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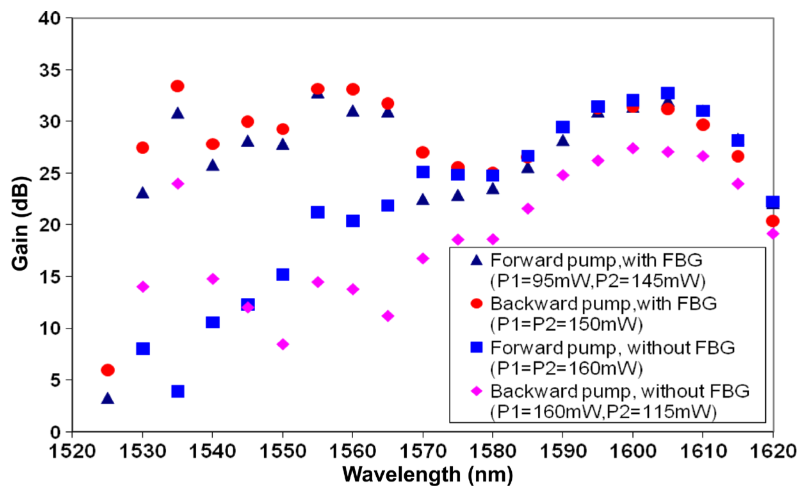
X. S. Cheng
R. Parvizi
H. Ahmad
S. W. Harun



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Wide-Band Bismuth-Based Erbium-Doped Fiber Amplifier With a Flat-Gain Characteristic

X. S. Cheng,[1] R. Parvizi,[2] H. Ahmad,[2] and S. W. Harun[1,2]

[1]Department of Electrical Engineering, Faculty of Engineering, University of Malaya, Kuala Lumpur 50603, Malaysia
[2]Photonics Research Center, University of Malaya, Kuala Lumpur 50603, Malaysia

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Abstract: In this paper, a bismuth-based erbium-doped fiber amplifier (Bi-EDFA) that operates in both the C- and L-band wavelength regions is demonstrated. The system employs two pieces of bismuth-based erbium-doped fiber (Bi-EDF) as the gain medium with a midway broadband fiber Bragg grating (FBG). The FBG functions to prevent the gain saturation at the C-band region, flatten the overall gain spectrum, and reduce the noise figure, particularly for the C-band. At an input signal power of -30 dBm and a pump power of 150 mW for both pumps, a flat gain of around 29 dB is obtained with a gain variation of ± 3.5 dB within the wavelength region from 1525 to 1615 nm using a backward-pumping scheme. At an input power of 0 dBm, the gain varies from 10 to 13 dB within the wavelength range from 1530 to 1620 nm, while the corresponding noise figure varies from 9.5 to 14 dB over this wavelength range.

Index Terms: Bismuth-based erbium-doped fiber, double-pass amplifier, Bi-EDFA.

1. Introduction

The tremendous growth of Internet and data traffic has created an enormous demand for transmission bandwidth of dense wavelength-division-multiplexed (DWDM) optical communication systems. Since the silica-based transmission fibers have a wide-band operating window ranging from 1400–1700 nm, optical amplifiers with a wider amplification bandwidth are required to cover the full range of the DWDM systems. In order to extend the wavelength range, several glass hosts such as tellurite [1], multi-component silicate [2], and bismuth-oxide-based glass [3] have been developed. However, the gain spectrum of these amplifiers still remains non-uniform with the variation of wavelength. Nevertheless, techniques for successful gain flattening have been investigated, that include cascade configuration [4], long-period fiber grating [5], co-dopant material [6], and side-polished fiber [7].

In an earlier work, a wide-band, bismuth-based erbium-doped fiber amplifier (Bi-EDFA) operating within a 58-nm wavelength bandwidth and employing a single-stage 253-cm-long bismuth-based erbium-doped fiber (Bi-EDF) and a 1480-nm laser was proposed [8]. The gain flatness of 3 dB was obtained within a 53.9-nm spectrum bandwidth. In another work, a two-stage broadband erbium-doped fiber amplifier (EDFA) with a gain bandwidth over the wavelength range of 1520 to 1600 nm was proposed [9]. In this paper, a wide-band and flat-gain Bi-EDFA is proposed using a two-stage configuration that allows it to operate over a wider wavelength region from 1530 to 1620 nm. The

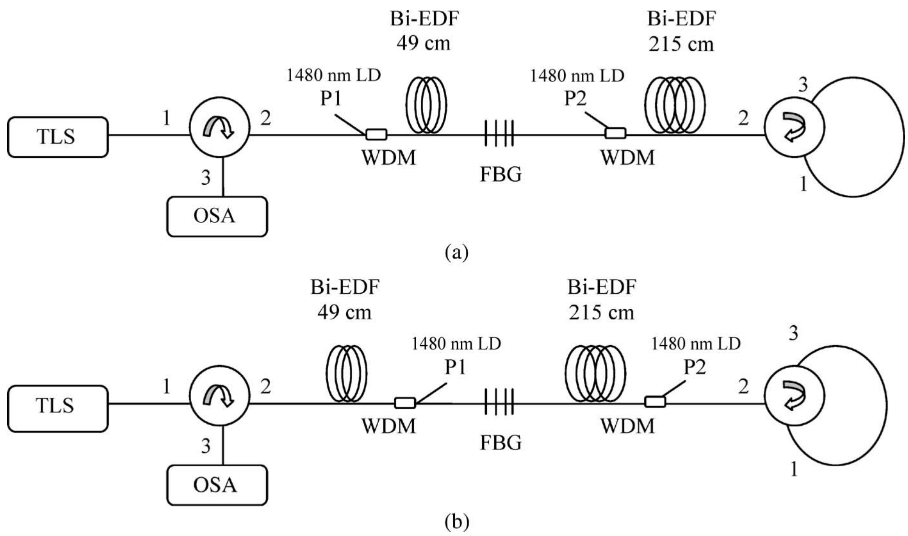

Fig. 1. Dual-stage Bi-EDFA configurations with (a) forward and (b) backward pumping.

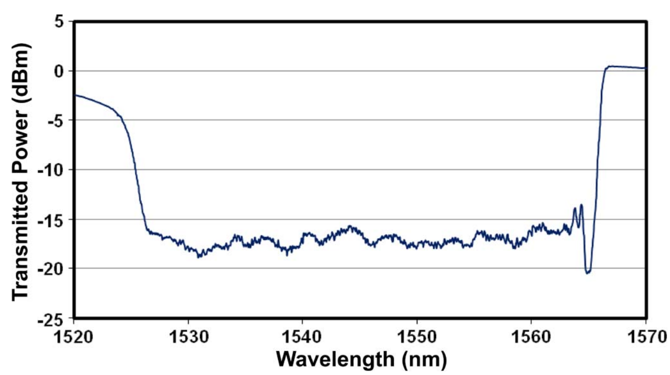

Fig. 2. Transmission spectrum of the broadband FBG.

dual-stage amplifier employs two pieces of gain medium in a linear setup in conjunction with a double-pass system. In this amplifier, a broadband FBG is incorporated in between the stages to prevent the gain saturation at C-band, to flatten the overall gain spectrum and to reduce the noise figure especially for C-band. The gain flatness of 4 dB was obtained within a 90-nm spectrum bandwidth in the proposed setup. The advantage of the Bi-EDFA, in comparison with the other type of EDFA, is that its gain bandwidth can cover the extended L-band region up to 1620 nm.

2. Experiments

Fig. 1(a) and (b) show the configurations for the proposed wide-band Bi-EDFA with forward and backward pumping, respectively. Both configurations consist of two pieces of Bi-EDF sections as gain media, a broadband fiber Bragg grating (FBG) and optical circulators. The Bi-EDF has an erbium ion concentration of 3250 ppm and a cutoff wavelength of 1440 nm, as well as a pump absorption rate of 83 dB/m at 1480 nm. The Bi-EDF's length is set at 49 cm and 215 cm for the first and second stages, respectively. Both 49-cm and 215-cm-long Bi-EDFs are pumped by a 1480-nm laser diode to provide amplifications in C-band and L-band, respectively. The FBG is placed in between the two stages to act as a reflector for the C-band Bi-EDFA. It reflects C-band signal and allows the L-band signal to be transmitted. Fig. 2 shows the transmission spectrum of the FBG. As shown in the figure, the FBG has a reflectivity of more than 98% centered at a wavelength of 1545 nm with a bandwidth of about 40 nm.

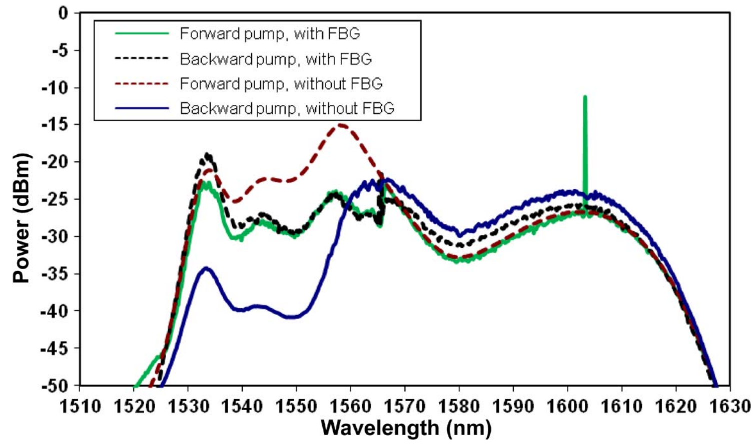

Fig. 3. ASE spectra of the Bi-EDFAs at the maximum pump powers.

The C-band signal, ranging from 1520 nm to 1565 nm, is amplified in the first stage, and the broadband FBG is used to reflect this signal back into the first stage to undergo amplification for the second time. The L-band signal, above 1565 nm will go through the FBG and is amplified in the second stage of the amplifier. The amplified signal is then reflected back into the system by a loop mirror that is constructed using an optical circulator. The loop mirror is constructed by connecting port 3 with port 1 so that the light from port 2 is routed back into the same port. A tunable laser source (TLS) is used in conjunction with an optical spectrum analyzer (OSA) to characterize the Bi-EDFA. The experiment is also carried out for the Bi-EDFA configured without the broadband FBG.

3. Results and Discussion

First, the observation of the ASE spectrum, as shown in Fig. 3, is performed at a maximum pump power of 160 mW for both pump lasers. In the experiment, the C-band Bi-EDF (49 cm) and L-band Bi-EDF (215 cm) are pumped with P1 and P2, respectively at the maximum pump power. All connections between the components are spliced with a loss of less than 0.1 dB. As shown in the figure, the ASE spectrum is flatter for the Bi-EDFA configured with the broadband FBG in between the stages. The FBG functions to block the C-band ASE from traveling between the stages and thus enhances and flattens the overall gain of the wide-band Bi-EDFA. Since the C-band gain is very low in the second stage, the lasing due to the oscillation of the C-band ASE between the FBG and loop mirror does not occur. With the forward-pumping scheme of Fig. 1(a), free-running lasing was observed at 1604 nm due to the spurious reflection in the cavity. Spurious reflections might occur from linear or nonlinear scattering in the optical fiber, or from reflections from the fiber splices. The free-running laser will suppress the ASE level beside it and affect the gain level in this region. For the Bi-EDFA configured without the FBG the C-band ASE leaks to the next stage and is then absorbed to emit L-band ASE. Therefore, the highest L-band ASE spectrum was obtained with this amplifier by using the backward pumping, as shown in Fig. 3.

The pump power of both pumps was adjusted to obtain a flat-gain spectrum and the gain spectrum measured in a single channel operation. At the optimum pump power, the gain and noise figure were measured across C- and L-band wavelength regions for two input signal level; -30 dBm and 0 dBm. Fig. 4 shows the gain characteristic across the wavelength region from 1525–1620 nm for an input signal power of -30 dBm. As shown in this figure the average gains are 28 dB with a gain variation of ± 5 dB from 1525 nm to 1615 nm for the Bi-EDFA configured with the FBG. Without the FBG the C-band gain is reduced due to the gain saturation. In this configuration the C-band signals must propagate twice through both Bi-EDF sections. With the FBG the backward pumping gives a flatter gain compared to the forward pumping. In the backward-pumping scheme as shown in Fig. 1(b) and at a pump power of 150 mW for both pumps, a flat gain of around 29 dB is obtained with gain variation of ± 3.5 dB over the wavelength region from 1525 nm to 1615 nm.

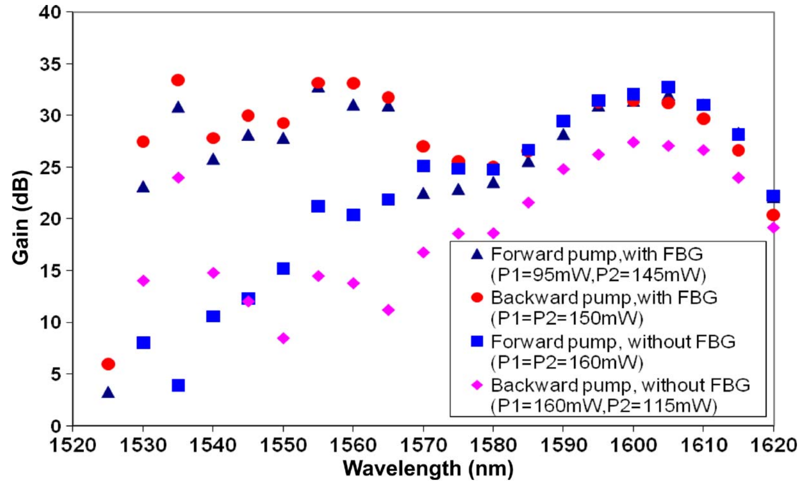

Fig. 4. Gain spectrum of the Bi-EDFAs at an input signal power of −30 dBm. The pump power was optimized to obtain a flat and high gain.

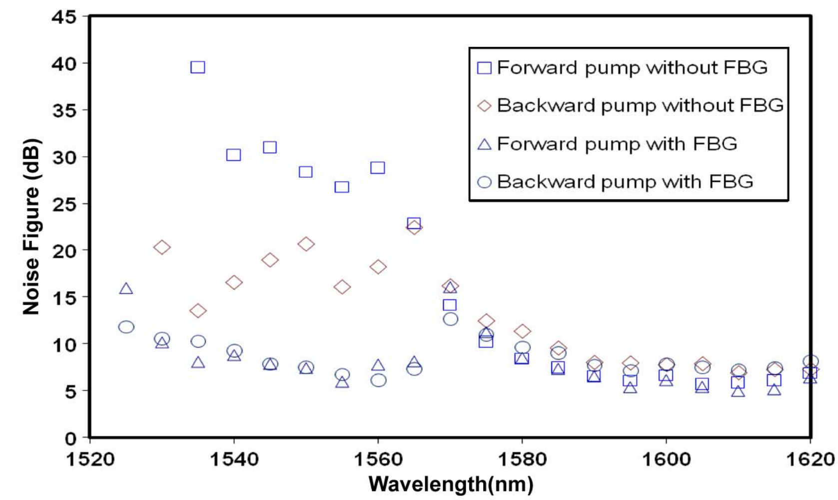

Fig. 5. Corresponding noise figure spectrum of the Bi-EDFAs at input signal power of −30 dBm.

Fig. 5 shows the corresponding noise figure spectrum at a small input signal of −30 dBm. As shown in this figure, the noise figure of the proposed backward-pumped amplifier varies from 6 dB to 12 dB over all wavelengths from 1525 nm to 1620 nm. Over the same wavelength region the noise figure of the forward-pumped amplifier varies between 5 dB to 16 dB. As shown in Fig. 5, the noise figure in the C-band region is high for the Bi-EDFA configured without the FBG. This is attributed to the backward ASE from the second stage, which is amplified by the C-band amplifier of the first stage. This resulted in a very high level of ASE noise in the input part of the amplifier, which reduces the population inversion at this input part and thus increases the noise figure significantly.

Figs. 6 and 7 show, respectively, the gain and noise figure spectra at a high input signal power of 0 dBm. With the FBG, the gain varies from 7 to 12 dB within a wavelength region from 1530 nm to 1620 nm with the forward-pumping scheme of Fig. 1(a). As shown in Fig. 7 the corresponding noise figure also varies from 9.5 dB to 19 dB within this wavelength region. However, as shown in Figs. 6 and 7 the gain and noise figure spectra are improved in term of its flatness and average value by using the backward pumping. With the backward pumping the gain varies from 10 dB to 13 dB, and the corresponding noise figure varies from 9.5 dB to 14 dB within the 90-nm bandwidth

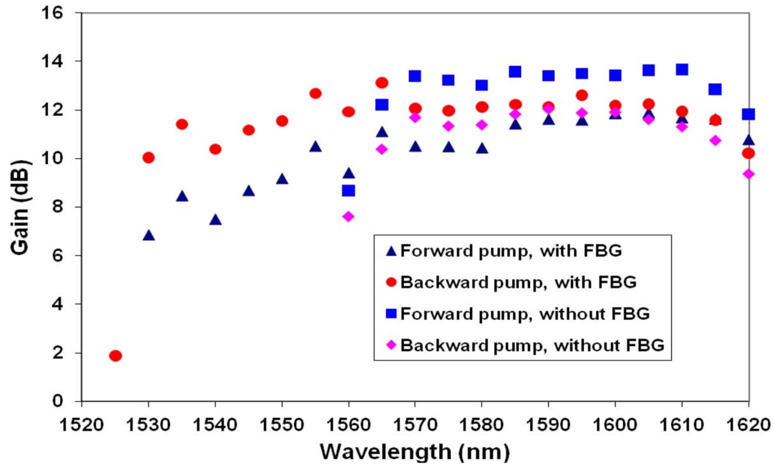

Fig. 6. Gain spectrum of the Bi-EDFAs at input signal power of 0 dBm.

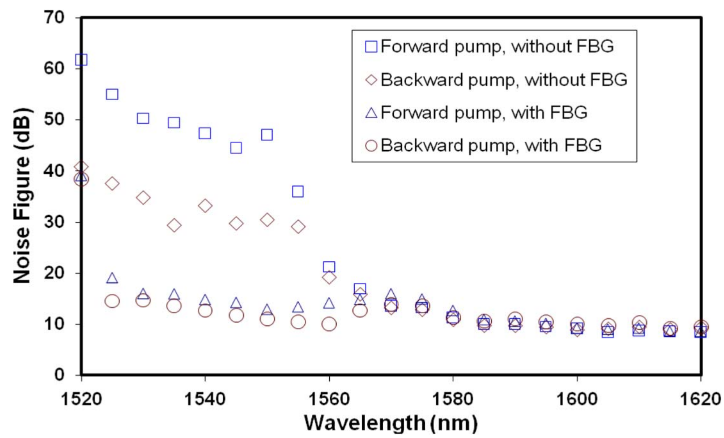

Fig. 7. Noise figure spectrum of the Bi-EDFAs at input signal power of 0 dBm.

wavelength region. As shown in Fig. 7 the noise figure is relatively lower at the longer wavelength. This is attributed to the gain characteristic which is higher at longer wavelength, as well as the loss characteristic which is lower at the longer wavelength. The higher gains were obtained in a smaller input signal of -30 dBm. This indicates that the effect of the population inversion is larger at the smaller input signals, whereas the high input signals suppress the population inversion and thus reduces the attainable gain.

The broadband FBG in the system reflects the C-band signals back to the first stage to limit the double-pass process to only the first stage (C-band Bi-EDFA). This can prevent the gain saturation effect for C-band as shown in Fig. 6. This figure shows that the gain is negative at wavelengths shorter than 1560nm due to the gain saturation. Meanwhile, the L-band signals are allowed to go through the FBG and undergo the double-pass process in both stages. The insertion of the FBG also blocks the backward C-band ASE of the second stage from entering the first stage. This resulted in an improved noise figure for C-band. As shown in Fig. 7 noise figure improvements of about $20 \sim 30$ dB and $3 \sim 12$ dB are observed by the incorporation of the FBG in the proposed amplifiers configured with forward and backward pumping, respectively. The C-band ASE is reflected back into the second stage to improve the L-band gain. The combination of these effects has flattened the gain and noise figure spectrum especially for the proposed backward-pumped Bi-EDFA. Future work should be focused on reducing the noise figure of this amplifier to avoid crosstalk in the DWDM networks.

4. Conclusion

A wide-band Bi-EDFA with a flat gain is demonstrated using a two-stage configuration with a broadband FBG and optical circulators to allow a double propagation of C-band and L-band signals. The backward-pumping scheme provides a better gain and noise figure spectrum compared with the forward-pumping scheme. A gain of about 29 dB is obtained for the proposed amplifier at an input signal power of -30 dBm, and it has a gain ripple of ± 3.5 dB over the wavelength range from 1525 nm to 1615 nm. For an input signal power of 0 dBm, the gain varies from 10 dB to 13 dB over the wavelength range from 1530 nm to 1620 nm. The corresponding noise figure varies from 9.5 dB to 14 dB over this wavelength range.

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