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Powerful Narrow Linewidth Random Fiber Laser

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Abstract: In this paper, we demonstrate a narrow linewidth random fiber laser, which employs a tunable pump laser to select the operating wavelength for efficiency optimization, a narrow-band fiber Bragg grating (FBG) and a section of single mode fiber to construct a half-open cavity, and a circulator to separate pump light input and random lasing output. Spectral linewidth down to 42.31 GHz is achieved through filtering by the FBG. When 8.97 W pump light centered at the optimized wavelength 1036.5 nm is launched into the half-open cavity, 1081.4 nm random lasing with the maximum output power of 2.15 W is achieved, which is more powerful than the previous reported results.

Keywords: Random fiber laser; distributed feedback; Rayleigh scattering; Raman scattering

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1. Introduction

Since the concept of random laser was first demonstrated by Letokhov *et al.* [1] in 1966, random lasers have drawn more and more attention. As is well-known, two key elements are necessary in the traditional laser scheme: a cavity which provides positive feedback and a gain medium which creates amplification. But in random lasers, there is no traditional resonator, which provides random lasers with special features compared with conventional cavity lasers. In earlier decades, researchers obtained random lasing in powder of active crystals [2], nanowires [3], and polymers [4]. The simplicity of realization of random lasers gives them an upper hand over conventional lasers. But such systems require high peak powers pump, and the laser efficiency is relatively low due to small active areas and low directionality, and more importantly, which are cumbersome or almost no control over the spectral properties of the emission [5].

Low-dimensional random systems can be used to solve these problems [6] by using optical fibers providing a lot of possibilities because of its waveguide property. Random lasing was demonstrated in the photonic crystal fiber with the hollow core filled with a suspension of TiO_2 nanoparticles [7], polymer optical fibers [8], and rare-earth doped fiber with randomly spaced gratings [9].

Recently, Turitsyn *et al.* [10] proposed a radically different branch named random fiber laser (RDFL), which operated via extremely weak random scattering in a single mode fiber (SMF). The

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random distributed feedback (DFB) was provided by backward random Rayleigh scattering, and the amplification was produced by the stimulated Raman scattering (SRS) effect. Following this research, a number of works were published, in which the RDFLs have been designed to have characters of high efficiency and high power output [11, 12], tunable [13, 14], multi-wavelength [15, 16], and polarized output [17, 18].

Due to its unique features, RDFL has found a large variety of application potentials, such as telecom and remote sensing [19−21]. However, most of RDFLs have relatively broad spectra (several nanometers). For some practical application fields such as coherent sensing and detection, suppressing the linewidth is required to increase the system performance. Ultra-narrow lasing has been reported in a coherent Brillouin random fiber laser [22, 23]. As for RDFLs based on Rayleigh scattering and Raman amplification, laser generation with a narrow linewidth down to 0.05 nm through filtering by the FBG was demonstrated in [5], and the corresponding highest output power approached 100 mW level. In this paper, we demonstrate a more powerful narrow linewidth (~40 GHz) RDFL by employing a higher power tunable pump laser, of which the output power reaches more than 2 W, which is about one order higher in magnitude than that of the previously reported results.

2. Experimental setup

Figure 1 shows a schematic diagram of the experimental setup. The pump source we employ is a tunable fiber laser, which consists of an Yb-doped fiber laser (YDFL) with a ring cavity geometry, in which we utilize a 1030 nm – 1090 nm tunable bandpass filter (T-BPF) to select the operating wavelength. To achieve higher output power, a standard master oscillator power amplifier (MOPA) configuration is used to amplify the seed laser, and the maximal power of the tunable fiber laser is about 9 W. To avoid unwanted feedback that influences the former system, an isolator (ISO) is positioned after the tunable pump source. The pump light input and the random lasing output are separated by a circulator. A 1% coupler is used to monitor the pump laser operation. A section of 3 km SMF-28e fiber functions as the Raman gain medium and the distributed feedback mirrors. To achieve narrow linewidth generation and decrease the lasing threshold, a narrow-band of 0.07 nm fiber Bragg grating (FBG) centered at 1081.29 nm is spliced to the SMF, which constructs a half-open cavity. So the feedback is provided both by FBG reflection and distributed Rayleigh scattering. The narrow-band lasing output is at the 3rd port of the circulator. To eliminate Fresnel reflection, all the end facets are cleaved at an angle of 8°. For the sake of simplicity, we define lasing output from circulator side and FBG side as Output A and Output B, respectively.

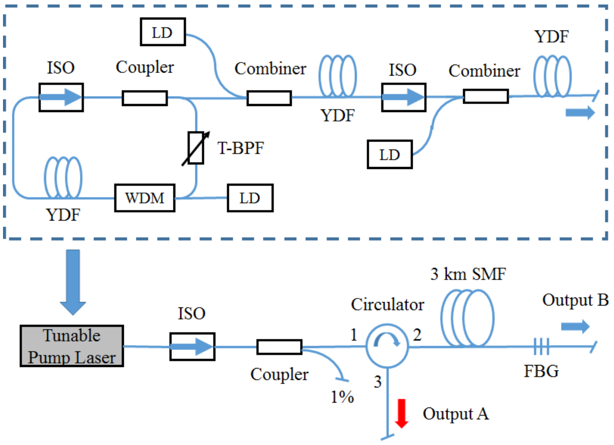
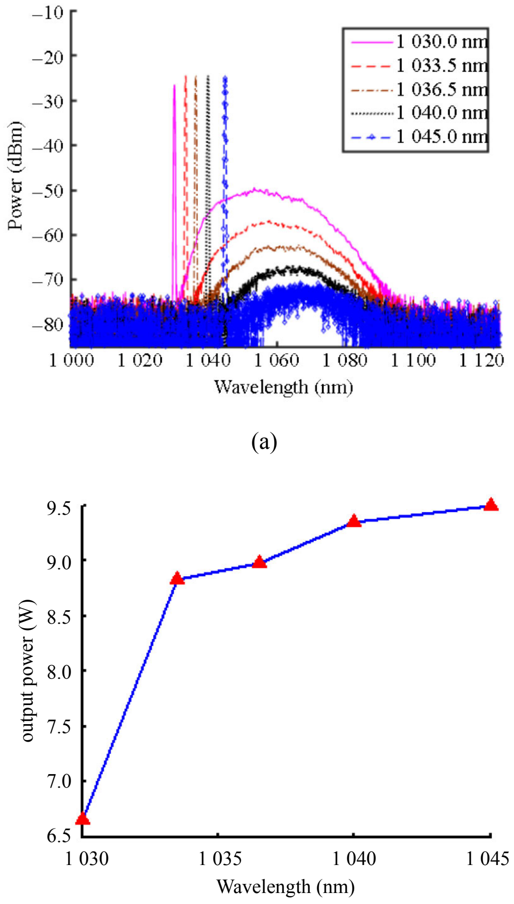


Fig. 1 Schematic of the narrow linewidth random fiber laser (ISO: isolator; YDF: Ytterbium-doped fiber; WDM: wavelength division multiplexing; T-BPF: tunable bandpass filter; LD: laser diode; SMF: single mode fiber; FBG: fiber Bragg grating).

3. Results and discussion

The wavelength tuning range of the pump laser is 1030 nm – 1090 nm. The spectra of lasing at 1030 nm – 1045 nm are shown in Fig. 2(a), and we can see that the amplified spontaneous emission (ASE) decreases with an increase in the wavelength. The ASE is about 25 dB lower than the signal laser at 1030 nm, and this value increases to about 45 dB at 1045 nm. Figure 2(b) shows the output power of the tunable fiber laser operating at different wavelengths, in which the maximal power of the pump laser reaches about 9 W when the wavelength is longer than 1033.5 nm, and the power of 1030 nm is relatively low because of stronger ASE.



(a)

(b)

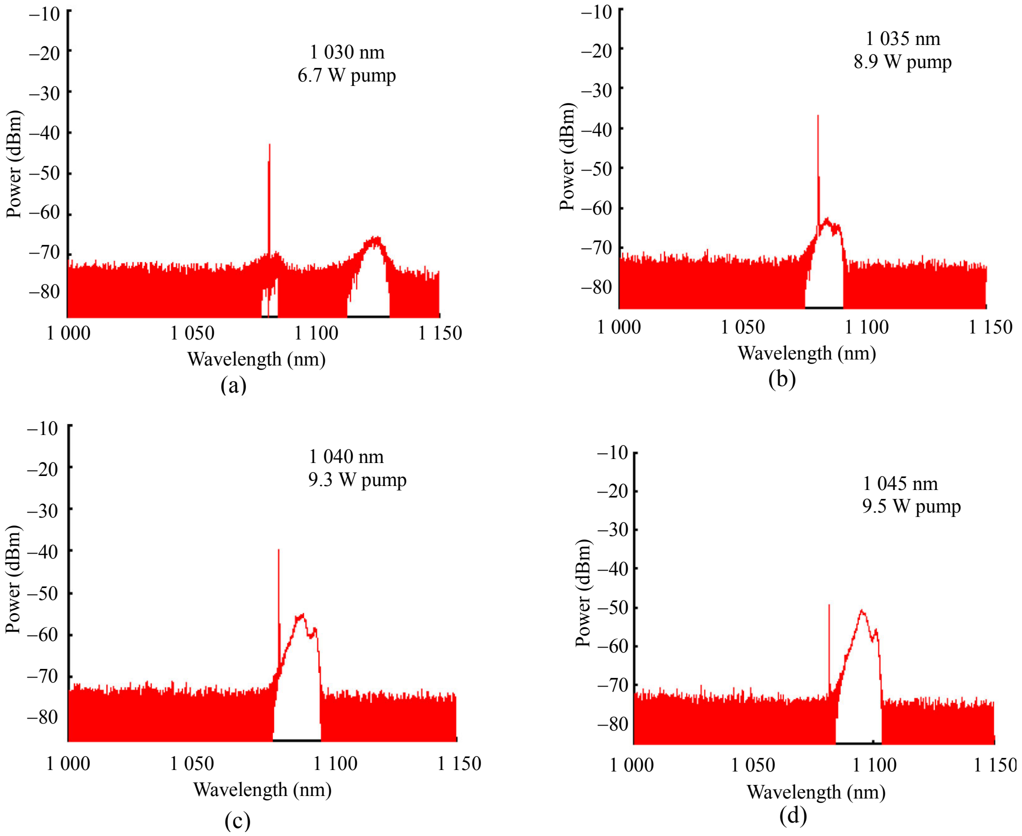
Fig. 2 Experimental results of the tunable pump laser: (a) spectra from 1030 nm to 1045 nm and (b) output power as a function of the wavelength.

The spectra of the laser emitting from Output A at different pump wavelengths are shown in Fig. 3. At 1030 nm, the 2nd order Raman Stokes light is measured, which is due to high peak power caused by the instability of temporal domain. However, with an increase in the pump wavelength, the spontaneous Raman scattering noise gets stronger. When the pump wavelengths are 1035 nm, 1040 nm, and 1045 nm, the powers of spontaneous Raman scattering noise account for 10%, 52%, and 96% of the total output power, respectively. To achieve a high enough power of the 1st order narrow linewidth emission, it is important to make sure that the spontaneous Raman scattering noise is relatively low, and no 2nd order Raman Stokes light exists, so we experimentally choose 1036.5 nm as the optimized operating pump wavelength.

Figure 4 depicts the output powers dependence on the pump power. The threshold pump value is about 2.3 W in this case, and the output powers grow linearly in both Output A and Output B while the pump power is higher than the threshold. When 8.97 W pump light centered at 1036.5 nm is launched into the half-open cavity, we obtain the maximum output power of 2.15 W from Output A. At the same time, by doing integration based on the spectrum data and measuring the total power from Output B, residual 1036.5 nm pump power is down to 22 mW, and the power of spontaneous Raman scattering from Output B is 3.26 W. The power leakage is relatively high due to the narrow linewidth of the FBG, and the other reason is that the higher the generation power is, the more pronounced the nonlinear spectral broadening is [24]. Also, it cannot achieve narrow linewidth emission from Output B.

The spectrum of Output A at the maximal power in Fig. 5(a) shows neither 2nd order Raman Stokes light nor pump light, the central wavelength is around 1081.4 nm, and the full width at half maximum (FWHM) is about 0.16 nm (see the inset), which is nearly equal to 40 GHz in this wavelength range. The spontaneous Raman scattering noise is 25 dB lower than the laser line in the output spectrum. As shown in Fig. 5(b), the transmitted pump light and spontaneous Raman scattering noise can be observed in the spectrum of Output B.

Table 1 shows the 3 dB linewidth and the equivalent bandwidth of Output A with different output powers, and we can see that the bandwidth increases at lower output power while approaches stable at higher output power.



(a) (b) (c) (d)

Fig. 3 Spectra of Output A with the maximal output power at different wavelengths of pump light: (a) 1030 nm, (b) 1035 nm, (c) 1040 nm, and (d) 1045 nm.

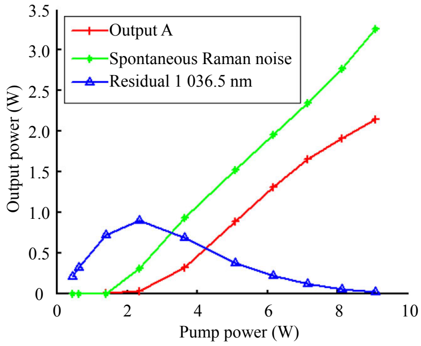
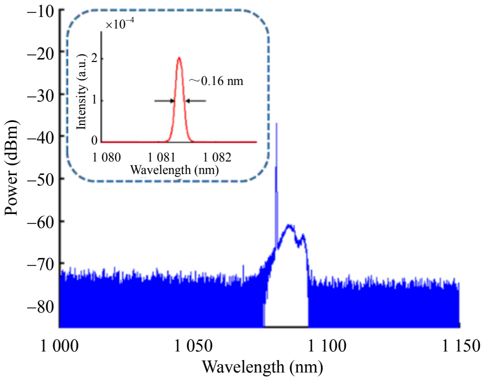
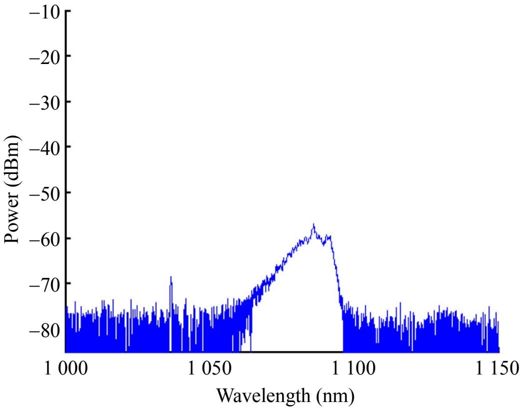


Fig. 4 Powers of Output A, spontaneous Raman scattering noise from Output B, and residual 1036.5 nm versus pump power.



(a)



(b)

Fig. 5 Spectrum of (a) Output A and (b) Output B with the maximal power.

Table 1 Output linewidth and equivalent bandwidth.

Output power (W)	Output linewidth (nm)	Equivalent bandwidth (GHz)
0.026	0.1267	32.51
0.320	0.1424	36.53
0.881	0.1529	39.22
1.310	0.1710	43.87
1.650	0.1663	42.66
1.910	0.1671	42.87
2.150	0.1649	42.31

The developed laser system is formed by a section of passive fiber with a point reflector (FBG) at one end, and it can achieve a narrow spectrum following the FBG reflection bandwidth. However, the distributed Rayleigh backscattering is extremely weak. To achieve laser generation, a sufficient feedback is required to satisfy the condition with the integral gain overcoming accumulated fiber losses. We also find that the narrow linewidth output power grows linearly and reaches more than 2 W, having approximately 32% slope efficiency.

4. Conclusions

In this paper, we investigate the half-open cavity random fiber laser to obtain powerful narrow linewidth output. We utilize a tunable fiber laser to select the operating wavelength for efficiency optimization. The feedback in our case is provided both by FBG reflection and distributed Rayleigh scattering, and the gain is provided by the Raman scattering effect along 3 km SMF-28e fiber. As a result, we obtain an RDFL with the maximum output power of 2.15 W centered at 1081.4 nm, and the corresponding bandwidth is as narrow as about 40 GHz. The demonstrated powerful narrow linewidth RDFL has great potential for being used in practical applications such as coherent sensing and detection.

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