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Generation of 1.3/1.4 μm random fiber laser by bismuth-doped phosphosilicate fiber

Hang Wang (王航)[1,†], Wencheng Jia (贾文成)[1,†], Yongjia Yao (姚永嘉)[1], Xinyun Yang (杨欣芸)[1], Mikhail Melkumov[3], Sergey Firstov[3], Alexey Lobanov[4], Zhipeng Dong (董志鹏)[1*], and Zhengqian Luo (罗正钱)[1,2]

[1] Fujian Key Laboratory of Ultrafast Laser Technology and Applications, School of Electronic Science and Engineering, Xiamen University, Xiamen 361005, China

[2] Innovation Laboratory for Sciences and Technologies of Energy Materials of Fujian Province (IKKEM), Xiamen 361005, China

[3] Prokhorov General Physics Institute, Dianov Fiber Optics Research Center, Russian Academy of Sciences, Moscow 119333, Russia

[4] Devyatykh Institute of Chemistry of High-Purity Substances, Russian Academy of Sciences, Nizhny Novgorod 603951, Russia

*Corresponding author: zpdong@xmu.edu.cn

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We have successfully generated a 1.3/1.4 μm random fiber laser (RFL) using bismuth (Bi)-doped phosphosilicate fiber. The Bi-doped RFL has shown excellent long-term operational stability with a standard deviation of approximately 0.34% over 1 h at a maximum output power of 549.30 mW, with a slope efficiency of approximately 29.21%. The Bi-doped phosphosilicate fiber offers an emission spectrum ranging from 1.28 to 1.57 μm, indicating that it can be tuned within this band. Here, we demonstrated a wavelength-tuning fiber laser with a wavelength of 1.3/1.4 μm, achieved through the using of a fiber Bragg grating or a tunable filter. Compared to traditional laser sources, the RFL reduces the speckle contrast of images by 11.16%. Due to its high stability, compact size, and high efficiency, this RFL is highly promising for use in biomedical imaging, communication, and sensor applications.

Keywords: random fiber laser; bismuth-doped fiber; wavelength tuning; fiber laser.
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1. Introduction

Over the past few decades, random lasers, which are caused by weak feedback in disordered media, have gained much attention due to their outstanding characteristics, including high stability, "modelessness," and simple structure[1]. Many materials, such as Rhodamine solution[2], dye-gold nanoparticles[3], and organic dye-doped gel film[4], have been used to achieve random lasers. In particular, Turitsyn *et al.* first demonstrated random lasers in fiber, naming them random fiber lasers (RFLs)[5], which were produced by Rayleigh backscattering caused by refractive index inhomogeneity in fibers. Since then, RFLs have rapidly developed into a vital research interest in fiber lasers due to their clear advantages, including compactness, directionality, high efficiency, and low cost. Various RFL schemes have been proposed with different mechanisms, including nonlinear effects and rare-earth-doped active fibers[6–8], and wavelength adjustment and high-power random lasers are developing rapidly[9-11]. Due to their outstanding features, RFLs have broad application potential in the fields of high-quality imaging[12], telecommunications[13], sensors[14], and nonlinear optics[15].

Nowadays, fiber lasers have contributed to significant advancements and have been applied in various fields. Optical biological imaging, particularly optical coherence tomography (OCT), has shown great promise in high-resolution, high-speed, and noninvasive imaging[16]. In OCT, a broadband adjustment laser around the O-band (1.3 μm) serves as a crucial component. Currently, a superluminescent diode (SLD) or LED at 1.3 μm is typically used as a light source to prevent speckle and obtain high-quality images. However, due to their intrinsic limitations in terms of low intensity and power[17], the development of OCT is somewhat restricted. The unique characteristics of RFLs make them a promising alternative to OCT[18,19]. While there have been reports of a 1.3 μm fiber laser based on nonlinear fiber effects, such as stimulated Raman[20–22] and soliton self-frequency shift[23], further improvements in the stability and power of lasers are still needed. Recently, Bi-doped fiber has garnered special interest due to its ultrawide emission spectrum[24–27]. Lobach *et al.* were the first to demonstrate a narrowband RFL near 1.42 μm using Bi-doped fiber[28]. They also predicted that the emission spectrum of Bi-doped fiber could be tuned by different host compositions, which could potentially increase its applications in the fields such as optical communications, medicine, metrology, and material processing.

In this paper, we present what we believe is the first demonstration of a 1.3/1.4 μm RFL using Bi-doped fiber. The active fiber consists of a 120 m section of Bi-doped fiber pumped by a homemade 1238.90 nm Raman fiber laser. A fiber Bragg grating (FBG) with a central wavelength of 1352 nm and 450 m SMF-28 fiber form a Bi-doped RFL with a half-open cavity structure. The proposed RFL exhibits a slope efficiency of approximately 29.21% and a maximum output power of 549.30 mW. The Bi-doped phosphosilicate fiber has the potential to realize a 1.28–1.57 μm laser due to its ultrawide emission spectrum. We have demonstrated a wavelength-tunable fiber laser operating at 1.3/1.4 μm by employing an FBG or a tunable filter. The proposed RFL is of compact size, is highly efficient, and is stable, making it suitable for various practical applications, such as biomedical imaging, fiber distributed sensing, and communication.

2. Experimental Setup

The experimental setup for the proposed Bi-doped RFL is depicted in Fig. 1. A phosphorus-doped Raman fiber laser centered at 1238.90 nm acted as a pump source, which was intracavity pumped by a 1064 nm fiber laser, as illustrated by the dotted line in Fig. 1. A section of 120 m Bi-doped (core diameter of 6.4 μm) fiber worked as gain fiber through a 1238.90/1350 nm wavelength division multiplexer (WDM). A high reflectivity (>98%) FBG with a central wavelength at 1352 nm served as a reflector and a wavelength selector. A 450 m SMF-28 fiber provided random distributed feedback based on Rayleigh scattering to form a classical half-open cavity. The function of the optical isolator (ISO) was to eliminate unexpected Fresnel reflection from the fiber end facets and ensure that the random feedback was provided only by SMF-28. Here, a power meter (Thorlabs PM100D), a 26.5 GHz radio-frequency (RF) spectrum analyzer, and an optical spectrum analyzer (ANDO AQ-6315E) were applied to achieve output power, an RF spectrum, and an optical spectrum, respectively.

The Bi-doped fiber includes both active bismuth centers associated with silicon (BACs-S) and phosphorus (BACs-P) based

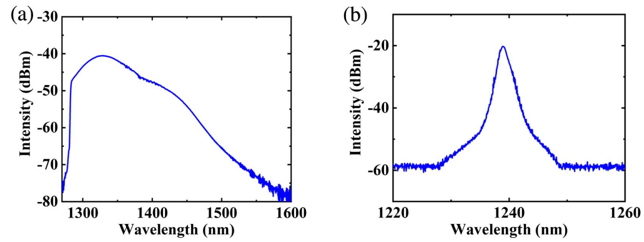

Fig. 2. (a) Emission spectrum of Bi-doped fiber; (b) spectrum of 1238.90 nm Raman fiber laser.

on the metal chemical vapor deposition technique[29], in which the emission spectrum covers from 1.2 to 1.5 μm spectral region under a 1238.90 nm pump, as illustrated in Fig. 2(a). The absorption of Bi-doped fiber is about 0.4 dB/m at 1239 nm. A homemade Raman laser based on phosphosilicate fiber offers a 1.87 W maximum power at a central wavelength of 1238.90 nm with a 3 dB linewidth of 1.2 nm [seen in Fig. 2(b)].

3. Result and Discussion

The central wavelength of Bi-doped RFL is located at 1352.03 nm with a 3 dB bandwidth of 0.92 nm when the pump power exceeds 136.50 mW, as illustrated in Fig. 3(a). The slope efficiency of Bi-doped RFL is about 29.21%, and the output power is about 549.30 mW at the maximum pump power of 1.87 W, as shown in Fig. 3(b). Figure 3(c) shows the excellent long-term output power stability of the RFL for 1 h, of which a standard deviation is about 0.34%. As we know, there is a fixed cavity for conventional fiber laser, and a longitudinal mode interval can be expressed as $\Delta\nu = c/2nL$, where c is the speed of light, n is the effective refractive index of the fiber, and L is the length of the cavity. A clear mode-beating signal can be obtained using an RF spectrum analyzer. However, owing to the uncertain cavity length characteristics of RFLs, there are

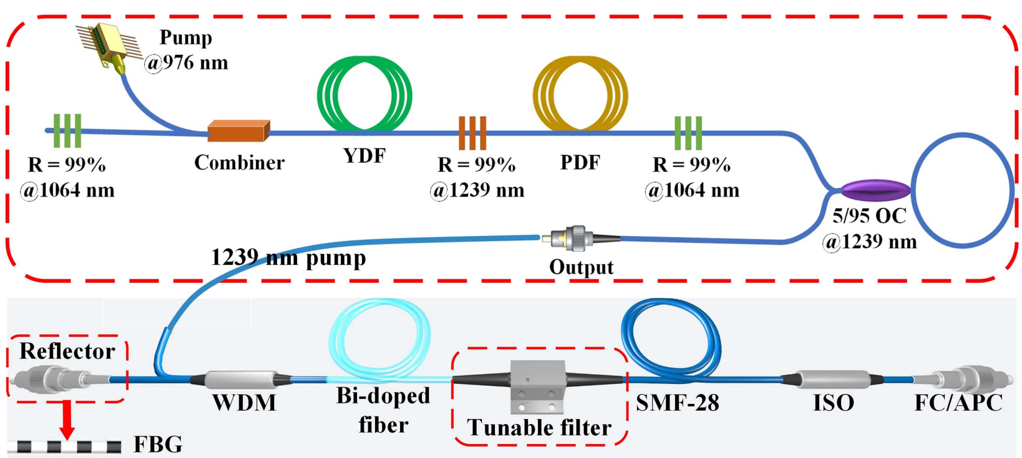

Fig. 1. The schematic of the RFL. FBG, fiber Bragg grating; reflector, high reflectivity fiber coated reflector at 1.4 μm; WDM, 1238.90/1350 nm wavelength division multiplexer; Bi-doped fiber, bismuth-doped fiber; tunable filter, tunable filter (JDSU mTBF-A1) with 1420–1620 nm; ISO, optical isolator; FC-APC, fiber end facets with 8°; PDF, phosphorus-doped fiber; YDF, ytterbium-doped fiber; OC, optical coupler; combiner, double-cladding pump combiner.

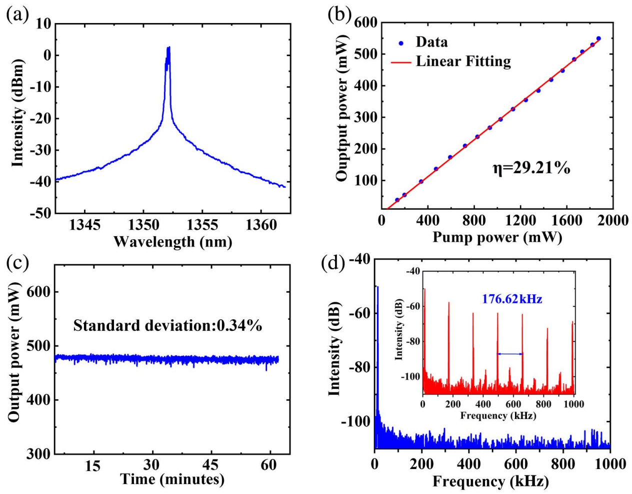

Fig. 3. (a) Optical spectrum of Bi-doped RFL; (b) Bi-doped RFL output power versus pump power at 1352.03 nm; (c) long-time output power stability of the RFL for 1 h; (d) RF spectrum of the RFL state; inset, the RF spectrum of convention cavity.

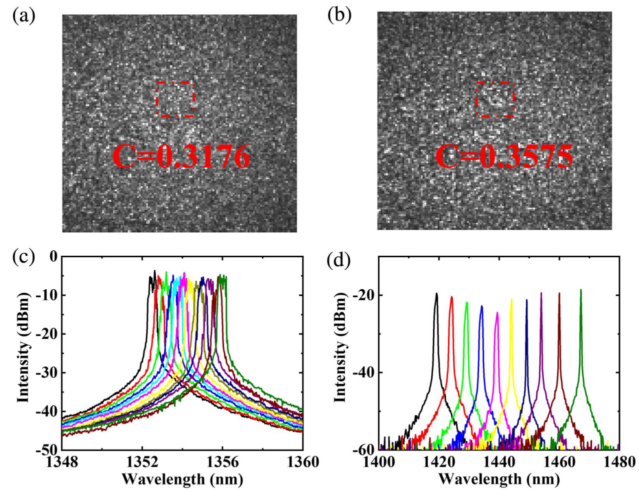

Fig. 4. (a) Speckle pattern of Bi-doped RFL; (b) speckle pattern of Bi-doped conventional fiber laser; (c) wavelength-tuning optical spectrum from 1352.03 to 1356.03 nm; (d) wavelength-tuning optical spectrum from 1419.20 to 1467.19 nm.

no well-defined cavity modes in the RF spectrum[30]. The RF spectra were measured by an RF spectrum analyzer with a 12 GHz photodetector to verify that the proposed fiber laser was operating at random laser state. Figure 3(d) shows the RF spectrum within a 1 MHz span, with a resolution of 300 Hz. Obviously, there is no longitudinal mode-beating signal corresponding to the fiber length ($\Delta\nu = c/2nL \approx 176\,\text{kHz}$, n is about 1.45), which indicates the laser operates at a random laser state. For comparison, we removed the ISO and replaced it with a flat fiber end facet to form a conventional resonance cavity, in which the reflection of the fiber end facet is about 4%. As shown in the inset of Fig. 3(d), an obvious beating signal with an interval of 176.62 kHz can be observed, satisfying the convention fiber laser theory.

Image quality is a critical parameter in the imaging field, which can be quantitatively characterized by speckle contrast, according to the speckle theory[31],

$$C = \frac{\delta_I}{\bar{I}},$$

where δ_I and $\bar{I}$ are the standard deviation of light intensity and the average value of light intensity, respectively. We measured the speckle patterns of the random laser and the traditional laser (the ISO was replaced with flat fiber end facet to form a conventional resonance cavity), respectively, as shown in Figs. 4(a) and 4(b). The speckle contrast decreased from 0.3575 to 0.3176, which indicates the proposed RFL can improve the image quality. Wavelength-tuning and multiwavelength fiber lasers are valuable instruments for various commercial and scientific applications. The Bi-doped fiber in our experiment offers an ultrawide gain spectrum, which supports broad wavelength-tuning and multiwavelength lasing. Figure 4(c) illustrates the wavelength-tuning spectrum of Bi-doped RFL by tensioning the FBG, which is tuned from 1352.03 to 1356.03 nm. Furthermore, a tunable filter (JDSU mTBF-A1) with 1420–1620 nm range was inserted between the Bi-doped fiber and the feedback fiber, and the FBG was replaced by a high-reflectivity fiber mirror at 1.4 μm. As shown in Fig. 4(d), the central wavelength can be tuned from 1419.20 to 1467.19 nm by adjusting the tunable filter. The maximum output power at 1455.82 nm is about 193.30 mW, with pump power of 1.87 W, as shown in Fig. 5(a). The output power is lower than at 1.35 μm wavelength because the gain of the fiber is weaker at 1.45 μm. A wider wavelength adjustment range can be imagined by employing a broadly tunable filter. When the FBG and tunable filter were removed, the unstable multiwavelength RFL covering the 1.30 to 1.45 μm range can be obtained, as shown in Fig. 5(b). The ultrawide emission spectrum of Bi-doped fiber enables it to support multiwavelength laser operation when the pump power is sufficient. The stability of the system, however, can be affected by both gain competition and external environmental disturbances[32,33]. By using double-cladding Bi-doped fiber with a master oscillator power amplifier structure, higher-power RFLs can be obtained in future work[34].

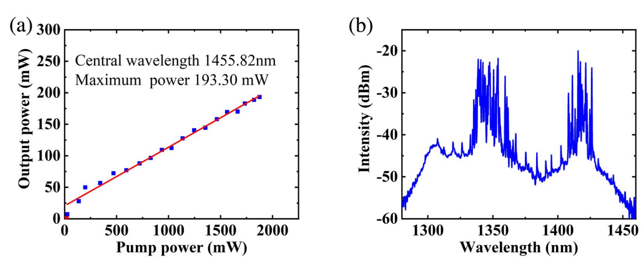

Fig. 5. (a) Bi-doped RFL output power versus pump power at 1455.82 nm; (b) multiwavelength of the Bi-doped RFL.

4. Conclusions

In summary, we report a stable 1.3/1.4 μm RFL by using Bi-doped phosphosilicate fiber, with a maximum output power of 549.30 mW and a slope efficiency of 29.21%. The proposed Bi-doped RFL has excellent stability for long-term operation, with a standard deviation of about 0.34% for 1 h. In addition, the wavelength tuning in the 1.35 and 1.47 μm region can be realized by tensioning the FBG or tunable filter, respectively. According to the Bi-doped ultrawide emission spectrum, the fiber laser with wavelength tuning from 1.28 to 1.57 μm can be imagined. It may be a useful laser source for the field of biomedical imaging, communication, and sensors, owing to its high efficiency and high stability.

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†These authors contributed equally to this work.

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