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# Adaptive upstream rate adjustment by RSOA-ONU depending on different injection power of seeding light in standard-reach and long-reach PON systems

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ABSTRACT

The wavelength division multiplexing-time division multiplexing (WDM-TDM) passive optical network (PON) using reflective semiconductor optical amplifier (RSOA)-based colorless optical networking units (ONUs) is considered as a promising candidate for the realization of fiber-to-the-home (FTTH). And this architecture is actively considered by Industrial Technology Research Institute (ITRI) for the realization of FTTH in Taiwan. However, different fiber distances and optical components would introduce different power budgets to different ONUs in the PON. Besides, due to the aging of optical transmitter (*Tx*), the power decay of the distributed optical carrier from the central office (CO) could also reduce the injection power into each ONU. The situation will be more severe in the long-reach (LR) PON, which is considered as an option for the future access. In this work, we investigate a WDM-TDM PON using RSOA-based ONU for upstream data rate adjustment depending on different continuous wave (CW) injection powers. Both standard-reach (25 km) and LR (100 km) transmissions are evaluated. Moreover, a detail analysis of the upstream signal bit-error rate (BER) performances at different injection powers, upstream data rates, PON split-ratios under stand-reach and long-reach is presented.


## 1. Introduction

Passive optical networks (PONs) are considered as the attractive last mile access with the benefits of high bandwidth, high capacity, easy upgradeability, good security and cost-effectiveness [1–3] in the fiber to the home (FTTH) applications. Therefore, the wavelength-division-multiplexed (WDM) and time-division-multiplexed (TDM)-PONs are the prospective solutions to deal with the increasing demand for bandwidth in access networks [4]. However, the requirement of wavelength-specific laser source is one of the important issues in WDM-PON. To achieve the cost-effective architecture, colorless light sources are desirable for each optical network unit (ONU) in the WDM-PON [5,6]. Recently, different technologies, such as using the tunable light source [7], spectrum-sliced source [8] or amplified spontaneous emission (ASE)-injected Fabry–Perot laser diodes [9], and reflective semiconductor optical amplifier (RSOA)-based remodulated light sources [10,11], have been proposed and investigated for the colorless operations. Among these methods, the RSOA has been considered as an attractive candidate in colorless ONU due to its low polarization sensitive and compact size as it can work as a modulator and a gain medium simultaneously. In order to achieve higher modulation rate, the RSOA requires larger injection power for signal modulation [12].

To reduce the cost and energy used of current PONs, the long reach (LR) PON [13,14] is also considered for an option of PON. Different fiber lengths and optical components inside the PON would introduce different downstream loss budgets. In addition, the power decay of the distributed optical carrier from the central office owing to the aging of optical transmitter (*Tx*) could also reduce the injected power into the RSOA. Hence, these would lead to different power budgets for each ONU and affect the upstream signal performance of the RSOA-based PON and LR PON.

In this demonstration, we demonstrate a RSOA-based WDM-TDM PON in standard-reach (25 km) and long-reach (100 km) with upstream data rate adjustment depending on different injection powers of the distributed CW signal. In the experiment, the upstream data rate can be switched to 622 Mb/s, 1.25 and 2.5 Gb/s, respectively, when the various distributed injection power levels launching into the RSOA in 25 and 100 km fiber transmissions. In addition, the proposed PON system performance has also been analyzed and discussed.

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## 2. Standard-reach PON

Fig. 1 shows the experiment setup for the proposed RSOA-based WDM/TDM PON system with data rate adjustment for upstream traffic in 25 km fiber transmission (standard-reach). As shown in Fig. 1, in the CO, a 1550.0 nm CW laser served as the CW lightwave. The CW lightwave and downstream signal were combined by a red/blue (R/B) filter and then launched into a WDM multiplexer. The CW carrier transmitted through 15 km feeder and 10 km distribution fibers, respectively, via an optical circulator (OC), a WDM multiplexer and an optical splitter (SP), and then into each ONU. In each ONU, the downstream data and CW signals would be separated by another R/B filter, as shown in Fig. 1. Besides, two feeder fibers were used to avoid Rayleigh backscattering (RB) beat noise in the experiment. In each ONU, the CW power was monitored (by $Rx_{(m)}$). The CW was injected into the RSOA for upstream signal remodulation, as shown in Fig. 1.

Different fiber lengths and optical components in PON would introduce different downstream power budgets to different ONUs. And, when the power decay of distributed CW signal occurred, it also affected the injection power into the RSOA. Here, to realize and investigate the relation of modulation rate and injection power on RSOA, different downstream injection powers were used in the experiment. To emulate different downstream powers lunching into the RSOA, we used an optical variable attenuator (OVA) prior to the RSOA to obtain various power levels in a 25 km fiber transmission. Fig. 2 shows the output powers of RSOA versus different CW injection powers at 1550.0 nm between −21 and 1 dBm, while the bias current of RSOA was operated at 80 mA. Here, the maximum and minimum output powers of RSOA were −5.1 and 2.8 dBm for the injected powers of −21 and 1 dBm, respectively.

Then, we would discuss the received power and measured bit error rate (BER) of RSOA-based upstream signal under different injected powers of CW. In this measurement, the RSOA, operating at 80 mA, could be directly modulated at 622 Mb/s, 1.25 Gb/s and 2.5 Gb/s under non-return to zero (NRZ) pseudorandom binary sequence (PRBS) format with pattern length of $2^{31}-1$ under different CW injection powers from −4 to −25 dBm through 25 km single mode fiber (SMF) transmission. The upstream signal was detected by an optically pre-amplified receiver, which consisted of a low-noise erbium doped fiber amplifier (EDFA), optical bandpass fiber to remove the out-of-band amplified spontaneous emission (ASE) and a 2.5 GHz PIN photodiode in the CO. Fig. 3 shows the measured lowest achievable BER values of upstream signal against different CW injection powers into the RSOA at the modulation rates of 622 Mb/s, 1.25 Gb/s and 2.5 Gb/s. Here, to achieve the BER of $10^{-9}$ after 25 km fiber propagation, the CW injection power into the RSOA must be larger than −21, −18 and −10 dBm under the modulation rates of 622 Mb/s, 1.25 Gb/s and 2.5 Gb/s, respectively.

Next, three upstream data rates of 622 Mb/s, 1.25 and 2.5 Gb/s were used in the proposed standard-reach PON for dynamically upstream rate adjustments. Fig. 4 presents the measured BER performance of upstream signal, when the RSOA is directly modulated at 622 Mb/s, 1.25 Gb/s and 2.5 Gb/s NRZ-PRBS format, respectively, with pattern length of $2^{31}-1$ under different CW injection powers among −8 to −21 dBm in 25 km SMF transmission. In this measurement, the CW injection powers into the RSOA of −21, −18 and −10 dBm are required to achieve the modulation rates of 622 Mb/s, 1.25 and 2.5 Gb/s in 25 km transmission,

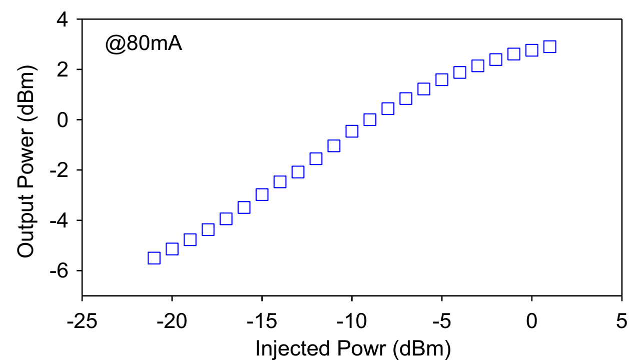


**Fig. 2.** Output powers of RSOA versus different CW injection powers.

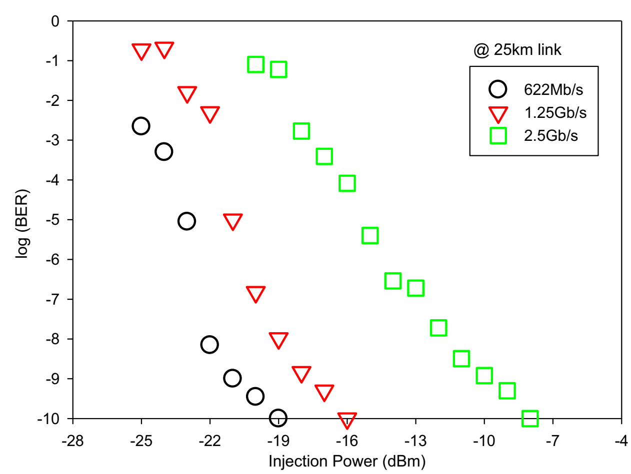


**Fig. 3.** The measured BER of upstream signal when different injection power of CW carrier into RSOA at the various modulation rates of 622 Mb/s, 1.25 Gb/s and 2.5 Gb/s, respectively, after 25 km SMF transmission.

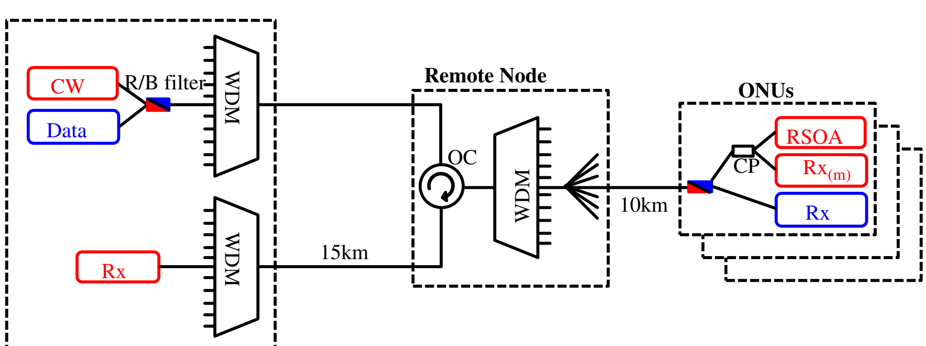


**Fig. 1.** Experimental setup for RSOA-based WDM/TDM PON system with dynamically rate adjustment for upstream traffic in 25 km fiber transmission length.

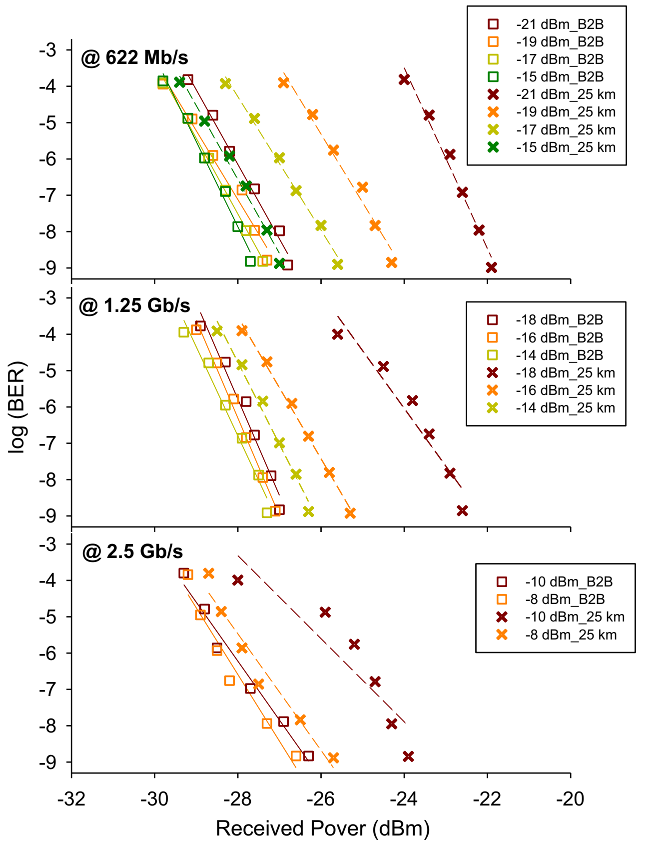


**Fig. 4.** BER performance of upstream signal in 25 km transmission when the RSOA is directly modulated at 622 Mb/s, 1.25 Gb/s and 2.5 Gb/s, respectively, under different downstream injection powers.

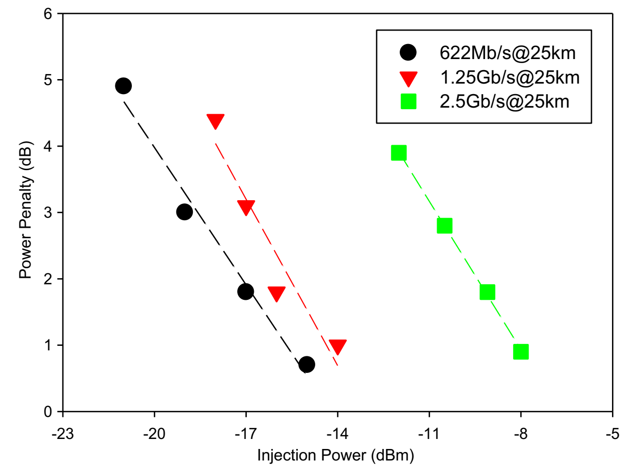


**Fig. 5.** The downstream injection power versus the measured penalty at the BER of $10^{-9}$ under 622 Mb/s, 1.25 and 2.5 Gb/s modulations, respectively, in 25 km fiber transmissions.

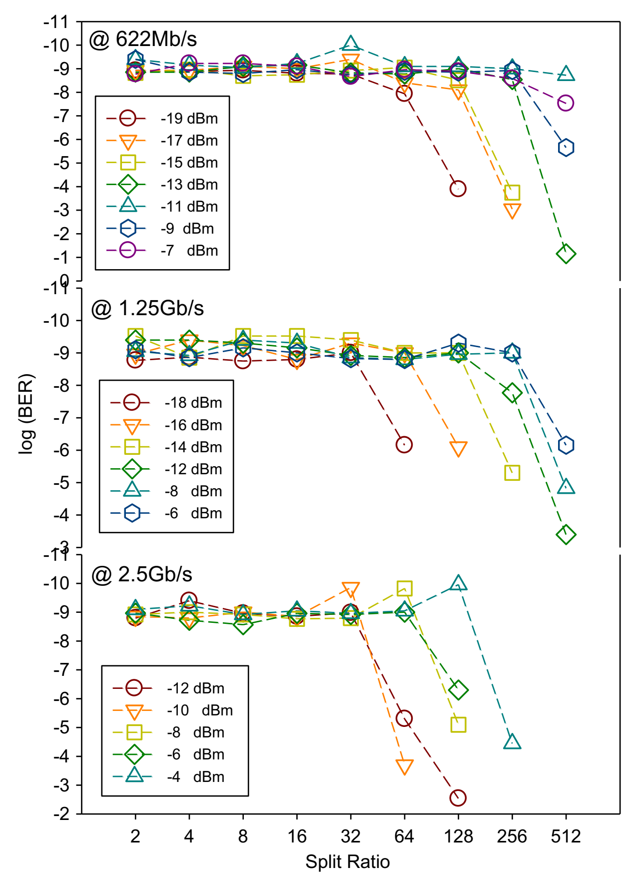


**Fig. 6.** BER curves versus different split ratios at the modulations of 622 Mb/s, 1.25 and 2.5 Gb/s, respectively, while different injection powers are launched into RSOA.

respectively, as shown in Fig. 4. However, these injection powers also introduced the power penalties of 4.8, 4 and 2.4 dB, respectively when compared with the back-to-back (B2B) cases. When the injection powers into the RSOA are −15, −14 and −8 dBm respectively, at 622 Mb/s, 1.25 Gb/s and 2.5 Gb/s modulation rates, the obtained penalties are less than 1 dB as seen in Fig. 4. Here, For example, if we use four WDM channels and each channel can support 16 ONUs in the proposed WDM-TDM PON system with 25 km fiber transmission length. The downstream signal would transmit through an OC (1 dB), a 1 × 4 WDM multiplexer (6 dB), 1 × 16 splitter (12 dB), an R/B filter (1 dB), a 1 × 2 CP (3 dB) and 25 km SMF (5 dB), and then into *Rx* and RSOA simultaneously. Thus, it would result in total power budget of 28 dB. Thus, if the output power from OLT is 7 dBm, the received injection power will become −21 dBm at each ONU. And the upstream signal only can be modulated at 622 Mb/s according to the results of Fig. 4. Hence, in this case, we may need to dynamically adjust the upstream data rate in order to maintain the upstream signal performance.

Furthermore, we also discuss the relationship of power penalties and the CW injection powers in the experiment. Fig. 5 shows the CW injection powers versus the measured penalties at the BER of $10^{-9}$ under 622 Mb/s, 1.25 and 2.5 Gb/s modulations in 25 km fiber transmissions, respectively. If we want to obtain the power penalty within 2 dB, the corresponding injection power levels must be larger than −17.1, −15.6 and −9.4 dBm according to the measured results at the three data rates.

Finally, to investigate the maximum achievable split ratio (number of supported ONUs) in the standard PON system, different split ratios were experimented and analyzed. Fig. 6 presents the BER curves versus split ratios at the modulations of 622 Mb/s, 1.25 and 2.5 Gb/s, respectively, while different injection powers are launched into RSOA. As seen in Fig. 6, when the injection power is −19 dBm, the split ratio is 32 in 622 Mb/s data rate at the BER of $10^{-9}$. If higher split-ratios of 64, 128 and 256 are required, the injection levels must be larger than −15, −13 and −11 dBm respectively at 622 Mb/s rate under the BER of $< 10^{-9}$. Furthermore, when the split-ratios of 32, 64, and 128 are required, the injection powers should be −18 and −12 dBm, −16 and −8 dBm, and −14 and −4 dBm for the modulation rates of

1.25 and 2.5 Gb/s, respectively. Besides, the split ratio can be up to 256 at 1.25 Gb/s when the injection power is −12 dBm, as illustrated in Fig. 6.

## 3. Long-reach PON

In this section, we will discuss and experiment the dynamic upstream rate adjustment in long-reach (LR)–PON. Fig. 7 shows the experimental setup for RSOA-based LR-PON system with dynamically rate adjustment of upstream traffic in 100 km fiber transmission. The 1550.0 nm DFB-LD in CO served as the CW light. The CW signal was transmitted through the 90 km feeder and 10 km distribution fibers respectively, and then into each ONU, as shown in Fig. 8. The exchange node (EN) was consisted of two EDFAs an OC, a WDM multiplexer and a SP. The two EDFAs, having 23 dBm saturated power and 5 dB noise figure, were used to compensate component loss during fiber transmission.

First of all, we investigated the relationship of CW injection power into the RSOA and measured BER for RSOA-based LR-PON. In this measurement, the RSOA, operating at 80 mA, could be directly modulated at 622 Mb/s, 1.25 Gb/s and 2.5 Gb/s NRZ-PRBS modulation, respectively, with pattern length of $2^{31}-1$ under different downstream injection powers among −25 to 5 dBm after 100 km SMF transmission. Fig. 8 shows the measured BER measurements of upstream signal when the different injection powers launches into RSOA at the various modulation rates of 622 Mb/s, 1.25 Gb/s and 2.5 Gb/s, respectively. To achieve the BER of $<10^{-9}$ after 100 km fiber transmission, the CW injected power must be larger than −17, −16 and −5 dBm under the modulation rates of 622 Mb/s, 1.25 Gb/s and 2.5 Gb/s, respectively, as seen in Fig. 8.

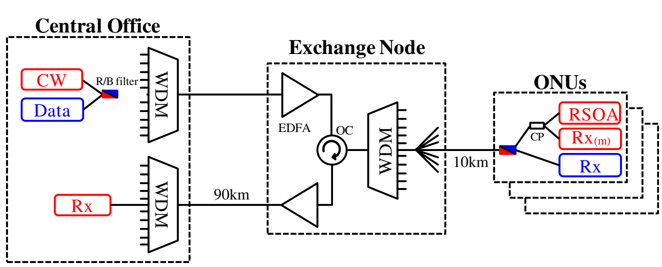


**Fig. 7.** Experimental setup for RSOA-based WDM/TDM PON system with dynamically rate adjustment for upstream traffic in 100 km fiber transmission.

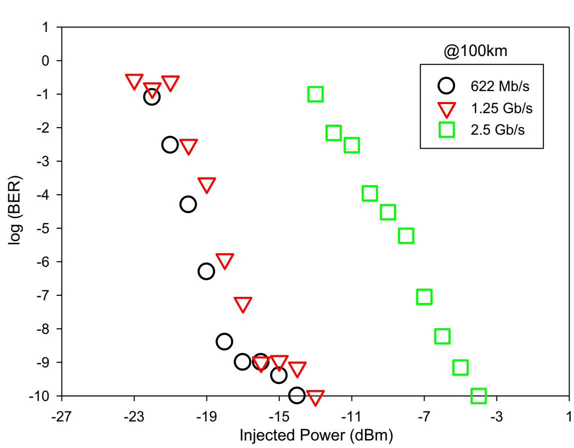


**Fig. 8.** The measured BER of upstream signal when different injection power of CW carrier into RSOA at the various modulation rates of 622 Mb/s, 1.25 Gb/s and 2.5 Gb/s, respectively, after 100 km SMF transmission.

Then, three upstream data rates of 622 Mb/s, 1.25 and 2.5 Gb/s were also used in the LR-PON system for dynamically upstream rate adjustment. Fig. 9 presents the measured BER performances of upstream signal, while the RSOA is directly modulated at 622 Mb/s, 1.25 Gb/s and 2.5 Gb/s NRZ-PRBS format, respectively, with pattern length of $2^{31}-1$ under different CW injection powers between −17 and 1 dBm in 100 km SMF transmission. In this measurement, the minimum injection powers of −17, −16 and −5 dBm are required to achieve the modulation rates of 622 Mb/s, 1.25 and 2.5 Gb/s in 100 km transmission, respectively, as shown in Fig. 9. However, these injection power levels also would introduce the power penalties of 4.3, 3.6 and 3.4 dB, respectively, under the three modulation rates. If the power penalty of within 1 dB is required, the CW injection power should be −13, −14 and −1 dBm respectively, under the three modulation rates, as also shown in Fig. 9. According to the measurement results of Figs. 4 and 9, higher modulation speed and lower power penalty can be obtained by increasing the injection optical power into the RSOA. This is due to the increase in relaxation oscillation frequency of the RSOA.

Next, Fig. 10 shows the injection power into the RSOA versus the measured penalty at the BER of $10^{-9}$ under 622 Mb/s, 1.25 and 2.5 Gb/s modulations in 100 km SMF transmissions, respectively. As shown in Fig. 11, in order to obtain the power penalty of 2 dB, the corresponding injection power levels must be −14.6, −14.6 and −1.3 dBm at the three data rates. Besides, as seen in Figs. 5 and 10, the power penalties of about 1 dB can be obtained in 25 and 100 km SMF transmissions under the same injection power of −14 dBm at 1.25 Gb/s modulation rate. However, as each wavelength channel may experience different optical losses

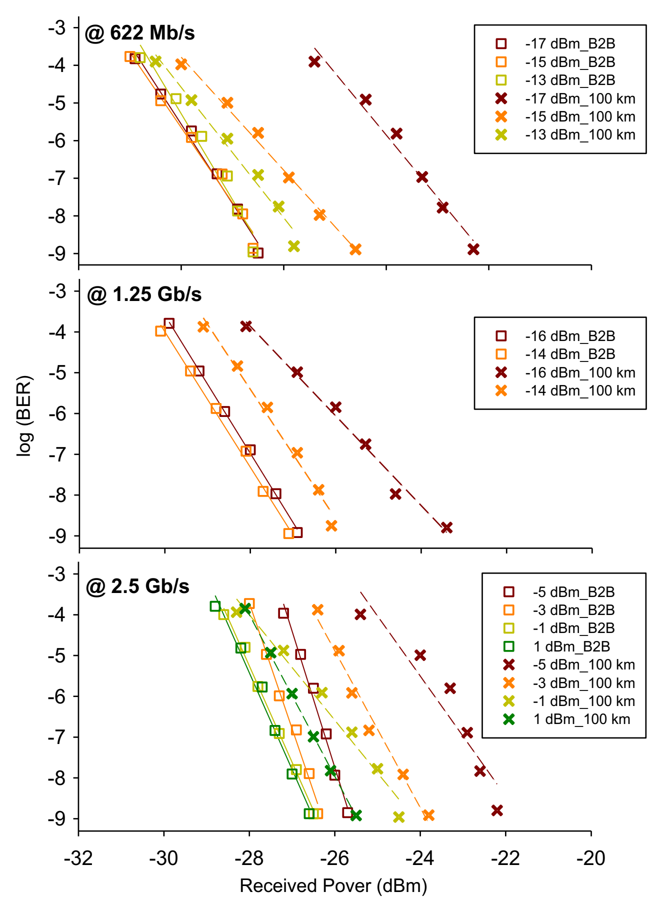


**Fig. 9.** BER performance of upstream signal in 100 km transmission when the RSOA is directly modulated at 622 Mb/s, 1.25 Gb/s and 2.5 Gb/s, respectively, under different downstream injection powers.

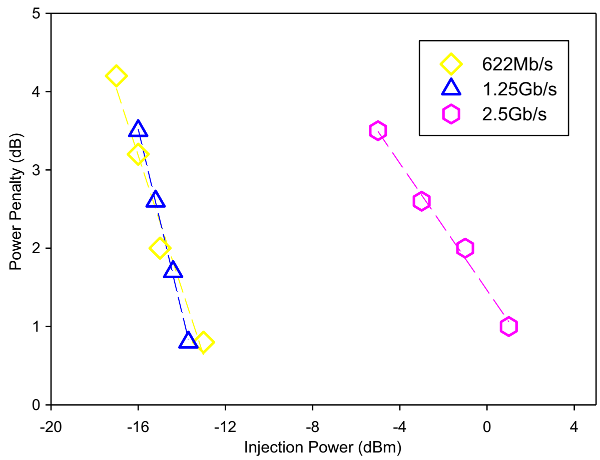


**Fig. 10.** The downstream injection power versus the measured penalty at the BER of $10^{-9}$ under 622 Mb/s, 1.25 and 2.5 Gb/s modulations, respectively, in 100 km fiber transmissions.

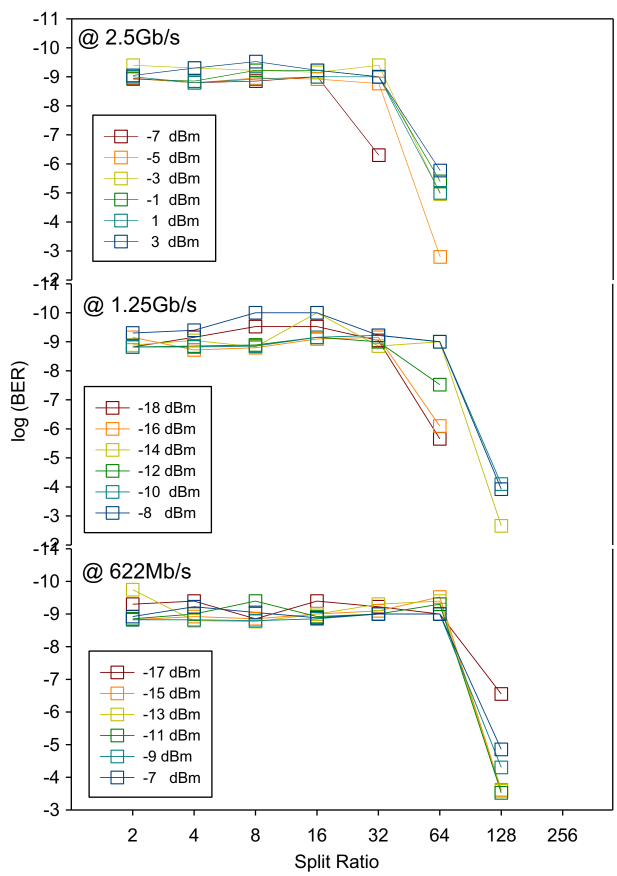


**Fig. 11.** BER curves versus different split ratios at the modulations of 622 Mb/s, 1.25 and 2.5 Gb/s, respectively, while different injection powers are launched into RSOA.

between the central office and ONU, particularly in the long-reach transmission (100 km); it is difficult to maintain a high level of injection power into the RSOA. Hence, in this case, we may need to dynamically adjust the upstream data rate in order to maintain the upstream signal performance.

Finally, to investigate the maximum number of supported ONUs in the LR-PON, the different split-ratios were experimented and analyzed. Fig. 11 presents the BER curves versus split-ratios at the modulations of 622 Mb/s, 1.25 and 2.5 Gb/s, respectively, while different injection powers are launched into RSOA. As seen in Fig. 11, to achieve the split-ratio of 32 in the LR-PON, the injection powers must be larger than −17, −18 and −3 dBm, respectively, when the data rates are 622 Mb/s, 1.25 and 2.5 Gb/s at the BER level of $10^{-9}$. Here, only the data rates of 622 Mb/s and 1.25 Gb/s can achieve 64 split ratio while the injection powers are −17 and −14 dBm, respectively, in the LR version.

## 4. Conclusion

The WDM-TDM PON using RSOA-based colorless ONUs is a promising candidate for the realization of FTTH. However, different fiber distances and optical components would introduce different power budgets to different ONUs. The situation will be more severe in the LR PON. Here we investigate the WDM-TDM PON using RSOA-based ONU for upstream data rate adjustment depending on different optical injection powers. A detail analysis of the upstream signal BER performances at different injection powers, upstream data rates, PON split-ratios under stand-reach and long-reach is presented. Here, the upstream data rate can be dynamically adjusted at 622 Mb/s, 1.25 and 2.5 Gb/s in the experiment, respectively, depending on various injection power levels into RSOA. To achieve 25 and 100 km PON transmissions at the three modulated rate, minimum injection powers of −21, −18 and −10 dBm, and −16, −15 and −5 dBm downstream injection powers are required, respectively, with the corresponding power penalties of 4.8, 4 and 2.4 dB and 4.3, 3.6 and 3.4 dB.

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