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Random lasing in a short Er-doped artificial Rayleigh fiber

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ABSTRACT

We report on random lasing observed with 5-m-long Er-doped fiber comprising an array of weak fiber Bragg gratings (FBGs) inscribed in the fiber core and uniformly distributed over the whole fiber length. The laser design ensures domination of dynamical population inversion grating over the FBGs in total distributed feedback enabling laser stabilization and nonlinear laser line filtering of the natural laser Lorentzian linewidth down to sub-300-Hz range, both observed in the experiment.

Random fiber lasers have recently become a topic of great interest for researchers around the world due to the fact that they are able to produce light with unique performance characteristics without imposing stringent requirements on the optical resonator [1–7]. Traditionally, random fiber lasers are implemented using long (10–100 km) Raman or Brillouin fiber amplifiers possessing inhomogeneous gain line broadening and comprising weak stationary ("frozen") scattering centers uniformly distributed over the fiber length (Rayleigh scattering). Current trends in random fiber lasers are associated with transition to short laser configurations based on short (~100 m) FBG array fibers referred to as artificial Rayleigh fibers (the term accepted in distributed fiber sensing) [8,9] and/or using active fibers [10–17]. In comparison with traditional random fiber lasers, the use of short Rayleigh fibers provides much lower spectral selectivity to the generated light; therefore, in general, such lasers operate much broader laser linewidths. In random lasers comprising the active fibers the distributed dynamic population inversion gratings inscribed by the lasing radiation in the active media may have a reverse effect on the writing laser radiation via a feedback they provide [18]. The integrated reflectivity induced by the dynamical gratings in active fibers could be as high as 8% [17]. Factually, during the lasing they are reformatting the random laser cavity initially formed by the stationary scattering centers and may drastically affect the laser dynamics [15–17]. Recently, some of us have reported random lasing based on Brillouin gain and combined action of stationary and dynamic reflecting structures demonstrating an unexpected narrowing of the laser line down to 10 kHz [19,20]. In that laser system, the effects of stationary random lasing and nonlinear laser line filtering provided by the dynamical population inversion grating occurred in different fibers, i.e. in 100-m length of a single-mode artificial Rayleigh fiber and a 1-m length of Er-doped fiber, respectively. Without the active fiber segment, the laser operated several spectral components. In this paper, we go two steps further demonstrating random lasing with sub-300-Hz laser Lorentzian linewidth achieved (i) in a single 5-m long artificial Rayleigh Er-doped fiber and (ii) under the population inversion amplification possessing inhomogeneous gain line broadening. In contrast to previous works on random lasing in Er-doped fibers comprising multiple discrete FBGs [10–14], in our experiment we use numerous gratings inscribed over the whole Er-doped fiber length and exhibiting very low individual reflectivity. Such laser design ensures domination of the reflectivity imposed by dynamical population inversion grating over weak stationary reflection centers, thus enabling effective nonlinear filtering immediately in the fiber cavity and laser Lorentzian linewidth narrowing down to sub-300-Hz frequency range.

The experimental configuration of the random laser is shown in Fig. 1(a). The artificial Er-doped Rayleigh fiber (FBG array fiber) has been fabricated from the preform using the IRE fiber drawing tower equipped with an KrF-excimer laser. The fiber preform with Er^{3+}-doped germanium-free silica core has been manufactured by the surface plasma chemical vapor deposition (SPCVD) method [21]. The refractive index fiber profile is provided by adding aluminum into the core silica glass network. The fiber core diameter is 6 µm, cladding diameter is 125 µm, core/cladding refractive index step difference is ~0.0045, numerical aperture is ~0.11, peak light absorption at 976 nm and 1530 nm is 13 and 20 dB/m, respectively. Multiple weak uniform 1-cm-long FBGs with an individual peak reflectivity of ~0.00003% at ~1547.6 nm are inscribed in the fiber core by the KrF- laser at

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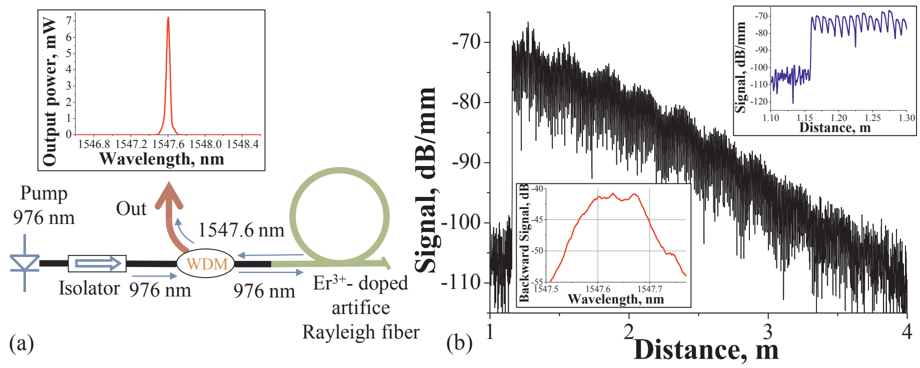

Fig. 1. Experimental setup (a) and laser optical spectrum (a, inset). The OFDR trace of the Er-doped artificial Rayleigh fiber (~60 m) (b), a zoom of the OFDR trace (b, top); Reflectivity spectrum of the fiber (~3m) (b, bottom).

248 nm (the pulse energy density is ~400 mJ/cm^2, pulse duration is 10 ns, repetition rate is 10 Hz) through a phase mask with a grating's pitch of 1070 nm, in-situ, one-by-one, immediately during the fiber drawing process (the drawing speed is 6 m/min) [9]. All FBGs are uniformly distributed over the fiber length with 100% fill factor (i.e. without an overlap and gap between the neighboring gratings). The total reflectivity measured with 3-m fiber length exhibits a ~0.01% peak at 1547.6 nm with ~0.2 nm spectrum FWHM width (Fig. 1(b, bottom inset)). The fiber longitudinal profile measured at 1547.6 nm by the optical frequency domain reflectometer (OFDR) Luna 4400 is shown in Fig. 1(b). The observed regularity with the period of ~1/cm highlights the inscribed FBG array (Fig. 1(b, top inset)). It is worth noting that due to the phase-based principle of the OFDR, a non-coherent luminescence (noise) induced by the interrogating signal does not make a significant contribution to the recorded traces. However, only first ~4 m of the fiber are observable in Fig. 1(b) due to high absorption at the testing wavelength. The artificial Er-doped Rayleigh fiber (FBG array fiber) is pumped at 976 nm through a wavelength-division-multiplexer (WDM) by 650mW pump laser diode (Gooch & Housego). The laser radiation is monitored through the second WDM arm. To avoid backreflections two free ends of the fiber configuration (i.e. belonging to WDM and Rayleigh fiber) are angled cleaved. The laser optical spectrum is centered at ~1547.6 nm as shown in Fig. 1(a, inset).

Fig. 2(a) shows the laser threshold pump power as a function of the fiber length. The minimal laser threshold level (~100mW) is observed with a long fiber (> 5m), while it increases up to 370mW for 3-m fiber. Fig. 2 (a, inset) shows the output laser power as a function of the pump power demonstrating the maximal conversation efficiency of 2.5% achieved at 300 mW. The recorded traces of the laser output power, like shown in Fig. 2 (b), exhibit small fluctuations around the average level highlighting behavior typical for random lasing [1]. The minimal standard deviation of the output power fluctuation is observed at level of ~250mW and estimated to be ~2%. This laser operation essentially differs from pulsations commonly observed with heavily Er-doped fiber lasers [22].

Fig. 2(b, inset) shows the self-heterodyne RF spectrum of laser radiation measured by RF analyzer (FSH8, Rohde & Schwarz) with an unbalanced Mach-Zehnder interferometer comprising ~40 MHz electro-optic modulator and ~50 km delay fiber. The recorded spectrum exhibits oscillations in the wings demonstrating that the laser coherence length is longer than the delay fiber [23]. There are two kinds of noise contributing to the spectrum: the laser white frequency noise providing a natural (Lorentzian) laser linewidth, and the 1/f frequency noise resulting in the approximate Gaussian linewidth [24]. The main cause of the 1/f frequency noise in fiber lasers is temperature fluctuations induced by pump intensity noise [25]. In the considered sub-coherent regime, the 1/f noise is partially filtered out from the measured spectrum [26], so we can just estimate the laser Gaussian linewidth to be between ~850 Hz and ~4 kHz. Here, the lower limit is determined by the measured 3-dB spectrum width (~1200 Hz) with the deconvolution factor of $\sqrt{2}$, while the upper limit is set by the resolution linked to the delay fiber length. The measured 20-dB spectrum width (~5800 Hz) is weakly affected by the Gaussian noise and in sub-coherent regime overestimates the FWHM Lorentzian linewidth (the deconvolution factor is $2\sqrt{99}$) [27]. Therefore, the natural Lorentzian

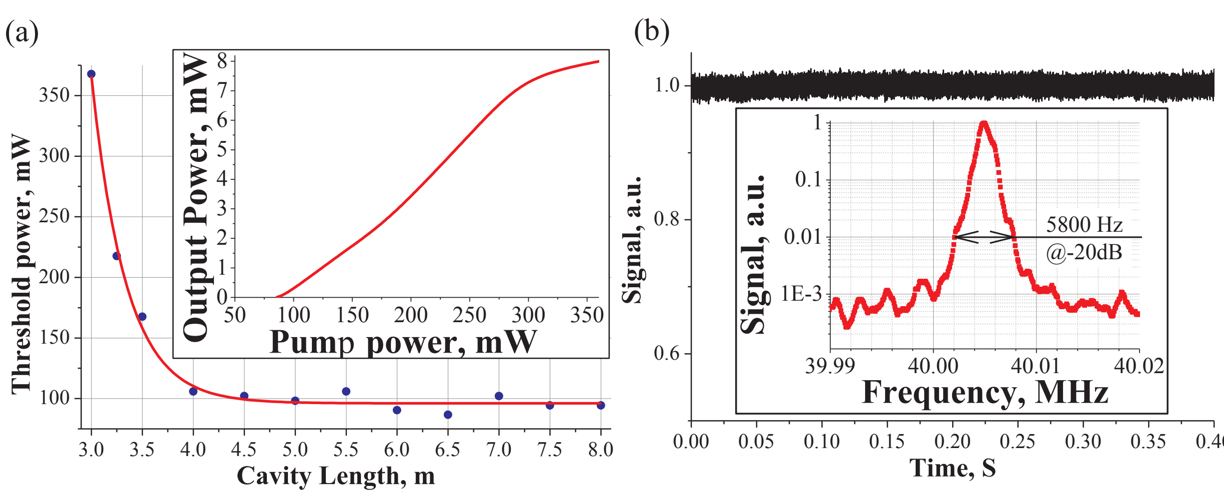

Fig. 2. Laser characteristics: the threshold pump power as a function of the fiber length (a), the output power as a function of the pump power (a, inset), a typical oscilloscope trace (b) and self-heterodyne spectrum (b, inset).

linewidth is found to be narrower than ~290 Hz. Note, the 1/f noise could be eliminated by using low-noise pumping [25].

We believe that such strong suppression of the laser Lorentzian linewidth is caused by the dynamical population inversion grating inscribed immediately in the random fiber cavity during lasing. The observed laser features differ drastically from the lasing of a few spectral components reported earlier with the Er-doped configurations comprising discrete FBGs with dominating stationary reflectivity [10].

In summary, we have observed random lasing in a short Er-doped artificial Rayleigh fiber pumped by the laser diode. The lasing is achieved due to the population inversion gain and feedback caused by weak FBGs uniformly distributed over the fiber length. The laser design ensures domination of the reflectivity imposed by dynamical population inversion grating over the stationary FBGs enabling laser stability and laser Lorenzian linewidth narrowing down to ~290 Hz, while the Gaussian linewidth is kept < 4 kHz. The proposed random laser is a simple, compact, and cost-effective solution for many practical applications.

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Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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