Remotely pumped EDFA-based 40-Gb/s downstream and 10-Gb/s upstream long-reach WDM PON employing RSOA and FBG equalizer

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We propose a remotely pumped Er-doped fiber amplifier (EDFA)-based 40-Gb/s downstream and 10-Gb/s upstream transmission long-reach wavelength division multiplexing passive optical network (WDM-PON) scheme with downstream and upstream transmission implemented by quadrature phase-shift keying (QPSK) transceiver and reflective semiconductor optical amplifier (RSOA)-based intensity modulation direct detection (IM-DD). Transmissions of the 40-Gb/s QPSK downstream, using a Mach-Zehnder modulator, and the 10-Gb/s non-return-to-zero on-off keying (NRZ-OOK) upstream, using a 1.2-GHz RSOA equalized by fiber Bragg grating (FBG), are demonstrated with 40-km fiber transmission.

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Wavelength division multiplexing passive optical network (WDM-PON) has been regarded as a promising solution to meet the ever-increasing access bandwidth requirements for delivering gigabit per second data and video services to a large number of users[1−3]. Given the exponential growth of internet traffic and bandwidth-hungry innovative services, WDM-PON access networks will migrate to the 40 Gb/s per channel in the near future[4,5]. Furthermore, long-reach optical links and large coverage are also becoming increasingly necessary with the enhancement of the transmission rate and the network capacity. The main challenges in the deployment of WDM-PON technology in an access network involves the low-cost and colorless light sources and avoidance of utilizing expensive external modulators and receiver in the optical network unit (ONU)[6,7]. A low-cost and easy-integration solution is the utilization of a reflective semiconductor optical amplifier (RSOA)-based modulator and intensity direct detection (DD) receiver at the ONU[8,9].

The modulation bandwidth of RSOA is limited to 1−3 GHz, resulting in the difficult of achieving 10 Gb/s or beyond 10 Gb/s of operation. Recently, several attempts have been performed to operate these low-bandwidth devices at 10 Gb/s and beyond, including advanced modulation formats[10], post-detection electrical signal processing (electronic equalization), and optical signal processing (optical equalization)[11,12]. Typical electronic equalization methods, including the decision-feedback equalizer (DFE) and maximum likelihood sequence estimation (MLSE) equalizer, have also been investigated in Refs. [13,14]. Typical optical equalization methods, including delay interferometer (DI) and optical filter (OF), have been investigated in Refs. [15,16]. However, electronic equalization is mainly being implemented by analog/digital converters and the electronic digital signal process. Thus, high cost is a huge disadvantage when the bit rate increases to 10 Gb/s or higher. Limited by the precise multichannel matching between the multiple pass-band channels of DI and the multiple uplink wavelengths transmitted by RSOAs, a DI is difficult to use as a multiple-channel optical equalizer because different channels are difficult to independently and precisely adjust. Similarly, an OF (including the WDM filter) with a fixed pass-band also cannot satisfy the need for optical equalization. Therefore, innovative low-cost equalization solution with tunable bandpass, simple structure, and easy implementation is still needed. Although 40-Gb/s downstream transmission can be achieved using a chirp-managed directly modulated laser in WDM-PON[17], the high spectral efficiency transmission scheme is still necessary to improve the transmission distance limited by the fiber dispersion and expand the variable length between the optical line terminal (OLT) and different ONUs in WDM PON.

Fiber Bragg grating (FBG) is an innovative low-cost equalization solution. Thus, it is a very attractive passive, linear, and compact component. Several schemes have been performed to operate FBGs as chromatic dispersion (CD) compensator, OF, and optical equalizer in an optical communication system[18]. In addition, as a single bandpass and tunable filter, the bandpass of the FBG can be flexibly adjusted to satisfy the requirement of a precise channel matching between the FBG passband channel and the uplink wavelength transmitted by RSOA. Therefore, compared with WDM and DI OFs, the tunable FBG filter has significant advantage. In this letter, we first propose a remotely pumped Er-doped fiber amplifier (RPEDFA)-based 40-Gb/s downstream and 10-Gb/s upstream transmission long-reach WDM-PON scheme. The downstream transmission is implemented using quadrature phase-shift keying (QPSK) transceivers, and the upstream transmission is implemented using FBG optical equalizer-based RSOA modulator and intensity DD receiver. The 40-Gb/s QPSK downstream, using Mach-Zehnder modulator (MZM) and DI-DD receiver, and 10-Gb/s non return-to-zero on-off keying (NRZ-OOK) upstream, using a 1.2-GHz RSOA equalized by FBG, are demonstrated with 40-km fiber transmission. The frequency responses of RSOA with/without FBG equalizer are also experimentally measured, and performance limitation analysis is also presented.

Figure 1 shows the proposed RPEDFA-based 40-Gb/s downstream and 10-Gb/s upstream transmission long-reach WDM-PON scheme. In the OLT side, the WDM downlink source consists of n C-band 40-Gb/s QPSK optical transmitters, one $n\times1$ array waveguide grating (AWG), one dispersion compensation fiber (DCF) module used to compensate the dispersion of the feeder fiber, and one red/blue (R/B) WDM filter used to couple the downlink transmitters and the seed light sources. The WDM uplink receiver consists of one $n\times1$ AWG, n FBGs, n optical circulators (OCs), and n optical receivers. In one ONU, one red/blue (R/B) WDM filter is used to couple the uplink transmitter and the downlink receiver. The uplink transmitter consists of one RSOA alone. The downlink receiver consists of a QPSK demodulator and photo-detectors (PDs), which are used to achieve the DD. In the remote node (RN), one RPEDFA and one $n\times1$ AWG are used to amplify the downstream and upstream signals and couple n ONUs, respectively. The RPEDFA consists of Er-doped fiber (EDF), a 980/1550 nm WDM filter, and a power tunable pump laser diode (LD) placed in one of the ONUs.

The principle of the FBG-based optical equalization process is analyzed by simulation using the VPI optical communication simulation software. Figure 2 shows the simulation setup. The output of a LD operating at 1549.32 nm with 2-dBm power and 1-MHz bandwidth is sent to a 25-km standard single mode fiber (SSMF) via an OC, and the seed light is injected into a RSOA with 10-dB optical gain and 1.2-GHz measured modulation bandwidth. The RSOA is directly modulated using a 10-Gb/s NRZ-OOK signal, and the upstream optical signal is sent to the SSMF. After transmission over the 25-km SSMF, the upstream signal is fed into a tunable bandpass FBG via the OC. Then, the reflected signal is sent to a RX.

The upstream transmission output of 10-Gb/s NRZ-OOK signal modulating 1.2-GHz ROSA shows a completely closed eye diagram and distorted spectrum caused by the severely limited modulation bandwidth of the RSOA (Fig. 2). The tunable bandpass FBG optical equalizer, which acts as a vestigial sideband filter and a spectrum reshaper, eliminates the low (or high) sideband and reshapes the higher (or lower) sideband where the

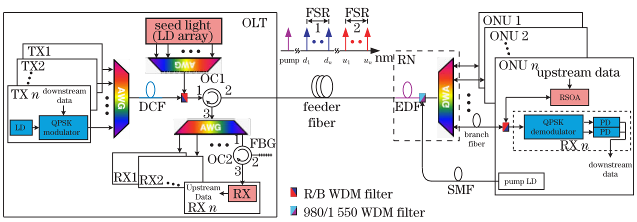

Fig. 1. Proposed high capacity and long-reach WDM-PON system architecture.

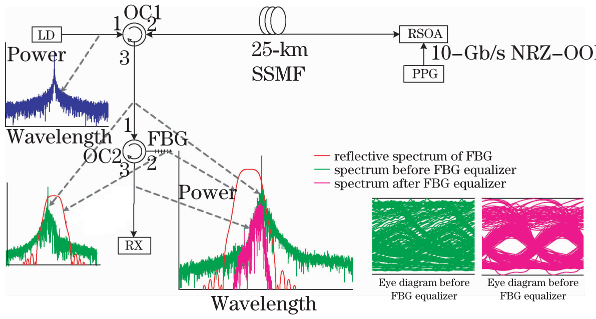

Fig. 2. Simulation setup and results.

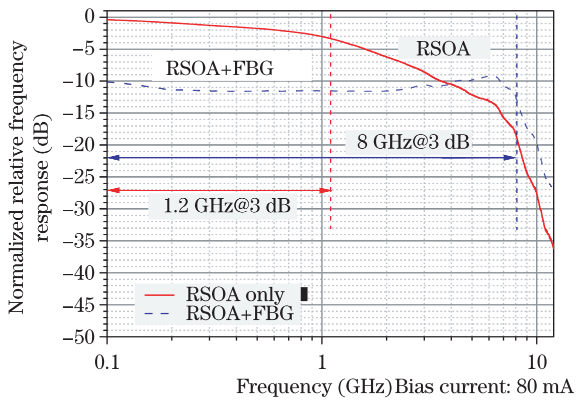

Fig. 3. Frequency response of RSOA and RSOA+FBG.

higher (or lower) spectral components are maintained and low (or high) spectral components are attenuated when the FBG center wavelength is set 1549.22 nm (or 1549.42 nm). The simulated equalization process and results are shown in Fig. 2, in which the equalized signals show a clear open eye diagram. To verify the theoretical accuracy, we have experimentally measured the frequency responses of the RSOA, and the RSOA+FBG with low sideband is eliminated, simultaneously, using a vector network analyzer. The RSOA (CIP SOA-RL-OEC-1550) is biased at 80 mA, whereas the power and spectral width of the injected LD light are -10 dBm and 1 MHz, respectively. The blue dashed line in Fig. 3 shows that the 3-dB bandwidth of RSOA+FBG with approximately 0.09-nm detuning (center wavelengths offset between the FBG and signal; FBG center wavelengths are longer than that of the signal) is nearly 8 GHz. Meanwhile, the red line in Fig. 3 shows that the 3-dB bandwidth of RSOA is only 1.2 GHz. Therefore, significantly enhanced performance of the RSOA-based transmitter is achieved using the FBG optical equalizer.

Figure 4 shows the experimental setup. In the downstream direction, a LD operating at 1540.562 nm with an average power of 12.5 dBm is sent to the QPSK modulator, where two 20 Gb/s pseudo random bit sequences (PRBSs) with a length of $2^{15}-1$ use a parallel MZM to generate a QPSK signal. The QPSK signal is then sent to the 40-km feeder SSMF via an AWG, a DCF module used to compensate the CD of the 40-km feeder SSMF, a R/B WDM filters, and an OC (OC1) with an overall 15-dB insertion loss. A RPEDFA comprising 10 m of EDF and a power tunable pump LD with 975.20 nm wavelength and maximal 500-mW output power is used to amplify the QPSK signal before being sent to the DI-DD QPSK receivers via another AWG with insertion loss of 4.5 dB. In the upstream direction, a tunable LD operating at 1549.332 nm with an average power of 3-dBm is first sent to the 40-km SSMF via an AWG, a R/B WDM filter, and an OC (OC1) with insertion losses of 4.5, 1, and 0.7 dB, respectively. The seed light is amplified by the RPEDFA before being injected into a RSOA (CIP SOA-RL-OEC-1550) through another AWG with insertion loss of 4.5 dB. In practical applications, the pump LD can be placed in an OLT using a 1480-nm pump wavelength. Moreover, the pump LD safety issue should also be considered and solved according to the IEC specification 60825. The optical gain of the RSOA is 12 dB when biased at 80 mA, and the optical power of the injected seed light is -2 dBm. The RSOA is directly modulated using a 10-Gb/s NRZ-PRBS with a length of $2^{31}-1$ generated from a pulse pattern generator (PPG) to produce the upstream optical OOK signal. The upstream optical signal is sent to the SSMF through the AWG with 4.5-dB insertion loss. After the transmission over the 40-km SSMF, the upstream signals are fed into a reflective FBG by an OC (OC2) with 0.7-dB insertion loss, and the reflected signals with ~10-dB loss are then sent to a variable optical attenuator followed by a PIN detector. Bit-error ratio is subsequently measured by the error detector.

Figure 4 also shows the eye diagrams of one of the two QPSK signals (in-phase and quadrature) obtained at point A after the DI and the upstream signals following the RSOA, 40-km SSMF transmission, and FBG equalizer. The spectra obtained at points C and D, as well as the reflective spectrum of the FBG filter, are also shown in Fig. 4. Given the severely limited modulation bandwidth of the RSOA, its output shows a completely closed eye diagram obtained at point B in Fig. 4. The dispersion and Rayleigh backscattering of the SSMF further worsens the eye diagram as shown at point C. However, the simple passive FBG with -20-dB bandwidth of 0.42 nm and center wavelength of 1549.241 nm, dramatically improves the performance and opens up the optical eye, as shown at point D in Fig. 4.

We first measure the BER performance of the RPEDFA -based 40-Gb/s QPSK downstream transmission long-reach subsystem. The black line with squares in Fig. 5 shows that the receiver sensitivity of the quadrature signal is -12 dBm, and the black line with circles shows that the receiver sensitivity of the in-phase signal is -11.5 dBm. The difference in the power penalties between the I and Q channels is caused mainly by the performance of the two non-identical MZMs (or two non-identical sub-MZMs in the dual parallel MZM) in the downstream

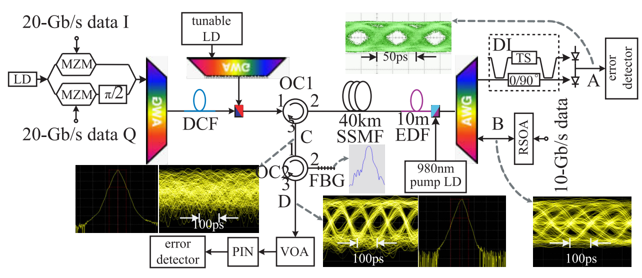

Fig. 4. Experimental setup and results.

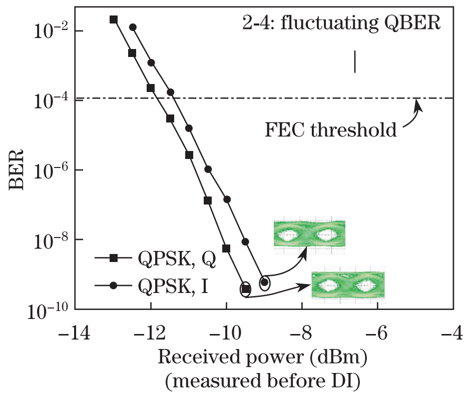

Fig. 5. Measured BER of the 40-Gb/s QPSK downstream transmission.

transmitter. The differences in the modulation characteristic and noise figure of the two MZMs (or two sub-MZMs in the dual parallel MZM) will produce different power penalties between the I and Q channels. The transmission distance, which is limited by the fiber dispersion of the 40-Gb/s QPSK downstream transmission, is more than 10 km. This condition confirms that the system can support error-free operation with the forward error correction (FEC) even if the branch fiber has been extended to 10 km from the current 0 km because the RPEDFA-based optical amplifier can effectively meet the requirement of the power budget.

We then measure the BER performance of the RSOA-based 10-Gb/s upstream transmission long-reach subsystem equalized by a FBG optical equalizer. Figure 6 shows the BER results of the upstream transmission with different optical powers into the fiber produced by tunable LD. The output power of the pump LD is changed, and the seed light power injected to the RSOA remains at unchanged 1 dBm. The curves show that both the upstream transmissions with different optical powers into the SSMF can support error-free operation with the FEC even when the SSMF is extended to more than 40 km. The results also show that the BER performance deteriorates with an increase in optical power into the SSMF from 2 to 8 dBm. The increase in the Rayleigh backscattering power worsens the BER performance. Therefore, the RPEDFA can overcome the challenge of the power budget of a long-reach WDM-PON system and improve the upstream transmission receiver sensitivity. The optical power into the SSMF can be decreased, and the power injected to the RSOA remains unchanged. The Rayleigh backscattering effect on the loopback RSOA-based upstream transmission performance is also investigated. The experimental results show that that an approximately 1 to 2 dB power penalty produced by the Rayleigh backscattering.

In conclusion, we propose and investigate a remotely pumped EDFA-based 40-Gb/s downstream and 10-Gb/s upstream transmissions long-reach WDM-PON scheme. The result shows that the proposed configuration of the RPEDFA-based 40-Gb/s downstream and 10-Gb/s upstream transmissions with directly modulated RSOA signals using a FBG equalizer has a good performance of BERs even when the SSMF is extended to more than 40 km. The BER measurements also show that the RPEDFA can overcome the power budget challenge of

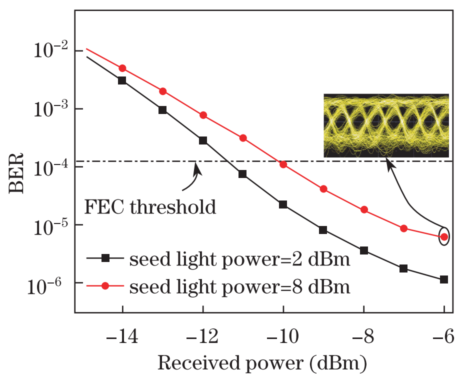

Fig. 6. Measured BERs of the 10-Gb/s upstream transmissions with different optical powers into the fiber power. The power injected to the RSOA is kept at 1 dBm.

a long-reach WDM-PON system and improve the upstream transmission receiver sensitivity because the optical power into the SSMF can be decreased, while the power injected to the RSOA is unchanged.

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