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Optical power equalization for upstream traffic with injection-locked Fabry–Perot lasers in TDM-PON

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ABSTRACT

An optical power equalization of upstream traffic in time-division-multiplexed passive optical network (TDM-PON) based on injection-locked Fabry–Perot lasers has been experimentally investigated. The upstream transmitters with stable spectrum are achieved by using an external injection light source in the optical line terminal (OLT). The different upstream powers can be equalized by injection locking a Fabry–Perot laser diode (FP-LD) biased below threshold current in OLT. The dynamic upstream power range from −8.5 to −19.5 db m is reduced to a 1.6 dB maximal power variation, when the uplink signal is directly modulated at 1.25 Gb/s.

1. Introduction

Recently, an access transmission with a high capacity is required to meet the rapid growth in the use of broadband services including video conferencing, video on demand (VoD), and the widely discussed concept of "cloud computing" etc. However, the current access technologies built with copper cables or hybrid fiber coaxial (HFC) cables are becoming difficult to support the increasing bandwidth demand from end users. Due to the huge capacity and upgrade flexibility of the fiber communication, fiber to the home (FTTH) is considered as a mature concept and a promising technology for the last mile access network. Passive optical network (PON) is emerging as a viable architecture for developing FTTH [1], since there is no active component between the central office and end users. A PON consists of an optical line terminal (OLT) at the central office and a number of optical network units (ONUs) near end users. This point-to-multipoint access configuration is connected by a passive power splitter at the remote node (RN). Nowadays, the time-division-multiplexing PONs (TDM-PONs) such as Ethernet PON (EPON) and gigabit PON (GPON) have been already deployed by the network carriers [2–5]. However, because the transmission lengths of each ONU to OLT are different, the upstream signal power levels at the OLT are different among ONU channels. The ONU transmitter with automatic power control (APC) for power equalization has been investigated [6,7]. The OLT receiver measures each ONU power and sends the control signals to ONUs during registration stage. Thus, the complexity and implementation cost are increased to the control circuit for achieving the shorter signal response time. Recently, an optical power equalization technique based on a Fabry–Perot laser diode (FP-LD) was reported [8]. The power equalization operation for the upstream signals is just performed by passing through a FP-LD in OLT and cost-effective for the end users. However, the critical restriction of this method is the spectrum stability of the upstream transmitter. According to the report [8], the upstream signals were seriously distorted when the injection wavelength was shifted over 0.08 nm.

In this paper, the optical power equalization of upstream traffic in TDM-PON based on injection-locked FP-LDs is experimentally demonstrated. Using the light injection mechanism, the injected FP-LD operated below threshold current can be used to equalize the upstream power at a constant level. A 1.6 dB maximal power variation under a dynamic upstream power range of −8.5 to −19.5 db m is achieved by using the proposed power equalizer. Moreover, all ONU transmitters in the proposed scheme are injection-locked by a common distributed feedback laser diode (DFB-LD) and emit the upstream lightwave with stable spectrum. Thus, the reliability of the power equalization based on an injected FP-LD can be effectively improved.

2. Architecture and operation principle

Fig. 1 shows the proposed architecture in a TDM-PON structure. In OLT, the proposed power equalizer consists of an FP-LD (LD-1) and a circulator connecting the receiver. A 1490-nm LD is used for downstream and a 1310-nm DFB-LD is applied as an external injection light source to lock the output wavelength of FP-LD in each ONU. In remote node (RN), a circulator is inserted for switching the upstream

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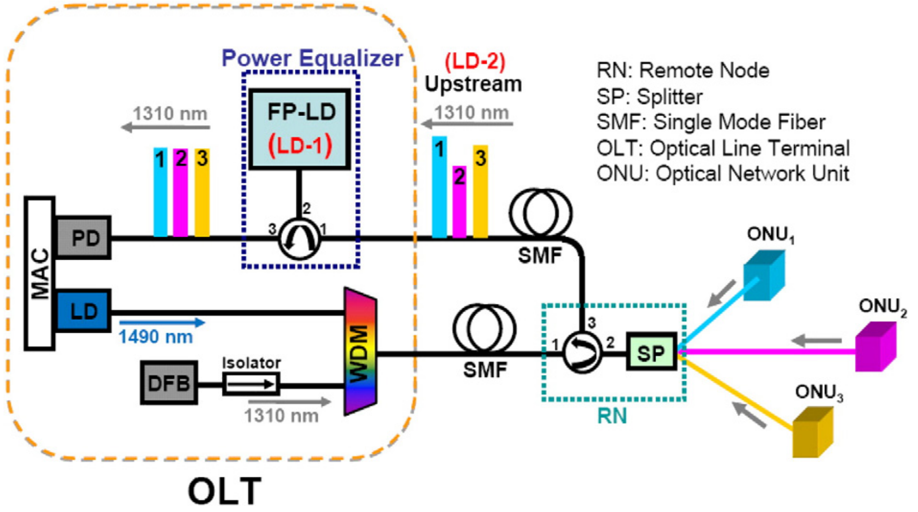

Fig. 1. Proposed architecture with power equalization of the upstream traffic in a TDM-PON structure.

signals of ONUs to another transmission fiber. Under this scheme, a pair of unidirectional transmission can avoid the major Rayleigh backscattering (RB) noise caused by the high-power injection light transmitting to the receiver in OLT. The upstream signals are then injected to the LD-1 for power equalization. According to Refs. [9,10], the effective threshold current (I_{th}) of FP-LD can be decreased by external injection, and thus a FP-LD operated below threshold current can emit the laser light by using the light injection. At the same time, due to the gain competition and rearrangement characteristic of FP-LD, the below threshold FP-LD can lead to the absorption or amplification of the injection light under various power levels, and then keep the upstream power at a constant level.

3. Experiment and results

The experiment setup is shown in Fig. 2. In this proof-of-principle experiment, we used C-band optical components for feasibility demonstration. Two 1.5 μm band FP-LDs were used as the power equalizer (LD-1) and the upstream signal source (LD-2). The threshold current (I_{th}) of the used FP-LDs is ~9.3 mA with mode spacing of ~1.4 nm. According to the report [8], the upstream signals will be seriously distorted by the power equalizer FP-LD if the injection wavelength of the upstream light is shifted over 0.08 nm. For this reason, we applied a tunable laser as an external injection light source for injection locking the output wavelength of the LD-2. A stable spectrum characteristic of LD-2 is required because the LD-1 should be guaranteed to be mode-locked by the upstream lightwave. In contrast to the free-running FP-LD, the output wavelength of the injection-locked FP-LD should be less influenced by the temperature. To verify this inference, we observed a specific mode of the LD-2 biased at 14.7 mA under different temperatures. The injection power of the tunable laser was −7.1 db m at wavelength of 1544.46 nm. From the measured results shown in Fig. 3, the mode wavelength of the light-injected LD-2 is locked by the external injection lightwave over the operating temperature from 23.15 to 27.15 °C, while the observed mode of the free-running LD-2 is shift from 1544.28 to 1544.53 nm at the same range of temperature. The injection-locked FP-LD performed the temperature tolerance of 4 °C than the free-running FP-LD.

In our experiment, LD-2 was biased at 15.8 mA and driven by a pseudo random binary sequence (PRBS) with a word length of $2^{15}-1$ provided by a pattern generator. The injection wavelength of the tunable laser was fixed at cavity mode of 1550.66 nm with injection power of −6.6 db m. Fig. 4 shows the measured optical spectra of a 1.25 Gb/s directly modulated FP-LD (LD-2) with and without injection locking. The side-mode suppression ratio (SMSR) of 45 dB is achieved by injection locking. In Fig. 2, an optical variable attenuator is used to adjust the different upstream powers. Fig. 5(a) and (b) respectively shows the optical spectra of the LD-1 without and with upstream injection when the bias current (I_b) of LD-1 was operated at 9 mA ($I_b<I_{th}$) and the injection power of the upstream signal was −13.5 db m. Fig. 6 presents the output powers of the LD-1 under different upstream injection powers. From the results shown in Fig. 6, the received output powers are distributed from −13.2 to −15.8 db m, while the upstream signals are at different power levels of −8.5 to −19.5 db m. The larger upstream power transmitted into the equalizer is absorbed and the

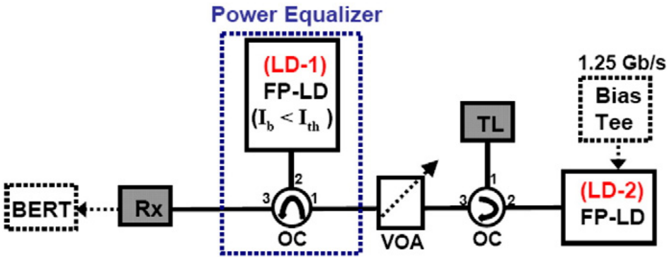

Fig. 2. Experimental setup for power equalization of the upstream traffic.

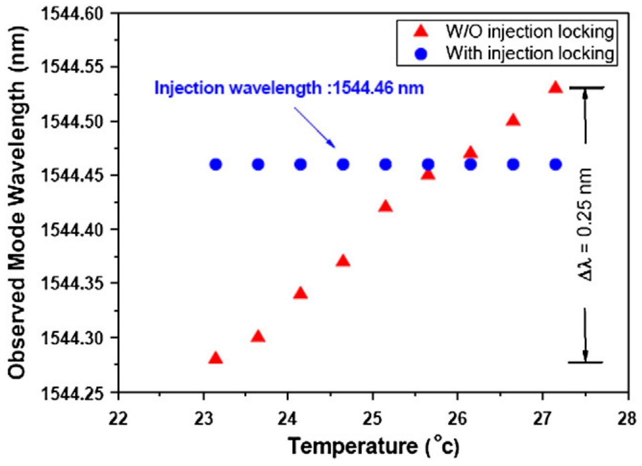

Fig. 3. The observed mode wavelength shifts of the injection-locked FP-LD and free-running FP-LD caused by temperature fluctuation.

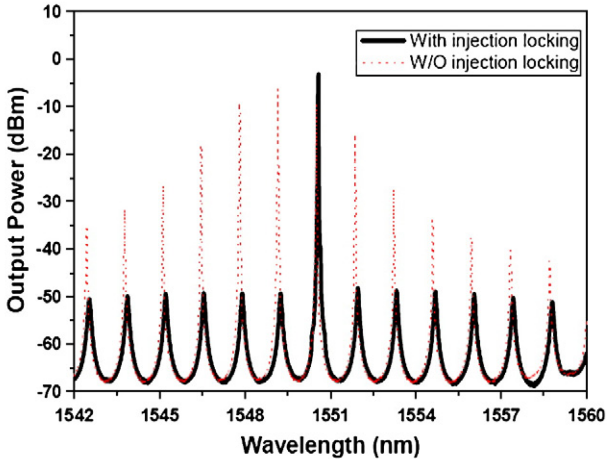

Fig. 4. Optical spectra of the upstream FP-LD (LD-2) with and without injection locking.

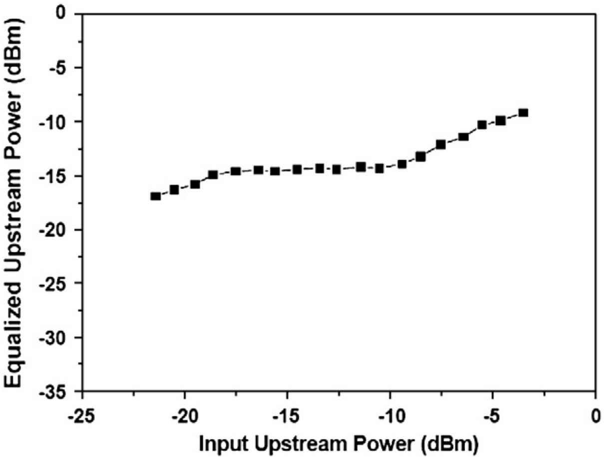

Fig. 6. Equalized upstream powers versus different input upstream powers when the upstream signals pass through the power equalizer.

smaller injection is amplified slightly. The power variation of the upstream signal is reduced from 11 dB to 1.6 dB.

Finally, we investigated the influence of the power equalizer on the transmission quality of the upstream traffic. The bit error rate (BER) performances and eye diagrams of the upstream transmission without and with the optical power equalizer (OPE) have been respectively measured. The measurement results are shown in Fig. 7 where the inlet eye diagrams are respectively the performances of the systems without and with the OPE at BER of 10^{-9}. One can notice that there is a power penalty of about 1.3 dB between the upstream transmission without and with the OPE. The power penalty should be attributed to the amplified spontaneous emission (ASE) noise at bit 0 and the amplitude fluctuation at bit 1 in the power equalization transformer. We infer this drawback can be improved further by using two-mode injection locking (TMIL) technique [11], which the ASE noise is suppressed by another CW injection light.

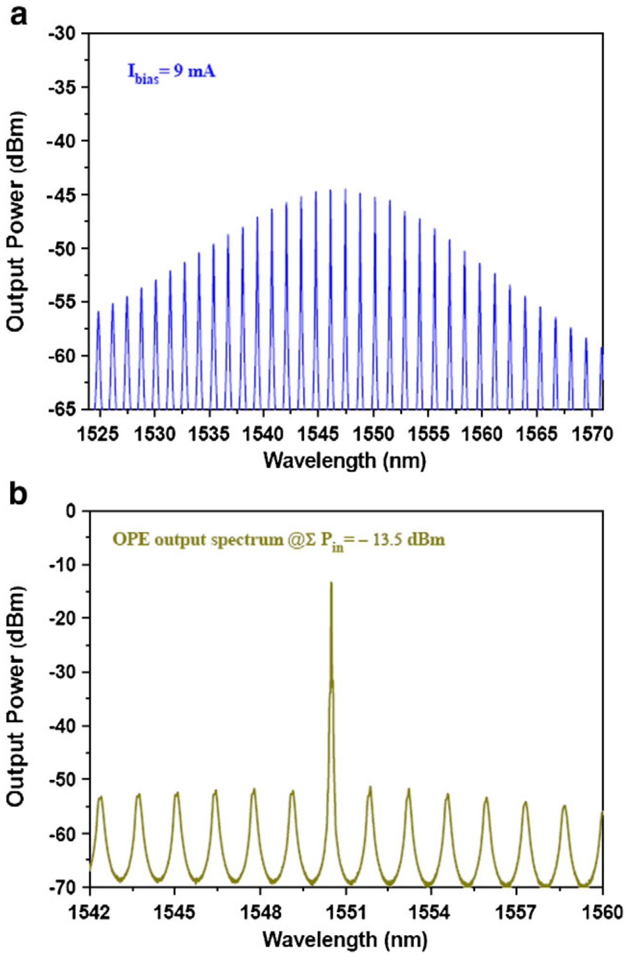

Fig. 5. Optical spectra of the below threshold FP-LD (LD-1) biased at 9 mA (a) before and (b) after injecting the upstream light with power of −13.5 db m.

4. Conclusion

An optical power equalization technique of upstream traffic in TDM-PON based on injection-locked FP-LDs has been experimentally investigated. We used two stage injection locking LD technique to realize the power equalization of the upstream signals. A single-longitudinal-mode LD was applied as an external injection light source to lock the output wavelength of the upstream transmitters. In contrast to the free-running FP-LD, the output wavelength of the injection-locked FP-LD is less influenced by temperature. The upstream lightwave with stable spectrum characteristic is required for mode-locking the power equalizer FP-LD. We injected the upstream lights with different powers into the below threshold FP-LD to equalize the received power of the upstream signals. By the

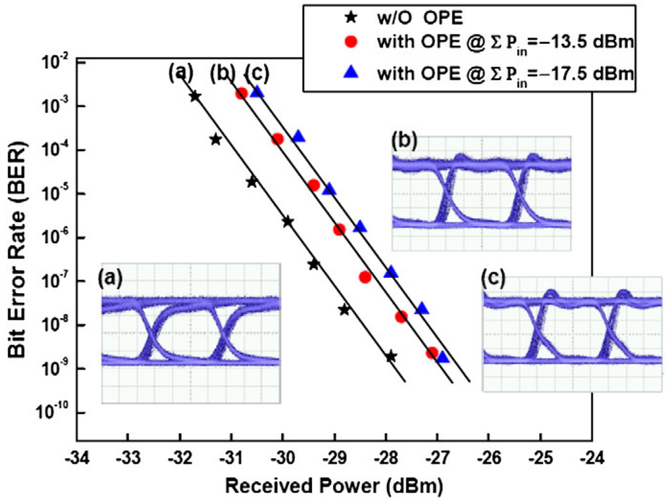

Fig. 7. BER performances and eye diagrams for upstream traffic of the proposed architecture without (line (a)) and with (line (b) and line (c)) optical power equalizer. The upstream powers of the cases (a) and (b) are respectively −13.5 and −17.5 dB m.

proposed equalizer, the dynamic upstream power range from −8.5 to −19.5 db m is reduced to a 1.6 dB maximal power variation. Under the 1.25 Gb/s upstream traffic test, we also investigated the influence of the power equalizer on the transmission quality of the upstream traffic.

According to the experimental results of Ref. [12], the response time of FP-LD to the external light injection is in picoseconds scale. We believe that the proposed power equalization technique can be also successfully implemented for a 10 G/s optical signal. In addition, if a reflective semiconductor amplifier (RSOA) is used as a reflective transmitter at the ONU, we can apply a high-power and cost-effective FP-LD instead of a single-longitudinal-mode DFB-LD to serve as the injection light source in the OLT. Hence, to study the feasibility by using a RSOA as the ONU transmitter in the proposed system will be our future wok in this research.

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