Optics Communications 284 (2011) 5148–5152

Contents lists available at ScienceDirect

Optics Communications

journal homepage: www.elsevier.com/locate/optcom

Using Fabry-Perot laser diode and reflective semiconductor optical amplifier for long reach WDM-PON system

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ARTICLE INFO

Article history:
Received 11 August 2010
Received in revised form 13 July 2011
Accepted 14 July 2011
Available online 29 July 2011

Keywords:
WDM-PON
Long reach
RSOA
Fabry-Perot Laser Diode (FPLD)
Self-seeding

ABSTRACT

In this investigation, we propose and investigate the simple self-injection locked Fabry-Perot laser diodes (FP-LDs) in optical line terminal (OLT); and wavelength-tunable optical network unit (ONU) using reflective optical semiconductor amplifier (RSOA) and FP-LD laser for downstream and upstream traffic in long reach (LR) wavelength division multiplexed-passive optical network (WDM-PON) respectively. The output performance of the proposed two laser sources in terms of power and side-mode suppression ratio (SMSR) has been discussed. Here, for the downstream traffic, the proposed optical transmitter can be directly modulated at 2.5 Gb/s on-off keying (OOK) format with nearly 0.4 dB power penalty at bit error rate (BER) of 10^{-9} through 75 km single-mode fiber (SMF) transmission. Moreover, the proposed upstream transmitter can be directly modulated at 1.25 and 2.5 Gb/s with nearly 0.5 and 1.1 dB power penalty, respectively, at the BER of 10^{-9}.

1. Introduction

Passive Optical Networks (PONs) are attractive solutions for next generation fiber to the home (FTTH) access applications [1], [2]. Wavelength division multiplexed (WDM)-PONs are considered as one of the most promising future fiber access architectures that can provide evolutionary upgrade to the existing time division multiplexed (TDM)-PONs [3]. In the conventional WDM-PON scheme, each optical network unit (ONU) is assigned with a separate pair of dedicated wavelengths for upstream and downstream directions respectively. Moreover, WDM-PON has the simple operation for providing the dedicated point-to-point connectivity, guaranteed quality-of-service (QoS), and increased security [4]. However, its deployment has been hindered nowadays by the lack of economical techniques for the WDM transmitters. Recently, “colorless” transmitters, such as spectrally sliced light emitting diodes, injection-locked Fabry-Perot laser diodes (FP-LD), and wavelength injection reflective semiconductor optical amplifiers (RSOAs), have been reported and analyzed [5–7]. In those schemes, RSOA-based ONU is easy to achieve colorless operation under different injection wavelengths by the centralized optical line terminal (OLT) [2,7]. Furthermore, in order to reduce the cost for the current fiber access networks, the long reach (or extend reach) WDM-PONs have also been proposed and studied [8–10].

In this study, we propose and demonstrate the self-injection locked FP-LD and wavelength-tunable RSOA-based laser sources in OLT and each ONU, respectively, for colorless operation in long reach WDM-PON. Experimental results show that the two proposed lasers can be directly modulated at 2.5 and 1.25 Gb/s with non-return-to-zero (NRZ) format for downstream and upstream traffic after 75 km single mode fiber (SMF) transmission without dispersion compensation. Moreover, the performance of the two proposed lasers in terms of power and side-mode suppression ratio (SMSR) is also discussed.

2. Architecture design

The experimental setup of proposed self-injected FP-LD laser and external-injected RSOA-based wavelength-tunable laser in OLT and ONU, respectively, acting as the downstream and upstream transmitters in the long reach WDM-PON system is illustrated in Fig. 1. Moreover, in remote node (RN), it is constructed by a 1 × N WDM multiplexer and a optical circulator (OC), which is used to separate the downstream and upstream link to avoid the Rayleigh backscattering noise [11].

3. Downstream traffic

For the downstream transmitter inside the OLT, the proposed WDM laser source is consisted of N FP-LDs, a 1 × 2 WDM multiplexer, a 1 × 2 optical coupler (CP), N polarization controller (PC), and a fiber mirror (FM). As shown in Fig. 1, each FP-LD connects to the PC and WDM multiplexer, and the 1 × 2 CP connects to the WDM multiplexer

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doi:10.1016/j.optcom.2011.07.031

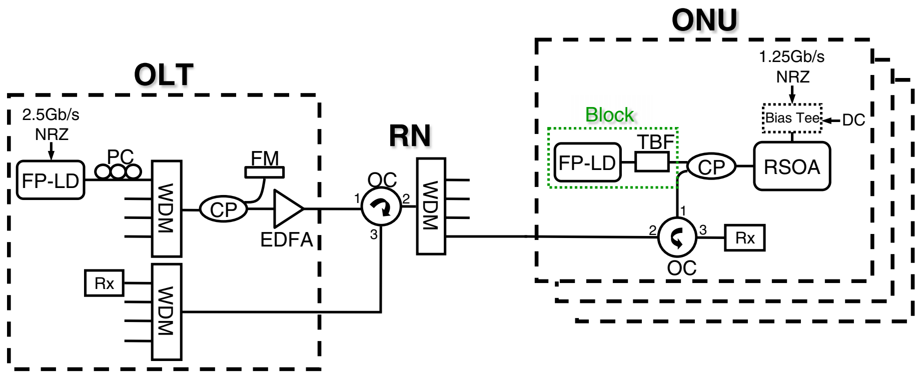

Fig. 1. Experimental setup of the RSOA based wavelength tunable fiber laser scheme in each ONU for uplink transmitter in WDM-PON system.

and the FM, respectively, to generate the WDM signals. The FM has ~99% reflectivity in the wavelengths of 1530 to 1560 nm. Furthermore, the multi-longitudinal-mode (MLM) FP-LD is aligned to the corresponding filter mode of the WDM multiplexer. So, the filtered longitudinal mode of the FP-LD will be reflected by the FM and then injected into the FP-LD due to the self-seeding. Hence, the FP-LD would generate at single-longitudinal-mode (SLM) wavelength due to self-injection locking. Moreover, the PC is used to maintain the polarization status and retrieve maximum output power in the proposed laser scheme.

In the experiment, the original MLM FP-LD used with 1.15 nm mode-spacing operates at the bias current of 24 mA at the temperature of 25 °C. The temperature control of FL-LD is adjusted to match one of the passband of the WDM multiplexer. And a 1×4 WDM with the insertion loss of 6 dB and 3 dB bandwidth of 100 GHz is used to filter one of the output longitudinal mode of the FP-LD. Thus, the free run output spectrum of the FL-LD without self-injection locking is shown in the dash line of Fig. 2. The output power level of >−25 dBm is observed in the wavelength range from 1544.00 to 1553.55 nm. When the self-injection is performed, the proposed fiber laser would generate the SLM output, as also shown in the solid line of Fig. 2. Here, the lasing light of 1545.35 nm wavelength is adjusted to match the passband of the WDM multiplexer. Hence, the measured output power and side-mode suppression ratio (SMSR) of the laser are −5.1 dBm and 54 dB, respectively. Actually, higher output power of FP-LD is easy to obtain a better output performance due to the gain competition and self-injection operating.

Fig. 3 shows the optical output wavelengths of FP-LD without (dash line) and with (solid line) self-injection operation under the lasing light of 1545.35 nm, while the bias current is 24 mA at 25 °C observing by using optical spectrum analyzer (OSA) with a 0.01 nm resolution. Comparisons of the output linewidth of the proposed fiber laser without and with self-injection, the linewidth of the FP-LD will be narrower after self-injecting operation. Moreover, using optical injection technology would increase the relaxation oscillation frequency [12], hence it could increase the speed of direct modulation to 2.5 Gb/s simultaneously.

Furthermore, to realize the output stabilities of power and wavelength of the proposed laser scheme, we measure the stabilities of output power and wavelength of the downstream signal at 1545.35 nm initially. After 30 min observation time, the maximum power fluctuation and wavelength variation are nearly 0.5 dB and zero, as shown in Fig. 4. As a result, using multiple FP-LDs in the proposed laser scheme, we can easily obtain multiple SLM wavelength sources in the OLT as the downstream channels. In addition, the cavity length of the proposed laser scheme could affect the output stability because of the environmental temperature. In order to maintain the good output stability of the laser and high modulation speed operation, the cavity length should be as short as possible.

To investigate the performances of proposed downstream transmitter inside the OLT, the bit error rate (BER) measurement in a long reach WDM-PON is performed. For the downstream traffic, the lasing wavelength set at 1545.35 nm with −5.1 dBm output power. As shown in Fig. 1, the output port of proposed downstream laser connects to an erbium-doped fiber amplifier (EDFA) which is used to compensate the insertion losses of other components. The self-injected FP-LD can be directly modulated at 2.5 Gb/s with a non-return to zero (NRZ) pseudo random binary sequence (PRBS) to produce the on-off keying (OOK) signal under the word pattern of $2^{15}-1$. Therefore, Fig. 5 shows the BER measurement in long reach WDM-PON at back-to-back (B2B), 25, 50 and 75 km SMF transmissions, respectively. The insets of Fig. 5 are the corresponding eye diagrams at the BER of 10^{-9} under back-to-back (B2B), 25, 50 and 75 km transmissions, respectively.

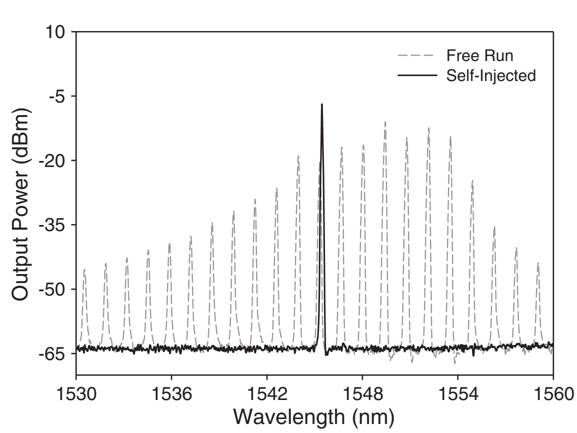

Fig. 2. The output spectra of FL-LD used in the experiment without (dash line) and with self-injected (solid line) operation.

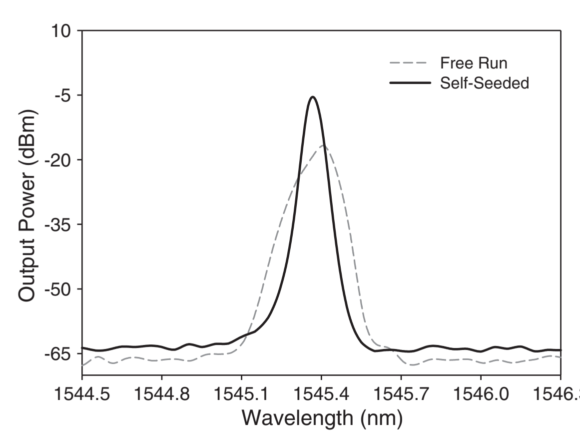

Fig. 3. The optical output spectra of the FP-LD without and with seed-injection in the wavelength of 1545.35 nm.

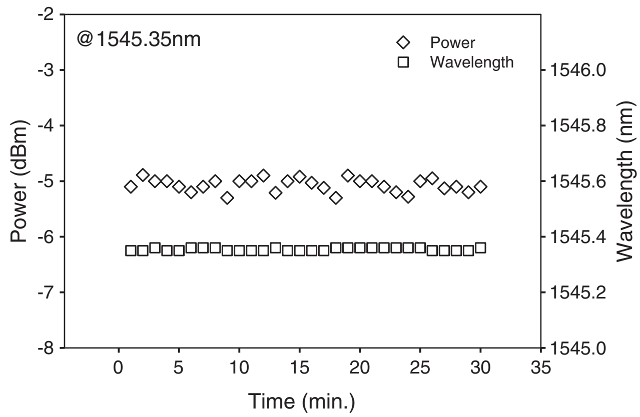

Fig. 4. Output stabilities of the proposed downstream wavelength at 1545.65 nm with −5.1 dBm output power initially.

We can observe clear wide open eyes in all cases. Moreover, ~0.4 dB power penalty at the BER of 10^{-9} was measured after 75 km transmission distance. As a result, based on the self-injection locked FP-LD laser scheme, we can easily obtain the WDM SLM wavelengths with 2.5 Gb/s OOK modulation for the downstream traffic in LR WDM-PON system, when the temperature of each FP-LD is controlled.

4. Upstream traffic

For the upstream link in WDM-PON, we proposed a simple laser scheme in each ONU for colorless operation. Hence, the proposed laser of each ONU is consisted of a FP-LD, a tunable bandpass filter (TBF), a 1×2 optical coupler (CP) and a RSOA, as shown in Fig. 1. The insertion loss and 3-dB bandwidth of the TBF are 3.5 dB and 0.4 nm respectively. The tuning range of the TBF is between 1525 and 1565 nm. In the experiment, the FP-LD is employed to serve as a continuous wave (CW) injection light injected into the RSOA. Moreover, the TBF is used to align and filter a corresponding mode of the FP-LD for optical injection in order to achieve the wavelength selection for colorless operation. In this measurement, the RSOA (CIP, SOA-R-OEC-1550) used has an electrical driving bandwidth of 1.2 GHz and operates at 75 mA. The MLM FP-LD used in ONU with 1.15 nm mode spacing operates at 30 mA at the temperature of 25 °C.

Fig. 6(a) shows the original output amplified spontaneous emission (ASE) spectrum of the RSOA with peak gain profile at about 1550 nm. And The FP-LD used in the experiment is a commercial available laser, not a special type. The effective gain bandwidth of the RSOA is between 1530 and 1560 nm. Fig. 6(b) presents the output spectrum of the MLM FP-LD under the bias current of 30 mA and the temperature of 25 °C. There are two maximum wavelength peaks occur at 1544.25 and 1562.35 nm for the MLM FP-LD with the peak powers of −14.5 and −2.2 dBm, respectively. When the TBF is aligned to the target mode of the MLM FP-LD for serving as CW injection light into RSOA, the output wavelength spectra of the proposed tunable fiber laser is shown in Fig. 7, over the operating range of 1526.65 to 1562.35 nm with 1.15 nm tuning step. Thus, we can see clearly that SLM outputs can be obtained by the proposed laser scheme. Then, we characterize the proposed laser scheme. Fig. 8 presents the output power and SMSR of the proposed fiber laser under different lasing wavelengths in the operating range of 1526.65 to 1562.35 nm with 1.15 tuning step. In the operating range, the output power and SMSR are larger than −6.5 dBm and 30.5 dB respectively. While the tuning range is between 1531.0 and 1562.35 nm, the output power and SMSR is above −4.0 dBm and 30.5 dB respectively. The maximum output power of −0.8 dBm is obtained at the wavelength of 1550.95 nm with

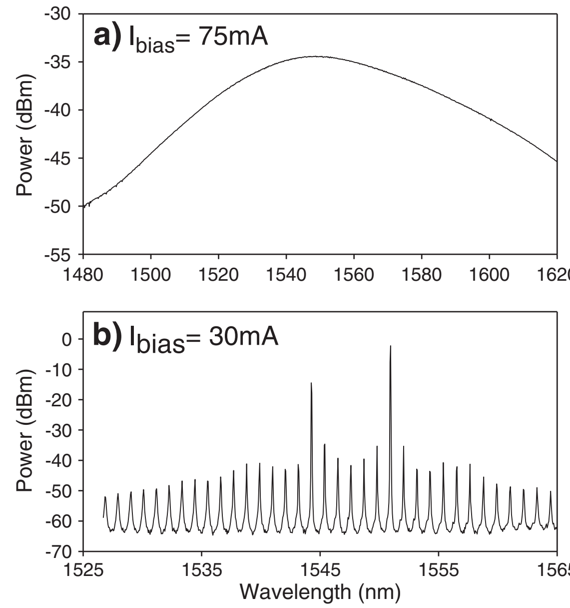

Fig. 6. (a) Original output ASE spectrum of RSOA and (b) output wavelength spectrum of MLM FP-LD under the bias current of 75 and 30 mA on the temperature of 25 °C, respectively.

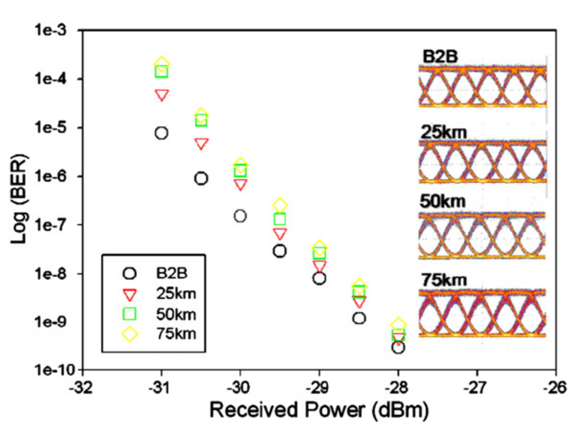

Fig. 5. BER performance for the downstream traffic in long reach WDM-PON network with 2.5 Gb/s NRZ format under B2B, 25, 50 and 75 km SMF transmissions, respectively. The inserts are the corresponding eye diagrams.

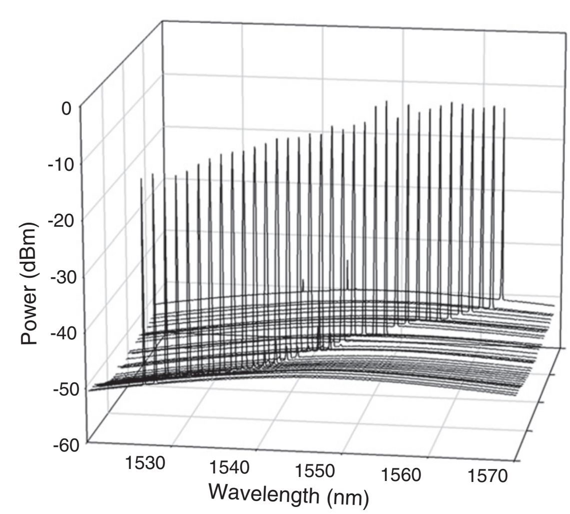

Fig. 7. Output spectra of the proposed RSOA based wavelength-tunable fiber laser in the wavelength range of 1526.65 to 1562.35 nm with 1.15 nm tuning step.

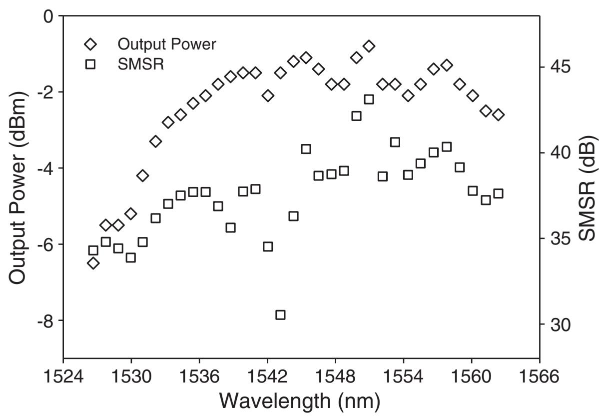

Fig. 8. Output power and SMSR curves of the proposed fiber laser under different lasing wavelengths in the operating range of 1526.65 to 1562.35 with 1.15 tuning step.

43.1 dB SMSR. The maximum output lasing wavelength matches the maximum output of the MLM FP-LD. It is also worth to mention that we can equalize the output powers of the proposed laser with variation less than 2 dB, in the wavelength range of 1531.0 and 1562.35 nm by proper controlling the bias currents of the FP-LD and the RSOA.

Then, we characterize the laser scheme. Fig. 8 presents the output power and SMSR of the proposed fiber laser under different lasing wavelengths in the operating range of 1526.65 to 1562.35 nm with 1.15 nm tuning step. In the operating range, the output power and SMSR are larger than −6.5 dBm and 30.5 dB respectively. While the tuning range is between 1531.0 and 1562.35 nm, the output power and SMSR is above −4.0 dBm and 30.5 dB respectively. The maximum output power of −0.8 dBm is obtained at the wavelength of 1550.95 nm with 43.1 dB SMSR. The maximum output lasing wavelength matches the maximum output of the MLM FP-LD. It is also worth to mention that we can equalize the output powers of the proposed laser with variation less than 2 dB, in the wavelength range of 1531.0 and 1562.35 nm by properly controlling the bias currents of the FPLD and the RSOA. Moreover, in this proposed laser scheme, we can control the temperature of FP-LD for continuous tuning.

For the upstream link, the lasing wavelength at 1545.40 nm with −1.1 dBm output power is selected for the upstream transmission when the CW light is injected into RSOA. The RSOA can be directly modulated at 1.25 Gb/s with the NRZ PRBS format to produce the OOK upstream signal at the pattern word of $2^{31}-1$. Hence, Fig. 9 shows the BER curves for the upstream connection in WDM-PON at B2B, 25, 50 and 75 km SMF transmissions, respectively. The insets of Fig. 9 are the corresponding eye diagrams at the BER of 10^{-9}. We can observe that clear wide open eyes can be seen in all cases. The power penalty of ~0.5 dB at the BER of 10^{-9} was measured after 75 km transmission distance.

The relaxation oscillation frequency of RSOA can be increased by optical injection [13]; hence higher optical power can increase the modulation speed of the RSOA. We then tried to over-clock (modulation speed of the RSOA is about 1.2 GHz) in our proposed laser to 2.5 Gb/s, however, high power penalty is observed even at the B2B case. Due to the unavailability of a higher power FP-LD source in the laboratory, a higher power laser with output power of about −11 dBm is used instead of the FP-LD in the proposed fiber laser (in Fig. 1). In this measurement, a wavelength of 1545.40 nm is used to inject into the RSOA, which is biased at 75 mA (the same biasing condition as in the case of 1.25 Gb/s operation). Fig. 10 shows the 2.5 Gb/s BER curves for the uplink connection in LR WDM-PON network at B2B, 25, 50 and 75 km SMF transmissions, respectively. The insets of Fig. 10 are the corresponding eye diagrams at the BER of 10^{-9}. We can see that 2.5 Gb/s long reach (75 km) operation can be achieved with power penalty of ~1.1 dB at the BER of 10^{-9}. Clear and wide open eye diagrams can be seen in all cases. Thus, in order to achieve the over-clock 2.5 Gb/s data rate, the CW injection power should be larger than −11 dBm. Hence, we believe that the proposed scheme using MLM FP-LD and RSOA based fiber laser can be operated at 2.5 Gb/s for long reach WDM-PON by using optimized optical components, such as higher power FPLD or lower insertion loss TBF.

In this experiment, we are using commercially available FP-LD and RSOA, hence the direct modulation speed are limited to 2.5 Gb/s and 1.25 Gb/s respectively. Special design FP-LD and RSOA are required for higher direct modulation speed, but this will increase the cost and the complexity. We believe that the proposed laser scheme in this manuscript can be applied to our previously reported wavelength multiplexing architectures for 10 Gb/s [14] and 40 Gb/s [15] implementation. In these wavelength multiplexing architectures, by using 4×2.5 Gb/s and 4×10 Gb/s, the chromatic dispersion tolerance can be greatly enhanced when compared with the single channel cases. And the typical PON transmission of 20 km single mode fiber without dispersion compensation can be achieved. Two new references [14,15] are included. Moreover, we believe that the FP-LD can be shared by many ONUs; hence each ONU only requires a RSOA for the upstream modulation. In the shared FP-LD scheme, an arrayed waveguide grating (AWG) with the channel spacing equals to the longitudinal mode spacing of the FP-LD should be used to select the longitudinal mode for the injection of the RSOA. We could also use another shared broadband light source (e.g. another SOA or EDFA) for the optical injection. And we believe that the upstream signal performances in the case of using a dedicated FP-LD for each ONU or using a shared FP-LD are similar, but the cost can be reduced by using a shared FP-LD. One difficulty for the shared FP-LD is that we need to have a FP-LD with the longitudinal mode spacing equals to the AWG. On the

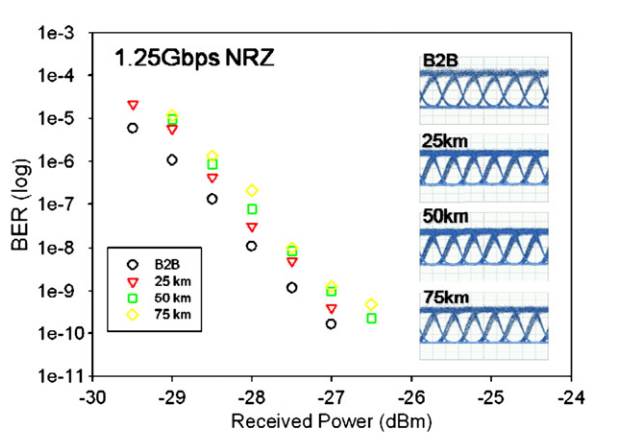

Fig. 9. BER curves for the uplink connection in WDM-PON network with 1.25 Gb/s NRZ format under B2B, 25, 50, 75 and 100 km SMF transmissions, respectively. The inserts are the corresponding eye diagrams at the BER of 10^{-9}.

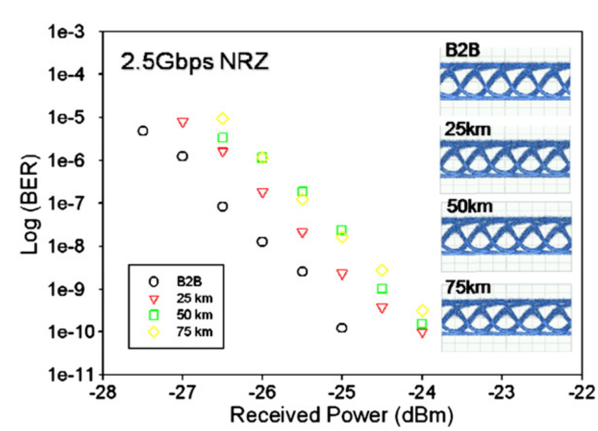

Fig. 10. BER curves for the uplink connection in WDM-PON network with 2.5 Gb/s NRZ format under B2B, 25, 50 and 75 km SMF transmissions, respectively. The inserts are the corresponding eye diagrams at the BER of 10^{-9}.

other hand, due to the incoherent nature of the broadband light sources (e.g. SOA and EDFA), the upstream generated by these broadband light sources could be degraded by the laser noises.

5. Conclusion

We have proposed and demonstrated two simple laser schemes in OLT and each ONU for downstream and upstream traffic for LR WDM-PON networks. Thus, in the OLT, the proposed multiple self-injection locked FP-LD lasers could obtain the WDM SLM output sources for downstream signals. In each ONU, the wavelength-tunable laser used the external-injection RSOA as the colorless transmitter for upstream transmission. The output performances of output power and SMSR for the two lasers have been also discussed and analyzed. For the downstream traffic, the proposed laser could be directly modulated at 2.5 Gb/s OOK format with power penalty of 0.4 dB at the BER of 10^{-9} through 75 km fiber transmission. For the upstream, the laser could be directly modulated at 1.25 and 2.5 Gb/s with nearly 0.5 and 1.1 dB power penalties at BER of 10^{-9} after 75 km SMF transmission. As a result, based on the two proposed downstream and upstream laser schemes, we not only can demonstrate the simple laser schemes, but also achieve LR fiber transmission to 75 km without any dispersion compensation.

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