Bi-doped fiber amplifier with a flat gain of 25 dB operating in the wavelength band 1320-1360 nm

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Bismuth (Bi) -doped phosphosilicate fibers have been fabricated by the modified chemical vapor deposition (MCVD) -solution doping technique under different process conditions. The influence of fabrication conditions on unsaturable loss in fibers has been investigated. Pump wavelength dependent Bi gain has been studied to obtain a flat gain over a wide bandwidth. A diode pumped all-fiber Bi-doped amplifier with a flat gain of 25 ± 1dB from 1320-1360nm (40nm) has been demonstrated for -10 dBm of input signal power with a noise figure (NF) ranging from 4–6 dB. Moreover, a small signal gain of 29 dB and a NF of 4.5dB at 1340 nm have been achieved for an input signal power of -30dBm.

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The demand for optical fiber communication is persistent over the last decade because of the increased accessibility of internet, cloud computing, and machine-to-machine communication arising from the Internet of Things, etc. Continuous research efforts are being made to develop various technologies to cope with the capacity requirements in optical fiber communication. One of them is the introduction of space-division multiplexing (SDM) in the C-band using multi-core fibers (MCF), multi-mode fibers (MMF), and multi-element fibers (MEF) [1-3]. Another approach is to develop efficient amplifiers in the second telecommunication window. The latter one would be the immediate solution to increase the capacity of optical fiber communication. Advances in fiber fabrication techniques have reduced the losses of silica fibers to <0.4 dB/Km in the O-band [4, 5]. However, lack of efficient amplifiers has rendered this window, currently, non-ideal for optical fiber communication. Recent developments in Bismuth (Bi) -doped fiber amplifiers covering the low loss window of silica fibers have shown great potential to enable a wideband transmission, thanks to its broad luminescence characteristics [6-11]. Bi-doped aluminosilicate, phosphosilicate and germanosilicate fibers have shown luminescence peaks around 1150, 1300, and 1450 nm, respectively [11-13]. Also, it has been shown that the luminescence window can be extended up to 1800 nm in a highly germanium (Ge) -doped Bi fibers [14, 15]. In particular, Bi-doped phosphosilicate fibers (BPSF) have specific importance as their emission wavelength region coincides with the O-band. A maximum gain of 24.5 dB has been reported at 1321 nm with a corresponding noise figure (NF) of 4-6 dB in a Bi-doped phosphogermanosilicate fiber amplifier. The amplifier used 200m of fiber length and a Raman fiber laser operating at 1230nm as a pump source with a pump power of 460mW [16, 17]. Here, we use Ge-free BPSFs to develop a flat and wideband amplifier in the O-band by careful selection of pump wavelengths. Also, commercially available laser diodes (LDs) were used as pump sources. At first, BPSFs were fabricated under different process conditions, since the performance of Bi-doped fiber depends considerably on the fabrication conditions. These fibers were characterized for their unsaturable loss (UL). Pump wavelength dependent Bi gain characteristics were also studied. An all-fiber LD pumped Bi amplifier operating in the spectral region 1300-1360nm has been demonstrated. The amplifier achieved a flat gain of 25±1dB in the wavelength region 1320-1360nm.

A set of three Bi-doped phosphosilicate preforms were fabricated using a modified chemical deposition (MCVD) -solution doping technique. Initially, phosphosilicate soot was deposited under similar fabrication conditions. The soot body was then impregnated with a Bi-solution. The Helium (He) /Oxygen (O_2) flow ratio was then varied in different preforms during the porous layer sintering and collapsing stages, while maintaining the total gas flow as a constant. All other fabrication conditions remain same for all preforms. The preforms were, then, drawn into fibers (from here onwards named as BPSF-1, BPSF-2, and BPSF-3) resulting in a core and clad diameter of 13 and 100 μm, respectively. The index difference (Δn) between the core and clad was measured and found to be around 0.004 for all BPSFs.

Table 1. Absorption and UL of BPSFs at two different pump wavelengths

Fiber		BPSF-1	BPSF-2	BPSF-3
He /O_2 flow ratio used during preform fabrication		1	0.25	only O_2
Absorption (dB/m)	1210nm	2	1.6	0.9
	1267nm	2.8	1.95	1
1210nm pump	%UL	46	17	14
1267nm pump	%UL	25	11	7

The absorption spectra of all BPSFs were measured by the cut-back method using a white light source (WLS) and an optical spectrum analyzer (OSA). The absorption values at 1210 and 1267nm pump wavelengths measured by the WLS are shown in Table 1. The UL was measured for all BPSFs using LDs pumped at 1210 and 1267nm wavelengths, respectively [18]. The influence of fabrication conditions on the UL can be seen from Table 1. The UL in BPSF-3 was reduced by a factor of three compared to BPSF-1. All three fibers were tested for lasing characteristics and BPSF-3 was found to be the most efficient among them [19]. This can be explained by the lower UL measured in BPSF-3. The Bi-doped preform of BPSF-3 was over jacketed and redrawn into a single mode fiber. The cut-off wavelength of the fiber was measured to be around 1100nm. This single mode BPSF-3 was then used to demonstrate a wideband Bi-doped fiber amplifier with a flat gain.

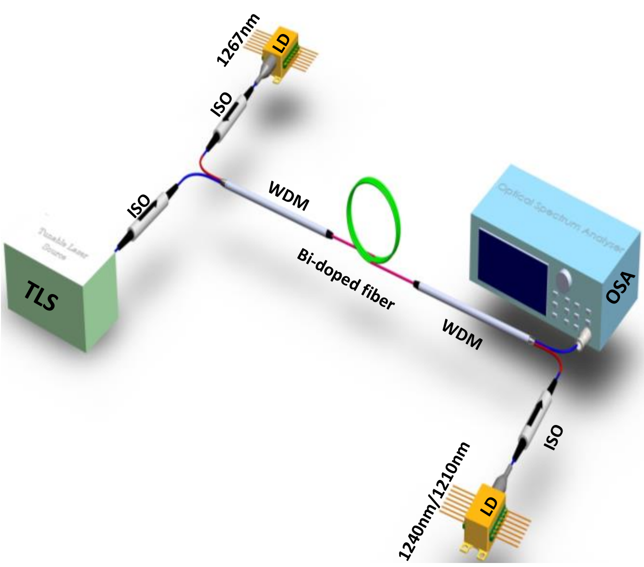

Fig. 1. Schematic experimental setup of Bi-doped fiber amplifier

The experimental setup of the Bi-doped fiber amplifier is shown in Fig. 1. It is comprised of a tunable laser source (TLS) with an operating wavelength region of 1260-1360nm. The Bi-doped fiber was pumped at 1267 or 1240nm and also at 1267nm in combination with 1240/1210nm as shown in Fig. 1. The maximum available power of 1267 and 1240nm LDs was 360 and 400mW, respectively. Whereas, the maximum power of the 1210nm LD was limited to 300mW. Isolators (ISO) were used to avoid back reflections and wavelength division multiplexers (WDMs) to combine/separate signal and pump wavelengths. The input and output signal spectra were taken using an OSA. The input signal was measured just before the Bi-doped fiber under test, whereas, the output signal was calculated by taking into account the WDM loss that was used to separate the pump from the signal. The gain and NF was then calculated by using the obtained input and output signal.

Initially, the fiber was individually pumped with 1267 or 1240nm LDs at their maximum available pump power and the amplified spontaneous emission (ASE) spectra measured just after the 100m long Bi-doped fiber is shown in Fig. 2. The ASE spectrum corresponding to the 1240nm pump has a peak at 1325nm, whereas the 1267nm pump has a peak around 1350nm, thereby, indicating that the gain can be pushed toward the longer wavelength using 1267nm pump. Subsequently, to develop an amplifier, the length of the fiber was optimized for a maximum gain using the experimental set up shown in Fig. 1. It was found that the 100m long fiber was optimum with the 1267nm pump for a pump power of 360mW and 75m was the optimum fiber length with the 1240nm pump for a pump power of 400mW. The gain and NF characteristics of optimum Bi-doped fiber corresponding to 1267 and 1240nm pumps are shown in Fig. 3. The input signal power was -10dBm. The 1267nm pumping provided a maximum gain of 15dB and a NF of 5dB at a wavelength of 1350nm. The gain at 1300nm was only 5dB.

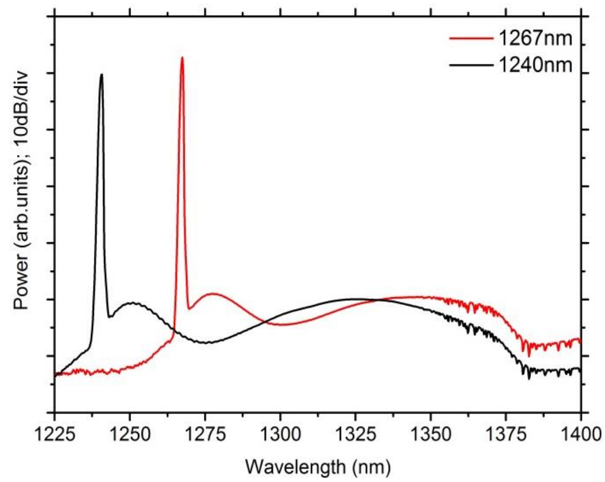

Fig. 2. ASE spectra for 1267nm or 1240nm pump wavelengths for a 100m long Bi-doped fiber when pumped with a maximum available power of LDs

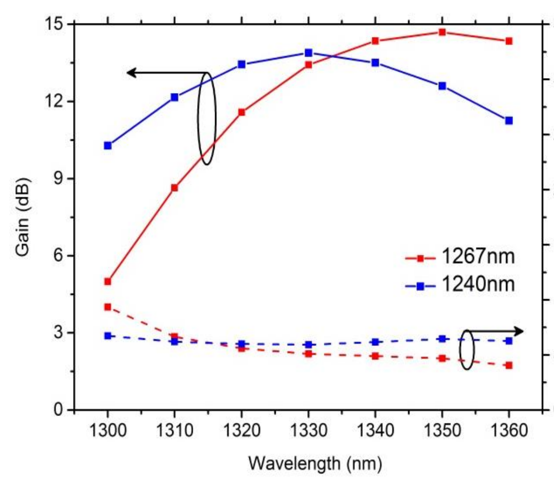

Fig. 3. Gain and NF characteristics for the maximum available power of 360mW (1267nm) or 400mW (1240nm) with optimum fiber lengths of 100m and 75m, respectively (Signal power: -10dBm)

In the case of the 1240nm pump, a maximum gain of 14dB and a NF of 6dB were obtained at 1330nm. It should be noted that the gain at 1300nm was 10dB, which is double the gain of the1267nm pumping. It can be concluded that the 1267nm pump can push the gain toward the longer wavelength, whereas the 1240nm pump allows the gain to operate at a shorter wavelength. Thus, by pumping the fiber using both the 1267 and 1240nm pumps, we could maximize the gain over a broad wavelength band. In order to realize this, the Bi-doped fiber was simultaneously pumped using both the pumps (1267 and 1240nm) operating at their maximum output power, as shown in Fig. 1. The total pump power of the LDs amounted to 760mW. The gain and NF characteristics of the amplifier with simultaneous pumping for an input signal power of -10dBm is shown in Fig. 4.

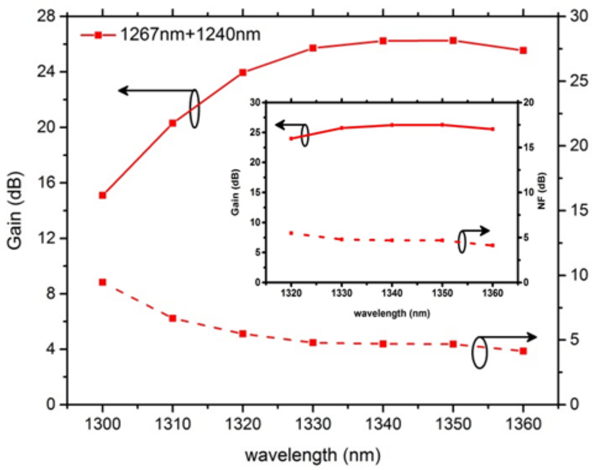

Fig. 4. Amplifier performance with bi-directional pumping by 1267nm (360mW) and 1240nm (400mW) LDs for a signal power of -10dBm (Inset shows the flat gain characteristics of the amplifier from 1320-1360nm)

The optimum length of the fiber for bi-directional pumping with 760mW of pump power was found to be 150m. A maximum gain of 26dB with a NF of about 5dB was obtained at 1340nm. The gain in the wavelength band of 1310-1360nm was more than 20dB. Moreover, a flat gain of 25±1dB with a NF of <6dB was achieved over a 40nm bandwidth (1320-1360nm), as shown in the inset of Fig. 4. The optical signal to noise ratio (OSNR) was more than 30dB. It can be noted that our amplifier could potentially operate even at wavelengths longer than 1360nm, which we are currently unable to measure due to the limitations of our signal source (TLS) operating wavelength range.

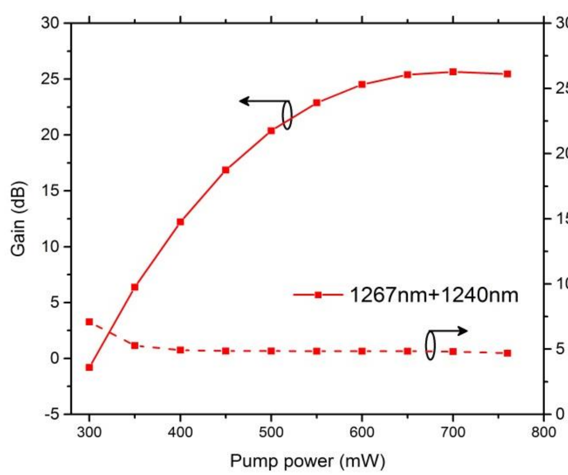

Fig. 5. Variation of gain and NF with pump power for bi-directional pumping at 1267nm and 1240nm for an input signal of -10dBm and operating at a wavelength of 1340nm

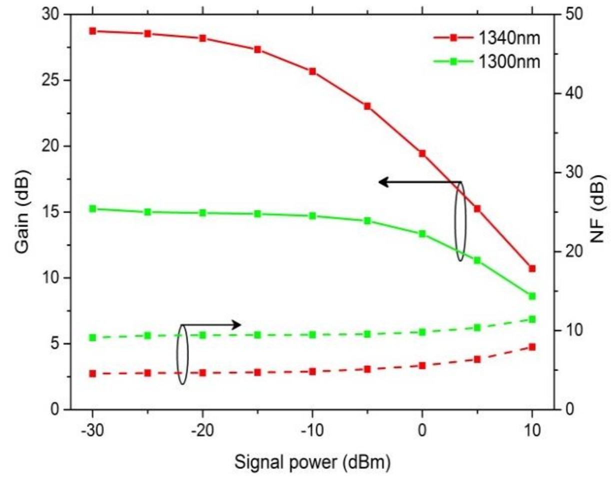

Fig. 6. Characteristics of the amplifier with input signal power at wavelengths of 1300nm and 1340nm when dual pumping with 1267nm and 1240nm LDs operating at their maximum power

Figure 5 shows the gain and NF variation with the pump power for the 150m long fiber in the bi-directional pumping measured at a wavelength of 1340nm. A maximum gain of 26dB with a NF of 5dB for a pump power of 760mW was obtained for an input signal power of -10dBm. The gain variation with input signal power is also shown in Fig. 6 at two signal wavelengths 1300 and 1340nm. The small signal gain for an input signal power of -30dBm, at a 1300nm wavelength was about 15dB whereas it was 29dB at 1340nm. Moreover, a NF of <5dB at 1340nm has been achieved for a broad range of input signal power.

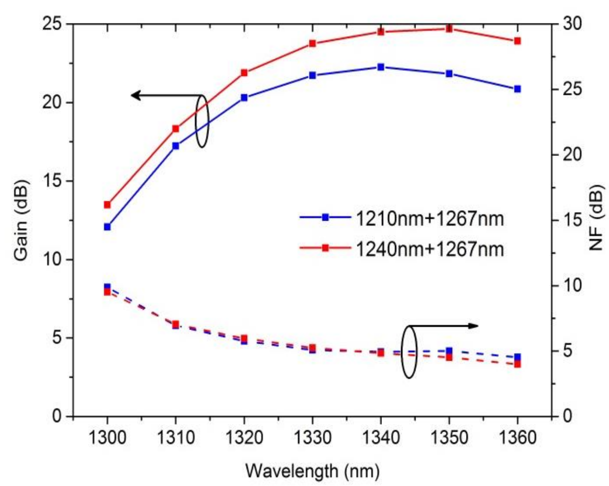

Fig. 7. Gain and NF characteristics of the amplifier by dual pumping at 1210nm or 1240nm pump in conjunction with 1267nm pump [pump powers: 1210nm (or 1240nm)–300mW; 1267nm–360mW, signal power: -10dBm]

We also investigated the amplifier performance for a pump wavelength shorter than 1240nm in combination with the 1267nm pump. A bi-directional pumping scheme was explored again, in which the 1267nm pump with an output power of 360mW was fixed at the signal input end of the amplifier. A second pump operating at a wavelength of 1210nm (or 1240nm) was used at the signal output end with a maximum power of 300mW. The total pump power amounted to 660mW in both cases for a fair comparison. A fiber length of 150m and an input signal power of -10dBm were used. A gain of 21±1dB with a NF of ≤5dB has been obtained in the wavelength region 1330-1360nm for 1210+1267nm pumping. When using 1240+1267nm pump the gain was increased to 24±1dB as shown in Fig. 7. This can be attributed to the higher UL in fiber at 1210nm compared to 1240nm pump. Thus the optimum pumping wavelengths for our dual pumped BPSF amplifier with a broad gain spectrum were found to be around 1240 and 1267nm.

In conclusion, we fabricated BPSFs under different oxidation conditions using MCVD-solution doping technique. The UL was measured at 1210nm and 1267nm pump wavelengths, respectively and was found to be lower at 1267nm in comparison with the 1210nm pumping. BPSF with the lowest UL was used to develop an all-fiber Bi-doped amplifier. The gain profile dependence of the amplifier on the pump wavelength was demonstrated. It has been shown that with the 1267nm pump the amplifier gain is pushed toward the longer wavelength with a gain peak appeared close to 1350nm, whereas with the 1240nm pump the gain is shifted to shorter wavelength side with a maximum gain obtained at around 1330nm. The amplifier was also bi-directionally pumped using two pumps in order to flatten the gain spectrum of the amplifier. A flat gain of 25±1dB was demonstrated over a 40nm bandwidth covering the wavelength region of 1320-1360nm (which is currently limited by the input signal source) by bi-directional pumping the fiber at wavelengths 1267 and 1240nm. Furthermore, a small signal gain of about 29dB was obtained for an input signal power of -30dBm, which, to best of our knowledge, is the maximum gain, reported from a BDFA operating in the second telecommunication window.

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