

Demonstration of using injection-locked Fabry-Pérot laser diode for 10 Gbit/s 16-QAM OFDM WDM-PON

C.H. Yeh, C.W. Chow, H.Y. Chen, J.Y. Sung and Y.L. Liu

A 10 Gbit/s OFDM upstream transmission has been investigated by using a Fabry-Pérot laser diode (FP-LD) based ONU with seeding-light in a colourless WDM-PON. Also demonstrated is the relationship of CW injection power and SNR of each OFDM subcarrier for a modelocked FP-LD. Moreover, when a 16-QAM OFDM modulation is applied in a modelocked FP-LD, -15.7 dBm received sensitivity at the BER of 3.8×10^{-3} can be obtained after 20 km fibre transmission.

Introduction: Passive optical networks (PONs) are the best solutions for next generation fibre access applications [1]. Therefore, wavelength division multiplexed (WDM)-PONs are the most promising future fibre access owing to their benefits such as large capacity, privacy, format transparency, guaranteed quality-of-service (QoS) and network security etc. [2]. In a conventional WDM-PON, each optical network unit (ONU) is assigned with a separate pair of specific wavelengths for upstream and downstream traffic, respectively. However, its deployment has been hindered owing to the lack of economical techniques for the WDM transmitters.

Recently, ‘colourless’ transmitters, such as spectrally-sliced and injection-locked Fabry-Pérot laser diodes (FP-LDs), and wavelength-injection reflective semiconductor optical amplifiers (RSOAs), have been reported [3–5]. However, the effective transmission rate of these transmitters is 2.5 Gbit/s via OOK-NRZ modulation [4, 5]. Besides, to increase the modulation rate of an injection-locked FP-LD to 10 Gbit/s, coherent lasers have been investigated in PON access [3]. However, it also resulted in an increase in cost. Furthermore, to increase the modulation rate and avoid fibre dispersion, optical orthogonal frequency division multiplexing (OOFDM) modulation has been proposed [6]. Owing to the highly spectral efficiency of the M-quadrature amplitude modulation (QAM) in each subcarrier of the OFDM signal, low-bandwidth optical components can still be used.

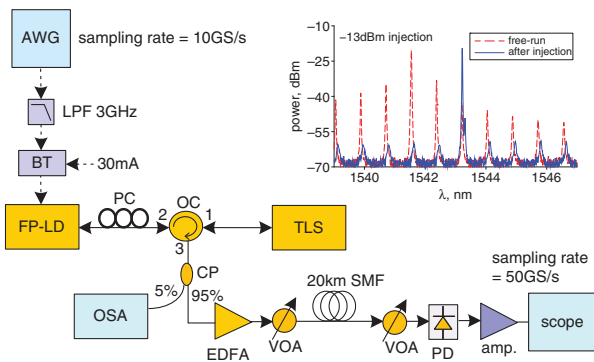


Fig. 1 Experimental setup of proposed injection-locked FP-LD for 10 Gbit/s upstream traffic by using 16-QAM OFDM modulation in colourless WDM-PON system

Inset: Output spectra of FP-LD used without and with CW injection, when I_{dc} was 30 mA and CW injection was -13 dBm

To achieve 10 Gbit/s traffic rate by using a 2.5 GHz bandwidth injection-locked FP-LD, the OFDM-QAM format is employed in this Letter. Here, we propose and investigate a 10 Gbit/s 16-QAM OFDM modulation upstream by using an injection-locked FP-LD in a WDM-PON. In the experiment, we first analysed and demonstrated the PON performance under different operating currents of the FP-LD and CW injection powers. According to the measured results, a larger bias current of the modelocked FP-LD could provide the best signal-to-noise ratio (SNR) of each OFDM subcarrier. Moreover, the received sensitivity of the upstream wavelength can be observed at -15.7 dBm at the bit error rate (BER) of 3.8×10^{-3} after 20 km singlemode fibre (SMF) transmission.

Experiment and results: Fig. 1 presents the experimental setup of the proposed injection-locked FP-LD for 10 Gbit/s upstream traffic by using 16-QAM OFDM modulation in a colourless WDM-PON

system. CW injection light was transmitted through the optical circulator (OC) and polarisation controller (PC), and then into the FP-LD for modelocking, as also shown in Fig. 1. The PC was used to control the polarisation state and maintain the maximum output power. To observe the output spectrum of the FP-LD, a 1×2 and 5:95 optical coupler (CP) was used. Here, a tunable laser source (TLS) of 1543.22 nm (with -15 to 7 dBm output range) was used to serve as a CW injection light. The bias current (I_{dc}) of the multimode FP-LD was set at 30 mA at a temperature of 25°C. The mode-spacing and threshold current of the FP-LD were 0.8 nm and 10 mA, respectively. The measured output spectrum of the FP-LD could be observed at the 5% output of CP, by an optical spectrum analyser (OSA) with a 0.05 nm resolution, as illustrated in Fig. 1. Hence, the inset of Fig. 1 shows the output spectra of FP-LD used without and with CW injection, when the I_{dc} was 30 mA and CW injection was -13 dBm.

In the measurement, 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 consisted of the serial-to-parallel conversion, QAM symbol encoding, inverse fast-Fourier transform (IFFT), cyclic prefix (CP) insertion, and digital-to-analogue conversion (DAC). 12 GSample/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 2.4805 GHz bandwidth of 0.0195 to 2.5 GHz, with a fast-Fourier transform (FFT) size of 512. Here, yielding 19.5 MHz subcarrier spacing and 10 Gbit/s total data rate could be observed. Hence, the produced electrical 16-QAM OFDM signal could be applied on the modelocked FP-LD via a bias-tee (BT). The upstream signal was direct-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. To demodulate the vector signal, the offline DSP program was employed. The demodulation process contained the synchronisation, FFT, one-tap equalisation, and QAM symbol decoding. Therefore, the bit error rate (BER) could be calculated according to the observed SNR.

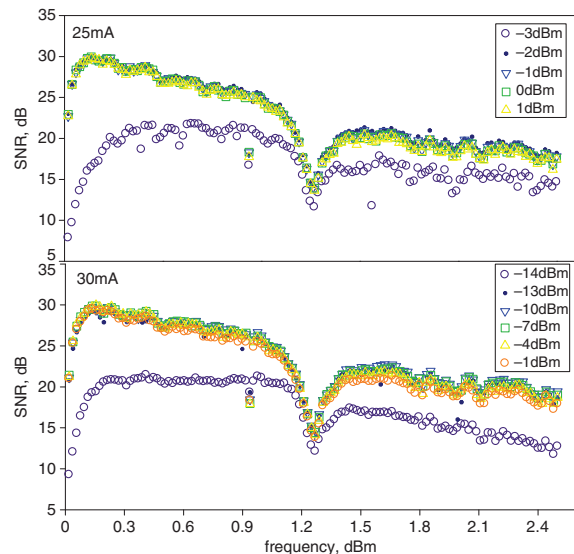


Fig. 2 Measured SNR of each OFDM subcarrier at B2B status, under different CW injection power levels of -14 to 1 dBm launching into FP-LD

To realise the relationships of SNR of each OFDM subcarrier and bias current of the modelocked FP-LD, the I_{dc} of 25 and 30 mA were used in the measurement, respectively. Fig. 2 shows the measured SNR of each OFDM subcarrier in the frequency bandwidth of 0.0195 to 2.5 GHz at the back-to-back (B2B) status, under different CW injection power levels of -14 to 1 dBm launching into the FP-LD. Here, the optical received power is set at -10 dBm. To achieve the forward error correction (FEC) threshold ($\text{SNR} = 16.5$ dB; $\text{BER} = 3.8 \times 10^{-3}$), the minimum injection powers are -2 and -13 dBm to inject into the FP-LD, when the bias current is 25 and 30 mA, respectively. According to the measured results, when the injection power is less than -2 and -13 dBm at 25 and 30 mA, respectively, each obtained SNR cannot be kept at the FEC limit, as shown in Fig. 2. Besides, when the bias current of the FP-LD is 25 mA, the required injection power must be ≥ -2 dBm to achieve FEC level. However, in a practical

standard-reach WDM-PON system, the ≥ -2 dBm injection power is hard to accomplish owing to the losses of passive components and link fibre. Here, if the operated current increases to 30 mA, the required injection power can reduce to -13 dBm to achieve FEC threshold, as illustrated in Fig. 2. In practice, the -13 dBm CW injection power seems to achieve PON access easily.

As we know, the higher SNR could lead to better BER value. According to the measured results of Fig. 2, a larger operated current for the modelocked FP-LD can obtain a better SNR under a smaller CW injection power. Thus, before measuring the BER performance, we first experimented on the SNR of each OFDM subcarrier for the modelocked FP-LD (bias current is set at 30 mA) after 20 km SMF transmission. Hence, as shown in Fig. 3a, the obtained SNR spectra are similar to those in Fig. 2 under different injected powers of -13 , -10 , -7 , -4 and -1 dBm, respectively. The measured SNR of each OFDM subcarrier is nearly the same under these injection powers, as seen in Fig. 3a.

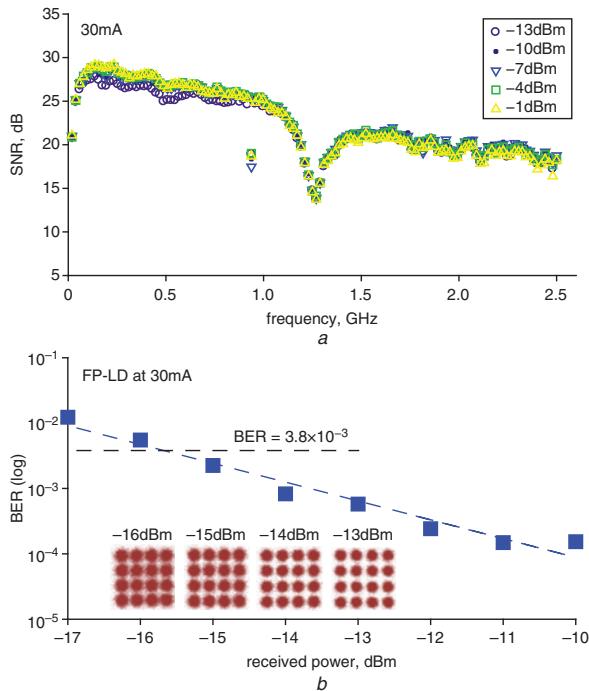


Fig. 3 Measured SNR of each OFDM subcarrier after 20 km transmission under different CW injection powers launching into FP-LD (Fig. 3a), and BER performances of 10 Gbit/s 16-QAM OFDM upstream after 20 km SMF transmission (Fig. 3b)

Inset: Corresponding constellations

Finally, according to the measured results of Fig. 3a, we set the CW injection power of -13 dBm launching into the FP-LD for the upstream

transmission. Hence, Fig. 3b presents the BER performances of 10 Gbit/s 16-QAM OFDM upstream after 20 km SMF transmission. The insets of Fig. 3b are corresponding constellation diagrams at the received powers of -16 , -15 , -14 and -13 dBm, respectively. In Fig. 3b, we can observe the received sensitivity of -15.7 dBm after 20 km SMF transmission, under the FEC threshold ($\text{BER} = 3.8 \times 10^{-3}$). Moreover, according to Figs. 2 and 3b, the neglected power penalty also can be obtained for the upstream traffic at B2B and 20 km fibre transmission.

Conclusions: We have proposed and investigated a 10 Gbit/s 16-QAM OFDM upstream modulation by using an external-injected FP-LD in WDM-PON access. Here, according to the measured results, the larger operating current of the FP-LD could provide the best SNR for each OFDM subcarrier. Moreover, when a 16-QAM OFDM modulation signal was applied in the FP-LD, the measured sensitivity of the upstream wavelength can be observed at -15.7 dBm under the BER of 3.8×10^{-3} after 20 km SMF transmission.

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One or more of the Figures in this Letter are available in colour online.

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References

- 1 Yeh, C.H., Chow, C.W., Chen, H.Y., and Chen, B.W.: 'Using adaptive four-band OFDM modulation with 40 Gb/s downstream and 10 Gb/s upstream signals for next generation long-reach PON', *Opt. Express*, 2011, **19**, pp. 26150–26160
- 2 Chan, C.A., Attygalle, M., and Nirmalathas, A.: 'Provision of independent services in WDM passive optical networks using closely separated dual baseband channels'. Proc. OFC, Anaheim, CA, USA, 2007, Paper JWA48
- 3 Xu, Z., Wen, Y.J., Zhong, W.-D., Chae, C.J., Cheng, X.-F., Wang, Y., Lu, C., and Shankar, J.: 'High-speed WDM-PON using CW injection-locked Fabry-Perot laser diodes', *Opt. Express*, 2007, **15**, pp. 2953–2962
- 4 Chow, C.W., Yeh, C.H., Wang, C.H., Shih, F.Y., and Chi, S.: 'Signal remodulation high split-ratio hybrid WDM-TDM PONs using RSOA-based ONUs', *Electron. Lett.*, 2009, **45**, pp. 903–905
- 5 Yeh, C.H., Chow, C.W., Wang, C.H., Shih, F.Y., Wu, Y.F., and Chi, S.: 'Using four wavelength-multiplexed self-seeding Fabry-Perot lasers for 10 Gbps upstream traffic in TDM-PON', *Opt. Express*, 2008, **16**, pp. 18857–18862
- 6 Yeh, C.H., Chow, C.W., Chen, H.Y., and Sung, J.Y.: 'Hybrid OFDM-based multi-band wireless and baseband signal transmission in PON access', *Electron. Lett.*, 2012, **48**, pp. 390–392