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50 cm of Zirconia, Bismuth and Silica Erbium-doped Fibers for Double-pass Amplification with a Broadband Mirror

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Erbium-doped fiber amplifiers (EDFAs) have saturated the technological market but are still widely used in high-speed and long-distance communication systems. To overcome EDFA saturation and limitations, its erbium-doped fiber is co-doped with other materials such as zirconia and bismuth. This article demonstrates and compares the performance using three different fibers as the gain medium for zirconia-erbium-doped fibers (Zr-EDF), bismuth-erbium-doped fibers (Bi-EDF), and commercial silica-erbium-doped fibers (Si- EDF). The optical amplifier was configured with a double-pass amplification system, with a broadband mirror at the end of its configuration to allow double-pass operation in the system. The important parameters in amplifiers such as optical properties, optical amplification and noise values were also examined and discussed. All three fibers were 0.5 m long and entered with different input signals: 30 dBm for low input and 10 dBm for high input. Zr-EDF turned out to be the most relevant optical amplifier as it had the highest optical gain, longest transmission distance, highest average flatness gain with minimal jitter, and relevant noise figures suitable for the latest communication technology.

Keywords : Bismuth fiber, Erbium doped fiber amplifier, Optical amplifier, Zirconia fiber
OCIS codes : (060.2320) Fiber optics amplifiers and oscillators; (060.2410) Fibers, erbium; (140.4480) Optical amplifiers

I. INTRODUCTION

The rapidly growing Internet traffic has dominated daily life in global communication and has therefore become indispensable for everyday life. With the use of fiber-to-the-home installations it has been proven that optical communication systems are able to support high data rates, including a transmission bandwidth that can carry trillions of information bits [1]. The fiber amplifier is a powerful piece of advanced communication technology and is based on wavelength division multiplexing (WDM). It is able to extend transmission distances to more than a thousand kilometres without the need for restoration or external devices such as repeaters. In fact, repeaters suffer more losses because they require information to be converted into electrical signals first before being regenerated by a transmitter.

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Rare-earth elements such as erbium (Er^{3+}), praseodymium (Pr^{3+}), ytterbium (Yb^{3+}), terbium (Te^{3+}), and thulium (Tm^{3+}) are doped into silica-based fibers to realise a gain medium for optical fiber amplifiers [2–5]. Rare-earth-doped fiber amplifiers are operated like a laser diode, without feedback, and with their amplified signal. The most popular doped fiber amplifier is the erbium-doped fiber amplifier (EDFA), in which the erbium ion emission falls within 1550 nm of the third communication window with the minimal loss of the device [6].

In addition, EDFA is well established, reliable, inexpensive and produces a high optical gain up of to 40 dB, has a minimal noise figure (NF); does not tolerate loss of coupling to the network fibers; is flexible enough to be used with fiber optic devices and telecommunications links; and offers polarization-insensitive amplification [7]. However, due to the demand for compact devices, many processes these rare earth materials by mixing them with other elements to shorten and improve the mean efficiency.

Therefore, in order to improve amplifier performance, extensive research has been carried out on EDFAs using various types of host and co-dopant materials such as bismuth, zirconia, phosphate, thulium, and aluminium [8]. The EDFA is characterized by its optical gain and NFs. The term gain is used broadly to describe the gain in optical amplifiers. Gain (G) is also known as the gain factor, measured in decibels and can be easily calculated as follows:

$$G\ (\mathrm{dB}) = 10 \log_{10} (P_{out}/P_{in}). \qquad (1)$$

P_{in} and P_{out} are the input and output powers of the continuous-wave (CW) signal being amplified [7, 8]. Additionally, the noise figure is another crucial parameter that contributes to the amplifier performance. An amplifier's NF comes from the amplitude spontaneous emission (ASE) noise that originates from the combination of the needed coherent signals with unwanted incoherent ASE signals, when a gain medium of fiber is pumped by laser diodes.

Large NF will cause to a small optical signal-to-noise ratio (OSNR) for the amplifier to reaching the needed signal owing to the spontaneous emissions that grow the noise during the amplification process. The NF also uses the same unit as optical gain, decibels (dB), and is calculated via

$$NF = OSNR_{in} / OSNR_{out}. \qquad (2)$$

A large population inversion can reduce the amount of ASE noise by operating in a deep saturation region, using many amplifiers, and placing isolators and bandpass filters between amplifier stages [7, 8]. For this paper, three types of fibers for gain mediums were compared for optical gain and NF to determine the performance of the EDFA. The study used zirconia-erbium-doped fiber (Zr-EDF), bismuthate-erbium-doped fiber (Bi-EDF) and a sole erbium element of silica-based, erbium-doped fiber (Si-EDF) that acted as gain mediums to perform the optical fiber amplification.

Si-EDF, also known as erbium-doped fiber (EDF), has been a commercial and matured fiber for many applications over the years [9, 10]. Meanwhile, the most recent Bi-EDF were bismuth-germanosilicate fiber and bismuth-hafnia silicate fibers [11, 12]. With the bismuth-germanosilicate fiber, an optical gain of 40 dB was successfully achieved, but no result of the flatness enhancement was observed. Nevertheless, a broadband transmission wavelength of 1515 to 1775 nm is accomplished, defined from the C to L to the U band range telecommunication network [11]. Bismuth-hafnia silicate fibers achieved a flatness gain of 10.9 dB with a maximum gain of 20.9 dB from 1520–1580 nm region [12]. Both experiments using 50 m fiber length as the gain medium.

In the meantime, with a 1 m long Zr-EDF as a gain medium, a flatness gain and a maximum optical gain of 19.5 dB and 40 dB from 1530 to 1570 nm have been accomplished [13]. Then with a longer Zr-EDF of 4 and 6 m in length, flatness gain of 15.9 dB and 9.9 dB, respectively, were achieved [14]. The goal of EDF is to composite with other materials like zirconia and bismuthate is to exceed the limit of EDF due to the deterrent effect of the erbium itself [15]. Thus, in this experimental configuration, only 50 cm is used to perform an amplifier for compact device purposes.

II. METHODS

Figure 1 shows the experimental configuration for an optical double pass amplifier using a broadband mirror. All three fibers of Zr-EDF, Bi-EDF and Si-EDF were used in the same experimental configuration and replaced in each experiment. The fibers were made as short as 50 cm to be compatible with future compact devices. The gain medium was pumped forward though a 980 nm laser diode via a 980/1550 nm wavelength division multiplex coupler which applied optical energy to the fibers to stimulate electrons into excited bands.

A tunable laser source was used to provide accurate input signals in conjunction with an optical attenuator for each wavelength from 1515 nm to 1620 nm. The performance of the amplifier was examined for two input signals: −30 dBm for low input signals and −10 dBm for high input signals. A circulator is used to launch the input signal from tunable laser source (port 1) into the gain medium (port 2) and route the amplified signal back into the optical spectrum analyzer for measurement (port 3). The broadband mirror was placed at the end of the configuration to allow reflection of the desired signal back to the configuration and create the double pass amplifier operation. Finally, the results of the optical amplification and the NF were recorded by an optical spectrum analyzer.

III. FIBER SPECIFICATIONS

A detailed fabrication process for the homemade Zr-EDF and Bi-EDF was published in our previous paper [16, 17]. The Zr-EDF was obtained from a fiber preform, which was fabricated in a ternary silica glass host consisting of Er_2O_3-doped ZrO^2 rich nano-crystalline particles, using a modified chemical vapour deposition (MCVD) in conjunction with a solution doping process. The same MCVD process was used to fabricate Bi-EDF, where the fiber consisted of Er^{3+} ions at a concentration of 7.6×10^{25} ions/m^3, with a lanthanum ion co-dopant concentration of approximately 4.4 wt%.

Table 1 presents the optical properties specifications for the three gain mediums of Zr-EDF, Bi-EDF and Si-EDF. For the first specification, Bi-EDF showed the highest erbium-doped concentration at 6300 ppm, followed by Zr-EDF and Si-EDF with 4000 ppm and 2200 ppm, respectively. For the absorption rates, Bi-EDF showed the highest rate, with 141 dB/m at a 1480 nm wavelength, followed by Zr-EDF with 80 dB/m and Si-EDF with 23.0 dB/m at a 980 nm region.

The reason for doping EDF with other elements, such as transition metals from zirconia ions and post-transition metals from bismuth ions, is to reduce the harmful effects of erbium concentrations [2, 7]. Such effects occur when a single erbium element used in silica fibers acts to limit concentration doping and obtain optical amplification. Therefore, Zr-EDF and Bi-EDF showed higher results for erbium-doped concentration and absorption rates compared to Si-EDF, in which had no other element doping in its fiber.

For the index of refraction, all the three gain mediums shared an almost equal difference of 0.01. The refractive index is expressed as the ratio of the speed of light in a vacuum to another substance [18]. Normal fibers have a standard index of refraction of 1.55, which means that light travels 1.55 times faster in a vacuum than within the fiber. Thus, all the three gain mediums showed very small differences, only 0.01 from the standard value. This shows that they have roughly the same speed of light in their fibers.

NA is the acceptance angle of the fiber, which refers to the maximum angle in the core of the fiber that is required for light to propagate [18]. By measuring the collected light in the fibers, it was shown that the larger NA of Bi-EDF demonstrated the larger amount of light accepted compared to Zr-EDF and Si-EDF.

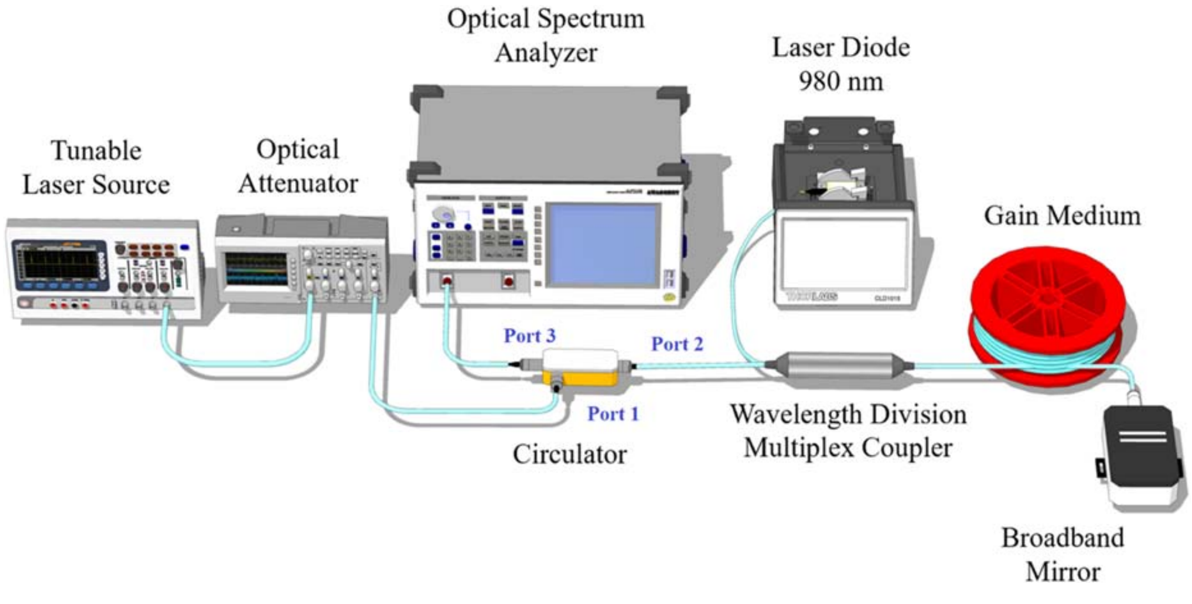


FIG. 1. Experimental configuration for the proposed double pass using a broadband mirror.

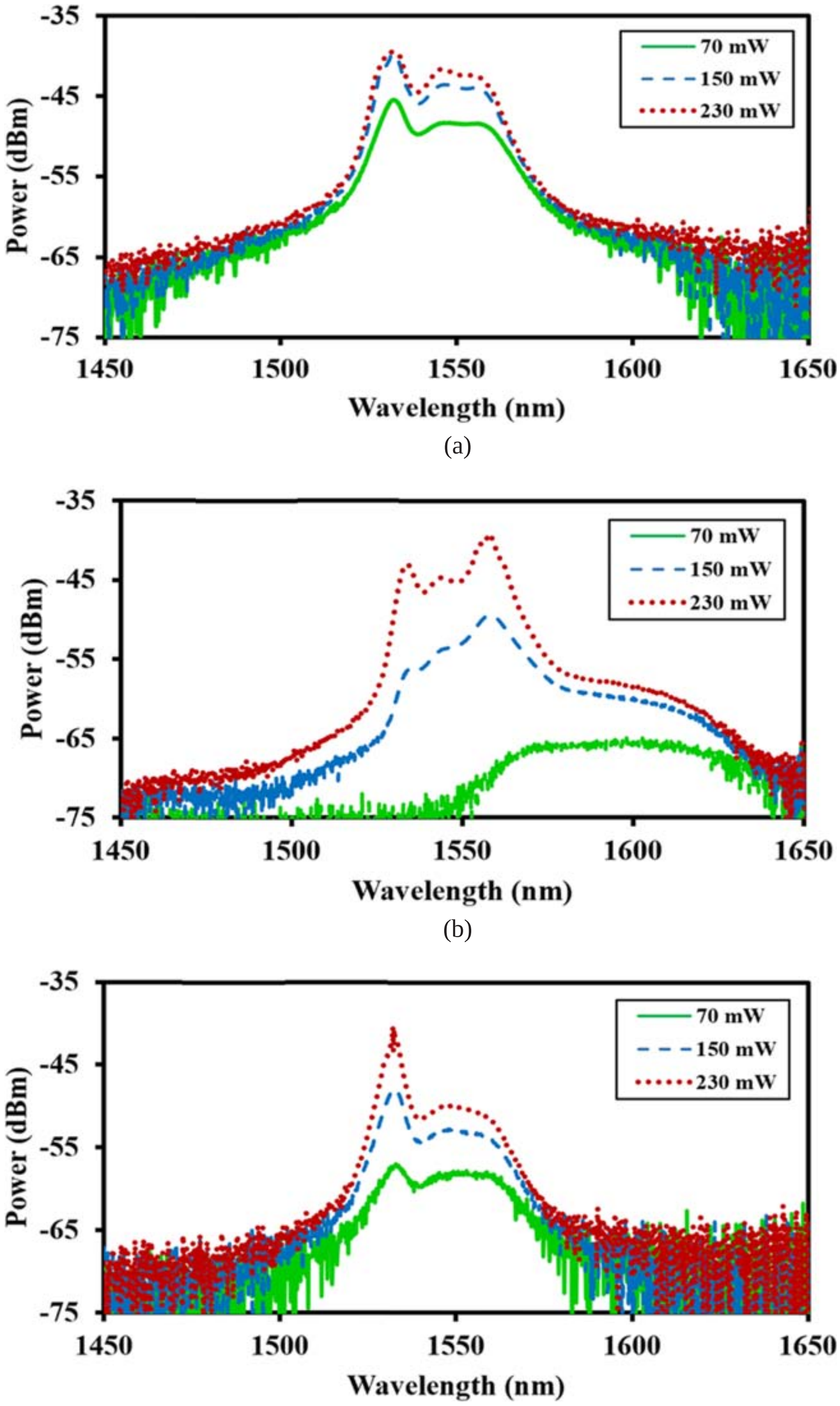
TABLE 1. Optical properties specifications for Zr-EDF, Bi-EDF and Si-EDF

Types	Zr-EDF	Bi-EDF	Si-EDF
Erbium-Doped Concentration (ppm)	4000	6300	2200
Absorption Rate	80.0 dB/m at 980 nm	141 dB/m at 1480 nm	23.0 dB/m at 980 nm
	220.0 dB/m at 1550 nm		40.0 dB/m at 1530 nm
Refractive Index Difference	0.012	0.01	0.01
Numerical Aperture (NA)	0.17	0.2	0.17

IV. RESULTS AND DISCUSSION

Figure 2 is an optical spectrum for Zr-EDF, Bi-EDF and Si-EDF at three different pump powers of 70 mW, 150 mW and 230 mW. The reason the pumping power stopped at 230 mW is because this was the surge line and there were no changes to further improve most of the spectra. The Zr-EDF and Bi-EDF fibers achieved almost the same peak pumping power of −37 dBm, while Si-EDF stopped at −39 dBm pumping power. For broadband transmission, Zr-EDF showed the broadest transmission wavelength from 1520 nm to 1580 nm with a total distance of 60 nm.

Meanwhile, the total distance for Si-EDF was 50 nm from 1520 nm to 1570 nm and Bi-EDF was only 40 nm from 1540 nm up to 1580 nm. The reason for the large transmission capacity of Zr-EDF was the high concentra-



(a)

(b)

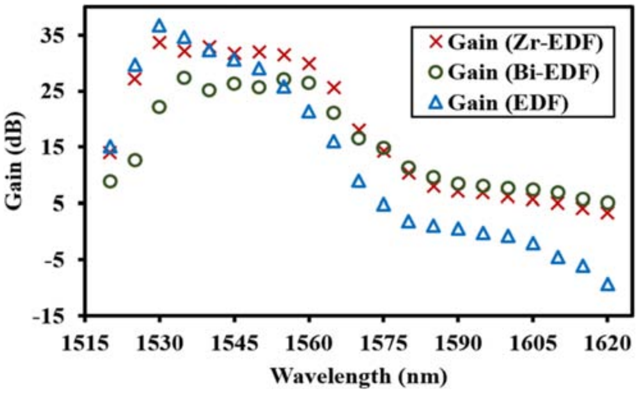
(c)

FIG. 2. Optical spectrum: (a) Zr-EDF, (b) Bi-EDF, and (c) Si-EDF.

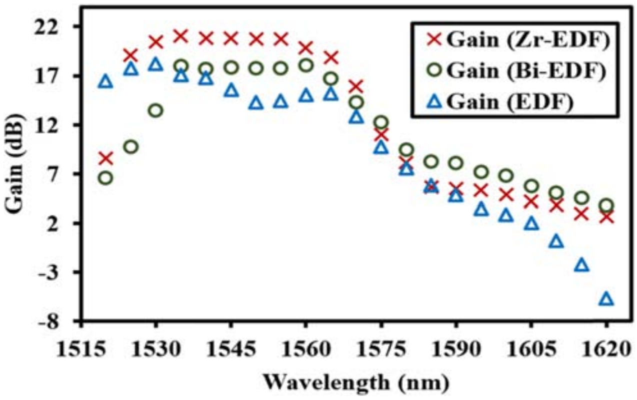
tion of EDFs. In addition, the pump power was set to 980 nm, which was close to the absorption wavelength of Zr-EDF and Si-EDF.

50 cm of gain medium was utilised for the experimental configuration which is designated at future compact device applications for the three fibers of Zr-EDF, Bi-EDF and Si-EDF. Two different input pump power of −30 dBm and −10 dBm signals were investigated for two important parameters of optical gain and NF. In fiber communications and fiber laser technology, an optical gain is a crucial parameter used to define the efficiency of transmission amplification, which is generated from a stimulated emission process.

Figure 3 shows an optical gain spectrum with different input signals: (a) −30 dBm for low input signals, and (b) −10 dBm for high input signals. The gain analysis consisted of Zr-EDF, Bi-EDF and Si-EDF versus wavelengths from 1520 nm to 1620 nm. At input signal −30 dBm, all three optical gains illustrated the same trendline, where it increased at the C-band wavelength of 1520 nm and decreased slowly at the L-band wavelength of 1565 nm. Then, Zr-EDF obtained the highest peak optical gain with 34 dB at 1530 nm wavelength, followed by Si-EDF with 31 dB at 1530 nm wavelength and Bi-EDF with 27 dB at 1555 nm wavelength. The average optical gain for Zr-EDF, Bi-EDF and Si-EDF were 26 dB, 20 dB and 22 dB, respectively, from the 1520 nm to 1580 nm wavelength region. The reason is due to the higher erbium doping concentration in the Zr-EDF, which consequently enhanced the number of excited ions able to be stimulated compared to the other fibers [2, 13]. Additionally, the massive amount of erbium ion concentrate increased the gain bandwidth of the amplifier to the L-band range.



(a)



(b)

FIG. 3. Optical gain spectrum at different input signals: (a) −30 dBm and (b) −10 dBm.

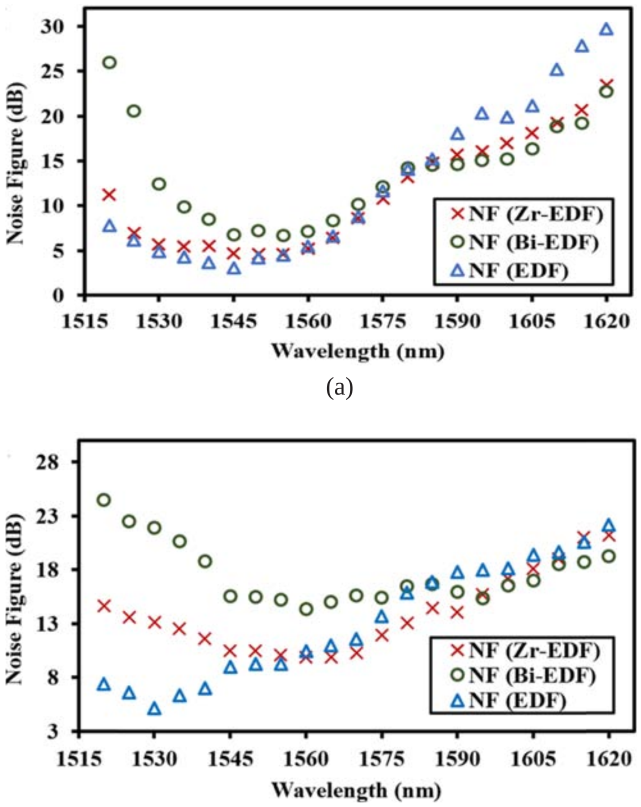
When the input signal was increased to −10 dBm, a flatness gain for all the optical gains was developed. Flatness gain is important for long-haul communication systems. A fluctuation of optical gain will cause losses in a single amplifier [18]. Therefore, long distance communication, which require many amplifiers, will cause large amounts of total loss to be sustained from the accumulated loss of each amplifier. This will affect the stability and efficiency of the long-haul communication network.

As a comparison, all flatness gains for each of the fibers were standardised for the 45 nm distance. From 1525 nm to 1570 nm, Zr-EDF produced the highest flatness gain of 20 dB, with low fluctuations of 2.4 dB. Then, Bi-EDF’s flatness gain was at 16.4 dB from 1530 nm to 1575 nm, with high fluctuations of 5.0 dB produced. Finally, Si-EDF performed similarly to Bi-EDF, at 16.1 dB from 1520 nm to 1565 nm, but struggled more with fluctuations than both Zr-EDF and Bi-EDF at 2.0 dB. The high and wide flatness gain of Zr-EDF was due to the efficient population inversion of the pump power of −10 dBm.

Figure 4 shows the NFs for the three fibers with different input signals, 4(a) −30 dBm and 4(b) −10 dBm. The NFs, or better known as losses, increased due to the ASE noise generated at the desired optical gains during the amplification process. These NFs influenced the value of the OSNR of the optical amplifier, which defined its stability according to the amplifier power. At the input signal of −30 dBm, Zr-EDF showed the lowest average NF of 11.3 dB, followed by Si-EDF and Bi-EDF with 13 dB and 14 dB, respectively. With an input signal of −10 dBm, the average NF for Zr-EDF and Si-EDF was 13 dB, but Bi-EDF produced an even larger NF of 18 dB.

The proposed fiber amplifier showed a reasonably low NF comparatively, especially at the C-band region, for the three fiber amplifiers, especially Zr-EDF. This is attributed to the majority of upper-level ions that had been used for amplification, which decreased the ASE noise, thus reducing the NF in the amplifier’s system.

However, Bi-EDF showed difficulties in suppressing NF, although it has a higher amount of erbium doping compared to Zr-EDF. Bi-EDF’s large NA created difficulties in compatibility with other single mode fibers and other photonic devices that used a standard fusion splicer (Corning® HI980; Corning, NY, USA) [19]. That being said, the results of Bi-EDF would cause high losses due to inconsistency in splicing between these fibers. However, the Bi-EDF can still achieve excellent optical gain even though its laser pumping range is not close to its absorption rate. The



(a)

(b)

FIG. 4. NFs at different input signals: (a) −30 dBm and (b) −10 dBm.

results would have been different if a 1480 nm laser pump had been used for this experiment, but we were limited by the laser diode limitation. Moreover, Almukhtar *et al*. [20], demonstrated a Zr-EDF amplifier using 1480 nm laser pump and achieved a flat gain and low NF from the C to L band regions.

V. CONCLUSION

All three fiber performances in the amplifier, using Zr-EDF, Bi-EDF and Si-EDF, were demonstrated and discussed in terms of optical specification, optical spectrum, optical gain and NFs at various input signals of −30 dBm and −10 dBm. From all the three fibers, Zr-EDF turned out to be the most relevant optical amplifier with the highest optical gain of 37 dB, the widest transmission distance at 60 nm from 1520 nm to 1580 nm, highest average flatness gain of 20 dB with low fluctuation of 2.4 dB, and the most relevant NF which is suitable for advanced communications nowadays.

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