Erbium doped random fiber laser and fiber mixing effect

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ABSTRACT

We demonstrate an active random fiber laser by directly pumping a 100 m erbium-doped fiber at 980 nm wavelength, with a fiber loop mirror forming a half-open cavity. Random lasing with competing spectral modes in the range from 1535 nm to 1560 nm is achieved, with the maximum lasing slope efficiency around 10%. We also study the effect of combining a dispersion compensated fiber with the erbium-doped fiber. The kilometers long dispersion compensated fiber reduces the random lasing threshold and increases the signal to noise ratio, while enhancing the tunability of the random laser's spectrum range by the fiber loop mirror feedback.

Keywords: random fiber laser, Erbium doped fiber, dispersion compensating fiber, fiber loop mirror

1. INTRODUCTION

Disordered structures and random scattering phenomena are ubiquitous in nature. Random laser has been a subject of intensive study for decades, with its merit of cavity-less, ultra-broad spectrum generation, cost-efficient for mass manufacturing, and its promising applications in the fields of communication, speckle free microscopy, etc. [1]. Recently, random lasing in optical fibers, called random fiber lasers (RFL), exploits the intrinsic Rayleigh scattering (RS) in optical fibers as feedback source and has been investigated intensively[2] [3], [4], with the added advantages of directionality and high power, compared to previously reported random lasing in suspensions, powders, etc.

The schemes of random fiber lasers mainly include open cavities by either forward or backward pumping, and half-open cavities which apply reflecting components such as Fresnel reflection, fiber Bragg grating (FBG) or fiber loop mirror (FLM), to decrease the lasing threshold and increase the efficiency. The gain of random fiber lasers mainly comes from the energy transition of dopants in active fibers [5]–[7], or by nonlinear optical frequency conversion in passive fibers, mainly, Raman scattering [8]–[13] and Brillouin scattering. As the Raman random fiber laser always requires a very high lasing threshold, and the Brillouin random laser is limited by its narrow spectrum generation, the investigation on active fiber random lasing is very promising, to lower the lasing threshold and explore the random lasing generation spectrum.

Since the conventional active fibers are usually short and their RS is negligible, the first active random fiber laser by pumping a Bismuth-doped fiber was only reported in 2016 [6]. Other random fiber laser by Erbium-doped fibers (EDF) mainly utilizes FBGs as the feedback, while the lasing output spectra is highly limited by the reflection spectra of the FBGs [14], or by combining the EDF with a single mode fiber to provide the Rayleigh scattering feedback [5]. Here we demonstrate an Erbium doped random fiber mirror by directly pumping a 100 m EDF heavily doped with GeO_2, and a FLM is used to lower the random lasing threshold and to tune the lasing spectrum range. Furthermore, we combine a 4 km dispersion compensating fiber (DCF) to the EDF, and find that the hybrid of DCF to the EDF can lower the lasing threshold, increase the optical signal to noise ratio, and enhance the tuning spectrum range of the random lasing with the FLM, with the tradeoff of a lower total output power due to the induced fiber loss.

2. RESULTS AND DISCUSSION

The experimental set-up of the proposed Erbium doped random fiber is shown in Figure 1. A 980 nm laser diode with maximum power around 138 mW is used to pump the EDF in the forward direction, through a 980-/1550-nm wavelength-division multiplexer (WDM). The EDF is a 100 m long fiber with light Erbium doping concentration of around 50 ppm, and heavy GeO_2 doping concentration of around 12.94 wt%. The EDF has the peak absorption coefficient of 0.15 dB/m at 1532 nm. The 1550 nm port of the WDM was connected to a FLM, made of a 3 dB coupler and a polarization controller (PC). The reflection of the FLM is measured between 11% and 65 %. An optical power meter or optical spectrum analyser (OSA) with spectrum resolution down to 0.02 nm were used to measure the laser output. In a second configuration, a 4 km DCF was placed after the EDF. The total loss of the DCF at 1550 nm is 3.5 dB. Finally an isolator was placed after the EDF (or EDF + DCF) to eliminate the unwanted Fresnel reflection.

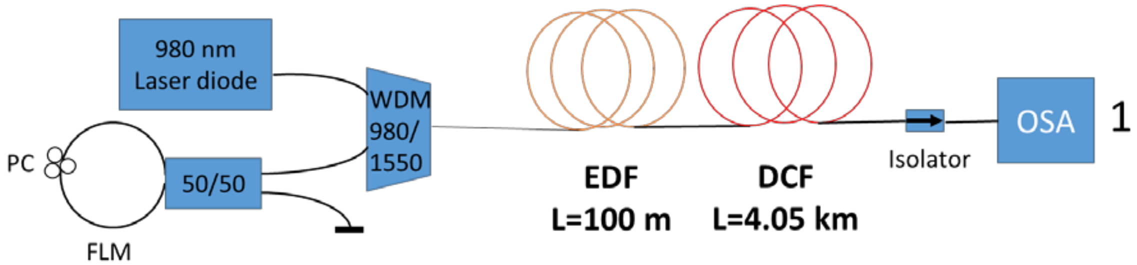

Figure 1. Experimental set-up. WDM: Wavelength division multiplexer. OSA: Optical spectrum analyser. PC: Polarization controller. FLM: Fiber loop mirror. EDF: Erbium doped fiber. DCF: Dispersion compensated fiber.

2.1 Random lasing threshold and efficiency

First we characterized the properties of random lasing from the 100 m EDF, with gain from Erbium dopants' energy transition, and Rayleigh scattering distributed feedback enhanced by the long length and GeO_2 heavy doping. Since the cavity contains no spectrally selective element, the random laser spectrum is very unstable and varies constantly, so that the random lasing at one certain wavelength fluctuates greatly. In order to better estimate the random lasing threshold and get its power dependence on the pump power, we collect the random laser spectra at different pump power levels, and average the power over the observed lasing range from 1530 nm to 1565 nm (Figure 2(a)). In this way, we were able to reduce the amplified spontaneous emission (ASE) at other wavelengths, especially below and close to the lasing threshold. From Figure 2(a), we can tell that the random lasing threshold from an EDF combined with a DCF is around 24 mW, and it is lower than the random lasing threshold from an isolated EDF which keeps around 50 mW. The first random lasing spikes were also observed separately in EDF and EDF+DCF under the pump power of 50 mW and 24 mW. This is in accordance with our expectation, as EDF+DCF provides more Rayleigh backscattering, similar to increasing the mirror reflectivity in a conventional laser cavity to reduce the lasing threshold. By adjusting the PC of the FLM, the random lasing threshold from both the EDF and EDF+DCF can be tuned within a range of approximately ±4 mW. The nonlinear growth of the power in the lasing spectra with the pump power before the lasing threshold is due to the ASE, and above the lasing threshold, the random laser power grows linearly with the pump power.

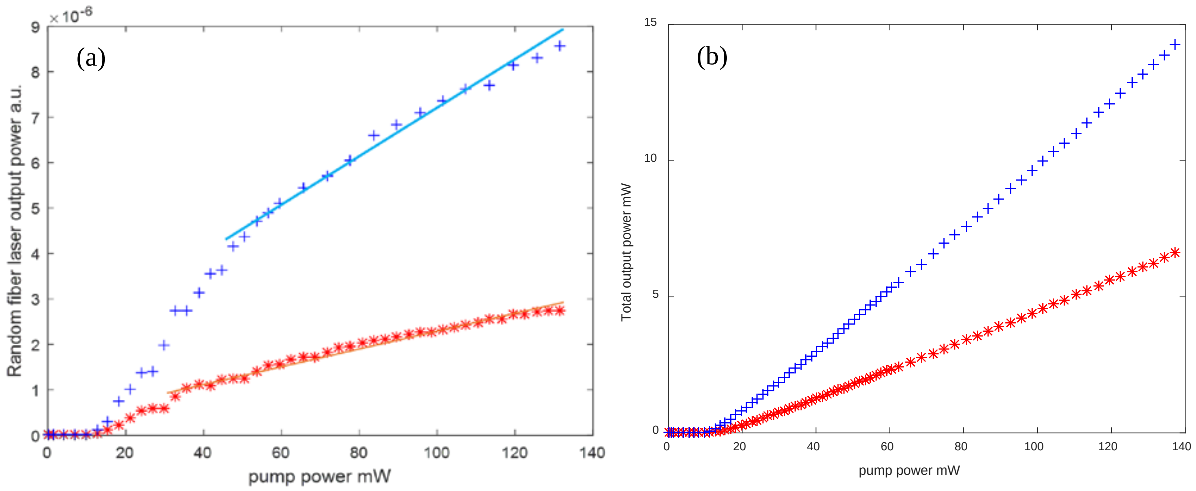

Figure 2. (a) The random laser power growth with pump power. (b) The total output power growth with pump power. The lines with blue crosses are from EDF, and the lines with red stars are from EDF hybrid with DCF.

The output power of the random lasing from only EDF is higher than the EDF+DCF, due to the 3.5 dB attenuation loss from the 4 km DCF. This shows that the Rayleigh scattering feedback in DCF helped to reduce the random lasing threshold, but does not improve the lasing efficiency, probably due to the fact that there is no gain but only attenuation provided by the DCF. It can be predicted that the DCF length is not optimized in our experiment, and further increase of the DCF length can only result in more loss, without any improvement of the random laser property. It is possible to optimize the random lasing property of the EDF+fibre by mixing with a shorter DCF.

Figure 2(b) shows the total output power from the EDF and EDF+DCF, measured by an optical power meter. At the pump power below the random lasing threshold, the total output power is dominated by the ASE over a broad wavelength range. Slightly above the random lasing threshold, broadband ASE and weak random lasing at several wavelengths co-exist and compete. The random lasing gradually dominates as the pump power increases. From Figure 2(b), we can tell the maximum output power dominated by random lasing from EDF is 14.3 mW under the pump power 137.1 mW, giving a slope efficiency of 10%, while the slope efficiency of random lasing from EDF+DCF is around 5%.

2.2 Random lasing spectrum

From Figure 3(a), we can see the random fiber laser spectrum of the EDF below, slightly above, and much above the lasing threshold. The random lasing spectrum concentrates around 1535 nm ± 2 nm, where the peak gain from the Erbium dopants is located, which means the gain is higher than optical losses around 1535 nm. On the other hand, the random fiber laser spectrum of the EDF+DCF concentrates around 1555 nm ± 5 nm (Figure 3 (b)), where the optical loss is minimum, and the gain is higher than optical losses around 1555 nm. The FLM can tune the output spectrum of EDF+DCF random laser, from the region around 1555 nm to 1535 nm (Figure 3 (b)). Under the maximum pump power given at 137 mW in our scheme, the output spectrum from the only EDF random laser was not able to be tuned, possibly due to its higher lasing threshold, or gain saturation in EDF, and we predict that its output spectrum can be tuned under higher pump power or higher concentration of Erbium dopants in EDF. We can also tell that the optical signal to noise ratio (OSNR) of random lasing from EDF+DCF is around 25 dB (Figure 3(b)), and is higher than the OSNR of random lasing from EDF of 15 dB (Figure 3(a)), which can be caused by the lower threshold and lower intensity of random lasing from EDF+DCF.

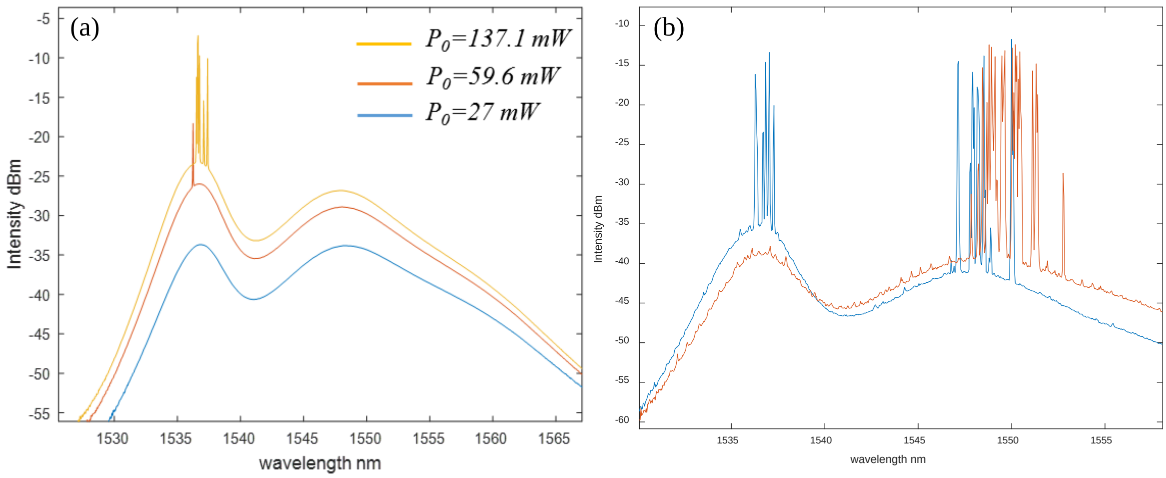

Figure 3. (a) Random fiber lasing spectrum from EDF, when the pump power is 27 mW, 59.6 mW, and 137.1 mW. (b) RFL spectrum from EDF hybrid with DCF is tuned by FLM, when the pump power is 137.1 mW.

3. CONCLUSIONS

In conclusion, we have studied random lasing by directly pumping a 100 meter long EDF with light Erbium doping and heavy GeO_2 doping. The enhanced Rayleigh scattering of the EDF heavily doped with GeO_2 provides the distributed feedback amplification, while a FLM is used to form a half open cavity to lower the lasing threshold down to 50 mW and tune the spectrum range. Both the random lasing threshold and the output spectrum can be tuned by the FLM. By appending a 4 km DCF after the EDF, the lasing threshold can be further lowered down to 24 mW, and the optical signal to noise ratio is increased from 15 dB to 25 dB, and the random lasing spectrum range shifts from around 1535 nm to around 1555 nm, due to the spectral competition between higher gain and lower loss. Due to the lower lasing threshold in EDF+DCF, the lasing spectrum can be more easily tuned with the FLM, shifting the random lasing spectrum between 1535 nm and 1555 nm. By optimizing the pump power and fiber length, the efficiency of the random lasing from EDF can be further improved. If the power is high enough, it is also of interest to further investigate random Raman lasing up to the wavelength range around 1660 nm in the proposed experimental scheme, especially from the EDF+DCF, while the DCF provides both higher Rayleigh scattering feedback and Raman gain.

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