Optical Fiber Technology 19 (2013) 579–582

Contents lists available at ScienceDirect

Optical Fiber Technology

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2.5–10 Gbit/s laser source based on two optical-injection Fabry–Perot laser diodes

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ARTICLE INFO

Article history:
Received 12 June 2013
Revised 6 August 2013
Available online 7 October 2013

Keywords:
Fabry–Perot laser diode
Optical-injection
OFDM
OOK

ABSTRACT

In this investigation, a wavelength tunable laser source based on optical-injection of two Fabry–Perot laser diodes (FP-LDs) is demonstrated. In the proposed laser source, a self-injection locked master FP-LD provides a stable continuous-wave (CW) lasing, which wavelength can be selected by means of an optical tunable bandpass filter (TBF). The CW wavelength is launched into another FP-LD (the slave laser) for direct signal modulation. In this two optical-injection FP-LD architecture, directly modulation of 2.5 Gbit/s on–off keying (OOK) and 10 Gbit/s orthogonal frequency division multiplexing (OFDM) signals can be achieved in the proposed laser source with negligible power penalty after 25 km single-mode-fiber (SMF) transmission.

1. Introduction

Recently, the wavelength division multiplexed (WDM) access systems [1,2] are proposed to meet the ever-increasing demand of data bandwidth by customers. Therefore, low cost WDM and wavelength-tunable laser sources, supporting direct modulation data rates of 2.5 Gbit/s to 10 Gbit/s are essential for these communication systems. There are several technologies to implement a cost-effective light source for the WDM access [3–6]. For examples, an injection-locked Fabry–Perot laser diode (FP-LD) with an external injection of the spectrum sliced amplified spontaneous emission (ASE) [7] and self-injection [8] were demonstrated. The injected ASE forces the FP-LD to act as a quasi-single mode laser; suppressing the mode partition noise of the FP-LD. Hence the injection-locked FP-LD can be a promising candidate of low cost laser source for passive optical network (PON), and many experimental results and the system demonstrations have been reported [9,10].

In the previous demonstrations, the injection-locked FP-LD schemes could only be directly modulated with 2.5 Gbit/s on–off keying (OOK) traffic rate [2,6,7], owing to the optical-injection power and limited bandwidth. In order to obtain a higher traffic rate within a limited modulation bandwidth of the laser source, the highly spectral efficiency orthogonal frequency division multiplexing-quadrature amplitude modulation (OFDM-QAM) has been also proposed and experimentally investigated [11,12].

In this work, we propose and experimentally demonstrate a stable and wavelength-tunable two optical-injection FP-LD structure for PON applications. The proposed two optical-injection FP-LD scheme is consisted of a master and slave FP-LDs. In the proposed laser source, a self-injection locked master FP-LD_1 provides a stable continuous-wave (CW) lasing, which wavelength can be selected by means of an optical tunable bandpass filter (TBF). The CW wavelength is launched into another FP-LD_2 (the slave laser) for direct signal modulation. Hence, the slave FP-LD_2 can be directly modulated at 2.5 Gbit/s on–off keying (OOK) and 10 Gbit/s 16-QAM OFDM modulation formats, respectively, having 0.2 and 0.4 dB power penalties, after 25 km single-mode fiber (SMF) transmission.

2. Experiment and results

Fig. 1 shows the experimental setup of proposed wavelength-tunable laser structure by using two optical-injection FP-LDs design. Here, the proposed laser is consisted of a master FP-LD_1 and a slave FP-LD_2. The master laser is produced by a self-injected FP-LD_1 scheme, constructing by a 2.5 GHz bandwidth FP-LD_1, a polarization controller (PC), a TBF, a 1×2 and 50:50 optical coupler (CP) and a fiber reflected mirror (FRM). In this measurement, the longitudinal mode-spacing and threshold current of FP-LD_1 and FP-LD_2 both are nearly 1.3 nm and 9.5 mA respectively. The tuning range and 3 dB bandwidth of TBF are 30 nm (1530–1560 nm) and 0.4 nm respectively. The TBF is utilized to

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http://dx.doi.org/10.1016/j.yofte.2013.09.007

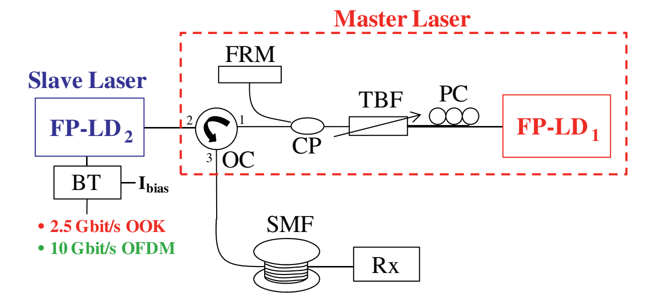

Fig. 1. Experimental setup of proposed wavelength-tunable laser structure by using two optical-injection FP-LDs.

match and filter the corresponding output longitudinal mode of FP-LD_1 and the filtered longitudinal mode would be reflected via a FRM with 98.5% reflectivity in C-band to produce self-injection mechanism. Here, the PC is employed to control polarization state and maintain the maximum output power for master FP-LD_1. Therefore, the single longitudinal mode output wavelength of master laser would be launched into the slave FP-LD_2 to suppress its side-mode and generate a single longitudinal mode output for wavelength-tuning. Moreover, the slave FP-LD_2 can be directly modulated by OOK and OFDM signals for data traffic. To observe and measure output wavelength and power, an optical spectrum analyzer (OSA) with a 0.01 nm resolution and a power meter (PM) are used.

In the experiment, the original FP-LD_1 operates at the bias current of 30 mA and temperature of 25 °C. When the self-injected operation is performed in master laser, the lasing CW wavelength of FP-LD_1 can be tuned within effectively gain amplification range. Fig. 2 shows the output wavelength spectra of free-run and self-injected FP-LD_1. Here, we observe that the central wavelength of free-run FP-LD_1 is 1536.5 nm with −0.4 dB m peak power. In addition, Fig. 2 shows the wavelength tenability of the FP-LD_1. In Fig. 2, we only present the two lasing wavelengths of 1536.5 and 1537.8 nm from the self-injected master laser, showing the other side-modes can be highly suppressed. In this measurement, we also measure the output power and side-mode suppression ratio (SMSR) of master laser under the wavelength range of 1528.6–1555.8 nm, as shown in Fig. 3.

Then, the lasing wavelength of the master laser is launched into the slave FP-LD_2. Here, the bias current and temperature of FP-LD_2 are 30 mA and 23 °C respectively. Here, if the temperature of FP-LD_1 or FP-LD_2 is change gradually, the wavelength also shifts slightly. And it would lead to the mode-locking performance disappearing. Thus, Fig. 4 shows the optical spectra of the output wavelengths from FP-LD_2 at the wavelengths of 1536.5 and 1537.8 nm.

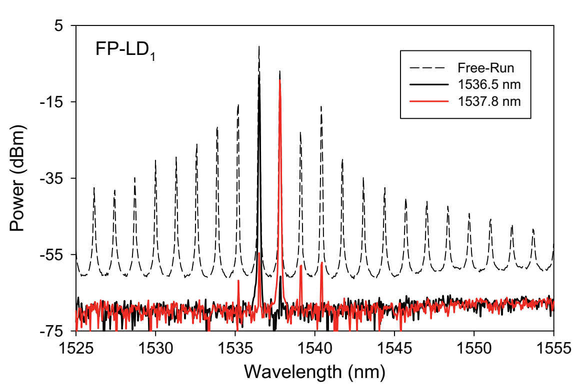

Fig. 2. Output wavelength spectra of free-run and self-injected FP-LD_1.

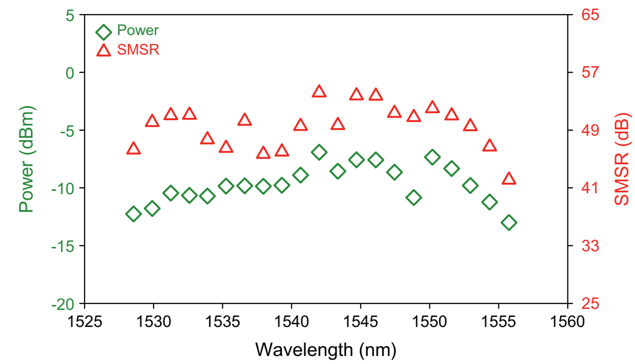

Fig. 3. Output power and side-mode suppression ratio of master laser under the wavelength range of 1528.6–1555.8 nm.

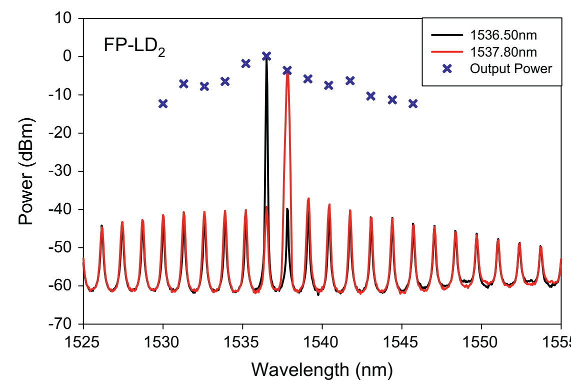

Fig. 4. Optical spectra of the output wavelengths from FP-LD_2 at the wavelengths of 1536.5 and 1537.8 nm.

Here, the SMSRs of 40 and 34 dB are obtained at 1536.5 and 1537.8 nm respectively, as illustrated in Fig. 4. Here, the measured output powers of slave FP-LD are 0.15 to −12.3 dB in the wavelength range of 1530.0 and 1545.7 nm, as also shown in Fig. 4, when the measured SMSR is larger than 25 dB. Next, 2.5 Gbit/s non-return-to-zero (NRZ) pseudo random binary sequence (PRBS) electrical data with a pattern length of $2^{31}-1$ can be applied to FP-LD_2. Fig. 5 shows the bit error rate (BER) measurement of two optical-injection FP-LD scheme at the lasing wavelength of 1536.5 nm. Power sensitivities of −26.5 and −25.3 dB m can be achieved at the back-to-back (B2B) and 25 km SMF transmission at the BER of 10^{-9}, as seen in Fig. 5. Furthermore, we also used a pre-amplified PIN receiver for the detection. Besides, 0.2 dB power

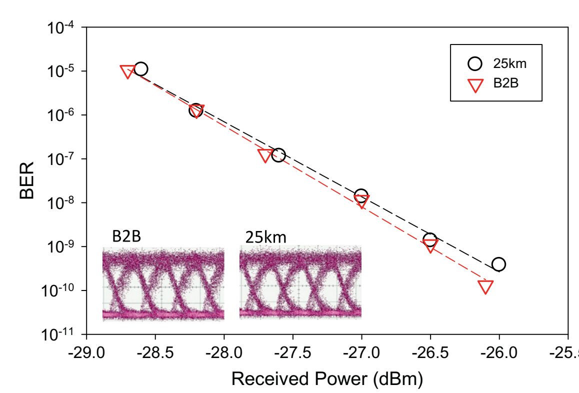

Fig. 5. Bit error rate (BER) measurement of 2.5 Gbit/s OOK of mode-locked FP-LD_2 scheme at B2B and after 25 km SMF transmission, respectively. Insets are the corresponding eye diagrams.

penalty is also observed after 25 km SMF transmission, and the insets are the corresponding eye diagrams at the back-to-back (B2B) and 25 km SMF transmission.

However, in order to provide efficient self-injection locking with good direct modulation bandwidth, special FP-LD with low front facet reflectivity 1% (AR coating) should be used, as described in [13]. In our proposed scheme, we used the typical FP-LDs with front-facet of 30%. Hence two optical-injection FP-LDs are used. The difference between the SMSR of FP-LD_1 and FP-LD_2 (shown in Figs. 2 and 4 respectively) is due to the fact that FP-LD_2 is under data modulation, while FP-LD_1 is only under CW self-injection.

Furthermore, to enhance the directly modulation rate, we can utilize the optical OFDM-QAM modulation in the same two optical-injection FP-LD laser source. Here, the proposed laser can be directly modulated at 16-QAM OFDM format to generate 10 Gbit/s upstream traffic rate. The baseband electrical OFDM upstream signal can be generated by an arbitrary waveform generator (AWG) using the Matlab® program. The signal processing of the OFDM transmitter consists of the serial-to-parallel conversion, QAM symbol encoding, inverse fast Fourier transform (IFFT), cyclic prefix (CP) insertion, and digital-to-analog conversion (DAC). 10 GSample/s sampling rate and 8 bit DAC resolution are set by the AWG, and CP of 1/64 is used. Thus, 128 subcarriers of 16-QAM format occupied nearly 2.5 GHz bandwidth from 0.0195 to 2.5195 GHz, with a fast-Fourier transform (FFT) size of 512. Here, 19.5 MHz subcarrier spacing and 10 Gbit/s total data rate are achieved. Thus, the produced electrical 16-QAM OFDM signal can be applied to the FP-LD_2. Then the traffic signal is direct-detected via a 2.5 GHz PIN Rx, and the received OFDM signal is captured by a real-time 50 GHz sampling oscilloscope for signal demodulation. To demodulate the vector signal, the off-line DSP program is employed. The demodulation process contains the synchronization, FFT, one-tap equalization, and QAM symbol decoding. Finally, the BER can be calculated according to the observed signal-to-noise ratio (SNR).

Fig. 6 presents the BER performances of 10 Gbit/s 16-QAM OFDM of mode-locked FP-LD_2 at the B2B and after 25 km SMF transmission, respectively, and the insets of Fig. 6 are the corresponding constellation diagrams, measuring at the forward error correction (FEC) threshold (SNR = 16.5 dB and BER = 10^{-3}). Here, when the FEC is utilized in the measurement, the received sensitivities are observed at −16.4 and −16.0 dB m, under the B2B and 25 km fiber transmission, respectively. As a result, the measured penalty is 0.4 dB after 25 km fiber transmission. Finally, as shown in Figs. 5 and 6, the sensitivities of 2.5 Gbit/s OOK and 10 Gbit/s 16-QAM OFDM signals of slave FP-LD_2 are −26.3 and −15.9 dB m (with 10.4 dB power difference) respectively, after 25 km fiber transmission. From the experimental results, the OFDM-QAM modulation for the proposed laser source can enhance the modulation data rate. However, it degrades the Rx sensitivity of the signal.

Here, to realize the stabilities of output power and wavelength, a short-term stability performance of the proposed structure is measured for the master and slave lasers respectively. Initially, the lasing wavelength is 1536.5 nm and the observing time is over 20 min. Thus, the wavelength variation and the power fluctuation of the master and slave lasers are within 0.01 nm and 0.4 dB and 0.01 nm and 0.6 dB, respectively. After 1 h of observation, the stable output of the proposed fiber laser is still maintained.

For example, the traditional tunable optical filter could be expensive for the cost-sensitive ONU. Tunable optical filters using cost-effective silicon-based micro-ring filter [14] or using the "set-and-forget" architecture [15] could be used to reduce the cost of the ONU.

For typical WDM-PON, a pair of arrayed-waveguide-grating (one located near the head-end; and one located at the remote node) is used for wavelength multiplexing and de-multiplexing of the WDM channels. The lasing wavelength of the proposed laser can be tuned to match with the pass-band of arrayed-waveguide grating. By deploying the proposed wavelength-tunable laser source at the ONU, the same components could be used for all the ONU; hence reducing the inventory cost. In this demonstration, a two-optical-injection FP-LD architecture is proposed. Direct modulation of 2.5 Gbit/s OOK and 10 Gbit/s OFDM signals can be achieved in the proposed laser source with negligible power penalty after 25 km SMF transmission. We believe that the proposed architecture could be interested by researchers working in WDM-PON and OFDM-PON.

3. Conclusion

We proposed and experimentally demonstrated a stable and wavelength-tunable two optical-injection FP-LD laser structure for PON applications. The proposed laser scheme is consisted of a master and slave FP-LDs. Here, the master self-injected FP-LD_1 can provide wavelength-tunable CW lightwave for the slave FP-LD_2. The proposed laser can be directly modulated at 2.5 Gbit/s OOK and 10 Gbit/s 16-QAM OFDM modulation formats, respectively, and it is suitable for the future PON and WDM-PON as an cost-effective laser source. Besides, the sensitivities of 2.5 Gbit/s OOK and 10 Gbit/s OFDM signals of slave FP-LD_2 are −26.5 and −16.4 dB m (with 10.4 dB power difference) respectively, at the B2B status. After 25 km SMF transmission, 0.2 and 0.4 dB power penalties can be measured under the 2.5 Gbit/s OOK and 10 Gbit/s OFDM formats respectively.

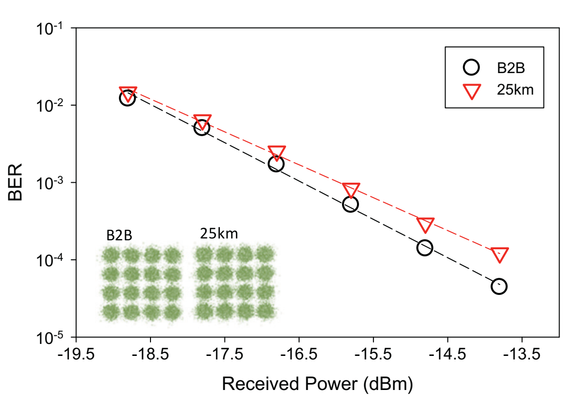

Fig. 6. BER performances of 10 Gbit/s 16-QAM OFDM of mode-locked FP-LD_2 at the B2B and after 25 km SMF transmission, respectively. Insets are the corresponding constellation diagrams.

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