Flat-gain optical amplification within 70 nm wavelength band using 199 cm long hybrid erbium fibers

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A flat-gain amplification covering a wideband wavelength window was accomplished by using dual-stage erbium doped fiber amplifier (EDFA). The amplifier was constructed by combining two different active fibers; Bismuth erbium doped fiber (Bi-EDF) and Hafnium-bismuth erbium doped fiber (HB-EDF) that provide amplification in C- and L-band region, respectively. It employed only 199 cm of the total active fibers in double-pass parallel configuration. The 1480 nm pump powers were fixed at 90 and 170 mW for first and second stages, respectively. At input signal power of -30 dBm, the gain of the amplifier varied from 13 to 27 dB within a wavelength region from 1535 to 1590 nm. At input signal power of -10 dB, a flat gain of about 14 dB was realized with gain fluctuation less than 1 dB over 70 nm wavelengths from 1535 to 1605 nm. On the other hand, the corresponding noise figures were maintained below 13 dB over wideband region for both input signal powers.

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1. Introduction

Increasing demands for transmission bandwidth of dense wavelength division multiplexed (DWDM) optical communication systems have been created in response to the massive growth of the internet and data traffic [1, 2]. Since silica fibers can operate within wide-band optical window, the transmission bandwidth could be increased by fully exploiting the low-loss band region of the fibers, which covers the full range of the DWDM systems. A wideband amplification is usually achieved by using a hybrid amplifier, which is constructed by connecting two amplifiers in parallel [3, 4]. In this amplifier, the input signal is first de-multiplexed into different bands by the wavelength division multiplexing (WDM) coupler, amplified by amplifiers that are suitable for the corresponding wavelength band, and finally multiplexed again with another WDM coupler. The main advantage of using a hybrid amplifier is extensibility, whereby one amplifier can initially work independently while another amplifier can be added into the system according to the demand for expansion. Lately, many efforts have been accomplished on the amplifier's evolution with high ion concentration to decrease the active fiber length.

Several techniques have been developed using different glass hosts such as Ytterbium-co-doped silica based fiber [5-8], tellurite-based fiber [9-11], bismuth-oxide-based glass [12] and Zirconia-based fiber [13, 14] with a view to increase the erbium doping ion concentration without changing in the amplifying performance and also to achieve wider bandwidth operation. In an earlier work, a wideband Silica based-erbium doped fiber amplifier (Si-EDFA) was investigated using two pieces of Silica erbium doped fibers (Si-EDFs) with total length of 10.5 m in double-pass parallel configuration [15]. This fiber has an erbium ion concentration of 2200 ppm. In another work, a wideband hybrid amplifier was also proposed by using a combination of Zirconia-based erbium doped fiber (Zr-EDF) and silica-based erbium doped fiber (Si-EDF) with total length of 11 m in a parallel configuration. Recently, a new type of EDF was developed by adding two materials of Hafnium and Bismuth ions in the erbium fiber and this fiber was referred to Hafnium-Bismuth Erbium co-doped Fiber (HB-EDF) [16]. The addition of both materials has successfully minimized the clustering effects in the fiber and thus the erbium ions concentration of the HB-EDF could reach about 12500 ppm.

In this paper, an efficient L-band optical amplifier and a flat-gain erbium doped fiber amplifier (EDFA) with a hybrid gain medium are proposed and demonstrated based on double-pass configuration by using the HB-EDF as the gain medium. Compared to enhanced Zirconia erbium doped fiber amplifier (Zr-EDFA), the HB-EDF amplifier (HB-EDFA) has achieved a comparable performance but using a shorter length of gain medium. It uses only 150 cm active fiber but provides a wider bandwidth amplification. Finally, a hybrid amplifier with a wideband region was demonstrated using a combination of Bismuth erbium doped fiber (Bi-EDF) for C-band stage and HB-EDF for L-band stage, with total fiber length of 199 cm in double-pass parallel configuration.

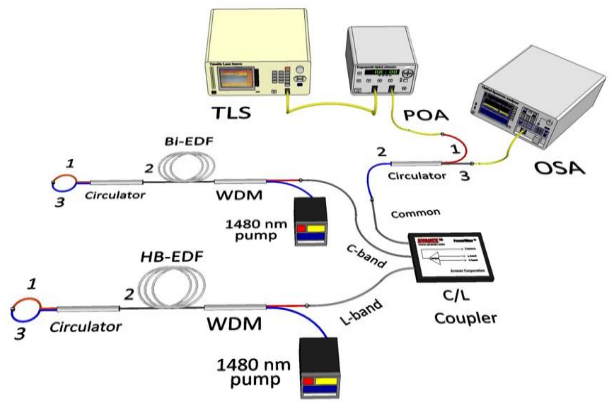


Fig. 1. Dual-stage configuration for the proposed hybrid amplifier

2. Experimental setup

Fig. 1 shows the proposed hybrid amplifier which utilizes Bismuth-based erbium doped fiber (Bi-EDF) and Hafnia-Bismuth erbium doped fiber (HB-EDF) as gain media in double-pass parallel configuration. Both fibers were drawn from the over cladded perform using fiber drawing technique at a temperature of 2000 °C. The HB-EDF has an erbium ion concentration of 12500 ppm while Bi-EDF has an erbium ion concentration of 6300 ppm. The 49 cm long of Bi-EDF and 150 cm long of HB-EDF were placed in first and second stage for C- and L-band, respectively. Both fibers were forward pumped by 1480 nm via wavelength division multiplexing (WDM) coupler. A C/L-band coupler was used to separate/combine both C- and L-band signals into/from first and second stage, respectively. Three optical circulators were used in the proposed configuration. The first one was acting as isolator to prevent reverse direction of amplified spontaneous emission (ASE). In addition, it was used to forward the input signal into the C/L band coupler and to route the amplified signal into the optical spectrum analyser (OSA). The second and third circulators were acting as mirrors to allow double propagation of the amplified signal in the gain medium via joining port 3 with port 1, thus the light is returned into port 2.

The performance of a single-stage L-band HB-EDFA was investigated by removing the C-band Bi-EDFA, C/L band coupler and connecting port 2 of the first circulator directly to the HB-EDF as illustrated in Fig. 2. For comparison purpose, the gain and noise figure characteristics of the single-pass of the L-band HB-EDFA were also obtained by removing the first circulator and measuring the amplified signal at the end of HB-EDF. All the experiments above were carried out by using a tunable laser source (TLS) as an input signal to the amplifiers while a programmable optical attenuator (POA) was used to obtain the accurate power of the input signal. All outputs were measured using the OSA.

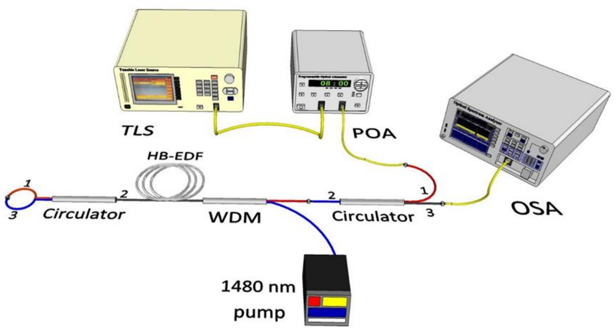


Fig. 2. Single-stage double-pass HB-EDFA configuration

3. Result and discussion

The effect of the laser diode pump wavelength was tested on the performance of the HB-EDFA within erbium fiber length of 150 cm. The EDF was forward pumped by 1480 nm, then the experiment was repeated with 980 nm pumping to compare the amplified spontaneous emission (ASE) performance in single-pass configuration. The pump powers were fixed at 170 mW for both pump wavelengths. As depicted in Fig. 3, the power level of the ASE was higher at 1480 nm pumping. This is attributed to the higher optical power conversion efficiency at 1480 nm pumping due to the single photon conversion process of erbium amplification. The lower effectivity of Erbium emission at 980 nm pumping is most probably due to the presence of excited state absorption (ESA) in the EDF. The presence of the ESA increases the loss-factor stemming from the clustering phenomenon [17-21].

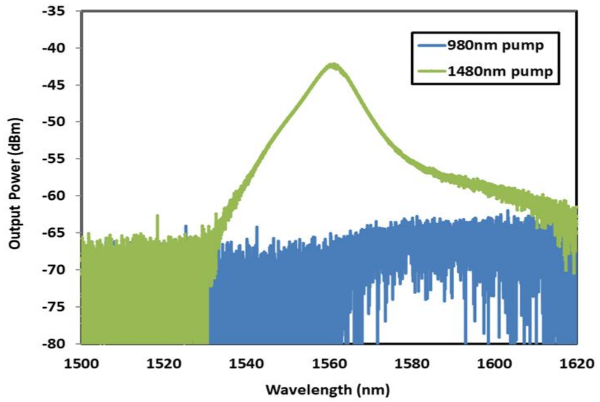
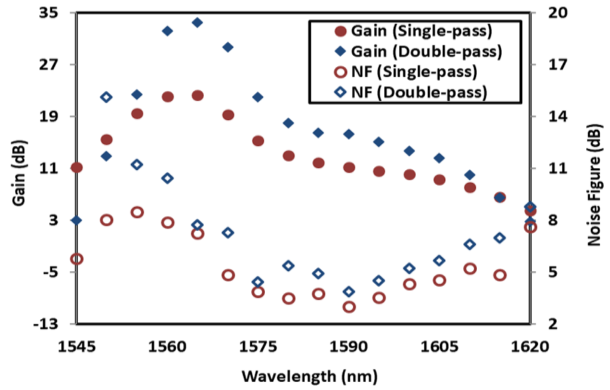


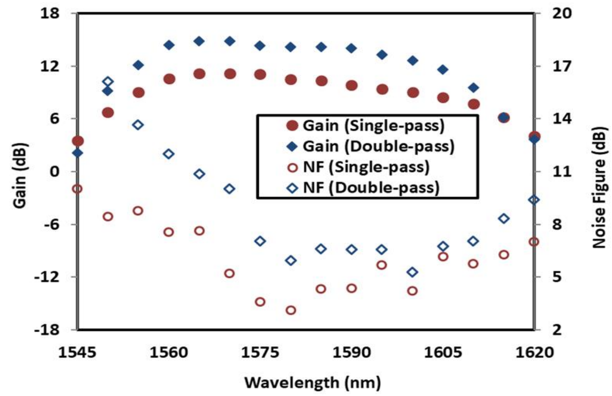
Fig. 3. Comparison of the ASE Spectrum of the single pass HB-EDFA at two different pumping wavelengths

Fig. 4 illustrates the comparison of gain and noise figure performances in single and double-pass HB-EDFA when the input signal powers were specified at -30 and -10 dBm. Since the ASE power level was higher within 1480 nm pump wavelength, this laser diode was used to pump the gain medium via WDM. In the experiment, the length of EDF and the pump power were fixed at 150 cm and 170 mW, respectively. At input signal of -30 dBm, the gain was higher in double-pass HB-EDFA as compared to that of single-pass as illustrated in Fig. 4 (a). For instance, the maximum gain of 22.2 dB and 33.4 dB were achieved at 1565 nm for single and double-pass configurations, respectively. This is attributed to doubly propagation of signal through the gain medium, which increased the population inversion resulting in a double increment of the gain. At input signal of -10 dBm as illustrated in Fig. 4(b), a higher flat gain of 14 dB was obtained with small gain fluctuation of 1 dB within wavelength region from 1560 to 1600 nm for double-pass HB-EDFA due to same reason above. On the other hand, the higher noise figure was obtained with double-pass HB-EDFA compared to that of single-pass due to the increased backward propagating ASE power at the input part of the amplifier, which reduces the population inversion.

Since the double-pass HB-EDFA provides a more efficient performance especially at L-band region, this performance was compared with the double-pass performance of another EDFA, which was obtained by using an enhanced Zr-EDF as a gain medium. The Zr-EDF has an erbium ion concentration of 4000 ppm and the optimal length for L-band amplification was 300 cm. In the experiment, the 1480 nm pump power and an input signal power were fixed at 170 mW and -10 dBm, respectively. As depicted in Fig. 5, the Zr-EDFA has relatively higher gain as compared to that of HB-EDFA over wavelength region from 1565 to 1610 nm. However, a shorter length of 150 cm was used for the proposed amplifier which is half of the Zr-EDF length due to high erbium ion concentration of the proposed fiber. As well, the HB-EDFA provided wider bandwidth amplification started from 1545 nm. The corresponding noise figure of the proposed HB-EDFA was lower as compared to that of Zr-EDFA.



(a)



(b)

Fig. 4. Gain and noise figure spectra in single and double-pass HB-EDFA at input signal power of (a) -30 dBm and (b) -10 dBm

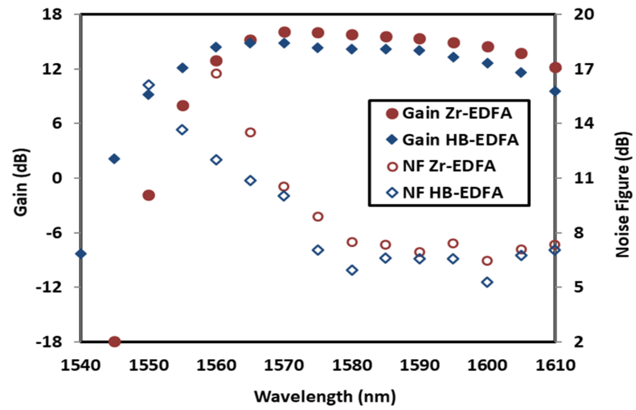


Fig. 5. Gain and noise figure comparison between HB-EDFA and Zr-EDFA in double-pass configuration at input signal power of -10 dBm

Since HB-EDFA provides a better result in terms of gain flatness especially at L-band region, this amplifier was merged with Bi-EDFA in parallel configuration to achieve a wideband amplification at C- and L-band regions. A 49 cm length of Bi-EDF and 150 cm length of HB-EDF were forward pumped by 1480 nm laser diode with the powers set at 90 and 170 mW for first and second stages, respectively. Fig. 6 illustrates the gain and noise figures of the proposed parallel amplifier for two input signal powers of -30 and -10 dBm. For input signal power of -30 dBm, a wideband amplification from 1535 to 1590 nm was demonstrated within gain verification from 13 to 27 dB. The gain was suddenly jumped to 27 dB at wavelength of 1560 nm due to the shift in the amplification medium from Bi-EDF to HB-EDF. At input signal power of -10 dB, a flat gain of about 14 dB was investigated with small gain fluctuation less than 1 dB over 70 nm wavelengths from 1535 to 1605 nm. As depicted from the figure, the corresponding noise figures were maintained below 13 dB over wideband region for both input signal powers.

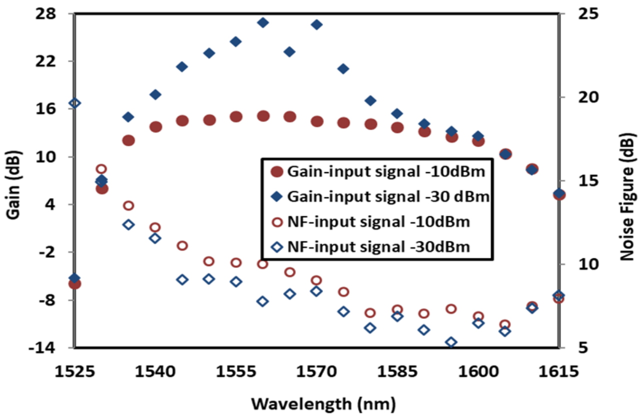


Fig. 6. Gain and noise figure characteristics for parallel amplifier using Bi-EDF and HB-EDF at two input signal powers of -30 and -10 dBm

Fig. 7 shows the gain and noise figure performances of the proposed amplifier at three different lengths of HB-EDF at 100, 150 and 200 cm for the L-band stage while Bi-EDF was fixed at 49 cm for the C-band stage. For input signal power of -10 dBm, the optimum length of HB-EDF was around 150 cm whereas the higher and flatter gain was observed within a wider wavelength region from 1535 nm to 1605 nm. At 100 cm length of HB-EDF, the gain spectrum was shifted to C-band region. For instance, the gain decreased from 14 dB to 11.4 dB at 1585 nm when the length changed from 150 to 100 cm, respectively. This is due to decrease in the number of erbium ions which decrease the population inversion and thus, decreases the gain for L-band. At 200 cm long HB-EDF, it is observed that the gain characteristic at the L-band region was relatively lower due to insufficient pump power to support population inversion with a longer gain medium. However, a flat gain of 6.3 dB was obtained within wavelength region from 1570 to 1610 nm for the amplifier with 200 cm gain medium. The gain spectrum of the C-band was unchanged due to fixed length of Bi-EDF. On the other hand, the highest noise figure was obtained at 200 cm which is attributed to the lower gain and higher (not fully bleached) loss characteristics associated with the shorter wavelength. However, the noise figure spectrum was maintained below 9 dB for the L-band operation with 150 cm HB-EDF

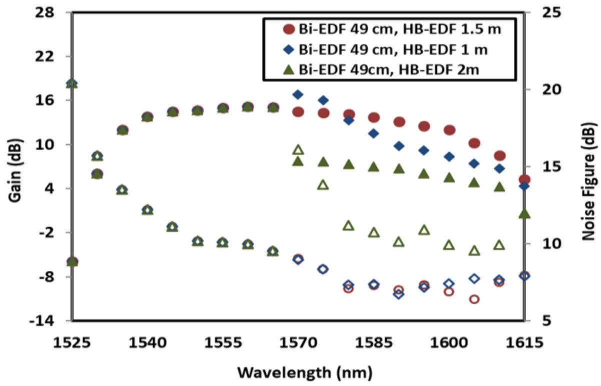


Fig. 7. Gain and noise figure performances of the parallel amplifier at different length of HB-EDF for L-band region at input signal power of -10 dBm

4. Conclusion

A compact L-band amplifier and flat gain characteristics were achieved using Hafnium-Bismuth erbium co-doped fiber (HB-EDF) as a gain medium in double-pass configuration within shorter length of 150 cm. As compared with the Zr-EDFA, the proposed amplifier provides a comparable performance but uses only about half of the Zr-EDF length. An efficient hybrid amplifier with wide-band and flat-gain characteristics was demonstrated using a combination of Bi-EDF and HB-EDF with total optimal length of 199 cm in double-pass parallel configuration. For input signal power of -30 dBm, a wideband amplification from 1535 to 1590 nm was demonstrated within gain verification from 13 to 27 dB. At input signal power of -10 dB, a flat gain of about 14 dB was obtained with gain fluctuation of less than 1 dB over 70 nm wavelength bandwidth from 1535 to 1605 nm. On the other hand, the corresponding noise figures were maintained below 13 dB over wideband region for both input signal powers.

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