A 40dB Gain all Fiber Bismuth-doped Amplifier Operating in O-band

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In this paper we investigated the gain and noise figure characteristics of Bi-doped fiber in single and double-pass configurations. A maximum gain of 25dB and noise figure of 3.6dB is measured in single pass configuration whereas in double pass configuration the gain of the amplifier is improved significantly to 14dB and achieved the best results of 39dB gain with a noise figure of 5dB. To the best of our knowledge this is the maximum gain reported to date with Bi-doped fiber as a gain media. Further, we also studied the effect of pump power, signal power and pump wavelength on gain and noise figure characteristics in double pass configuration. It is reported that similar gain and NF performance can be achieved in double pass configuration with less pump power and shorter length of the Bi-doped fiber compared to single pass configuration.

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The global optical communication with the increased demand for data transfer rates is in constant search for the next generation of optical communication systems with increased capacity. This high demand is the outcome of many internet based applications such as mobile communication, cloud computing, social media, e-learning and e-commerce etc. The capacity of conventional single mode fiber (SMF) is limited to 11THz due to the available amplification bandwidth (1530-1620nm) of erbium (Er)-doped fiber. On the other hand the capacity of SMF considering the loss of <4dB/Km can be scaled upto 47THz (1260-1530nm and 1625-1675nm). The use of this window in combination with efficient fiber amplifiers can surge the capacity to more than four fold. To develop RE-doped fiber amplifiers in this window from 1260-1530nm and 1625-1675nm many amplifier technologies such as praseodymium (Pr) and neodymium (Nd)-doped fiber amplifiers (in O-band), Raman fiber amplifiers (in E-band), extended Er- doped fiber amplifiers (in S-band) and thulium (Tm)-doped fibre amplifiers (in U-band) are being explored [1]. In this paper we focus on the development of fiber amplifier to cover the O-band (1260-1360nm). Amplification in O-band can be achieved by conventional RE-doped fibres (Pr and Nd- doped fluoride fibers) or by non-linear wavelength amplification (Raman fibre amplifiers). However, in case of Pr and Nd- doped fibers fluoride glass host must be used instead of silica to reduce the unwanted processes such as up-conversion and excited state absorption (ESA). Whereas in case of Raman fiber amplifiers, the high power requirement is a drawback compared to RE-doped fiber amplifiers [2]. Recently, Bi as a dopant in fibers with different host materials such as aluminosilicate, phosphosilicate and germanosilicate shown promising results to develop amplifiers in the wavelength bands covering from 1150-1500nm [3, 4]. A maximum gain of 10dB at 1180nm and 25dB at 1340nm was demonstrated using Bi-doped aluminosilicate and phosphosilicate fibers, respectively [5, 6]. M. A. Melkumov et. all, reported a maximum gain of 24dB at 1430nm using Bi-doped phosphogermanosilicate fibers [7]. Also, high concentration germanium up to 50mol% was used to develop Bi-doped fiber amplifiers at 1700nm and a maximum gain of 23dB was reported [8, 9]. These fibers in different wavelength bands are not only useful to develop amplifiers for optical fiber communication but they also have applications in medicine and in astrology. Here, we use Bi-doped phosphosilicate fibers to develop amplifier in the O-band. Developing amplifiers in the O-band would allow the upgrade of presently installed systems based on conventional single mode fibers. Although, Bi-doped fibers are a promising active medium to develop efficient fiber amplifiers in the wavelength band inaccessible by RE-doped materials, a comparatively low gain per unit length is the current challenge. This is due to the unwanted losses such as unsaturable loss and ESA that are present in Bi-doped fibers [10-12]. One way to improve the performance of Bi-doped fiber amplifiers is to use alternative approaches such as bi-directional pumping or wavelength selective pumping, single or multi-stage amplifier configurations etc. [13-16]. Here, we explore the possibility of increasing the performance of Bi-doped fiber in terms of gain and NF characteristics by exploiting the double pass amplifier configuration and compared the results with conventional single pass amplifier configuration. In addition, pump power, signal power and pump wavelength dependent gain and NF characteristics were studied in double pass configurations. A gain of 25dB and NF of 3.6dB is measured at 1360nm in single pass configuration whereas it is improved significantly to 40dB in double pass configuration.

A Bi-doped phosphosilicate fiber used in this work was fabricated by conventional MCVD-solution doping technique. The fiber has a core and cladding diameter of 9 and 125μm. The index difference (Δn) between the core and clad was around 0.004. The cut off wavelength of the fiber was measured to be around 980nm. The absorption spectrum of the fiber was measured by cut-back method using a white light source (WLS) and an optical spectrum analyzer (OSA). The absorption at 1270nm pump wavelength was 0.57dB/m whereas at signal wavelength of 1330nm it was 0.5dB/m.

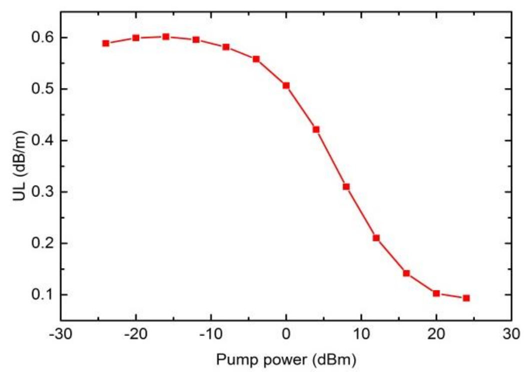


Fig. 1. Variation of loss with pump power of Bi-doped fiber at 1240nm

Variation of loss with pump power (unsaturable loss) was measured using a laser diode (LD) operating at 1240nm as shown in Fig. 1. With a small signal loss of 0.59dB/m measured by LD, the percentage of UL was 15%. The experimental setup to measure gain and NF of Bi-doped fiber in single pass (solid) and double pass (dashed) configurations are shown in Fig. 2. Two LDs operating at 1270nm with a pigtail fiber output power of 500mW each were used to pump the Bi-doped fiber under test. A 1240nm LD was also used to study the pump wavelength dependent gain of Bi-doped fiber. Isolators were used to protect the pump and tunable laser source (TLS).

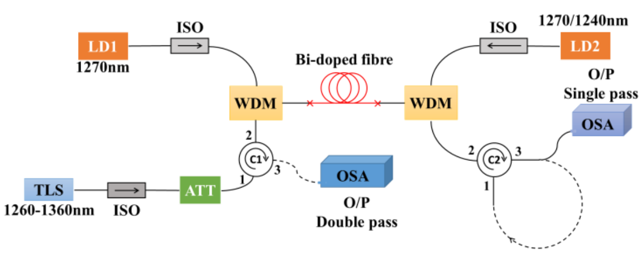


Fig. 2. Experimental set-up of single (solid) and double (dashed) pass Bi-doped fiber amplifier

Two wavelength division multiplexers (WDMs) were used to combine and separate the pump and signal wavelengths, respectively. An attenuator (ATT) was used to vary the input signal power whereas two circulators (C1, C2) operating in O-band were used to construct the double pass configuration. Circulator 1 (C1) was used at the amplifier input to couple signal into and out from the active fiber. A signal source operating from 1260-1360nm in conjunction with an optical spectrum analyzer (YOKOGAWA AQ6370) was used to measure the gain and NF of the Bi-doped fiber (BDF). The amplifier performance is compared with the single pass configuration which was obtained by disconnecting the ports 3 and 1 of circulator 2 (C2).

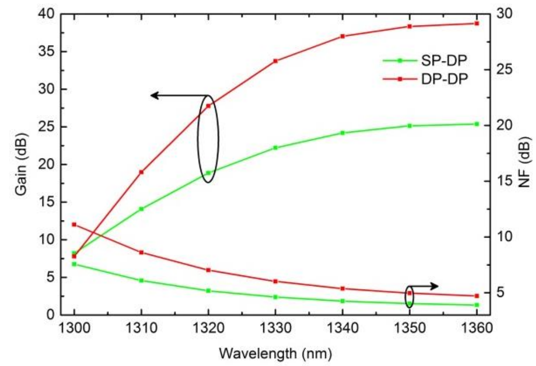
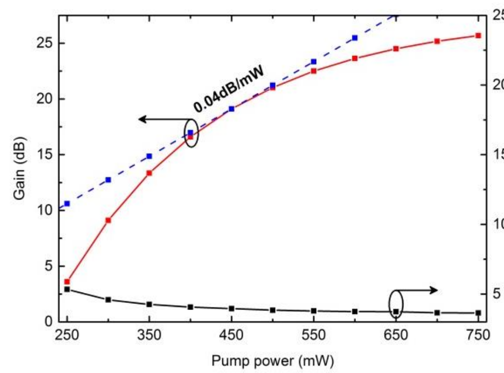


Fig. 3. Gain and NF characteristics of 152m long Bi-doped fiber for -23dBm input signal power in single pass and double pass configuration

Initially, the gain and NF were measured in single pass configuration as shown in Fig. 2. Two 1270nm LDs in bi-directional pumping configuration were used. The total pump power launched into the Bi-doped fiber was amounted to be 785mW with LD1 diode power of 385mW and LD2 diode power of 400mW at the input of the active fiber. The gain and NF were measured in 152m long BDF with a signal power of -23dBm in a single pass configuration and are shown in Fig. 3. A maximum gain of 25dB and NF of 3.6dB was achieved at 1360nm. Moreover the gain from 1325-1360nm is more than 20dB with a NF less than 5dB. It can be noted that our amplifier could potentially operate greater than 1360nm, which we are currently unable to measure due to the limitations of our signal source (TLS) operating only in the O-band. We then investigated the double pass configuration as shown in Fig. 2. The gain and NF of 152m length of the BDF was measured with a total pump power of 785mW and is shown in Fig. 3. A maximum gain of 39dB and NF of 4.7dB at 1360nm was measured, whereas the gain is only 7.79dB at 1300nm for an input signal power of -23dBm. A gain improvement of 35% with slight increment in NF was achieved with double pass configeration compared to single pass configeration. Also the gain from 1320-1360nm is more than 25dB. Note here in both cases (single pass and double pass) the pump power and fiber length were same. The increased gain in double pass configeration is due to the feedback of the signal into the active media where as the increase in NF is due to the backward amplified spontaneous emission (ASE) that is high at the input part of the fiber that reduces the population inversion and hence increase the NF.

Figure 4. a. shows the gain and NF with pump power in single pass configeartion for -23dBm input signal power in a 152m long BDF at 1360nm. Here the total pump power used from both LDs was 750mW. A maximum gain of 25dB with a NF of 3.6dB was measured at 1360nm. The gain starts to saturate after 550mW of pump power. The gain coefficient was caluculated and found to be 0.04dB/mW as shown in Fig.4. a. We also measured the variation of gain and NF with pump power at 1360nm in double pass configeration for -23dBm input signal power as shown in Fig. 4. b. A maximum gain of 39 and NF of 4.1dB were measured for -23dBm input signal power. A 3dB saturation pump power was 550mW. Gain coefficient of the Bi-doped fiber amplifier in double pass configuration was calculated and found to be 0.07dB/mW.



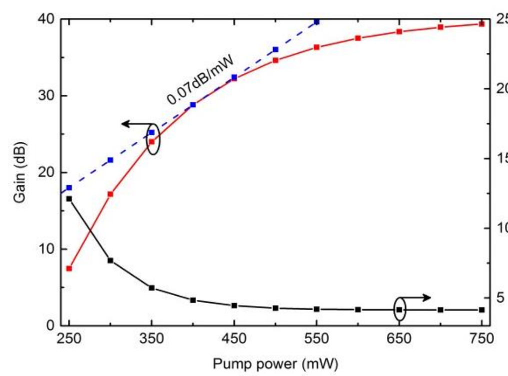


Fig. 4. Gain and NF with pump power for 152m long Bi-doped fiber at 1360nm for -23dBm input signal power a) in single pass configeration b) in double pass configeration

The gain with signal power was measured at 1360nm as shown in Fig. 5. for a double pass configuration with a pump power of 785mW. A maximum gain of 40dB with a NF of 5.4dB was measured at 1360nm for -30dBm of input signal power. We noticed that the gain saturation is faster with signal power in case of double pass configeration compared to single pass configeration due to the high ASE power that leads to self saturation in double pass configeration compared to single pass configeration.

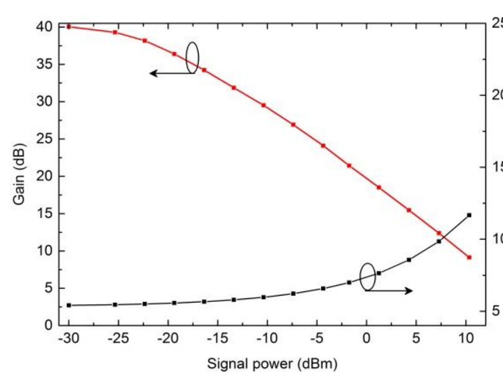


Fig. 5. Gain and NF with signal power for 152m long Bi-doped fiber at 1360nm with a pump power of 785mW

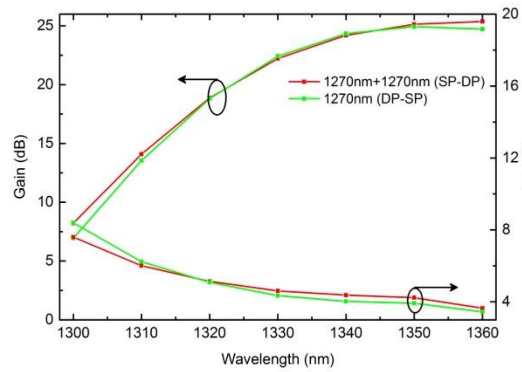


Fig. 6. Gain and NF comparison of single pass double pump (SP-DP) and double pass single pump (DP-SP) configurations for a signal power of -23dBm

It is important to note that the same gain and NF were achieved as in case of single pass and double pump configuration with double pass and single pump configuration. The pump power used in case of single pass double pump configuration was 785mW whereas in case of double pass single pump configuration it was reduced to 385mW. Moreover, the required length in case of double pass and single pump configuration was reduced to 33% from 150m to 100m. A max gain of 25dB with NF of 3.5dB was achieved in both cases for an input signal power of -23dBm. The comparison of gain and NF of single pass double pump and double pass single pump configuration is shown in Fig. 6.

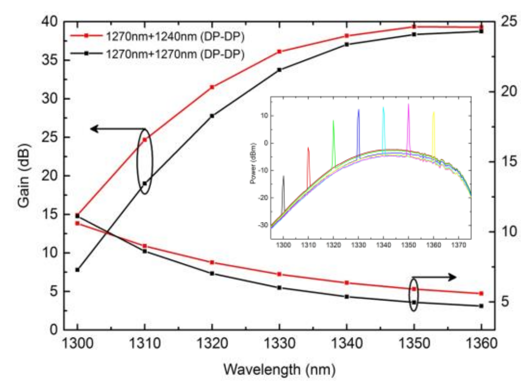


Fig. 7. Gain and NF comparison of 152m long Bi-doped fiber in double pass configuration with double pump for different wavelength combination for a signal power of -23dBm (Inset shows the amplified spectra of the -23dBm input signal measured in case of 1270nm+1240nm pump configuration)

Further, the gain and NF were also measured in 152m long BDF using double pass configuration with double pump for different pump wavelength combination for a signal power of -23dBm and is shown in Fig. 7. A total pump power of 785mW was used for 1270nm+1270nm pump combination, whereas 760mW was used for 1270nm+1240nm pump combination. The gain is more flat in case of 1270nm+1240nm pump combination compared to 1270nm+1270nm pump combination, whereas there is slight increase in NF in 1270nm+1240nm pump configeration. We also measured the amplified spectra of the -23dBm input signal power in case of

1270nm+1240nm, as shown in inset of Fig. 7. A maximum optical signal to noise ratio (OSNR) of 19dB was observed at 1350nm.

In conclusion, we measured the gain and NF of Bi-doped phosphosilicate fiber in single and double pass configurations. The gain and NF in single pass configurations was 25 and 3.6dB, respectively whereas in double pass case it was increased to 39dB with a NF of 4.7dB for -23dBm of signal power. Further, a record gain of 40dB was measured in double pass configeration for -30dBm signal power. To the best of our knowledge this is the maximum gain reported from a Bi-doped fiber amplfier operating in O-band. The gain variation with pump power was also studied for single and double pass configurations and calculated the gain coefficient in both cases. 40% increment in gain coefficient was obtained in double pass configeration compared to single pass configeration. The double pass configuration clearly helps to increase the gain of the Bi-doped fiber by propagating the signal again through the active fiber with a slight increase in NF. The double pass configuration can also help to reduce the fiber length and pump power required to achieve the similar gain that are possible with longer lengths and higher pump powers in single pass configuration.

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