10 Gb/s symmetric WDM-PON using stable multi-longitudinal mode Brillouin/SOA fiber laser as upstream colorless source

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We propose a stable multi-longitudinal Brillouin/semiconductor fiber laser (BSFL) as the upstream source in a bidirectional single-fiber wavelength-division multiplexing-passive optical network (WDM-PON). The downstream wavelength serves as the pump of the BSFL. Brillouin-frequency-shifted (∼10.8 GHz) upstream carrier is generated to suppress the Rayleigh backscattering and back reflection-induced crosstalk. The stable multi-longitudinal operation of the BSFL, attributed to the four-wave mixing (FWM) effect in the semiconductor optical amplifier (SOA) reduces the difficulty of generating a stable single-longitudinal fiber laser-based upstream carrier. Bidirectional symmetric transmission at 10 Gb/s over a 12.5-km single mode fiber with less than 2-dB power penalty is demonstrated.

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Bandwidth demand in access networks has increased rapidly. As a result, wavelength-division multiplexing-passive optical network (WDM-PON) has become a promising option because of its high bandwidth accessible property. The colorless optical network unit (ONU) is one of the main research topics in this field. Centralized light sources in the optical line terminal (OLT) have been considered as a good solution. In OLT, the downstream wavelength is reused at the ONU for upstream data modulation[1] or another set of laser sources differing from the downstream ones are specifically assigned to upstream carriers[2]. The wavelength reuse techniques are limited by the Rayleigh backscattering and back reflection-induced crosstalk in a single-fiber bidirectional transmission scenario[3], resulting in a power penalty of 5–9 dB[4]. Adoption of two-fiber system becomes necessary although it increases the system deployment difficulty. Furthermore, two sets of laser sources in the OLT will increase the system cost.

Complicated modulation schemes have been adopted to generate the frequency difference between the downstream and upstream wavelengths which is intended to suppress the Rayleigh backscattering-induced crosstalk[2,4−6]. A hybrid single longitudinal mode Brillouin/erbium fiber laser (BEFL) has been proposed to mitigate the Rayleigh backscattering and back reflection-induced crosstalk by frequency-shifting the downstream wavelength away by ∼0.08 nm using a stimulated Brillouin scattering (SBS) effect for the upstream carrier. A 1.25-Gb/s symmetric transmission over a 20-km single mode fiber (SMF) has been demonstrated[7]. However, the single-longitudinal operation is relatively difficult to realize. Mode-hopping is unavoidable due to environmental fluctuations, which limit its practical applications. Furthermore, the BEFL is mainly operated around the gain peak of the erbium-doped fiber (EDF) of ∼1 558 nm and the wavelength tunable range is only several nanometers[8]. Therefore, achieving a colorless ONU requires a tunable filter to tune the output wavelength of the BEFL. This increases ONU costs.

In this letter, we propose a hybrid multi-longitudinal mode Brillouin/semiconductor fiber laser (BSFL) where a semiconductor optical amplifier (SOA) is incorporated to Brillouin fiber laser. This serves as the colorless upstream source for Rayleigh backscattering and back reflection-induced crosstalk mitigation. A stable multi-longitudinal mode operation of the BSFL is achieved due to the four-wave mixing (FWM) effect of the SOA, which enables high-speed upstream data modulation and transmission. Moreover, the effect reduces the difficulty of generating a single longitudinal mode fiber laser. The BSFL can operate within the entire gain bandwidth of the SOA[9] and the output wavelength is only determined by the downstream wavelength. Therefore, it is a colorless laser source that does not require a tunable filter. In this letter, the bidirectional symmetric transmission of non-return-to-zero (NRZ) data at 10 Gb/s over 12.5-km SMF has been demonstrated with less than 2-dB power penalty using the BSFL as the upstream source. It should be noted that the proposed scheme is effective on any downstream signal with a strong carrier, such as quadrant amplitude modulation (QAM) and orthogonal frequency division multiplexing (OFDM) signals.

A bidirectional single-fiber WDM-PON architecture employing the BSFL as upstream source is depicted in Fig. 1. The ONU consists of an optical circulator (OC), BSFL, a downstream optical receiver, and an upstream Mach–Zehnder modulator (MZM). The downstream signal is launched into the BSFL through the OC to serve as the Brillouin pump. The BSFL has two outputs, namely,

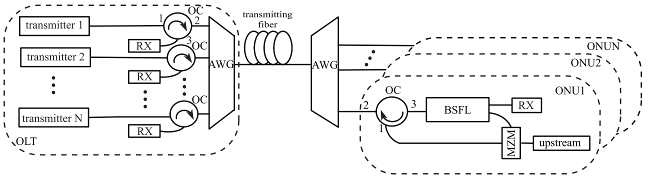

Fig. 1. Schematics of the proposed WDM-PON.

the laser with a Brillouin frequency shift for upstream data modulation and the residual downstream signal obtained after carrier depletion and which will be used for direct detection. The passband of the 100-GHz arrayed waveguide grating (AWG) is ∼0.8 nm. Therefore, the downstream and upstream wavelengths can pass through the same port of the AWG. Due to the wavelength-tunable property of the BSFL, the output wavelength of the BSFL will vary correspondingly with the downstream wavelength. Therefore, the proposed ONU is a colorless configuration.

We set up an experiment to demonstrate the high-speed symmetric data transmission based on the proposed multi-longitudinal mode BSFL, as shown in Fig. 2. At the OLT side, a downstream 10-Gb/s NRZ transmitter operating at 1 553.54 nm is launched into a 12.5-km-long SMF through an OC and an AWG with an input power of 0 dBm. After transmission, the downstream signal is sent to the BSFL through another set of AWG and OC. An EDF amplifier (EDFA) is used to amplify the downstream signal carrier to the Brillouin threshold level of the BSFL to obtain the Brillouin laser. The high speed downstream data, which serve as the Brillouin pump, have a pulse duration which is considerably shorter than the lifetime of the phonon in SBS process. Hence, the high speed downstream data act as a continue-wave Brillouin pump when the carrier power is higher than the Brillouin threshold of the BSFL. The BSFL consists of an OC, SOA, optical isolator (ISO), 3-dB coupler, 15-m-long high nonlinearity fiber (HNLF), and polarization controller (PC). The ISO is used to prevent the residual downstream signal power from saturating SOA. The PC is employed to maximize the Brillouin and SOA gain. The counterclockwise output of the BSFL is directly sent to the receiver for downstream data detection. The clockwise output of the BSFL is sent to MZM2 for upstream data modulation. With an EDFA power of 16 dBm and a SOA driving current of 200 mA, the output power of the Brillouin laser is approximately 9 dBm. The upstream signal is recirculated into the 12.5-km transmitting fiber through OC2 and AWG2. Inset (a) of Fig. 2 shows the optical spectra of the 10-Gb/s downstream signal, Brillouin laser, 10-Gb/s upstream signal, and passband of the AWG channel. The wavelength difference between the downstream and upstream signals is approximately 0.074 nm, corresponding to the Brillouin frequency of the HNLF. Both the downstream and upstream wavelengths fall into the passband of the AWG channel. Therefore, they can share the same port of the AWG meanwhile mitigating the Rayleigh backscattering and back reflection-induced crosstalk. Inset (b) shows the ASE spectrum of the employed SOA. The SOA has a flat gain spectrum of 1 540–1 580 nm, which enables the wavelength tunability of the BSFL[9].

A short cavity and a stable environment are required to generate a single-longitudinal laser for upstream data modulation in a BEFL. The short cavity enhances the threshold of the Brillouin laser. A stable environment is needed because the single longitudinal mode operation is difficult to maintain due to environmental fluctuation. On the other hand, the multi-longitudinal fiber laser, which is obtained in a relatively easy manner, is extremely unstable due to the mode competition in the homogeneous gain medium. Therefore, it cannot be used for upstream data modulation. However, in BSFL, the FWM effect of the SOA can suppress the mode competition and achieve a stable multi-longitudinal operation. The neighboring longitudinal modes experience the FWM effect at the saturation region of the SOA. The generated new frequencies are overlapped with the existing longitudinal modes. The FWM effects experienced by all the neighboring longitudinal modes redistribute the mode power and achieve a balance with the mode power competition. Finally, the stable multi-longitudinal operation can be achieved, as shown in Fig. 3(a). The total cavity length is approximately 20 m, corresponding to a mode spacing close to 6.3 MHz. The inset shows the stable power of the multi-longitudinal laser in time domain. For comparison, we also measured the unstable multi-longitudinal operation in Brillouin fiber laser (BFL) by removing the SOA from the BSFL, and in BEFL by replacing the SOA with EDFA. The BFL and BEFL have a similar cavity length with the BSFL, and therefore correspond to the same mode spacing. The power fluctuation

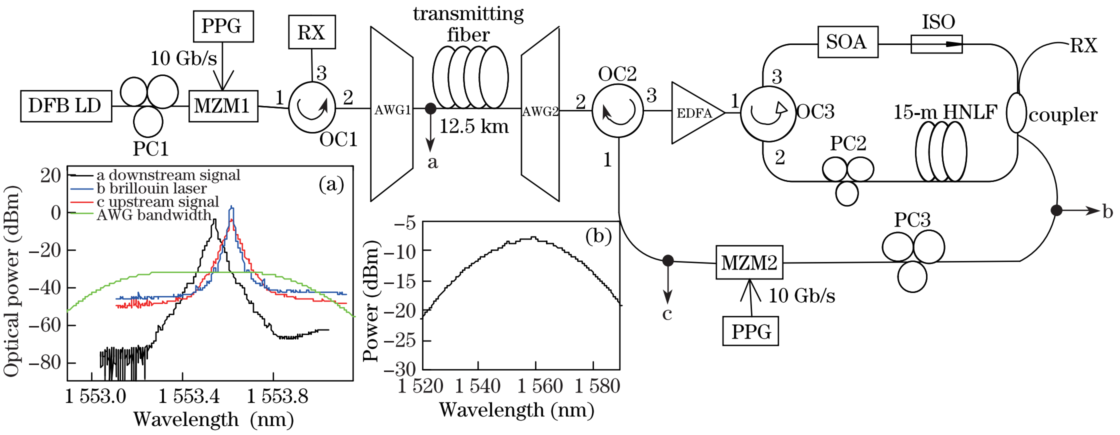

Fig. 2. Experimental setup. DFB LD: distributed feedback laser diode, PPG: pulse pattern generator.

of the laser due to strong mode competition is shown in Fig. 3(b) for both frequency domain and time domain. It should be noted that in BSFL, the longitudinal modes, except for the main longitudinal mode, are suppressed after the external modulation with 10-Gb/s pseudo-random bit sequence (PRBS) data. After modulation, the upstream data are similar with the single longitudinal mode case and, therefore, enable high speed and long distance transmission. The electrical spectrum of the BSFL after a 10-Gb/s NRZ data modulation with a word length of 2^7-1 is shown in Fig. 3(c), where the inset shows the clear eye diagram of the upstream 10-Gb/s NRZ signal. For the BFL or BEFL, however, the modulated power remains unstable.

We evaluated the system performance of the proposed WDM-PON by measuring the bit-rate error (BER) and eye diagrams of the downstream and upstream signals in back-to-back (BtB) case and after a 12.5-km SMF transmission. The measurement results are shown in Fig. 4. The sensitivities of the 10-Gb/s NRZ downstream signal in the BtB case, bidirectional transmission case with wavelength-shifted upstream signals, and unidirectional transmission case where the upstream wavelength is turned off are almost the same. This proves that the Rayleigh backscattering effect is mitigated due to the 0.08 nm wavelength shift between the downstream and upstream signals. The BtB sensitivity of the 10-Gb/s NRZ upstream signal is ~1 dB worse than the downstream signal due to the different property of the laser source. The insets show the eye diagrams of both downstream and upstream data at different cases. After the 12.5-km transmission in the SMF, the power penalty of the 10-Gb/s upstream data is less than 2 dB, which verifies the feasibility of using the stable multi-longitudinal mode BSFL as a colorless upstream source. Notably, the proposed WDM-PON architecture is suitable for any downstream signal with a strong carrier, such as QAM and OFDM signals.

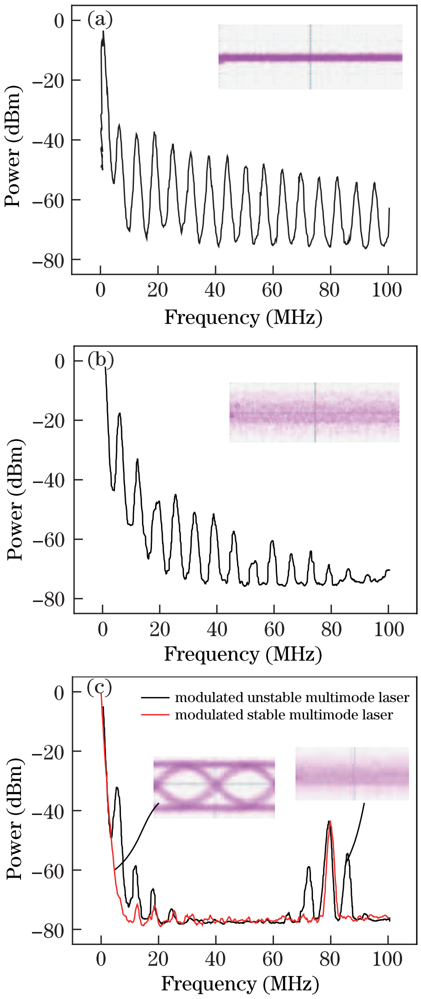

Fig. 3. (a) Stable multi-longitudinal operation of the BSFL, (b) unstable multi-longitudinal operation of the BFL and BEFL, and (c) electrical spectra and eye diagrams of the BSFL and BFL after 10-Gb/s NRZ data modulation.

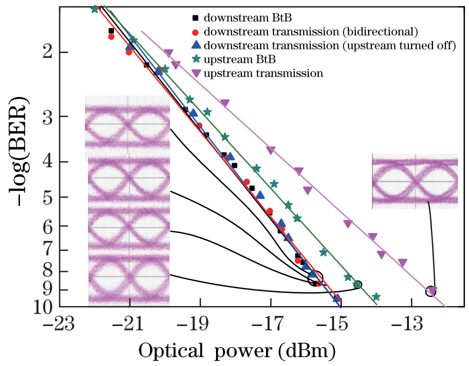

Fig. 4. BER and eye diagrams of the downstream and upstream data in the BtB case and after transmission.

Considering the practical application viewpoint, low cost components are required for the ONUs in WDM-PON. Due to the lack of a suitable splicer in the proof-of-concept experiment, the splice loss between HNLF and SMF is approximately 4 dB. High cavity loss results in the high power threshold of the BSFL. By reducing the splicing loss and optimizing the output coupling ratio of the fiber laser, the BSFL threshold can be significantly reduced to approximately 3 dBm[7]. Therefore, one EDFA can be shared by all ONUs to reduce the high cost when EDFA is not owned by individual ONUs. Moreover, the SOA in the cavity and the external modulator can be replaced by a reflective SOA (R-SOA). This allows simultaneous realization of amplification and modulation, thereby further reducing the ONU cost.

In conclusion, we propose a stable multi-longitudinal mode BSFL as the colorless upstream source in a single-fiber bidirectional WDM-PON. The downstream wavelength serves as the pump of the fiber laser, generating a Brillouin-frequency-shifted upstream carrier to mitigate the Rayleigh backscattering and back reflection-induced crosstalk. The FWM effect in the SOA ensures the stable multi-longitudinal operation of the laser source, which enables high-speed upstream data modulation and transmission, as well as reduces the difficulty of the single longitudinal mode fiber laser generation. The proposed WDM-PON demonstrates a bidirectional symmetric transmission at 10-Gb/s over 12.5-km SMF, with a power penalty of less than 2 dB. This system architecture is suitable for any downstream data format with a strong carrier.

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