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All-fiber E + S band continuously tunable bismuth-doped germanosilicate fiber laser

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In this Letter, we present an all-fiber bismuth (Bi)-doped germanosilicate fiber laser that is continuously tunable within the range of 1425–1475 nm, enabled by a tunable optical filter. A maximum output power of 86.4 mW was achieved at 1450 nm with a slope efficiency of 13.7%. It is, to the best of our knowledge, the first demonstration of an all-fiber tunable continuous-wave (CW) bismuth-doped fiber laser (BDFL) operating in the E + S band. Moreover, a bismuth-doped fiber amplifier (BDFA) was constructed to further scale the laser output power to 159.2 mW with a 21% slope efficiency. Across the 1425–1475 nm range, we achieved >117 mW output power with >50 dB in-band optical signal-to-noise ratio (OSNR).

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Introduction. Bismuth (Bi)-doped fibers (BDFs) have gained significant attention as a promising next-generation active laser medium, particularly for expanding the data-carrying capacity in optical fiber communications beyond the conventional C and L bands [1]. Bi-doped fiber lasers (BDFLs) offer distinctive advantages over traditional rare-earth (RE)-doped fiber lasers, particularly due to their ability to provide wideband lasing across nearly the entire wavelength range of 1.1–1.5 and 1.6–1.8 μm [2]. The unique luminescence properties of near-infrared (NIR)-emitting bismuth centers are highly dependent on the glass host, offering ultra-wide spectral coverage including the O-band, E-band, S-band, U-band, and beyond. This wide spectral range is achieved through the formation of Bi active centers (BACs) associated with aluminum (BACs-Al), phosphorus (BACs-P), and germanium (BACs-Ge) [3]. By tailoring the glass compositions in BDFs, it is potential to achieve lasing over a tunable range of wavelengths.

The first continuous-wave (CW) BDFL was reported in 2005, covering the 1150–1300 nm range with a maximum output power of 460 mW, utilizing a Bi-doped aluminosilicate fiber (BASF) [4]. Following this, Bi-doped phosphogermanosilicate fibers (BPGSFs) were developed for CW lasers operating from 1270 to 1500 nm [5,6]. Lasing around 1340 nm was demonstrated in Bi-doped phosphosilicate fibers (BPSFs) [7,8], while Bi-doped germanosilicate fibers (BGSFs) exhibited lasing across 1390–1540 nm [9–11]. Bi-doped high-Ge germanosilicate fibers (BHiGSFs) with ≥50 mol% GeO_2 have shown lasing capabilities beyond 1600 nm [12,13].

However, there is relatively less work on tunable BDFLs, which is crucial for advancing fiber laser technology. In the O + E band, BPSFs have been utilized to develop continuously tunable lasers by applying a fiber-pigtailed tunable filter [14,15] or a mechanically tunable fiber Bragg grating (FBG) [16]. Recently, a wideband watt-level BDFL was reported with a maximum output power of 1.705 W at 1320 nm, achieved using a 5.18 W pump power at 1239 nm. An 80 m length of BPSF was employed, enabling a tunable range from 1283 to 1460 nm by applying a blazed diffraction grating [17]. Research on tunable Bi-doped germanosilicate fiber lasers has been less explored. The limited existing research includes a BGSF-based tunable laser employing an external plane diffraction grating and a loop reflector in the cavity to achieve tunability from 1366 to 1507 nm in the E + S band. However, the laser output power was limited to 25–50 mW [18]. Additionally, high-Ge BGSF (50 mol% SiO_2/50 mol% GeO_2) has been utilized to achieve tunable lasing beyond 1.65 μm with a maximum laser output power of 6 mW, facilitated by a diffraction grating [19]. These tunable BDFLs show significant potential in applications such as wavelength-division multiplexing (WDM) telecom systems, sensing and metrology, spectroscopy, and medical diagnostics [2].

In this Letter, we report a single-mode BGSF CW laser continuously tunable from 1425 to 1475 nm, achieving a maximum output power of 86.4 mW and a slope efficiency of 13.7%. A 48 m length of BGSF and a 75% output coupling ratio were utilized in a ring cavity, assisted by a tunable filter. To further enhance the output power from the tunable BDFL, an E + S band Bi-doped fiber amplifier (BDFA) was integrated, utilizing a 39 m length of BGSF in the amplifier stage. This master oscillator power amplifier (MOPA) configuration improved the maximum output power to 159.2 mW with a 21% slope efficiency at 1450 nm. Compared to existing E + S band tunable BDFL with 25–50 mW output power by applying an external diffraction grating [18], our all-fiber tunable BDFL offers a much higher output power. To the best of our knowledge, the laser output power in this work is the highest reported from a tunable Bi-doped germanosilicate fiber laser source.

Experimental setup. Using the modified chemical vapor deposition (MCVD) and solution doping technique, a Bi-doped germanosilicate preform was fabricated in-house and then drawn

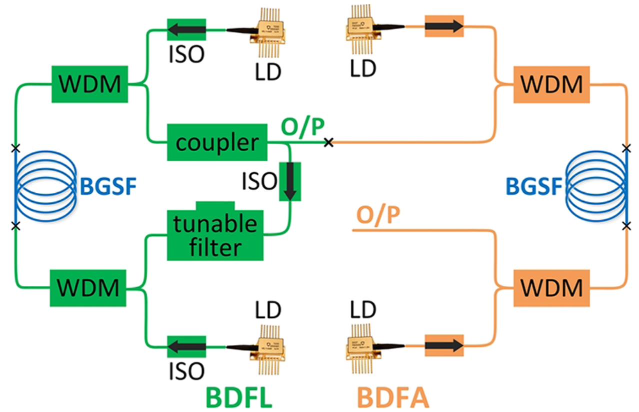

Fig. 1. Schematic of the experimental setup of the E + S band tunable BDFL and MOPA system including the BDFL and BDFA stages.

into a single-mode (SM) fiber. The BGSF had a NA of 0.25 and a cutoff wavelength of 1.15 µm. The fiber core and cladding diameters were 3.6 and 125 µm, respectively. The absorption at the pump wavelength of 1340 nm was measured to be 2 dB/m, with a 11.2% unsaturable loss. The background loss at 1100 nm was ∼0.15 dB/m. The GeO_2 concentration was found to be ∼16 mol%

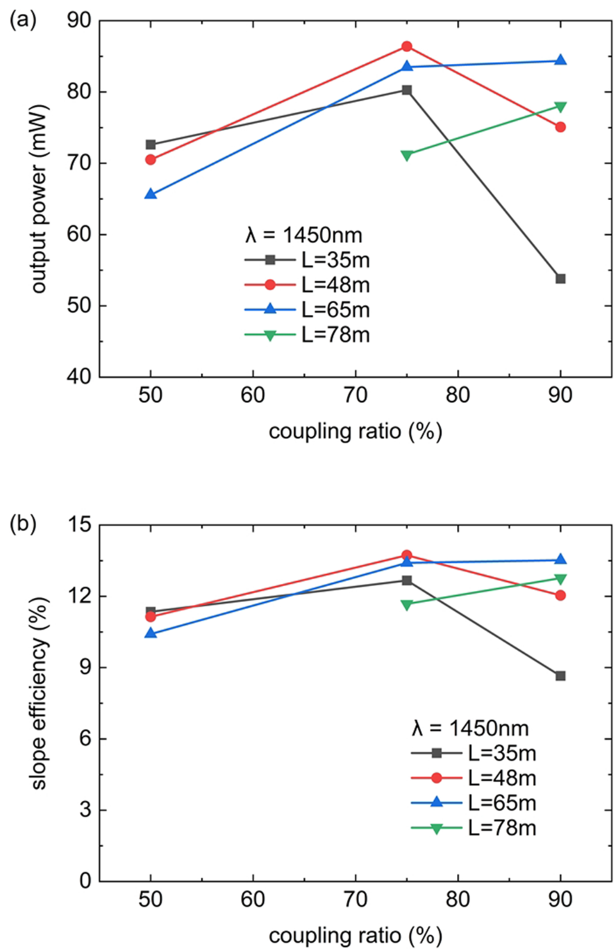

Fig. 2. (a) Laser output power and (b) slope efficiency at 1450 nm using different output coupling ratios for different lengths of BGSF.

measured by an electron probe microanalyzer (EPMA), with a Bi_2O_3 content of less than 0.01 mol%.

The tunable BDFL was built in a ring cavity incorporating a fiber-pigtailed E + S band tunable filter (FOTF, Agiltron), as illustrated in Fig. 1. The insertion loss of the tunable filter was ∼2.9 dB. The fiber was bi-directionally pumped by two laser diodes (LDs) operating at 1340 nm. The maximum launched pump power was 676 mW (358 + 318 mW), measured after splicing a short piece of BGSF (<0.05 m) after the wavelength division multiplexer (WDM). Two WDMs were used to combine the pump and signal, with a flat insertion loss of 0.7 ± 0.03 dB from 1425 to 1475 nm. Two isolators (ISOs) after the LDs were used to prevent damage from back reflections. Another ISO was used in the ring cavity to ensure unidirectional lasing operation. The output from the cavity was extracted using a fiber coupler. Different couplers with an output coupling ratio ranging from 50% to 90% were characterized to optimize the ring cavity configuration. Additionally, a 99:1 coupler was connected to monitor the power and spectrum via an optical powermeter (PM; S144C, Thorlabs) and an optical spectrum analyzer (OSA; 70, Yokogawa), respectively.

To further scale the output power of the BDFL, a MOPA system was constructed by coupling the tunable BDFL with a Bi-doped fiber amplifier (BDFA), as illustrated in Fig. 1. The BDFA was built in a single-pass and dual-pump configuration, using a pump wavelength of 1340 nm. The maximum launched pump power was 804 mW (403 + 401 mW). The output was monitored by the PM and OSA via a 99:1 coupler. The component loss within the BDFA stage was measured to be ∼0.49 dB at the signal band. The same BGSF was employed in the BDFA stage, with both fiber length and pump power optimized to maximize the MOPA system's output. The splice loss between the BGSF and the commercial SMF-28 used in the setups was measured to be ∼1.23 dB.

Results and discussions. In BDFL, the output power and slope efficiency were first measured at 1450 nm for different lengths of BGSF and different output coupling ratios, as shown in Figs. 2(a) and 2(b). Using a 48 m length of BGSF and a 75% output coupling ratio, the output power and slope efficiency reached the maximum of 86.4 mW and 13.7%, respectively, limited by the available pump power in this work. For a

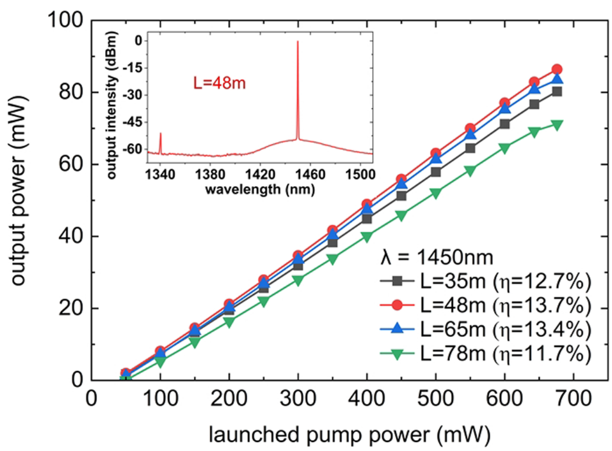

Fig. 3. Variations in laser output power at 1450 nm as a function of the launched pump power using different lengths of BGSF for a 75% coupling ratio. The inset shows the output spectrum for 48 m of BGSF under full pump power using an OSA resolution bandwidth of 0.5 nm.

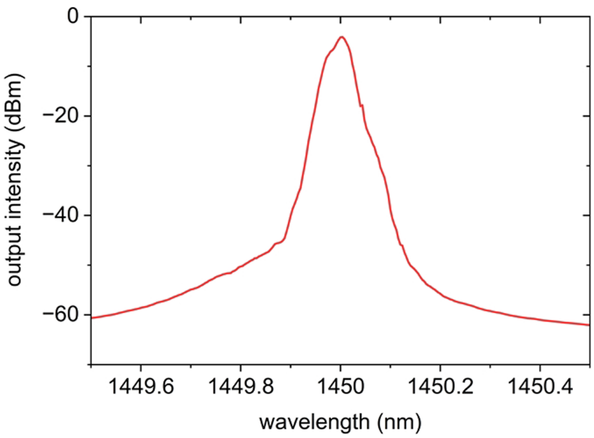

Fig. 4. Linewidth of the tunable BDFL at 1450 nm using an OSA resolution bandwidth of 0.02 nm.

75% coupling ratio and different fiber lengths, the variations in laser output power at 1450 nm as a function of the launched pump power were illustrated in Fig. 3. The slope efficiency (η) was calculated to be 12.7 ± 1% for different lengths of BGSFs (35–78 m), with a lasing threshold of 43 ± 7 mW. The inset of Fig. 3 illustrates the output spectrum for the 48 m of BGSF under full pump power, measured by the OSA with a resolution bandwidth of 0.5 nm, where the in-band optical signal-to-noise ratio (OSNR) was derived.

Figure 4 illustrates the 3 dB linewidth of the tunable BDFL measured by the OSA with a resolution bandwidth of 0.02 nm. The linewidth was observed to be ~0.06 nm at 1450 nm. Notably, if the insertion loss of the tunable filter is accounted for, the maximum output power at 1450 nm could exceed 168 mW.

Under optimal laser operating conditions, the output power and slope efficiency spectra were characterized for the 48 m BGSF with a 75% coupling ratio, as shown in Figs. 5(a) and 5(b). The laser was continuously tunable from 1425 to 1475 nm, limited by the tunable filter, and delivered an output power of >63 mW with >10% slope efficiency.

Then, the BDFL output was connected to the BDFA for power scaling studies. In the BDFA stage, the BGSF length was optimized to 39 m with respect to the highest output power under the full pump power of 804 mW. The output power spectrum after the MOPA was illustrated in Fig. 5(a), with a maximum output power of 159.2 mW at 1450 nm. From 1425 to1475 nm, we achieved >117 mW output power, corresponding to a gain of ~2.7 dB from the amplifier.

Figures 6(a) and 6(b) illustrate the output spectra of the tunable BDFL and the MOPA system, respectively, measured by the OSA with a resolution bandwidth of 0.5 nm. From 1425 to 1475 nm, the in-band OSNR was >52.3 dB for the tunable BDFL and slightly dropped to >50 dB after amplification.

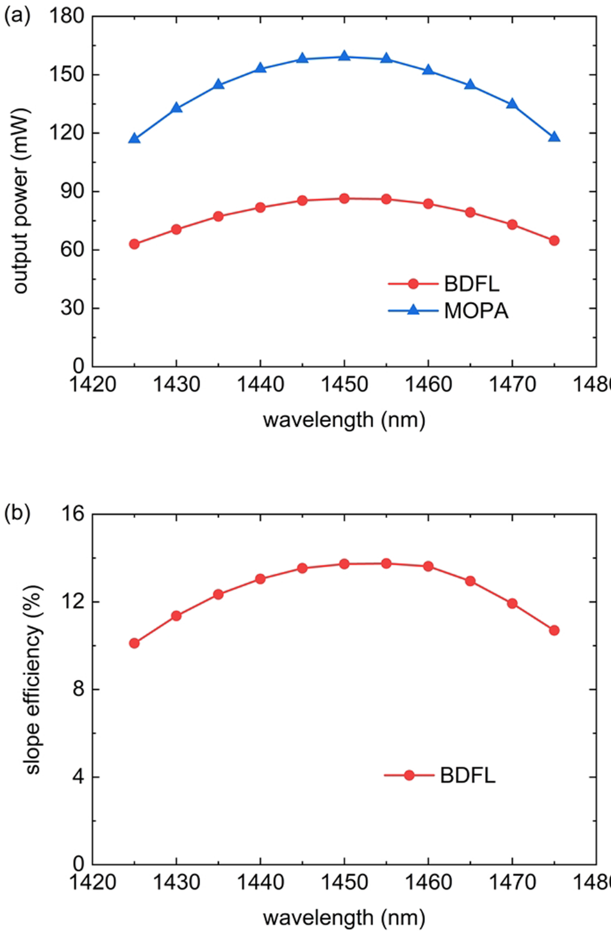

Fig. 5. (a) Output power spectra from the tunable BDFL (L = 48 m) and MOPA system (L = 48 m in BDFL; L = 39 m in BDFA) under full pump power. (b) Slope efficiency spectrum from the tunable BDFL (L = 48 m).

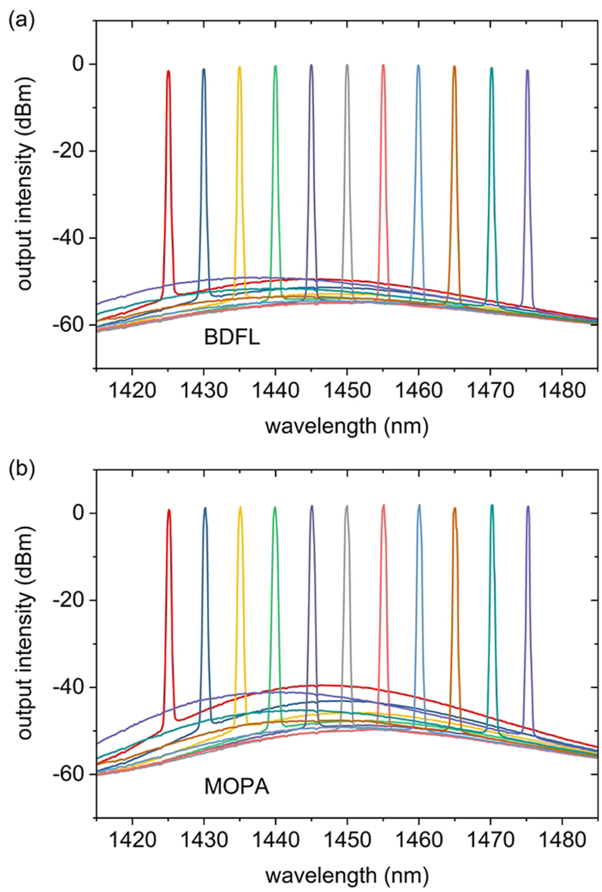

Fig. 6. Output spectra from the (a) tunable BDFL (L = 48 m) and (b) MOPA system (L = 48 m in BDFL; L = 39 m in BDFA) under full pump power using an OSA resolution bandwidth of 0.5 nm.

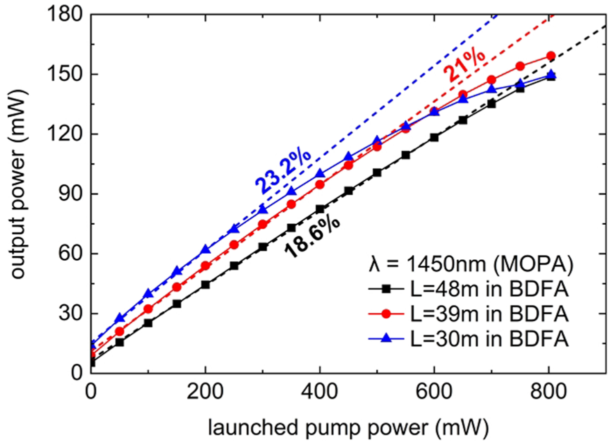

Fig. 7. Variations in MOPA output power at 1450 nm as a function of the launched pump power in the BDFA stage using different lengths of BGSF in the BDFA stage.

Furthermore, the variations in the MOPA output power at 1450 nm with the launched pump power in the BDFA stage were measured for different lengths of BGSF, as shown in Fig. 7. The amplifier started to saturate at higher pump powers, with 39 m of BGSF providing the maximum output power under the full pump. As presented in Fig. 7, the slope efficiency reached 21% for the 39 m BGSF in the BDFA stage. For 30 and 48 m lengths, the slope efficiency was 23.2% and 18.6%, respectively.

Conclusion. We experimentally demonstrate an all-fiber continuously tunable CW BDFL in the E + S band utilizing BGSF fabricated in-house. In a ring cavity with a 75% output coupling ratio and 676 mW pump power at 1340 nm, 48 m of BGSF offered >63 mW output power and >10% slope efficiency across a tuning range of 1425–1475 nm, facilitated by a tunable filter. The maximum laser output was achieved at 1450 nm, with 86.4 mW power and 13.7% slope efficiency. Furthermore, a MOPA system was employed, incorporating an E + S band BDFA to further amplify the BDFL output power. In the single-pass BDFA with 804 mW pump power at 1340 nm, 39 m of BGSF enhanced the maximum output power to 159.2 mW, with a 21% slope efficiency. From 1425 to 1475 nm, the in-band OSNR maintained >50 dB. To the best of our knowledge, this work is the first all-fiber tunable E + S band BDFL achieved in BGSF. These results indicate great potential for applications such as optical communications, metrology, sensing, and spectroscopy.

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Disclosures. The authors declare no conflicts of interest.

Data availability. The data for this work is accessible through the University of Southampton Institutional Research Repository [20].

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