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Abstract. In this demonstration, we propose and investigate a long reach passive optical network (PON) using four wavelength-multiplexed signals with both on–off keying modulations for 40 Gb/s downlink traffic in 100 km fiber transmission without dispersion compensation. In the exchange node, we can use four channels with video services broadcasting to each optical network unit (ONU) for the uplink signal remodulation. Hence, four wavelength-multiplexed video signals also can be used to inject into the corresponding reflective semiconductor optical amplifiers in each ONU for uplink signal remodulation to achieve a 4×2.5 Gb/s data rate. In addition, under the 32 split ratio PON system, the power penalties of nearly 6.7 and 1 dB could be measured at the bit error rate of 10^{-9} for the downlink and uplink traffic, respectively. [DOI: 10.1117/1.3662395]

Subject terms: long-reach; passive optical network; on-off keying modulation; time-division-multiplexed.

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1 Introduction

Recently, passive optical networks (PONs) have been considered as the attractive broadband access networks with the benefits of high bandwidth, high capacity, easy upgradeability, good security, and cost-effectiveness.[1–4] Hence, several time-division-multiplexed (TDM) access technologies have been deployed and standardized, such as Ethernet-PON, Broadband-PON, and Gigabit-PON.[5–7] However, the rapid growth of multiservices, such as the Internet, voice, CATV, IP-TV, HD-TV, digital cinema, and online gaming, would also lead to the data rate up to 10 Gb/s or more. So, the capacity of the current PONs are not enough to satisfy the ever-increasing bandwidth demand in the future multimedia access systems.[8,9] Thus, the next-generation PON system would be growing up to 40 Gb/s.[10,11] Based on current PON standards,[5–7] the maximum fiber transmission length was around 20 km. In order to reduce the cost of fiber access infrastructure simultaneously, the long reach (LR) PONs which integrate the metro and access sections of the networks have been proposed and studied.[12,13] Moreover, using the on–off keying (OOK) modulation format with data rate of 40 Gb/s by single-wavelength could be the simplest way and most cost-effective. However, the 40 Gb/s data rate will limit the transmission distance in the optical network within a few kilometers due to the fiber chromatic dispersion.[10,11]

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In this investigation, we propose and demonstrate an LR TDM-PON using both OOK modulations for 40 Gb/s downlink and 10 Gb/s uplink traffic via four wavelength-multiplexing wavelengths at different wavelength bands; together with the multivideo services broadcasting. Hence, the power penalties of 6.7 and 1 dB can be measured at the bit error rate (BER) of 10^{-9} for downlink and uplink connections in 100 km fiber transmission without dispersion compensation.

2 Experiment and Discussions

In the 40 Gb/s TDM-PON, a single wavelength with 40 Gb/s could be used in the optical line terminal for broadcasting downlink data. Due to the unavailability of 40 Gb/s nonreturn-to-zero (NRZ) source in the laboratory, we used the commercial software (VPI Transmission Maker V7.5) to numerically analyze the 40 Gb/s OOK downlink traffic in a PON system. In this simulation, the 40 Gb/s OOK signal was generated by encoding a continuous wave (cw) signal (wavelength = 1550 nm, average power = 0 dBm) via a Mach–Zehnder modulator (MZM). The dispersion parameter of the fiber was 17 ps/nm/km.

Figure 1 presents the simulated BER performance at the back-to-back (B2B), 5 and 10 km transmissions, respectively. We could observe a power penalty of 6.3 dB at the BER of 10^{-9} in 5 km transmission due to the fiber chromatic dispersion. When the transmission length is up to 10 km, the BER almost cannot be measured because of the larger fiber

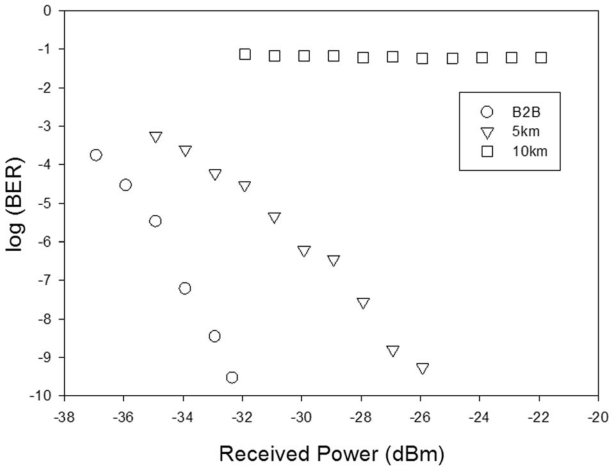

Fig. 1 Numerical analysis of BER performance at 40 Gb/s NRZ modulation format under B2B, 5, and 10 km transmission, respectively.

dispersion effect (dispersion parameter = 17 ps/nm/km), when 40 Gb/s data rate is applied in 1550 nm, as also shown in Fig. 1. Furthermore, using 40 Gb/s differential phase shift keying downstream and 40 Gb/s remodulated OOK upstream signals via a single lightwave for PON transmission has been proposed.[10] However, the entire data transmission only could achieve a few kilometers long in such PON system. To overcome the dispersion effect at 40 Gb/s rate in the current PON architecture, using four wavelength-multiplexed signals with 10 Gb/s rate to implement the 40 Gb/s rate transmission in a PON system would be the best solution.[14]

Figure 2 shows the experimental setup of our proposed LR TDM-PON architecture. In the head-end (HE), we employ four wavelength-multiplexed signals connecting four external MZMs with 10 Gb/s OOK modulation to achieve 40 Gb/s for downlink traffic. And the four cw laser diodes (LDs) used are 1540.1, 1541.3, 1542.5, and 1543.7 nm, respectively, with the same output power of around 3.0 dBm in this experiment. Here, in each optical network unit (ONU), we use four reflective semiconductor optical amplifiers (RSOAs) serving as the uplink optical transmitter. The four RSOAs are multiplexed by a 4×1 wavelength division multiplexed (WDM) multiplexer. Besides, in the exchange node (EN), we also place four cw wavelength-multiplexed channels to act as the external injection lights for injecting four corresponding RSOAs in each ONU. The output wavelengths of four injection laser diodes (ILDs) are at 1549.7, 1550.9, 1552.1, and 1553.3 nm, respectively. Besides, to achieve the multivideo services (such as CATV, DVB-T, IP-TV, and HD-TV), each ILD also can carry different video service for uplink signal remodulation. Thus, each ONU would receive the 40 Gb/s downlink information by four WDM channels from HE and each RSOA in the ONU would be injected by the ILD from EN to generate the uplink reuse signal. The erbium-doped fiber amplifier is used to compensate the losses of optical components for the proposed architecture in the remote node (RN). In this experiment, the transmission distances between HE and EN, EN and RN, and RN and each ONU are 80, 10, and 10 km, respectively. In this experiment, we use a 1×32 optical splitter in RN to serve 32 end-users.

For the downlink traffic, each cw LD is modulated at 10 Gb/s NRZ format with pseudorandom binary sequence (PRBS) pattern length of $2^{31}-1$ by MZM. In the BER measurement, we use the wavelength of 1541.3 nm to represent the downlink signal. Hence, Fig. 3 shows the BER performance under B2B and 100 km single-mode fiber (SMF) transmission length, respectively, at 10 Gb/s OOK modulation without any dispersion compensation. As shown in

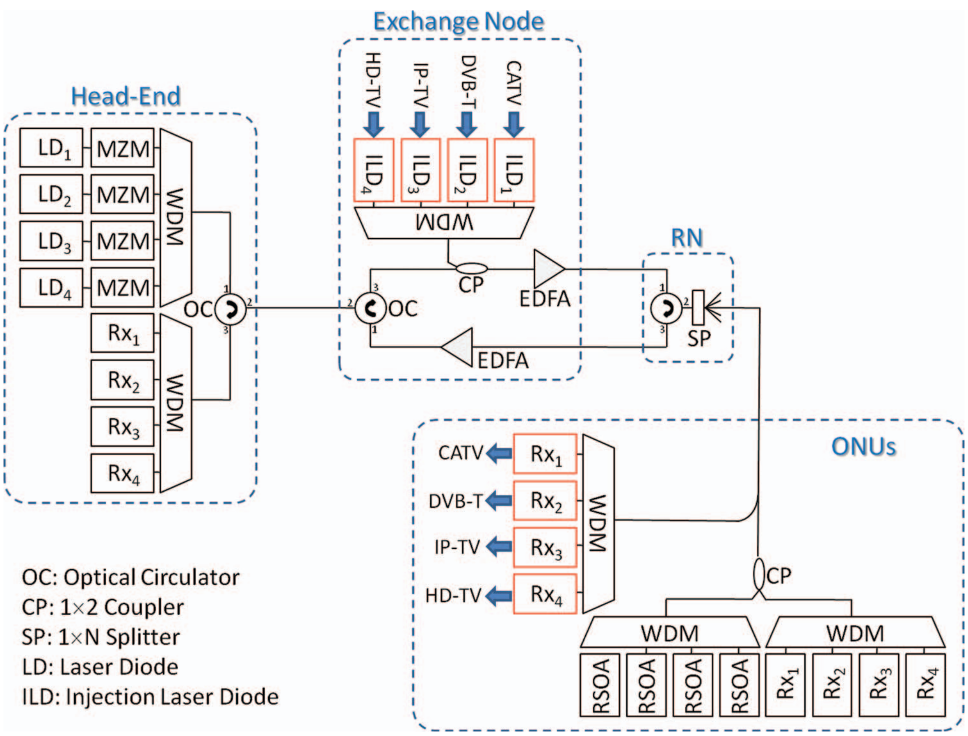

Fig. 2 Experimental setup of the proposed LR TDM-PON architecture.

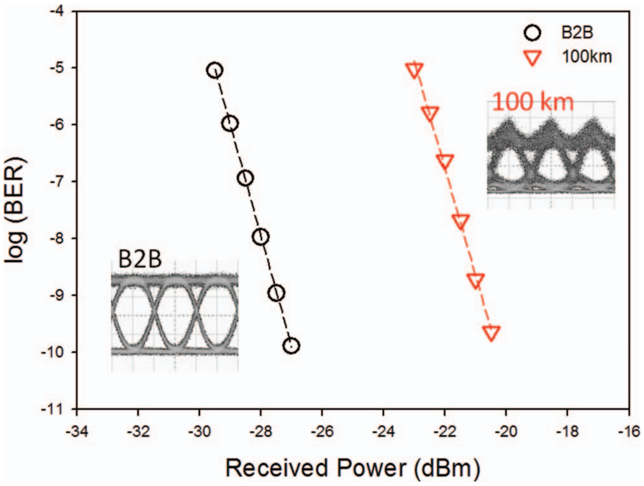

Fig. 3 BER measurements of downlink traffic with B2B and 100 km SMF transmission. Inserts are the corresponding eye diagrams.

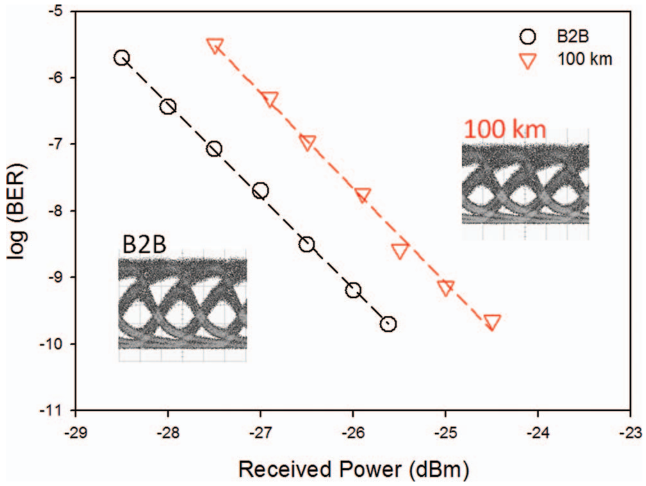

Fig. 5 BER measurements of uplink traffic with B2B and 100 km SMF transmission. Inserts are the corresponding eye diagrams.

Fig. 3, nearly 6.7 dB power penalty is observed after 100 km SMF transmission at the BER of 10^{-9}. The corresponding eye diagrams are clear and wide open after 100 km transmission, as also shown in the insets of Fig. 3. Thus, the larger power penalty is obtained due to the chromatic dispersion. In addition, when we increase the split ratio to 64, the error free cannot achieve, this is mainly limited by the signal-to-noise ratio of the signal.

For the multivideo broadcasting, we use the CATV channel in ILD_1 (1549.7 nm) to serve as one of the multivideo services in the experiment for uplink signal reuse. To confirm the proposed technology, the CATV signal having the operating bandwidth from 50 to 750 MHz with 6 MHz channel spacing is used in the proposed access network. When multiple CATV channels are transmitted through a nonlinear device, such as an optical amplifier, carrier-to-noise ratio (CNR), the composite second order (CSO), and composite triple beat (CTB) would be generated to affect and distort the video signal.[15] In addition, in this experiment we also measure the values of CNR, CSO, and CTB under different NTSC channels from 83.25 to 733.25 MHz in our proposed access network, as illustrated in Fig. 4. The maximum distorted values of CNR, CSO, and CTB are 1.2, 1.8, and 4.3 dB at 181.24 MHz frequency band are measured, respectively, after 20 km SMF transmission through our proposed PON system.

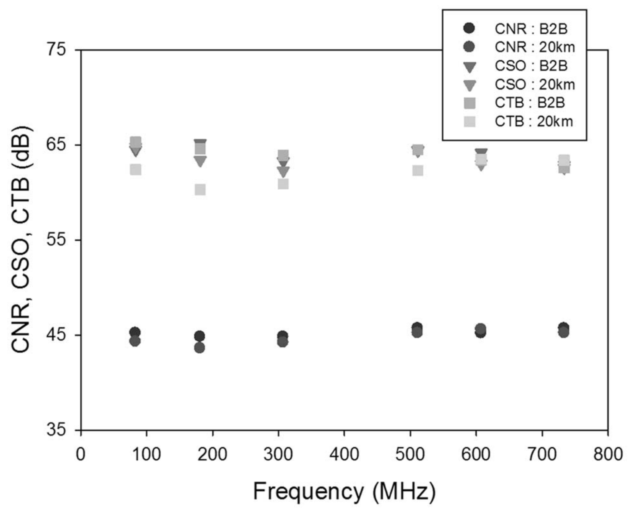

Fig. 4 Measured values of CNR, CSO, and CTB under different NTSC channels from 83.25 to 733.25 MHz under B2B and 20 km SMF transmission.

To implement the 10 Gb/s uplink traffic, each RSOA would be injected by the video-carried light (ILD_1 to ILD_4) from EN. To keep the direct modulation rate up to 2.5 Gb/s, the external injected power must be larger than -10 dBm.[16] Each RSOA can be directly modulated at 2.5 Gb/s OOK format with PRBS under a pattern length of $2^{31}-1$, when the video-service light ILD_1 is injected, for uplink signal remodulation. Figure 5 shows the BER performance of the uplink signal (using 1549.7 nm video injected light) under B2B and 100 km fiber transmission, respectively, without any dispersion compensation. The insets of Fig. 5 are the corresponding eye diagrams. The measured eyes are clear and wide after 100 km transmission. As shown in Fig. 4, the power penalty of ~1 dB is measured after 100 km SMF transmission at the BER of 10^{-9}. Moreover, compared with the orthogonal frequency division multiplexing (OFDM) modulation based LR-PON with the remodulated OOK upstream traffic,[17] our proposed PON architecture can provide the multivideo services and mitigate Rayleigh backscattering beat noise simultaneously, via the different wavelength bands.

3 Conclusion

In summary, we have proposed and experimentally investigated an LR TDM-PON using both OOK modulations for 40 Gb/s downlink and 10 Gb/s uplink traffic in 100 km fiber transmission without dispersion compensation. We used the four wavelength-multiplexed signals with external modulation by MZM to achieve a 40 Gb/s downlink rate. Furthermore, we also employed four RSOAs with direct modulation to generate the 10 Gb/s uplink traffic. Here, under the 32 split ratio PON system, the power penalties of nearly 6.7 and 1 dB were observed at the BER of 10^{-9} for the downlink and uplink traffics in 100 km transmission, respectively. Moreover, the proposed LR TDM-PON system also can provide multivideo services for end-users. As a result, we believe that the proposed LR TDM-PON could be a promising solution for the new generation 40 Gb/s PON architecture.

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