Narrow Linewidth Bismuth-Doped All-Fiber Ring Laser

E. J. R. Kelleher, J. C. Travers, K. M. Golant, S. V. Popov, and J. R. Taylor

***Abstract*—We report a novel narrow linewidth Bismuth-doped all-fiber ring laser, operating at 1177 nm. We achieve a 10-mW output in a 4-GHz linewidth, direct from the oscillator under 7 W of pumping, delivered by an Yb-fiber laser. Mode suppression in the 50-m unidirectional ring cavity is provided by a narrowband fiber Bragg grating and two fiber integrated Fabry–Pérot (FP) filters. The FP filters provide a factor of 20 mode suppression, while improving the relative intensity noise by up to 20 dB/Hz. The optical signal-to-noise ratio (OSNR) is ∼60 dB.**

***Index Terms*—Bismuth, fiber laser, narrow linewidth, ring laser.**

I. Introduction

Spectrally narrow fiber-based sources employing rare-earth-doped fiber have been widely studied. Extending the range of available wavelengths has driven research into novel laser gain media such as Bismuth-doped (Bi-doped) fiber, but to date well-established techniques for achieving narrow-line or single-longitudinal-mode (SLM) operation in rare-earth-based fiber lasers has not, to the best of our knowledge, been applied to Bi-doped fiber sources, primarily because of the relatively low gain of the active fibers. In this letter, we use fiber-integrated filters to suppress longitudinal modes and a narrowband fiber Bragg grating (FBG) to achieve a narrow-line output from an all-fiber continuous-travelling-wave Bi-doped fiber laser.

Near-infrared luminescence from Bi-doped silica glass was first observed by Fujimoto *et al.* in 2001 [1]. Favorable properties, such as a broad emission band in the region 1100–1250 nm and a long fluorescence lifetime make Bi-doped glasses attractive gain media. Dvoyrin *et al.* were the first to move from bulk glasses and demonstrate photoluminescence in Bi-doped silica glass fiber [2], where the core was doped using a modified chemical vapor deposition (MCVD) process, extending the new material to application in the field of fiber laser engineering. This technological step prompted the first demonstration of a continuous-wave (CW) Bi fiber laser pumped using a Neodymium-doped Yttrium Aluminium Garnet (Nd : YAG) solid-state laser [3]. However, the broadband absorption spectrum of Bi-doped fiber permits various pump sources including Yb-doped fiber lasers, resulting in all-fiber Yb-pumped Bi-doped fiber lasers, with significantly improved efficiencies. Such systems have been demonstrated in [4] and [5], with record optical-to-optical efficiencies of 50% reported from a linear cavity configuration with a gain fiber cooled to 77 K to reduce the unsaturable loss that limits room-temperature operation [5].

Narrow linewidth and single-frequency CW fiber sources enable efficient single-pass frequency doubling in highly nonlinear materials, such as periodically poled crystals. The bismuth gain band covers the important wavelength of 1178 nm that can be frequency doubled to 589 nm, a region of the visible spectrum where high-brightness sources are required in medicine for ophthalmic and dermatological use, as well as in astronomy for adaptive optic correction using laser guide stars. Although orange sources based on frequency-doubled high-power Bismuth oscillators have been reported in [6] and [7], using narrowband FBGs to limit the overall linewidth, efficiency has been limited by linewidth-broadening due to the large number of modes supported by the long lengths of active fiber required to obtain sufficient pump absorption. It is advantageous for narrow-line operation to use a short cavity to maximize the free-spectral range (FSR) and reduce the number of allowed modes under the gain spectrum; in addition, long cavities suffer from spectral broadening due to nonlinear processes. These effects can be minimized in Er- and Yb-based fiber lasers, because of the large available gain. However, long lengths of current Bismuth fibers are typically required to obtain lasing. In [6] and [7], the lengths of the gain fiber alone were in excess of 55 m, pulled from preforms fabricated using a thermodynamically equilibrated MCVD process. Bufetov *et al.* proposed applying an alternative synthesis method to the fabrication of Bi-doped fibers: surface-plasma chemical vapor deposition (SPCVD) [8]. Despite reduced optical-to-optical efficiency, lasing in the reported Bi-fiber laser was achieved with significantly reduced lengths of active fiber than had been previously possible, due to an order of magnitude increase in the number of active Bi centers, while keeping background loss unchanged. However, subsequent results demonstrating similar performance from short-length Bi-doped lasers using active fiber fabricated by MCVD have been reported [9].

Single-frequency lasers cannot be directly amplified in standard fiber configurations because of Brillouin scattering. To overcome this, linewidths of megahertz to gigahertz are required, and final stage amplification of a seed laser to Watt level can be realized in short length Raman or Bismuth fiber amplifiers. To achieve such a seed laser, we adopt a scheme developed

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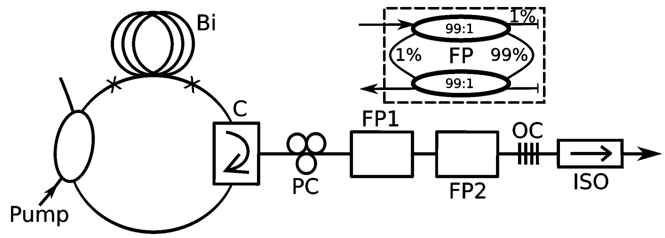

Fig. 1. Schematic of the narrow-line Bi-doped all-fiber laser. Bi: Bismuth-doped fiber; C: optical circulator; PC: polarization controller; FP: Fabry–Pérot fiber integrated filter; OC: FBG output coupler; ISO: inline optical isolator.

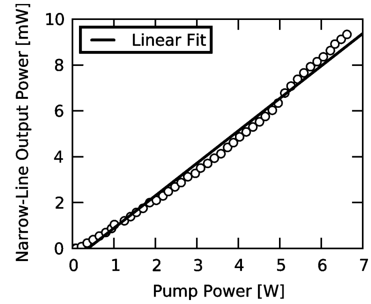

Fig. 2. Narrow-line output power as a function of the pump power.

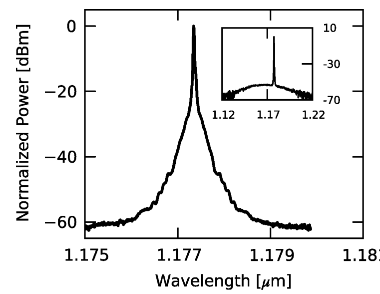

Fig. 3. Normalized optical spectrum shown to be device limited (resolution of 0.01 nm). Inset: a broader span (100 nm) showing the low level ASE pedestal.

by Das *et al.* used to obtain SLM operation in a diode-pumped Er–Yb-codoped fiber laser, emitting at 1570 nm [10]. To overcome the limiting effect of the long cavity on narrow-line operation, we employed two fiber-integrated Fabry–Pérot (FP) filters, as well as a coarsely selective narrowband FBG, to provide an order of magnitude reduction in the laser linewidth compared to previously published results [7]. We use a fiber similar to [8], fabricated using SPCVD. A travelling-wave ring resonator design is used to prevent spatial hole-burning of the gain medium broadening the laser line through increased mode competition. We use the electrical spectrum to investigate the effect of the FP filters on suppression of high-order beat notes and the overall relative intensity noise (RIN) of the laser. This initial experiment demonstrates a practical approach to achieving SLM operation in long-gain-length Bi-doped fiber lasers.

II. Experimental Setup

A schematic of the fiber ring laser is shown in Fig. 1. The alumo–silicate core, Bi-doped fiber preform was fabricated using an SPCVD process [8] and drawn into a single-mode fiber compatible with commercial Corning HI-1060 to facilitate direct fusion splicing to passive cavity components with low loss: typically less than 0.1 dB. A 30-m gain fiber was core-pumped through a custom wavelength-division multiplexer (WDM) with a commercial 10-W Yb fiber laser at 1065 nm. A three-port polarization-independent optical circulator, with $\sim$2.3-dB insertion loss at 1178 nm, guaranteed unidirectional propagation. A polarization controller was included to provide control over the polarization of light in the cavity, however, the cavity fiber was isotropic so the output polarization was random. For efficient frequency conversion, narrow-line linearly polarized sources are required and can be realized with the use of polarization-maintaining (PM) components. A narrowband, 91% reflective FBG provided optical feedback, with the 9% transmission providing output coupling, and coarse mode-selection in a 0.1-nm band around the lasing wavelength of 1177.35 nm. To increase the longitudinal mode spacing within the passband of the grating, we used a technique first reported in [10]: two fused fiber couplers, with a coupling ratio of 99 : 1, were used to form a high-finesse fiber integrated FP optical filter (see inset Fig. 1), with an FSR controllable through the lengths of the feedback arms. Two FP filters, with a marginally offset FSR, were needed to provide sufficient mode-suppression through the Vernier effect, without introducing unsupportable loss preventing lasing. Finally, an inline optical isolator was used to prevent back-reflected light destabilizing the lasers narrowline output. The total length of the ring cavity was $\sim$40 m, the two filters were 2.25 and 2.3 m, respectively. The corresponding FSRs were $\mathrm{FSR}_{\mathrm{ring}} \approx 5.1$ MHz, $\mathrm{FSR}_{fp_1} \approx 89.3$ MHz, and $\mathrm{FSR}_{fp_2} \approx 91.3$ MHz.

III. Results and Discussion

Fig. 2 shows the narrow-line output at 1177 nm as a function of pump light at 1065 nm. The threshold pump power was 250 mW, with a slope efficiency of 0.14%, limited by relatively low pump absorption and the high-unsaturable loss of the active fiber. To reduce the effect of unsaturable loss, the active fiber was cooled to 77 K in a liquid nitrogen bath. We achieved a 10-mW output in a 4.04-GHz line under 7 W of pumping, characterized using an optical spectrum analyzer (resolution 0.01 nm) and a scanning FP spectrum analyzer, with a resolution limit of 511 MHz and an FSR of 8.33 GHz.

Fig. 3 shows the device-limited, normalized narrow-line optical spectrum, with an optical signal-to-noise ratio (OSNR) of $\sim$60 dB. The inset figure shows the low-level amplified spontaneous emission (ASE) pedestal. The scanning FP spectrum of the laser output at maximum output power is shown in Fig. 4; although no formal mode stability tests were performed, the lasers output spectrum was observed to be stable for long time scales (hours).

We investigated the lasers RIN using a radio-frequency (RF) spectrum analyzer, while monitoring the dc photocurrent. Fig. 5 shows the effect of the fiber-integrated FP filters on suppression of the beat notes in the RF spectrum. The inclusion of two filters [see Fig. 5(c)] provides greater than an order of magnitude reduction in the power in high-order modes, within the bandwidth of the detection system, with most of the power contained in the

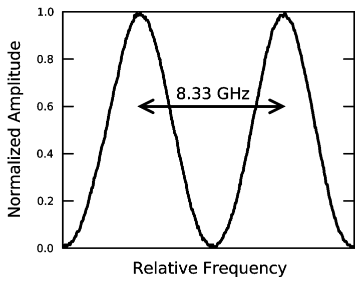

Fig. 4. Scanning FP spectrum of the narrow-line laser at maximum output power (∼10 mW).

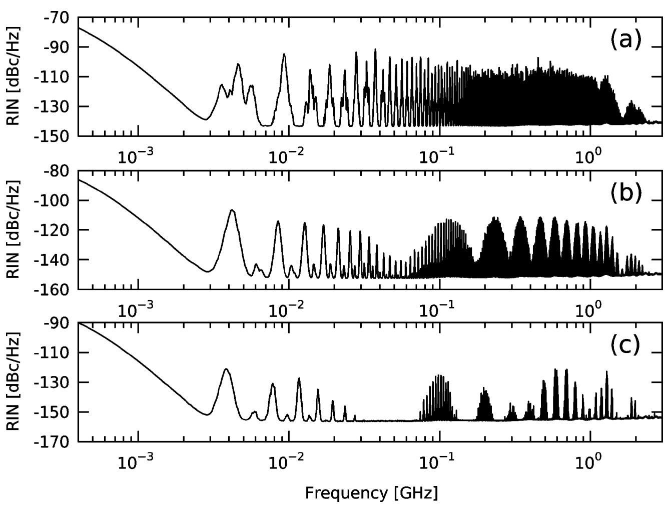

Fig. 5. Beat note-suppression imposed by the inclusion of the FP filters. (a) narrowband FBG only; (b) narrowband FBG and one fiber-intregrated FP filter; (c) narrowband FBG and two fiber-integrated FP filters.

fundamental mode. Although the filters provide mode-suppression, there is no measurable reduction in the overall linewidth. In addition, the use of FP filters in lasers based on other gain media has resulted in SLM operation [5]; the multimode nature of the output of this system suggests strong inhomogeneity of the Bi-doped active fiber.

IV. CONCLUSION

The first narrow-line Bi-doped ring laser, with an output power of ∼10 mW in a linewidth of ∼4 GHz has been reported, an order of magnitude improvement compared to previously achieved. This is the first time well-established techniques for obtaining SLM operation in rare-earth-doped fiber lasers have been applied to a Bi-doped fiber laser. The multimode nature of the output implies strong inhomgeneity of the gain medium. Two fiber-integrated FP filters, retaining the advantages of an all-fiber format, were used in conjunction with a narrowband FBG to suppress the large number of longitudinal modes supported by the long cavity; leading to a 20-dB/Hz reduction in the lasers RIN. Careful control over the temperature of the gain fiber to limit the available gain in high-order modes should result in SLM operation.

REFERENCES

[1] Y. Fujimoto and M. Nakatsuka, "Infrared luminescence from Bismuth-doped silica glass," *Jpn. J. Appl. Phys.*, vol. 40, pp. L279–L281, 2001.
[2] V. V. Dvoyrin, V. M. Mashinsky, E. M. Dianov, A. A. Umnikov, M. V. Yashkov, and A. N. Guryanov, "Absorption, fluorescence and optical amplification in MCVD Bismuth-doped silica glass optical fibres," in *31st Eur. Conf. Optical Communication (ECOC 2005)* , 2005, vol. 4, pp. 949–950.
[3] E. M. Dianov, V. V. Dvoyrin, V. M. Mashinsky, A. A. Umnikov, M. V. Yashkov, and A. N. Gur'yanov, "CW Bismuth fibre laser," *Quantum. Electron.*, vol. 35, pp. 1083–1084, 2005.
[4] I. Razdobreev, L. Bigot, V. Pureur, A. Favre, G. Bouwmans, and M. Douay, "Efficient all-fiber Bismuth-doped laser," *Appl. Phys. Lett.*, vol. 90, p. 031103-3, 2007.
[5] V. V. Dvoyrin, V. M. Mashinsky, and E. M. Dianov, "Efficient Bismuth-doped fiber lasers," *IEEE J. Quantum. Electron.*, vol. 44, no. 9, pp. 834–834, Sep. 2008.
[6] E. M. Dianov, A. V. Shubin, M. A. Melkumov, O. I. Medvedkov, and I. A. Bufetov, "High-power CW Bismuth-fiber lasers," *J. Opt. Soc. Amer. B*, vol. 24, pp. 1749–1755, 2007.
[7] A. B. Rulkov, A. A. Ferin, S. V. Popov, J. R. Taylor, I. Razdobreev, L. Bigot, and G. Bouwmans, "Narrow-line, 1178 nm CW Bismuth-doped fiber laser with 6.4 W output for direct frequency doubling," *Opt. Express*, vol. 15, pp. 5473–5476, 2007.
[8] I. A. Bufetov, K. M. Golant, S. V. Firstov, A. V. Kholodkov, A. V. Shubin, and E. M. Dianov, "Bismuth activated alumosilicate optical fibers fabricated by surface-plasma chemical vapor deposition technology," *Appl. Opt.*, vol. 47, p. 4940, 2008.
[9] M. Kalita, S. Yoo, and J. Sahu, "Bismuth doped fiber laser and study of unsaturable loss and pump induced absorption in laser performance," *Opt. Express*, vol. 16, pp. 21032–21038, 2008.
[10] G. Das and Z. J. Chaboyer, "Single-wavelength fiber laser with 250 mW output power at 1.57 μm," *Opt. Express*, vol. 17, pp. 7750–7755, 2009.