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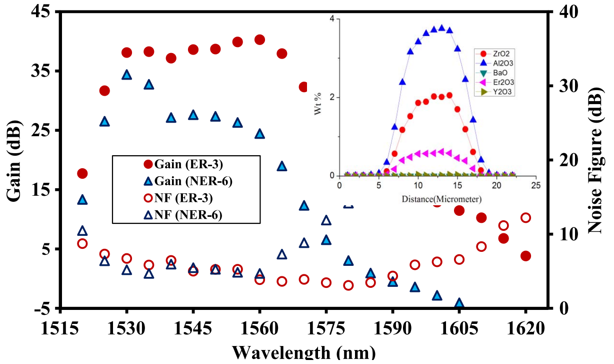

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Abstract: An efficient optical amplifier is demonstrated using an improved erbium–zirconia–yttria–aluminum co-doped fiber (Zr-EDF) as the gain medium. With a combination of both Zr and Al, we could achieve a high erbium doping concentration with an absorption loss of around 80.0 dB/m at 980 nm. The Zr-EDF is obtained from a fiber preform, which is fabricated in a ternary glass host, i.e., a zirconia–yttria–aluminum co-doped silica fiber, using a modified chemical vapor deposition, in conjunction with a solution doping process. At the optimum length of 1 m, the Zr-EDF amplifier produces a flat gain of 38 dB within a wavelength region between 1530 and 1565 nm with a gain variation of less than 3 dB when the input signal power and 980 nm pump power are fixed at -30 dBm and 130 mW, respectively. The highest gain of 40.3 dB is obtained at 1560 nm wavelength. Compared with the previous Zr-EDF amplifier, the proposed Zr-EDFA shows improved gain, particularly at longer wavelengths. The gain is enhanced by about 15.8 dB at a wavelength of 1560 nm for an input signal of -30 dBm.

Index Terms: Zirconia–yttria–aluminum co-doped fiber (Zr-EDF), erbium-doped fiber, wideband optical amplifier.

1. Introduction

The capacity of fiber optical communication systems has grown enormously during the last few years in response to huge capacity demand for data transmission. With the available wavelength division multiplexing (WDM) components, commercial systems transport more than 100 channels over a single fiber [1]. The systems can be upgraded many times without adding a new fiber, which makes it possible to build inexpensive WDM systems with much greater capacity [2]. Increasing the number of channels in such systems will eventually result in the usage of optical signal de-multiplexing components with a higher optical attenuation. Additionally, when transmitted over long distances, the optical signal is highly attenuated, and therefore, to restore the optical power budget, it is necessary to implement optical signal amplification. For an optical amplifier, preference is given to an erbium-doped fiber amplifier with a high and flat gain, broad bandwidth, and low noise figure [3], [4].

In our previous work, a wideband erbium-doped fiber amplifier (EDFA) is demonstrated using a new type of erbium-doped fiber (EDF), which is fabricated in a ternary glass host, zirconia–yttria–aluminum (Zr–Y–Al) co-doped silica fiber. With a combination of both Zr and Al, we could achieve a high erbium doping concentration of 2800 ppm in the glass host without any phase separations of rare-earths [5]. It is found that a zirconia co-doped EDFA (Zr-EDFA) can achieve a better flat-gain value and bandwidth, as well as lower noise figure than the conventional Bismuth-based EDFA [6]. In this paper, a new Zr-EDF with a higher erbium concentration is proposed and developed to improve the attainable gain and reduce the noise figure. An efficient Zr-EDFA with an improved gain is demonstrated using a new gain medium, in conjunction with a double-pass configuration.

2. Fabrication Procedure and Optical Characteristic of the New Zr-EDF

A new class of Zr–Y–Al co-doped EDF with a higher erbium ion concentration is developed in this study. At first, a Zr–Y–Al co-doped EDF preforms based on zirconia–yttria–alumina–phospho silica glass with a high doping level of ZrO_2 around 2 wt% is fabricated using the modified chemical vapour deposition (MCVD) process. The doping of Er_2O_3 into the zirconia–yttria–alumina–phospho silica based glass is done via solution doping process [7]. A small amount of Y_2O_3 and P_2O_5 is added at this stage to serve as a nucleating agent. This step is necessary to increase the phase separation for the generation of Er_2O_3 doped micro crystallites in the core matrix of optical fiber preform [6]–[8]. The glass formers incorporated by the MCVD process are SiO_2 and P_2O_5 along with the glass modifiers Al_2O_3, ZrO_2, Er_2O_3, and Y_2O_3, which are also incorporated by the solution doping technique using an alcoholic–water mixture of suitable strength (1:5) to form the complex molecules $ErCl_3 \cdot 6H_2O$, $AlCl_3 \cdot 6H_2O$, $YCl_3 \cdot 6H_2O$, and $ZrOCl_2\ 8H_2O$. The inclusion of the Y_2O_3 particulates into the host matrix also serves the additional purpose of slowing down or eliminating changes in the ZrO_2 crystal structure. This is a crucial factor in the fabrication process. Pure zirconium dioxide can exist in three distinct crystalline structures in a bulk glass matrix, depending on the temperature range.

At above 2350 °C, ZrO_2 behaves as a cubic structure, while at temperatures between 1170 °C and 2350 °C, it forms a tetragonal structure. Below 1170 °C, pure zirconium dioxide crystals exist as a mono-clinic structure. The problem posed by these different states is that the shift from the tetragonal to monoclinic structure is very fast and involves an increase in volume between 3 to 5%. This rapid increase results in a significant cracking in the developed fiber during the cooling process (observed primarily in the core region, as this is where the concentration of ZrO_2 crystallites is the highest) and destroys the mechanical properties of the fiber. Adding a minute amount of Y_2O_3, or other oxides such as MgO, CaO can slow down or stop the changes in the crystalline structure by preserving the mechanical strength and integrity of the fiber [5]. It can be seen that ZrO_2 crystallites are able to sustain their crystalline structures at a temperature used to collapse the silica rod and draw the fiber from the preform. This clearly confirms the existence of some ZrO_2 crystallites within the host matrix of the preform and, subsequently, the drawn fiber. After the fabrication of the preform by the MCVD process, it was annealed at 1100 °C for 3 hour in a closed furnace under heating and cooling rates of 20 °C/min to generate Er_2O_3-doped ZrO_2 rich nano-crystalline particles.

The fiber was drawn at around 2000 °C from the annealed preform and simultaneously coated with resin using fiber drawing tower. The nano-crystalline host of ZrO_2 was preserved in the silica glass matrix as confirmed by the transmission electron microscopy (TEM) analyses with energy dispersive X-ray analysis (EDX) spectra and electron diffraction patterns [8]. The average particle sizes were around 10–20 nm. The core and cladding geometry of the fiber was inspected by an optical microscope (Olympus BX51). The core was homogeneous and had no observable defects at the interface between the core and the silica cladding. The fiber cross-section view is

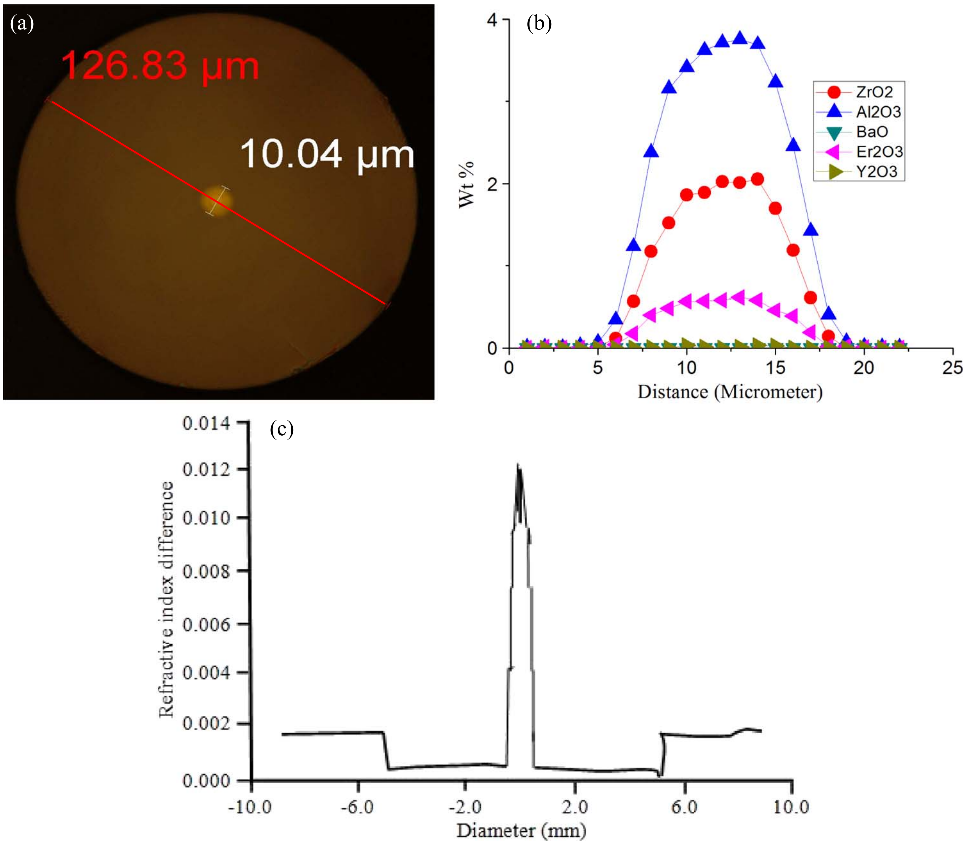

Fig. 1. (a) Cross-sectional view of the high ZrO_2 co-doped EDF. (b) Dopant distribution profile of the fiber. (c) Refractive index profile of the fiber preform.

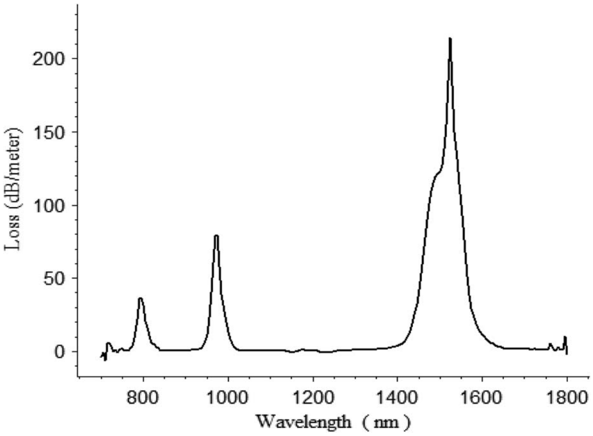

Fig. 2. Absorption loss curve of the enhanced Zr-EDF with high ZrO_2 co-doping.

given in Fig. 1(a), which shows the core and cladding diameters of the fiber at 10.04 μm and 126.83 μm, respectively. The average dopant distribution along the diameter of the core is shown in Fig. 1(b). The preform RI profile is shown in Fig. 1(c) as measured by a preform analyser. The spectral attenuation curve of the fiber is given in Fig. 2, and it shows 80.0 dB/m absorption loss at 980 nm wavelength. The fiber core contains SiO_2, Al_2O_3, Y_2O_3, ZrO_2, P_2O_5, and Er_2O_3 doping host. The fiber has a numerical aperture of 0.17.

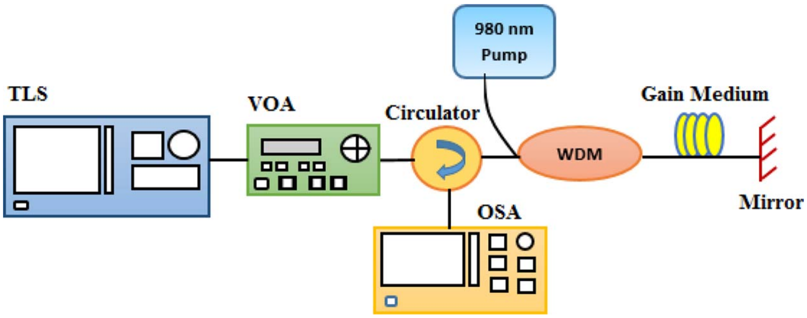

Fig. 3. Configuration experiment setup of double pass Zr-EDFA by using a broadband fiber mirror.

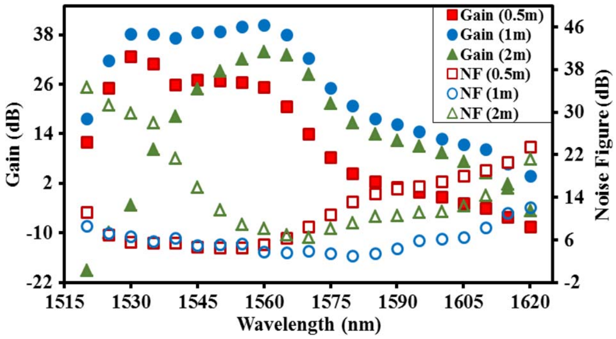

Fig. 4. Gain and noise figure spectrum with different lengths of the new Zr-EDFs when the input signal and pump powers are fixed at −30 dBm and 130 mW, respectively.

3. Experimental Setup

Fig. 3 shows the proposed double-pass EDFA using a short piece of the newly developed Zr–Y–Al based EDF as a gain medium with a broadband reflector. The EDF is forward pumped by a 980 nm laser diode via a 980/1550 nm WDM coupler. A broadband fiber mirror is used to route the forward amplified spontaneous emission (ASE) and the input signal back into the amplifier's system. An optical circulator is used to launch the input signal into the gain medium and route the amplified signal into the optical spectrum analyzer (OSA). The circulator prevents any reverse direction of ASE from entering the input fiber to cause detrimental effects. The performance of the proposed double-pass Zr-EDFA is characterized using a tunable laser source (TLS) in conjunction with an OSA. A variable optical attenuator (VOA) is used to control the input signal power into the optical amplifier.

4. Result and Discussion

At first, the gain and noise figures of the Zr-EDFA configured with the new EDF were investigated at different lengths of EDF. In the experiment the pump power was fixed at 130 mW, while the fiber length was varied from 0.5 to 2 m. The results are shown in Figs. 4 and 5 for input signal powers of −30 and −10 dBm, respectively. At input signal of −30 dBm, the gain improves, and its spectrum moves toward a longer wavelength region as the EDF fiber length is increased from 0.5 to 1 m. However, the gain reduces as the EDF is further increased to 2 m. Among the 3 different lengths of the fiber tested, it is found that 1 m gives the best amplification performance. At 1 m length, the EDFA operates in the C-band region with a flat gain of 38.0 ± 1.5 dB within a wavelength region between 1530 to 1565 nm. The highest gain of 40.3 dB is obtained at 1560 nm wavelength. The noise figure within the flat-gain region is lowest at 1 m at less than 6 dB. The noise starts to increase as the operating wavelength increases above 1570 nm. This is attributed to the amplifier's gain, which reduces at a longer wavelength.

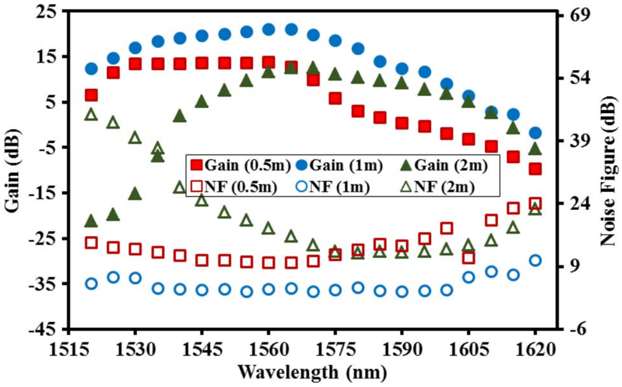

Fig. 5. Gain and noise figure spectra with different lengths of Zr-EDFs when the input signal and pump powers are fixed at −10 dBm and 130 mW, respectively.

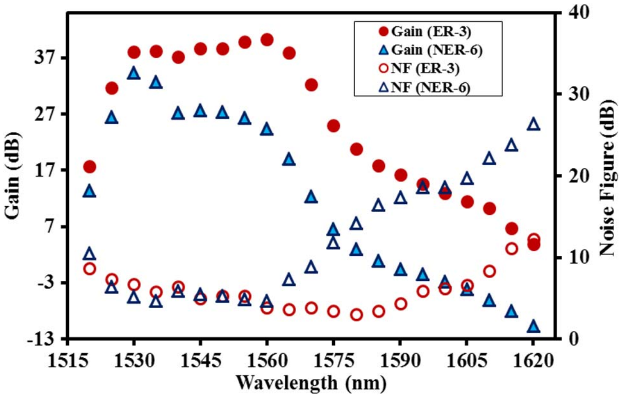

Fig. 6. Comparison of the gain and noise figure spectra between the new Zr-EDFA (with ER-3 fiber) and the previous Zr-EDFA (with NER-6 fiber) when the input signal and pump powers are fixed at −30 dBm and 130 mW, respectively.

At the input signal power of −10 dBm, the highest gain spectrum is also obtained at Zr-EDF length of 1 m. As shown in Fig. 5, the measured gain varies from 12.5 to 21.1 dB within the wavelength region from 1520 nm to 1580 nm, where the noise figure is maintained at below 9 dB. The highest gain of 21.1 dB is obtained at the input signal wavelength of 1560 nm. Besides that, the flat-gain operation at 13.5 dB is obtained at a shorter EDF length of 0.5 m with gain variation of less than 2 dB. Using a length of 2 m, the gain spectrum shifts to a longer wavelength but with a lower value compared to a shorter length. The gain reduction with a longer fiber is due to pump attenuation along the gain medium. Close to the end of the fiber there is loss instead of gain for the signal due to insufficient pump power to support population inversion. The reduced gain also increases the noise figure at a longer wavelength. The noise figure spectrum is relatively higher with 2 m long EDF. The red-shift in the operating wavelength of the EDFA with a longer EDF is attributed to a quasi-two level system effect in the gain medium which absorbs the shorter wavelength photons and emits at longer wavelengths.

The performance of the new Zr-EDFA is also compared with the conventional Zr-EDFA, which was obtained using a previous Zr-EDF with an absorption characteristic of 14.5 dB/m at 980 nm as the gain medium. Fig. 6 shows the measured gain and noise figure spectra of both amplifiers with the doped fiber length of 1 m, respectively, as the input signal and 980 nm pump power is set at −30 dBm and 130 mW, respectively. As shown in the figure, the gain of the proposed Zr-EDFA improves especially at a longer wavelength, as compared to that of the previous Zr-EDFA. For instance, the gain enhancement of about 15.8 dB is obtained at wavelength of

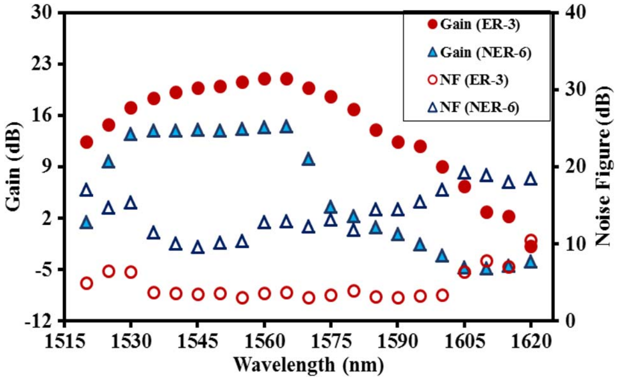

Fig. 7. Comparison of the gain and noise figure spectra between the new Zr-EDFA (with ER-3 fiber) and the previous Zr-EDFA (with NER-6 fiber) when the input signal and pump powers are fixed at −10 dBm and 130 mW, respectively.

1560 nm. This is attributed to the higher concentration of erbium ion doping in the new fiber and, thus, enhances the numbers of excited ions to be stimulated. Additionally, the higher erbium ion concentration increases the gain bandwidth of the amplifier to cover L-band region. Moreover, the proposed amplifier shows a reasonably low noise figures especially at L-band region. This is attributed to the majority of upper level ions that have been used for amplification and, thus, decreases the ASE, which in turn reduces the noise figure.

The gain and noise figure comparison between both fibers is also carried out at input signal power of −10 dBm, which shows a similar trend as depicted in Fig. 7. In the experiment, the pump power is fixed at 130 mW. The new Zr-EDFA shows a higher measured gain at all wavelength tested compared to the previous Zr-EDFA. For the new Zr-EDFA, the gain is maintained at above 12.5 dB within a wavelength region of 1520 nm to 1590 nm. The maximum gain of 21.1 dB is obtained at 1560 nm wavelength. For the previous Zr-EDFA with NER-6 fiber, a flat-gain of 14.1 dB is obtained within the wavelength region from 1530 nm to 1565 nm with a gain variation of less than 1 dB. On the other hand, the noise figure is significantly improved in the new Zr-EDFA compared to the previous amplifier. This is attributed to the population inversion, which is higher in the new fiber. The noise figure is maintained at a level below 6.5 dB within the wavelength region from 1520 nm to 1590 nm.

A wideband operation within 1520 to 1615 nm is observed as zirconium oxide has a stretching vibration at about 470 cm^{-1}, which is very low compared with that of Al_2O_3 (870 cm^{-1}) and SiO_2 (1100 cm^{-1}) [9]. In the proposed fiber, the particles possess lower phonon energy and thus reduce non-radiative decay, which in turn increase the emission cross section [8]. The introduction of Zr^{4+} in the fiber avoids the formation of Er^{3+} clusters in silica host and, consequently, increases the Er^{3+} ion density to make more intense luminescence [5]. By replacing the intermediate Al_2O_3 with the modifier ZrO_2, the number of non-bridging oxygen is expected to increase, which makes the silica network structure more open. As the result, Zr-EDF has wider emission spectra as compared to silica-EDF, especially at longer wavelengths around 1620 nm because of its larger emission cross-section [6]. The widening of the ASE spectra towards a longer wavelength is believed to be the result of the Stark level of the Er^{3+} ions in the Zr-EDF, which has a larger separation due to the intense ligand field. This is due to the inhomogeneous energy level splitting that the ligand field of the zirconia host glass induces as a result of site-to-site variations, also known as the Stark effect, causing the widened optical transitions.

5. Conclusion

A new Zr-EDFA with improved gain and noise figure characteristics is successfully demonstrated using a newly developed Zr-EDF as the gain medium. The Zr-EDF is obtained from a fiber preform, which is fabricated in a ternary glass host, zirconia–yttria–aluminum co-doped silica fiber using a MCVD in conjunction with solution doping process. The fiber consists of Er_2O_3-doped ZrO_2 rich nano-crystalline particles and thus it has a high erbium doping concentration with absorption loss of around 80.0 dB/m at 980 nm. At the optimum length of 1 m, the Zr-EDFA produces a flat-gain of 38 dB within a wavelength region between 1530 to 1565 nm with gain fluctuation of less than 3 dB when input signal power and 980 nm pump power are fixed at -30 dBm and 130 mW, respectively. Compared with the previous Zr-EDF amplifier, the gain of the proposed Zr-EDFA improves, especially at a longer wavelength region. The gain enhancement of about 15.8 dB is obtained at wavelength of 1560 nm for -30 dBm input signal.

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