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Abstract. In a wavelength division multiplexed-passive optical network (WDM-PON), different fiber lengths and optical components would introduce different power budgets to different optical networking units (ONUs). Besides, the power decay of the distributed optical carrier from the optical line terminal owing to aging of the optical transmitter could also reduce the injected power into the ONU. In this work, we propose and demonstrate a carrier distributed WDM-PON using a reflective semiconductor optical amplifier-based ONU that can adjust its upstream data rate to accommodate different injected optical powers. The WDM-PON is evaluated at standard-reach (25 km) and long-reach (100 km). Bit-error rate measurements at different injected optical powers and transmission lengths show that by adjusting the upstream data rate of the system (622 Mb/s, 1.25 and 2.5 Gb/s), error-free ($<10^{-9}$) operation can still be achieved when the power budget drops. *© 2011 Society of Photo-Optical Instrumentation Engineers (SPIE).* [DOI: 10.1117/1.3625425]

Subject terms: long-reach; passive optical network; wavelength division multiplexed; reflective semiconductor optical amplifier.

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1 Introduction

The passive optical network (PON) has been considered an attractive solution for the last mile access network. Its advantages include high capacity, easy upgradeability, and cost-effectiveness.[1–3] A variation of PON, wavelength division multiplexed (WDM)-PON, is promising for meeting the demand of rapid increase in bandwidth. A colorless optical network unit (ONU) is desirable for the WDM-PON.[4] Different methods, such as using tunable light source,[5] spectral-sliced light source,[6] amplified spontaneous emission- injected Fabry–Pérot laser diodes,[7] and remodulated light sources[8,9] have been proposed for the colorless ONU. Recently, we proposed and demonstrated the use of a distributed optical carrier from the optical line terminal (OLT) and reflective semiconductor optical amplifier (RSOA) as the colorless ONU.[10,11] RSOA can serve as a wideband data modulator and a gain medium at the same time. Besides, the low polarization dependency and compact size of this approach are also attractive.

In the WDM-PON, different fiber lengths and optical components would introduce different power budgets to different ONUs. Besides, the power decay of the distributed optical carrier from the OLT owing to aging of the optical transmitter (Tx) could reduce the injected power into the RSOA. In this work, we propose and demonstrate a WDM-PON that can adjust its upstream data rate to accommodate different injected optical powers into the ONU. The WDM-PON is evaluated at standard-reach (25 km) and long-reach (LR) (100 km). The upstream data rates can be switched to 622 Mb/s, 1.25 and 2.5 Gb/s, depending on the injected continuous wave (cw) optical powers. Bit-error rate (BER) measurements at different injected optical powers, data rates, and transmission lengths are analyzed and discussed. The results show that by adjusting the upstream data rate of the system, error free (bit error rate of $<10^{-9}$) operation can still be achieved when the power budget drops.

2 Experiment and Results

Figure 1 shows the experimental setup for the RSOA-based WDM-PON. Inside the central office, a 1550 nm distributed feedback laser diode was used to generate the distributed cw carrier. For the standard-reach PON (25 km), the cw signal was propagated through 15 km of feeder fiber and 10 km of distribution fiber via an optical circulator (OC) in the remote node (RN). For the LR-PON, the cw signal was propagated through 90 km of feeder fiber and 10 km of distribution fiber. Two erbium-doped fiber amplifiers (EDFAs) were used in RN to compensate for the transmission loss.

In each ONU, 1% of the injected optical power was tapped and monitored. The medium access control (MAC) of each ONU could manage and dynamically adjust the data rate of

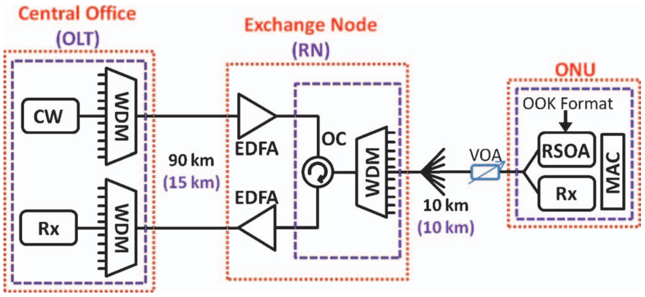

Fig. 1 Experimental setup for a RSOA-based WDM-PON system with data rate adjustment of upstream traffic. cw: continuous wave; OC: optical circulator; RN: remote node; OLT: optical line terminal; MAC: medium access control; EDFA: erbium-doped fiber amplifier; RSOA: reflective semiconductor optical amplifier.

the RSOA depending on the injected optical power levels. The rest of the cw carrier was launched into the RSOA to produce the upstream signal, as shown in Fig. 1. The upstream signal was then sent to the receiver at the OLT via another feeder fiber. Dual-feeder fiber architecture was used to mitigate the Rayleigh backscattering noise.

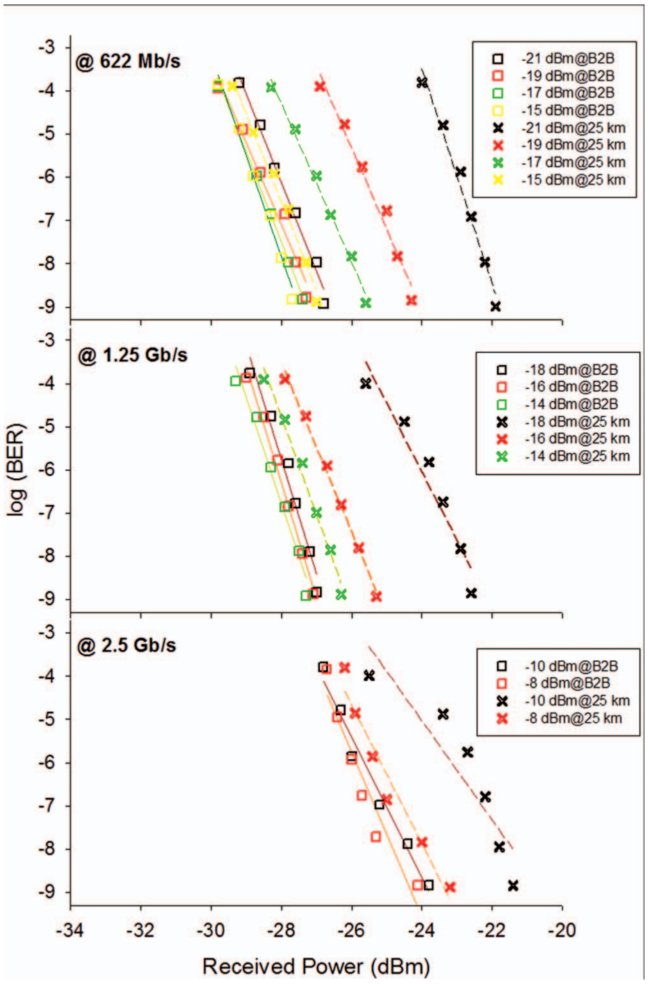

Fig. 2 BER performance of upstream signal in 25 km transmission when the RSOA is directly modulated at 622 Mb/s, 1.25 Gb/s, and 2.5 Gb/s, respectively, under different downstream injection powers.

As mentioned before, different fiber lengths and optical components would introduce different power budgets to different ONUs in the WDM-PON. Here, the relationship between the direct modulation speeds and the injection powers of the RSOA was analyzed. A variable optical attenuator was used to adjust the input power levels from −21 to 1 dBm. The RSOA was an InP buried heterostructure device with modulation bandwidth of about 1.2 GHz (manufactured by CIP). It exhibits a small signal gain of 20 dB and noise figure of 7 dB. It has a low polarization dependent gain of < 1 dB.

First, we studied the WDM-PON at standard-reach [25 km single mode fiber (SMF) transmission]. Figure 2 shows the measured BER performances of upstream signals when the RSOA was directly modulated at 622 Mb/s, 1.25 Gb/s, and 2.5 Gb/s nonreturn to zero data, respectively, with the pseudorandom binary sequence pattern length of 2^{31} to 1. The corresponding eye diagrams are shown in the insets. The injected powers varied from −8 to −21 dBm. In the measurements, the minimum injected powers were −21, −18, and −10 dBm to achieve the modulation rates of 622 Mb/s, 1.25 Gb/s, and 2.5 Gb/s, respectively, as shown in Fig. 2. However, these injection powers produced power penalties of 4.8, 4, and 2.4 dB, respectively. If the power penalty of 1 dB is required in the access system, higher cw injection power is needed. In the experiment, injection powers of −15, −14, and −8 dBm were required at data rates of 622 Mb/s, 1.25 Gb/s, and 2.5 Gb/s, respectively, to obtain a power penalty of 1 dB.

In order to achieve long-reach operation, injection powers of −17, −16, and −5 dBm into the RSOA were needed for the data rates of 622 Mb/s, 1.25 Gb/s, and 2.5 Gb/s, respectively, as shown in Fig. 3. The received powers of −27.5, −26.8, and −25.7 dBm were measured at the BER of 10^{-9}, respectively. These injection powers produced power penalties of 4.3, 3.6, and 3.4 dB, respectively. When the injection powers were −13, −14, and −1 dBm, respectively, at 622 Mb/s, 1.25 Gb/s, and 2.5 Gb/s, the power penalty was within 1 dB, as also shown in Fig. 3. According to the measurement results of Figs. 2 and 3, 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. However, as each wavelength channel may experience different optical losses 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.

To reduce the power penalty within 1 dB at BER of 10^{-9}, larger injection powers into RSOA are required. Figure 4 shows the injection powers versus the measured penalties at the BER of 10^{-9} under 622 Mb/s, 1.25 Gb/s, and 2.5 Gb/s in 25 and 100 km fiber transmissions, respectively. We can see from Fig. 4 that in both 25 and 100 km fiber transmissions, the power penalty of <1 dB can be achieved at 1.25 Gb/s while the injection power was <14 dBm. A higher data rate (2.5 Gb/s) with power penalty of 1 dB is also possible by increasing the injection optical power. The results show that by adjusting the upstream data rate of the system, error-free ($<10^{-9}$) operation can still be achieved when the power budget drops.

For example, in our proposed 25 km PON scheme, the insertion losses of two WDM multiplexers, an OC, and

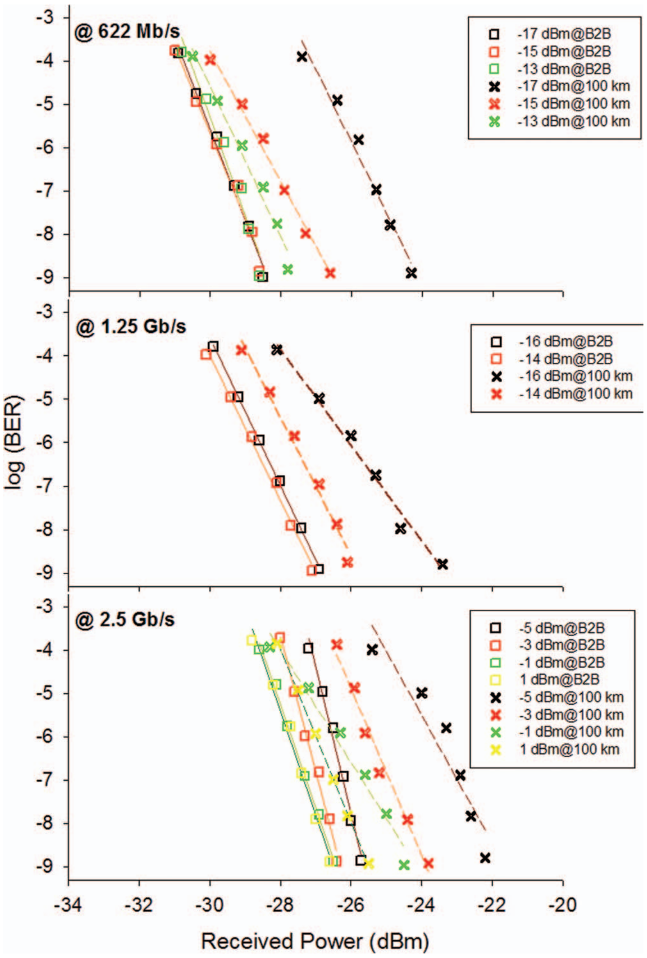

Fig. 3 BER performance of upstream signal in 100 km transmission when the RSOA is directly modulated at 622 Mb/s, 1.25 Gb/s, and 2.5 Gb/s, respectively, under different downstream injection powers.

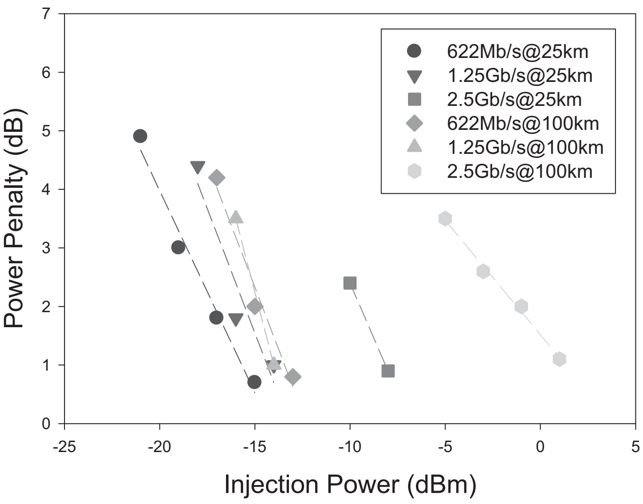

Fig. 4 The downstream injection power versus the measured penalty at the BER of 10^{-9} under 622 Mb/s, 1.25 Gb/s, and 2.5 Gb/s modulations, respectively, in 25 and 100 km fiber transmissions.

25 km SMF before the RSOA are 12, 1, and 4 dB, respectively, as illustrated in Fig. 1. Since we can use a high gain EDFA (+30 dBm) and no split-ratio is considered, we can have a high power budget. Moreover, a detailed analysis about the optical signal to noise ratio (OSNR) and the fiber length at a different optical gain of a RSOA has been reported in Ref. 12. In our experiment shown in Fig. 4, we also discovered that the power penalty increases (OSNR decreases) when the fiber length increases for the same optical injection power. For example, in Fig. 4, at the bit-rate of 622 Mb/s and the injection power of −17 dBm, the power penalty increases from <2 dB to >4 dB when the fiber length increases from 25 to 100 km. Hence, when the fiber length increases, the RSOA should be operated at a lower bit-rate (as reported in this paper), or operated at higher gain (as reported in Ref. 12).

3 Conclusion

In the WDM-PON, different fiber lengths and optical components would introduce different power budgets to different ONUs. Besides, the power decay of the distributed optical carrier from the OLT owing to the aging of the optical Tx could reduce the injected power into the RSOA. Here, we proposed and demonstrated a WDM-PON that can adjust its upstream data rate to accommodate different injected optical powers into the ONU. The WDM-PON is evaluated at standard-reach (25 km) and LR (100 km). The upstream data rates can be switched to 622 Mb/s, 1.25 Gb/s, and 2.5 Gb/s, depending on different injected cw optical powers. To achieve transmissions over 25 and 100 km at the three data rates, at least −21, −18, and −10 dBm, and −16, −15, and −5 dBm 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. The results show that by adjusting the upstream data rate of the system, error-free ($<10^{-9}$) operation can still be achieved when the power budget drops.

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