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Demonstrations of 10 and 40 Gbps upstream transmissions using 1.2 GHz RSOA-based ONU in long-reach access networks

C.H. Yeh [a,*], C.W. Chow [b], Y.F. Wu [a,b], H.Y. Chen [a]

[a] Information and Communications Research Laboratories, Industrial Technology Research Institute (ITRI), Chutung, Hsinchu 31040, Taiwan
[b] Department of Photonics and Institute of Electro-Optical Engineering, National Chiao Tung University, Hsinchu 30010, Taiwan

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ABSTRACT

Carrier-distributed long-reach passive optical network (LR-PON) is a promising candidate for future access networks. In this work, we analyze and compare the 4 × 2.5 Gb/s and 4 × 10 Gb/s upstream traffics in a carrier-distributed LR-PON using four wavelength-multiplexed 2.5 Gb/s on–off keying (OOK) and 10 Gb/s optical orthogonal frequency division multiplexing-quadrature amplitude modulation (OFDM-QAM) signals. Four commercial 1.2 GHz bandwidth reflective semiconductor optical amplifiers (RSOAs) are used in each optical networking unit (ONU) for the generation of the upstream signal. Due to the limited bandwidth of the RSOA, only up to 2.5 Gb/s upstream OOK signal can be generated. However, by using the spectral efficient modulation, such as OFDM-QAM, 10 Gb/s data rate can be achieved. 20, 50 and 75 km fiber transmissions are also compared using the two different kinds of modulation respectively.

1. Introduction

Due to the increase in popularity of broadband multi-services, such as the data, voice, IPTV, CATV, HD-TV, and 3D-TV, the passive optical network (PON) would be the promising solution for next generation broadband PON system [1,2]. Thus, to deliver the high-speed and broadband services economically, the operators must reduce the cost to maintain the profit margins. The possible access technology is to simplify the optical network configuration. And therefore the number of equipment interfaces and network components can be minimized. Hence the long-reach (LR) PONs have been proposed and investigated to overcome this issue [1,3]. The metro and access networks can be integrated into a single system for the LR-PON. The LR-PON also has the benefits of high capacity, high split-ratio (hence can support more users), and LR transmission (>60 km) [4]. However, in some WDM-PONs, such as the extended-reach WDM-PON (60–100 km), optical amplifiers are usually required to compensate the transmission loss. The optical amplifier, such as erbium doped fiber amplifier, has the limited bandwidth of 30 nm. Hence it is not possible to increase the capacity by simply increasing the number of wavelength channels.

Furthermore, hybrid wavelength division multiplexing–time division multiplexing (WDM–TDM) PON has been selected as a potential solution in PON [5,6]. Because of the bandwidth-sharing of the TDM-PON, the WDM–TDM PON would provide a relatively lower per-subscriber cost than the pure WDM-PON by dividing a single wavelength to multiple subscribers, while still keeping a relatively high per-subscriber bandwidth [7]. In these hybrid WDM–TDM PONs, using centralized light source (CLS) in central office (CO) has been proposed to reduce the cost and simply the wavelength management by removing the laser source from each optical network unit (ONU) for colorless operations [8]. However, the upstream signal generated by the CLS will result in Rayleigh backscattering (RB) interferometric beat noise at the optical receiver (Rx) in the CO. Several methods, such as the phase and bias-current dithering, wavelength shifting, and advanced modulation formats, have been proposed in order to mitigate the RB noise in PONs [1,9].

Besides, the standardized 10 Gb/s TDM- or WDM–TDM PONs may not be enough to support the multimedia services in the future fiber access [10,11]. Hence, PONs may need to upgrade to 40 Gb/s [12] due to the high quality video bandwidth demand of 1 Gb/s for single user in the future [13]. Employing single wavelength with 40 Gb/s data traffic for single-mode fiber (SMF) transmission could be possible, however the 40 Gb/s single channel would limit the fiber transmission length within a few kilometers using on–off keying (OOK) modulation due to the fiber chromatic dispersion [14]. In addition, the 40 Gb/s upstream traffic requires 40 Gb/s burst-mode Rx for TDM access. Due to the unavailability of commercial 40 Gb/s burst-mode Rx, the deployment of 40 Gb/s PON will be restricted. In order to solve the dispersion and burst-mode Rx issues, four wavelength-multiplexed lasers have been proposed and used in each ONU to achieve 4 × 2.5 or 4 × 10 Gb/s

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[*] Corresponding author. Address: Industrial Technology Research Institute (ITRI), Bldg. 14, 195, Sec. 4, Chung-Hsing Rd., Chutung, Hsinchu 31040, Taiwan.
E-mail addresses: yeh1974@gmail.com, depew@itri.org.tw (C.H. Yeh).

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upstream data rates [15,16]. Usually, reflective semiconductor optical amplifier (RSOA) was used in each ONU for colorless transmission in the carrier-distributed PON systems. And the present commercially available 1.2 GHz bandwidth RSOA could only achieve ~2.5 Gb/s OOK remodulation even under a high injection power [8].

In this work, for the downstream case, we use four channels of 10 Gb/s OOK signals to generate the 4 × 10 Gb/s downstream signal. For the upstream case, RSOA is used for the cost-sensitive ONU and the direction modulation bandwidth is about 1.2 GHz. We use four channels of 10 Gb/s optical orthogonal frequency division multiplexing-quadrature amplitude modulation (OFDM-QAM) signals to generate the 4 × 10 Gb/s downstream signal. The OFDM-QAM signal is very spectral efficient. As described in the technology roadmap of the next-generation (NG) PON in Ref. [17], OFDM is considered as a promising option for higher data rate operation in NG-PON2. However, when upgrading from the present GPON and EPON to 10 Gb/s PON or higher bit-rates, using OFDM signal can be an alternative since lower bandwidth optical components optimized for GPON and EPON can still be used.

Hence a symmetric 40 Gb/s upstream and 40 Gb/s downstream PON is constructed. Besides, for the upstream signal, four channels of 2.5 Gb/s OOK (4 × 2.5 Gb/s) is also included for comparison. Due to the limited bandwidth of the RSOA, we can only over-modulate the RSOA to up to 2.5 Gb/s using OOK signal. Besides, our proposed PON can mitigate the RB beat noise by using dual-feeder fiber architecture together with an optical circulator (OC) in each ONU.

2. Experiment and discussions

Fig. 1 shows the experiment setup for the proposed LR-PON system. For the downstream transmission, four wavelength-multiplexed CW lasers, which are 1546.0, 1546.8, 1547.6 and 1548.4 nm in the CO, respectively, are used to generate 4 × 10 Gb/s OOK downstream data rates via four Mach–Zehnder modulators (MZMs). And the measured output powers of four downstream wavelengths are nearly 5.0 dBm before leaving the CO. The 4 × 10 Gb/s OOK downstream traffic is transmit to the optical Rx in each ONU via a three ports OC at the CO [port 1 → port 2], the upper SMF, and the 4-ports OC at the ONU (port 3 → port 4), as illustrated in Fig. 1. In the experiment, the SMF lengths of 20, 50 and 75 km are used for the signal transmission and performance analysis. In the CO, we also use four CW wavelengths, which are 1550.1, 1550.9, 1551.7 and 1552.5 nm, respectively, acting as the external injection light source and launching into each RSOA on ONU for the upstream signal generation. As shown in Fig. 1, the CW injection wavelengths leave the CO via the lower SMF and four ports OC (port 1 → port 2) before injecting into RSOA for upstream signal generation. Therefore, 4 × 2.5 and 4 × 10 Gb/s RSOA-based transmitters can be achieved by applying 2.5 Gb/s OOK and 10 Gb/s 64-QAM OFDM modulations to the RSOA, respectively. And then the upstream signals transmit via the OC at the ONU (port 2 → port 3), upper SMF and OC at the CO (port 2 → port 3) for the upstream traffic. RB can be mitigated in the proposed network.

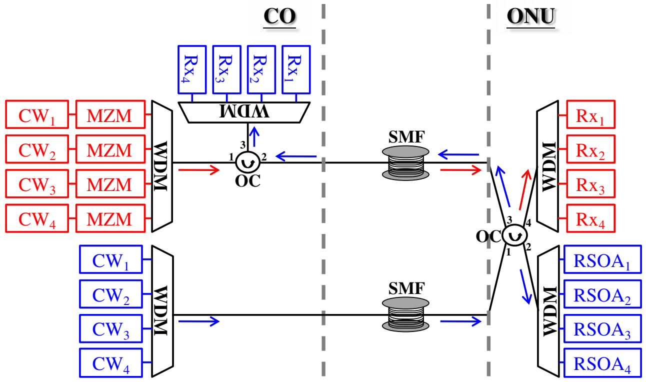

Fig. 1. Experimental setup of the proposed LR-PON for 4 × 2.5 and 4 × 10 Gb/s upstream RSOA-based ONU by OOK and OFDM modulations, respectively.

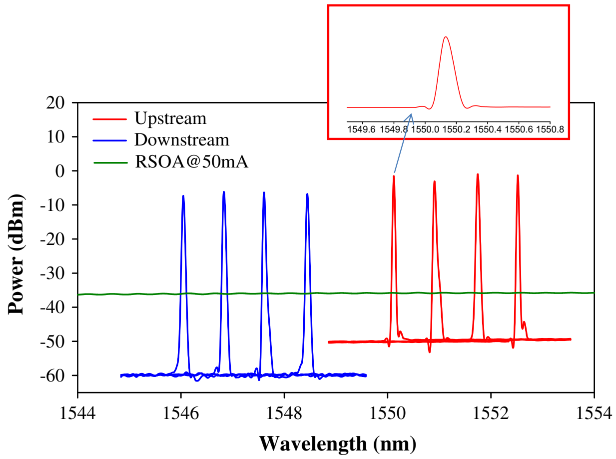

Fig. 2. Output spectra of downstream (blue line), upstream wavelengths (red line) and ASE of RSOA (green line) in the experiment, when the bias current of RSOA is 50 mA. Insert is the enlarged spectrum of 1550.1 nm upstream signal.

In the experiment, the output spectra of downstream (blue[1] line) and upstream wavelengths (red line) are measured by an optical spectrum analyzer (OSA) with a 0.01 nm resolution, as shown in Fig. 2. And the four wavelength-multiplexed downstream and upstream channels are with 0.8 nm channel-spacing (100 GHz) for data traffic at the wavelengths of 1546.0, 1546.8, 1547.6 and 1548.4 nm and 1550.1, 1550.9, 1551.7 and 1552.5 nm, respectively. Besides, Fig. 2 also presents the amplified spontaneous emission (ASE) spectrum of RSOA (green line) operating at 50 mA bias current. In Fig. 2, the background ASE noise of RSOA would be reduced by 15 dB while the four CW wavelengths are injected.

First of all, we demonstrate the downstream traffic in the proposed PON. In the CO, four downstream wavelength-multiplexed signals are modulated by four MZMs with 10 Gb/s OOK format to achieve 40 Gb/s downstream data rate. As illustrated in Fig. 1, the four downstream signals are multiplexed by 1 × 4 wavelength-division-multiplexer (WDM) with 0.8 nm channel-spacing. The downstream traffic will transmit through an OC and a standard SMF to each ONU. In this measurement, SMF lengths of 20, 50 and 75 km are used to analyze the performance of the proposed PON. And these signals are received using a 10 GHz PIN receiver (Rx) without optical pre-amplification. We select the 1546.0 nm wavelength channel for the bit error rate (BER) measurement. It is modulated by a 10 Gb/s non-return to zero (NRZ) signal, with pseudorandom binary sequence (PRBS) of $2^{31}-1$. Fig. 3 presents the measured BER performances of the downstream traffic under B2B, 20, 50 and 75 km SMF transmissions, respectively, without dispersion compensation. In Fig. 3, the power penalties of 0.6, 0.9 and 3.1 dB are also observed at the BER of 10^{-9} after 20, 50 and 75 km SMF transmissions, respectively. And the corresponding Rx sensitivities of −17.5, −16.9, −16.6 and −14.4 dBm are also retrieved. Besides, the insets of Fig. 3 are the corresponding eye diagrams, and these measured eyes are clear and widely open after different SMF transmissions.

In this session, we will show the experiment and discuss the RSOA-based ONU for 4 × 2.5 and 4 × 10 Gb/s upstream data rate

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[1] For interpretation of color in Fig. 2, the reader is referred to the web version of this article.

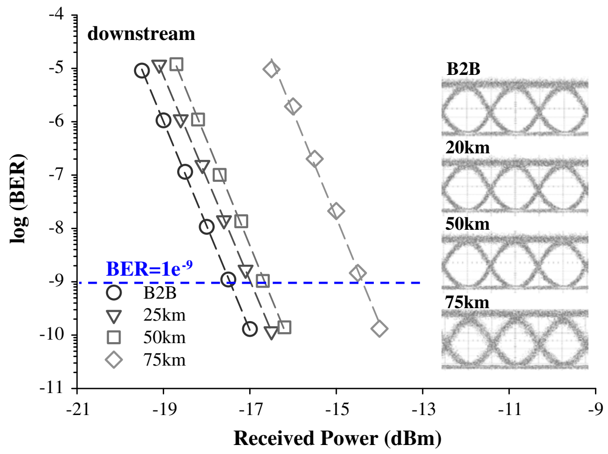

Fig. 3. BER measurements of the downstream traffic under B2B, 20, 50 and 100 km SMF transmissions, respectively, at 1546.0 nm wavelength with 10 Gb/s OOK format. The insets are the corresponding eye diagrams.

by using 2.5 Gb/s OOK and 10 Gb/s OFDM-QAM modulations, respectively. In the experiment, a commercial 1.2 GHz bandwidth RSOA (CIP) is used. Fig. 4a presents the different output powers of the RSOA under various CW injection powers from −15 to 5 dBm. The CW is selected at 1550.1 nm wavelength in this measurement. To obtain the output power of the RSOA at about 5 dBm similar to the downstream signal, the CW injection power must be larger than −1 dBm, as seen in Fig. 4a. Furthermore, the relaxation oscillation frequency of RSOA can be increased by optical injection [8], hence higher optical power can increase the modulation speed of the RSOA. Fig. 4b shows the different output powers of RSOA at −1 dBm CW injection power, when the bias currents of the RSOA are from 20 to 80 mA. When the bias current is 50 mA, the output power can be observed at 5.1 dBm. As shown in Fig. 4b, the output power would start to saturate when the bias current is larger than 60 mA.

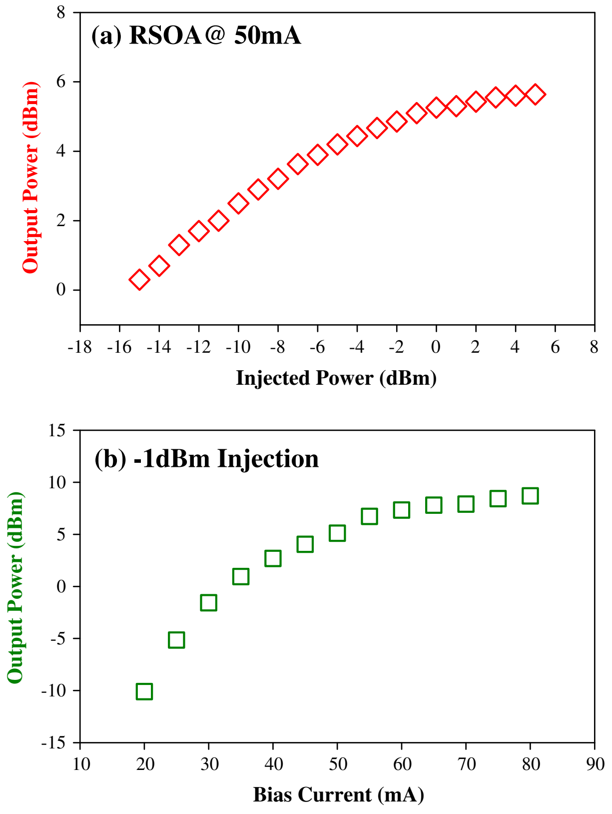

Fig. 4. (a) The different output powers of RSOA versus CW injection powers of −15 to 5 dBm at the wavelength of 1550.1 nm while the RSOA is 50 mA. (b) The different output powers for the −1 dBm CW injection power when the bias currents are 20–80 mA applying on RSOA.

At the ONU, the baseband OFDM upstream signal was produced by using an arbitrary waveform generator (AWG) via the Matlab® program. The signal processing of the OFDM transmitter consists of serial-to-parallel conversion, QAM symbol encoding, inverse fast Fourier transform (IFFT), cyclic prefix (CP) insertion, and digital-to-analog conversion (DAC). 12 GSample/s sampling rate and 8-bit DAC resolution are set by the AWG, and CP of 1/64 is used. Thus, 72 subcarriers of 64-QAM format occupy nearly 1.66 GHz bandwidth of 0.26–1.92 GHz, with a fast-Fourier transform (FFT) size of 512. Here, yielding ∼22 MHz subcarrier spacing and ∼10 Gbps total data rate is achieved. Thus, the produced electrical 64-QAM OFDM signal can be applied on RSOA via a bias-tee (BT). According to the above discussion, we set the bias current of RSOA at 50 mA for upstream signal remodulation via optical OFDM-QAM modulation in the next experiment. Then the upstream signal propagates via the OC and lower SMF to the CO, as shown in Fig. 2. The upstream signal is directly detected via a 2.5 GHz PIN receiver at the CO without using pre-amplifier, and the received OFDM signal is captured by a real-time 12.5 GHz sampling oscilloscope for signal demodulation. To demodulate the vector signal, the off-line DSP program is employed. And the demodulation process contains the synchronization, FFT, one-tap equalization, and QAM symbol decoding. Therefore, the bit error rate (BER) can be calculated based on the observed signal-to-noise ratio (SNR). Therefore, if we want to get the better BER performance, to obtain the higher SNR would be an important issue.

Fig. 5a–d shows the measured SNR of each OFDM subcarrier in the frequency bandwidth of 0.26–1.92 GHz at the back-to-back (B2B), 20, 50 and 75 km SMF transmissions, respectively, without dispersion compensation, when the CW injection power levels of −5, −3, −1 and 1 dBm are used. In this measurement, the optical received power is set at −6 dBm. When the CW injection power of −5 dBm is launched into RSOA, the entire measured subcarriers can achieve the forward error correction (FEC) threshold (BER = 3.8×10^{-3} (SNR = 21.2 dB) and redundancy ratio of 7%) [18], at the B2B and 20 km fiber transmission, respectively, as shown in Fig. 5a and b. For the 50 km transmission as shown in Fig. 5c, −1 dBm CW injection power is required when the received SNR of all the subcarriers >21.2 dB. When the SMF length extends to 75 km long and the injection power is −1 dBm, one third of the subcarrier at the higher frequency band cannot have the measured SNR above the FEC limit as shown in Fig. 5d. This is due to fiber chromatic dispersion in the LR transmission.

We can also observe that when the CW injection power is decreased, the OFDM subcarriers at high frequency will experience SNR penalty owing to the reduction in relaxation oscillation frequency of the RSOA. This can be observed from Fig. 5a–d.

Based on the measured SNR performance of all the subcarriers in the OFDM signal, the average BER can be evaluated. Fig. 6 shows the BER measurements of the RSOA-based transmitter using optical 64-QAM OFDM modulation for upstream traffic at the B2B, 20, 50 and 75 km SMF transmissions, respectively, when the injection wavelength and power are set at 1550.0 nm and −1 dBm respectively. Here, we can observe the power penalties of 0.4, 2.1 and 5.3 dB after 20, 50 and 75 km SMF transmissions without dispersion compensation, respectively. Although one third of the subcarrier SNR is below FEC limit in 75 km fiber link, as shown in Fig. 5d, the measured average BER still can achieve FEC for LR transmission. Besides, the insets of Fig. 6 are corresponding constellation diagrams at the BER of 3.8×10^{-3}. In Fig. 6, we can also

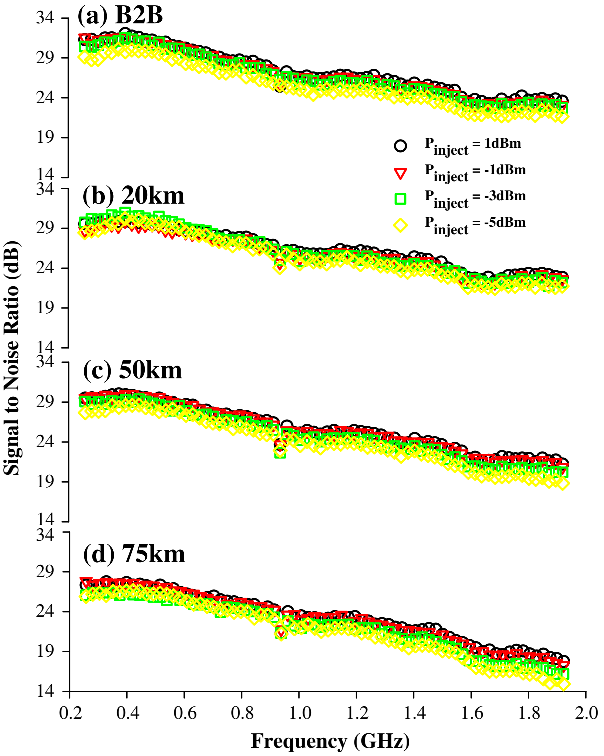

Fig. 5. Measured SNR of each OFDM subcarrier in the frequency bandwidth of 0.26–1.92 GHz at: (a) B2B, (b) 20, (c) 50 and (d) 75 km SMF transmissions, respectively, without dispersion compensation, when the different CW injection power levels of −5 to 1 dBm are launching into RSOA.

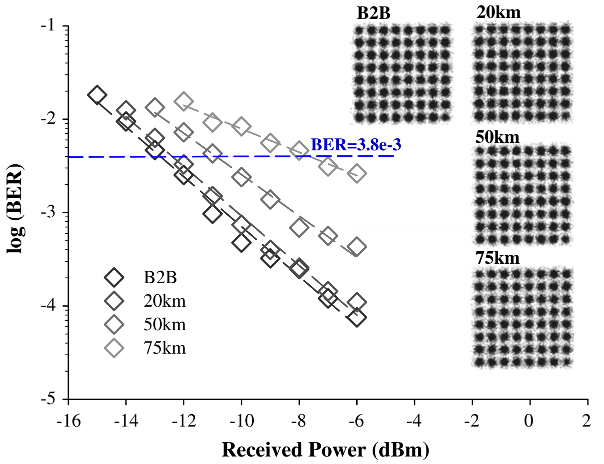

Fig. 6. Measured BER measurements of the RSOA-based transmitter via optical 64-QAM OFDM modulation for upstream transmission at the B2B, 20, 50 and 75 km SMF propagations, respectively, when the CW injection wavelength and power are 1550.0 nm and −1 dBm. The inserts are the corresponding constellation diagrams.

measure the Rx sensitivities are −12.8, −12.4, −10.7 and −7.5 dBm at B2B, 20, 50 and 75 km fiber transmissions, respectively at the FEC limit. When the transmission fiber length is extended to 100 km long, the average BER cannot achieve FEC limit for upstream traffic.

In this proof-of-concept experiment, we use the arbitrary waveform generator (AWG) and real-time oscilloscope as the DA and AD converters for OFDM generation and demodulation. The BER measurements are performed off-line. Very high speed real-time OFDM transmitter (DAC output delivers 28 GS/s and feeds the IQ-modulator for generating a 101.5 Gbit/s [19]) and OFDM receiver (operates at 41.25 Gb/s [20]) have been demonstrated in research. For practical PON implementation, we could use the 2 GS/s sampling rate and six bits resolution DA/AD converter for OFDM encoding and decoding.

Then we experiment the RSOA-based transmitter using 2.5 Gb/s OOK modulation. In the measurement, we use the same operation conditions as mentioned above. While the −1 dBm injection power launches into RSOA from the CO, the RSOA could be directly modulated at 2.5 Gb/s OOK format with the pattern length of PRBS of $2^{31}-1$. Fig. 7 shows the measured BER performances of upstream traffic at B2B, 20, 50, 75 and 100 km SMF transmissions without dispersion compensation, respectively. And the insets are the corresponding eye diagrams at the BER of 10^{-9}. In Fig. 7, we can observe the Rx sensitivities are −18.7, −18.2, −18.0, −17.9 and −17.9 dBm at B2B, 20, 50, 75 and 100 km fiber transmissions, respectively, at BER of 10^{-9}. In Fig. 7, we cannot only achieve 100 km SMF transmission, but also obtain the similar power penalty of ∼0.8 dB at BER of 10^{-9} in both 75 and 100 km fiber transmissions.

In order to achieve the different SMF transmissions of 20, 50, 75 and 100 km when the RSOA is directly modulated at 2.5 Gb/s OOK format, respectively, we also experiment and analyze the relationship of the observed penalty and minimum injection power level. Hence, when the fiber transmission length is achieved to 20, 50, 75 and 100 km at the BER level of 10^{-9}, respectively, the minimum CW injection power must be −10, −9, −7 and −5 dBm injecting into RSOA, as shown in Fig. 8. And, their corresponding power penalties are also observed at 0.5, 1, 1.5 and 2.2 dB respectively. For example, if we want to have a 75 km fiber transmission length in the PON, the minimum required CW injection power is −7 dBm for achieving BER of 10^{-9}.

According to the results of Figs. 6 and 7, using 10 Gb/s OFDM modulation in RSOA only can achieve 75 km fiber transmission at FEC threshold; together with 5.3 dB power penalty without dispersion compensation, and its corresponding sensitivity is −7.5 dBm without optical amplification. If we employ the 2.5 Gb/s OOK modulation in RSOA, the measured penalty of 0.8 dB can be observed after 75 km SMF transmission, and its corresponding sensitivity is measured at −17.9 dBm. And, the 2.5 Gb/s OOK signal even can transmit through 100 km with 0.8 dB penalty. As a result, using OFDM modulation on RSOA can enhance the total data rate, but requires the larger CW injection power.

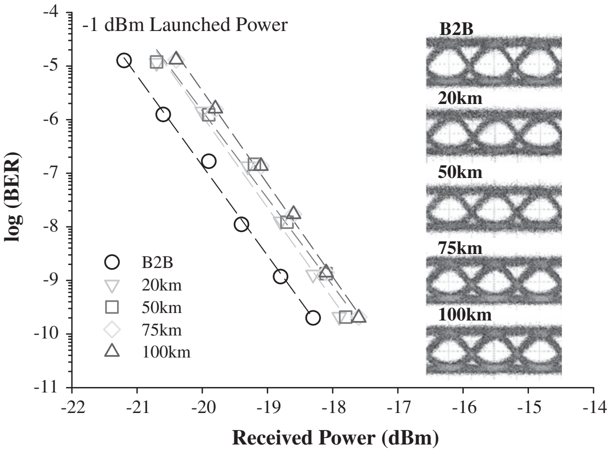

Fig. 7. Measured BER measurements of the RSOA-based transmitter via 2.5 Gb/s OOK modulation for upstream transmission at the B2B, 20, 50, 75 and 100 km SMF transmissions, respectively, when the CW injection wavelength and power are 1550.0 nm and −1 dBm. The inserts are the corresponding eye diagrams.

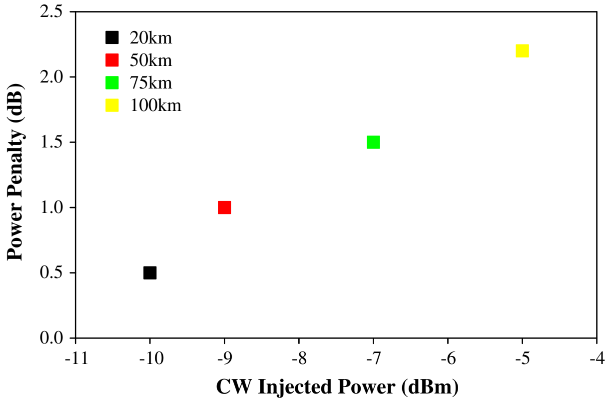

Fig. 8. Measured power penalties of the RSOA-based transmitter via 2.5 Gb/s OOK modulation for upstream transmission at 20, 50, 75 and 100 km SMF transmissions, respectively, under different the CW injection power levels.

3. Conclusion

Carrier-distributed LR-PON is a promising candidate for future access networks. In this work, for the downstream case, we use four channels of 10 Gb/s OOK signals to generate the 4 × 10 Gb/s downstream signal. For the upstream case, RSOA is used for the cost-sensitive ONU and the direction modulation bandwidth is about 1.2 GHz. We use four channels of 10 Gb/s OFDM-QAM signals to generate the 4 × 10 Gb/s downstream signal. The OFDM-QAM signal is very spectral efficient. Hence a symmetric 40 Gb/s upstream and 40 Gb/s downstream PON is constructed. Besides, for the upstream signal, four channels of 2.5 Gb/s OOK (4 × 2.5 Gb/s) is also included for comparison. Due to the limited bandwidth of the RSOA, we can only over-modulate the RSOA to up to 2.5 Gb/s using OOK signal. In the proposed LR-PON, the power penalties of 0.8 and 5.3 dB can be observed at the BERs of 1×10^{-9} and 3.8×10^{-3} after 75 km fiber transmission without dispersion compensation and optical amplification, when the RSOA is directly modulated at 2.5 Gb/s OOK and 10 Gb/s OFDM-QAM modulations, respectively.

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