, as shown in Fig. 5. A CW light source from a laser diode (LD) at 1549.3 nm is first fed into a PM and driven by a 10-Gb/s $2^{31}-1$ pseudorandom binary sequence (PRBS) to generate the P2P DPSK signal. Then, the DPSK signal is split into two parts by a 3-dB OC. One half is amplified by an EDFA and fed into a 20-km SMF for the downstream transmission between the CO and RN. The other half is further intensity modulated by another 10-Gb/s $2^{31}-1$ PRBS data source via MZM 1 to generate the broadcast OOK signal. Then, the broadcast signal is amplified and fed into another 20-km SMF for the downstream transmission. At the RN, a 16×16 AWG (NEL, A0816GPMES-A098A) is used to realize the function of the AWG router in Fig. 1. The first and ninth input ports of the AWG are used. After the AWG, the broadcast OOK signal is directly detected by PD 1 after it is exported by an optical circulator. Meanwhile, the power of the P2P DPSK signal is split by a 3-dB OC. One portion is fed into a 10-Gb/s DPSK demodulator (ITF, DPSK0995S40), and a single-end detection is done. The other portion of the DPSK signal is fed into the MZM 2 and remodulated by a 10-Gb/s $2^{31}-1$ PRBS to generate the upstream OOK signal. Then, the upstream signal is sent back to the CO after passing through the AWG and the SMF link. After exported by another optical circulator and amplified by an EDFA for loss compensation, the upstream OOK signal is fed to PD 3 for detection.

We have performed the BER measurement of the 10-Gb/s transmission of the downstream P2P signal, the broadcast signal, as well as the upstream signal, as shown in Fig. 6. The P2P DPSK, the broadcast OOK signal, and the upstream OOK signal suffer from about 0.6-, 0.9- and 1.4-dB power penalty after 20-km transmission, respectively. The experimental results agree well with the above simulation results. The eye diagrams for both back-to-back and after 20-km transmission are also shown in the insets of Fig. 6. In Fig. 6(c), the eye diagrams for upstream OOK signal suffer obvious intensity noise due to the fiber dispersion induced phase-to-intensity conversion [31]. Besides, the

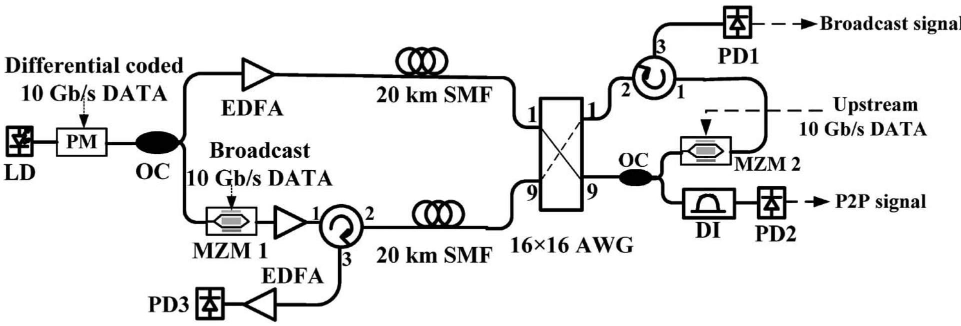

Fig. 5. Experimental setup.

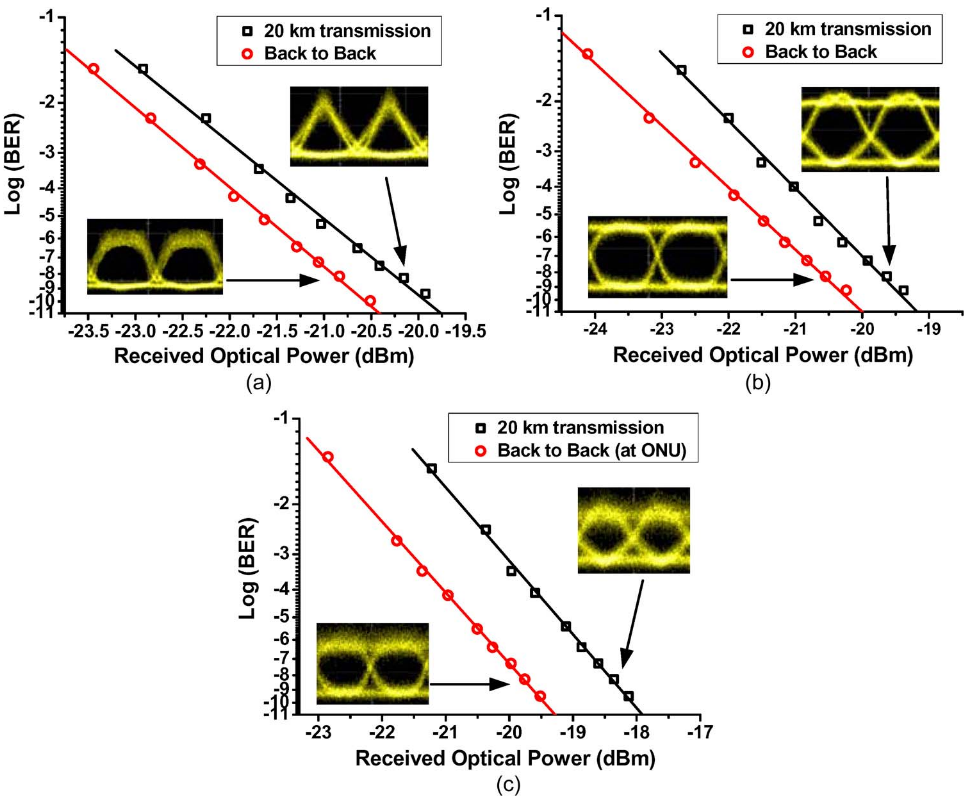

Fig. 6. BER measurements for (a) P2P DPSK signal, (b) broadcast OOK signal, and (c) upstream OOK signal. Insets are the measured eye diagrams.

amplified spontaneous emission (ASE) noise of the EDFA used before the upstream signal detection also degrades the eye opening. The optical power of downstream signals before fed into each transmission link is about 4 dBm. The total downstream loss caused by SMF and AWG router is around 7 dB. After an optical circulator, the exported broadcast OOK signal has a power of about -5 dBm. The received optical power for the 10-Gb/s broadcast OOK signal gives more than 14-dB system margin, while that for the 10-Gb/s P2P DPSK signal after DI is around -10 dBm, implying about 9.5-dB system margin. The power of the upstream seeding light is around -6 dBm. After passing through MZM 2, the optical circulator, the AWG router, and fiber link, the optical power of the upstream OOK signal at the CO is around -21 dBm without amplification. However, by using an optical amplifier before detection, a large system margin can be provided for the upstream OOK signal.

5. Conclusion

We have proposed and experimentally demonstrated a WDM-PON architecture with centralized light source and broadcast capability. Simultaneous delivery of 10-Gb/s P2P DPSK and 10-Gb/s broadcast OOK signal, as well as the remodulating of 10-Gb/s upstream OOK signal, are experimentally demonstrated. The impacts caused by multichannel transmission and fiber nonlinearity to the WDM-PON system are investigated through simulation. The simulation and experimental results verify the good quality of the proposed WDM-PON scheme, which is a good candidate for providing broadcast service through WDM-PON.

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