High-speed WDM-PON using CW injection-locked Fabry-Pérot laser diodes

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Abstract: We propose a new WDM-PON architecture using Fabry-Pérot laser diodes (FP-LDs) that are injection-locked by continuous wave (CW) seed light. The modulation characteristics of the CW light injection-locked FP-LD are first investigated. Both uplink and downlink transmissions at 10 Gb/s are experimentally demonstrated using the proposed CW injection-locked FP-LDs. It is shown that up to 16 laser cavity modes can be selectively injection-locked with side mode suppression ratio larger than 30dB. The effects of the location of FP-LD cavity modes, transmission distance, and injection wavelength detuning on the overall transmission performance are investigated. The possibility of eliminating polarization dependence of the proposed CW injection scheme is also experimentally demonstrated by properly configuring a depolarizer. The deployment cost for the proposed WDM PON is potentially low from the fact that the CW laser sources located at the central office can be shared by many WDM-PONs and low-cost FP-LDs are used as light sources for data rates as high as 10 Gb/s.

OCIS codes: (060.4510) Optical communications; (060.4250) Networks

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1. Introduction

Current access networks are built mainly with copper cables and/or hybrid fiber coax (HFC) cables, which have a limited capacity and are becoming difficult to meet the ever increasing bandwidth demand arising from many new broadband services including broadband internet access, video conferencing, video-on-demand, etc. As such, current transmission medium needs to be replaced with optical fiber for higher bandwidth. The passive optical network (PON) is very attractive, since it provides much higher bandwidth than copper or coax based solutions [1-3]. Furthermore, PON offers additional advantages like high reliability and easy maintenance. These characteristics are important with the fiber-to-the-home (FTTH) deployment. Well-developed wavelength division multiplexing (WDM) technology can be advantageously added to PONs to vastly increase the overall capacity. In a WDM-PON, different subscribers are assigned distinct, dedicated wavelength channels and these channels are routed by a passive wavelength routing device located at a remote node (RN) close to the customer premises. In addition to increasing network capacity, a WDM-PON also helps to eliminate power splitting loss and enhances privacy of the end users. However, cost-effective, wavelength-stable light sources are the key for practical implementation of WDM-PONs, especially for customer premises equipment.

Light sources considered so far include spectrum-sliced light-emitting diodes (LEDs), amplified spontaneous emission source (ASE) from an erbium doped fiber amplifier (EDFA) [4], wavelength-seeded reflective semiconductor optical amplifiers (SOAs) [5,6], self-seeding SOAs [7], spectrum-sliced free running FP-LDs [8], and received downstream signals for remodulation [9]. Although most of these methods eliminate the need of wavelength-specific optical transmitters at the customer premises, each has its own drawbacks. The methods using LEDs and SOAs suffer from low power budget and high packaging cost, respectively. Spectrum slicing of a free-running FP-LD suffers from strong intensity noise, while the re-modulation scheme requires further development to suppress crosstalk from the residual downlink data and to alleviate the dependence of polarization state of the downlink signal [9]. The scheme of injection-locking FP-LDs using amplified spontaneous emission (ASE) noise, reported recently in [10-13], has many attractive features as compared with the other earlier proposed schemes. Using such a scheme, upstream transmission was demonstrated with bit rate up to 1.25 Gb/s [10-13]. We also recently demonstrated 2.5 Gb/s upstream transmission

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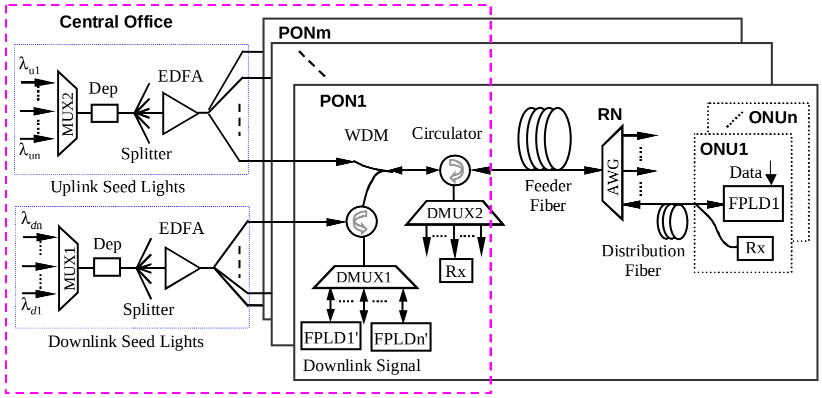

Fig.1. Proposed WDM-PON architecture using CW-injection-locked FP-LDs.

by injection-locking FP-LDs using a polarization insensitive supercontinuum pulse source [14].

Using FP-LDs injection-locked by spectrum-sliced broad-band incoherent light source, the data rate is limited because of the conversion of excess intensity noise (IN) from the seed light to the FP-LDs. In order to further increase the data rate, the use of high-quality seed light sources with low IN is essential. In this paper, we propose a new WDM-PON architecture using Fabry-Pérot laser diodes (FP-LDs) that are injection-locked by continuous wave (CW) coherent seed light (a preliminary version was presented in [15]). The CW seed light sources are located at the central office and can be shared by many WDM-PONs and hence the implementation cost is potentially low. We experimentally demonstrate that up to 16 FP-LD cavity modes can be individually selected for 10 Gb/s transmission by direct modulation scheme. Compared with the loopback modulation scheme in [16], our proposed method does not need an amplifier and an external modulator at each optical network unit (ONU), and hence can considerably reduce the ONU's implementation cost.

The rest of the paper is organised as follows. Section 2 describes the proposed WDM-PON using CW light injection-locked FP-LDs as light sources. Section 3 shows the characterization of CW light injection-locked FP-LD. Section 4 demonstrates the upstream and downstream transmissions for the proposed WDM-PON. In this section, the transmission performance, transmission length, and injection wavelength detuning are investigated. In Section 5, the feasibility of polarization-insensitiveness is demonstrated using a fiber depolarizer in conjunction with a dual fiber ring. The conclusions are given in Section 6.

2. Proposed WDM-PON architecture using CW light injection-locked FP-LDs

Figure 1 shows the schematic of our proposed WDM-PON architecture using CW light injection-locked FP-LDs. In the central office (CO), there are two sets of CW laser sources, one of which is used as the uplink seed light source and the other as the downlink seed light source. In the following discussion, we assume that the downlink and uplink are operated at different wavebands, including C band and/or L band. As shown in Fig. 1, the CW laser outputs for the uplink or downlink seeding are multiplexed by an optical multiplexer (MUX1 or MUX2) and the multiplexed lights pass through a depolarizer (Dep), which converts a linearly polarized light into a depolarized light, thus eliminating the polarization-dependence of the conventional injection-locking. These multiplexed and depolarized lights are used as the WDM seed light. As shown in Fig. 1, the multiplexed seed light is split into many parts by a power splitter. Each split branch is then amplified through an Erbium doped fiber amplifier (EDFA) and split again by another power splitter. Therefore, a single set of WDM CW laser sources can be shared by many WDM-PONs. This is expected to significantly reduce the cost for the deployment of WDM-PONs.

Within each WDM-PON, a split branch of the downlink seed light is fed into the FP-LDs

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via an optical circulator and a demulitplexer (DMUX1) such that each FP-LD is injection-locked to a single longitudinal mode. The injection-locked FP-LDs are then directly modulated with downlink data, producing the downlink optical signals. The downlink signals are then combined with the uplink seed light by a WDM coupler and launched into a feed fiber (single mode fiber) via an optical circulator. The combined downlink signals and the uplink CW seed light are then demultiplexed at the remote node (RN) by a cyclic arrayed waveguide grating (AWG). Note that the wavelengths for the uplink and downlink are allocated in such a way that the uplink wavelengths occupy one free spectrum range (FSR) of the cyclic AWG used, and the downlink wavelengths occupy another FSR of the AWG. Due to the periodicity of the cyclic AWG [17], the uplink CW seed light at λ_{ui} and the downlink signal at λ_{di} go to the same i-th optical network unit (ONUi, i=1, 2, ... n), where they are separated by a coarse WDM filter. The downlink signal is directly detected by a photo-detector. The uplink seed light at λ_{ui} is then fed into a temperature-controlled FP-LD to injection-lock its cavity mode at λ_{ui}. The FP-LD is directly modulated with uplink data and its output is combined with other uplink channels at the AWG and sent back to the central office via the same feeder fiber. Note that only one ONU (i.e., ONU1) is shown in Fig. 1 for clarity. Compared with a conventional downlink transmitter using a CW laser and an external modulator, a CW-injection-locked FP-LD provides better link budget since it does not suffer from power loss arising from the external modulator and also needs a much lower driving voltage.

3. Characterization of injection-locked FP-LDs

We first investigate the modulation characteristics of a CW light injection-locked FP-LD, since they determine the transmission performance of the WDM-PONs we proposed. The FP-

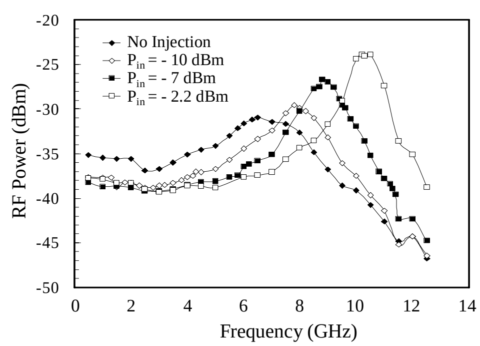

Fig.2. Small signal modulation responses of a FP-LD with different CW injection powers.

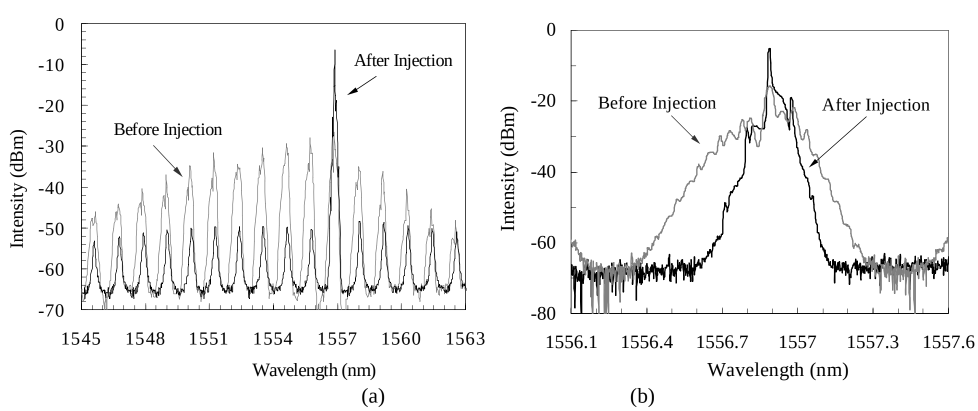

Fig. 3. Optical spectra of FP-LD outputs before and after injection with injection power of –8 dBm. (a) full span spectra, (b) close look of the cavity mode at 1556.8 nm.

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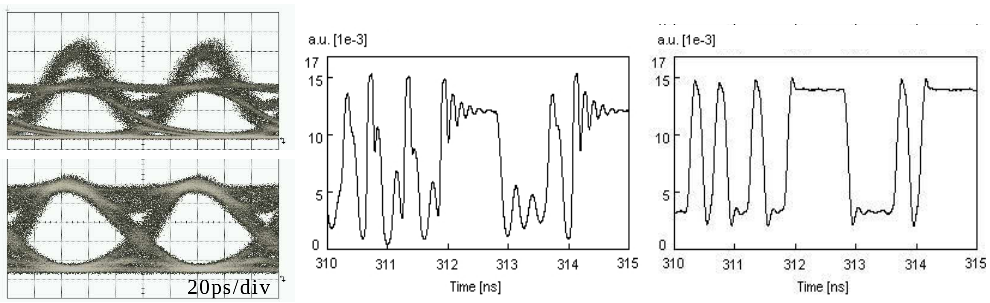

(a) (b)

Fig. 4. (a) Measured back-to-back eye diagrams of a FP-LD without (upper) and with injection locking (lower). (b) Simulated waveforms of a FP-LD without (left) and with injection locking (right).

LD used in our experimental demonstration has a threshold current of 18 mA and was biased at 40 mA (with around 1 dBm output power) to achieve sufficient modulation bandwidth. The operating temperature of the laser was maintained at room temperature with a temperature controller. First we evaluated the modulation bandwidth of the FP-LD under a CW optical injection. Here, the injected wavelength was fixed at the cavity mode of 1556.88 nm. Figure 2 shows the small signal modulation response (not normalized) of the FP-LD with different optical injection powers. The results show that the relaxation oscillation frequency (resonance peak) increases with the increase of the optical injection power. The relaxation oscillation frequency of the free running FP-LD with 40 mA bias current was 6.5 GHz. It was increased to 7.8 GHz, 8.9 GHz and 10.2 GHz at the optical injection power of -10 dBm, –7 dBm and –2.2 dBm, respectively.

Figure 3 shows the measured optical spectra of a 10 Gb/s directly modulated FP-LD with and without the injection of optical CW seed light. The laser was biased at 40 mA again and driven by a pseudo random bit sequence (PRBS) with a word length of 2^{15}-1 provided by a pulse pattern generator (PPG). The driving voltage of 2 Vp-p from the PPG was applied without any drive amplifier. Without optical injection, multiple cavity modes were oscillated with wavelength ranging from 1545 nm to 1563 nm and with mode spacing of around 140 GHz as shown in Fig. 3 (the gray curve). After the injection of CW light at 1556.88 nm with injection power of –8 dBm, the cavity mode located at that wavelength was injection-locked and enhanced in intensity, while other modes were suppressed significantly. The intensity difference between the locked mode at 1556.88 nm and the other side modes was more than 40 dB as shown in the solid curve of Fig. 3. This high side mode suppression ratio (SMSR) and a very narrow spectral width were observed even after a 10 Gb/s data signal was modulated to the laser, as shown in Fig. 3(b). The significantly reduced linewidth after injection-locking helps to achieve a larger dispersion tolerance and considerably reduce crosstalk from adjacent channels.

In addition to the single mode operation and narrower linewidth, injection-locking can also drastically suppress the relaxation oscillation. Figure 4(a) shows measured back-to-back eye diagrams of the directly modulated FP-LD without (the upper part) and with injection-locking (the lower part). Without injection-locking, the overshoot was very strong because of the relaxation oscillation. This relaxation was considerably suppressed when the FP-LD was injection-locked by an external seeding light. Compared with the waveform before injection-locking, the DC component (or logical "0" level) was slightly increased after injection-locking. This slightly reduces extinction ratio, but is not expected to introduce any significant penalty as the transmission distance is short, particularly in the access and metro applications. The observations were also verified by simulation using the commercial software, *VPIcomponentmaker*. Figure 4(b) shows the simulated waveforms with and without CW injection. As can be seen in Fig. 4(b), the relaxation oscillation is significantly suppressed with CW injection.

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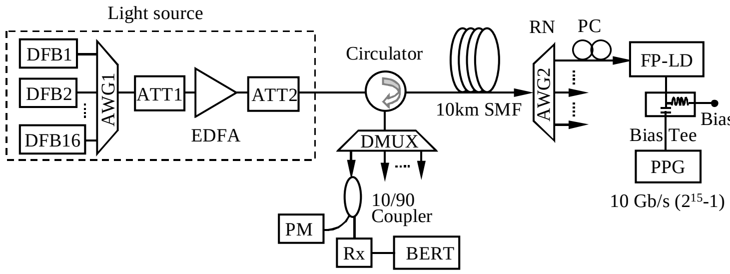

Fig. 5. Experimental setup for WDM-PON uplink transmission.

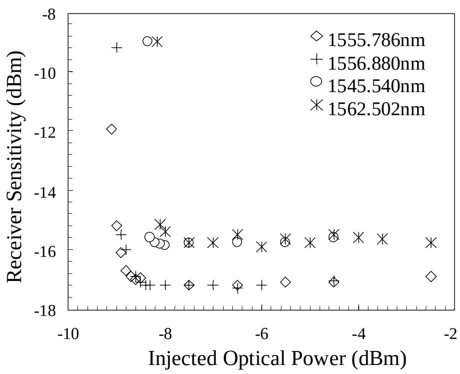

Fig. 6. Measured receiver sensitivity as a function of the injected CW optical power.

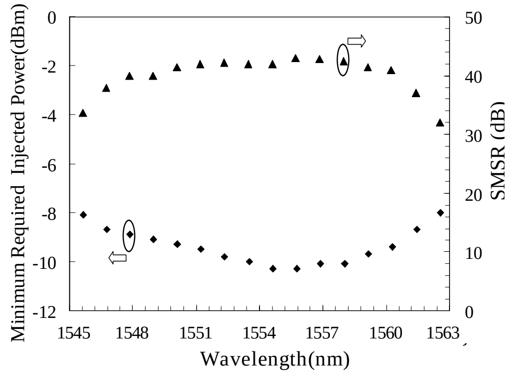

Fig. 7. Measured SMSR of the FP-LD and minimum required injected CW optical power

4. Experimental results and discussions

After characterizing the FP-LD, we here experimentally investigate the transmission performance for the WDM-PON proposed in section 2. The experimental setup for the uplink transmission is shown in Fig. 5. 16 distributed feedback lasers (DFB) were combined together as the multi-channel coherent seed light source through an AWG (AWG1). The power of each channel was 3 dBm. The combined seed light was fed to an optical attenuator (ATT1) with 12 dB insertion loss, which was intended to emulate an optical splitter with 16 branches. The power of each channel of the combined light source was then amplified to 6 dBm by an EDFA. Another optical attenuator (ATT2) was inserted to emulate another power splitter and to adjust the injected light power. The length of the feeder fiber was 10 km. The depolarizer was temporarily replaced with a polarization controller (PC) before injection. The combined seed light was demultiplexed by AWG2 at RN. The 16 separated channel seed lights were then fed to 16 corresponding ONUs to injection-lock FP-LDs. In this experiment, the same FP-LD was used as the upstream transmitter for each ONU by injection-locking different individual mode, respectively. The FP-LD was injection-locked to a CW seed light channel and directly modulated with a 10 Gb/s data. The received upstream optical power was monitored by a power meter (PM) through a 10:90 coupler. The detected upstream signal was measured by a bit error rate tester (BERT) after a receiver (Rx), which consists of a PIN photo detector, a limiting amplifier and a clock and data recovery module.

Figure 6 shows the measured receiver sensitivities at 10^{-9} BER after 10 km uplink transmission as a function of injected CW light power for four different uplink channels (wavelengths). The back-to-back receiver sensitivity was -18.3 dBm, which was limited by the performance of our non-optimized optical receiver. As shown in Fig. 6, the sensitivity is significantly improved with the increase in the injected power when the injected power is less than a certain critical value (approximately -8 dBm), but it remains almost unchanged when

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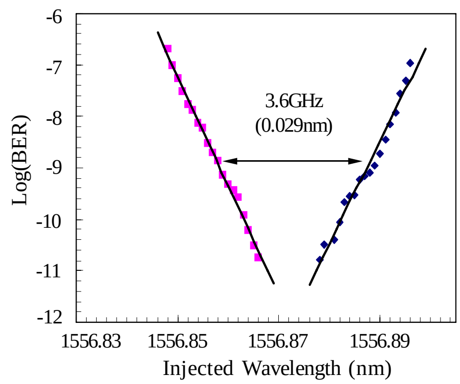

Fig.8. BER vs. injection wavelength detuning.

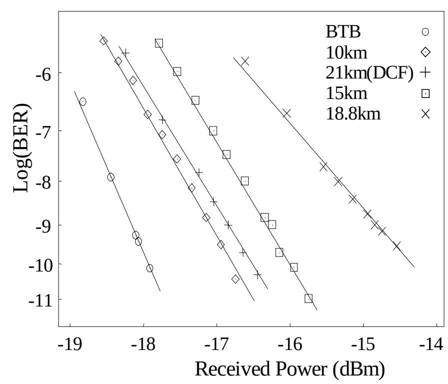

Fig.9. Measured bit error rate versus received optical power for different transmission distances

the injected power is greater than the critical value. This is partly because the modulation bandwidth decreases with the reduction in the injected power. For example, at the injection wavelength of 1555.786 nm, bit error rate (BER) less than 10^{-9} was achieved without BER floor when the injected power was greater than -9.1 dBm. As the injected power was increased to greater than –8.6 dBm, the sensitivity remained almost unchanged at -17.2 dBm. Further increase in the injected power from –8.6 dBm to -2 dBm resulted in no noticeable change in receiver sensitivity. This is desirable for practical systems since the injected power may fluctuate because of various reasons including component degradation. Considering the power loss between light source and the FP-LD in our experiments was about 7.5 dB (including the insertion loss of circulator, feeder fiber, AWG and PC) and the required injection optical power was –8 dBm, the required output power of seeding light source for each channel was –0.5 dBm, which can be easily met with typical DFB lasers and EDFAs.

In order to demonstrate that the FP-LD can indeed be used as an wavelength-independent light source with many wavelength channels selectable using the injected CW light, we injection-locked the FP-LD at any of the 16 cavity modes (refer to Fig. 3) individually. When injection wavelengths were located at the relatively strong cavity modes (close to the gain spectrum peak) such as 1555.786 nm and 1556.88 nm, the receiver sensitivity was higher. On the other hand, when relatively weak cavity modes (1545.54 nm and 1562.502 nm) were used for injection-locking, the receiver sensitivity became worse because the SMSR ratio was relatively low at these wavelengths.

Figure 7 shows the measured SMSR of the directly modulated FP-LD with different injection-locked cavity modes. Here, all the 16 cavity modes (refer to Fig. 3) can be individually selected with high SMSR. As shown in Fig. 7, flat SMSR with less than 3 dB ripple is achieved for 12 central wavelengths. Even for the wavelengths located at the far edge sides, the SMSR is still greater than 30 dB. Fig. 7 also shows the measured minimum required injection power for achieving BER of 10^{-9} for different uplink wavelengths. Here, the received optical power at the receiver was fixed at –15 dBm. The minimal required injection power for the best case was –9 dBm at both wavelengths of 1555.786 nm and 1556.88 nm. While it was –8.2 dBm for the worst case at the edge wavelength of 1562.502 nm. Even when the injection wavelength was located at the far edge of the FP-LD gain spectrum, BER$<10^{-9}$ was still achieved without BER floor when the injected optical power was greater than –8 dBm. This is an important advantage of using FP-LD as the uplink wavelength source of ONUs. That is, many wavelengths can be selected flexibly, thus reducing the inventory requirement of the service providers for WDM-PON operation.

In practical systems, the wavelengths of both the seed light source and the FP-LD vary with the temperature and bias current. Even with a temperature controller, its central wavelength may still fluctuate slightly and randomly. So it is important to examine the detuning range between the injected wavelength and injection-locked wavelength. Large detuning range is desirable to offer more operational margin. We experimentally studied the

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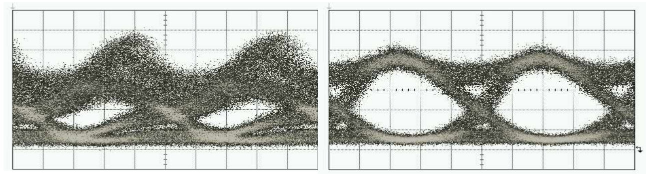

Fig. 10. Eye diagrams of FP-LD after 21 km uplink transmission.

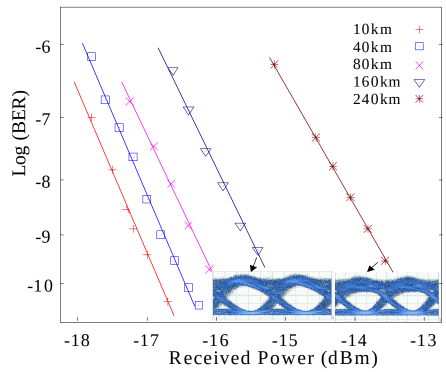

Fig. 11. BER versus the received optical power for different downlink transmission distances. Insets: the eye diagrams with 160 km and 240 km transmission.

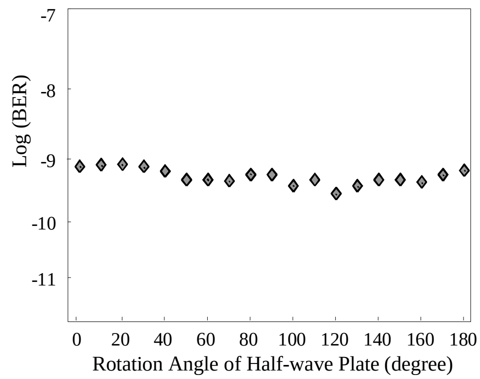

Fig. 12. BER performance as a function of rotation angle of half-wave plate in the polarization controller.

locking range by measuring BERs after 10 km uplink transmission while detuning the external injection wavelength. In this experiment, one DFB laser was temporarily replaced with a tunable laser to adjust the wavelength detuning and the cavity mode with a wavelength of 1556.87 nm was used for testing the injection-locking range. The measured results are shown in Fig. 8. Here, the injected optical power and bias current were maintained at –7 dBm and 40 mA, respectively, and the received optical power was set at -15.5 dBm for all cases. Fig. 8 shows that slightly longer injection wavelength than the free running cavity mode wavelength gives better performance [18]. As shown in Fig. 8, the BER is dependent on the injected wavelength, and the detuning range is about 0.029 nm (3.6 GHz) for which the BER less than10^{-9} was achieved. This large tolerance to injection wavelength is of practical importance.

Figure 9 shows the measured bit error rate versus received optical power for various uplink transmission distances. Here, the injected optical power was fixed at –7 dBm. As shown in Fig. 9, the power penalty increases with the transmission distance. For the back-to-back (BTB) case, the receiver sensitivity at BER of 10^{-9} was –18.3 dBm. This was degraded to –17.1 dBm, -16.2 dBm and –14.8 dBm for the transmission fiber of 10 km, 15 km and 18.8 km, respectively. For longer transmission fiber, the BER floor occurs at BER > 10^{-9} mainly due to chromatic dispersion. Figure 10 shows the eye diagrams of the 21 km uplink transmission without and with dispersion compensation. Apparently, significant distortion of the eye diagram occurred after 21 km transmission without dispersion compensation. In order to study the influence of the dispersion, we inserted one piece of dispersion compensation fiber (DCF) with –340 ps/nm before the demultiplexer. With the dispersion compensation, the eye opening was considerably improved. The receiver sensitivity at BER of 10^{-9} for 21 km transmission with dispersion compensation was –16.8 dBm, as shown in Fig. 9. This is much better than the case of 15 km and 18.8 km without dispersion compensation. Note that even with the dispersion compensation, the power penalty for 21 km uplink transmission was still slightly greater than that for 10km transmission. This might be due to backward reflections of the seed light, including the laser front facet reflection, Rayleigh backscattering, and stimulated Brillouin scattering (SBS). These reflections were mixed with the uplink data which could not be separated by the WDM demultiplexer, and contributed to in-band crosstalk.

We also carried out experiments to investigate the transmission performance for the downlink using the proposed CW light injection-locked FP-LDs as the transmitters. The main difference between the downlink and uplink transmission is that the CW light injected into the FP-LDs for the downlink does not go through the feeder fiber. In the demonstration of the downlink transmission, our emphasis is on future application to metropolitan-scale optical networks.

Figure 11 shows the BER versus the received optical power for different downlink transmission lengths. Here, the injected optical power was fixed at –8 dBm, while the transmission length was varied in a large range from 10 km to 240 km. When the transmission length was 10 km and 15 km, the downlink signal received at the ONU was in good eye opening. Once the transmission fiber is longer than 20 km, fiber dispersion induces considerable distortion to the received signal. However, with dispersion compensation, the proposed light source can be used to extend the application further to the metropolitan-scale optical networks. Figure 11 shows that the transmissions over 40 km, 80 km, 160 km and 240 km could be achievable with 0.5 dB, 0.9 dB, 1.7 dB, and 3.6 dB power penalty, respectively. The eye diagrams with 160 km and 240 km transmission are shown in the insets. Here, each span of transmission fiber was 80 km, which was fully compensated by a dispersion compensation fiber. Two EDFAs in each span were used to compensate the fiber loss, which were located before and after the dispersion compensation fiber.

5. Elimination of polarization effects

The performance of injection-locked FP-LDs intrinsically depends on the polarization state of the injected light. In a practical system, the polarization state of the injected light varies due to the temperature change and strain of fiber and environment which are difficult to predict and control. Therefore, polarization-insensitive injection-locking scheme is crucial. Unfortunately, our experiment showed that the commercial depolarizer based on delayed polarization orthogonal multiplexing technique could not effectively eliminate the polarization dependence. Different from non-coherent injection, injection-locking requires more diversified polarization states of the injected light since its optical phase is also involved in the interaction between the optical fields of the FP-LD and the injected light [14]. To achieve better and random polarization diversity, we propose to use a dual fiber ring structure [19] combined with a commercial conventional depolarizer. With this scheme, the polarization dependence of the proposed seed light source can be greatly reduced. Figure 12 shows the back-to-back BER performance with different polarization states. Here, the injection wavelength was 1555.786 nm, the injected power was –2 dBm and the received optical power was –15.5 dBm. In this experiment, the fiber ring depolarizer was not temperature-controlled and the induced phase fluctuation in the ring introduced some instability in the output of the depolarizer. We believe that the required injection power can be reduced considerably if a stabilized dual ring depolarizer is used. We rotated the angle of the half-wave plate in PC over 0 to 180 degrees, which corresponds to the rotation range of 0 - 360 degree in the polarization state of seed light [20]. Figure 12 shows that over the whole 0 - 180 degree rotation angle of the half-wave plate, only slight BER variation is observed due to random polarization states of the injected light. This result shows that the proposed depolarization configuration is indeed polarization insensitive for injection-locking.

6. Conclusions

We proposed a high-speed WDM-PON architecture using CW light injection-locked FP-LDs, and experimentally demonstrated its transmission performance for both the uplink and downlink. The study on the modulation characteristics of the injection-locked FP-LDs shows that injection-locking offers increased modulation bandwidth, reduced relaxation oscillation and narrower linewidth even after data modulation. 10 Gb/s uplink transmission over 10 km as well as 15 km single mode feeder fiber showed a good performance and up to 16 cavity

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modes of the FP-LD could be used for injection-locking. Transmission length was affected mainly by the fiber dispersion and backward reflections. With proper dispersion compensating, the proposed light source is shown to be useful for longer transmission needed in metropolitan optical networks. The allowable wavelength detuning range at BER of 10^{-9} was observed to be up to 3.6 GHz. The polarization-insensitive injection-locking was also demonstrated by combining a conventional depolarizer and a dual-fiber ring structure. The proposed WDM PON architecture is expected to be cost-effective from the fact that the multiple channel CW laser sources located at the central office can be shared by many WDM-PONs and low-cost FP-LDs are used as light sources for data rates as high as 10 Gb/s.

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