Study on bismuth-based erbium-doped fiber for optical amplification

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Bismuth-based EDF (Bi-EDF) is comprehensively studied as an alternative medium for optical amplification. The bismuth glass host provides the opportunity to be doped heavily with erbium ions to allow a compact high-power system design. The proposed methods have resulted in an increase of useable gain bandwidth and output power with minimal noise figure. The gain spectrum of the Bi-EDF amplifier has a measured amplification bandwidth of 80 nm with a quantum conversion efficiency of 20% obtained using 1480 nm pumping. This glass host will find more ample applications in the expansion of Dense Wavelength Division Multiplexing (DWDM) accommodating more channels in support of ever-increasing data traffic.

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1. Introduction

Erbium Doped Fibre Amplifiers (EDFAs) are a key enabling technology for the deployment of long-haul optical communications networks. EDFAs are a widely popular choice as amplifiers in optical networks as they do not require converting the optical signal to an electronic signal before amplification. It also has the advantage of an all-optical fibre system for easier connections to the optical network. Furthermore, optical amplifiers can amplify multiple signals simultaneously unlike electronic regenerators, thus allowing for the deployment of Dense Wavelength Division Multiplexed (DWDM) technology. These factors make the EDFA a practical solution in optical network amplification and thus allowing for the deployment of commercially viable long-haul optical links.

Typically, Conventional (C-) and Long-Wavelength (L-) Band optical amplification can be achieved using Erbium as the active gain medium in a silica-glass host. Silica-glass was the chosen host for the EDFA as it had many advantages such as being easy to splice to conventional silica-glass transmission fibres and also being significantly easier to fabricate compared to other exotic host materials such as phosphorous [1] and telluride [2] based glasses. However, the use of the silica-glass host infers a limitation on the highest dopant concentration that the host can sustain, with a maximum reported dopant concentration of only 2.0×10^{25} ions/m^3 [3]. This limits the performance of the EDFA in terms of power output, which largely depends on the dopant concentration. This can be achieved by increasing EDF length but this no longer allows the design of a compact device. This limitation arises as the rare earth concentration in the silica-glass host increases the ion distribution and distance is reduced due to residual interactions such as ion clustering [3] and local charge compensation [4]. This in turn leads to detrimental effects such as the reduction of fluorescence bandwidth and lifetime known as concentration quenching [3, 4, 5] and this effect are especially profound in Si-EDFAs.

As the concentration limit is an inherent characteristic of the silica-glass host, other methods must be found to increase the doping concentration of the erbium ions so as to be able to produce shorter EDFAs length. Co-doping erbium ions with ytterbium ions have been able to increase the gain of the Si-EDFA [6], while other hosts such as phosphate, fluorophosphates, fluoride and tellurite [1,2,3] glasses have also been considered. However, the use of these hosts is not practical as they are difficult to fabricate and cannot be easily spliced with the silica-based transmission fibres already in use. Recently however, Bismuth glass-based hosts have shown increasing potential for use in highly doped EDFA applications due to their ability to accommodate more erbium ions in the glass matrix while at the same time having good broadband properties (i.e. broader flat gain amplification region) [7] as well as being relatively easy to splice to currently used silica and bismuth glass transmission fibres. Other works such as Hayashi et. al. [8] has also reported Bismuth-based wide-band amplifiers with cascaded configurations with a Power Conversion Efficiency (PCE) of about 19% or a Quantum Conversion Efficiency (QCE) of about 20%. For high-dopant EDFs, Bismuth-based glass hosts have an advantage compared to other host materials such as phosphate, tellurite in terms of easier fabrication, thus making them a more commercially viable option for high gain and compact optical amplifiers. Furthermore, this Bismuth-based glass has high thermal and chemical stability, which can make it a suitable option for applications in long-haul transoceanic links.

In this paper we report a comprehensive study on Bismuth-based EDFs (Bi-EDFs) as an alternative medium of optical amplification. The optical performance of the Bi-EDF amplifier (Bi-EDFA) is characterized and compared with that of Si-EDFA. Furthermore, the material analysis using Energy Dispersive X-Ray Spectroscopy (EDX) is also described. This analysis was performed as currently there is no information available on the Bi-EDFA composition manufactured by Asahi Glass Co. Ltd. The efficiency of the amplifier measured under a bi-directional 1480 nm pumping configuration is also investigated to determine the efficiency of the pump to signal photon conversion.

2. Experiment

The experimental setup for the Bi-EDFA characterisation is given in Fig. 1. In this experiment, the Bi-EDFA is characterised for its luminescence and its lifetime. Then, the performance of the Bi-EDFA is characterised for its gain and noise figure. As shown in the figure, the active medium is bi-directionally pumped by a 1480nm laser diode with total power of 288mW. Wavelength selective coupler (WSC) is used to combine the pump light and 1550nm signal. Optical isolators (FI) are used to ensure the unidirectional operation of the amplifier. The Bi-EDF used in this experiment is commercially available from Asahi Glass Co and has an Er^{3+} ion concentration of 7.6×10^{25} ions/m^3 with a Lanthanum ion co-dopant concentration of approximately 4.4 wt%. The fibre used has a length of 181.9 cm, a core/cladding refractive index of 2.03/2.02 and a NA of 0.20. It is angle spliced to a single-mode fiber in order to reduce splice point reflections.

For the luminescence experiment, the two 1480 nm pump laser diodes are operated in CW mode while for the lifetime experiment the 1480 nm pumps are pulse modulated using a square-wave function generator at 70 Hz. The 1550 nm fluorescence spectra and decay of the Bi-EDF is monitored at the WSC 1550 nm output port, with the spectra detected using an optical spectrum analyser (OSA) and the decay detected using HP 83440B photodiodes with a HP54510A 250 MHz digital oscilloscope. The decay oscillogram is transferred to a computer via General Purpose Interface Bus (GPIB) hardware, and the decay lifetime is obtained by fitting the single-exponential function to the experimental fluorescence decay curves. The gain and noise figure of the Bi-EDFA are also investigated. The experiment is then repeated using a 30 m commercially available Fibercore Limited Si-EDF with an Er^{3+} doping concentration of 2.0×10^{25} ions/m^3 for comparison purposes.

The complete compositional analysis of the Bi-EDF glass is then investigated and measured using Energy Dispersive X-Ray Microanalysis (EDX) techniques. In this measurement, the sample is bombarded with electron energy accelerate at 20 kV and the emitted X-Rays from the sample are captured and analysed with the system software.

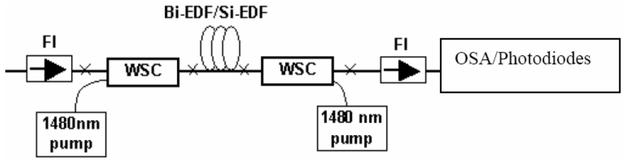


Fig. 1. Experimental setup for Bi-EDF/Si-EDF Characterisation. WSC= wavelength selective coupler, FI=Fibre Isolator.

3. Results and discussion

Fig. 2 shows the measured and calculated emission cross-section using the McCumber theory and also the Si-EDF emission cross-section as a comparison. The McCumber emission cross-section was calculated using absorption cross-sections provided by Asahi Glass Co, and it can be seen in the figure that the calculated emission cross-section agrees well with the experimental data. This optical emission peaks at the 1.53 μm, which is obtained due to the population inversion between energy level $^4I_{13/2}$ and $^4I_{15/2}$. Also from Fig. 2 it can be seen that the Bi-EDF has wider emission spectra as compared to Si-EDF, especially at the longer wavelengths at 1620 nm because of its larger emission cross-section. The Si-EDF has a bandwidth of only 40 nm while the Bi-EDF bandwidth is almost double at 80 nm for the same emission intensity. The widening of the emission spectra is believed to be a result of the Stark level of the Er^{3+} ions in the Bi-EDF is separated to a larger degree due to the larger ligand field as shown by the absorption cross-section. As shown in Fig. 2, despite the Bi-EDF having a higher absorption cross-section of 7.58×10^{-25} m^2 at the 1530 nm peak as compared to the Si-EDF absorption cross-section (which is only 4.39×10^{-26} m^2), the peak full-width half maximum (FWHM) of the Bi-EDF is narrower than the FWHM of the Si-EDF. This is due to the larger inhomogeneous energy level degeneracy that the ligand field of the Bismuth host glass induced as a result of site-to-site variations, also known as the Stark effect [9], causing the widened optical transitions. Other elements such as potassium oxide also have similar glass basicity expender effects [10] and are used in the fabrication of Bi-EDF to obtain a broader amplification region.

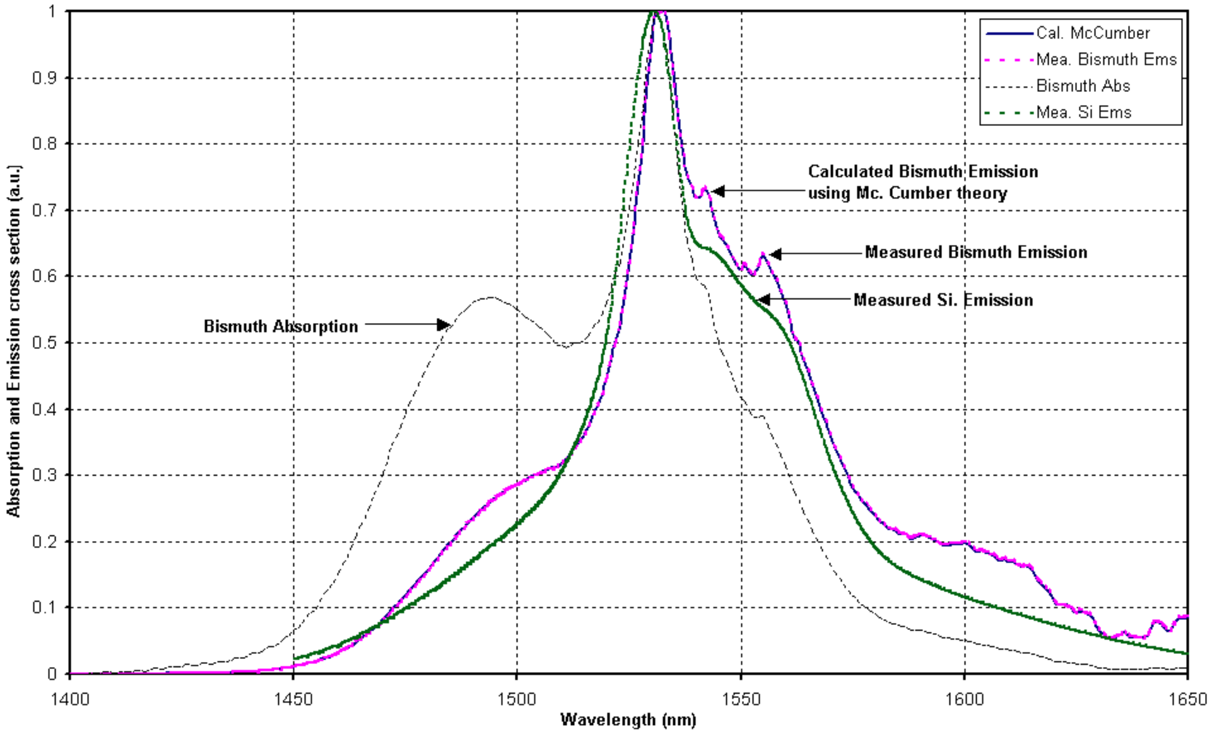


Fig. 2. Absorption and emission cross-section of Bi-EDF and Si-EDF. (The Bismuth absorption cross-section is obtained from Asahi Glass Co.).

Fig. 3 shows the lifetime decay curve of Er^{3+} ions of Bi-EDF, which was measured at wavelength of 1530nm. The decay curve is fitted with the single exponential decay as shown by the solid line. From the fitting curve, the lifetime of the erbium ion was measured to be approximately 2.84 ms, which is shorter than that measured by Yang et. al. [11] and much more lower than the compared lifetime of Er^{3+} ions in a silica host glass [9]. The quantum efficiency η and non-radiative transition rate W^{NR} at the 1550 nm emission are calculated to be 63.0 % and 130.3 s^{-1}, respectively.

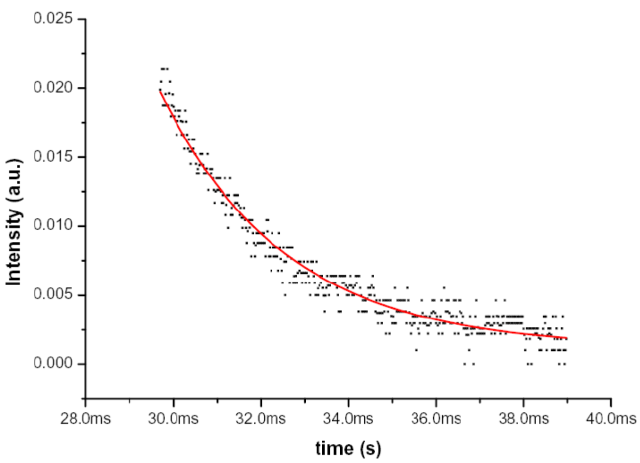


Fig. 3. The measured lifetime of the erbium ion in Bi-EDF at 1530nm. The fitting curve to the data is represented by the solid line.

This shows that the Bi-EDF is capable of generating the sought-after high population inversions with only a modest pump power [12]. Furthermore, this indicates that glass hosts with low phonon energies such as bismuth glass (500 cm^{-1}) can be used to design an efficient optical amplifier with a wider fluorescence bandwidth [11, 12]. The wider fluorescence bandwidth is also attributed to the effect of the alumina and Lanthanum co-dopants towards the Er^{3+} ions distribution in the Bi-EDF which reduces the concentration quenching effect of the Er^{3+} ions, thus increasing the quantum efficiency [13, 14].

The complete compositional analysis of the Bi-EDF glass using EDX is summarized in Table 1. From the analysis, the glass network formers for the Bi-EDF are determined to be bismuth oxide, silica and alumina while the other markers are determined to be the glass network modifiers. The glass former is more prevalent elements in the glass structure than the glass modifier. By utilizing bismuth oxide and alumina as the main glass network former, the local glass basicity near the Er^{3+} ions sites is expanded as reported by Jianhu Yang et. al. [15] and Ainslie et. al. [13], effectively increasing the crystal field (ligand field) of the glass. This has the result of enhancing the 1530 nm fluorescence full-width-half-maximum (FWHM) spectrum [13, 15] making it comparably broader than that obtainable with a silica glass host.

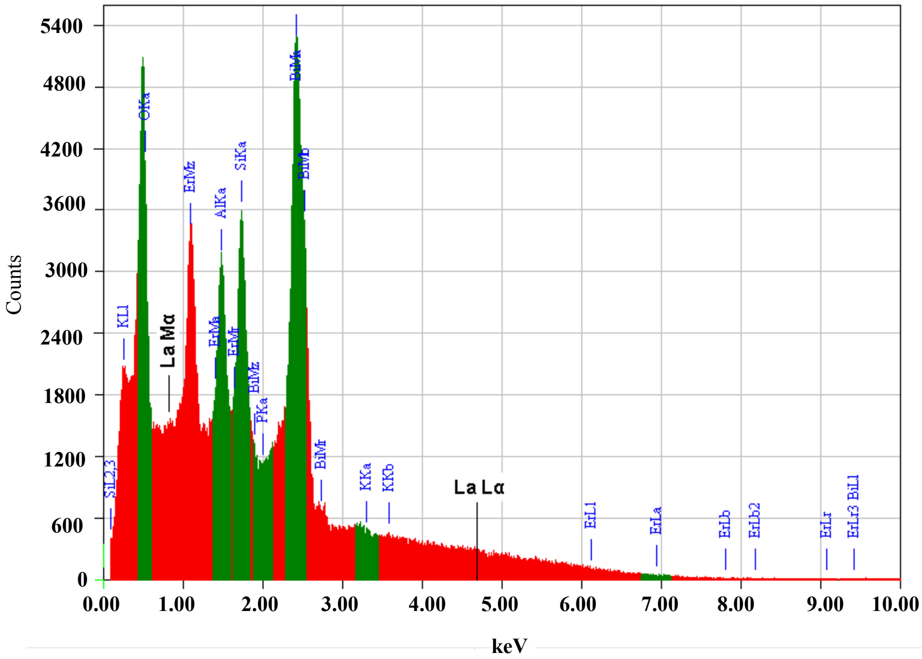
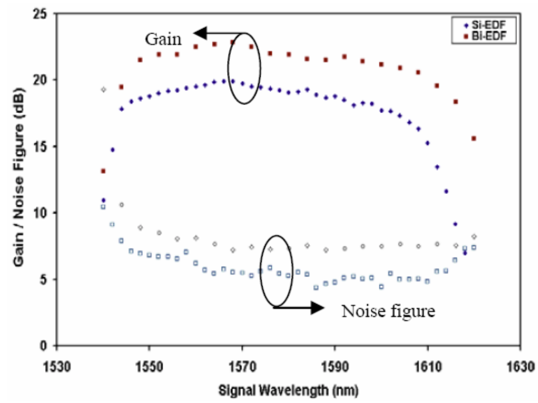


Fig. 4. The measured energy spectra of the Bi-EDF using EDX.

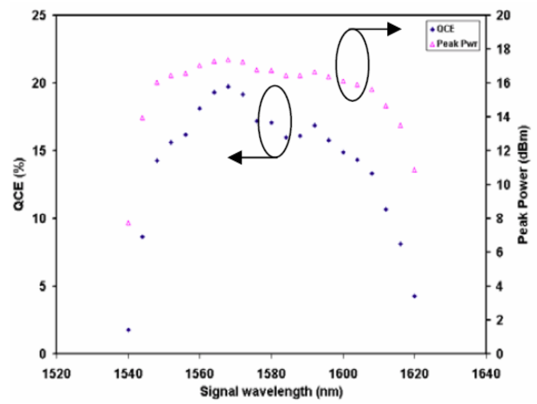
Table 1. The Bi-EDF glass composition analysis using EDX.

Element	Mass (%)	Error (%)
Bi_2O_3	67.80	1.88
SiO_2	14.24	0.81
Al_2O_3	16.96	0.87
K_2O	0.05	0.29
P_2O_5	0.53	0.64
Er_2O_3	0.42	1.67
Total	100.00	6.17

In order to gauge the behaviour of the Bi-EDF in optical amplification, then Bi-EDF optical amplifier characteristics and performance is evaluated by measuring the signal gain and noise figure as shown in Figure 5 (a) as well as its QCE as shown in Figure 5 (b) for a 0 dBm input signal. The gain of the Bi-EDF is approximately 3 dB or 50% higher than that of the Si-EDF optical amplifier with a flat gain profile. The Bi-EDF gain bandwidth is also wider by 15 nm than that of the Si-EDF, to give the Bi-EDF a gain bandwidth of approximately 80 nm spanning from 1540 nm up to 1620 nm. This 15 nm increase in the gain bandwidth represents the potential addition of 18 signal channels of a 100GHz transmission system with the implementation of Bi-EDF optical amplifiers [16]. However, the high Er^{3+} ions doping concentration and high insertion loss of the Bi-EDF incur a higher noise figure penalty of approximately 2.6 dB than the noise figure penalty of a Si-EDF when spliced to a conventional SMF. This increased noise figure is attributed to the effect of multiple reflections from both the fibre splice points whereby the signal is reflected back into the Bi-EDF due to the large refractive index difference, causing multi-path interference (MPI) noise [9].



(a)



(b)

Fig. 5. Measured signal gain and noise figure (a) and QCE (b) of 0 dBm input signal power from 1540 nm to 1620 nm for Si-EDF and Bi-EDF.

Fig. 5 (b) on the other hand shows the quantum conversion efficiency (QCE) and output power of the Bi-EDF. The QCE is pump wavelength independent and defined as [9]:

$$QCE = \left(\frac{\lambda_s}{\lambda_p}\right)\frac{P_s^{out} - P_s^{in}}{P_p^{in}} \quad (1)$$

where $\lambda_{p,s}$ are the pump and signal wavelengths, $P_s^{out,in}$ are the signal output and input powers and P_p^{in} is the pump power. From energy conservation principles, the maximum value for the QCE is given by:

$$QCE(\max) = \frac{\lambda_p}{\lambda_s} \quad (2)$$

The highest QCE is determined by Eq. (2) to be approximately 19.7 % at 1568 nm while the lowest QCE is calculated to be 1.7 % at 1540 nm. The higher QCE is due to the phonon energy of the glass host is much lower than the Er^{3+} ions energy gaps and this significantly reduces the pump photon energy loss to non-radiative emission [4, 7]. Therefore, almost all the pump photons are converted to signal photons in the amplification process. With its high pump to signal conversion efficiency, the Bi-EDF is an efficient optical amplifier with shorter fibre length as compared to Si-EDF.

4. Conclusions

The composition and characteristic of the Bi-EDF and its optical performance with 1480nm excitation have been comprehensively studied. Compared to the current Si-EDF, the Bi-EDFA only requires a shorter length of active fibre to achieve amplification and can significantly reduce the complexity and cost of optical amplifier manufactures and will bring down the total cost of operations. The Bi-EDF is also capable of producing high quantum efficiency amplifiers that significantly benefits optical amplifier designers. The Bi-EDF has a shorter 1530 nm emission lifetime due to the high refractive index and Er^{3+} doping concentration, and has a wider amplification bandwidth of 80 nm and high QCE of 19.7% using 1480 nm pumping. However, high insertion losses and multipath reflections between splice points arising from splicing joints to SMFs must be improved before the Bi-EDF can be implemented in optical communication networks.

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