LD-Pumped Random Fiber Laser Based on Erbium-Ytterbium Co-Doped Fiber

Qingyang MENG[1], Han WU[1], Bing HAN[1], Jiaqi LI[1], and Zinan WANG[1,2*]

[1]*Key Lab of Optical Fiber Sensing & Communications, University of Electronic Science &Technology of China, Chengdu 611731, China*

[2]*Center for Information Geoscience, University of Electronic Science and Technology of China, Chengdu 611731, China*

[*]Corresponding author: Zinan WANG E-mail: znwang@uestc.edu.cn

Abstract: In this paper, a cladding-pumped erbium-ytterbium co-doped random fiber laser (EYRFL) operating at 1550 nm with high power laser diode (LD) is proposed and experimentally demonstrated for the first time. The laser cavity includes a 5-m-long erbium-ytterbium co-doped fiber that serves as the gain medium, as well as a 2-km-long single-mode fiber (SMF) to provide random distributed feedback. As a result, stable 2.14 W of 1550 nm random lasing at 9.80 W of 976 nm LD pump power and a linear output with the slope efficiency as 22.7% are generated. This simple and novel random fiber laser could provide a promising way to develop high power 1.5 μm light sources.

Keywords: Random fiber laser; erbium-ytterbium co-doped; cladding pumping

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1. Introduction

Random fiber lasers (RFLs) operating via the Rayleigh scattering along a single mode fiber (SMF) as the random distributed feedback attract a great deal of attention since the first demonstration in 2010 [1, 2]. This kind of random lasers has certain advantages, such as single transverse mode output, long-distance signal delivery ability, low intensity noise, cavity simplicity, and high lasing efficiency. With the good laser performance and relative simplicity of implementation, RFLs have also been proved to be an important novel light source for optical communications [3, 4], imaging [5–8], and high power applications [9–13]. In recent works, RFLs have been tailored to be multi-wavelength [14, 15], wavelength tunable [16, 17], narrow bandwidth [18, 19], polarized output [20–23], high efficiency, and high output power [24–27].

Hundred-watt-level high power RFLs operating at 1 μm regime have been reported, with high power laser as the pump sources [11, 12]. As for the "eye-safe" and "telecommunication" wavelength range around 1.5 μm, it has been widely applied in optical communications, light detection and ranging (LIDAR), medical research, etc. However, the reported maximum output power of 1.5 μm RFL is below 2 W [15, 28]. An alternative way to realize the 1.5 μm RFL is utilizing the active fiber, such as erbium-doped fiber (EDF) [29, 30]. This kind of RFL utilizes EDF to provide gain, and a long single mode fiber (SMF) is connected after the EDF to provide sufficient Rayleigh feedback. For erbium-doped RFLs, the threshold could be reduced to tens of milliwatts. However, the loss introduced in the long SMF will decrease the laser efficiency,

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resulting in the low slope efficiency (less than 15%), and the output power of erbium-doped RFL is quite low (<500 mW) [29, 31]. For Raman gain or erbium-Raman hybrid gain based RFLs, the laser efficiency could be high (>60%) with the proper cavity design [15, 28]. However, the pump used in these systems is 1.4 μm, and the restricted 1.4 μm pump power is the main limitation for further power scaling. In recent years, cladding-pumped erbium-ytterbium co-doped fibers are emerging as the preferred choice for high-power fiber lasers around 1.5 μm which can be pumped by the high power LD source [32–34]. However, there is no research about RFLs based on erbium-ytterbium co-doped fiber until now.

Here, in this paper, we propose and experimentally demonstrate a cladding-pumped erbium-ytterbium co-doped random fiber laser (EYRFL) with the 976 nm LD pump. The output power of 1550 nm random lasing is 2.14 W at 9.80 W LD pump power. This paper provides a promising way to increase the output power of 1.5 μm RFLs.

2. Experimental setup and principle

Figure 1 shows the schematic setup of the proposed system. The multimode 976 nm LD is used as the pump source. The LD pump is injected into 5 m double-cladding erbium-ytterbium co-doped fiber (6/125 μm) through a (2+1) × 1 pump combiner. A section of standard single-mode fiber (SMF) with 2 km length which provides random Rayleigh distributed feedback is attached after erbium-ytterbium co-doped fiber. An FBG with the 1550 nm center wavelength is connected at the signal port of the combiner, forming the half open cavity for the (EYRFL). The laser output is measured at the far end of the SMF. To record the spectrum, we connect a 1 : 99 optical coupler to the end of the SMF and use the 1% port as a monitor port.

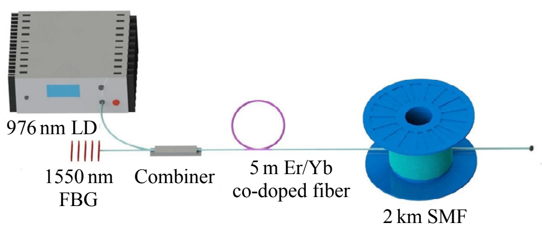

Fig. 1 Configuration of proposed EYRFL.

In the EYRFL system, the pumped erbium-ytterbium co-doped fiber can provide the gain for random lasing. Figure 2 shows the energy level diagram of erbium-ytterbium co-doped system. With the 976 nm LD pump, the Yb^{3+} ions in the $^2F_{7/2}$ level absorb the pump photons, and jump to the $^2F_{5/2}$ level, and transfer energy to the neighboring Er^{3+} ions in the $^4I_{15/2}$ level further. The Er^{3+} ions in the $^4I_{15/2}$ level absorb the pump photons and the excited Yb^{3+} ions, and then excite them to the $^4I_{11/2}$ level. The excited Er^{3+} ions will quickly relax to the metastable level $^4I_{11/2}$ due to the short lifetime of the $^4I_{11/2}$ level. The signal is amplified through the stimulated transitions between the $^4I_{13/2}$ level and $^4I_{15/2}$ level. C_{up} is the up-conversion process taking place between Er-ions which has been discussed in previous work [35–37].

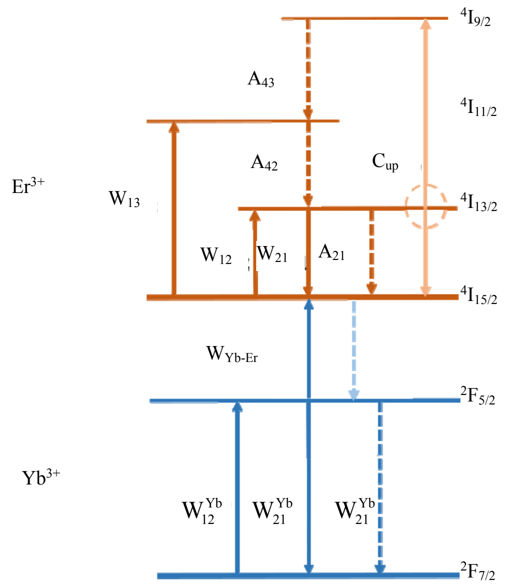

Fig. 2 Energy-level diagram of erbium-ytterbium co-doped system.

Compared with the ordinary EDF, the introduction of appropriate Yb^{3+} ions can not only effectively suppress the concentration quenching of Er^{3+} ions (i.e., increase the permissible Er^{3+} concentration) and increase the pump absorption, but also transfer pump energy from Yb-ions to Er-ions non-radioactively, which then emit around 1.55 μm [35].

With the 976 nm pump, the amplified spontaneous emission (ASE) light around 1550 nm can be stimulated in erbium-ytterbium co-doped fiber. The 1550 nm light will propagate to the SMF and experience the random distributed Rayleigh feedback in SMF. Therefore, in this way, by combining the FBG and the random distributed Rayleigh feedback, the 1550 nm random lasing can be stimulated with the help of the erbium-ytterbium co-doped gain. All the fiber ends are angle-cleaved to avoid the unwanted backward reflection.

3. Results and discussion

Figure 3 shows the output spectrums at different pump power levels. The spectrum is measured by an optical spectrum analyzer (OSA, Ando AQ6317B) with 0.01 nm resolution. The lasing spectrum is unstable with a large amount of narrow spikes appearing randomly at 1.05 W pump power. After increasing the pump power, the spectrum becomes stabilized and smooth, but the base of the spectrum (20 dB bandwidth) rises significantly. When the pump power reaches 9.80 W, the 3 dB bandwidth of the spectrum is about 0.16 nm.

Figure 4 shows the experimentally measured output power of the 1550 nm random lasing versus launched pump power. The launched LD pump power is measured after the pump combiner. The threshold of the EYRFL is 0.6 W. After the pump power is increased over the threshold, the lasing power increases linearly as expected with the slope efficiency of about 22.7 %. The maximum output power of 1550 nm random lasing is 2.14 W at 9.80 W LD pump power. It could be inferred that the output power could be further increased with the more powerful pump. Also, the laser efficiency could be improved by optimizing the erbium-ytterbium co-doped fiber and SMF's length.

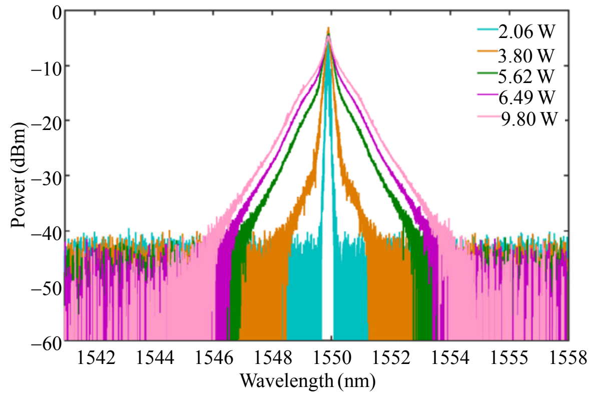

Fig. 3 Measured lasing spectral evolution with different pump powers.

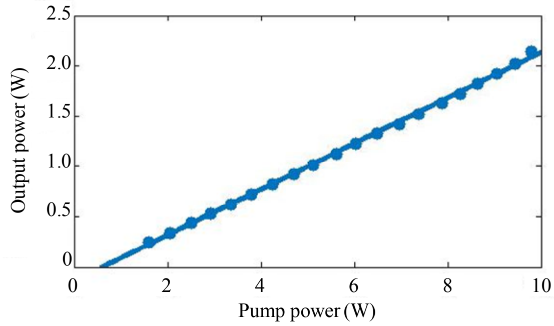

Fig. 4 Output lasing power versus LD pump power.

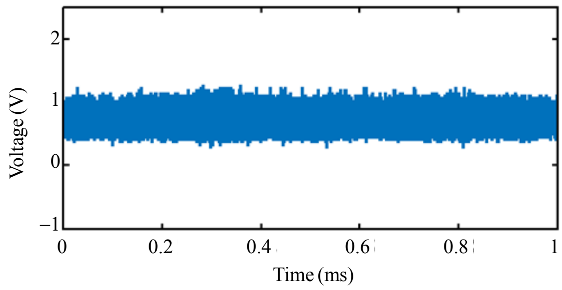

Fig. 5 Time-domain behavior of the EYRFL.

The time domain characteristic of the output lasing is measured by an InGaAs photodetector with 10 MHz bandwidth and an oscilloscope with 500 MHz sampling rate. Figure 5 shows the time domain properties of the 1550 nm lasing at 9.80 W of LD pump power. The lasing exhibits quasi-CW output behavior, without significant amplitude fluctuation. Therefore, the stable 1550 nm random lasing is achieved in this simple cavity design.

The output power of Raman gain or erbium-Raman hybrid gain based RFLs is limited by low 1.4 μm pump power. As for erbium-doped RFLs, the output power is restricted by conversion efficiency. In this paper, we propose and experimentally demonstrate an EYRFL cladding pumped by the 976 nm LD pump. The output power is 2.14 W which is believed to be the highest value ever reported for 1550 nm RFLs. A linear output with the slope efficiency as 22.7 % is achieved, which has the potential to realize ten-watt-level 1550 nm RFLs with more powerful LD pumps and higher splicing quality.

4. Conclusions

In conclusion, we have proposed and experimentally demonstrated a cladding-pumped EYRFL that can generate 1550 nm random lasing utilizing high power LD source for the first time. With the 976 nm LD pump, the 1550 nm random lasing is achieved via the gain provided by erbium-ytterbium co-doped fiber and the random Rayleigh feedback in passive SMF. With the pump power increasing, the laser spectrum becomes stable and smooth and the base of the spectrum broadens significantly. As a result, with 5-m erbium-ytterbium co-doped fiber and 2-km SMF, 2.14 W of 1550 nm random lasing at 9.80 W of 976 nm LD pump power is generated successively, and the slope efficiency of the linear output is 22.7%. The power scaling of the laser can be further realized with more powerful LD pumps. The proposed EYRFL provides the promising way to further increase the power of 1.5 µm random lasing, which has the potential value in the field of optical communications and LIDAR.

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