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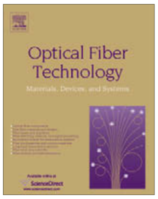

Utilization of self-injection Fabry–Perot laser diode for long-reach WDM-PON

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ABSTRACT

In this investigation we propose and demonstrate a wavelength widely tunable laser source employing a self-injected Fabry–Perot laser diode (FP-LD) for long-reach wavelength-division-multiplexed passive optical network (WDM-PON). By using a tunable bandpass filter and an optical circulator inside the gain cavity, a stable and single-longitudinal-mode (SLM) laser output is achieved. Besides, the proposed laser sources are directly modulated at 2.5 Gb/s for both downlink and uplink transmissions of 85 km single mode fiber (SMF) in PON without dispersion compensation.

1. Introduction

Wavelength-division-multiplexed passive optical network (WDM-PON) is an efficient technique for fiber access networks. It is an emerging and efficient method providing the point-to-point connectivity to multiple remote locations through optical fiber. Therefore, WDM-PON can provide high data rate than present time division multiplexed (TDM)-PON through the use of wavelength domain [1,2]. However, the WDM light sources both in optical line terminal (OLT) and optical network unit (ONU) face challenges for mass deployment nowadays due to their high cost [1].

Several stable and wavelength-tunable laser sources were reported and demonstrated in different operating ranges, such as S–, C–, L–bands for the optical communications [3–6]. Previous works employing fiber grating as the tuning element have been proposed [7–12], however, the wavelength tunability maybe limited by the grating, and the wavelength stability of the laser greatly depends on the temperature stability of the grating. Conventional tunable lasers or different fixed wavelength lasers could be used in each ONU; however, a cost-effective solution would ideally use the same components in each ONU [13]. Using injection locked Fabry–Perot laser diode (FP-LD) is a potential low cost candidate for the WDM-PON. Previous study using a FP-LD and an optical filter inside the ring cavity can produce a stable and tunable single-wavelength output [6]. Using external light sources to injection lock the ONUs for the WDM-PON could be attractive; however, this would also increase the cost [14–18]. Besides, if the external light sources [19,20] are sending from the OLT, interferometric beat noise caused by Rayleigh backscattering [2] will produce impairments to the upstream signal. Signal remodulation PON, where the upstream signal is generated by the downstream signal using reflective semiconductor optical amplifier (RSOA), has been reported [21,22]. Previous demonstration using fiber reflective mirror for self-injection locking of FP-LD can produce stable and single mode laser output [23]; however, the output power of the laser depends on the reflectivity of the fiber mirror, and the tunability of the laser may be limited by the coating characteristics of the fiber mirror.

In this work, we propose and experimentally demonstrate a widely wavelength-tunable laser source with single-longitudinal-mode (SLM) output (having high side-mode suppression ratio (SMSR) >40.7 dB), employing self-injected FP-LD for long-reach WDM-PON network. Besides, there is no external source or fiber amplifier inside the gain cavity of the proposed laser source, hence, the network could be cost-effective. The output performances of the laser source used in the WDM-PON are also analyzed and discussed. The proposed laser source is directly modulated at 2.5 Gb/s and shows less than 1 dB power penalty at the bit error rate (BER) of 10^{-9} after 85 km transmission distance without dispersion compensation.

2. Experimental setup

Fig. 1 shows the experimental setup of the proposed laser source in the OLT and the ONU for the long-reach WDM-PON architecture. In the OLT side, the WDM downlink source consists of N multi-mode FP-LDs, a 2 N × 1 AWG with insertion loss of 4 dB, a 1 × 2 and 50/50 optical coupler (CP) with insertion loss of 0.5 dB, an optical circulator (OC) with insertion loss of 1 dB and a

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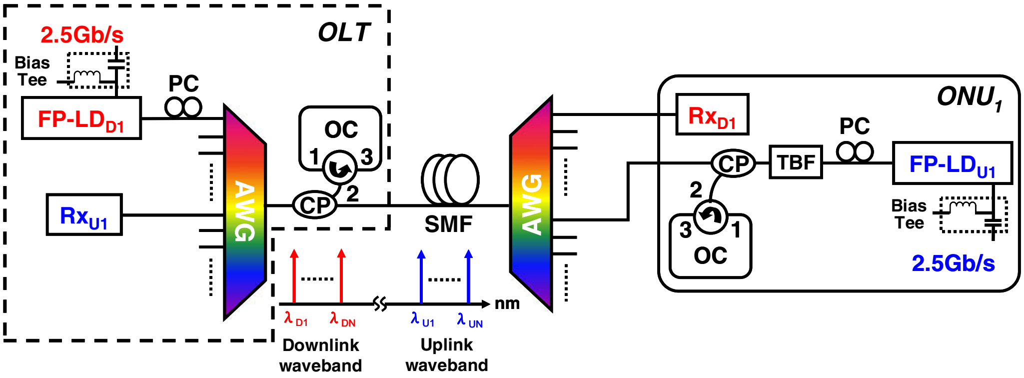

Fig. 1. Proposed long reach WDM-PON system based on broadly tunable self-injected Fabry–Perot laser diode. Inset: the wavelength plan of uplink and downlink signals.

polarization controller (PC). The 3-dB bandwidth of the AWG is 1 nm. The AWG can be used to filter and align the corresponding mode of the FP-LD. Then the filtered mode would be reflected by OC and inject into the FP-LD. Hence, the SLM output is generated. It is worth to mention that only one OC loop is required for all the FP-LDs inside the OLT to produce the multiple wavelength light sources. Moreover, the polarization dependence issue of injection locking can be mitigated since the FP-LDs, AWG and the OC loop are located at the same module and polarization maintaining fibers can be used.

In each ONU, the wavelength-tunable optical transmitter is constructed by a multi-mode FP-LD, a 1 × 2 and 50/50 CP, an OC, a PC, and a tunable bandpass filter (TBF). In this experiment, the multimode FP-LD has 1.32 nm mode spacing ($\Delta\lambda$) and 9.5 mA threshold current, respectively. The PC is used to maintain the polarization state of the self-injected light for successful injection locking. The TBF is used to select the output wavelength of the laser source, with the 3-dB bandwidth and insertion loss of 0.8 nm and 3.5 dB, respectively. And its tuning range is from 1524 to 1564 nm. For practical implementation, the TBF can be replaced by low cost "set and forget" filter, as described in [24]. In order to achieve SLM output, the pass-band of the TBF is tuned to match with the corresponding longitudinal mode of the FP-LD. Hence, the 1.32 nm tuning step is determined by the longitudinal mode of the FP-LD. The side-mode of the FP-LD can be suppressed due to self-injection when the TBF is tuned to the corresponding longitudinal mode, with proper bias current and temperature. The output spectrum and optical power are measured by an optical spectrum analyzer (OSA) with resolution of 0.02 nm and power meter, respectively. Experimental results show that 3 dBm average power was observed at the output of the ONU. And this is just enough to achieve the long-reach (LR) transmission by considering that the transmission loss of 85 km SMF fiber (17 dB) and the insertion losses from two AWGs (total 8 dB) and the 3-dB coupler (CP). Optical amplifiers in the transmission link should be needed if higher power margin is required in the proposed long-reach PON.

3. Results and discussion

The operation mechanism of the proposed self-injected laser is the same in both OLT and ONU. For the laser in the OLT, we use a fixed bandpass filter (the AWG). For the laser in ONU, we use a TBF. The experimental characterization of the laser is performed at the ONU side. Fig. 2 shows the measured output spectrum of the free-run FP-LD without self-injection (red line) when the bias current and temperature of the FP-LD is 25 mA and 25 °C, respectively. When the self-injection is operated, as also shown in Fig. 2, the output wavelength of the FP-LD (blue line) is locked and tuned in the wavelength range of 1535.64–1557.44 nm in this experiment.

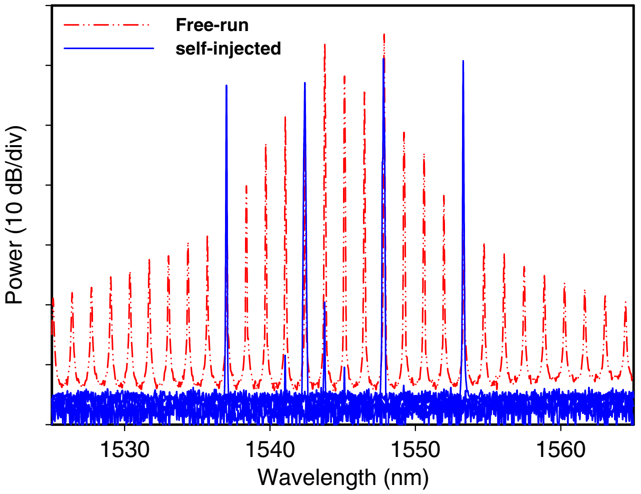

Fig. 2. Output spectra of free-run FP-LD (red, dotted line) and the lasing wavelength of proposed laser source (blue, solid line) between 1547.80 nm and 1556.04 nm when the bias current and temperature is 25 mA and 25 °C, respectively. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

Fig. 3 shows the output power and SMSR versus different wavelengths for the proposed self-injected FP-LD. The minimum output optical power and SMSR are 1.76 dBm and 40.7 dB within the tuning range from 1535.64 to 1557.44 nm, respectively. When compared with the previously proposed laser in [23], the self-

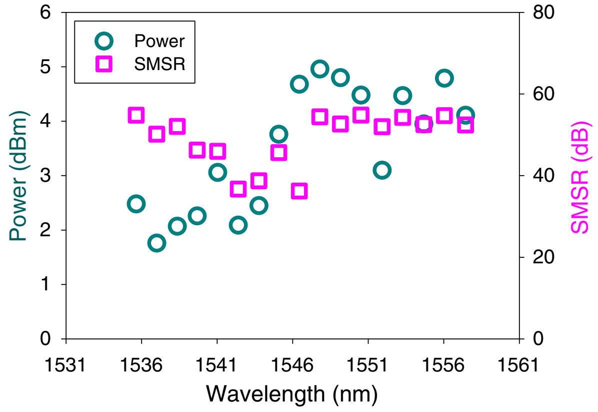

Fig. 3. Output Power and SMSR versus different lasing wavelength with ~1.32 nm tuning steps.

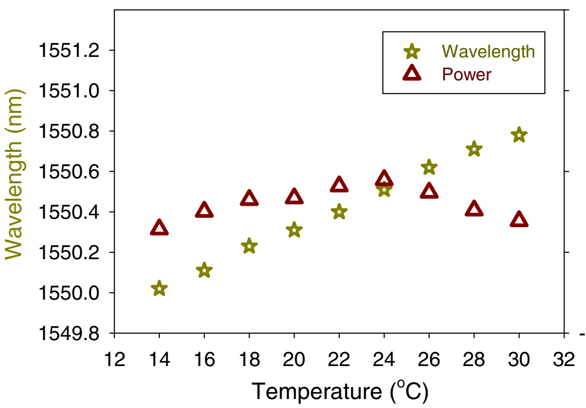

Fig. 4. Output power and wavelength versus different temperature of FP-LD (14–30 °C) in the proposed wavelength-tunable laser source.

injection locking is easier to achieve in the proposed laser. Besides, as shown in Fig. 3, the proposed laser can have a higher output power (>1 dBm) in the operation wavelength 1535–1557 nm, with smaller mode-to-mode power variation (3.2 dB). However, in the laser reported in [23], it has smaller output power (~−8 dBm) in the operation wavelength 1535–1557 nm, with higher mode-to-mode power variation (5 dB).

To investigate the wavelength locking stability, we measured the output power and SMSR as a function of temperature as shown in Fig. 4. The locked wavelength increases when the temperature increases. It increases from 1550.02 nm to 1550.78 nm when the temperature increases from 14 to 30 °C. We believe that the power change is mainly due to the mismatch of the temperature coefficients of the FP-LD and the TBF. This shows that non-precise temperature control can be used to maintain the wavelength locking and output power (also maintaining the output wavelength within the AWG channel). This may further reduce the transmitter cost. Besides, we also performed the short-term stability test of the proposed light source as shown in Fig. 5. The lasing wavelength is initially at 1550.53 nm and the observing time is over 30 min. Fig. 5 shows that the power fluctuation and the wavelength variation for the proposed laser source are 0.76 dB and 0.01 nm, respectively.

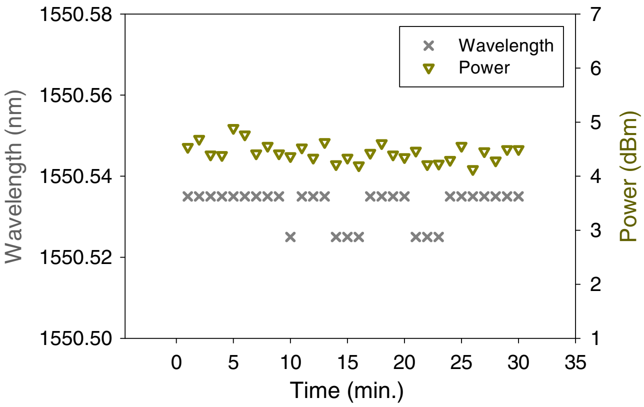

Fig. 5. Output power fluctuation and wavelength variation for the proposed wavelength-tunable laser source. Lasing wavelength is 1550.535 nm initially and the observing time is over 30 min.

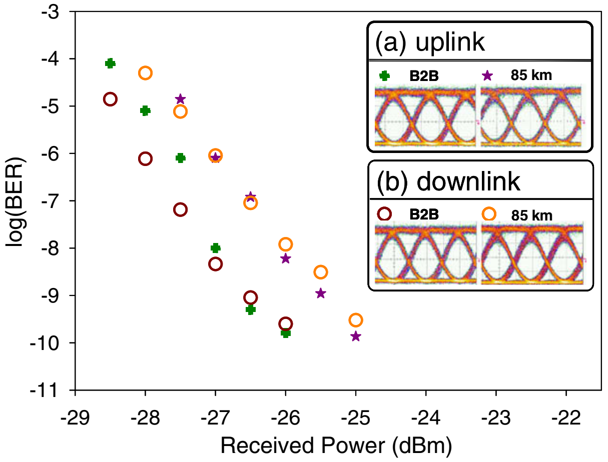

Fig. 6. BER of 2.5 Gb/s directly modulated self-injection laser source for the back-to-back and transmission of 85 km SMF. The inserts are the corresponding eye diagrams for the uplink and downlink signals.

In order to investigate the transmission performance of the proposed laser source, bit error rate (BER) measurement is performed in the LR-PON. The proposed self-injection laser source is directly modulated by a 2.5 Gb/s non-return-to-zero (NRZ) pseudo random binary sequence (PRBS). In this measurement, we choose two lasing wavelengths at 1547.80 and 1556.04 nm for the uplink and downlink channels, respectively. Fig. 6 shows the measured BER versus the received power at back-to-back and transmissions of 85 km of single mode fiber (SMF), respectively, without dispersion compensation. The corresponding eye diagrams are also illustrated in the inserts of Fig. 6. Under 85 km transmission, the power penalties in uplink and downlink traffic are both less than 1 dB at BER of 10^{-9}.

4. Conclusion

We proposed and experimentally demonstrated a widely tunable laser source by self-injected FP-LD for long-reach WDM-PON. The output power is over 1.76 dBm and the SMSR is large than 40.7 dB in the proposed laser source. Besides, the stability of the output power, wavelength and SMSR are also investigated. The proposed wavelength-tunable laser source has the advantages of simple architecture, good performance of output power stability and wide wavelength tuning range. For practical implementation, the TBF can be replaced by low cost "set and forget" filter. At the OLT, only one OC loop is required for all the FP-LDs to produce multiple wavelength light sources for the downlink data. Error free 2.5 Gb/s BER measurements at back-to-back and 85 km SMF transmission are achieved.

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