Wavelength-Tunable Laser for Signal Remodulation in WDM Access Networks Using DPSK Downlink and OOK Uplink

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***Abstract*—In this investigation, a simple wavelength-tunable laser based on a Fabry–Pérot laser diode (FP-LD) and an erbium-doped fiber amplifier to serve as a downlink signal in a colorless wavelength-division-multiplexed passive optical network (PON) is proposed and experimentally demonstrated. The tuning range of the proposed laser is between 1529.48 and 1560.72 nm, and the output performance of proposed laser is discussed. Colorless operation is implemented by using an FP-LD and a reflective semiconductor optical amplifier in each optical network unit for uplink signal remodulation, respectively. In addition, error-free data signal remodulation using 10-Gb/s downlink differential phase-shift keying and 2.5-Gb/s uplink on–off keying is achieved in a 25-km reach PON.**

***Index Terms*—Fabry–Pérot laser diode (FP-LD), millimeter-wave, radio-over-fiber.**

I. Introduction

TODAY, fiber-to-the-x (FTTx) is a promising technology for the last mile optical access networks due to the great capacity, high flexibility and cost-effectiveness [1]. The rapid growth of triple-play services (internet data, voice, and video) is demanding more and more bandwidth. The wavelength-division-multiplexed passive optical network (WDM-PON) is one of the potential and attractive solutions for the next-generation FTTx due to its high capacity and cost-effectiveness [2]–[5]. However, the cost of WDM-PON is relatively high due to the need of a wavelength-specific laser source in each optical network unit (ONU). In addition, tunable laser sources are required in the dynamic wavelength assignment WDM networks [5]–[9]. As a result, tunable lasers still need to be further developed for WDM-PONs. For the "colorless" operation in the WDM-PON, several optical-injection methods with signal remodulation for uplink transmitters have been reported and studied, such as using spectrum-sliced light-emitting diodes [7], light-injected reflective semiconductor optical amplifiers (RSOAs) [3], and injection-locked Fabry–Pérot laser diodes (FP-LDs) [4], [5]. Here, the signal remodulation by reusing the downlink wavelength for generating the uplink signal can also reduce the cost [3]–[5].

In this study, we propose a simple wavelength-tunable laser based on an FP-LD and an erbium-doped fiber amplifier (EDFA) in the optical line terminal (OLT) acting as a downlink signal source. The downlink wavelength is modulated at 10-Gb/s differential phase-shift keying (DPSK) format and the uplink signal uses 2.5-Gb/s on–off keying (OOK) remodulation by wavelength-injected FP-LD and wavelength-injected RSOA in each ONU, respectively. Compared with [5], our proposed tunable laser is not only simple, but also can achieve a 2.5-Gb/s uplink remodulation rate under 25-km single-mode-fiber transmission. Compared with our previously proposed laser source [10], the proposed laser in this letter can produce larger output power, and have more stable and easily adjustable single-wavelength output. In the past study [10], in order to achieve a stable output, we needed to carefully control the temperature and polarization state of the FP-LD due to self-injected operation is used. Here, the network performance of the experiment is also analyzed and discussed.

II. Experiment and Discussion

Fig. 1 illustrates the proposed colorless WDM-PON architecture using an FP-LD-based wavelength-tunable laser for the 10-Gb/s downlink signal. The proposed laser consists of a multilongitudinal-mode (MLM) FP-LD, a tunable bandpass filter (TBF), a polarization controller (PC), and an EDFA module. Here, the EDFA is constructed by a 980-nm pump laser with 70 mW, a 10-m EDF, a 980/1550-nm WDM coupler (WC), and an optical isolator (OIS). This EDFA module has a saturation power of ~18 dBm and noise figure of 6 dB. The 3-dB bandwidth and tuning range of TBF are 0.4 and 35 nm (1525–1560 nm), respectively. The PC is employed to control the output polarization state of the proposed laser. In the experiment, the bias current of the MLM FP-LD is 28 mA at a temperature of 24 °C. An optical spectrum analyzer (OSA) with a 0.02-nm resolution and a power meter are used to measure the output wavelength and output power, respectively. Fig. 2(a) shows the output spectrum of the MLM FP-LD with 1.1-nm mode spacing (observed at location "a") and the central wavelength (maximum peak power) is observed

Manuscript received March 10, 2009; revised July 23, 2009. First published September 25, 2009; current version published October 30, 2009. The work of C. W. Chow was supported by the National Science Council, Taiwan, R.O.C., under Contract NSC 96-2218-E-009-025-MY2, 97-2221-E-009-038-MY3.

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Digital Object Identifier 10.1109/LPT.2009.2032072

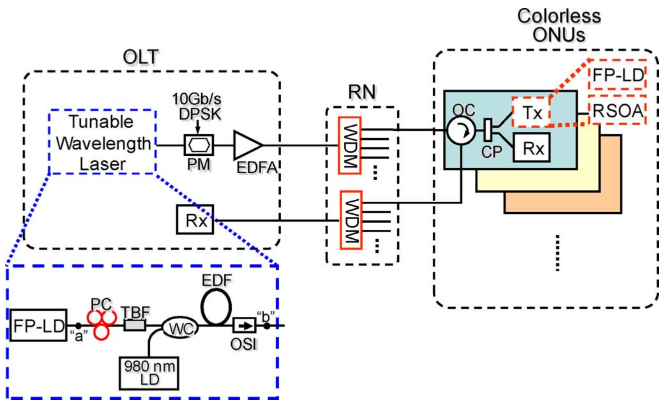

Fig. 1. Proposed wavelength-tunable laser for wavelength remodulation WDM-PON using DPSK downlink and OOK uplink.

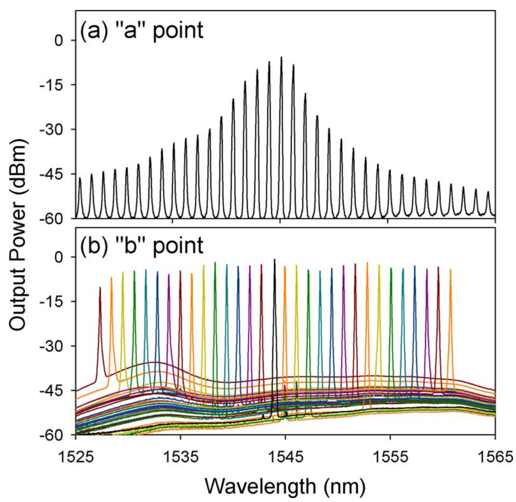

Fig. 2. (a) Originally output spectrum of MLM FP-LD used operates at 28 mA in the temperature of 24 °C. (b) Output spectra of proposed laser in the wavelengths of 1529.48–1560.72 nm with tuning step of 1.1 nm.

at 1545.12 nm. The TBF is used to align the corresponding mode of the MLM FP-LD, and the filtered backward amplified spontaneous emission (ASE) power of the EDFA module could be injected into the FP-LD. Then, the target mode of the FP-LD will be amplified after passing through the EDFA module. The injected ASE power at the input of the FP-LD was −7 dBm. This generates a single-longitudinal-mode (SLM) output. The phase modulator (PM) encodes the 10-Gb/s DPSK signal. Another EDFA (saturation power of ~23 dBm and noise figure of 5 dB) after the PM is used to compensate the transmission loss, as shown in Fig. 1. Fig. 2(b) presents the output spectra of proposed laser observing at location "b" in Fig. 1 in wavelength range from 1529.48 to 1560.72 nm with a tuning step of 1.1 nm.

Fig. 3(a) shows the output power and the sidemode suppression ratio (SMSR) in the wavelength range from 1529.48 to 1560.72 nm with a 1.1-nm tuning step. The output powers and SMSRs are between −1.8 and 0.3 dBm and 37.2 and 49.7 dB, respectively, in the effectively operating range, as shown in Fig. 3(a). The maximum output power is 0.3 dBm with 46.4-dB SMSR at the wavelength of 1544.92 nm. In Fig. 3(a), the minimum outputs are observed in both sides of the wavelength range. Since high SMSR can be achieved, we

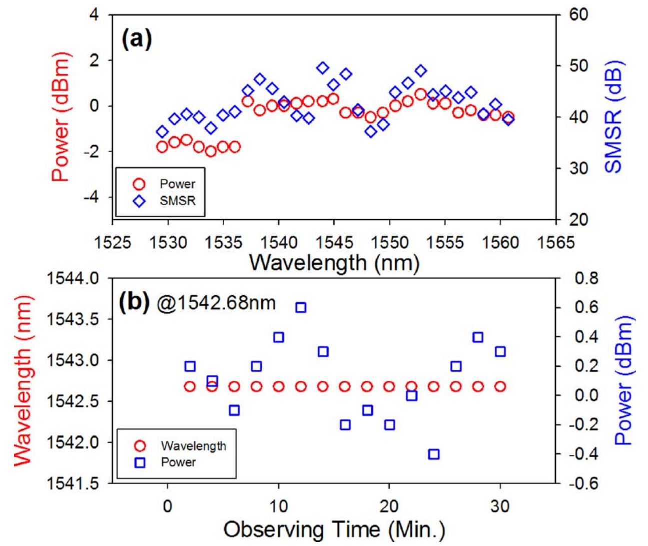

Fig. 3. (a) Output power and SMSR spectra in the wavelength range of 1529.48–1560.72 nm with a 1.1-nm tuning step. (b) Output variations of central wavelength and power at 1542.68 nm initially under 30 min observing time.

believe that the partition noise is highly suppressed. This can also be observed in the previous report of ASE injection locking [11]. The temperature of FP-LD used in the proposed laser is maintained at 24 °C in order to obtain the stable outputs. To demonstrate and analyze the performance of output power and wavelength stability, a short-term output stability test of the proposed laser is performed. The lasing single-mode wavelength is 1542.68 nm initially with 0.2-dBm output power and the observation time is over 30 min. The maximum variation of the central wavelength and output power in the proposed tuning laser are 0 and 0.9 dB, respectively, as shown in Fig. 3(b). Moreover, the stabilized output of the proposed wavelength tunable laser is still maintained during 4 h of observation.

In addition, the temperature applied to the FP-LD could cause the output wavelength of the FP-LD to shift slightly. According to the measurement result, when the temperature variation $\Delta T = \pm 4$ °C of FL-LD, the lasing wavelength could be tuned in the 0.16-nm range. Thus, the proposed laser could be continuously tunable by controlling the temperature of the FP-LD.

In the experiment, the output wavelength of the proposed laser is modulated at 10-Gb/s DPSK format via a $LiNbO_3$ PM for downlink traffic in the colorless WDM-PON. The PM is driven by a differentially precoded 10 Gb/s at pseudorandom binary sequence (PRBS) nonreturn-to-zero (NRZ) with $2^{31} - 1$ pattern length. The downlink DPSK signal launches into the ONU via an optical circulator (OC), and 10% of the downlink power is received by an optically preamplified receiver (Rx), consisting of a variable optical attenuator (VOA), an EDFA, a delayed interferometer (DI) for DPSK demodulation, and a 10-GHz PIN. Here, we use the FP-LD and RSOA in each ONU for uplink remodulation. The FP-LD and RSOA are wavelength-injected by the residual power (90%) of the downlink signal, and they are directly modulation at 2.5 Gb/s by NRZ PRBS format with $2^{31} - 1$ word length, respectively. In each ONU, the FP-LD-based transmitter has the same characteristic as the

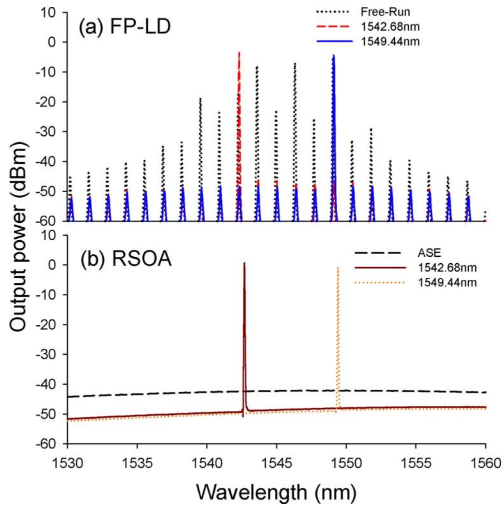

Fig. 4. Output spectra of (a) FP-LD and (b) RSOA without and with downlink injection under the two wavelengths of 1542.68 and 1549.44 nm, respectively.

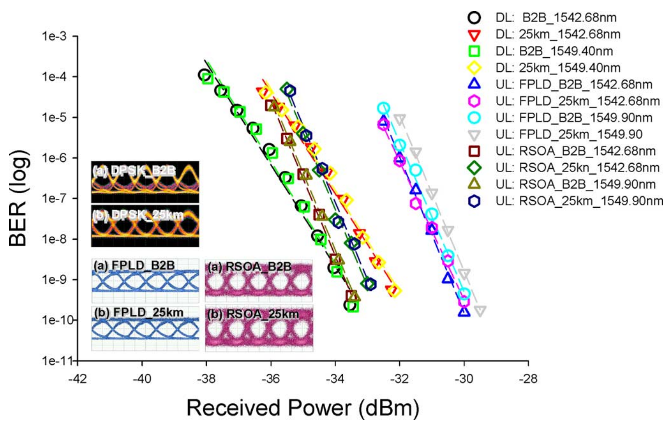

Fig. 5. BER measurements of the downstream and upstream signals at back-to-back (B2B) and after 25-km fiber transmission without dispersion compensation. Inserts are the corresponding eye diagrams. DL: downlink.

FP-LD used in OLT. The operating currents of the FP-LD and the RSOA used are 26 and 70 mA at a temperature of 25 °C, respectively. Thus, Fig. 4(a) and (b) presents the output spectra of the FP-LD and the RSOA without and with the downlink injection at the wavelengths of 1542.68 and 1549.44 nm, respectively. And the black dashed lines of Fig. 4 are the free-run output spectra of FP-LD and RSOA without any optical injection. In addition, in order to achieve a 2.5-Gb/s OOK uplink traffic by optical injection, the launched optical power into the FP-LD and RSOA should be larger than -16 and -10 dBm, respectively.

To measure the bit-error-rate (BER) performance of the proposed PON architecture, we arbitrary select two wavelengths, 1542.68 and 1549.90 nm, from the proposed wavelength-tunable laser source in the OLT for downlink traffic and signal remodulation. Fig. 5 presents the BER measurements of the downlink and uplink signals at back-to-back and after 25-km fiber transmission without dispersion compensation. The insets of Fig. 5 are the corresponding eye diagrams at 1542.68 nm. As shown in Fig. 5, error-free operation is observed in each case with clear and wide open eye. About 1.4-dB power penalty at a BER of 10^{-9} in the downlink DPSK signal is observed. In addition, we also obtain negligible power penalty in the uplink OOK signal after the 25-km transmission using FP-LD and RSOA, respectively.

III. Conclusion

We proposed and experimentally demonstrated a simple wavelength-tunable laser based on an FP-LD and an EDFA to serve as a downlink signal in colorless WDM-PON. The output powers and SMSRs of the proposed laser are between -1.8 and 0.3 dBm, and 37.2 and 49.7 dB, respectively, in the effective operating range from 1529.48 to 1560.72 nm. Here, the colorless operation is implemented by using the FP-LD and RSOA in each ONU for uplink signal remodulation. Error-free remodulation using 10-Gb/s DPSK downlink and 2.5-Gb/s uplink OOK remodulation are achieved in a 25-km reach WDM-PON without dispersion compensation. Since colorless reflective modulators are used, this can also reduce the cost of wavelength referencing and stabilization at the ONU. In addition, cost can be further reduced in the signal remodulation network by wavelength reuse. We believe the cost-effective network architecture can justify the cost of the ONU and OLT.

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