Using OOK Modulation for Symmetric 40-Gb/s Long-Reach Time-Sharing Passive Optical Networks

Chien-Hung Yeh, Chi-Wai Chow, Chia-Hsuan Wang, Yu-Fu Wu, Fu-Yuan Shih, and Sien Chi

***Abstract*—Due to the requirement of broad bandwidth for next-generation access networks, present passive optical networks (PONs) will be upgraded to 40 Gb/s or higher data rate PONs. Hence, we propose and experimentally demonstrate a simple and efficient scheme to achieve a symmetric 40-Gb/s long-reach (LR) time-division-multiplexed PON by using four wavelength-division-multiplexed 10-Gb/s external on–off keying format channels to serve as the optical transmitter for downstream and upstream traffic simultaneously. Moreover, the system performance of LR transmission and split ratio have also been analyzed and discussed without dispersion compensation.**

***Index Terms*—40 Gb/s, long reach (LR), passive optical network (PON), time-division multiplexing (TDM).**

I. Introduction

THE bandwidth demand for broadband services, such as the high-definition Internet protocol television (HD-IPTV), digital cinema, tele-presence, online gaming, etc., will make the future access networks supporting higher and higher data rates. Thus, passive optical network (PON) architecture would be the best choice for the last mile access due to the benefits of high-capacity and cost-effectiveness. Several time-division-multiplexed PON (TDM-PON) architectures have been developed and standardized, such as the broadband PON (BPON), Ethernet PON (EPON), and gigabit PON (GPON) [1]–[3]. And these PONs have already been deployed by Internet service providers (ISPs) today [4]–[6].

Moreover, the bandwidth of standardized 10-Gb/s TDM-PONs may not be large enough to meet the continually-increasing bandwidth demand for future multimedia services [7]–[9]. Therefore, next-generation PONs will be supporting data rates of up to 40 Gb/s or higher. Using a single channel of 40-Gb/s data rate for transmission systems could be possible. However, the 40-Gb/s data rate signal will limit the transmission distance in the optical network to within a few kilometers by using on–off keying (OOK) modulation due to the fiber chromatic dispersion. In addition, the unavailability of the commercial 40-Gb/s burst-mode receiver (Rx) is also one of the major restrictions to deploying the 40-Gb/s TDM-PON system. Furthermore, to reduce the cost of the future fiber access networks, long-reach (LR) PONs have also been proposed and studied [10]–[13].

Here we propose and investigate a simple and efficient architecture to achieve 40-Gb/s LR TDM-PON deployment using four wavelength-division-multiplexed (WDM) 10-Gb/s external modulated distributed-feedback laser diodes (DFB-LDs) acting as the optical transmitters for downstream and upstream directions. As a result, a 40-Gb/s traffic can be efficiently achieved without changing the network infrastructure. In addition, the proposed 40-Gb/s LR TDM-PON requires a moderate upgrade of components at the optical networking unit (ONU) and the optical line terminal (OLT). The synchronization of these four externally modulated DFB-LDs and the four burst-mode Rxs is performed in the media access controller (MAC) layer. Using external modulation and optical amplifiers could increase the deployment cost of the LR-PON. However, these LR-PONs would replace the separate metro and access networks with a single and integrated system. This approach is expected to produce significant capital and operational cost savings, since the number of network elements and interfaces can be reduced, together with the design complexity and power consumption [13].

II. Experiment and Discussion

The experimental setup of the proposed 40-Gb/s LR TDM-PON is illustrated in Fig. 1. At the OLT, the 40-Gb/s downstream signal is achieved by using four WDM DFB-LDs with 10-Gb/s external OOK modulation. In the experiment, a Mach–Zehnder modulator (MZM) was used. As shown in Fig. 1, the four DFB-LDs (LD_1 to LD_4) are multiplexed by a 4×1 wavelength-division multiplexer (WDM) with insertion loss of 5 dB. The downstream traffic is broadcasting through a three-port optical circulator (OC) and 80-km standard single-mode fiber (SMF) to the remote node (RN). In the RN, a bidirectional erbium-doped fiber amplifier (EDFA) is used to compensate the insertion losses of other components and a $1 \times N$ optical splitter (SP) is used for broadcasting downstream information to ONUs. In each ONU, the upstream signals are also produced by four WDM DFB-LDs with 10-Gb/s OOK external modulation to achieve 40 Gb/s. Besides, the inset of Fig. 1 shows the wavelength arranging for the downstream and upstream channels.

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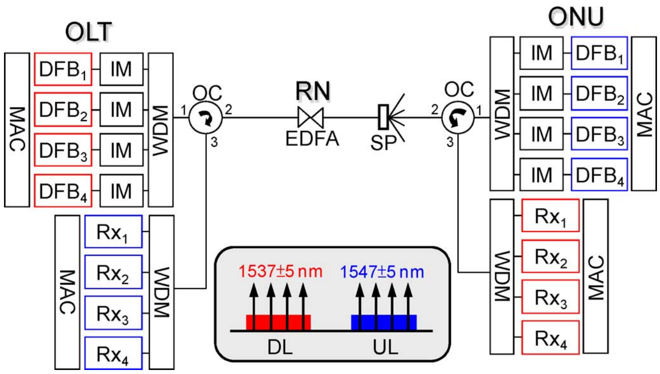

Fig. 1. Proposed LR TDM-PON architecture. DFB: distributed-feedback laser diode; IM: intensity modulator; WDM: wavelength-division multiplexer; SMF: single-mode fiber; RN: remote node; MAC: media access control; ONU: optical networking unit; Rx: receiver.

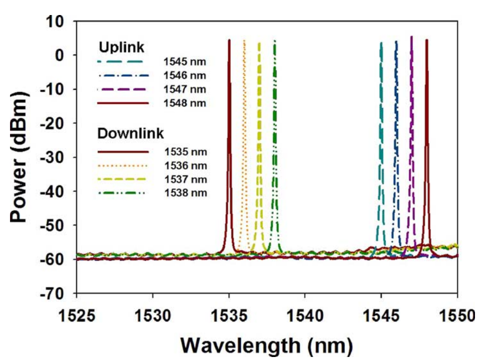

Fig. 2. Measured optical spectra of four downstream channels (from 1535 to 1538 nm) and upstream channels (from 1545 to 1548 nm), respectively.

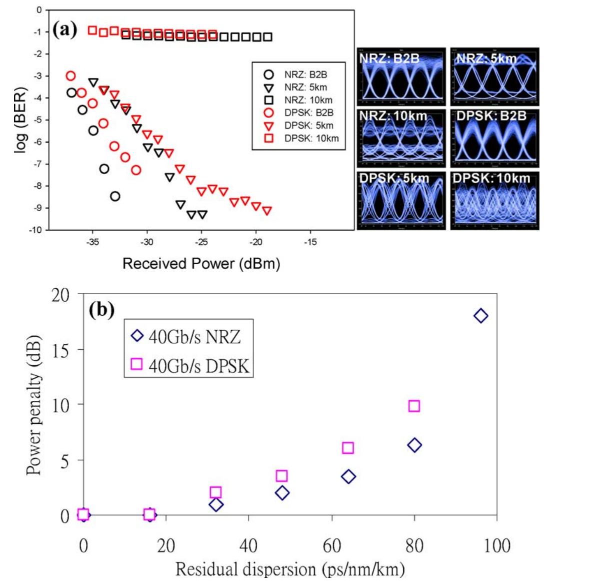

Fig. 3. (a) Numerical analysis of BER performance at 40-Gb/s NRZ and DPSK modulation formats under B2B, 5-, and 10-km transmission, respectively. (b) Received power penalty under different residual dispersion at 40-Gb/s NRZ and DPSK modulation formats. The insets are the corresponding eye diagrams.

Fig. 2 shows the optical spectra of downstream and upstream wavelengths which are measured by an optical spectrum analyzer (OSA) with a resolution of 0.01 nm. In the experiment, four WDM wavelengths at 1535, 1536, 1537, and 1538 nm with output powers of about 3, 2.9, 2.7, and 2.7 dBm, respectively, are used for downstream channels. And another four wavelengths at 1545, 1546, 1547, and 1548 nm, with output powers of about 2.7, 2.8, 3.1, and 3 dBm, respectively, are used for upstream signals. Each DFB-LD is modulated at 10-Gb/s nonreturn-to-zero (NRZ) format, with a pseudorandom binary sequence (PRBS) of $2^{31}-1$ by intensity modulator (IM).

In the 40-Gb/s TDM access network, a single channel with 40-Gb/s data rate could be used. In accordance with the present PON standards [1]–[3], the maximum transmission length is 20 km. However, the transmission of 40-Gb/s OOK signal would be limited by fiber chromatic dispersion. Here, we use commercial software (VPI Transmission Maker V7.5) to numerically analyze the 40-Gb/s OOK and differential phase-shift keying (DPSK) downstream signals in the PON. In the simulation, both signals are at 1545 nm, average output power of 0 dBm. The OOK and DPSK signals are generated by an MZM and a phase modulator, respectively. Both signals are launched into different lengths of SMF (dispersion parameter $= 17$ ps/nm/km). The DPSK is demodulated by using a 1-bit delay interferometer and is detected using single-end. Fig. 3(a) shows the bit-error-rate (BER) performance at back-to-back (B2B), 5- and 10-km transmission, respectively. We can observe the power penalties of 6.3 and 9.8 dB at the BER of 10^{-9} of OOK and DPSK in 5-km transmission due to fiber chromatic dispersion. When the transmission extends to 10 km, the BER almost cannot be measured, as also seen in Fig. 3(a). The insets of Fig. 3(a) show the corresponding eye diagrams. We also studied the case when dispersion compensation is used. In the simulation, a 20-km standard SMF was dispersion compensated by dispersion-compensating fiber (DCF). However, exact dispersion compensation never occurs due to the temperature changes and/or different dispersion slopes of the SMF and DCF. Fig. 3(b) shows that power penalty of $\sim$2 dB was observed in the NRZ signal when residual dispersion was 48 ps/nm/km ($\sim$3 km of SMF). As a result, in order to overcome the fiber dispersion at higher data rates, we could employ four WDM channels with 10 Gb/s to perform the 40-Gb/s transmission in TDM-PON.

In the experimental BER measurement of our proposed LR-PON, we use a 1545-nm wavelength to represent the data traffic. Fig. 4 presents the BER performance under B2B, 75- and 100-km transmission lengths, respectively. As shown in Fig. 4, error-free operation can be achieved when the transmission distance is up to 100 km. The 3- and 4-dB power penalties were observed after 75- and 100-km transmission of SMF, respectively. The power penalties were due to the dispersion of the SMF since no dispersion compensation was used. The corresponding eye diagrams are also shown in the insets of Fig. 4.

Signal splitting capability is one important issue in a TDM-PON. Here, the split-ratio of our proposed scheme is also investigated. Fig. 5 shows the BER performances of 10-Gb/s NRZ data at wavelength 1545 nm with PRBS $2^{31}-1$ with different split-ratio in the transmission link of 75 and 100 km without any dispersion compensation. The corresponding eye diagrams are shown in the insets of Fig. 5. According to the

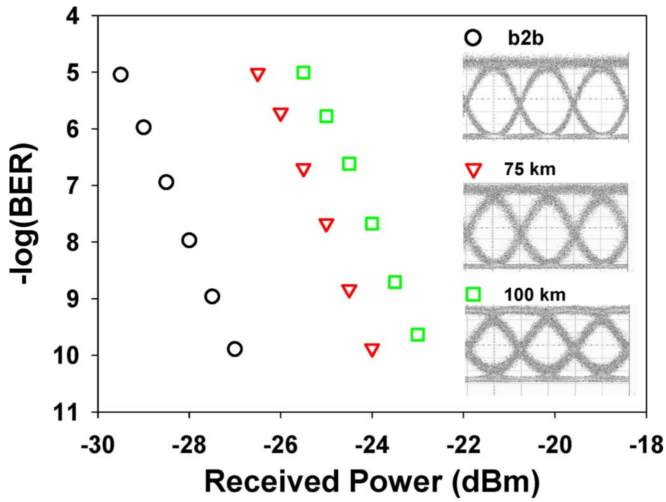

Fig. 4. BERs versus received optical power of the proposed 40-Gb/s TDM-PON with B2B, 75-, and 100-km SMF transmission. Insets: the corresponding eye diagrams of B2B, 75-, and 100-km SMF transmission at 1545-nm wavelength.

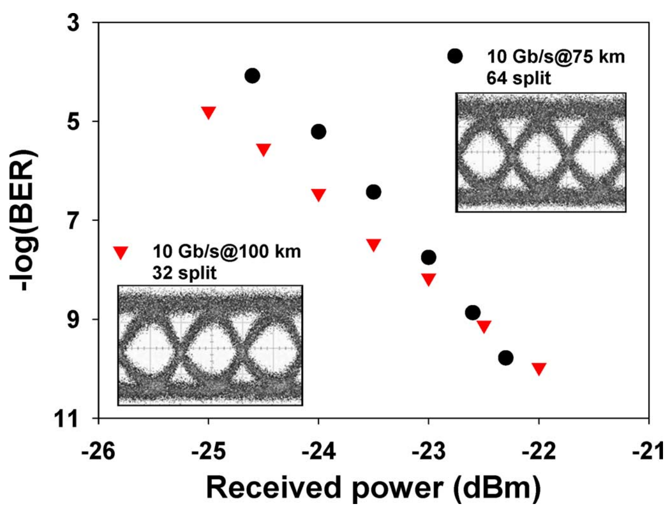

Fig. 5. BER performances of 10-Gb/s NRZ signals with 64- and 32-split after 75- and 100-km SMF transmission link, respectively. Insets show the corresponding eye diagrams.

proposed PON system, the error-free operation can both be achieved with 64- and 32-split after 75- and 100-km SMF transmission, respectively. At the OLT, each 10-Gb/s wavelength channel of the 40-Gb/s downstream signal has an average optical power of 3 dBm (after wavelength multiplexed by the first WDM coupler). By considering the insertion losses of the circulator = 0.5 dB, 100-km fiber loss = 20 dB, typical 1×64 optical splitter = 20 dB, and the second WDM coupler at the ONU = 5 dB. When the EDFA has a gain = 27 dB and the Rx sensitivity at BER of $10^{-9} = -22$ dBm, the power budget of the 100-km reach system supporting 64 ONUs (each ONU has a symmetric downstream and upstream data rates of 40 Gb/s) is 6 dB. In our measurement, as shown in Fig. 5, we can achieve 32 splits at 100-km transmission. This is mainly limited by the signal-to-noise ratio of the signal. Although only the upstream signal was demonstrated, the downstream signal will have similar performances.

III. Conclusion

We have proposed and experimentally demonstrated a network architecture to achieve 40-Gb/s TDM-PON by employing four WDM 10-Gb/s externally OOK modulation channels. The transmission and the split-ratio of our proposed scheme have been analyzed. Error-free operation can be observed under 75- and 100-km SMF transmission with 64 and 32 split-ratios, respectively, without dispersion compensation. We believe that the proposed architecture could be a promising candidate for next-generation 40-Gb/s TDM-PON.

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