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10 Gb/s TDM passive optical networks using four wavelengths multiplexed channels

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ABSTRACT

We propose a new architecture for 10 Gb/s upstream traffic in TDM-PON using externally injection-locked Fabry–Perot laser diodes (FP-LDs) in each optical network unit (ONU). Four directly modulated 2.5 Gb/s FP-LDs were injection-locked by continuous wave (CW) carriers distributed from the optical line terminal (OLT). Hence, a total of 10 Gb/s upstream traffic can be achieved. Experimental results show negligible power penalty at a transmission of 25 km standard single mode fiber (SMF) without dispersion compensation. The performance of the injection-locked FP-LD is also studied.

1. Introduction

Recently, multimedia services, such as video-conferencing, video-on-demand, online gaming and high-definition television, etc., are becoming more and more popular due to the popularity of the Internet and the rapid development of the performances of digital electronics and computers. Therefore, individual user will need more than 50–100 Mb/s data bandwidth in the near future [1]. However, current access networks using copper cables are reaching their bandwidth limit [1]. As a result, developing new access network architecture, supporting high data rate with guaranteed bandwidth for the future applications, becomes an important issue. As a cost-effective, high flexibility and scalable technology, passive optical network (PON) is regarded as a promising solution to provide various end users with broadband access [2–5].

Currently, Internet service providers (ISPs) use time division multiplexing (TDM) for PON deployment. Users access and share the bandwidth in time domain. Due to the cost-effectiveness, TDM-PON has emerged as the current generations of PONs, such as broadband PON (BPON), Ethernet PON (EPON) and Gigabit PON (GPON) [6–8]. However, the bandwidth of these TDM-PONs might not be large enough to meet the increasing bandwidth demand for future multimedia services [9,10]. Hence, recently, next generation 10 Gb/s TDM-PONs including 10 Gb/s EPON and 10 Gb/s GPON are under intensive studied [11,12].

In this paper, we propose a new and simple architecture to achieve 10 Gb/s TDM-PON deployment using externally injection-locked Fabry–Perot laser diodes (FP-LDs) in each optical network unit (ONU). For the uplink traffic, we use four 2.5 Gb/s directly modulated FP-LDs, which are injection-locked by the distributed continuous wave (CW) carriers generated at the optical line terminal (OLT). In such a way, a 10 Gb/s uplink traffic can be efficiently achieved by using the existing optical components developed for GPON (~2.5 Gb/s). In addition, the proposed 10 Gb/s TDM-PON only requires a moderate upgrade of the components at the ONU and the OLT, and the modification of the existing GPON network infrastructure is not required. Besides, since the 10 Gb/s burst-mode receiver (Rx) is still in the research stage and may not be commercially available in the near future, hence, using four 2.5 Gb/s burst-mode Rxs for the upstream traffic can further fascinate the deployment of 10 Gb/s TDM-PON. The synchronization of these four directly modulated FP-LDs and the four burst-mode Rxs is performed in the media access controller (MAC) protocol. Although using four 2.5 Gb/s wavelength multiplexed channels could be costly due to the addition of extra components, power budget can be enhanced since the Rx sensitivity of receiving 2.5 Gb/s signal is much lower than that at 10 Gb/s. A network demonstration was performed, showing negligible power penalty at the bit error rate (BER) measurement of a 25 km standard single mode fiber (SMF) transmission. Furthermore, performances of various injected CW carrier powers were also investigated; showing small injected power (−18 dBm) is enough to sustain the injection locking for data transmission. We believe that the output power of each CW carrier at about 5 dBm is large enough to simultaneously

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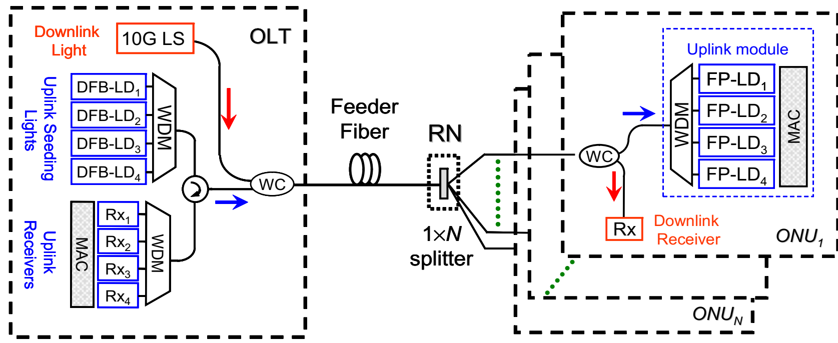

Fig. 1. Proposed 10 Gb/s uplink transmission in TDM-PON using injection-locked FP-LDs.

injection-locked 32 ONUs (by considering that the 15 dB splitting loss from the 32-split and the insertion losses from fiber and other optical components). This can further reduce the cost since a single CW laser can be shared by 32 subscribes.

2. Experimental setup

Fig. 1 shows the proposed architecture of the 10 Gb/s TDM-PON using injection-locked FP-LDs. At the OLT, the 10 Gb/s laser source (LS) is used to broadcast the downlink information. For the uplink traffic, four distributed feedback laser diodes (DFB-LDs) are used to serve as the uplink seeding light sources. As shown in Fig. 1, the four CW seeding light sources are multiplexed by a 1×4 wavelength division multiplexer (WDM) with insertion loss of 4 dB and transmitted through a wavelength coupler (WC) with insertion loss of 0.5 dB to the remote node (RN). In the RN, a $1 \times N$ optical passive power splitter is used for sharing the broadcasting downlink information and the CW seeding light sources to all the ONUs in the same TDM-PON. Therefore, each seeding light source can be shared by all the subscribers and is expected to substantially reduce the cost of the proposed TDM-PON. In ONUs, the four CW seeding lights are de-multiplexed by a 1×4 WDM, athermal arrayed waveguide grating (GN Nettest, MICS-32/050), and each CW light is injected into a FP-LD. The four FP-LDs inside the ONU have similar characteristics. Polarization controllers (PCs), located between the WDM and the FP-LDs, are used to adjust proper polarization states for injection locking. The temperature of the FP-LD should be controlled in ±2.5 °C to allow efficient injection locking. Besides, four 2.5 Gb/s burst-mode Rxs at the OLT are multiplexed by a 1×4 WDM and are used to detect the uplink signal from the ONU. Each 10 Gb/s ONU consists of four 2.5 Gb/s directly modulated FP-LDs connected with a 1×4 WDM, and is served as a uplink module. The synchronization of these four directly modulated FP-LDs and the Rxs at OLT can be performed in MAC layer protocol. Due to the use of four arrayed FP-LDs in each ONU, information was divided into four sections during transmission in our proposed scheme. Four divided information also can be rearranged by MAC layer protocol. The FP-LD has multi-longitudinal-mode output with ~1.35 nm mode spacing and ~45% front-facet reflectivity. The CW laser generated by the DFB-LD located at the OLT distributed the seeding light through an optical circulator (OC) with insertion loss of 1 dB and transmitted over 25 km SMF and then launched into the FP-LD. We used a variable optical attenuator (VOA) to emulate different PON split-ratio in the RN in the proposed architecture. After injection locking, the uplink data was generated, which was then sent back through the 25 km SMF towards the 2.5 Gb/s Rx at the OLT. Experiment results show that the attenuation value of VOA can achieve maximum 18 dB when output power of each CW carrier is about 7 dBm.

3. Results and discussion

Fig. 2a shows the free-run optical spectrum of the multi-mode FP-LD from 1520 to 1570 nm with ~1.35 nm mode spacing, at the bias current and temperature of 25 mA and 25 °C, respectively. It was measured by an optical spectrum analyzer with resolution of 0.01 nm. Next, we can choose four injection-locked wavelengths from four FP-LDs with similar characteristics of wavelength range and mode spacing to achieve the 10 Gb/s uplink transmission. In Fig. 2b, four lasing wavelengths at 1540.25, 1541.61, 1542.96 and

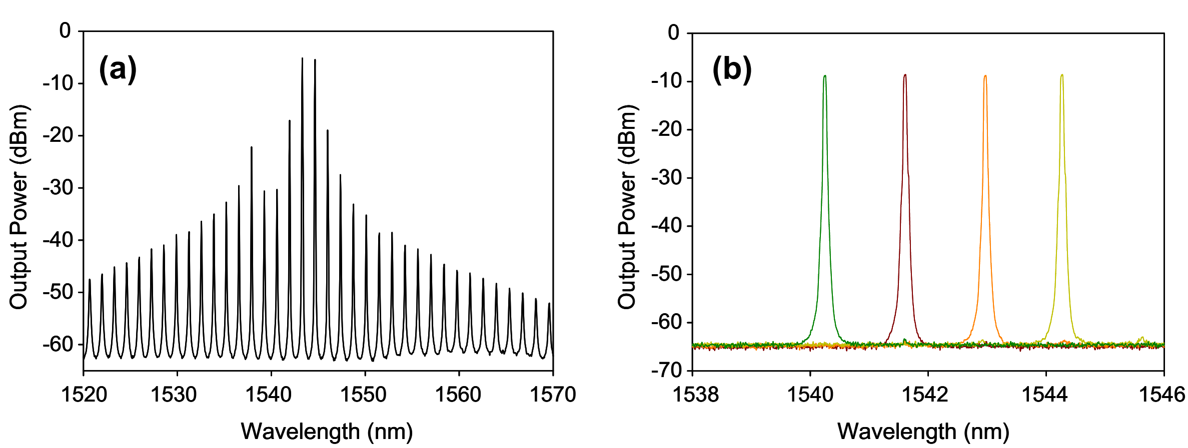

Fig. 2. (a) Free-run optical spectrum of multi-mode FP-LD and (b) four injection-locked single longitudinal mode (SLM) spectra we choose as the uplink transmission channels, while the bias current and temperature is 25 mA and 25 °C, respectively.

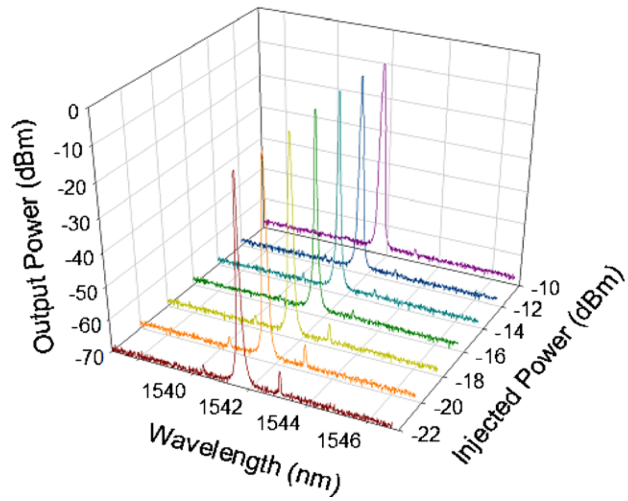

Fig. 3. Output spectra of injected FP-LD with output power and wavelength versus the different injected power of CW laser (−10 to −22 dBm) in the proposed architecture.

1544.28 nm, and with the output power of about −8.7, −8.6, −8.6 and −8.7 dBm, respectively, were achieved at the ONU. The side-mode suppression ratios (SMSRs) of the four lasing wavelengths are all greater than 50 dB. Besides, we also investigated the output power and lasing wavelength stabilities (at wavelength 1541.61 nm). After 60 min measurement, the injection-locked FP-LD shows high stability with the maximum of 0.03 nm wavelength variation and 0.55 dBm power fluctuations.

In order to investigate the effect of different seeding powers on date transmission, we adjust the CW laser powers from −22 to −10 dBm. Fig. 3 shows the optical spectra of the injection-locked FP-LD under different injected powers. The output wavelength of the FP-LD is locked to the choosing mode (for example 1541.61 nm). We have observed that injection locking can be sustained during these injected powers. The bias current and temperature of FP-LD is maintained at 25 mA and 25 °C, respectively. In Fig. 4a, we plot the output power and SMSR achieved for the wavelength-locked FP-LD at different injected powers. The corresponding eye diagrams of the injection-locked FP-LDs are depicted in Fig. 4b, showing clear wide open eye can be achieved with small injection power of −18 dBm.

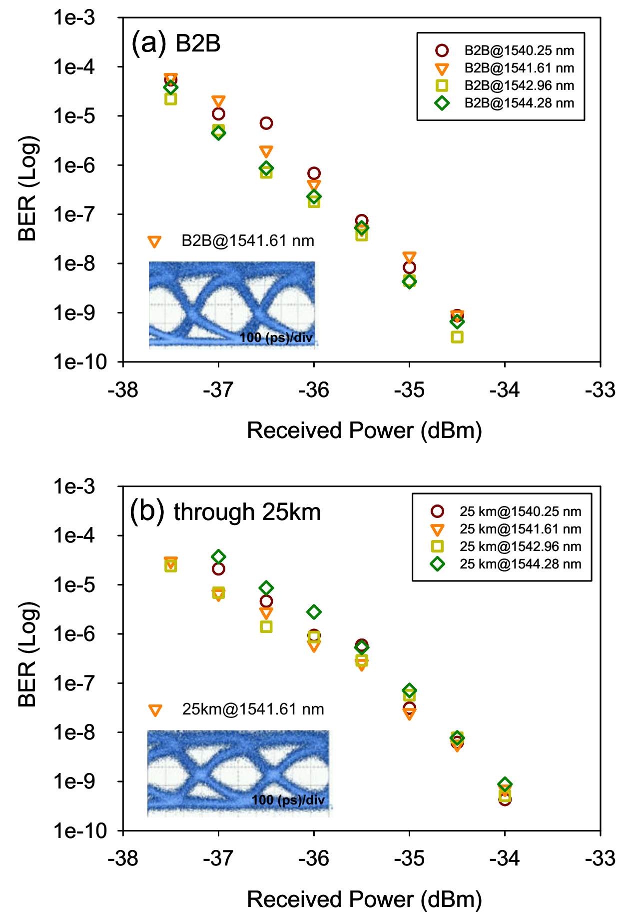

Fig. 5. BERs versus received optical power for uplink traffic of the proposed architecture with (a) B2B and (b) 25 km SMF transmission. Insets: (a) the eye diagrams of B2B and (b) 25 km SMF transmission (for example 1541.61 nm). BERs are measured by an optically pre-amplified Rx, consisting of an erbium-doped fiber amplifier (EDFA), an optical filter to filter the out-of-band amplifier spontaneous emission (ASE), a 2.5 GHz p-i-n photodiode.

In order to confirm the transmission performance of the proposed 10 Gb/s traffic TDM-PON, BER measurements were performed. We observed less than 1 dB power penalty in the 10 Gb/s downstream transmission. The power penalty was due to the dis-

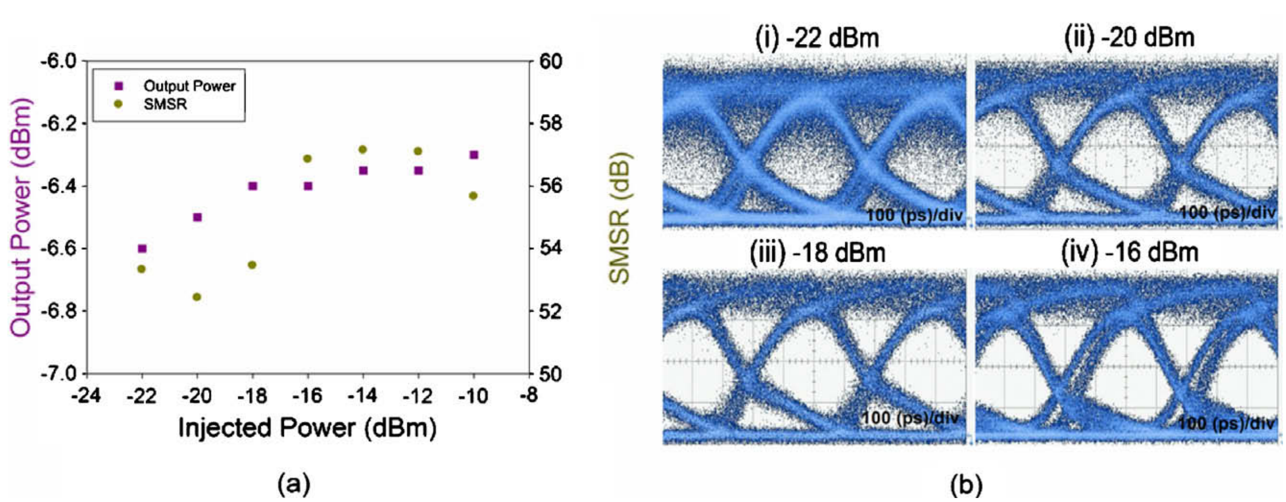

Fig. 4. (a) Various injected CW power versus the output power and SMSR and (b) eye diagrams of different injected CW power of the proposed scheme.

persion of the SMF since no dispersion compensation was used in the setup. In the upstream measurement, four FP-LDs, and each was directly modulated by a 2.5 Gb/s non-return-to-zero (NRZ), $2^{31}-1$ pseudo random binary sequence (PRBS) data. We chose four different lasing wavelengths as the uplink transmission channels and these four wavelengths were located at 1540.25, 1541.61, 1542.96 and 1544.28 nm, respectively. Fig. 5a and b show the measured BERs of the proposed uplink module versus the received optical power for the back-to-back (B2B) and transmission of 25 km SMF without dispersion compensation, respectively. Comparing these two figures we can find that the power penalties in each optical channel are all <0.5 dB at BER of 10^{-9}. We arbitrary selected the eye diagrams at wavelength of 1541.61 nm, and are shown in the insets. The results show that the proposed architecture could be a promising candidate architecture for upgrading the present GPON to the 10 Gb/s TDM-PON.

4. Conclusion

We proposed and demonstrated a simple architecture to achieve 10 Gb/s TDM-PON deployment. For the downlink traffic, we used a 10 Gb/s signal generated by external modulation. For the uplink traffic, we used four 2.5 Gb/s directly modulated FP-LDs in the ONU, which were injection-locked by the distributed CW carriers generated at the OLT. In such a way, a total of 10 Gb/s uplink traffic can be efficiently achieved. Negligible power penalty was observed in both the downlink and uplink signals after 25 km standard SMF transmission without dispersion compensation. Furthermore, performances of various injected CW carrier powers showing that small injected power (−18 dBm) is enough to sustain the injection locking for data transmission. This can further reduce the cost since a single CW carrier distributed from the OLT with reasonable output power can be shared by the 32 ONUs without additional amplification. In addition, the proposed 10 Gb/s TDM-PON only requires a moderate upgrade of the components at the ONU and the OLT. We believe that the proposed 10 Gb/s TDM-PON can be considered as a relatively simple solution to upgrade the conventional PON to 10 Gb/s TDM-PON without modifying the existing GPON or EPON network infrastructures.

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