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A Flat-Gain Double-Pass Amplifier with New Hafnia-Bismuth-Erbium Codoped Fiber

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An efficient and compact double-pass optical fiber amplifier is demonstrated using a newly developed hafnia bismuth erbium co-doped fiber (HBEDF) as a gain medium. The HBEDF is fabricated using a modified chemical vapor deposition in conjunction with solution doping. The fiber has an erbium ion concentration of 12500 ppm. At the optimum length of 0.5 m, the HBEDF amplifier (HBEDFA) achieves a flat gain of 26 dB with a gain variation of less than 1.5 dB within a wavelength region from 1530 to 1560 nm when the input signal and pump power are fixed at −30 dBm and 140 mW, respectively. On the other hand, at the input signal power of −10 dBm, the HBEDFA also achieves a flat gain of 14.2 dB with a gain variation of less than 2.5 dB within a wide wavelength region from 1525 to 1570 nm. Compared with the conventional zirconia erbium co-doped fiber based amplifier, the proposed HBEDFA obtains a more efficient gain and lower noise figure. For an input signal of −30 dBm, the gain improvements of 6.2 dB and 4.8 dB are obtained at 1525 nm and 1540 nm, respectively.

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Optical amplifiers are considered to be important devices in optical communication systems due to their ability in overcoming the problem of high signal attenuation. To cope with the heavy increase of communication traffic in the last few years, a great deal of research has been accomplished for developing optical fiber amplifiers that are highly efficient, compact and broadband.[1−3] Currently, the erbium-doped fiber amplifiers (EDFAs) are one kind of the most important optical amplifiers that are widely used in different kinds of fiber-optic communication systems. They use erbium ions as active rare-earth-doped materials and thus their operation is limited to a spectral region of 1530–1610 nm. To date, many research studies have been carried out on the development of compact optical amplifiers with high ion concentration in gain media to decrease the active fiber length. However, the high ion concentration of erbium may cause a pair induced quenching (PIQ) effect, which potentially minimizes the pump power conversion efficiency.[4]

Researchers have investigated EDFAs using different glass hosts, such as phosphate,[5,6] telluride[7] and bismuth[8] to shorten the length of the active fiber and to reduce the size and cost of the device. Recently, a zirconia erbium co-doped fiber (Zr-EDF) with an erbium ion concentration of more than 6000 ppm was also reported as an effective gain medium for realizing compact optical amplifier and laser devices.[9] The Zr-EDF is a new class of fibers, in which Zr, Y and Al ions are co-doped with Er ions in the active fiber for achieving a higher erbium ion concentration. Most recently, there has been interest in hafnia-bismuth co-doped silicate fibers that can be useful for near infra-red applications compared with a standard silica-based one.[10] The choice of a SiO_2-HfO_2 network of core-glass stems from the known fact that HfO_2 is a material with a high refractive index (RI), transparent over a wide wavelength range, 0.4–6.0 μm.[11] In this work, the performance of a new optical fiber amplifier based on a hafnia bismuth erbium co-doped fiber (HBEDF) is investigated and demonstrated. The fiber has a high erbium concentration. An efficient HBEDFA is obtained using the newly developed HBEDF as the gain medium in conjunction with the double-pass configuration.

The HBEDF was obtained from hafnium bismuth erbium co-doped yttria-alumina-silica glass based preform. The preform was fabricated through deposition of a porous silica layer at around 1500℃ by the modified chemical vapor deposition (MCVD) followed by the solution doping (SD). Suitable strength of $Al(NO_3)_3{\cdot}9H_2O$, $HfCl_3$, $Bi(NO_3)_3 \cdot xH_2O$, $Y(NO_3)_3{\cdot}6H_2O$ and $ErCl_3 \cdot xH_2O$ were used for soaking of the porous layer for a period of one hour in the SD process to incorporate all the co-dopants such as Al_2O_3, HfO_2, Bi_2O_3, Y_2O_3 and Er_2O_3. All the halide and nitrate salts are retained in the porous layer after draining out of the solution followed by air drying with the flow of N_2 gas at room temperature. Such salts were converted to their respective oxides through an oxidation process with a flow of O_2 gas at around 800–900℃ temperature. Sintering of the porous layer containing such oxides was carried out by gradually increasing temperature from 1300℃ to 1900℃ to form a

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transparent glass. The glass was converted to a solid preform by collapsing stages where it was over clad with a thick silica tube to reduce the core diameter. The final fiber was drawn from the over clad preform in a conventional way using a fiber drawing tower, at ∼2000℃.

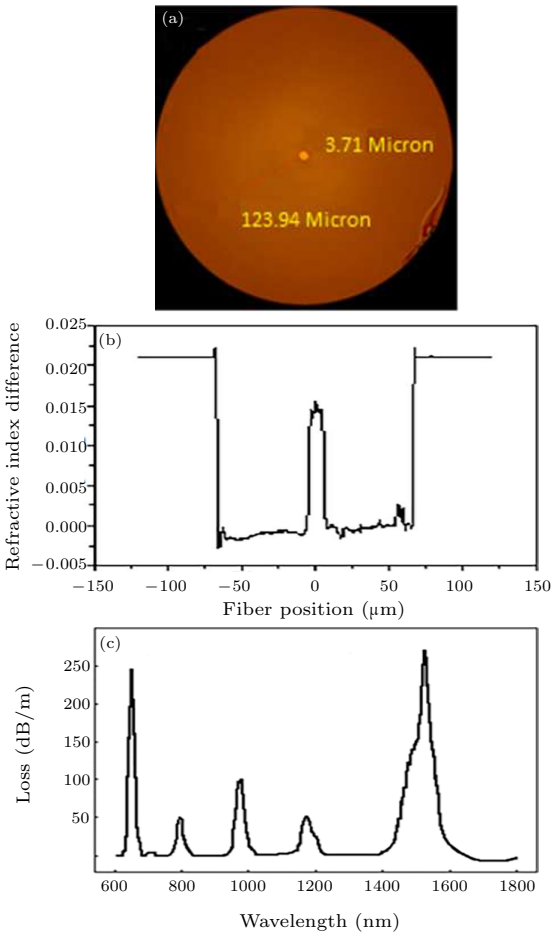

Fig. 1. HBEDF characteristics: (a) microscopic view, (b) refractive index profile, and (c) absorption loss curve.

The doping level within the core region of the fabricated fiber was measured by electron-probe microanalysis (EPMA). The EPMA measurement is very important for obtaining the elemental distribution along the diameter of core region, which signifies the uniformity of different dopants from the core-clad boundary to the center of the core region. The average dopant percentages in samples were measured by a JEOL EPMA machine. For this, around 12 mm of the fiber sample was ground and polished on both sides. Finally EPMA of the polished fiber was carried out with the maximum spatial resolution of 1 μm after applying a thin graphite coating layer. The spatial resolution of the analysis depends primarily on the required beam energy and properties of the specimen, but will typically be in the micron range. Quantitative analyses were automated to allow acquisition of profiles (e.g., chemical gradients or interface studies). Sensitivity is also variable with respect to major and minor elements (to 0.05 wt%). The EPMA data was taken with a spatial resolution of 1.0 μm. It is found that the fiber core glass contains 6.0 wt% Al_2O_3, 1.23 wt% Er_2O_3, 2.2 wt% HfO_2 and 0.035 wt% Bi_2O_3. The fiber cross sectional view is given in Fig. 1(a), which shows that the core and cladding diameters of the fiber are 3.71 and 123.94 μm, respectively. The RI profile of the fabricated fiber is shown in Fig. 1(b). Based on the RI profile, the numerical aperture is calculated to be 0.21. The spectral attenuation curve of the fiber is shown in Fig. 1(c). The absorption loss at 980 nm is found to be 100 dB/m, which is equivalent to 12500 ppm of Er_2O_3. The high erbium ions concentration is achieved due to the co-doping with hafnium (Hf) and bismuth (Bi) ions, which reduces the ions clustering effects.

The experimental setup of a typical double-pass optical amplifier is schematically illustrated in Fig. 2. The HBEDFA was constructed using a scheme with forward pumping. As a pumping source we used commercially available laser diodes with a maximum output power of 140 mW. The active HBEDF was core-pumped through a commercially available WDM. Optical circulators were spliced to the input and output of the amplifier. The first one was used to forward the input signal into the WDM and to route the twice amplified signal into the optical spectrum analyzer (OSA). The circulator also prevented any reverse direction of amplified spontaneous emission (ASE) from entering the input fiber to cause detrimental effects. The second one was used as a reflector to allow double propagation of the test signal in the gain medium. The amplified signal is reflected back into the gain medium via joining port 3 with port 1, thus the light from port 2 is routed back into the same port. The performance of the double-pass amplifier was investigated using a tunable laser source (TLS) in conjunction with an OSA. The programmable optical attenuator (POA) was used to obtain the accurate input signal power of the setup.

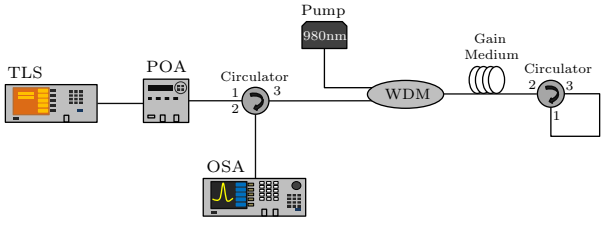

Fig. 2. Configuration of the double-pass HBEDFA.

Firstly, the amplified spontaneous emission (ASE) spectrum of the new HBEDF is investigated at three different doped fiber lengths, 0.2 m, 0.5 m and 1 m. The ASE spectra are shown in Fig. 3 when the pump power was fixed at 140 mW. It is shown that the ASE power is improved as the length is increased from 0.2 to 0.5 m, but is degraded as the fiber length is further increased to 1 m. At the 0.5-m-long HBEDF, the ASE generation is optimum where the 980 nm pump photons are fully absorbed to create a population inver-

sion, which then supports spontaneous and stimulated processes in the gain medium. At a longer length, the population inversion is dramatically decreased due to the saturation effect.

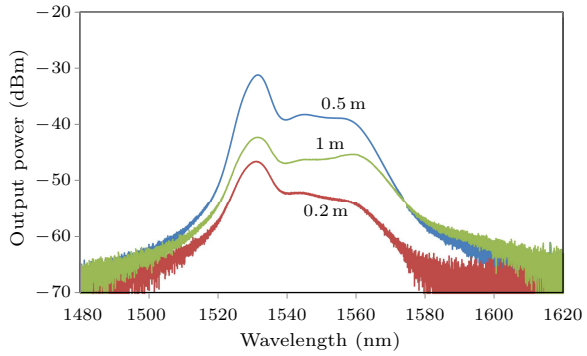

Fig. 3. ASE spectra from the double-pass HBEDFA under the pumping power of 140 mW.

Figures 4 and 5 represent the spectral dependences of the gain and the noise figure of the double-pass HBEDFA for the input signal powers of 30 dBm and 10 dBm. These dependences were obtained under the pumping power of 140 mW. At the input signal power of 30 dBm, it is found that the one of 0.5 m obtains the best amplification performance especially in the C-band region. At 0.5 m, a flat gain of 26 dB is obtained with the gain fluctuation of less than 1.5 dB within a wavelength region from 1530 to 1560 nm. The highest gain of 27.5 dB is obtained at a wavelength of 1530 nm. The noise figure is maintained below 6.7 dB within the flat-gain region.

In the experiment, it is obtained that the gain of the amplifier peaks at 1530 nm at both lengths of 0.5 and 0.2 m. However, at the 1-m-long HBEDF, the gain spectrum shifts to a longer wavelength of 1560 nm. This indicates that the optimum length of the amplifier operation in the C-band region is around 0.5 nm. As the length of the gain medium increases, the operating wavelength shifts to the L-band region due to a quasi-two level absorption effect. The shorter wavelength photons are absorbed to emit at longer wavelengths. Thus the overall gain spectrum is shifted from the C-band region to the L-band region.

At the input signal of 10 dBm, it is found that the highest gain spectrum is also obtained at 0.5 m length of HBEDF. At 0.5 m, a flat gain of 14.2 dB is obtained with the gain fluctuation of less than 2.5 dB within a wide wavelength region from 1525 to 1570 nm. The corresponding noise figure is maintained below 8 dB within the flat-gain region. Meanwhile, a flat gain of 11.1 dB with gain fluctuation of less than 1 dB is also achieved for the HBEDF length of 0.2 m within a wavelength region from 1525 to 1560 nm. At the 1-m-long HBEDF, the gain spectrum shifts to the L-band region but with lower values. This is attributed to insufficient pump power to support population inversion with a longer gain medium. Figure 6 summarizes the gain of the HBEDFA against the active fiber length when the input wavelength and pump power are fixed at 1540 nm and 140 mW, respectively. It clearly indicates that the optimum active fiber length is around 0.5 m.

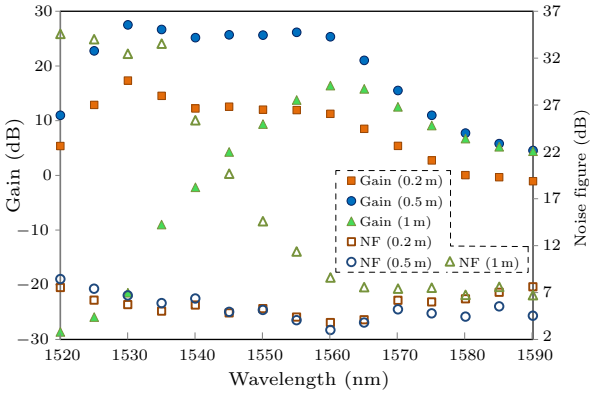

Fig. 4. Gain (solid symbol) and noise figure (hollow symbol) performance with various lengths of HBEDFs at the input signal power of 30 dBm and the pump power of 140 mW.

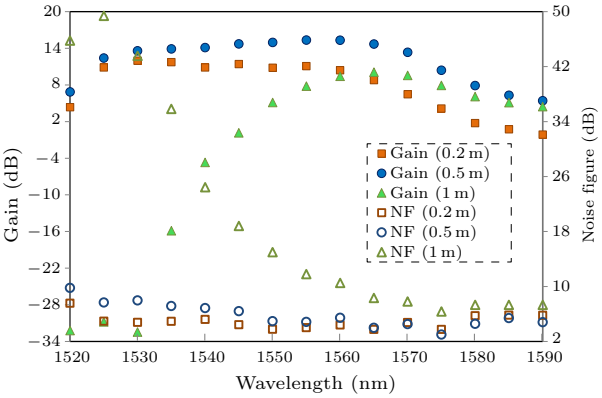

Fig. 5. Gain (solid symbol) and noise figure (hollow symbol) performance with various lengths of HBEDFs at the input signal power of 10 dBm and the pump power of 140 mW.

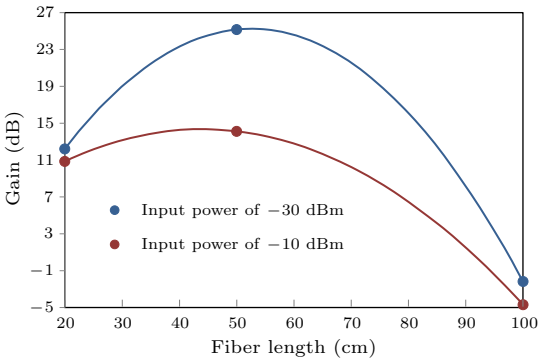

Fig. 6. The relation between the gain and the fiber length at 1540 nm wavelength and the pump power of 140 mW.

Finally, the performance of the new HBEDFA is compared with the conventional Zr-EDFA. The conventional Zr-EDF is obtained from a fiber perform, which is fabricated in a ternary class host, zirconia-yttria-aluminum co-doped silica fiber using

MCVD.[12,13] The Zr-EDF has an absorption loss of 80 dB/m at 980 nm, which translates to the erbium ion concentration of 4000 ppm. In this experiment, the doped fiber length is fixed at the optimum length of 0.5 m for both HBEDF and Zr-EDF. The comparison performances of both double-pass amplifiers are depicted in Fig. 7, as the input signal and the pump power are fixed at 30 dBm and 140 mW, respectively. As shown in the figure, the proposed HBEDFA achieves a higher gain at all wavelengths tested compared with Zr-EDFA. For instance, the gain enhancements of 6.2 dB and 4.8 dB are obtained with HBEDF at 1525 nm and 1540 nm, respectively. Furthermore, the new HBEDFA obtains a flatter gain compared with Zr-EDFA at the wavelength region from 1530 to 1560 nm. On the other hand, the noise figure is comparatively improved in the proposed HBEDF. This is due to the population inversion, which is higher in the new HBEDF. The noise figures are maintained below 7.7 dB and 13.6 dB at a flat gain region for the HfBiEDFA and Zr-EDFA, respectively.

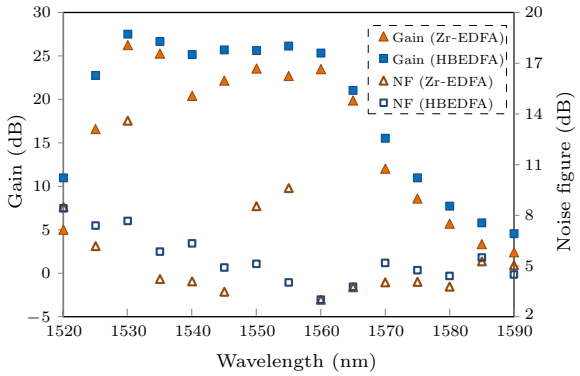

Fig. 7. Comparison of the gain (solid symbol) and noise figure (hollow symbol) performances between the HBEDFA and Zr-EDFA at an input signal power of 30 dBm and a pump power of 140 mW.

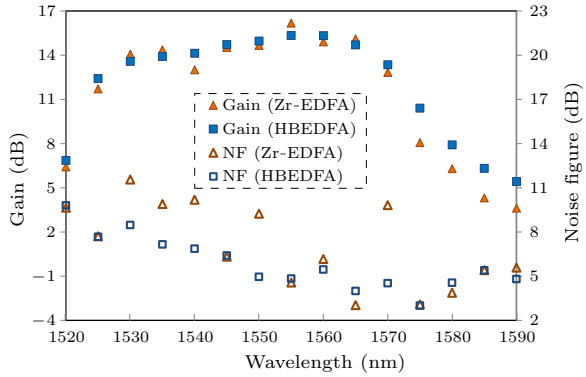

Fig. 8. Comparison of the gain (solid symbol) and noise figure (hollow symbol) performances between the HBEDFA and Zr-EDFA at an input signal power of 10 dBm and a pump power of 140 mW.

Figure 8 shows the gain and noise figure characteristics across the wavelength region from 1520 to 1620 nm for an input signal and a pump power of 10 dBm and 140 mW, respectively. It is observed that the gain is slightly flatter with HBEDFA compared with Zr-EDFA for the wavelength region from 1530 nm to 1570 nm. In addition, the gain is higher with the HBEDFA at the L-band region. This is due to the higher concentration ion erbium doping in the proposed HBEDF. Therefore, the number of excited ions to be stimulated is improved. The noise figures are maintained below 8.5 dB and 11.6 dB at a flat gain region for the HfBiEDFA and Zr-EDFA, respectively.

In conclusion, a compact optical amplifier with a flat-gain characteristic at the C-band region has been demonstrated using a new HBEDF as the gain medium. The HBEDF is obtained from hafnium bismuth erbium codoped yttria-alumina-silica glass based preform, which is fabricated through deposition of the porous silica layer by MCVD followed by the SD process. At the optimum length of 0.5 m, HBEDFA achieves a flat gain of 26 dB with a gain variation of less than 1.5 dB within a wavelength region from 1530 to 1560 nm when the input signal and pump power are fixed at 30 dBm of 140 mW, respectively. However, at the input signal power of 10 dBm, HBEDFA also achieves a flat gain of 14.2 dB with a gain variation of less than 2.5 dB within a wide wavelength region from 1525 to 1570 nm. Compared with the conventional Zr-EDFA, the proposed HBEDFA obtains a more efficient gain and lower noise figure. For an input signal of 30 dBm, the gain improvements of 6.2 dB and 4.8 dB are obtained at 1525 nm and 1540 nm, respectively.

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