Narrow-Linewidth Er-Doped Fiber Lasers With Random Distributed Feedback Provided By Artificial Rayleigh Scattering

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(Invited Paper)

***Abstract*—A compact random fiber laser based on a short artificial Rayleigh reflector and heavily-doped Er fibers (custom-made and commercial as a reference) has been proposed, characterized and optimized in terms of efficiency, linewidth and noise level. A 10-cm artificial Rayleigh reflector with mean scattering level of +41.3 dB/mm relative to the natural Rayleigh scattering of the host fiber and low insertion loss level (∼0.05 dB/cm at 1535 nm) was fabricated using a femtosecond direct writing technique. Its implementation as a distributed output mirror in a half-open cavity of a 980-nm diode pumped Er-doped fiber laser results in random lasing at 1535 nm in single- and few-mode regimes with power up to 100 mW, slope efficiency up to 16.5%, and signal-to-noise ratio up to 60 dB. A single-frequency regime with ∼10 KHz linewidth was observed at output power up to 2.5 mW. Tunability potential of such random lasers is also demonstrated.**

***Index Terms*—Distributed feedback, erbium, fiber lasers, random, single-frequency, tunable.**

I. Introduction

RANDOM distributed feedback (RDFB) fiber lasers have attracted a lot of interest from the scientific community thanks to simple and cheap cavity schemes, as well as highly efficient generation of laser radiation in a wide wavelength range [1]. Their application is shown to be relevant in many areas, from remote sensing [2], [3], to mid-infrared laser generation [4], and second harmonic generation in visible range [5]. One of the first examples of random fiber lasers was realized with RDFB via Rayleigh scattering on the refractive index fluctuations of the medium, and light amplification due to the effect of stimulated Raman scattering (SRS) in a passive optical fiber [6].

This class of lasers usually has a cavity length from hundreds of meters to several tens of kilometers. Without additional spectral filtering the wavelength and linewidth of the RDFB Raman fiber laser are determined by the SRS spectrum. Near the threshold the laser line experiences Schawlow-Townes narrowing (to ∼1 nm), then turns to broadening at Watts-level power due to nonlinear effects [1], [7]. Another type of RDFB fiber laser combining light amplification in an active rare-earth-doped fiber and random distributed feedback due to Rayleigh scattering in long (∼1–10 km) segment of passive fiber, was demonstrated thereafter [8]. A half-open cavity configuration with a mirror placed at one fiber end is usually used to lower the threshold of RDFB laser generation. In addition, a mirror having spectral filtering properties such as fiber Bragg grating (FBG) or fiber loop mirror with a narrowband filter determines the wavelength and linewidth of laser generation in this configuration [9]. Although a relatively narrow linewidth (0.01–0.1 nm) and high slope efficiency have been obtained for RDFB fiber lasers, the long-length cavity is the main drawback of these types of lasers.

Since standard optical fibers provide extremely weak reflection due to Rayleigh backscattering, distributed feedback may be enhanced by introducing artificial point-like or continuous reflectors in the fiber core, which can significantly reduce the length of RDFB laser cavity. A fiber Bragg grating (FBG) with random variation in period and amplitude (coupling coefficient) along the optical axis [3], [10], [11], an array of FBGs with random intervals and reflection coefficients [12], [13], and point reflectors forming Fabry-Perot interferometers [14] could be used as such randomized reflector. In general, in these lasers both multi- and single-frequency generation regimes are observed depending on the resonator length, pump power, and the type of random structure providing distributed feedback. For example, the generation spectrum of a 1535-nm random erbium fiber laser with RDFB provided by an array of FBGs inscribed in the active fiber [12] consists of 2 longitudinal modes for a laser with 7 gratings and 5–7 competing modes for a laser with a larger number of gratings (from 14 to 31). In recent work [15], a highly reflective (R = 93.5%) FBG array consisting of eight 0.75-mm

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FBGs with a random spacing of 2–8 cm between the neighboring gratings was used in an Er-doped fiber laser. The array was incorporated into the ring cavity by means of a circulator in order to provide a strong resonant random feedback. As a result, the laser generation threshold was achieved at a pump power of 5.7 mW, whereas the laser linewidth was measured to be about 0.4 pm near the threshold. The authors explain the low generation threshold and the presence of discrete modes in the generation spectrum by the effect of the Anderson localization within the random-distributed FBG array. In [16], a random lasing was achieved in an LD-pumped 5-m-long Er-doped fiber comprising an array of weak uniformly distributed FBGs with the individual peak reflectivity of $\sim$0.00003% at $\sim$1547.6 nm. Due to the feedback arising at the reflection from multiple FBGs, the authors managed to reach the laser generation threshold at a pump power of 100 mW while the generation linewidth amounted to 300 Hz. In [10], long (20–30 cm) random FBGs were inscribed in an erbium-doped fiber with small phase errors randomly but continuously distributed along the grating profile. Depending on the length and the pump power, the random lasers exhibited both multi- and single-frequency operation near 1534 nm with the linewidth reduced to $<$0.5 pm. In [11], a 41-mm FBG consisting of 10 segments of equal length, each with a randomly varying coupling coefficient and a random phase shift relative to the previous segment, was used as a cavity of a 1030-nm Yb-doped fiber laser. Compared to a regular DFB laser based on an FBG containing a single π phase shift in the central region, the laser exhibited 3.5–5 times higher efficiency at a comparable generation linewidth of $<$100 kHz. The intra-cavity intensity distribution reveals the localization of Anderson type with exponential tales, whereas its spatial width is sufficiently broader than that for the π-shifted FBG of the same length.

In addition to FBGs, RDFB fiber lasers employ distributed reflectors based on refractive-index modification of arbitrary shape inscribed by means of a localized exposure of fiber to a CO_2 laser radiation [17] or by a direct writing technique with the use of femtosecond laser [14]. For example, ring-cavity erbium fiber laser is demonstrated, in which RDFB is provided by eight 1-cm single-mode fiber segments containing randomly-spaced deep refractive index planes [14]. The authors show that randomly spaced planes exhibit a complex interference pattern caused by the presence of Fabry-Perot interference (via core-core modes coupling) and Mach-Zehnder interference (via core-cladding modes coupling). As a result, numerous low-finesse spectral filters provided a single-frequency operation of the laser within a wavelength-locking range. The generation linewidth did not exceed 2.1 kHz and the output power reached 2.9 mW. It is also possible to create an artificial Rayleigh reflector by femtosecond-pulse inscription of random refractive-index structure in hundred-meter long passive fibers and to use it as a distributed laser mirror [18].

In this paper, we report on the development of extremely short ($\sim$10 cm) artificial random Rayleigh reflector with low losses and its implementation as a distributed output mirror in Er-doped fiber lasers with a half-open cavity. As an active medium we use different Er-doped fibers (commercially available from Fibercore, and custom-made with phosphate-based core) and compare the output characteristics of the random lasers based on the fibers. Single-frequency, narrow-linewidth and tunable operation regimes of such lasers have been demonstrated and optimized.

II. Experiments and Results

A. Artificial Rayleigh Scattering Fiber

To create a compact artificial Rayleigh scattering fiber, we applied the femtosecond laser direct writing technique allowing for the distributed modification of refractive index inside transparent materials [19]. This approach has been previously shown to be a good alternative to nanoparticle-doped fibers [20], due to the possibility to induce scattering structures with arbitrary geometry in almost any type of optical fiber without violating the integrity of the protective coating. In terms of structural changes inside the material, the significant enhancement of scattering in the femtosecond laser exposure region is the result of the formation of nanogratings with typical crack thickness of $\sim$1$\sim$10 nm and periods of $\sim$100 nm, which has been previously studied using scanning electron microscopy and demonstrated in a number of papers [21]–[23]. The effect of nanogratings formation is explained by various mechanisms: the interference between the field of the femtosecond laser pulse and the field of the electron plasma formed during pulse absorption [24], exciton-polariton self-organization [25], nanoplasmonic model [26] etc. At present, the use of artificial Rayleigh reflectors fabricated with the use of femtosecond laser is mainly associated with sensing applications [21], [23], however, spectral properties of Rayleigh reflectors make them also attractive for a development of compact random fiber lasers. In [21], the ability to inscribe a continuous Rayleigh reflector with an enhanced backscattering level of about +40 dB at a loss rate of 0.15 dB/cm was demonstrated. In [27], after optimizing the inscription parameters, an induced scattering level of +35 dB at a loss rate of 0.01 dB/cm was achieved.

In this work, we used a Yb:KGW Light Conversion Pharos 6 W laser, which generated pulses of 232 fs duration, 1026 nm wavelength, 10 kHz pulse repetition rate, and $\sim$280 nJ energy. Femtosecond radiation was focused into the core region of the Corning SMF-28e+ fiber using a Mitutoyo 50X Plan Apo NIR HR microobjective (NA = 0.65). During irradiation, the fiber was moved along optical axis using an Aerotech ABL1000 linear stage at a constant speed of 0.1 mm/s. Under these conditions, the pulse density was 100 pulses/μm, which resulted in structural changes inside the fiber core region and formation of inhomogeneities enhancing both Rayleigh and Mie scattering [28], [29]. To monitor the induced backscattering level we used a high-resolution LUNA OBR4600 backscatter reflectometer. The total length of the fabricated sample was 100 mm, and the averaged induced backscattering level was +41.3 dB/mm relative to the natural Rayleigh scattering level of the fiber used (Fig. 1(a)). Note that an important feature of the manufactured sample is a low level of induced loss rate, which in our case was about 0.05 dB/cm at 1535 nm (Fig. 1(b)). This was achieved by optimizing the sample speed while the inscription process, as well as the period and energy of femtosecond laser pulses.

As can be seen from the loss spectrum for the created sample of artificial Rayleigh scattering fiber, the losses have a

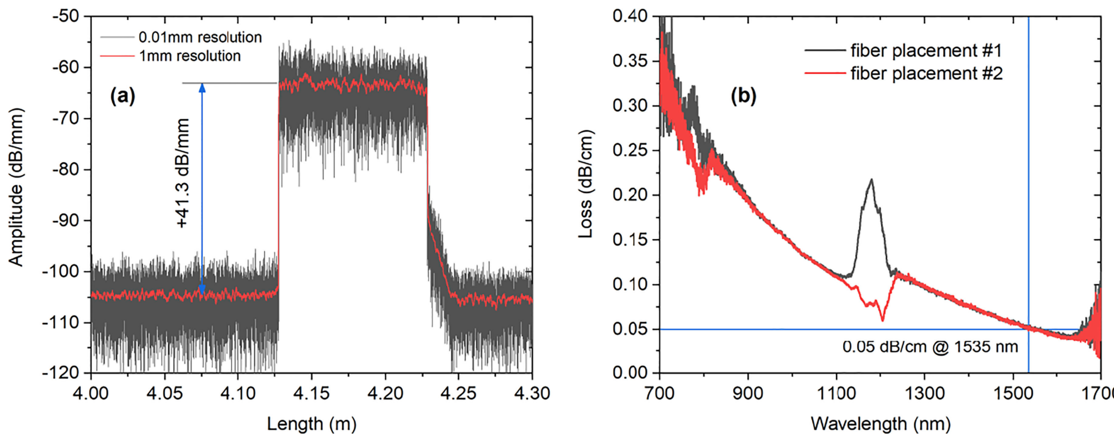

Fig. 1. Reflectogram (a) and loss spectrum (b) of the 10-cm artificial Rayleigh scattering fiber. The loss spectrum was measured with different optical fiber placement, resulting in a strong loss dependence in the cutoff wavelength range.

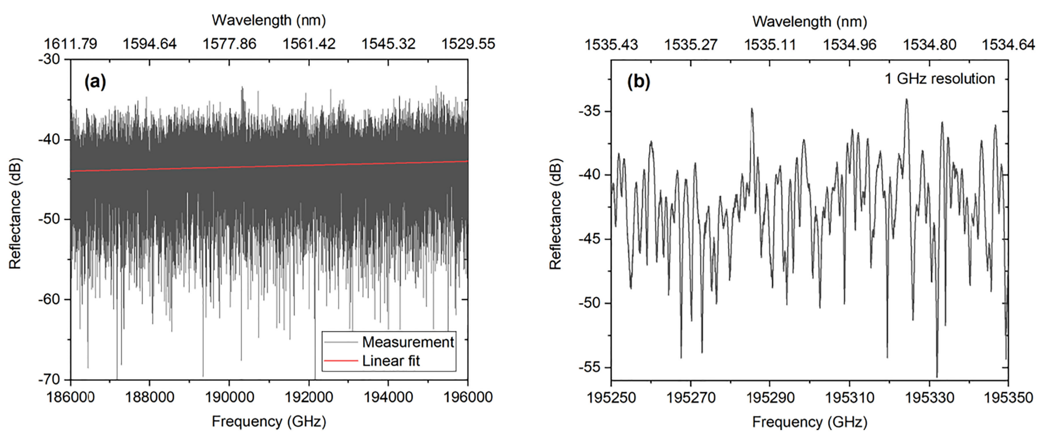

Fig. 2. Reflectance spectrum of the 10-cm artificial Rayleigh reflector measured with LUNA OBR4600 in 1530–1610 nm wavelength range (a) and enlarged spectral region near 1535 nm (b).

strong wavelength dependence. In the wavelength region of 1250–1600 nm with decreasing wavelength losses increase from 0.04 dB/cm to 0.1 dB/cm. Further, at wavelengths of 1100–1250 nm there is a peak/dip in the spectrum, depending on the fiber placement, which we attribute to reaching the cut-off wavelength of the SMF-28e+ fiber. At 1100 nm the loss level is of 0.1 dB/cm and then increases to 0.35 dB/cm at 700 nm.

It can be concluded from the obtained experimental data that the created 10-cm artificial Rayleigh reflector has an average reflectance $R_{ARSF} = 0.004\%$, which is equivalent to the total reflectance from a 1.36-km fiber segment of SMF-28e+ fiber, and a total loss of 0.5 dB at a wavelength of 1535 nm.

Due to a large number of inhomogeneities in a short fiber section, in the frequency domain the artificial Rayleigh reflector looks as a broadband set of narrow peaks/dips. Their separation is limited by spectral resolution of the measuring device ($\sim$1 GHz), as shown in Fig. 2(a) for the wavelength range of 1530–1610 nm, and in Fig. 2(b) for a narrow band near 1535 nm. The obtained spectral pattern indicates the effective interference of propagating optical signal on the induced inhomogeneities.

B. Random Laser Schematic

The half-open cavity of a random laser is formed by a high-reflection narrow-band FBG ($R_{FBG} \approx 90\%$, $\lambda_{FBG} = 1535$ nm, $\Delta\lambda_{FBG} = 0.065$ nm, see the inset in Fig. 3), which is used to select the output wavelength of the laser, short segment of Er-doped fiber, and a 10-cm artificial Rayleigh reflector fabricated by femtosecond laser writing technique serving as a low-reflection output coupler as shown in Fig. 3. As an active medium we used commercially available Fibercore I-25(980/125) Er-doped fiber and custom-made heavily-doped fibers (Er 1 wt.% [30], [31] and Er 3 wt.% [32]) fabricated by Fiber Optics Research Center (FORC, Moscow, Russia), whose main parameters are summarized in Table I. The cavity was pumped by a 980-nm laser diode (LD) with maximal output power of 680 mW. To minimize the influence of back reflection from the components, an optical isolator was placed right after the Rayleigh reflector, and the opposite end of the cavity was spliced with an angled polished fiber connector. Output radiation of a laser co-propagating with the pump radiation was divided into two measuring channels by the 1×2 coupler. The first channel was connected to Yokogawa

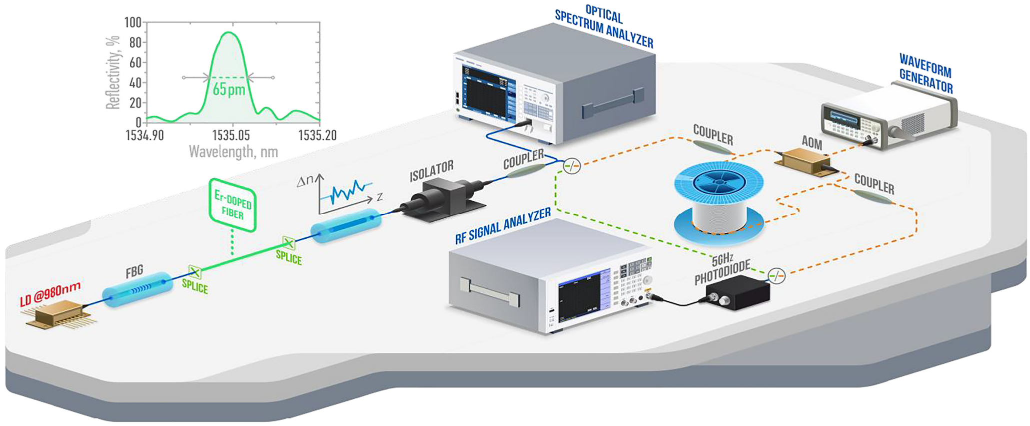

Fig. 3. Experimental setup of a RDFB fiber laser with half-open cavity. The FBG reflection spectrum is shown in the inset.

TABLE I
ER-DOPED FIBERS PARAMETERS

Symbol	FORC Er 3 wt.%	FORC Er 1 wt.%	Fibercore I-25(980/125)
Fiber section length	0.155 m	0.37 m	1.25 m
Mode field diameter	4.5 @ 1550 nm	4.9 @ 1550 nm	5.3–6.3 μm @ 1550 nm
Weak signal absorption	1.4 dB/cm @ 980 nm 4 dB/cm @ 1535 nm	0.4 dB/cm @ 980 nm 1.4 dB/cm @ 1535 nm	35–45 dB/m @ 1531 nm
Total weak signal absorption for a chosen fiber length	21.7 dB @ 980 nm 62 dB @ 1535 nm	14.8 dB @ 980 nm 51.8 dB @ 1535 nm	43.8–56.8 dB @ 1531 nm
Background loss	2 dB/m @ 1300 nm	1 dB/m @ 1300 nm	≤ 10 dB/km @ 1200 nm

AQ6370 optical spectrum analyzer (OSA) to measure output power and spectra, and the second channel was used to analyze relative intensity noise (RIN), laser linewidth and mode composition with Agilent N9010A radio frequency (RF) signal analyzer and a 5-GHz Thorlabs DET08CFC photodiode. When measuring the linewidth, a self-heterodyne technique based on the use of a Mach–Zehnder interferometer (MZI) was employed. One of the MZI arms contained a 25-km delay line corresponding to the limiting spectral resolution of ≈8.3 kHz, and another arm contained acousto-optic modulator (AOM) driven by Agilent 33250A waveform generator at a carrier frequency of 80 MHz.

The use of specialized heavily-doped erbium fibers fabricated by FORC was motivated by the desire to reduce the length of a laser cavity in order to reduce the number of longitudinal modes while maintaining an acceptable level of laser generation efficiency. Since the optical fiber was made by sintering phosphate glass in a silica tube and then drawing the preform [33] an unprecedented level of concentration of erbium ions (1 and 3 wt.%) without their clustering was achieved in the used fiber waveguides [32].

C. Random Laser Output Characteristics

First, the laser generation threshold and slope efficiency were measured for each of the active fibers in Table I. As shown in Fig. 4(a), the lowest laser generation threshold has been achieved for Fibercore I-25(980/125) fiber at a pumping power of ∼62 mW. For FORC Er 1 wt.% and 3 wt.% fibers the threshold

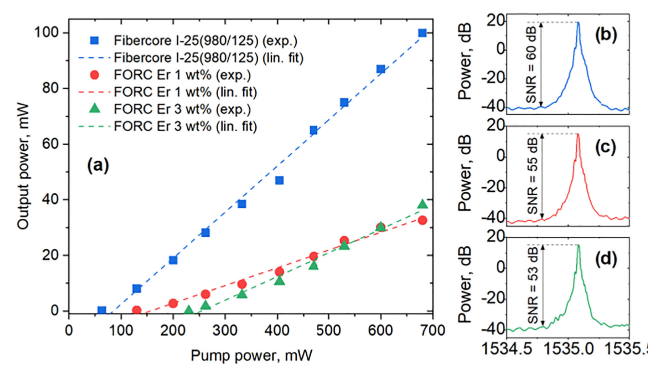

Fig. 4. (a) Output power of a RDFB laser with half-open cavity as a function of pump power and active fiber type. Generation spectra for each of the active fibers measured at maximum output power: Fibercore I-25(980/125) (b), FORC Er 1 wt.% (c) and 3 wt.% (d).

was at pump powers of ∼130 mW and ∼230 mW, respectively, which can be explained by higher intra-cavity losses, as well as a lower value of the overlap integral between the cores modes of active and passive fibers. In terms of efficiency, the best result is obtained for the laser scheme based on Fibercore I-25(980/125), for which the slope efficiency amounts to 16.5%. For FORC Er 3 wt.% and 1 wt.% the slope efficiency is fitted to be 8.5% and 6.4%, respectively. As one can see from the lasing spectra in Fig. 4(b)–(d), the obtained signal-to-noise ratio (SNR) reach 55–60 dB for the lasers based on Fibercore I-25(980/125) and FORC Er 1 wt.% fibers, which is comparable with regular DFB lasers [32], and 53 dB for the laser based on FORC Er 3 wt.% fiber.

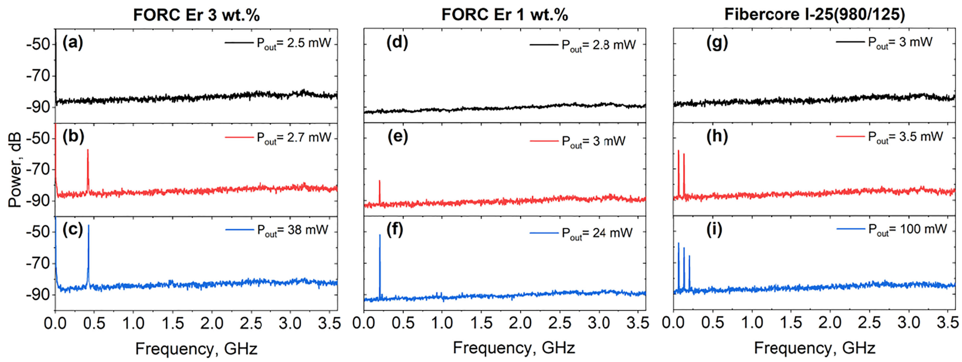

Fig. 5. RF spectra of inter-mode beating for RDFB lasers based on different fibers: (a) FORC Er 3 wt.%, (b) FORC Er 1 wt.%, (c) Fibercore I-25(980/125).

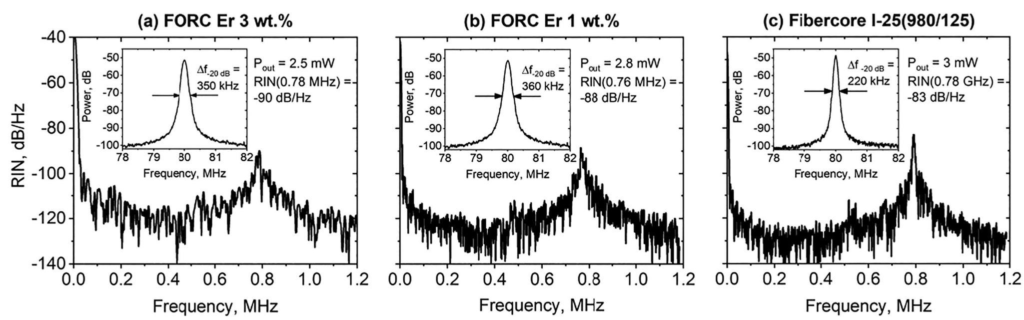

Fig. 6. RIN spectra of RDFB lasers operating in single-frequency regime: (a) FORC Er 3 wt.%, (b) FORC Er 1 wt.%, (c) Fibercore I-25(980/125). The insets illustrates the corresponding linewidth of the lasers measured with self-heterodyne technique.

Next, the mode composition of the lasers output radiation was determined by the measuring RF spectra of intensity fluctuations due to inter-mode beating (Fig. 5). No beating peaks were observed for all RDFB lasers in the low power range (from threshold to 2.5–3 mW), which guarantees the single-frequency regime in this domain. For the FORC Er 3 wt.% and 1 wt.% fibers no more than 1 peak was observed in the RF spectrum, which corresponds to 2 longitudinal modes at the output power above 2.7 mW and 3 mW, respectively. For Fibercore I-25(980/125) fiber no more than 3 peaks were observed in the RF spectrum, which corresponds to 4 longitudinal modes at the output power above 3.5 mW. The mode composition in the three studied configurations remains almost unchanged up to power level of 38, 24 and 100 mW, respectively. The data obtained were also used to estimate the effective length of the cavities. Thus, in the case of Fibercore I-25(980/125) fiber, the beat frequency of neighboring modes was 65 MHz, corresponding to effective cavity length of 158 cm. The beat frequency and effective cavity length are 200 MHz and 51 cm for FORC Er 1 wt.% fiber, and 415 MHz and 25 cm for FORC Er 3 wt.% fiber, respectively. The spectral bandwidth of RDFB lasers does not exceed 3.3 pm in all cases. Though the intermode beating frequency is defined by the effective length, the random character of artificial reflector and its disturbances lead to the randomized sub-structure of the beating peaks.

When each of the lasers was in single-frequency regime, the RIN and the linewidth values were also measured. As can be seen from Fig. 6(a)–(c), the peak of the relaxation oscillations is observed at 0.76–0.79 MHz for all RDFB lasers, with peak amplitudes of -90 dB/Hz, -88 dB/Hz, and -83 dB/Hz for FORC Er 3 wt.%, FORC Er 1 wt.%, and Fibercore I-25(980/125), respectively. The generation linewidth was measured using the self-heterodyne technique as previously described and shown in Fig. 3. The narrowest linewidth was achieved in the laser based on Fibercore I-25(980/125) fiber, for which the width of beat spectrum between the modulated signal and delayed signal was $\Delta f_{-20\mathrm{dB}} = 220$ kHz at –20 dB level, which corresponds to the -3dB (FWHM) linewidth of 11 kHz. For FORC Er 3 wt.% and FORC Er 1 wt.% fibers, the generation linewidths were 17.5 kHz and 18 kHz, respectively.

Since the artificial Rayleigh reflector acts as a broadband mirror, a tuning of the laser generation wavelength by mechanical stretching of the high-reflective FBG was realized for the RDFB laser based on the FORC Er 3 wt.% fiber. In this experiment, we used another FBG with a resonant wavelength $\lambda_{\mathrm{FBG}} = 1533$ nm, reflection coefficient $R_{\mathrm{FBG}} \approx 90\%$, and spectral bandwidth $\Delta\lambda_{\mathrm{FBG}} = 0.08$ nm. As can be seen from Fig. 7(a), the laser generation was observed exclusively at the resonant wavelength of FBG at its tuning in the spectral range of 1533.4–1545 nm. RF beating spectra of the generation modes measured for different wavelengths in the tuning range at power of ~30 mW showed the presence of up to 4 modes. In the longer wavelength range ($\lambda > 1545$ nm) the laser generation went into an unstable regime, in which the spectral line at the wavelength of the maximum gain of the erbium fiber ($\lambda \approx 1535$ nm) is appeared, as shown in Fig. 7(b).

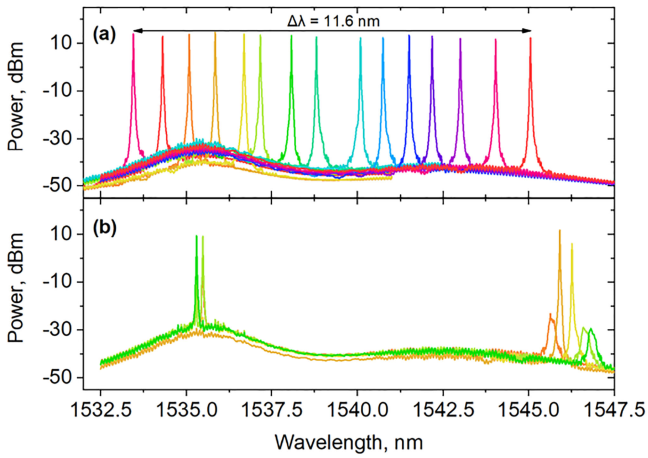

Fig. 7. Wavelength tuning for the RDFB laser based on the FORC Er 3 wt.% fiber: single (a) and multiple (b) wavelength operation regimes.

III. Conclusion

Thus, we have demonstrated the femtosecond laser technology for fabricating extremely short (<10 cm) artificial Rayleigh reflectors with low losses (<0.1 dB) and broadband random reflection spectrum, which have great potential for the development of compact and efficient narrowband Er-doped fiber lasers. Such reflector used as a distributed random mirror in a half-open cavity with short heavily-doped Er fiber enables single-longitudinal-mode (of ∼10 kHz linewidth) generation with output power up to ∼3 mW. At higher powers (up to 100 mW) a few-mode generation with narrow linewidth (≤3 pm) is obtained. At the same time, the studied RDFB fiber laser has slope efficiency of 6–16% (depending on active fiber used) that is uniquely high for narrowband Er-doped fiber lasers. Moreover, due to the narrowband reflection of the artificial Rayleigh reflector, its use together with the tunable FBG resulted in broad-range tuning with the linewidth kept narrow. Such laser is potentially tunable within the whole Er fiber gain bandwidth. Artificial random reflectors may be also used in combination with the regular DFB fiber lasers for the sake of narrowing their linewidth. These features together with a compactness of the reflector make this approach very attractive for applications in telecom and sensing providing new solutions for compact narrow-linewidth low-noise broadly tunable laser sources.

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