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Repeated Bidirectional Transmission Using Two 4-Port Optical Circulators and a Bidirectional EDFA without Isolators

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By using a newly designed bidirectional erbium-doped fiber amplifier, we demonstrated a 2 × 2.5 Gb/s repeated bidirectional transmission over a 100-km single-mode fiber. Two tunable optical bandpass filters were used to suppress the Rayleigh backscattering and amplified spontaneous emission in the bidirectional transmission system. The bit error rate performances were measured for both directions. A negligible power penalty of 0.2 dB for the 2 × 2.5 Gb/s transmission due to backreflections was observed when comparing the bidirectional transmission with single-channel, unidirectional transmission.

INTRODUCTION

Compared with unidirectional transmission, bidirectional transmission offers the advantages of full duplex transmission over a single-mode fiber (SMF), double capacity, and interactivity. Bidirectional transmission also yields a large savings in cost of components [1, 2]. The features of bidirectional transmission have been discussed, and several successful repeaterless or repeated bidirectional transmission experiments were demonstrated using single and/or multiple wavelengths in previous works [3–6]. Economic and practical considerations may lead to the choice of a SMF link with bidirectional propagation, which may require a bidirectional erbium-doped fiber amplifier (B-EDFA). The simplest and least expensive design is a B-EDFA without optical isolators [7, 8]. Such a design also has the additional advantage of enabling the use of optical time-domain reflectometry (OTDR) technology in bidirectional transmission to supervise EDFA gain characteristics along the fiber link and to locate and prevent possible faults. However,

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when the B-EDFA without optical isolators and/or optical circulators (OCs) for the bidirectional transmission are used, the system performance may degrade seriously such as by optical reflections, stimulated Brillouin scattering (SBS) and Rayleigh backscattering [9]. A B-EDFA may cause a power-dependent noise figure (NF) and enhancement of the crosstalk [10]. The presence of reflections due to Rayleigh backscattering (refection power typically is of the order of -30 to -34 dB for a long length of fiber) limits the maximum tolerable gain to about 19 dB if no optical isolator is incorporated in the amplifiers [11]. This fact must be considered in designing bidirectional transmission.

To reduce the backreflections, we propose a B-EDFA in this paper by containing several fiber gratings (FBGs) (i.e., FBG-chain) in each direction with corresponding wavelengths to match the counterpropagating signals in the opposite direction. The 4-port OCs combining FBG-chains are used to provide isolation and to suppress the counterpropagating (backreflection) signals of the bidirectional system. A tunable optical bandpass filter (OBPF) can be used to replace the FBG-chain to filter out both the amplified Rayleigh backscattering and the amplified stimulated emission (ASE) accompanying the signal for single-channel bidirectional transmission. A 2×2.5 Gb/s over a 100-km SMF bidirectional transmission system using two 4-port OCs and a B-EDFA without optical isolators is demonstrated. For both directions, we measured the bit error rate (BER) performance to verify crosstalk and backreflection effects. The results show that negligible power penalty was induced when the B-EDFA configuration was used. Our results indicate the advantage in upgrading existing unidirectional systems to full bidirectional systems.

PROPOSED B-EDFA MODULE

As shown in Fig. 1a, the proposed B-EDFA module consists of two 4-port OCs to separate and recombine the counterpropagating signals, a section of erbium-doped fiber (EDF), a 980-nm-pumped laser diode and a 980/1550-nm wavelength division multiplexing (WDM) coupler. Two FBG-chains with central reflective wavelengths are designed to match the counterpropagating signals in the opposite direction. The FBG-chains are located between ports 4 and 1 of each 4-port OC to ensure that signals propagated only in one direction and to prevent them from propagating in the reverse direction. In other words, the FBG1, FBG3, and FBG5 are designed to reflect the downstream signals, while the FBG2, FBG4, and FBG6 are designed to reflect the upstream signals. Thus, the reflected signals are blocked between ports 4 and 1 of either 4-port OC. For example, if the reflectivity of FBGi ($1 \leqq i \leqq N$) is 99%, only 1% of the counterpropagating (back reflection) signal i could pass through the 4-port OC. Its equivalent configuration is also shown in Fig. 1b. The 4-port OCs pair located before and after the EDF can provide bidirectional transmission of the two counterpropagating signals by properly connecting each port of the 4-port OCs with some desired ports (nodes) in the system. Also, the 4-port OCs can act as optical isolators to prevent backscattering of signals and ASE generated by the B-EDFA. For the downstream transmission (i.e., forward direction), the isolation characteristic of the left 4-port OC, from port 3 to port 2, makes itself equivalent to the first built-in optical isolator located before the

980/1550 WDM coupler. The isolation characteristic of the right 4-port OC, from port 4 to port 3 and then port 2 to port 1, makes itself equivalent to the second and third built-in optical isolators cascaded together behind the EDF. The configuration is similar for the upstream transmission (i.e., backward direction). The 4-port OCs combining two FBG-chains can provide a two-path configuration for the bidirectional transmission. The backscattering signals were reflected by the FBG-chains and isolated by the 4-port OCs. Because of their characteristics of high interport isolation and low insertion loss, the 4-port OCs have the advantages that no extra loss and NF penalties are incurred and no optical isolators are required.

EXPERIMENTAL SETUP

Based on the general idea, two OBPFs are used to replace the proposed two FBG-chains to suppress both the Rayleigh backscattering signals and most of the ASE noise generated by the B-EDFA. The experimental setup, depicted in Fig. 2,

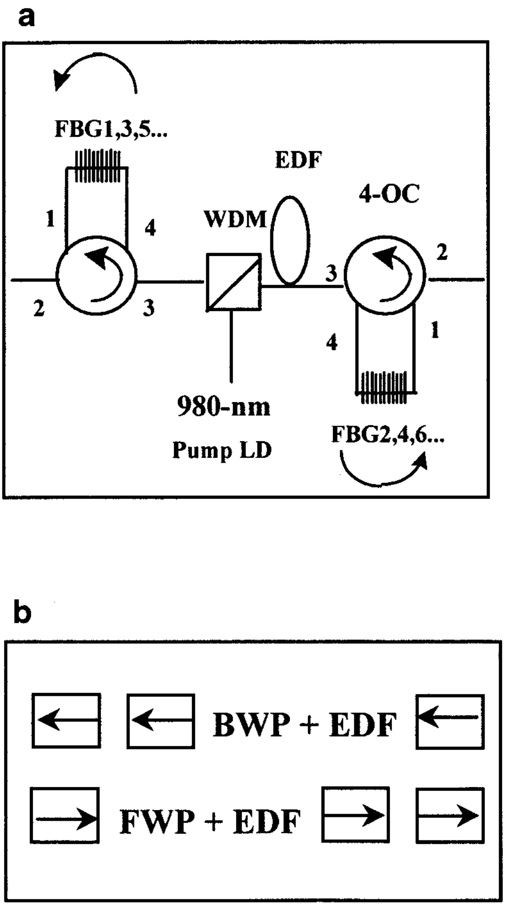

FIG. 1. (a) Configuration of the proposed bidirectional EDFA. (b) Equivalent configuration of the bidirectional EDFA. FWP, forward pumping; BWP, backward pumping; FBG, fiber Bragg grating; EDF, erbium-doped fiber; 4-OC, 4-port optical circulator.

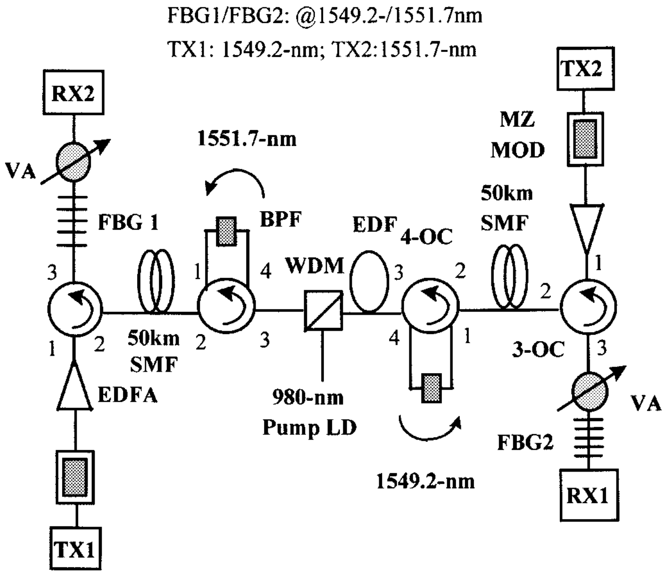

FIG. 2. Experimental setup. MZ MOD, Ti:LiNbO3 Mach–Zehnder external modulator; BPF, optical bandpass filter; VA, optical variable attenuator; WDM, 980/1550 multiplexer.

was used to demonstrate the bidirectional transmission with one channel in each direction. The downstream transmission signal at 1549.2 nm was generated by TX1. A 2.5 Gb/s pseudo-random PRBS 2^{23}-1 NRZ electrical signal was used to modulate a chirp-adjustable Ti:LiNbO$_3$ Mach–Zehnder external modulator for the downstream channel. A polarization controller was used to maximize the signal output power from the external modulator. A transmitter power amplifier was employed after the external modulator to boost the 1549.2-nm signal up to 13 dBm. The amplified signal is then passed through a 3-port OC provided the combination and separation of both transmission signals. After the 3-port OC are a 50-km SMF and a 4-port OC with an OBPF inserted in the latter. The OBPF has full-width at half-maximum (FWHM) bandwidth of 1.2 nm and insertion loss of 35 dB at ±4 nm away from the passband center. Therefore, the power level of the reflected signal is effectively attenuated by the OBPF when compared to the transmitted signals. After the 4-port OC were a 980/1550-nm WDM coupler, a 980-nm laser diode, and a piece of EDF. The B-EDFA had a saturated power of 10.0 dBm for the downstream transmission and 10.5 dBm for the upstream transmission simultaneously. The pumping schemes are forward and backward for the downstream and upstream signals, respectively. After the EDF was another 4-port OCs, another spool of 50-km SMF, and another 3-port OC. In the detection of the 1549.2-nm signal, an FBG with bandwidth 0.25 nm and centered at 1551.7 nm, 99% reflectivity, and 0.2-dB insertion loss acted as an optical notch filter to filter out the counterpropagating signal at 1551.7 nm. The 1549.2-nm signal was then detected with a high-sensitivity InGaAs PINFET receiver RX1 and the BER performance was measured. Another signal at 1551.7 nm was transmitted in the opposite direction and the configuration is symmetrical for both directions. For the downstream transmission, the insertion loss of the first built-in optical isolator is 1.2 dB due to the insertion loss of the left 4-port OC from port 2 to port 3. The total insertion loss of the second and third built-in optical isolators at the right 4-port OC is about 2.5 dB. The loss is attributed to the insertion loss of ports 3 and 4 (1.2 dB), splicing loss of port 4 with port 1 (0.1 dB), and insertion loss of ports 1 and 2 (1.2 dB). The average attenuation of the SMF is about 0.25 dB/km corresponding to a total attenuation of 25 dB for a 100-km transmission. The interport insertion loss and isolation are 1.2 and 45 dB, respectively, for all of the 3- and 4-port OCs. All the connectors used here have return loss of less than -45 dB. Two optical variable attenuators located before the receivers are used to adjust the received powers for both directional transmissions.

RESULTS AND DISCUSSION

Because spontaneous emission comes together with optical amplification, the ASE noise is added when a signal is amplified by an EDFA. For the downstream transmission, the pump beam (forward pumping) of the B-EDFA travels in the same direction as that of the signal beam. For the upstream signal, the pump and signal beams travel in opposite directions. In general, the NF characteristic of an EDFA depends on the direction and pumping power of the pumping laser diode, EDF length, and Er^{3+} concentration. The NF, the gain, and the output power of the backward pumping scheme are usually larger than those of the forward pumping scheme. A channel wavelength separation of 2.5 nm was used in the experiment. However, the narrow bandwidth FBG located before the receiver will play a more prominent role in filtering out the backscattered signal when the channel spacing becomes smaller. Figure 3 shows the experimental BER results for both the downstream and upstream signals with or without turning off the counter-propagating signals of 1551.7 and 1549.2 nm, respectively. First, comparing the performance of the forward (1549.2 nm) and backward (1551.7 nm) unidirectional transmission, we obtain a difference in receiver sensitivity of about 0.6 dB at 10^{-9} BER. This can be accounted for mostly by the differences of gain compression and gain saturation, as well as different NF results from different pumping schemes of the B-EDFA. Second, we compare the system performance of the bidirectional and unidirectional transmissions (i.e., 1549.2 nm w/ 1551.7 nm versus 1549.2 nm w/o 1551.7 nm). The results showed that there was nearly no sensitivity degradation between the bidirectional and unidirectional transmissions. A negligible system BER penalty of only 0.2 dB was observed. The small penalty in receiver sensitivity is attributed to the cross-phase modulation by the 2.5-nm channel spacing in this experiment and/or other possibilities of fiber nonlinear effects.

CONCLUSION

A successful repeated 2 × 2.5 Gb/s bidirectional transmission experiment over a 100-km conventional SMF was demonstrated using a new B-EDFA. The B-EDFA is integrated with two 4-port OCs, a section of EDF, a 980-nm laser diode, two

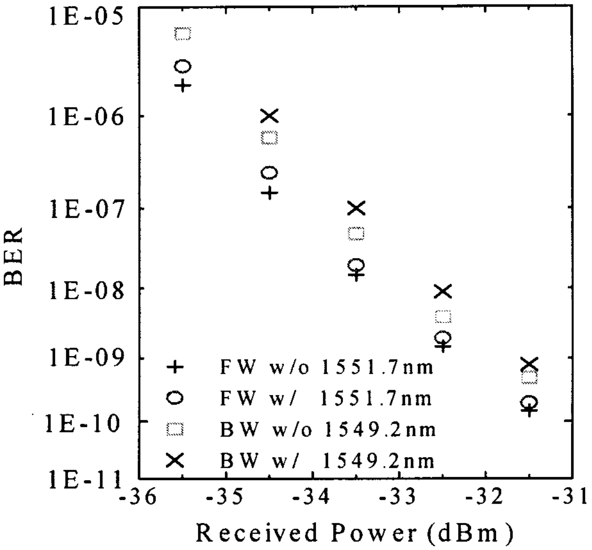

FIG. 3. Experimental BER results of NRZ signals at bit rate of 2.5 Gb/s for the downstream and upstream, uni- or bidirectional transmission as a function of the received power.

OBPFs, and a 980/1550-nm multiplexer. The OBPFs can provide an effective way of suppressing the Rayleigh backscattering signals and ASE to improve the BER performance. The optical NF characteristic also can be improved for both the upstream and downstream transmissions by using the 4-port OCs. In our experiment, by using the B-EDFA as repeater and reflection attenuator, the backreflection effects were negligible since the BER degradation of either the upstream or the downstream channel is only 0.2 dB when comparing bidirectional transmission with single-channel, unidirectional transmission. The experimental results confirmed the system performance of the bidirectional transmission when the proposed B-EDFA without optical isolators is used as an in-line repeater.

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