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Bi-doped fiber amplifiers and lasers [Invited]

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Abstract: Bismuth (Bi) doped fibers have shown promising potential for lasers and amplifiers in the 1150-1500 nm and 1600-1800nm wavelength region. Bi-doped aluminosilicate, phosphosilicate and germanosilicate fibers provide luminescence around 1150 nm, 1300 nm and 1450 nm, respectively. Recent results have demonstrated the possibility to extend the Bi luminescence window beyond 1600 nm using Bi-doped high (≥ 50 mol %) germanosilicate fibers. These spectral regions can serve a wide range of applications in medicine, astronomy, defense and to extend the optical fiber communication. However, Bi-doped fiber lasers and amplifiers are still far from their optimum performance owing to the unclear nature of the near-infrared emitting Bi active centers. In this paper, we review the current state of the art of Bi-doped silica fiber lasers (CW and pulsed) and amplifiers in different wavelength bands. Also, we present our work on the development of Bi-doped aluminosilicate and phosphosilicate fiber lasers and amplifiers in the 1180 nm and 1330 nm bands. These lasers and amplifiers find applications in generating visible light sources and to access the second telecommunication window. The fibers used here were fabricated by modified chemical vapor deposition-solution doping technique and characterized for their unsaturable loss. Moreover, we present the influence of pump wavelengths on the gain, noise figure and laser efficiency of these Bi-doped fiber amplifiers and lasers. We also discuss Bi-doped fibers for pulsed laser application and demonstrate a mode-locked Bi-doped fiber laser operating at 1340 nm.

1. Introduction

Over the years the performance of rare earth (RE)-doped fibers have been improved significantly in the wavelength bands around 1 µm, 1.5 µm, and 2 µm using Ytterbium (Yb), Erbium (Er) and Thulium (Tm) or Holmium (Ho)-doped fibers, respectively. Concurrently, exploring new dopant materials as a gain media in optical fibers to develop lasers and amplifiers has become a burgeoning research area, especially to access the wavelength bands not covered by RE-elements such as 1150-1500 nm. The interest stems from the widespread applications offered by the amplifiers and lasers in these wavelength bands [1–5]. Bismuth (Bi)-doped fibers have paved the way to develop amplifiers and lasers in these missing wavelength bands, thanks to its host dependent luminescence characteristics. Bi-doped silica fibers in different glass hosts (i.e., aluminosilicate, phosphosilicate and germanosilicate) have shown broad luminescence covering from 1150-1500 nm. It is also possible to extend the Bi luminescence window beyond 1600 nm using Bi-doped high (≥50 mol %) germanosilicate fibers (BHiGSFs). Among, Bi-doped lasers in germanosilicate host have reached laser efficiencies higher than 50% [6]. On the other hand, the achieved laser efficiencies of Bi-doped aluminosilicate (BASFs) and Bi-doped phosphosilicate fibers (BPSFs) are comparatively low. In particular, there is a necessity to develop efficient BASFs and BPSFs because of their capacity to generate visible light by frequency doubling, and lasers and amplifiers in the second telecommunication window, respectively. Initial demonstrations

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based on BASFs and BPSFs have created interest in the scientific community, and efforts are now focused on improving the performance in terms of amplifier gain and laser efficiency. However, few challenges need to be addressed to improve the performance of Bi-doped fiber amplifiers (BDFAs) and lasers. One of them is the unknown Bi-state that contributes to near-infrared (NIR) luminescence. Bi is a heavier element that has a fundamentally different electronic structure in comparison to commonly used RE-elements such as Yb, Er and Tm or Ho. Bi has the electronic configuration of (Xe) $4f^{14}5d^{10}6s^{2}6p^{3}$, where the outer 6s and 6p electrons can have the significant interaction with the host glass, thereby showing host dependent absorption and emission properties. In addition, Bi exhibits a number of oxidation states such as + 1, +2, +3 and + 5 [7]. There are a number of hypotheses regarding the origin of NIR luminescence centers in Bi glasses: Bi clusters [8], BiO [9], Bi^{5+} [10], Bi^{+} and some other low valence states of Bi ions including metallic Bi [11,12], point defects [13], and Bi dimers [14]. In recent years, it was reported that the oxygen deficiency center in combination with Bi in low oxidation state in BGSFs contributes to NIR luminescence [15–17]. Despite all these experimental and theoretical predictions, the topic is still an interesting scientific problem that needs to be solved in order to develop efficient Bi-doped fibers for amplifiers and lasers. Another one is the unwanted losses of these fibers caused by unsaturable loss (UL) and excited state absorption (ESA) [18–20]. UL and ESA are two detrimental effects that can reduce the efficiency of amplifiers and lasers. In this paper, we review our work on the BASF and BPSF lasers and amplifiers for 1180 nm and 1330 nm wavelength bands, respectively. The 1180 nm wavelength has applications in astronomy and the 1330 nm wavelength region is to access the O-band for optical fiber communication. We study the dependence of pump wavelength on the performance of these Bi-doped fiber lasers and amplifiers. We also investigate the gain and noise figure (NF) characteristics of BPSF amplifier, while operating in single and double pass configurations. Furthermore, BPSFs with relatively high Bi concentration were fabricated for applications such as pulsed fiber lasers. These fibers were tested for the lasing performance. One of the high concentration Bi-doped fiber that shown lasing in 10 m long Bi-doped fiber (BDF) was used to develop mode-locked Bi-doped fiber laser operating at 1340 nm.

2. State of the art of Bi-doped aluminosilicate and phosphosilicate fibers

2.1. Bi-doped fiber lasers and amplifiers from 1100-1250nm

In 2001, Fujimoto and Nakatsuka discovered wideband NIR luminescence from Bi and Al co-doped silica glass, which took place in the spectral region of 1100-1500 nm [21]. Subsequently, a large number of glass compositions were investigated to obtain luminescence in the wavelength range from 1000-1600 nm and the details can be found in a review by Fujimoto [22]. After five years in 2005, the first Bi-doped fiber was fabricated by MCVD-solution doping technique [23,24]. In the same year, the first Bi-doped fiber laser was demonstrated in aluminosilicate host [25]. The BASF exhibits absorption bands at 500, 700, 800 and 1000 nm and a luminescence band around 1150 nm with a full width at half maximum (FWHM) of 150 nm. The luminescence lifetime in these fibers was ~1 ms. In the first experiment with BASFs, a linear cavity with fiber Bragg gratings (FBGs) was constructed to develop CW lasers. Lasers were demonstrated at 1146 nm and 1215 nm by changing the FBGs. An Nd: YAG laser at 1064 nm was used as a pump source with a 5W of pump power. The obtained slope efficiency was 10% and 14% at 1146 nm and 1215 nm, correspondingly. At that point, the motivation to develop these fibers was to access the 1100-1250 nm wavelength band with possible applications to develop broadband amplifiers and tunable ultrafast lasers. Afterward, the application area was broadened by developing sources in the yellow wavelength range from 575-590 nm by frequency doubling, which are of great importance in dermatology [26], ophthalmology [27] and in astronomy [28]. Fiber lasers are advantageous to develop efficient, compact and reliable sources for these applications. After this, a number of CW BASF lasers were developed at 1150 nm, 1160 nm, 1178 nm, 1205 nm

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and 1215 nm by changing the pump wavelength and FBGs. Among these, maximum efficiency of up to 28% at room temperature and up to 50% at 77 K was reported at 1160 nm [29–32]. Influence of cooling on Bi-doped fiber laser and amplifier performance was studied at 1179 nm and reported that effective heat removal can boost the laser and amplifier performance by reducing the temperature dependent UL in the fiber [33]. These fiber lasers are suitable for visible light generation by frequency doubling using non-linear crystals. To demonstrate this potential, a 580 nm laser with a 300 mW of output power was developed by frequency doubling the 1160 nm laser with a potassium titanyl phosphate (KTP) crystal. A visible laser at 589 nm was also demonstrated by frequency doubling the 1178 nm laser by periodically poled MgO-doped lithium niobate crystal (MgO-PPLN) [34,35]. Figure 1 shows the output power and slope efficiency of BASFs operating in the wavelength band from 1140-1230 nm. Maximum power of 15W was demonstrated at 1160 nm with a slope efficiency of 22%.

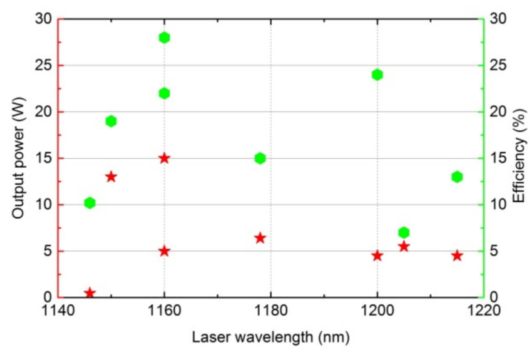

Fig. 1. Output power and slope efficiency of Bi-doped aluminosilicate fiber lasers in the wavelength band from 1140-1220 nm [25,29–36].

Although the efforts were appreciated to develop BASF lasers, there was much less progress made in developing amplifiers around 1100 nm. To the best of our knowledge, a maximum gain of about 5 dB was demonstrated in BASF amplifier at room temperature operating at 1180 nm [37]. As a pump source, a high-power Yb-doped fiber laser operating at 1060 nm with a maximum output power of 6.5W was used. In the next section, we discuss our work on an all-fiber amplifier operating at 1180 nm with a maximum gain of 12 dB.

2.2. Bi-doped aluminosilicate fiber amplifier at 1180nm

The Bi-doped aluminosilicate preform fabricated by MCVD-solution doping technique was used to develop an amplifier in the 1180 nm wavelength band [38]. The preform was drawn into a fiber that has the core diameter of 8μm with an index difference (Δn) of 0.008. The cladding diameter of this fiber was 100μm. The fabricated fiber was characterized for absorption and UL and the results are shown in Fig. 2 and Table 1. The small signal absorption was 0.28dB/m and 0.66dB/m, whereas UL was found to be 35% and 65% at 1120 nm and 1047 nm pump wavelengths, respectively.

Table 1. Small signal loss and UL at 1120 and 1047 nm pump wavelengths [38]

Wavelength (nm)	Small signal loss (dB/m)	UL (dB/m)	%UL
1120	0.28	0.1	35
1047	0.66	0.43	65

The maximum pump power used in both cases was 350 mW. Figure 3(b) shows the ASE spectra with 1120 nm and 1047 nm pumping, the ASE peak with 1047 nm pump appeared around

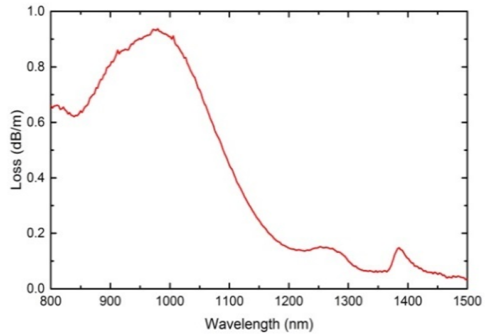

Fig. 2. The absorption spectrum of BASF [38].

1150 nm, whereas, 1120 nm pumping helps to push the ASE to slightly longer wavelength with a peak at 1180 nm. This indicates that higher gain can be extracted at longer wavelengths by pumping with 1120 nm LD. A 1120 nm LD with an output power of 350 mW was used to measure the gain of BDFA. We obtained a maximum gain of 7.5 dB at 1180 nm for a fiber length of 100 m. The input signal power was -1dBm. Whereas a maximum gain of 4.4 dB was obtained in 20 m long BDFA with 1047 nm pump wavelength with the same input signal power. The 1120 nm pump provided a gain enhancement of 70% compared to 1047 nm pumping.

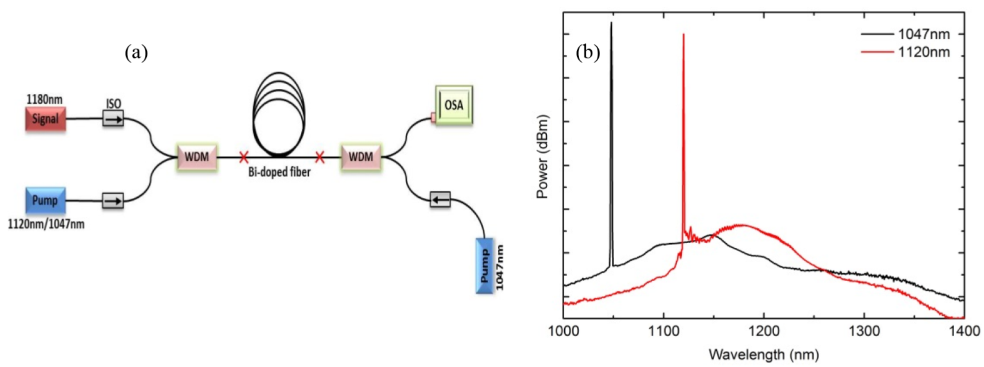

Fig. 3. (a) Schematic of BASF amplifier (b) ASE spectra for 1047 and 1120 nm pump wavelengths (Pump power: 350 mW) [38].

Further, the gain variation with pump power was measured for -4dBm input signal power in 100 m long BDF. Both 1120 nm and 1047 nm pump wavelengths were used to enhance the gain of the amplifier. A maximum gain of 10 dB was obtained via simultaneous pumping of BASF at 1120 nm and 1047 nm as shown in Fig. 4(a). A relatively small gain enhancement under dual pumping conditions can be explained by an increase in UL with the addition of 1047 nm pump as shown in Fig. 4(b). This clearly indicates that higher pump power at a wavelength around 1120 nm will be more suitable to increase gain in BASF operating at around 1180 nm. A further 2 dB improvement was noticed by optimizing the length of BDF in double pumping configuration. A maximum gain of 12 dB was achieved in 140 m long BDF by dual pumping at 1120 nm and 1047 nm with a total pump power of 700 mW.

2.3. Bi-doped fiber lasers and amplifiers from 1300-1500nm

The successful demonstration of lasers and amplifiers in BASFs elevated the interest to study the Bi-dopant in different host materials and it was found that instead of Al if co-doped the core with

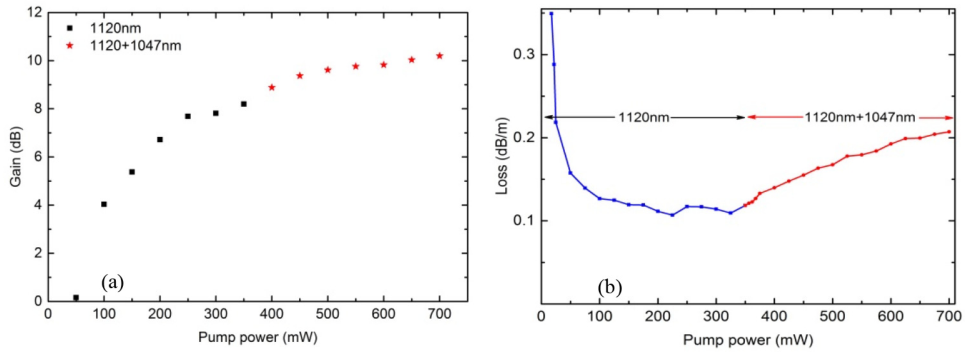

Fig. 4. (a) Gain with pump power at 1180 nm for a 100 m long fiber with a signal power of -4dBm (b) Loss variation in BDF for single 1120 nm pumping (blue line) and for 1120 nm + 1047 nm pumping (red line) by varying the power of 1047 nm pump while operating the 1120 nm pump at its maximum power of 350 mW [38].

P and Ge then the NIR luminescence shift towards longer wavelength side. Later, BPSFs and Bi-doped germanosilicate fibers (BGSFs) were studied to demonstrate lasers and amplifiers in the wavelength range from 1270-1500 nm. However, it was observed that the performance of BPSFs was better when introduced a small amount of Ge in the core. The addition of Ge makes the luminescence window broad covering the entire 1300-1500 nm band. Here, we review the lasers and amplifiers developed using Bi-doped phosphogermanosilicate fibers (BPGSFs). The lifetime in these fibers was measured to be ~600µs at 1300 nm by pumping at 808 nm. The first fiber laser in the wavelength band from 1270-1400 nm was demonstrated in BPGSF [39]. A Raman fiber laser operating at 1230 nm was used as a pump source. A 30 m BPGSF was used as an active gain media. Laser at 1310 nm was demonstrated with an efficiency of 3.2% (T = 300 K) and 5.4% (T = 77 K). Further, at high pump powers, the slope efficiency was different and reached 19% (T = 300 K) and 29% (T = 77 K). By changing the pump wavelength to 1210 nm lasing at 1310 nm was also demonstrated. The lasing efficiency was 1.4% (T = 300 K) and upon cooling to 77 K it was 5%. The observed laser slope efficiency strongly depends on temperature and increased at liquid nitrogen temperature due to four-level laser behavior.

Later, lasing at 1280 nm and 1330 nm were demonstrated using the BPGSFs by pumping at 1230 nm with efficiencies of 12% and 24%, respectively [40]. In addition, lasers at 1280 nm, 1330 nm, 1340 nm, 1360 nm and 1480 nm were also demonstrated with 90-100 m long BPGSF. FBGs with different output coupling (OC) ratio were used to test the laser efficiencies. A Raman fiber laser operating at 1230 nm was used as a pump source to demonstrate Bi-doped fiber lasers between 1280-1360 nm and a 1340 nm Raman fiber laser pump was used to demonstrate lasing at 1480 nm. The maximum available pump power of these pump sources were 30W and 10W, respectively.

It was observed that the slope efficiency depends on the OC of FBGs and the laser wavelength. The most linear dependence was observed in the case of a 1330 nm laser with 25% OC of FBG. Among all these lasers a maximum slope efficiency of 37% was reported in case of a 1330 nm laser with 50% OC of FBG with an output power of 10.6W [44]. Further, a tunable laser operating between 1366 nm to 1507 nm was demonstrated with the help of an external diffraction grating and using a long-period fibre grating in the laser cavity. The laser cavity was formed by a loop reflector (Sagnac mirror) and a plane diffraction grating. The active fiber length was 65 m. A 1.34 µm Raman fiber laser with a pump power of 300 mW was used as a pump source. The output power of the laser varies from 25 mW to 50 mW [45]. A summary of BPSF lasers operating in

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the wavelength band 1250-1550 nm is shown in Fig. 5. Maximum power of 10.6W with a slope efficiency of 37% was demonstrated at 1330 nm.

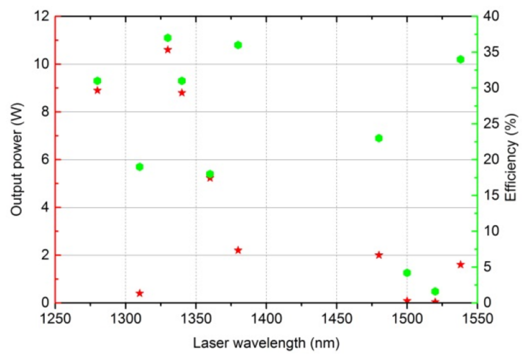

Fig. 5. Output power and slope efficiency of Bi-doped fiber lasers in the wavelength band from 1250-1550 nm [39–43]

Compared to BASF amplifiers, good progress was made in the development of Bi-doped amplifiers within the wavelength range 1300-1500 nm using Bi-doped fibers with a phosphogermanosilicate host. This was driven by the need for amplifiers in the second telecommunication band. A conventional experimental setup was used to measure the gain and NF. Two CW Raman fiber lasers operating at 1230 nm and 1318 nm were used as pump sources. The length of the Bi-doped fiber was 200 m. A pump power of 460 mW and 190 mW at 1230 nm and 1318 nm respectively were used to measure the gain and NF of the amplifiers. A maximum gain of 24.5 dB and 20.7 dB were measured at 1321 nm and 1442 nm, respectively. The minimal NF of 4-6 dB was reported for both amplifiers [44,46]. Also, a bismuth-doped fiber amplifier at 1430 nm pumped by a 65 mW commercial laser diode at 1310 nm was reported in [47]. A common amplifier scheme was used to measure the gain and NF of 125 m long Bi-doped fiber. A maximum gain of 24 dB at 1427 nm with a NF of 6 dB was measured for -20dBm input signal power. The maximum gain co-efficient was 0.4 dB/mW. The power conversion efficiency was measured at 50 mW and 250 mW pump powers. A maximum power conversion efficiency of 60% was reported for a pump power of 250 mW in the saturated regime. In the following section, we discuss our work on the development of Bi-doped phosphosilicate fiber lasers (CW and tunable) and amplifiers in the O-band.

2.4. Bi-doped phosphosilicate fiber lasers (CW and tunable) and amplifiers for O-band optical fiber communication

The Bi-doped phsophosilicate preform used in this work was fabricated by MCVD-solution doping technique. The preform was then drawn into a fiber with a core and cladding diameter of 9 μm and 125 μm with an index difference (Δn) of 0.004.

The absorption at 1270 nm pump wavelength was 0.59 dB/m. The UL was measured as 15%. The cut-off wavelength of the fiber was measured to be around 980 nm. This BPSF was then used to demonstrate a Bi-doped fiber laser. All-fiber laser in a ring cavity has been developed by pumping bi-directionally with two 1270 nm LDs as shown in Fig. 6(a). FBG of 50% OC and a fiber length of 70 m were used. The resulting laser operating at 1340 nm has an efficiency of 14.5% with an output power of >100 mW at 1340 nm as in Fig. 6(b).

Further, a wideband tunable Bi-doped fiber laser operating in the O-band was constructed with the same BDF. The schematic of the tunable Bi-doped fiber laser is shown in Fig. 7(a). A fiber coupled tunable filter was used to achieve the tuning between 1317-1375 nm. A total pump power of 790 mW from the two 1270 nm LDs was used. A maximum output power of 60 mW with a

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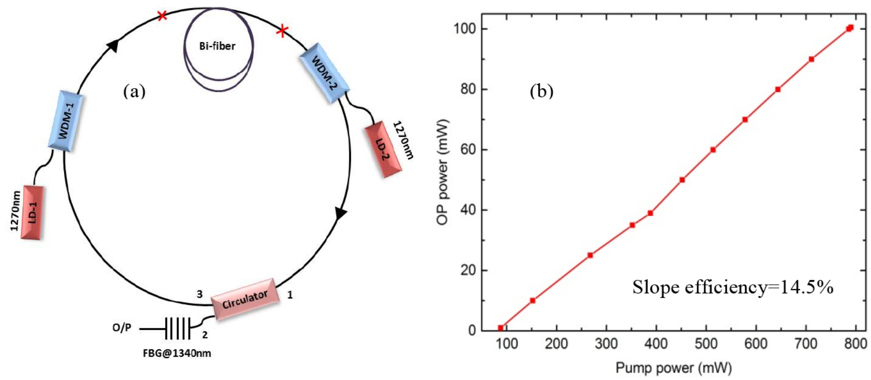

Fig. 6. (a) Schematic experimental set up of BPSF ring laser (b) Output power in BPSF laser with a launched pump power for 50% FBG reflectivity with 70 m long fiber (Pump and laser wavelengths: 1270 nm and 1340 nm).

slope efficiency of 10% was obtained at 1353.3 nm. The linear dependence of output power on pump power indicates that the output power can be scaled further by increasing the pump power of the laser diodes. Moreover, the output power was more than 50 mW from 1333 nm to 1362 nm in 29 nm bandwidth. The spectra of the tunable laser are shown in Fig. 7(b). The optical signal to noise ratio (OSNR) of more than 48 dB was achieved in the entire tuning range (1317-1375 nm) with 0.5 nm OSA resolution bandwidth. Further, a Bi-doped fiber amplifier (BDFA) was used to increase the output power of the tunable Bi-doped fiber laser. Two pump LDs operating at 1270 nm and 1240 nm with a combined pump power of 763 mW was used in the amplifier. A maximum output power of 144 mW was measured at 1335 nm. Also, the output power of more than 100 mW was obtained from 1318 nm to 1370 nm in 52 nm bandwidth.

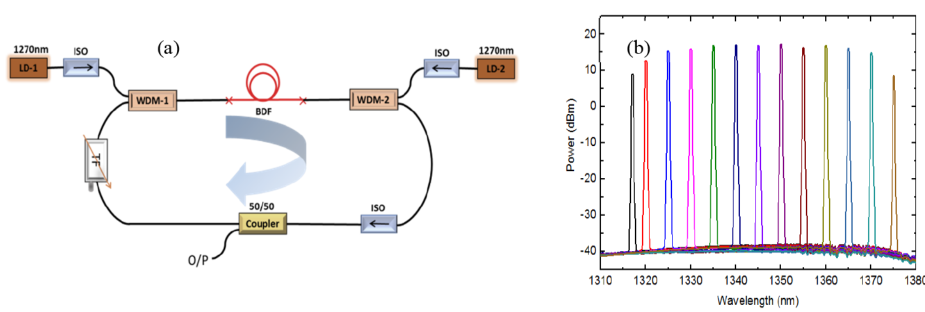

Fig. 7. (a) Schematic experimental setup of a tunable Bi-doped fiber laser (b) Spectra of the tunable Bi-doped fiber laser from 1317 nm to 1375 nm with 5 nm spacing between 1320-1375 nm.

In addition to the aforementioned demonstrations, a single pass BPSF amplifier was constructed as shown in Fig. 8(a) (solid). Initially, the BDF was individually pumped by 1270 nm and 1240 nm LDs with pump powers of 385 mW and 378 mW, respectively to evaluate the gain and NF. The input signal power was -10dBm.

A flat gain of 22 ± 1 dB with a NF of <6 dB was achieved over a 40 nm bandwidth from 1320-1360 nm (limited by the wavelength range of our tunable laser source), for the 150 m long BPSF as shown in Fig. 8(b). On the other hand, by using the two 1270 nm LDs instead of a combination of 1270 nm and 1240 nm, the gain towards shorter wavelength side at 1300 nm was dropped down to approximately 4 dB. Thus the 1240 nm pump can shift the gain towards

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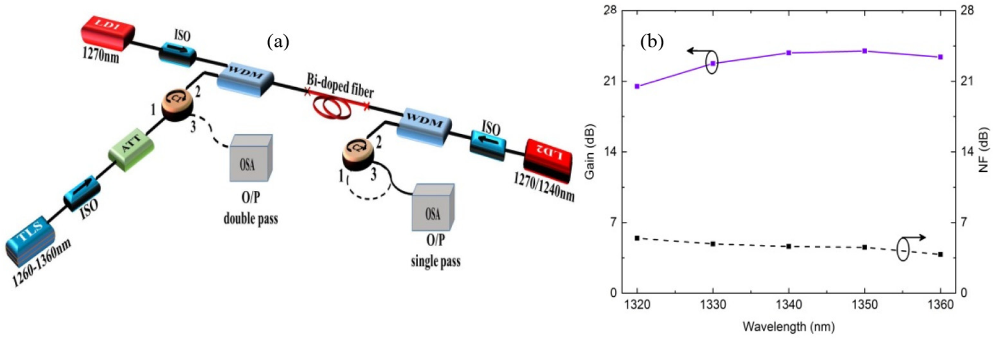

Fig. 8. Bi-doped fiber amplifier: (a) Schematic experimental setup for single and double pass configuration, and (b) gain characteristics with a flat gain of 22 ± 1 dB from 1320-1360 nm in single pass configuration.

shorter wavelength side and helps to achieve flat gain [48,49]. The flat gain BPSF amplifier developed was used to demonstrate both course and dense wavelength division multiplex (WDM) transmission systems spanning over 100 km and 120 km of SMF-28e, respectively in the O-band. Details of the transmission experiment can be found in [50].

Further a double pass BDFA was constructed by feeding back the signal into the active fiber with the help of a circulator as shown in Fig. 8(a) (dashed) [51]. The gain and NF characteristics of the double pass BDFA with wavelength are shown in Fig. 9. A gain of 31 dB with a NF of 7 dB for -10dBm of input signal power was achieved at 1360 nm with a total pump power of 763 mW. It is to be noted that the gain is more than 20 dB from 1310 nm to 1360 nm in the double pass configuration. Moreover, the gain from 1330-1360 nm is nearly 29 ± 1 dB, such an amplifier is suitable for dense wavelength division multiplexing (DWDM) optical fiber communication applications. The gain coefficient of the amplifier was 0.06 dB/mW. The power conversion efficiency for -10dBm input signal was also calculated and found to be 11% at 1340 nm. The gain of the amplifier was further improved by reducing the input signal power to -30dBm and achieved a 40 dB gain at 1360 nm. It is also observed that the same gain as in the single pass case can be achieved using the double pass configuration with a reduced pump power or BDF length.

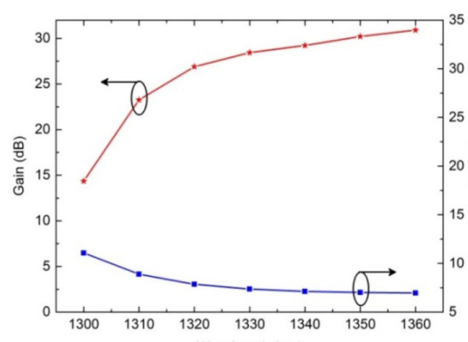

Fig. 9. Gain and NF characteristics for -10dBm input signal, of 152 m long BDF in double pass configuration with a pump power of 763 mW (1270nm-385 mW, 1240nm-378 mW) [51].

The current BDF length required to develop the amplifier is long (100 m and above) due to the low Bi concentration. It is possible to increase the Bi concentration during preform

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fabrication but the NIR gain contribution in Bi-doped fibers depends on BAC rather than the total Bi concentration in the fiber. Few examples are given in Table 2, to show the influence of Bi concentration in BPSFs on the amplifier performance. In case of BPSF-1, in which the UL and OH are low, a maximum gain of 40 dB was achieved in double pass configuration in 150 m long BDF. Comparing BPSF-2 and BPSF-1, we have shown that by increasing the Bi concentration it is possible to bring the device length of the fiber around 100 m, however, the maximum gain achieved was 30 dB due to increased UL and OH content compared to BPSF-1. Also, comparing BPSF-3 and BPSF-4, it is clear that the OH content in Bi-doped fiber has a strong influence on the gain of the amplifier.

Table 2. UL and OH influence on performance of BPSF

Fiber	BPSF-1	BPSF-2	BPSF-3	BPSF-4
Diameter (µm)	125	100	100	100
Abs (dB/m) @ 1270nm	0.59	1.6	0.35	0.3
Abs (dB/m) @ 1550nm	0.01	0.07	0.06	0.13
UL (%) @ 1240nm	15	27	24	23
OH conc. (ppm)	1.2	3.8	1.1	10
Gain (dB)	40	30	32	20
Length (m)	152	98	276	300

2.5. Bi-doped fiber lasers and amplifiers from 1600-1800nm

It has been observed that by increasing the Ge concentration to ≥ 50mol% in Bi-doped silica fibers it is possible to access the wavelength range from 1600-1800nm. This eye-safe wavelength band has many important applications. For example, the band around 1700nm is optimum for laser surgery [52], multi-photon fluorescence imaging [53], endoscopy [54] and to develop high resolution optical coherence tomography [55]. This wavelength region is also attractive for remote optical sensing and detection because it falls in the atmospheric transparency window [56]. Moreover, the band between 1700-1900nm has significant attention recently to increase the capacity of optical communication using hollow core photonics band-gap fibers [57]. MCVD in combination with gas phase technique was used to develop these BHiGSFs. The lifetime of these fibers was measured to be ~500μs at 1700nm under pumping at 975 nm. Firstov et al., showed the possibility of laser generation between 1600-1800nm using a linear laser scheme with different FBGs inscribed in the active fiber [58]. An Er-Yb co-doped fiber laser operating at 1568 nm was used as a pump source. A Watt level laser at 1700nm was reported with a slope efficiency of 33% and output power of 1.05W using 25 m long BDF [59]. Further, a tunable laser from 1.65 µm to 1.85 µm was developed by using a 55 m long Bi-doped germanosilicate fiber with high germanium concentration [60]. A ring cavity with broadband spectral elements was constructed and the tuning was achieved by an external plane diffraction grating in the Littrow configuration. As a pump source, a double clad Er/Yb fiber laser at 1.564 µm with a pump power of 300 mW was used. The laser output power was 6 mW through a 70% port of the coupler in the ring cavity for a pump power of 300 mW at 1.7 µm. The laser spectral linewidth was 0.07 nm, while the laser radiation spectral density exceeded the spontaneous emission level by more than 60 dB.

BDFAs were also demonstrated at 1700nm in BHiGSFs. Two laser diodes each with 150 mW power operating at 1550 nm was used as pump sources. A maximum gain of 23 dB at 1710nm with a NF of 7 dB was reported using 50 m long BDF. The 3 dB gain bandwidth of the developed amplifier was 40 nm [61,62].

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3. State of the art of Bi-doped pulsed fiber lasers

Pulsed fiber lasers in the wavelength band from 1100-1500 nm and 1600-1800nm are important for many applications including spectroscopy, material processing, and to achieve fast data transfer rates. The advantages of passively mode-locked fiber lasers are that they are compact, low-cost, flexible and simple in design. The broad luminescence offered by Bi-doped fibers is a useful characteristic to develop ultrafast fiber lasers. Various Bi-doped pulsed fiber lasers were demonstrated using saturable absorbers (SA) such as semiconductor saturable absorber mirror (SESAM), carbon nanotube (CNT), and non-linear polarization rotation (NPR) etc. In the following section, we discuss the pulsed fiber lasers in different wavelength bands using aluminosilicate, phosphosilicate, germanosilicate, phosphogermanosilicate and also high germanosilicate host Bi-doped fibers.

3.1. Bi-doped pulsed fiber lasers from 1150-1250nm

Figure 10 presents the pulsed BASF lasers reported using different saturable absorbers. Mode-locked Bi-doped fiber laser (ML-BDFL) with 50ps pulses operating at 1161.6 nm with an average power of 2 mW was demonstrated using a 6 m long fiber. Mode-locking was achieved by using SESAM as a saturable absorber. The fiber was pumped with Yb-doped fiber laser operating at 1063.8 nm with a pump power of 800 mW. The total dispersion of the cavity was in the normal dispersion regime [63]. A mode-locked laser at 1165 nm with 1.9ps pulses with 6 MHz repetition rate using SESAM was demonstrated using 15 m long BASF. Here a chirped fiber Bragg grating (CFBG) was used to bring the dispersion to the anomalous regime for soliton operation. A 1062 nm Yb-doped fiber laser was used as a pump source. The pulse width with total cavity length was measured and observed that it depends on the total dispersion of the cavity [64]. Also, a 1.1ps mode-locked fiber laser in the wavelength range 1158-1168 nm was demonstrated using SESAM as a saturable absorber using 10 m long BASF. A 1075 nm Yb-doped fiber laser with 2.7W pump power was used to pump BDF [65]. Further, 5ps pulses at a repetition rate of 2.4 MHz in the wavelength range from 1160 nm to 1185 nm were demonstrated in [66]. Pulse parameters were optimized by controlling the intracavity group velocity dispersion with a diffraction grating pair.

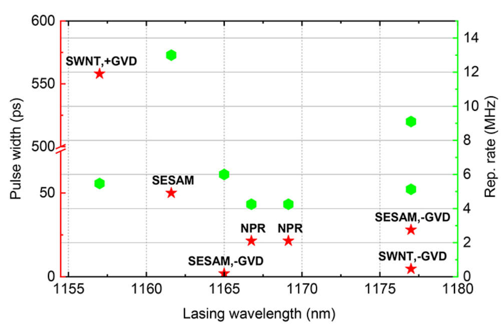

Fig. 10. Pulse width and repetition rate of Bi-doped pulsed lasers in the wavelength band from 1150-1180 nm (GVD: group velocity dispersion) [63–70,72].

In another experiment, a picosecond mode-locked Bi-doped master oscillator power fiber amplifier (MOPFA) operating at 1177 nm for frequency conversion was demonstrated. A three-stage experimental setup was used to develop MOPFA. In the first stage, a ML-BDFL was developed. In the second stage, two BDFAs were used to amplify the pulses. In the third stage, a $LiNbO_3$ crystal was used to frequency double the mode-locked laser. The mode-locked laser was constructed with a 5 m long BASF and SESAM. A 1065 nm Yb-doped fiber laser was used

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as a pump source. A CFBG was used to make the dispersion of the cavity to be anomalous. A 3.9ps pulses with an output power of −4dBm were demonstrated and then amplified using the second stage amplifiers. In this second stage, a 30 m long BASF was used to develop two BDFAs. A pump power of 2W and 5W were used for the first and second BDFAs, respectively. Finally, after MOPFA a pulse width of 28ps with an average power of 150 mW and a peak power of 580W was demonstrated. In the third stage, a $LiNbO_3$ crystal was used to develop 588.5 nm mode-locked laser with an average power of 13.7 mW. Note here that all the active fiber in different stages was cooled to liquid nitrogen temperature to improve the performance [67]. In addition, a single-walled carbon nanotube (SWCNT) was also used to demonstrate mode-locking in both normal and anomalous dispersion regime. A CFBG was used to modify the dispersion of the cavity with 30 m long BASF. A Yb-doped fiber laser was used as a pump source. A 558ps pulses with a repetition rate of 5.47 MHz were demonstrated at 1157 nm in the normal dispersion regime. In the anomalous dispersion regime, 4.7ps pulses with 5.13 MHz repetition rate were demonstrated at 1177 nm. The fiber used here was cooled to 77 K to increase the gain [68]. Further, a tunable mode-locked Bi-doped soliton fiber laser was reported in the 1153-1170 nm range with 0.9ps pulses using SESAM. A CFBG was used to compensate the dispersion of the fiber and to change the dispersion from normal to anomalous for soliton operation [69]. A tunable and switchable dual wavelength passively mode-locked Bi-doped fiber ring laser was demonstrated using nonlinear polarization rotation (NPR) technique. The constructed ring cavity has a 36 m long Bi-doped fiber and a 90/10 coupler. Bi-doped fiber was pumped by an Yb-doped fiber laser operating at 1060 nm with a maximum pump power of 1.5W through a 1060/1160 nm WDM. NPR phenomena was implemented using a polarization dependent isolator placed between two polarizers. The two lasing wavelengths centered at 1166.75 nm and 1169.13 nm, respectively. The wavelength separation of dual wavelength mode-locked pulses was tunable between 2.38 nm and 20.45 nm by exploiting the spectral filtering effect caused by the combination of the polarizer and intracavity birefringence. Moreover, by rotating the polarization controller dual wavelength switchable operation was achieved. The pulse train has a repetition rate of 4.254 MHz and a pulse width of 21.4ps. Apart from the intensity difference, the pulses at two wavelengths were similar [70]. The same group demonstrated a dissipative soliton resonance (DSR) in a passively mode-locked Bi-doped fiber ring laser operating at 1169.5 nm based on NPR technique. The same experimental set up as mentioned earlier was used to develop DSR mode-locked Bi-doped fiber laser except as a pump source an Yb-doped fiber laser with a pump power of 1.8W and an additional 550 m SMF-28e was used to increase the nonlinear effects or to manage the dispersion of the cavity. The CW regime of the Bi-doped fiber laser was achieved at a pump power of about 500 mW due to the relatively low gain of the Bi-doped fiber. When the pump power was above 730 mW, the mode-locked pulses with a fundamental repetition rate was formed by adjusting the polarization controllers. The pulses has a repetition rate of 343.7KHz with a pulse width of 9.3 ns at 1.34W pump power. The peak power of the pulse was calculated and was 1.89W. A 50 dB signal to noise ratio was measured using RF spectrum analyser [71]. The DSR technique could broaden the pulse width while keeping the amplitude constant. Thus, the pulse in DSR regime permits its energy to increase virtually infinitely despite of overdriven intracavity nonlinear effects.

Furthermore, Bi-doped fiber was used as a saturable absorber for mode-locking other RE-doped fibers. In an example by using Bi-doped fiber as a saturable absorber, a Yb-Bi Q-switched laser was demonstrated in the spectral range of 1050-1200 nm. The pulse width and repetition rate were 1μs and 100 kHz, respectively. This demonstrates that the Bi-doped fiber can itself work as a saturable absorber to develop RE-doped pulsed fiber lasers [72]. Pulse dynamics in Bi-doped fibers with different saturable absorbers were studied and reported that by changing the recovery time of the saturable absorber the dynamics of pulse changes. In case of slow recovery time, the saturable absorber favours the multiple pulsing whereas the fast saturable absorber favours the single pulse operation [73].

3.2. Bi-doped pulsed fiber lasers from 1300-1500nm

A 1320 nm mode-locked BPGSF laser based on SESAM in both normal and anomalous dispersion regime was studied. A 1220 nm semiconductor disk laser was used to pump the 39 m long BDF. A high reflecting plane mirror and a CFBG were used to change the dispersion of the cavity. In the anomalous dispersion regime, the laser produces 2.51ps pulses with an average power of 0.3 mW and a peak power of 40W. By replacing the CFBG with a plane reflecting mirror the dispersion of the cavity was changed to normal and the laser produces pulses of 25.5ps. The pulses were compressed down to 580fs by further sending them through a 300 m long single mode fiber. The average power was increased to 0.8 mW with a corresponding peak power of 470W. The superior performance was achieved in case of net normal dispersion regime as it prevents the wave breaking which leads to multiple pulse operation with an increase in pump power [74]. Later, a 1440 nm all-bismuth fiber master oscillator power amplifier (MOPA) was demonstrated by pumping with 1320 nm semiconductor disk laser. The two-stage MOPA has one stage to generate mode-locked pulses in the normal dispersion regime and another stage to amplify and compress the pulses. The first stage of the master oscillator was developed by a 3.4 m BGSF. The cavity was adjusted to the normal dispersion regime by using an 80 cm dispersion compensating fiber. The master oscillator delivered 2.1ps pulses with an average power of 1.5 mW at a pump power of 320 mW using SESAM as a saturable absorber. The time-bandwidth product was 6.1, indicates a large chirp which is typical for dissipative solitons in the normal dispersion regime. The pulses were then sent through a power amplifier made by 35 m long BDF. A power of 400 mW was used for pumping the power amplifier. A pulse width of 240fs with 15 mW average power and 3.1 kW peak power was demonstrated after the power amplifier [75]. Also, a non-linear Kerr effect mode-locking at 1300 nm based on the figure of eight scheme in both non-linear amplifying loop mirror (NALM) and non-linear optical loop mirror (NOLM) configurations was demonstrated using 30 m long BPSF. A 1240 nm laser diode and a Raman fiber laser were used as a pump. A high Ge-doped fiber was used to provide large positive dispersion and non-linearity to operate the mode-locking in the dispersive soliton regime. A 13.8ps pulses with a repetition rate of 3.9 MHz were demonstrated based on NALM configuration. Whereas, 11.3ps pulses with a repetition rate of 3.5 MHz was demonstrated using a NOLM configuration with an average power of 6 mW. The time-bandwidth product of the pulses was 33.5, which indicates a strong chirp. The pulses were further amplified and compressed by a BDFA and a diffraction grating. The average power after BDFA was increased to 30 mW and the pulses are compressed down to 530fs [76]. Recently, a Bi-doped phosphosilicate mode-locked fiber laser operating at 1320 nm was demonstrated using SWCNT [77]. A 1.5W CW Raman laser operating at 1230 nm was used as a pump source. A total length of the fiber was 20 m in the cavity including 15 m long BDF. It reported 7.8ps pulses with pulse energy of 117pJ in the dissipative soliton regime.

Further, a self Q-switched laser was demonstrated at 1463 nm by using BGSF. A 1.8μs pulses at 1463 nm wavelength was reported by using 10 m long BGSF. Two laser diodes operating at 1310 nm with a total pump power of 260 mW was used as pump sources in bi-directional pumping configuration [78]. Furthermore, a burst mode pulse generation through self-Q-switched mode-locking from BGSF was demonstrated with similar pumping configuration and using 10 m BGSF. A passive fiber length in the cavity was varied from 10-90 m to adjust the dispersion of the cavity. Self-Q-switched mode-locking with a pulse repetition rate of 31.5 KHz, 3.088 MHz and width of 4.7μs, 1.2 ns were demonstrated with a cavity length of 65 m [79]. Soliton grouping was observed and reported in BGSFs at 1450 nm. A laser cavity was designed by 4 m long BDF. SESAM and frequency shifted feedback technique were used to mode-lock the Bi-doped fiber laser. 1310 nm and 1320 nm semiconductor disk lasers were used as pump sources. Fundamental cavity soliton width of 900fs and 1.89ps were reported [80,81]. Pulse width and repetition rate of Bi-doped mode-locked fiber lasers in the band of 1300-1470 nm are shown in Fig. 11.

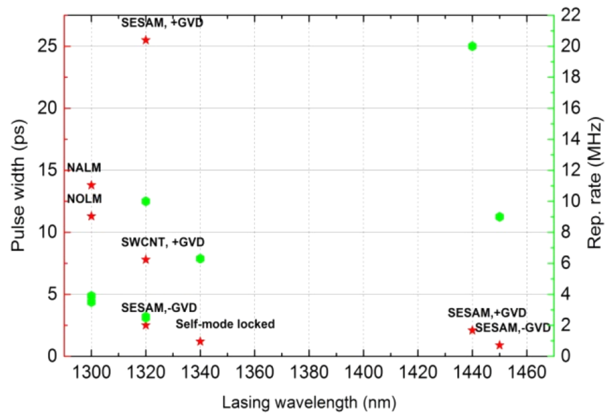

Fig. 11. Pulse width and repetition rate of Bi-doped pulsed fiber lasers in the wavelength band from 1300-1500 nm [74–81].

3.3. Bi-doped pulsed fiber laser operating at 1340nm

High concentration Bi-doped fibers are important specifically when designing pulsed fiber lasers and cladding-pumped fiber lasers. We optimized the MCVD-solution doping process to increase the Bi concentration in a phosphosilicate host without influencing UL. Fibers with core and clad diameter of 13μm and 100μm were drawn from the fabricated preforms. The absorption, UL of these high concentration Bi-doped phosphosilicate fibers (HiBPSFs) are shown in Table 3.

Table 3. Absorption and UL of high concentration Bi-doped phosphosilicate fibers

Fiber No	Absorption @ 1267 nm (dB/m)	%UL	Lasing length (m)	Output power (mW)
HiBPSF-1	1.5	27	20	3
HiBPSF-2	1.7	17	10	2
HiBPSF-3	2.2	22	18	3
HiBPSF-4	2	20	16	4

These HiBPSFs were tested for lasing characteristics using a ring cavity and the performance of each fiber towards laser efficiency is shown in Table 3. Among, HiBPSF-2 has a low UL and shown lasing in only 10 m long BDF in a ring cavity with an output power of 2 mW. This fiber was used to design a mode-locked fiber laser and to study the pulsing phenomena without any saturable absorber such as SESAM or CNT within the cavity [82].

The ML-BDFL was constructed with ring cavity architecture as shown in Fig. 12(a). A laser diode operating at 1270 nm with a total power of 335 mW was used to pump the Bi-doped fiber. A 95/5 coupler was used to extract a 5% signal out of the ring cavity. Initial measurements on the effect of fiber length on ML-BDFL performance showed a pulse width of 3 ns with a maximum output power of 3 mW at a fiber length of 25 m. For this length, the ML-BDFL generated stable 1340 nm pulses with a repetition rate of 6.3 MHz that agrees with the cavity round trip time. We also observed that the pulse width increased slowly with pump power from 1.5 ns to 3 ns as shown in Fig. 12(b). Note that here the pulse width increased with pump power clearly indicating that the pulsing behaviour is not due to Q-switching in which the pulse width would be expected to decrease with increasing pump power [83]. Throughout this experiment, the pulse repetition

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rate remained fixed at the cavity round trip time, further indicating that the BDFL was operating in the mode-locked regime instead of Q-switched regime. The total cavity length was 32.8 m with approximately 7.8 m of passive fiber due to all components.

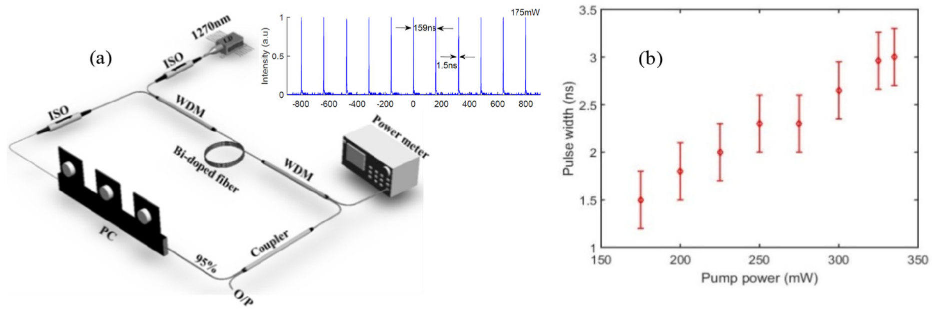

Fig. 12. (a) Schematic experimental setup of mode-locked Bi-doped fiber laser (inset shows the pulse spectrum of ML-BDFL at 175 mW pump power) (b) pulse width variation with a pump power of 25 m long BDF for a 1270 nm laser diode pumping [82].

The pulse train with a pulse width of 3 ns and a pulse period of 159 ns was measured by an oscilloscope at a pump power of 335 mW. The optical spectrum shows a central wavelength at 1342 nm and a 3 dB bandwidth of 1.6 nm at the maximum pump power of 335 mW as shown in Fig. 13(a). The appearance of Kelly sidebands in the optical spectrum indicates that the ML-BDFL operates in the anomalous dispersion regime. From the optical spectrum, and assuming that the pulses were transform limited, the output pulse width was expected to be ~1ps. The measured larger pulse width can be attributed to soliton bunching while the increase in pulse width with pump power is expected due to the increase of soliton number [84,85]. However, the existence of sub-picosecond pulses within the pulse envelope could not be directly confirmed because of the limitations imposed by the bandwidth of the detector and oscilloscope. The measured sideband shift from the central wavelength was around 9 nm to the first order sideband. The calculated dispersion from the first order sidebands was $4.5 \mathrm{ps km^{-1} nm^{-1}}$ at 1342 nm confirming that the cavity operates in the anomalous dispersion regime and the laser operates in the soliton pulse regime. The RF spectrum of the ML-BDFL is presented in Fig. 13(b). The measured RF spectrum shows good harmonic purity with an SNR of 65 dB thereby indicating a stable pulsing.

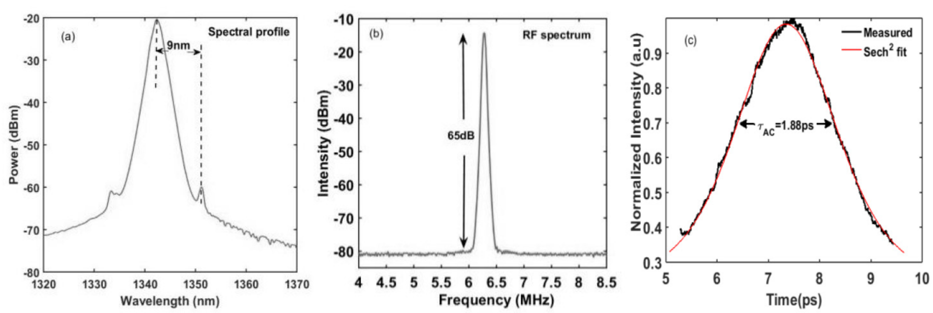

Fig. 13. (a) Optical spectrum (b) RF spectrum of the ML-BDFL at a pump power of 335 mW for a 25 m long Bi-doped fiber (c) the sech^2 fitting of the autocorrelation trace [82].

In order to amplify the signal power of the ML-BDFL, a BDFA was constructed using 100 m long BPSF. A 1240 nm pump laser diode having a maximum pump power of 420 mW was used to pump the Bi-doped fiber in amplifier configuration. At a fixed seed power of 2.5 mW

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(3.95dBm), the MOPA signal power increased with a slope efficiency of 7.25% up to a maximum of 18 mW and is limited by the maximum available pump power of 420 mW. The laser spectrum and pulse profile measured at the output of the MOPA shows that no significant distortions were introduced by the 100 m long BDF. A pulse width of 2.5 ns with corresponding peak power and the pulse energy of 1.15W and 2.9nJ were achieved. The measured autocorrelation trace after BDFA has a large pedestal, which is a signature of soliton bunching in mode-locked fiber laser systems [86–89]. Figure 13(c) shows the autocorrelation trace excluding the pedestal fitted to a hyperbolic-secant function. The FWHM of autocorrelation (τ_{AC}) was found to be 1.88ps. Assuming a hyperbolic-secant pulse shape, the pulse width at FWHM of ML-BDFL was 1.2ps. To analyze the stability of the ML-BDFL, the spectrum was monitored for 2hrs at a maximum output power of 18 mW. The stability of the acquired spectra over time indicates that the operation of the mode-locked Bi-doped fiber laser was stable. Here, it is possible that the Bi-doped fiber itself acting as a saturable absorber [90]. For example, Bi-doped aluminosilicate and germanosilicate fibers were used as saturable absorbers to enable pulsing in Yb and Tm-Ho doped fiber lasers [72,91]. The wavelength of operation of these lasers was at 1 μm and 1.93 μm, respectively. Additionally, the mode locking could be due to the polarization dependent loss in the cavity as well. Indeed, further studies need to be performed to understand the mechanism of mode locking.

3.4. Bi-doped pulsed fiber lasers from 1600-1800nm

The emission band of Bi-doped silica fibers was further extended to 1700nm by BHiGSFs. Pulses of 1.65ps at 1730nm were demonstrated with a fundamental repetition rate of 4 MHz. A CNT was used to initiate the mode-locking and was studied in both normal and anomalous dispersion regimes. The dispersion of the cavity was adjusted by using different length of single mode fiber within the cavity. An Er-doped fiber laser operating at 1563 nm was used as a pump source. A 5 m length of the Bi-doped fiber was used as an active medium. In the normal dispersion regime, 14ps pulses were obtained at a pump power of 170 mW. The pulses were compressed further and obtained a pulse width of 1.2ps [92]. A mode-locked Bi-doped fiber laser operating at 1700nm was demonstrated using the figure of eight all-fiber design with a NALM. A 15 m long Bi-doped fiber was used. The mode-locked laser delivered 17.7ps pulses with 3.57 MHz repetition rate. Peak power and pulse energy were 4.7W and 84pJ, respectively. Further the pulse energy was increased to 5.7nJ using a 100 m long BDFA, however, the pulse duration increased to 28.1ps. Furthermore, the amplified pulses were compressed to 630fs by passing through 150 m long SMF-28 [93]. Pulsed lasers in this wavelength band (1600-1800nm) have important applications in medicine as this wavelength region falls into the transparency window of living tissues, and in addition, they can be used for the three-photon technique that offers a better precision in comparison with two-photon microscopy [94].

In addition to fiber amplifiers and fiber lasers (CW and pulsed), super fluorescent sources at 1.34 μm, 1.44 μm, and 1.73 μm were also demonstrated using Bi-doped fibers in phospho- and germanosilicate hosts [95–97]. A random laser at 1.42 μm was also demonstrated [98].

4. Conclusion

In conclusion, the field of Bi-doped fibers for lasers and amplifiers is active for the past one and half decades. Over the years, the progress to fabricate Bi-doped fibers and to demonstrate lasers and amplifiers using these fibers was significant. MCVD based fabrication process; a technique widely adopted commercially for low loss RE-doped fiber fabrication was used to introduce Bi-dopant in different host materials such as aluminosilicate, phosphosilicate, and germanosilicate. These Bi-doped fibers paved the way to access the wavelength band from 1150-1500 nm and 1600-1800nm for lasers and amplifiers. Even though a matured fabrication technique such as MCVD is used to fabricate BDFs, however, the formation of Bi active centres is

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sensitive to process parameters such as temperature and atmospheric conditions and the amount of Bi introduced into the fiber core.

Here, we showed that the pump wavelengths are critical in order to develop efficient and broadband BDFAs. A maximum gain of 12 dB was demonstrated at 1180 nm in BASF through proper pump selection. Further improvements of gain values are necessary to generate visible lasers by frequency doubling. We also demonstrated a BDFA covering from 1300-1360 nm with a flat gain of up to 25 dB in 40 nm bandwidth in single pass configuration with -10dBm signal power. Further, the gain of the amplifier was increased to 31 dB using double pass configuration with the same input signal power. Finally, a 40 dB gain was achieved for -30dBm input signal power. The potential of this amplifier was experimentally proven by conducting experiments in an optical fiber communication test bed. The amplification bandwidth offered by these fibers can be extended further towards IEEE standard wavelength band from 1270-1330 nm by studying them with different host materials and by optimizing the pumping wavelengths. Note that, we only used phosphosilicate host to develop Bi-doped fiber lasers (CW and pulsed) and amplifiers in the O-band. It is possible to extend this wavelength band further up to 1500 nm starting from 1270 nm by studying the BPGSFs. Also, it is possible to develop tunable lasers using Bi-doped fibers as they have a broad gain spectrum. We demonstrated an all-fiber tunable Bi-doped fiber laser operating from 1317 nm to 1375 nm with a maximum power of 60 mW. The OSNR of more than 48 dB was achieved with 0.5 nm OSA resolution bandwidth. After amplification, the output power of the tunable laser was increased to ≥ 100 mW in 52 nm (1318 nm to 1370 nm).

Up till now, the Bi concentration used in fibers is relatively low to demonstrate lasers and amplifiers. The low Bi-concentration leads to longer device length. On the other hand, the increased amount of Bi in the core introduces unwanted losses such as UL and ESA that are detrimental to laser and amplifier performance. However, fabrication of high concentration Bi-doped fibers with low UL and ESA will lead to develop lasers and amplifiers that are suitable for pulsed operation and power scaling through cladding pumping. We have shown that by optimizing the fiber fabrication conditions it is possible to increase the Bi concentration in the core without compromising the UL and demonstrated lasing in 10 m long BDF. Further an-all fiber mode-locked Bi-doped laser operating at 1340 nm was reported. The wideband emission observed in Bi-doped fibers is useful for ultrafast fiber lasers. Especially, development of mode-locked fiber lasers around 1.3 µm wavelength band is important for faster data transfer rates in the second telecommunication window. Even after more than 10 years of first pulsed Bi-doped fiber laser demonstration, the pulse dynamics in Bi-doped fiber without saturable absorber such as SESAM and CNT have not yet well understood. A systematic study needs to be performed to understand the underlying phenomenon. There are many other challenges, one of them is to find out the active state in Bi-doped fibers that is causing NIR luminescence. Many hypotheses were reported based on the experimental facts but none of them confirmed all the properties seen in Bi-doped fibers. By knowing the active state of Bi that contributes to NIR emission, the fiber fabrication conditions can be optimized to develop efficient fibers for lasers and amplifiers. This needs significant attention, once resolved this can revolutionize the field of next-generation Bi-doped fiber lasers and amplifiers.

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