# Ultra-broadband Bismuth-Doped Fiber Amplifier Covering a 115-nm Bandwidth in the O and E Bands

Yu Wang, Naresh K. Thipparapu, David J. Richardson, *Fellow, IEEE* and Jayanta K. Sahu

***Abstract*—In this paper, we experimentally demonstrate an all-fiber optical amplifier using Bi-doped phosphosilicate fiber (BPSF) operating in both the O-band and the E-band, providing >20dB gain from 1345nm to 1460nm for an input signal power of -23dBm. A maximum gain of 31dB with a noise figure (NF) of 4.8dB was achieved at 1420nm for -23dBm input signal, whereas for an input signal power of -10dBm it was 26dB with a NF of 5.3dB. The in-band OSNR of the proposed Bi-doped fiber amplifier (BDFA) was >22dB from 1345nm to 1460nm for a -23dBm input signal. The gain coefficient was found to be 0.04dB/mW for a -23dBm input signal. Also, the temperature dependent gain and NF performance of the BDFA within -40 to +60°C were characterized. The temperature-dependent-gain (TDG) coefficient for a -23dBm input signal was found to be -0.015dB/°C at a signal wavelength of 1420nm where the BDFA gain is maximum, while for an input signal power of -10dBm it was -0.01dB/°C at 1420nm. The TDG coefficient of the proposed BDFA from 1350-1460nm was in the range from -0.079dB/°C to -0.008dB/°C. The BDFA gain and NF performance were also measured and compared using BPSFs with different unsaturable loss (UL) characteristics.**

***Index Terms*—Optical fibers; Doped fiber amplifiers; Bismuth; Broadband amplifiers.**

## I. Introduction

THE tremendous growth of data transfer over the global internet resulting, for example, from increased usage and development of online multimedia applications such as 4K videos, cloud services and associated data center interconnection has created an enormous capacity demand for the transmission bandwidth of modern dense wavelength-division-multiplexed (DWDM) optical communication systems. The transmission performance of standard single mode fiber (SSMF) is by now well optimized and the intrinsic capacity of SSMF-based communication systems is limited to approximately 10THz by the available amplification bandwidth of the erbium (Er)-doped fiber amplifier (EDFA). Extending the amplification bandwidth outside the currently used C+L-bands (1530nm-1620nm) i.e. covering from the O-band to the U-band (1260nm-1675nm) where the transmission loss in existing telecom fibers is ≤0.4dB/km would provide an appealing and potentially near term solution. There have been many efforts to achieve optical amplification using different dopants in glass hosts such as praseodymium (Pr) [1], neodymium (Nd) [2], thulium (Tm) [3, 4] and bismuth (Bi) [5, 6]. The broadband near-infrared (NIR) luminescence properties of bismuth (Bi)-doped silica-based fibers, which span the O-, E-, S- and U-bands indicate that Bi is a promising dopant to develop ultra-wideband optical amplifiers [4].

Previous reports have demonstrated a Bi-doped fiber amplifier (BDFA) operating in the O-band with a flat gain of 25dB from 1320-1360nm over a 40nm bandwidth for an input signal power of -10dBm [7], whereas a gain of 40dB was achieved at 1360nm using a double pass amplifier configuration [8, 9]. The temperature dependent performance of the O-band BDFA has been characterized in the temperature range from -60°C to +80°C, and the temperature-dependent-gain (TDG) coefficient was found to be -0.06dB/°C and -0.08dB/°C for input signal powers of -10dBm and -23dBm, respectively [10, 11]. An O-band BDFA has been tested in a transmission experiment over a 50-km length of SSMF with four WDM channels of 40-Gbit/s Nyquist-OOK [12]. The demonstrations confirmed the suitability of the O-band BDFA for high capacity WDM transmission. On the other hand, a BDFA operating in the E-band has been reported with a 24-dB gain at 1430nm with a 3-dB bandwidth of about 40nm using Bi-doped phosphogermanosilicate fibers [13]. A data transmission experiment with a 10.6Gbit/s IM/DD signal has been demonstrated from 1441nm to 1453nm over 80km of TrueWave fiber using this E-band BDFA [14]. The above results indicate that the BDFA has great potential for extending the usable transmission bandwidth in commercial telecom systems. However, the amplification bandwidth of BDFAs has been reported both in the O- and E-band with a gap in between from 1360nm-1430nm. In this work we report an ultra-wideband Bi-doped fiber optical amplifier operating all the way from 1345-1460nm [15].

In this paper, we report an all-fiber wideband optical

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TABLE I
BASIC CHARACTERISTICS OF BPSFS IN THIS WORK

| | Abs@1240nm (dB/m) | Abs@1270nm (dB/m) | Abs@1310nm (dB/m) | Abs@1432nm (dB/m) | UL@1240nm (%) | UL@1432nm (%) | OH conc. (ppm) | BL@1550nm (dB/m) |
|---|---|---|---|---|---|---|---|---|
| BPSF-1 | 0.55 | 0.57 | 0.52 | 0.27 | 16.4 | 16.3 | 1.2 | 0.01 |
| BPSF-2 | 0.5 | 0.53 | 0.48 | 0.17 | 13 | 22.8 | 2 | 0.02 |
| BPSF-3 | 0.5 | 0.47 | 0.4 | 0.16 | 15.5 | 27.4 | 0.8 | 0.04 |

amplifier using Bi-doped phosphosilicate fiber (BPSF) fabricated in-house. The gain and NF characteristics were measured with respect to the input signal power, pump power and ambient temperature. A >20dB gain was obtained covering part of the O-band and the entire E-band from 1345nm to 1460nm with an ultra-wide bandwidth of 115nm. A maximum gain of 31dB with a NF of 4.8dB was achieved at a signal wavelength of 1420nm for a -23dBm input signal. The temperature dependent gain and NF performance from 1350nm to 1460nm were characterized in the range from -40 to +60℃. The TDG coefficient for a -23dBm input signal was found to be -0.015dB/℃ at a signal wavelength of 1420nm, while for an input signal power of -10dBm it was -0.01dB/℃. The TDG coefficient of the BDFA from 1350-1460nm was in the range from -0.079dB/℃ to -0.008dB/℃, which is similar to that of a typical EDFA [16]. This confirms the extraordinary thermal stability of the proposed O+E-band BDFA. We also measured the gain and NF characteristics of the proposed BDFA using BPSFs with different unsaturable loss (UL) parameters for comparison.

## II. EXPERIMENTAL SETUP

Bi-doped phosphosilicate preforms were fabricated in-house using the modified chemical vapor deposition (MCVD)-solution doping technique, and then drawn into fibers with core and cladding diameters of 11μm and 150μm (for BPSF-1), or 15μm and 125μm (for BPSF-2 and BPSF-3), respectively. The fiber core was composed of Bi, phosphorous (P), and silica ($SiO_2$). The $P_2O_5$ content was estimated as ~5mol% based on the refractive index difference (Δn) of ~0.004. The measured cutoff wavelength of BPSF-1 was ~1000nm, and it was ~1400nm and ~1600nm for BPSF-2 and BPSF-3, respectively. The absorption spectra were measured by the cut-back technique using a white light source (WLS) and an optical spectrum analyzer (OSA). The percentage of unsaturable loss (UL) was calculated from the variation of fiber loss as a function of the input pump power. The OH concentration was estimated from the water absorption peak at around 1380nm. The background loss (BL) was measured at 1550nm to avoid the Bi absorption bands. The absorption at the pump wavelengths of 1270nm and 1310nm, the percentage of UL at a pump wavelength of 1240nm and a signal wavelength of 1432nm, and the OH concentration and the BL of the BPSFs tested in our work are presented in Table 1. The measured absorption spectrum and refractive index profile of BPSF-1 is present in Fig. 1, and the other two fibres have similar absorption spectra as BPSF-1.

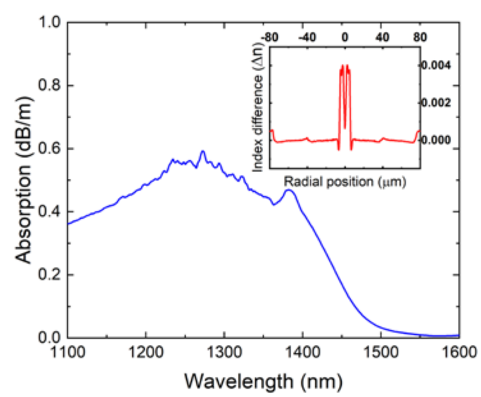


Fig. 1. Absorption spectrum of BPSF-1 (the inset represents the refractive index profile of BPSF-1).

The experimental setup used to demonstrate and characterize the Bi-doped phosphosilicate fiber amplifier (BPSFA) is shown in Fig. 2. Laser diodes (LDs) operating at pump wavelengths of ~1310nm and 1270nm were utilized to provide bi-directional pumping. A tunable laser source (TLS) with a linewidth of 400kHz was used to provide input signals spanning from 1345nm to 1460nm for amplification. By setting the output power from the TLS and adjusting the attenuator (ATT), the input signal power was set to either -10dBm or -23dBm which was measured at the input of the BPSF. Two isolators (ISOs) were used to protect the LDs from any back reflections, while

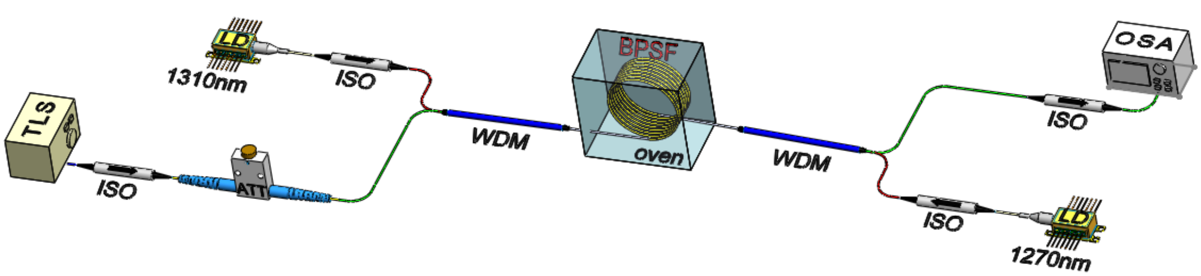


Fig. 2. Experimental schematic of the Bi-doped phosphosilicate fiber amplifier.

one output isolator was utilized to avoid signal back reflections. Two wavelength division multiplexers (WDMs) were used to combine or separate the pump and signal wavelengths. The input and output signal spectra were recorded by an OSA (YOKOGAWA AQ6370) using a resolution bandwidth of 0.02nm. The BPSF was placed inside a temperature-controlled oven with an operating temperature range from -40°C to +60ºC.

## III. Experimental Results and Discussion

A 220m length of BPSF-1 was found to be optimal in terms of overall gain performance and was characterized in the experiments described herein. The total pump power that can be launched into BPSF-1 was 850mW (475mW from the forward pump at ~1310nm and 375mW from the backward pump at 1270nm). The gain and NF characteristics were measured from 1345nm to 1460nm for input signal powers of -10dBm and -23dBm at room temperature, as shown in Fig. 3. An ultra-wide gain of >20dB and a NF of 4.6~7.1dB were realized in the wavelength range from 1345nm to 1460nm. An overall gain of 22.5±3.5dB and 25.5±5.5dB was achieved across the 115nm bandwidth for -10dBm and -23dBm input signals, respectively. Note that the lowest gain of ~20dB with a correspondingly higher NF of ~7dB at around 1380nm is due to the OH content of 1.2ppm in BPSF-1, which induced a loss of ~13dB over the 220m of BPSF-1 used in the experiment. Therefore, the double hump gain spectrum is not intrinsic to

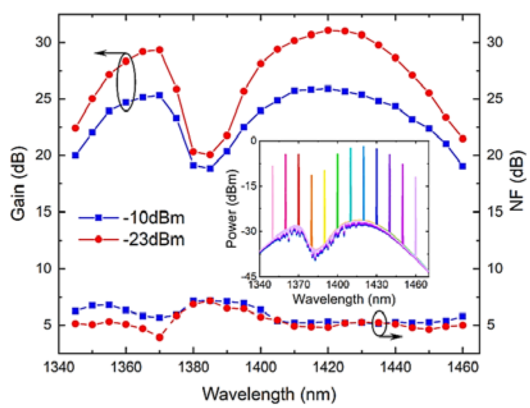


Fig. 3. Gain and NF spectrum of BPSF-1 from 1345nm-1460nm for input signal powers of -10dBm and -23dBm at room temperature, where the inset shows the signal and ASE spectrum for a -23dBm input signal from which the in-band OSNR is derived (fiber length = 220m, total launched pump power = 850mW).

BPSF and could ultimately be reduced or eliminated by improving the drying process during preform fabrication. The in-band optical-signal-to-noise-ratio (OSNR) for a -23dBm input signal was found to be >22dB across the wavelength band of 1345nm-1460nm, as shown in the inset of Fig. 3. For an input signal power of -10dBm, the in-band OSNR was >35dB from 1345nm-1460nm.

The gain and NF performance of BPSF-1 was also measured at room temperature as a function of pump power and input signal power. As shown in Fig. 4, an increase in gain with a small decrease in NF were observed with an increase in pump power for both input signal powers. The gain coefficient at

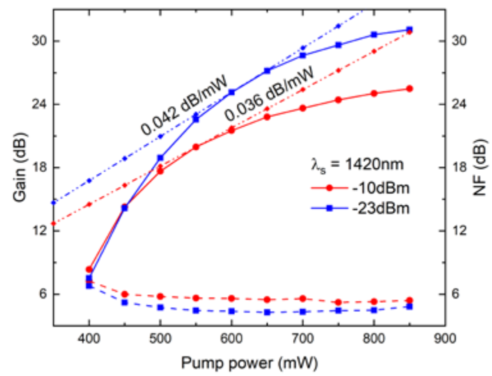


Fig. 4. Gain and NF characteristics of BPSF-1 as a function of the pump power at a signal wavelength of 1420nm for signal powers of -10dBm and -23dBm at room temperature (fiber length = 220m).

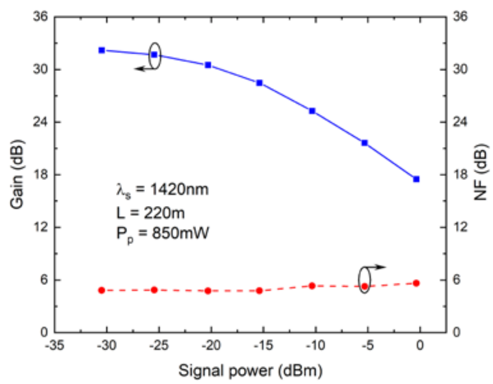


Fig. 5. Gain and NF characteristics of BPSF-1 as a function of the input signal power at a signal wavelength of 1420nm at room temperature (fiber length = 220m, total launched pump power = 850mW).

1420nm was found to be 0.036dB/mW and 0.042dB/mW for -10dBm and -23dBm input signals, respectively. Fig. 5 shows the dependence of the gain and NF characteristics on the input signal power of BPSF-1 at a signal wavelength of 1420nm. A gain increase was observed while the NF remained almost constant as the input signal power decreased. The gain showed a saturation behavior at 1420nm when the input signal power was reduced below -20dBm. A maximum gain of 32dB at 1420nm was obtained for an input signal power of -30dBm with a NF of 5.6dB.

The temperature dependent gain and NF performance of BPSF-1 was also measured from 1350nm to 1460nm, as shown in Fig. 6, for input signal powers of -10dBm and -23dBm in the temperature range from -40°C to +60ºC at intervals of 20°C. As can be seen, the gain increases and the NF shows a small change as the temperature is reduced from +60°C to -40ºC. The gain variation with temperature change is insignificant at the long E-band wavelengths (especially 1420nm-1460nm), and in the O-band region the variation is more noticeable. The temperature dependent gain and NF characteristics at around 1380nm are similar to those at the adjacent wavelengths. The OH content in the fiber did not have any observable impact on the thermal behavior of the BDFA.

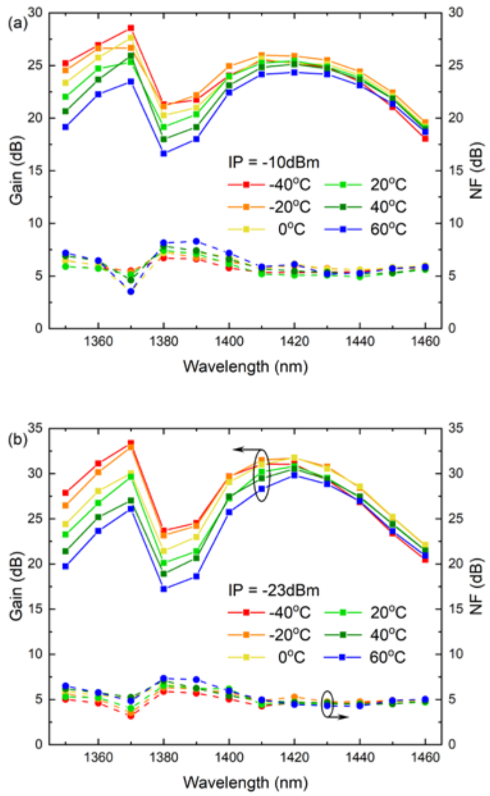


Fig. 6. Temperature dependent gain and NF characteristics of BPSF-1 in the temperature range from -40ºC to +60ºC for (a) -10dBm and (b) -23dBm input signal powers (fiber length = 220m, total launched pump power = 850mW).

To quantify the temperature dependence of the gain characteristics we calculated the TDG coefficient, which is defined as the amount of signal gain change per unit of temperature change, in [dB/ºC]. The TDG coefficient at 1360nm was calculated to be -0.048dB/°C and -0.076dB/°C for input signal powers of -10dBm and -23dBm, respectively, which is identical to the TDG coefficient of the O-band BDFA as reported in [10]. The TDG coefficient at 1420nm was calculated to be -0.01dB/°C and -0.015dB/°C for -10dBm and -23dBm input signals, respectively, as shown in Fig. 7. This is similar to the TDG coefficients of EDFAs [16] and the O-band BDFAs [10, 11], and thus illustrates the excellent thermal stability of the proposed O+E-band BDFA.

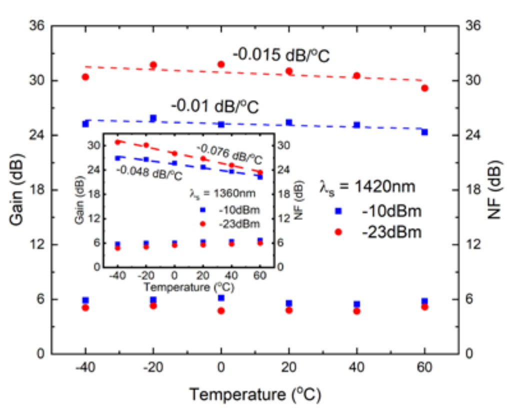


Fig. 7. Gain and NF characteristics of BPSF-1 from -40°C to +60°C at 1420nm for input signal powers of -10dBm and -23dBm, where the slope of dashed line represents the TDG coefficient. (fiber length = 220m, total launched pump power = 850mW; the inset represents gain and NF characteristics of BPSF-1 from -40°C to +60°C at 1420nm).

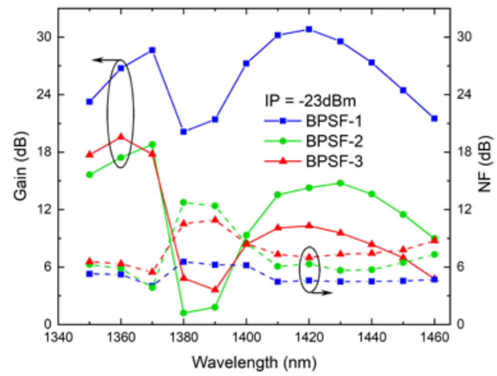


Fig. 8. Gain and NF spectrum of BPSF-1, BPSF-2, BPSF-3 from 1350nm-1460nm for an input signal power of -23dBm at room temperature (BPSF-1: fiber length = 220m, total launched pump power = 850mW; BPSF-2: fiber length = 212m, total launched pump power = 844mW; BPSF-3: fiber length = 210m, total launched pump power = 869mW).

The gain and NF characteristics of BPSF-2 and BPSF-3 were also measured at signal wavelengths from 1350nm to 1460nm in the same experimental setup as demonstrated in Fig. 2. For BPSF-2, an optimal length of 212m was used in the experiment, and the total pump power that can be launched into BPSF-2 was 844mW. For BPSF-3, the optimal fiber length of 210m was used and the total pump power that can be launched into BPSF-3 was 859mW. The gain and NF spectrum comparison of BPSF-1, BPSF-2 and BPSF-3 for an input signal power of -23dBm at room temperature were presented in Fig. 8.

As shown in Fig. 8, a local drop of the gain spectrum and correspondingly a NF increase at around 1380nm was observed in all three fibers. We reiterate that the gain dip is not an intrinsic feature of the proposed O+E-band BDFA but results OH induced loss in the fibers. For example, BPSF-2 has an OH content of 2ppm which will induce a 21dB loss at ~1380nm in the 212m long fiber, and the OH content of 0.8ppm in BPSF-3 will induce a loss of 8.4dB at ~1380nm in a fiber length of 210m. The gain degradation of BPSF-2 at around 1380nm was greater and slightly wider than that of BPSF-3. It is important to mention that no special measures were incorporated in the fabrication process to reduce the OH content for this current generation of fibers.

It is clearly observed from Fig. 8 that the gains in the O-band and the E-band are significantly different for BPSF-1, BPSF-2 and BPSF-3. The overall gain of BPSF-1 is higher than that of BPSF-2 and BPSF-3. For example, in the O-band the gain of BPSF-1 at 1360nm was ~28dB, while the gain at 1360nm of BPSF-2 and BPSF-3 was ~18dB. Also, in the E-band the gain at 1420nm of BPSF-1 is more than 30dB, whereas that of BPSF-2 and BPSF-3 is 14dB and 10dB respectively. Comparing the basic physical parameters of the fibers listed in Table 1, we believe this overall gain difference is most likely

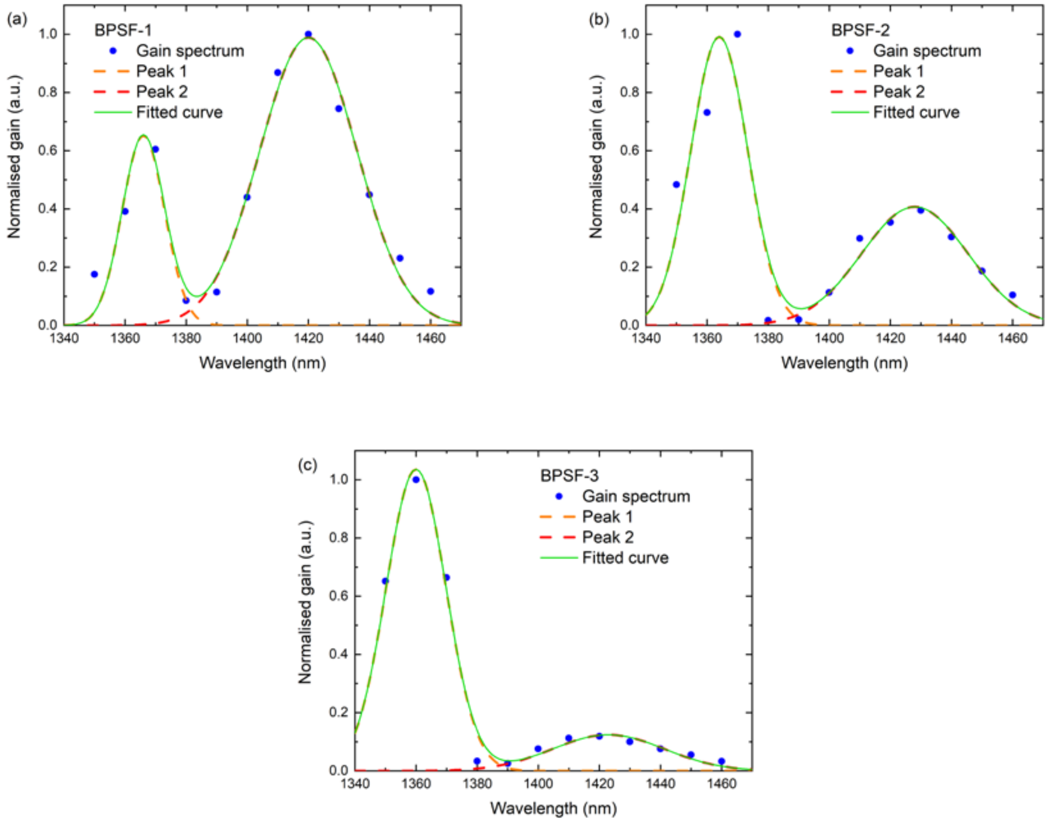


Fig. 9. (a) (b) (c) Two Gaussian peaks curve fitted at ~1360nm and ~1420nm based on the gain spectra for -23dBm input signal of BPSF1, BPSF-2 and BPSF-3. (BPSF-1: fiber length = 220m, total launched pump power = 850mW; BPSF-2: fiber length = 212m, total launched pump power = 844mW; BPSF-3: fiber length = 210m, total launched pump power = 869mW).

attributed to the significantly higher BLs of BPSF-2 and BPSF-3, which are 2 and 4 times higher that of BPSF-1 respectively. Furthermore, the high OH concentration of 2ppm in BPSF-2 also contributed to the lower gain at ~1360nm. In addition, the UL at a signal wavelength of 1432nm of BPSF-1 is ~16%, while for BPSF-2 and BPSF-3 it is ~23% and ~27% respectively. This is related to the gain performance of BPSF-1, BPSF-2 and BPSF-3 observed at 1420nm.

Fig. 9 (a), (b) and (c) illustrate a fitted curve to the gain spectrum of BPSF-1, BPSF-2 and BPSF-3 for a -23dBm input signal at room temperature. All the gain spectra and fitting curves in Fig. 9 are presented on a linear scale. The dashed lines represent individual Gaussian fits to the gain peaks located at ~1360nm and ~1420nm respectively, and the solid lines demonstrate the aggregation of these two Gaussian peaks. The origin of the gain peak in the O-band is attributed to Bi active center (BAC)-P, whereas in the E-band it is associated with BAC-Si [17]. However, the nature of the BAC is still lacking in terms of detailed understanding. The full width at half maximum (FWHM) of the Gaussian peaks is ~21nm in the O-band, and ~39nm in the E-band for all three fibers. The ratios of the peak gain in the O-band and in the E-band are calculated to be 0.66 for BPSF-1, 2.43 for BPSF-2 and 8.35 for BPSF-3, which correlates with the UL at 1432nm of the three fibers as shown in Table 1. This study indicates that it is important to reduce the UL of BPSFs in the E-band to achieve wideband O+E-band operation.

## IV. Conclusion

In this paper, we fabricated BPSF in-house using the MCVD-solution doping technique and demonstrated an all-fiber optical amplifier targeting the O and E band. The proposed BDFA provided >20dB gain from 1345nm to 1460nm with an ultra-wide bandwidth of 115nm covering part of the O-band and the entire E-band, which, to the best of our knowledge, is the widest ever reported from a BDFA. A maximum gain of 31dB with a NF of 4.8dB was achieved at 1420nm for a -23dBm input signal, whereas for an input signal power of -10dBm a maximum gain of 26dB with a NF of 5.3dB was obtained. The proposed BDFA exhibits compromised gain performance at wavelengths around 1380nm due to the OH content in our current BPSFs. Optimization of the preform fabrication process will reduce or eliminate the OH in the fiber and hence improve the BDFA performance. At a signal wavelength of 1420nm, the gain coefficient was 0.042dB/mW for a -23dBm input signal, and 0.036dB/mW for an input signal power of -10dBm. The in-band OSNR was found to be >35dB from 1345nm to 1460nm for a -10dBm input signal. The temperature dependent characteristics of the proposed O+E-band BDFA was studied. The TDG coefficient in the entire E-band region was in the range from -0.076dB/°C to -0.008dB/°C, which is similar to that of a conventional EDFA [16], and thus illustrates the excellent thermal stability of the proposed BDFA. We also measured the gain and NF characteristics of the BDFA using BPSFs with different UL parameters in the E-band and compared them to reveal the impact of UL on the BDFA gain performance.

## ACKNOWLEDGEMENT

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