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Weak feedback assisted random fiber laser from 45°-tilted fiber Bragg grating

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Abstract: We have demonstrated the realization of a high-polarization random fiber laser (RFL) output based on the hybrid Raman and Erbium gain with the tailored effect provided by a 45°-tilted fiber Bragg grating (45°-TFBG), revealing an improvement in the polarization extinction ratio (PER) and achieving a PER of ~15.3 dB. The hybrid RFL system incorporating the 45°-TFBG has been systematically characterized. The random lasing wavelength can be fixed under the extremely weak feedback effect of the 45°-TFBG with reflectivity of 0.09%. In addition, numerical simulation has verified that the weak feedback can boost the random lasing emission with fixed wavelength using a power balance model, which is in good accordance with the experiment results.

1. Introduction

To solve two problems—high threshold and non-directivity—of random lasers (RLs), optical fibers have been used to confine the random laser system, bringing about the development of random fiber lasers (RFLs) [1]. Furthermore, a coherent RFL based on nanoparticles (NPs) scattering in the extremely weakly scattering regime has been obtained [2–4], which extends RFL from incoherent to coherent random lasing. To extend the application of RFL, D. V. Churkin and S. K. Turitsyn *et al.* have demonstrated RFLs in the telecommunication fiber based on a random distributed feedback due to the Raman amplified Rayleigh backscattering [5,6]. And X. Bao *et al.* have reported Rayleigh scattering-assisted Brillouin lasing with single frequency and narrow linewidth in cascaded low-loss communication fiber [7,8]. However, the threshold of random laser is still high in the telecommunication single mode fiber (SMF) due to the low back-scattering coefficient. Therefore, there are two main ways to decrease the random lasing threshold: 1) bring active fibers in the RFL system, *e.g.*, Erbium doped fibers [9]; 2) add a fiber Bragg grating (FBG) to form a half-open cavity [6]. Therefore, H. Wu *et al.* have used the hybrid Erbium-Raman fiber system (ERFS) with assistance of a FBG to obtain low threshold, high efficient RFL [10]. In the hybrid Erbium-Raman fiber with FBG system, the role of FBG is to reflect the fixed wavelength light based on the Bragg law and boost random lasing with the fixed wavelength. Nevertheless, in the hybrid system without FBG, there are multi-modes stochastic lasing due to nearly equal probability of the dense multi-longitudinal modes in ultra-long fiber cavity. The reflectivity of FBG used in the random fiber laser system is >90% to obtain narrow random lasing with fixed wavelength. They also have investigated the role of point reflector with reflectivity of 1%-90% on the lasing threshold and power distribution in random fiber lasing process. The power distribution

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and threshold tend to be stable when the reflectivity reaches a relatively high level [11]. In our previous work [2], the waveguide effect can boost the random lasing in the extremely weakly scattering regime. To date, ***super-low reflectivity (<0.1%)*** feedback how to influence the random lasing process and ***stabilize random lasing wavelength*** have not been reported in the RFL system.

The polarized lasers are important in the applications of sensor and optical communication. Nevertheless, it is hard to obtain the polarized RFL based on Rayleigh scattering since the local birefringence along SMFs is strongly influenced by external perturbations, leading to the deterioration of the RLs characteristics. L. Zhang *et al.* reported the linearly polarized multi-wavelength Brillouin laser comb by cascading multiple Brillouin random lasing oscillations in a semi-open polarization maintaining fiber-based composite cavity [12]. B. Yao *et al.* have obtained singly-polarized pulse RFL using the broadband saturable absorption of monolayer graphene [13]. A. E. Budarnykh *et al.* have demonstrated an operation of a linearly polarized Raman fiber laser with random distributed feedback based on a polarization maintaining twin-core fiber [14]. H. Wu *et. al.* have reported a polarization-modulated RFL that generates pulsed output is proposed due to the different lasing threshold for two polarization states [15]. S. Babin *et. al.* have proposed approach enables high-efficiency generation of high-quality linearly-polarized laser radiation in a polarization-maintaining fiber [16]. The hitherto reported polarized RFLs are mainly based on adding saturable materials or polarization-maintaining devices in the fiber system. To decrease the complexity and extend the application of polarized RFL, we focus on the research of low-cost and all fiber polarized RFLs.

To simplify the fabrication procedures and decrease the cost of polarizers, the ultraviolet (UV) inscribed 45°-tilted fiber Bragg grating (45°-TFBG) has been fabricated as a polarizer in a standard commercial SMF that possesses significant advantages, *e.g.* low-cost, effective and all fiber system, over traditional polarizers [17–19]. In principle, the TE light through such grating shows large transmission loss whereas the TM-light loss remains small due to Brewster's Law. Therefore, the 45°-TFBGs have been applied in optical communications and fiber laser systems as a broadband polarizer [20]. Moreover, the reflectivity of 45°-TFBGs is weak. Therefore, the 45°-TFBGs comes into our sight to research how super-low reflectivity influences the random laser. Furthermore, this could also provide a simple way to realize polarized RFL in the all fiber hybrid ERFS system.

In this paper, firstly, characteristics of the RLs in the hybrid ERFS without 45°-TFBG have been investigated. The wavelengths of random lasing fluctuate randomly with time with the absence of the 45°-TFBG. Interestingly, when the 45°-TFBG with ***super-low reflectivity*** of 0.09% has been integrated in the hybrid ERFS, the RLs wavelength can be fixed and the threshold decreases comparing with the hybrid system without 45°-TFBGs. In our experiment, the reflectivity of Rayleigh backscattering of SMF is 0.05% based on the Rayleigh backscattering coefficient $\varepsilon = 4.5 \times 10^{-5}\ \text{km}^{-1}$ [21] and fiber length of 11 km, which is similar with that of the 45°-TFBG. Therefore, we prove that the ***weak feedback*** can boost ***random lasing with fixed wavelength*** in ERFS. Moreover, ***a low-cost, effective and all fiber polarized RFL with PER of 15.3 dB*** has been obtained since only TM light can transmit through the 45°-TFBG. Finally, the influence of weak feedback on boasting the random lasing process and fixing the lasing wavelength is simulated.

2. Experiments

Figure 1 shows the setup of RFL based on hybrid ERFS. A 1455 nm Raman fiber laser (IPG) with a maximum output power of 5 W is used to pump both the Erbium doped fiber (EDF, 2 m length) and the SMF (11 km length) through a 1455/1550-1600 nm wavelength division multiplexer (WDM). The EDF provides active amplification, while the SMF provides both amplification based on simulated Raman scattering and feedbacks through distributed random Rayleigh scattering. And all the fiber ends are angle cleaved to avoid the Fresnel reflection

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through using APC fiber. To research the effect of super-low reflectivity feedback on the RFLs and realize polarized RLs, a 45°-TFBG is connected after the 1500-1600 nm port of the WDM. A fiber polarization controller (PC) and a polarizer (P) are successively placed after the 45°-TFBG to measure the polarized property of the RFL. The 45°-TFBG is fabricated in the SMF based on the way in [17].

Firstly, we research the RFL emission from the ERFS without the 45°-TFBG feedback. Figure 2 shows the random lasing spectra and threshold from Port 2. In this case, the EDF provides gain medium and SMF performs Raman gain with random distributed feedback. The random lasing can be initiated under the co-work of gain of EDF and Raman with random feedback of SMF. When the pump power is small, only a typical wideband amplified spontaneous emission (ASE) of the EDF can be observed. As the pump power increases, the narrow random lasing spikes with main peak wavelength of 1556 nm randomly appear on the top of the ASE spectrum. As shown in the inset of Fig. 2, the threshold of the RFL is 3.8 W, which is higher than the value in [22]. This can be attributed to two reasons: 1) the length of SMF and EDF in our system is shorter than that of [22], causing weak gain in our system; 2) the pump way is double direction pump in [22], nevertheless we only use single direction pump. And the wavelengths of the random lasing spikes fluctuate with the same pump power of 4.4 W, as shown in the Fig. 3. It is an important feature of RL. In the ERFS, the reflectivity of Rayleigh backscattering is calculated to be 0.05% based on the Rayleigh backscattering coefficient $\varepsilon = 4.5 \times 10^{-5}$ km^{-1} [20] and fiber length of 11 km. This small reflectivity of SMF makes it hard to boost more photonics feedback, and thus the random lasing threshold is high and wavelength is random emission.

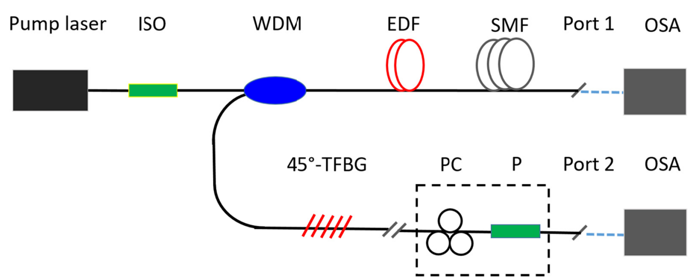

Fig. 1. The schematic setup of the proposed hybrid ERFS with 45°-TFBG feedback. WDM: wavelength-division multiplexer with 1455 nm, 1500-1600 nm and common ports; 45°-TFBG: 45°-Tilted Fiber Bragg Grating; ISO: isolator; PC: polarization controller; P: polarizer, OSA: optical spectrum analyzer; EDF: Erbium doped fiber; SMF: single mode fiber.

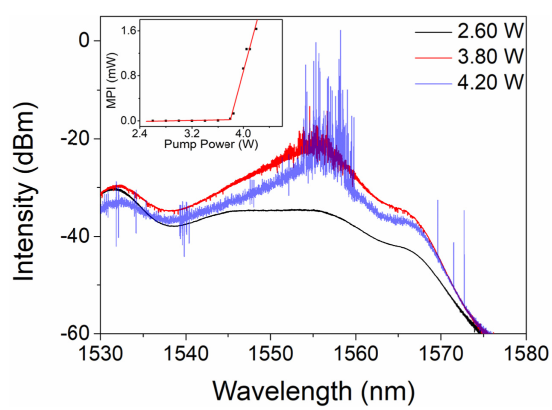

Fig. 2. The RFL spectra at different pump power. Inset: the output power of RFL versus pump power, MPI: Main peak intensity.

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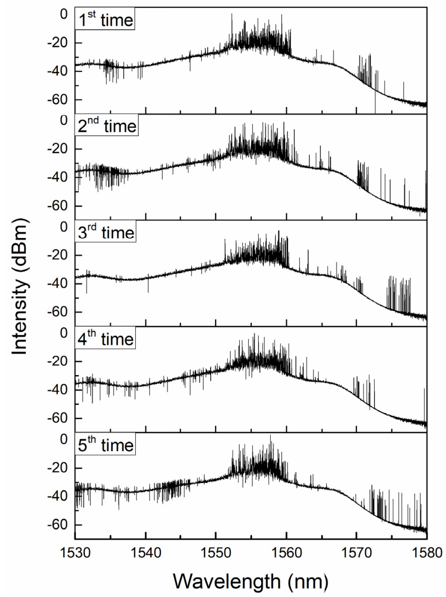

Fig. 3. The random lasing spectra at different pump time with pump power of 4.4 W.

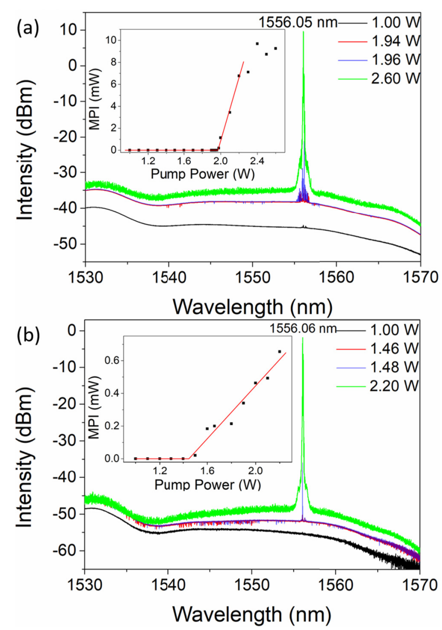

Fig. 4. The random lasing spectra in ERFS with the 45°-TFBG for Port 1 (a) and 2 (b). Inset: the output power of RFL versus pump power corresponding Port 1 and 2.

Displayed in Fig. 4 are the random lasing spectra from Port 1 (2) and the input-output relationship in the ERFS with the 45°-TFBG. For the Port 1 and 2, when the pump power is low, there is only ASE. As the pump power increases over the threshold, the random lasing can be observed on the top of the ASE. Moreover, the random lasing mode number decreases with the pump power increasing. Interestingly, the main peak wavelength can be fixed in the 1556.05 (1556.06) nm for Port 1 (2) at different pump power, which is a different phenomenon from that of the ERFS without 45°-TFBG. This phenomenon is caused by the weak cavity feedback formed by weak feedback of Rayleigh of SMF and reflection of 45°-TFBG. As shown in the inset of Fig. 4, it can be seen that the threshold is 1.97 W (1.45 W) for the Port 1 (2), which is lower than that of ERFS without 45°-TFBG. Therefore, the feedback of 45°-TFBG plays a key role to realize a low threshold random laser with fixed wavelength. As shown in Fig. 5, the reflection wavelength of 45°-TFBG is 1555.19 nm. The deviation between the reflection wavelength and the random lasing wavelength should be resulted from the measurement error by the two OSA. And the polarization dependence loss of the 45°-TFBG can be found in the [19,23]. This observation echoes well to the aforementioned description that the feedback of the 45°-TFBG boosts random laser. Meanwhile, the reflectivity of the 45°-TFBG is calculated to be very weak value of 0.9% using fiber circulator measurement, which is almost same value with that of backscattering of the SMF with 11 km length. The two weak feedback can form a weak cavity to boost the random lasing emission.

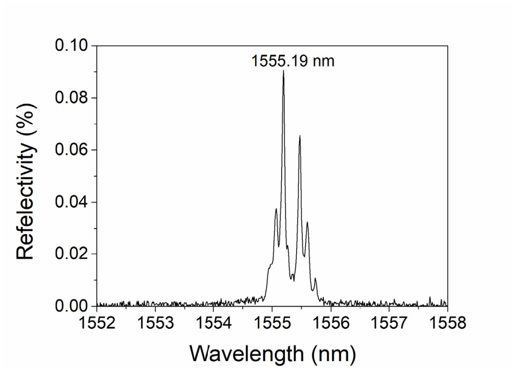

Fig. 5. The reflection spectrum of the 45°-TFBG.

To future research the wavelength stability of ERFS with the 45°-TFBG, the random lasing spectra in different pump time at pump power of 2.3 W have been shown in the Fig. 6. It can be seen that random lasing mode at wavelength of 1556.05 (1556.06) nm can been fixed for Port 1 (2). Nevertheless, the other lasing modes changes at different pump time. These results prove that the weak reflectivity from the 45°-TFBG can also provide a closed cavity with backscattering of the SMF to obtain fixed random lasing emission.

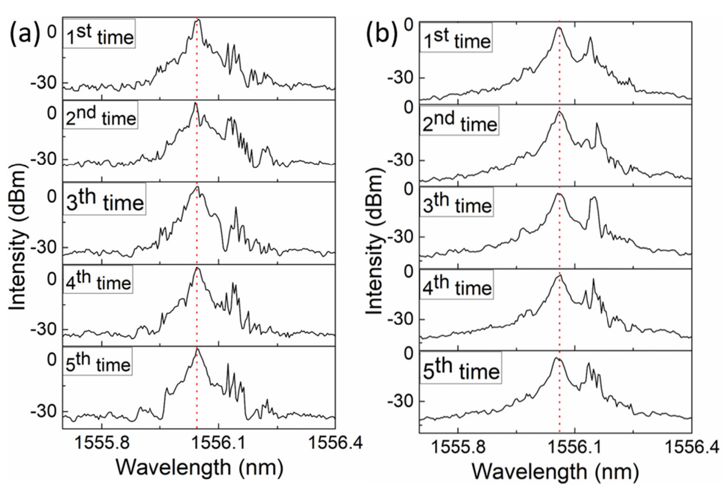

Fig. 6. The random lasing wavelength stability from Port 1 (a), and 2 (b).

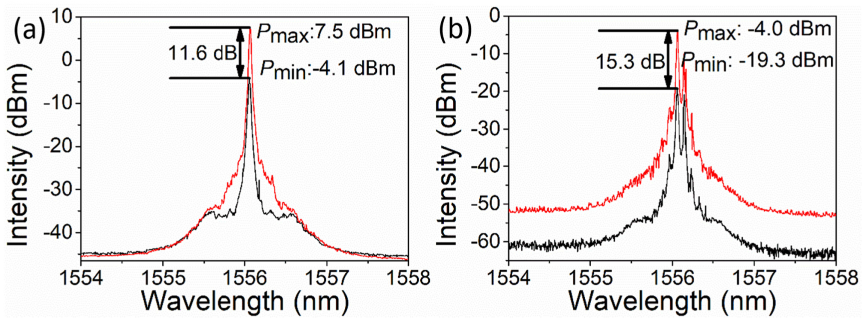

Fig. 7. The PER spectra from Port 1 (a), and 2 (b).

Based on the experimental setup with the 45°-TFBG shown in the Fig. 1, the maximum (max) and minimum (min) power of random laser have been obtained by adjusting the PC. Figure 7 gives the measured random laser PER spectra, showing a PER of 11.6 (15.3) dB for Port 1 (2). We can see that the 45°-TFBG can be considered as a near-ideal polarizer. The random laser PER value from Port 1 is lower than that from Port 2, because the polarization of feedback random laser is disturbed by the SMF.

3. Simulations

The weak feedback's influence on the random lasing wavelength is further investigated theoretically. The output spectrum can be analyzed through a power balance model, which considers both the EDF and Raman gain as shown in the following equations [22]. It is worth to mention that in the simulation the 45°-TFBG is simplified as a point reflector with the measured reflective profile given in Fig. 5. Through considering pump wavelength (1455 nm) and Stokes light waves in a bandwidth, the lasing process and output spectrum can be simulated.

$$\frac{\overline{N_2}}{\overline{N_t}} = \frac{\sum_{k=0}^{N} \frac{(P_k^+ + P_k^-)\alpha_k}{h\upsilon_k \zeta}}{1 + \sum_{k=0}^{N} \frac{(P_k^+ + P_k^-)(\alpha_k + g_k)}{h\upsilon_k \zeta}} \tag{1}$$

$$\begin{aligned} \frac{dP_k^\pm}{dz} &= \pm(\alpha_k + g_k)\frac{\overline{N_2}}{\overline{N_t}} P_k^\pm \pm 2g_k \frac{\overline{N_2}}{\overline{N_t}} h\nu_k \Delta\nu_k \\ &\mp (\alpha_k + l_k) P_k^\pm + \varepsilon_k P_k^\mp \end{aligned} \tag{2}$$

$$\begin{aligned} \frac{dP_k^\pm}{dz} &= \mp a_k P_k^\pm \pm \eta g_k (P_0^+ + P_0^-) P_k^\pm \pm \varepsilon_k P_k^\mp \\ &\mp (1-\eta) \sum_{k'=1}^{N} \frac{v_0}{v_{k'}} (P_{k'}^+ + P_{k'}^-) P_0^\pm \end{aligned} \tag{3}$$

Equations (1) and (2) are the Giles model for the EDF [24], while Eq. (3) is the Raman gain based model for the SMF [25]. In the three equations, ' ± ' represents the forward and backward propagating light waves. Subscript k denotes the light waves with the k_{th} wavelength. $k = 0$ corresponds to the 1455 nm pump and $k > 0$ describes the stokes light. η is a control index, which means for pump wavelength ($k = 0$), η is set to be 0 and for stokes light ($k > 0$), η is set to be 1.

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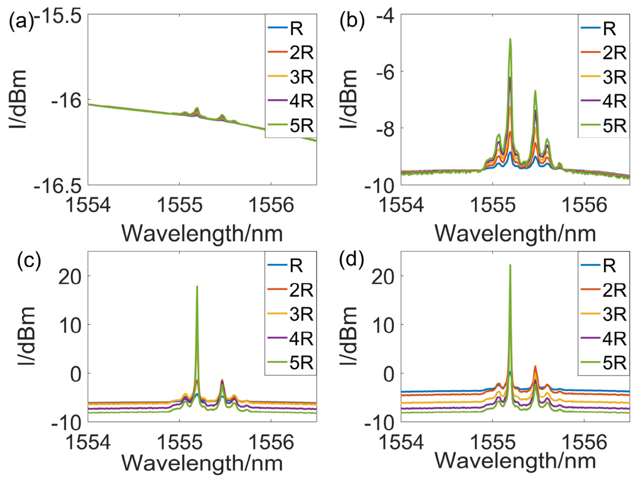

Fig. 8. Numerical simulated output spectra in forward direction for different reflectivity correspond to pump power of 0.5 (a), 1.5 (b), 2 (c) and 2.5 W (d). R: the reflectivity of the 45°-TFBG.

The relationship of reflection strength and lasing process is analyzed numerically by increasing the reflectivity of the 45°-TFBG (R) at different pump power, as shown in Fig. 8. For pump power under the lasing threshold, the peaks in the spectrum are amplified simultaneously with the increase of reflectivity, as shown in Fig. 8(a). However, for pump power higher than the threshold, the lasing wavelength (1555.19 nm, the highest reflective peak in the 45°-TFBG reflection profile) dominates in the output spectrum, while the background light, the power of the peaks with lower reflectivity and the 3-dB bandwidth of the lasing wavelength are all strongly suppressed with the increase of reflection, as shown in Fig. 8(d). Therefore, weak feedback in this level has a remarkable impact on the random lasing process and the dominant lasing wavelength is only selected by the highest reflective peak of the 45°-TFBG. Figure 9 gives the simulated backward output spectra. The evolutionary process of the backward spectra follows the main characteristics of the forward ones, except with a much lower output power and lower background light which both coincide with the experimental results as shown in Fig. 4.

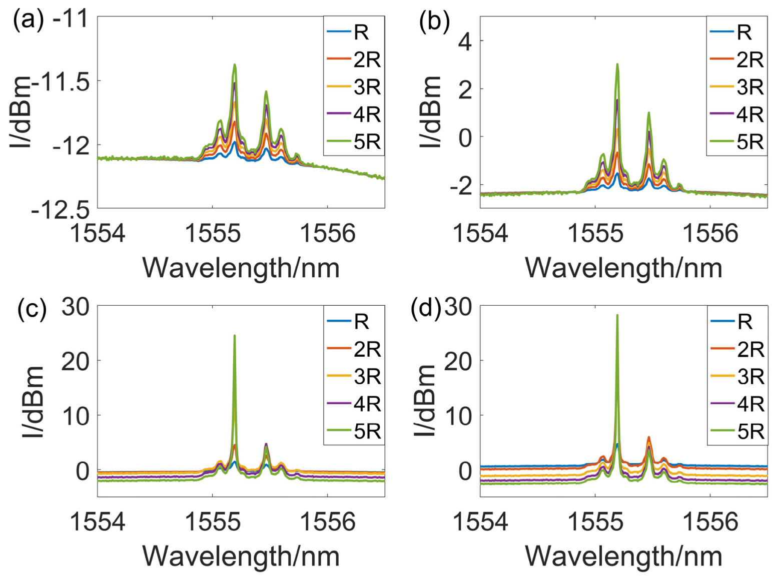

Fig. 9. Numerical simulated output spectra in backward direction for different reflectivity correspond to pump power of 0.5 (a), 1.5 (b), 2 (c) and 2.5 W (d).

4. Summary

In summarize, we have reported a fixed wavelength random fiber laser emission with the weak feedback assistance of 45°-TFBG that located in the reflection of 45°-TFBG in the hybrid Raman and erbium gain fiber. Meanwhile, we prove the weak feedback of 45°-TFBG plays a key role to obtain fixed wavelength random lasing in experiment and simulation. Moreover, we obtain random laser with high polarization extinction ratio of ~15.3 dB. Therefore, this work provides a way to control the emission wavelength by weak scattering feedback.

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