Bismuth-doped All Fiber Mode-locked Laser Operating at 1340nm

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We demonstrate a 1340nm mode-locked Bismuth (Bi)-doped fiber laser without any saturable absorber. The effect of pump power on pulse width is studied and a variation from 1.5 to 3ns is reported. The output of the mode-locked Bi-doped fiber laser (ML-BDFL) is further amplified using a master oscillator power amplifier (MOPA) configuration and a peak power of 1.15W is achieved. Soliton bunching is observed and a true pulse width of 1.2ps is reported from the measured autocorrelation trace. Stable operation of the mode-locked laser is verified from the RF spectrum with a fundamental repetition rate of 6.3MHz, and SNR of 65dB.

OCIS codes: *(060.2290) Fiber materials; (060.2280) Fiber design and fabrication; (060.2270) Fiber characterization; (140.4050) Mode-locked lasers; (060.2320) Fiber optics amplifiers and oscillators.*

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Mode-locked fiber lasers have proved to be an important tool in many different applications including telecommunication, spectroscopy, medicine, materials processing, imaging and frequency metrology. The advantages of passive mode-locked fiber lasers are that they are compact, low cost, flexible and simple in design. The maturity of rare earth (RE) fiber fabrication technology to develop Ytterbium (Yb), Erbium (Er) and Thulium(Tm) or Holmium (Ho) doped fibers made them an obvious choice to explore 1, 1.5 and 2µm pulsed fiber lasers, respectively [1, 2]. However, the wavelength band from 1.15 to 1.45 µm remains relatively unexplored due to the unavailability of efficient RE gain media despite several important applications [2]. The specific applications of lasers and amplifiers in this wavelength window include sources for second telecommunication band as well as development of visible lasers through the second-harmonic generation [3, 4]. In the past, praseodymium (Pr) and Neodymium (Nd) doped fibers were studied extensively in a silica host to develop amplifiers and lasers around 1.3µm. However, the high phonon energy in a silica host makes these dopants inefficient. Changing the host to fluoride with low phonon energy makes them comparatively efficient but they are unsuitable to splice with conventional silica fibers as required in many applications for a compact all-fiber devices [5]. Bismuth (Bi)-doped fibers have shown prominent progress in developing amplifiers and lasers covering the wavelength band from 1.15 to 1.8µm in different glass hosts (i.e., aluminosilicate, phosphosilicate and germanosilicate). Bi-doped fiber amplifiers and lasers have seen extensive progress in the last few years reaching gain and efficiency values close to 30dB and 50%, respectively [6-9]. In addition, the broad luminescence of Bi-doped fibers is an added leverage to develop sub-picosecond pulsed lasers. Although, Bi-doped fibers are a promising active medium to develop efficient pulsed fiber lasers in the wavelength band inaccessible by RE doped materials, a comparatively low gain per unit length is the current challenge to develop mode-locked fiber lasers with short length active fiber gain medium. The first Bi-doped pulsed fiber laser was demonstrated in 2007 with 50ps pulses at 1161nm using a semi-conductor saturable absorber mirror (SESAM) [10]. Since then a number of studies have reported on Bi-doped pulsed fiber lasers based on saturable absorbers, such as SESAM and carbon nanotube (CNT) [11-14]. Bi-doped aluminosilicate and germanosilicate fibers were used as saturable absorbers to enable pulsing in Yb and Tm-Ho doped fiber lasers. The wavelength of operation of these lasers was at 1 and 1.93µm, respectively [15, 16]. However, the pulse dynamics in Bi-doped fibers have not yet well understood due to the quenching effects such as unsaturable loss (UL) and excited state absorption in these fibers [17]. In recent years, Bi-doped germanosilicate fibers mode-locked by SESAM and frequency shifted feedback technique were reported. The operating wavelength of these mode-locked fiber lasers was 1450nm. Pulse bunching was observed in both cases. Pulses of bunches with a width of 5ns were measured in case of frequency shifted feedback technique and the autocorrelation spectrum revealed picosecond pulses [18, 19]. Pulse bunching is a phenomenon that occurs due to interaction between the solitons generated in mode-locked fiber lasers with a total cavity in anomalous dispersion [20, 21]. Some numerical models were also reported to understand the soliton interaction and bunch formation in Bi-doped fibers [19, 22].

In this study, a Bi-doped phosphosilicate preform was fabricated by Modified Chemical Vapour Deposition (MCVD) process in conjunction with standard solution doping technique. Phosphosilicate soot was deposited on the inner wall of silica tube and Bi dopant was incorporated into the soot by soaking the tube in Bi precursor solution. The soot was dried, sintered and finally the tube was collapsed into a Bi-doped phoshosilicate prefom. The preform was drawn into fiber with a core/clad diameter of 13/100 µm and an NA of 0.09. This fiber was used to design a ring cavity mode-locked fiber laser and to study the pulsing phenomena at 1340nm without any saturable absorber such as SESAM or CNT within the cavity. The effect of pump power on pulse width was studied with results showing that the pulse width variation from 1.5 to 3ns. Further, the output of mode-locked Bi-doped fiber laser (ML-BDFL) was amplified in a master oscillator power amplifier (MOPA) configuration wherein a 100m long Bi-doped fiber was used to achieve a maximum average power of 18mW. Soliton bunching was confirmed and a true pulse width of 1.2ps was reported with the measured autocorrelation.

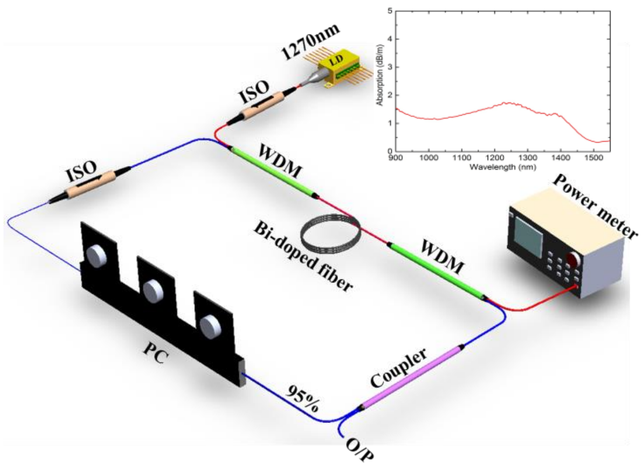

Figure 1 | Schematic experimental setup of mode-locked Bi-doped fiber laser (Inset shows the absorption spectrum of the Bi-doped fiber)

The ML-BDFL was constructed with a ring cavity architecture as shown in Fig. 1. Initially a laser diode (LD) operating at 1270nm with a total power of 335mW was used to pump the Bi-doped fiber. An isolator was placed to ensure unidirectional operation; while a 95 : 5 coupler was used to extract a 5% signal out of the ring cavity. A polarization controller (PC) was employed to control the polarization in the cavity for stable pulsing. An optical spectrum analyser (OSA), RF spectrum analyser (400MHz), InGaAs photodetector (5GHz) and an oscilloscope (2.5GHz) were used to study the ML-BDFL characteristics. The active fiber was characterised for absorption and UL using a white light source (WLS) and a laser diode (LD) prior to its use in the ring cavity. The measured small signal absorption and the UL at 1270nm pump wavelength were 1.7dB/m and ~17%, respectively.

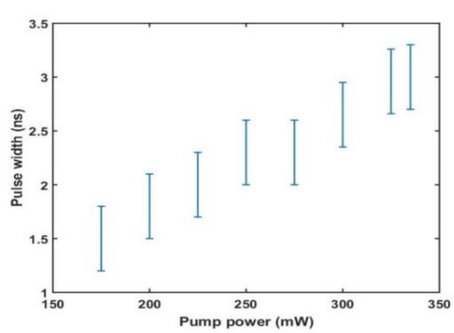

Figure 2 | Pulse width variation with pump power of 25m long Bi-doped fiber for a 1270nm laser diode pumping

Initial measurements on the effect of fiber length on ML-BDFL performance showed a pulse width of 3ns with a maximum output power of 3mW at a fiber length of 25m. For this length the ML-BDFL generated stable 1340nm pulses with a repetition rate of 6.3MHz that agrees with the cavity round trip time. We also observed that the pulse width increased slowly with pump power from 1.5 to 3ns as show in Fig. 2. 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. Throughout this experiment the pulse repetition rate remained fixed at the cavity round trip time, further indicting that the BDFL was operating in the mode-locked regime instead of q-switched regime. The cavity contains approximately 7.8m of passive fiber due to the WDMs, isolators, couplers and a polarization controller in addition to 25m of Bi-doped fiber.

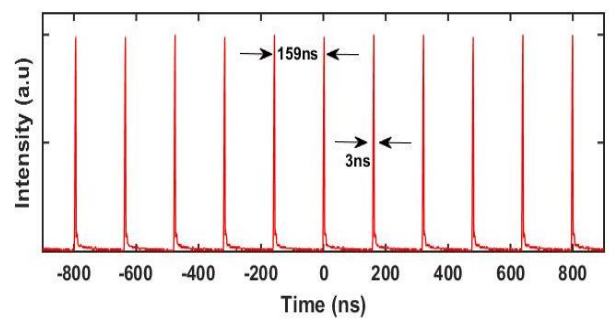

Figure 3 | Pulse train of the ML-BDFL at maximum pump power of 335mW with a pulse width of 3ns

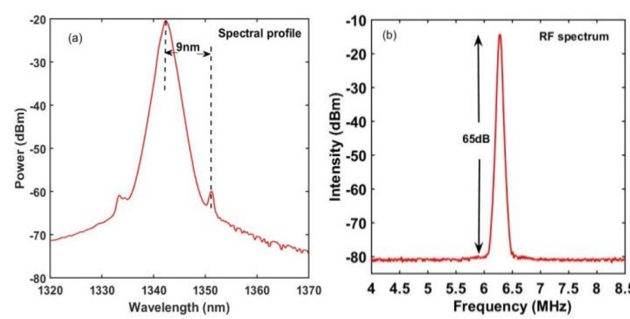

Figure 4 | a. Optical spectrum **b.** RF spectrum of the ML-BDFL at a pump power of 335mW for a 25m long Bi-doped fiber

The pulse train with a pulse width of 3ns and a pulse period of 159ns was measured by an oscilloscope at a pump power of 335mW and is presented in Fig. 3. The optical spectrum shows a central wavelength at 1342nm and a 3dB bandwidth of 1.6nm at the maximum pump power of 335mW as shown in Fig. 4 (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 [21, 23]. 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 detector and oscilloscope.

The measured side band shift from the central wavelength was around 9nm to the first order sideband as shown in Fig 4(a). From the measured optical spectrum the total dispersion of the cavity can be calculated by the following equations [24, 25]

$$\Delta\lambda = \pm\frac{\lambda^2}{2\pi c t_0}\sqrt{1+\frac{8nZ_0}{Z_a}}, \quad (1)$$

$$Z_0 = \frac{\pi {t_0}^2}{2|\beta_2|}, \quad (2)$$

Where c and n are speed of light in vacuum and order of the sideband, respectively. Z_0 is soliton period, Z_a is the cavity length and $T_{FWHM} = 1.763t_0$ is pulse duration at full width at half maximum (FWHM).

The calculated dispersion from the first order sidebands was 4.5pskm^{-1}nm^{-1} at 1342nm 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. 4 (b). The measured RF spectrum shows good harmonic purity with a SNR of 65dB thereby indicating a stable pulsing.

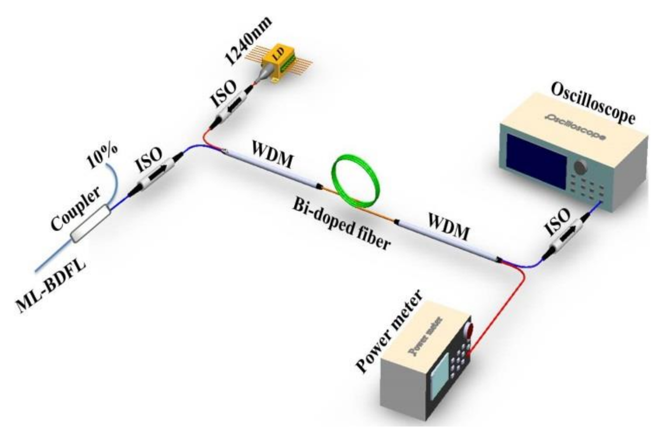

Figure 5 | Experimental setup of master oscillator power amplifier (MOPA)

In order to amplify the signal power of the ML-BDFL, the MOPA as shown in Fig. 5 was constructed. A 90/10 coupler was inserted between the ML-BDFL and the amplifier. The 10% port was used to monitor the output of ML-BDFL while the 90% port was used as input to the amplifier. A 1240nm pump laser diode having a maximum pump power of 420mW was used to pump Bi-doped fiber. Two WDMs were used to combine and separate pump and signal at the input and output, respectively. Isolators were used to avoid back reflections into the cavity of the ML-BDFL and to protect the 1240nm pump. The active Bi-doped fiber used in the MOPA was different from the fiber used for ML-BDFL. This Bi-doped fiber had a core and clad diameter of 11 and 150µm, respectively. The UL in this Bi-doped fiber was ~7%.

Figure 6 shows the dependence of MOPA output signal power on pump power for a fixed seed power of 2.5mW (3.95dBm). At this seed power the MOPA signal power increased with a slope efficiency of 7.25% up to a maximum of 18mW, and is limited by the maximum available pump power of 420mW. In a second experiment, the MOPA pump power was fixed at 420mW while the seed power was increased as shown in Fig. 7. Here, the MOPA output power increased with ML-BDFL seed power, again reaching a maximum of 18mW. The laser spectrum and pulse profile measured at the output of the MOPA shows that no significant distortions were introduced by the 100m long Bi-doped fiber. A maximum average power of 18mW was achieved with a pule width of 2.5ns. Corresponding peak power and the energy were 1.15W and 2.9nJ.

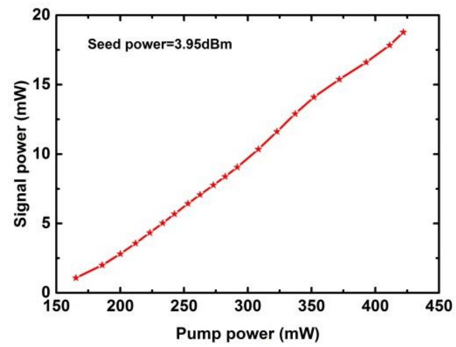

Figure 6 | Variation of signal power with pump power of MOPA for a fixed input seed power of 2.5mW (3.95dBm)

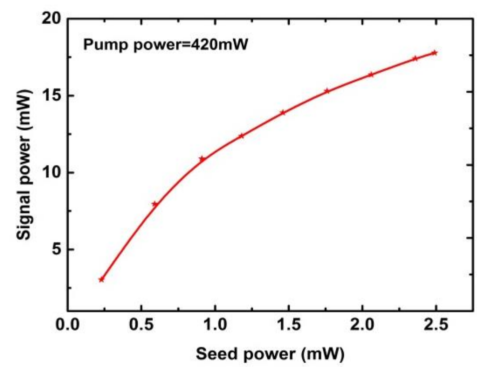

Figure 7 | Signal power variation of MOPA with seed power for fixed pump power of 420mW

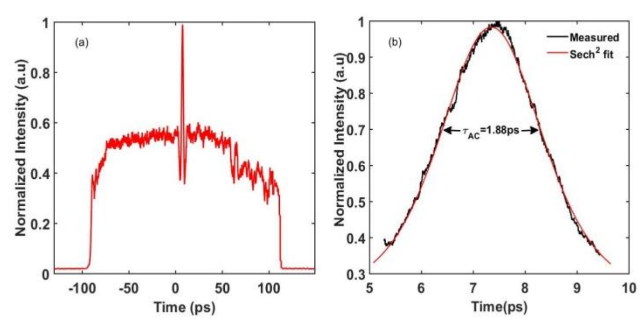

Figure 8 | a. Autocorrelation trace of the mode-locked Bi-doped fiber laser **b.** The sech^2 fitting of the autocorrelation trace

The true pulse width of the mode-locked Bi-doped fiber laser was measured by an autocorrelator (Femtochrome, FR-103XL) in conjunction with an oscilloscope and is shown in Fig. 8 (a). The measured autocorrelation trace has a large pedestal which is a signature of soliton bunching in mode-locked fiber laser systems [19-25]. Figure 8 (b) 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.

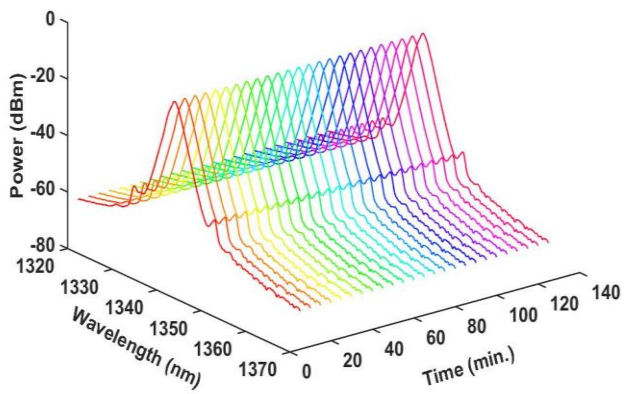

Figure 9 | Optical spectrum of the ML-BDFL observed over 2hrs of time

To analyse the stability of the ML-BDFL the spectrum was monitored for 2hrs at maximum output power of 18mW as shown in Fig. 9. The stability of the acquired spectra over time indicates that the operation of the mode-locked Bi-doped fiber laser was stable.

In conclusion, a Bi-doped phosphosilicate fiber fabricated by the MCVD-solution doping technique was used to study the pulsing phenomenon in an all-fiber Bi-doped mode-locked laser operating at 1340nm without any saturable absorber. The impact of pump power on pulse width was examined and a pulse width variation from 1.5 to 3ns was reported. The maximum average output power of the ML-BDFL was 3mW with a 3ns pulse width. The average output power was further increased to 18mW using a MOPA and a corresponding peak power of 1.15W and pulse energy of 2.9nJ were achieved. The measured autocorrelation of the ML-BDFL confirms the soliton bunching phenomenon with a true pulse width of 1.2ps. A stable operation of the ML-BDFL was verified by the RF spectrum with an SNR of 65dB at a fundamental repetition rate of 6.3MHz. To the best of our knowledge, for the first time we observed picosecond pulses from a Bi-doped mode-locked fiber laser without any saturable absorber such as SESAM or CNT in the cavity. We are currently studying the underlying mechanism of such pulsing phenomenon in Bi-doped fibers.

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