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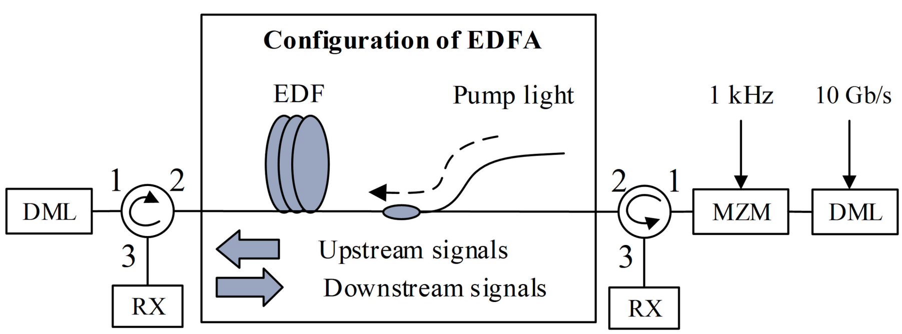

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Single-Fiber Bi-Directional Burst-Mode EDFA for TWDM-PON

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Abstract: In this paper, we propose a single-fiber bi-directional burst-mode erbium-doped fiber amplifier (EDFA) to simultaneously improve upstream and downstream loss budget in time and wavelength division multiplexed–passive optical network (TWDM-PON). Instead of additional light sources for upstream gain clamping, the downstream signal acting as saturation signal effectively suppresses the upstream burst surge, which widens the input dynamic range of upstream burst signal. For potential reflections caused by the absence of optical isolators, experimental results have demonstrated the degradation of receiver sensitivity at bit-error rate of 1×10^{-3} is negligible with a reflection power up to -14 dBm, which proves the promising applications in PONs of the proposed single-fiber bi-directional burst-mode EDFA.

Index Terms: Time and wavelength division multiplexed – passive optical network (TWDM-PON), erbium-doped fiber amplifier (EDFA), burst mode.

1. Introduction

TIME and wavelength division multiplexed-passive optical network (TWDM-PON) architecture has been selected as the primary solution for the next generation passive optical network stage-2 (NG-PON2) by Full Service Access Network (FSAN) group [1]. Considering the increased power budgets required to support more users in a longer reach transmission system, amplifiers such as erbium-doped fiber amplifiers (EDFAs) are necessary [2], [3]. Among all the challenges facing in the PON applications of EDFAs, upstream pre-amplification is one of the biggest issues since the fast gain transient effect of EDFA that generates burst surge at the rising edge of each frame results in serious signal performance degradation. Because the power of burst signal from different optical network units (ONUs) suffers significant difference, the gain transient effect of EDFA limits the input power dynamic range in upstream signal detection. In order to solve this issue, several novel EDFAs have been proposed [4]–[7]. These burst-mode EDFAs employ an extra forward or backward injected light source to keep the erbium-doped fiber (EDF) saturated and stabilize the erbium ion inversion therefore eliminating the detrimental transient effect. However, these burst-mode EDFAs amplify only upstream signal and a separate downstream amplifier is still required, which will increase the system cost. Single-fiber bi-directional EDFA is the most attractive solution since it requires the fewest optical components, however the signal performance suffers from the back-reflection, such as stimulated Brillouin scattering, Rayleigh backscattering (RBS) and Fresnel back-reflection,

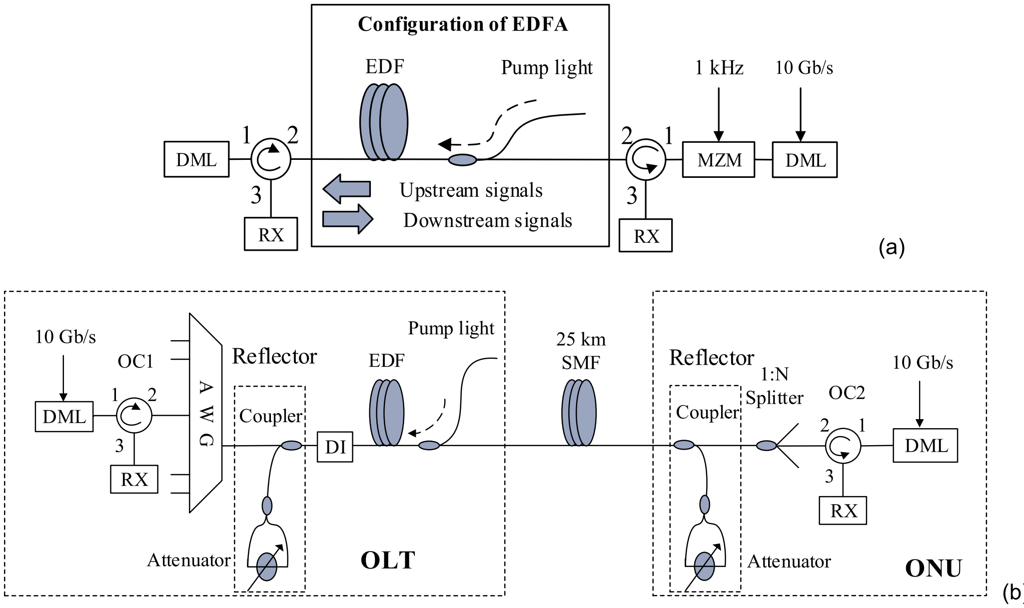

Fig. 1. Experimental setup. (a) The configuration of the proposed bi-directional EDFA. (b) The schematic of the TWDM-PON system with a bi-directional EDFA, ONU: optical network unit, OLT: optical line terminal, OC: optical circulator.

therefore it was suggested that optical isolators or circulators had to be implemented in access applications [8], which limits the applications of the simplest single-fiber bi-directional EDFA in PONs.

In this paper, we prove that the simplest single-fiber bi-directional EDFA without isolators has the potential to be used in TWDM-PON for simultaneously downstream and upstream signal amplification. Experimental results have demonstrated that, instead of an additional light source, the downstream signal acting as saturation signal can keep the inversion of the EDF constant. As a result, with the downstream input power of −5 dBm, the upstream burst surge can be effectively suppressed. Considering that the downstream input power is often higher than −5 dBm, the capability of burst surge suppression can be further enhanced. For Fresnel back-reflections from connectors or splices and RBS in transmission fiber, the configuration without optical isolators indeed results in amplification of these detrimental reflections therefore induces crosstalk, and error floor can be observed for high reflection cases. But considering forward error correction (FEC) will be eventually used for high-speed PONs, bit-error rate (BER) of 1×10^{-3} should be the judging point. In this case, the degradation of receiver sensitivity after 25-km single-mode fiber (SMF) transmission is negligible with a reflection power up to −14 dBm, which can represent most of the serious reflection cases. Therefore, the proposed single-fiber bi-directional burst-mode EDFA is a good option to improve the loss budget in TWDM-PON.

2. Experimental Setup

The configuration of the proposed single-fiber bi-directional EDFA is shown in Fig. 1(a). The upstream signal is injected into EDF (8 m) in the same direction of the pump light for low noise figure (NF). Without downstream signal, the EDFA amplifies only upstream signal and it can be regarded as a traditional unidirectional EDFA. When the downstream light is injected from the reverse direction, it plays an equivalent role of saturated light sources therefore stabilizing the erbium ion inversion of the EDF and eliminating the excessive transient gain at the rising edge of upstream

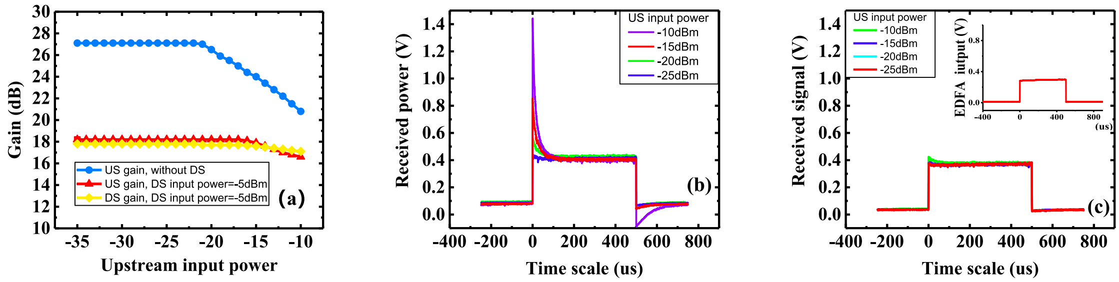

Fig. 2. Steady gain and transient surge suppression performance of the proposed EDFA. (a) Upstream and downstream gain performance. (b) Upstream traces without downstream signal. (c) Upstream traces with −5 dBm downstream signal.

signal. The noise figure of the proposed EDFA is around 5 dB. This structure with only pump and EDF is extremely simple and economical.

We first investigated the steady gain performance and transient surge suppression performance of the EDFA as shown in Fig. 1(a). In the upstream direction, a directly modulated laser (DML) is driven by the 10 Gb/s pseudo-random bit sequence (PRBS) signal, followed with a Mach-Zehnder modulator (MZM) driven by a lower-rate rectangular signal to generate burst-mode signal. The period is set to 1 ms when the MZM is driven at 1 kHz. We can get burst signals with different interval time by changing the zero duration time of the rectangular signal. In this experiment, the interval time is set to 500 ms. The downstream light acting as saturated light source is injected from the reverse direction. Fig. 1(b) shows the schematic of the TWDM-PON system with a bi-directional EDFA. At the optical line terminal (OLT) side, a DML driven by a 10-Gb/s PRBS signal is used as downstream source. The PRBS signal with a word length of $2^{31} - 1$ is generated by a pulse pattern generator (PPG). An arrayed waveguide grating (AWG) is used to multiplex all downstream signal. Due to the strong nonlinearity-tolerance provided by the broad spectrum of the directly modulated signal, a post-amplification is allowed to improve the downstream loss budget in OLT [9]. A delay interferometer (DI) acting as an optical spectral reshaping filter to suppress the frequency chirp of DML for both downstream and upstream directions [10]. The free-spectral-range (FSR) of DI is set at 25 GHz for simultaneous multi-channel operation with 4 nm spacing. The downstream input power into the EDF is around 2 dBm considering all the insertion loss of passive components. After being amplified by the EDFA, the downstream signal with high output power launches into a 25-km SMF for transmission. The optical circulator (OC) in both OLT and optical network unit (ONU) is used to separate downstream and upstream signal. Reflectors composed of two 1:2 couplers and an optical attenuator are assigned at ends of the 25-km SMF and EDF for the back-reflection crosstalk evaluation. The reflection power can be varied by tuning the attenuator in the reflector. At the ONU side, the upstream signal is generated from a DML driven by a 10-Gb/s PRBS signal. The center wavelengths of the upstream and downstream signal are 1547 nm and 1551 nm respectively. The 1550 nm wavelength can either be the CATV channel or the point-to-point WDM channel in NG-PON2.

3. Experimental Results

3.1 Steady and Transient Gain Performance

The gain performance of uni-directional and bi-directional amplification with the same pump light are shown in Fig. 2(a). At the input power of −22 dBm, the gain of upstream signal without downstream begins to saturate. Though the upstream gain of uni-directional amplification is higher than that of bi-directional amplification with −5 dBm downstream input power over the entire input range, the saturation in the gain of uni-directional amplification limits the upstream input power range. Up to an input power of −13 dBm, the bi-directional EDFA obtains a nearly flat gain for both upstream

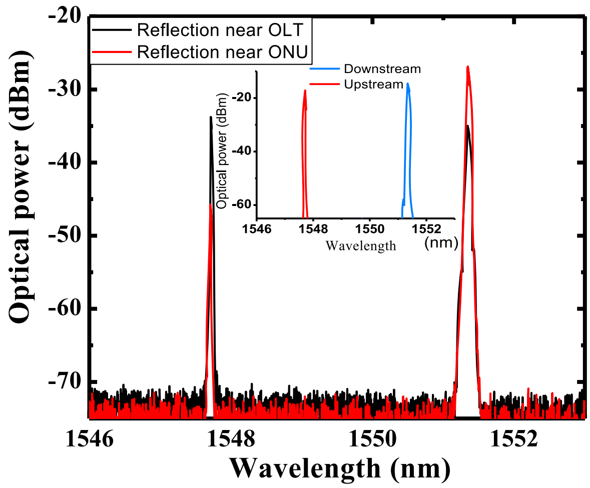

Fig. 3. Reflection spectra at OLT and ONU.

and downstream signal. The measured upstream and downstream gain is around 18.2 and 17.8 dB with a pump power of 180 mW, which is sufficient to improve the loss budget of TWDM-PONs. The output power of the upstream and downstream signal increases with the pump power of the EDFA and affects the loss budget of the system. Besides, with the increase of the pump power, the downstream power into the EDFA also needs to increase to saturate the EDFA therefore suppress the upstream burst surge.

The transient burst-mode operation of the EDFA was investigated with four different upstream input power of −10 dBm, −15 dBm, −20 dBm, and −25 dBm. Fig. 2(b) shows burst surge of upstream signal caused by varied erbium ion inversion that accumulates during interval time. As the power of upstream signal increases, the burst surge varies severely. The reason is that the gain at the end of the bursts owes to steady gain. Compared to low power signal, the steady gain of high power signal is smaller, which means larger gain differences between the front and the end of high power signal causes larger burst surge. From Fig. 2(c), with −5 dBm downstream signal, significant improvement can be seen in transient surge suppression for all conditions. Even for the −10 dBm input power, the transient surge is negligible. Considering that the downstream input power is often higher than −5 dBm, the capability of burst surge suppression can be further enhanced. According to the feature of TWDM-PON, the maximum upstream power at the OLT is −13 dBm [11]. If the burst surge of the upstream signal at −13 dBm is suppressed, the overshoot of all the upstream burst signal at lower input power can be suppressed since higher upstream input power will cause stronger burst surge. The downstream signal power of −5 dBm is the lowest power to suppress the burst surge for all conditions in TWDM-PON. Therefore, the proposed EDFA satisfies this requirement and could be used as a burst-mode pre-amplifier in OLT.

3.2 Reflection Performance

In the following analysis, we evaluated the influence of the crosstalk induced by reflections on the performance of downstream and upstream signal. Figure 3 shows the reflection spectra near OLT and ONU. Each reflection contains both upstream and downstream waveband because of reflectors and the amplification of EDFA. For example, a small part of downstream signal is reflected by the reflector near ONU firstly, and then the reflected lights experience reverse transmission arriving at the other reflector after EDFA amplification. This reflection-induced crosstalk is considered as multi-path interference (MPI), which is a serious problem in bi-directional amplifier. The measured BERs of downstream and upstream signal with various reflection power are shown in Fig. 4 and Fig. 5. An error rate floor appears when the receive power increases. This is because that the reflected lights

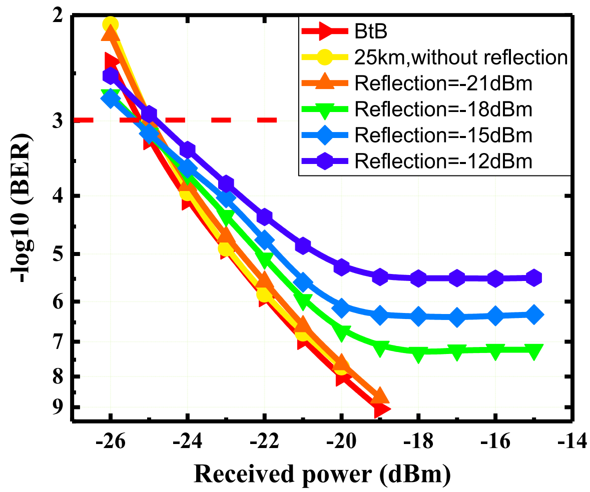

Fig. 4. Measured BER of downstream signal in BtB and 25 km transmission.

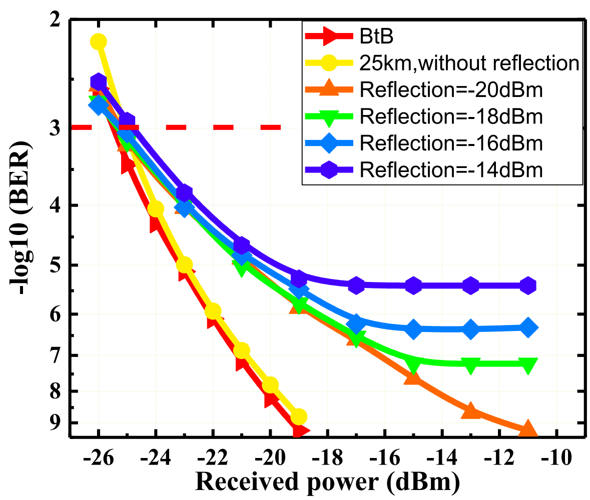

Fig. 5. Measured BER of upstream signal in BtB and 25 km transmission.

created by reflectors and present lights in the same wavelength arrive at the receiver at the same time, resulting in MPI. The degradation of downstream receiver sensitivity with BER of 1×10^{-3} after 25-km SMF transmission is less than 1 dB with a reflection power up to -12 dBm. The upstream signal power is smaller and tends to get greater impact, but the degradation of sensitivity is also less than 1 dB with a reflection power up to -14 dBm. Considering FEC will be eventually used for high-speed PONs, we think it is reasonable to evaluate the receiver sensitivity degradation at BER of 1×10^{-3}. Considering all the insertion loss of passive components, the downstream input power into the fiber without EDFA is -2 dBm with the commercial DML output power of 3 dBm. After the amplification of EDFA, the downstream signal gets the gain of 12 dB, which is the increase of downstream loss budget since the receiver sensitivity is almost unchanged. For the upstream signal, the transmit power doesn't change. The improvement of upstream loss budget equals to the increase of receiver sensitivity which is 6 dB. Figure 6 shows eye diagrams of downstream signal in BtB and 25 km transmission as examples. These results prove the proposed single-fiber bi-directional EDFA is an effective and simple solution for upstream burst surge suppression and its reflection is highly tolerant in bi-directional PON systems.

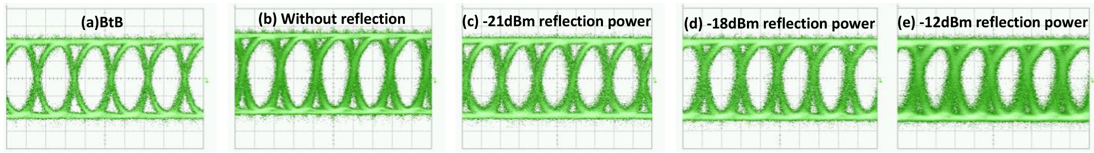

Fig. 6. Measured eye diagrams of downstream signal in BtB and 25 km transmission.

4. Conclusion

We propose a novel burst-mode EDFA that simultaneously amplifies downstream signal and upstream signal using single EDF without any optical isolator or additional light source. The upstream burst surge can be effectively suppressed with a downstream input power of −5 dBm. For potential reflections caused by the absence of optical isolators, experimental results have demonstrated high tolerance to the reflection. Therefore, the proposed single-fiber bi-directional burst-mode EDFA is a good candidate to improve the loss budget in TWDM-PON.

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