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Hsing-Yu Chen
Chien-Hung Yeh
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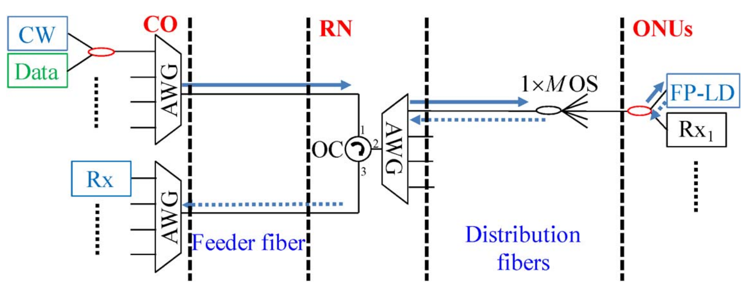

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Investigation of Using Injection-Locked Fabry–Pérot Laser Diode With 10% Front-Facet Reflectivity for Short-Reach to Long-Reach Upstream PON Access

Hsing-Yu Chen,[1,2] Chien-Hung Yeh,[2,3] Chi-Wai Chow,[1] Jiun-Yu Sung,[1] Yen-Liang Liu,[2] and Jeyhong Chen[1]

[1]Department of Photonics and Institute of Electro-Optical Engineering, National Chiao Tung University, Hsinchu 30010, Taiwan
[2]Information and Communications Research Laboratories, Industrial Technology Research Institute (ITRI), Hsinchu 31040, Taiwan
[3]Graduate Institute of Applied Science and Engineering, Fu Jen Catholic University, New Taipei 24205, Taiwan

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Abstract: In this paper, we propose and investigate an injection-locked Fabry–Pérot laser diode (FP-LD) with 10% front-facet reflectivity by using orthogonal frequency-division multiplexing-quadrature amplitude modulation (OFDM-QAM) in each optical network unit (ONU) for colorless operation in the carrier-distributed passive optical network (PON). Here, the 10-Gb/s 16-QAM OFDM upstream traffic can be generated via a 2.5-GHz-bandwidth injection-locked FP-LD for the short-reach (SR)-to-long-reach (LR) transmission. In this measurement, the CW injection power of -12 dBm for an injection-locked FP-LD is required to achieve 100-km single-mode fiber (SMF) transmission. Hence, error-free transmissions of 20-, 50-, 75-, and 100-km fiber lengths are achieved with the power penalties of 0.33, 0.86, 1.20, and 1.76 dB at the bit error rate (BER) of 3.8×10^{-3}, respectively, for upstream traffic. Moreover, the relationship of CW injection power and signal-to-noise ratio (SNR) of each OFDM subcarrier in the injection-locked FP-LD has also been analyzed.

Index Terms: Mode-locked, Fabry–Pérot laser diode (FP-LD), orthogonal frequency-division multiplexing (OFDM).

1. Introduction

Passive optical networks (PONs) are the promising last mile access to provide the wide bandwidth to end users economically [1]. Moreover, to cope with the ever-increasing requirement in access networks, wavelength-division-multiplexed (WDM)-PON has been considered as a favorable solution for next-generation PON system [2], [3]. And in traditional WDM-PON, each optical network unit (ONU) is assigned with a separate pair of specific wavelengths for upstream and downstream signals, respectively [4]. However, the deployment was delayed because of the lack of economical techniques for the optical WDM transmitters. Hence, reducing the cost of WDM-PON is an important challenge for the cost-effective transmitter in each ONU. Thus, the colorless ONU in PON access has been proposed to reduce the cost of optical transmitter [5]–[9], such as using spectrally

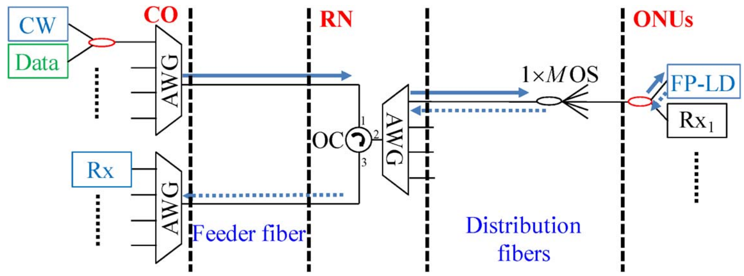

Fig. 1. Proposed carrier-distributed PON access system using injection-locked FP-LD-based ONU for 10-Gb/s upstream traffic by OFDM-QAM modulation.

sliced and mode-locked Fabry–Pérot laser diodes (FP-LDs) and employing wavelength-seeding reflective semiconductor optical amplifiers (RSOAs). However, the modulation rates of the transmitter are either 1.25 or 2.5 Gb/s by using the on–off keying (OOK) modulation [6], [7]. Furthermore, to increase the modulation rate of injection-locked FP-LD to 10 Gb/s, the coherent light sources have been used [10]. Though, it also resulted in the increase in cost. To overcome the drawback, 20-Gb/s orthogonal frequency-division multiplexing (OFDM) transmission of 52-km single-mode fiber (SMF) based on injection locking of FP-LD has also been reported [11]. However, this paper does not report the launching power into the FP-LD, which will affect the modulation bandwidth of the FP-LD.

Recently, to effectively enhance the modulation rate and reduce the cost, using optical OFDM-quadrature amplitude modulation (OFDM-QAM) in carrier-distributed PONs has raised research interests [12]–[14]. Moreover, hybrid WDM-time-division multiplexing (TDM) PON has also been considered as a potential solution for next-generation PON. Due to the bandwidth sharing of the TDM-PON, hybrid WDM-TDM PON would provide a relative lower per-subscriber cost than pure WDM-PON by dividing a single wavelength to multiple subscribers while still maintaining a relatively high per-subscriber bandwidth [7]. Moreover, to reduce the total cost of PONs simultaneously, a possible means is to simplify the network architecture, and then the number of equipment interfaces and network devices can be reduced. Therefore, long-reach (LR)-PONs have also been proposed to overcome the issue [15], [16]. In addition, the LR-PON has the characteristic of high capacity and high split ratio, and its transmission length can reach more than 40–100 km long [17].

In this paper, we propose and experimentally investigate an injection-locked FP-LD with 10% front-facet reflectivity in each ONU for colorless operation in the short-reach (SR) to LR carrier-distributed PON access. Hence, a 10-Gb/s upstream signal can be produced by using 16-QAM OFDM modulation occupying in a 2.5-GHz-bandwidth injection-locked FP-LD with direct modulation. In this measurement, error-free upstream transmissions of 20-, 50-, 75-, and 100-km SMFs are achieved with the power penalties of 0.33, 0.86, 1.20, and 1.76 dB at the bit error rate (BER) of 3.8×10^{-3} [18], respectively, when a -12-dBm CW injection power is used for launching. Moreover, the relationship of CW injection power and signal-to-noise ratio (SNR) of each OFDM subcarrier for the injection-locked FP-LD has also been analyzed in this measurement.

2. Experiment and Discussions

Fig. 1 shows the proposed carrier-distributed PON using mode-locked FP-LD-based ONU for 10-Gb/s OFDM upstream traffic from SR to LR transmission. In the central office (CO), we can use two wavelength bands for the downstream data and CW signals distributing to each ONU via a $1 \times N$ array waveguide grating (AWG) and a $1 \times M$ optical splitter (OS). The downstream data and CW wavelengths are divided by a 1×2 WDM coupler (WC) into each ONU, as shown in Fig. 1. Here, the CW injection wavelength will launch into the FP-LD for mode-locking and generating the up, stream OFDM signal. The effect of feeder fiber to the CW light is mainly the attenuation. Fig. 1 shows that we use a two-feeder-fiber structure, in which the feeder fiber is consisted of the longest fiber length. Hence, the Rayleigh backscattering generated from the CW light in the upper feeder fiber will not

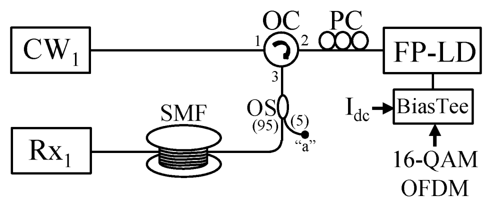

Fig. 2. Experimental setup for evaluating the proposed carrier-distributed PON by using injection-locked FP-LD with 10% front-facet reflectivity.

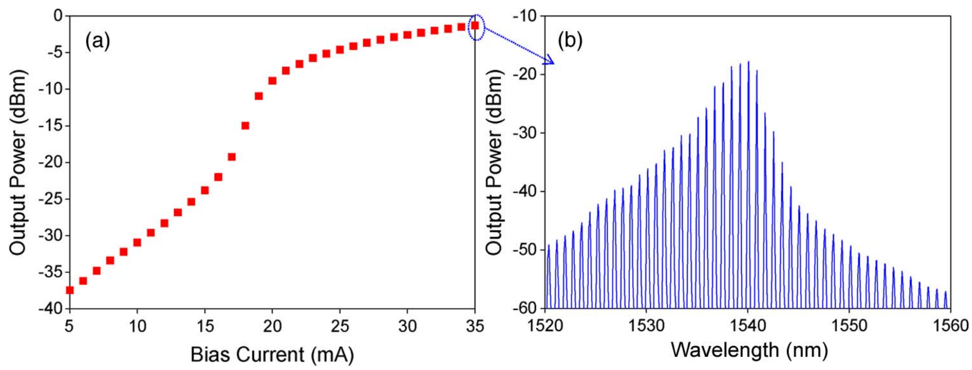

Fig. 3. (a) Measured output power of free-run FP-LD under different bias currents at the temperature of 25 °C. (b) Measured output spectrum of FP-LD at 35-mA operated current.

enter the Rx connected in the lower feeder fiber. The effect of Rayleigh backscattering can be negligible.

Fig. 2 presents the experimental setup for evaluating the proposed carrier-distributed LR-PON to achieve the 10-Gb/s 16-QAM OFDM upstream data rate. Here, the FP-LD was injected by an external CW light from the tunable laser (TL) via an optical circulator (OC) and a polarization controller (PC), as illustrated in Fig. 1. Hence, the corresponding output mode of FP-LD could be locked due to the CW injection lightwave. The PC was used to adjust the polarization state and maintain maximum output power for injection-locking mechanism. The output spectrum of the injection-locked FP-LD could be monitored via a 1 $\times$ 2 and 95:5 OS and observed by an optical spectrum analyzer (OSA) with a 0.01-nm resolution. Besides, the SMFs of 20, 50, 75, and 100 km, respectively, were used in this experiment for the upstream signal transmissions.

Fig. 3(a) shows the output power of original FL-LD without optical injection at the temperature of 25 °C under different bias currents. As shown in Fig. 3(a), the threshold current was measured around 16.5 mA. And the total output powers of FP-LD were measured at -8.8, -4.6, -2.6, and -1.3 dBm by using a power meter (PM), respectively, when the bias currents were 20, 25, 30, and 35 mA. Hence, with the increase in operated current gradually, the obtained output was also increase. Here, Fig. 3(b) presents the output spectrum of free-run FP-LD at 35-mA bias current under the temperature of 25 °C. And the central wavelength and mode-spacing of FP-LD were measured at 1540.38 and 0.8 nm, respectively.

In this measurement, the threshold current and front-facet reflectivity of FP-LD utilized were 16 mA and 10%, respectively. The dc current and the 10-Gb/s 16-QAM OFDM signal could be combined by a bias tee (BT) and applied to the FP-LD. Here, Fig. 4(a) and (b) presents the output wavelengths of FP-LD without and with CW injection lightwave, observing and monitoring at the 5% output port of 1 $\times$ 2 OS, when the bias currents were 20, 25, 30, and 35 mA at the temperature of 25 °C, respectively. The CW injection power was -12 dBm in this experiment. As shown in Fig. 4(a), when the applied current increases gradually, the output spectrum of the FP-LD can shift to the longer wavelength simultaneously. Fig. 4(b) shows the output spectra of the injection-locked

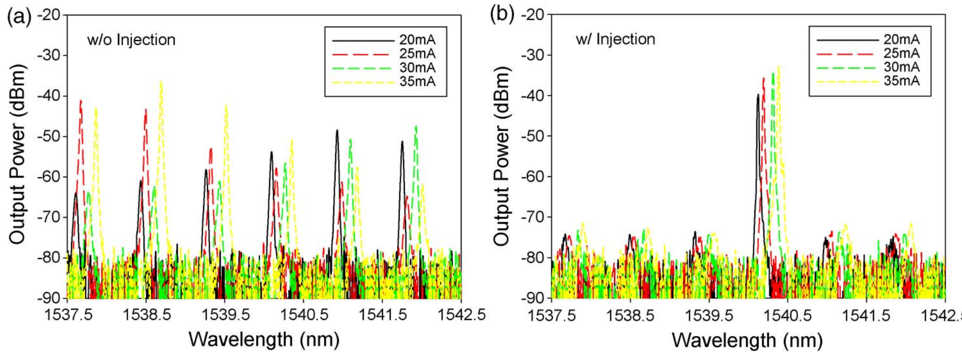

Fig. 4. Output wavelengths of FP-LD (a) without and (b) with CW injection lightwave, observing and monitoring at the 5% output port of 1 $\times$ 2 OS, when the bias currents were 20, 25, 30, and 35 mA, respectively.

FP-LD at the operated currents of 20, 25, 30, and 35 mA at 25 °C temperature, respectively. And its corresponding central wavelengths of 1540.12, 1540.19, 1540.31, and 1540.38 nm could also be measured, as illustrated in Fig. 4(b). Besides, the side-mode suppression ratios (SMSRs) of 35, 38, 40, and 41 dB were also obtained, respectively. The results showed that the higher SMSR of injection-locked FP-LD can be retrieved when increasing the bias current under the same injection power level.

In this measurement, the injection-locked FP-LD could be directly modulated by using a 10-Gb/s 16-QAM OFDM signal. Hence, the baseband electrical OFDM upstream signal was generated by an arbitrary waveform generator (AWG) using the MATLAB program. The signal processing of the OFDM transmitter was constructed by 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 (GS/s) sampling rate and 8-bit DAC resolution were set by the AWG; and CP of 1/64 was 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 and CP of 8. Here, 19.5-MHz subcarrier spacing and 10-Gb/s total data rate are achieved. Hence, the produced electrical 16-QAM OFDM signal could be applied to the FP-LD via a BT. Then, the upstream signal was directly detected via a 2.5-GHz PIN receiver, and the received OFDM signal was captured by a real-time 50-GHz sampling oscilloscope for signal demodulation. And the real-time scope has the maximum sampling rate of 50 GS/s. Ideally, the sampling rate of the receiver needs only 5 GS/s according to the sampling theory. In order to demodulate the vector signal, the offline DSP program was employed. And the demodulation process contained the synchronization, FFT, one-tap equalization, and QAM symbol decoding. Therefore, the BER could be calculated according to the observed SNR.

In order to realize the relationship of operated currents and CW injection powers of the injection-locked FP-LD with 16-QAM OFDM signal, the bias currents Idc of 20, 25, 30, and 35 mA were utilized, respectively. In the measurement, first, we investigated and observed the SNR characteristic of injection-locked FP-LD after 20-km fiber transmission, when a CW injection power was -12 dBm. Hence, Fig. 5 shows the measured upstream SNR of each OFDM subcarrier in the frequency bandwidth of 0.0195–2.5195 GHz at 20-km fiber transmissions at the received power of -13 dBm. Here, as the operated current of injection-locked FL-LD increased, the obtained SNR could be also enhanced, as shown in Fig. 5. Furthermore, the OFDM subcarriers at high frequency would also experience SNR penalty and could not achieve FEC threshold [$\mathrm{BER} = 3.8 \times 10^{-3}$; $\mathrm{SNR} = 15.2$ dB], due to the frequency response of FP-LD under the various bias currents, as shown in Fig. 5.

Then, we executed the BER performances of injection-locked FP-LD, which was operated at different bias currents of 20, 25, 30, and 35 mA, respectively, under different CW injection powers from -6 to -18 dBm after 20-km SMF transmission since the received power was at -13 dBm.

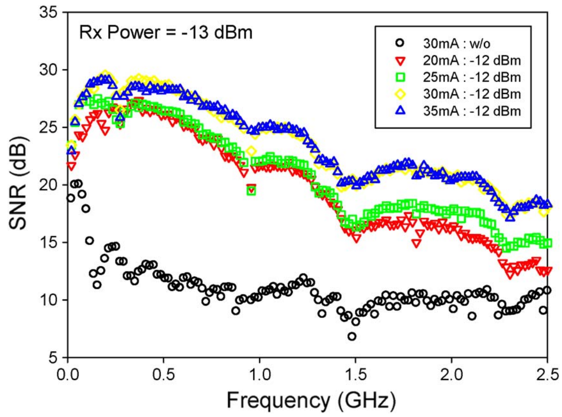

Fig. 5. Measured upstream SNR of each OFDM subcarrier of mode-locked FP-LD under different operated currents in the frequency bandwidth of 0.0195 to 2.5195 GHz at 20-km fiber transmissions, when the CW injection power and received power are set at −12 and −13 dBm, respectively.

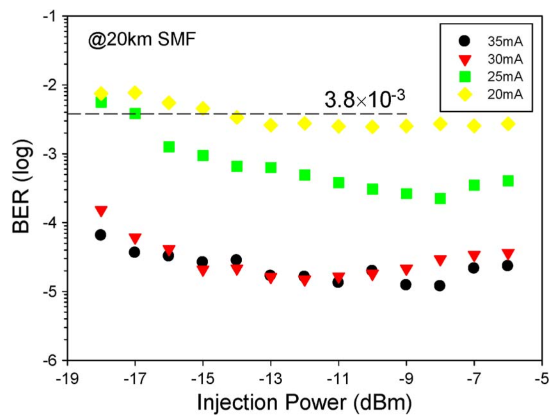

Fig. 6. BER performances of injection-locked FP-LD, which was operated at different bias currents of 20, 25, 30, and 35 mA, respectively, under different CW injection power since the received power was at −10 dBm.

If the measured BER will be less than FEC threshold, the injection power should be larger than −14 dBm for launching into FP-LD driving at 20 mA, as shown in Fig. 6. For example, in an SR access of 20-km fiber transmission, to achieve the FEC threshold level, a −17-dBm CW injection power was only needed for mode-locking when the bias current of FL-LD was larger than 25 mA. Furthermore, when the operated currents of the injection-locked FP-LD were 30 and 35 mA, respectively, as also shown in Fig. 6, the measured BERs could be less than 1.52×10^{-4} and 6.48×10^{-5}, respectively. Moreover, while the bias currents of injection-locked FP-LD were 30 and 35 mA, their corresponding BER curves were similar in the same injection range. Therefore, to achieve the better BER performance in the proposed SR-to-LR-PON system, the larger bias current and CW injection power were required for proposed injection-locking FP-LD scheme. As we know, when the front-facet reflectivity of FP-LD was 10%, the longitudinal mode of the FP-LD could be locked under the lower injection power for increasing the power budget in PON access. In addition, by lowering the front-facet reflectivity of the FP-LD using antireflection (AR) coating, the required optical injection power for successful injection locking of the FP-LD is much lower [19]. Hence, the power budget for the distributed CW light is increased. Besides, according to ref. [20], lowering the front-facet reflectivity can increase the optical injection locking range; hence, the wavelength accuracy of the injection CW light is reduced. However, lowering the front-facet reflectivity decreases the optical coherence of the FP-LD, making the lasing more difficult.

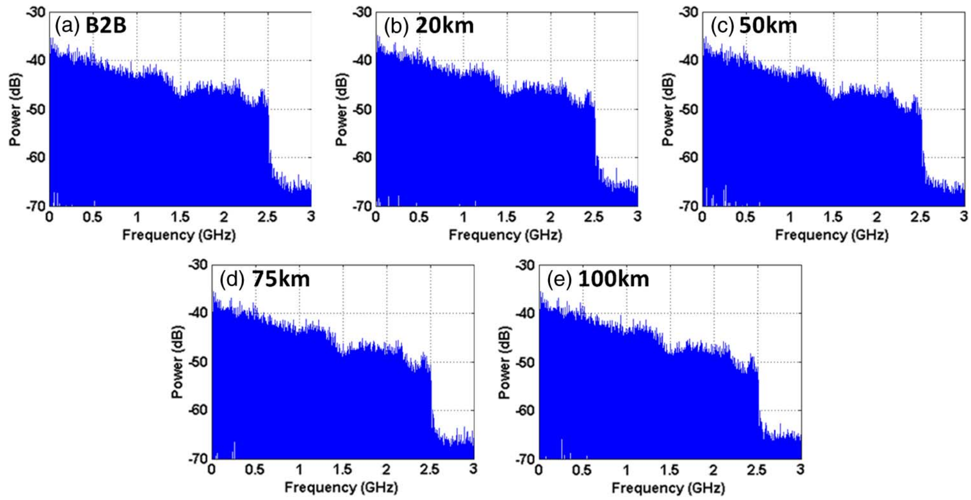

Fig. 7. Measured electrical spectra of the optical OFDM signal at (a) the B2B state and after (b) 20-, (c) 50-, (d) 75-, and (d) 100-km fiber transmissions, respectively, when a −12-dBm injection power launches into the FP-LD.

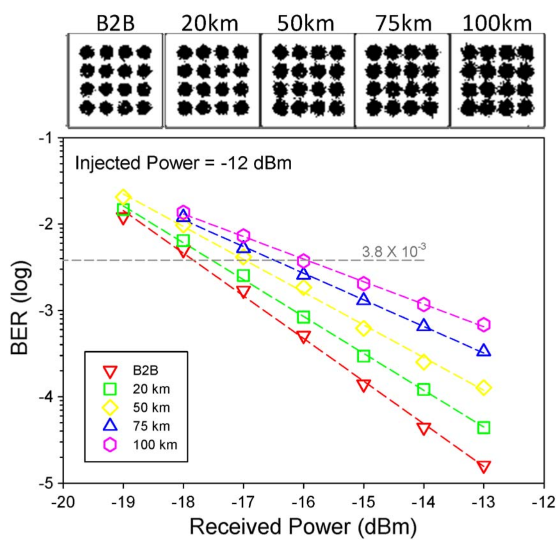

Fig. 8. BER measurements of 10-Gb/s 16-QAM OFDM upstream traffic at the B2B, 20-, 50-, 75-, and 100-km SMF transmissions, respectively. The insets are the corresponding constellation diagrams.

In the next measurement, we set the CW injection power of −12 dBm for the proposed injection-locked FP-LD, driving at 30 mA, in the SR-to-LR fiber transmission. Therefore, Fig. 7(a)–(e) shows the measured electrical spectra of the optical OFDM signal, when a −12-dBm injection power launches into the FP-LD, at the back-to-back (B2B) state and after 20-, 50-, 75-, and 100-km fiber transmissions, respectively. With the increase in fiber transmission length gradually, the electrical power would also degrade in the higher frequency domain due to the RF fading and fiber chromatic dispersion.

Here, in order to achieve the SR-to-LR signal transmission, a properly CW injection power was required for the FP-LD. According to the above measurement results, we set the operated current of FP-LD at 30 mA. And the 1540.31-nm CW lightwave with −12-dBm injection power was used to launch into FP-LD for injection locking. Hence, Fig. 8 presents the BER measurements of 10-Gb/s 16-QAM OFDM upstream traffic at the B2B state and after 20-, 50-, 75-, and 100-km SMF transmissions, respectively. The insets in Fig. 8 were the corresponding constellation diagrams, measuring at the FEC threshold, and the received power was set at −16 dBm. Hence, when the FEC was used in the proposed access network, the received sensitivities were observed at −17.76, −17.43, −16.90, −16.56, and −16.00 dBm under the B2B, 20-, 50-, 75-, and 100-km fiber transmissions, respectively. As a result, the measured power penalties were 0.33, 0.86, 1.20, and 1.76 dB, respectively, in the fiber transmission lengths of 20, 50, 75, and 100 km. Moreover, if the CW injection power was less than −12 dBm in this experiment, the measured BER could not achieve the FEC threshold in a 100-km fiber transmission. For example, in an LR-PON (∼100 km) system, it usually uses an EDFA at 50 km of the transmission path for loss compensation, so it does not need 8-dBm launched power per ONU. Besides, we only need an 8-dBm output power at CO for 100-km transmission without using EDFA to achieve −12-dBm launched power to FP-LD for mode-locking in this measurement.

3. Conclusion

We have proposed and investigated an injection-locked FP-LD with 10% front-facet reflectivity utilizing optical OFDM modulation in each ONU for colorless operation in a PON system. Here, the 10-Gb/s 16-QAM OFDM upstream traffic was generated via a 2.5-GHz-bandwidth injection-locked FP-LD for the SR-to-LR transmission. In this measurement, the CW injection power of −12 dBm for the injection-locked FP-LD was required in a 100-km fiber transmission. Therefore, error-free upstream transmissions of 20-, 50-, 75-, and 100-km SMFs are completed also with the power penalties of 0.33, 0.86, 1.20, and 1.76 dB at the BER of 3.8×10^{-3} (FEC threshold), respectively. In addition, the relationships of CW injection power, bias current, and SNR of each OFDM subcarrier for injection-locked FP-LD have also been discussed.

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