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Single-frequency erbium-doped fibre laser with random distributed feedback based on disordered structures produced by femtosecond laser radiation

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Abstract. **Inscription of structures by a femtosecond laser beam allows one to produce disordered structures capable of increasing the Rayleigh backscatter intensity in the fibre at relatively low induced losses, which makes them potential candidates for use as reflectors in fibre lasers. Here we report a narrow-band erbium fibre laser with random distributed feedback produced by femtosecond laser writing in half-open cavity and ring cavity configurations. In the half-open cavity configuration, single-frequency lasing is observed at output powers up to 2.8 W, with a linewidth near 10 kHz. In the ring cavity configuration, single-frequency operation is observed over the entire range of output powers studied. At the highest output power, 7 mW, the linewidth does not exceed 0.7 kHz.**

Keywords: *single-frequency fibre laser, random distributed feedback, femtosecond laser modification of the refractive index.*

1. Introduction

Recent years have seen great interest in lasers with random distributed feedback (RDFB) based on disordered structures. Since such high-power, narrow-band light sources are easy to produce, they have found application in many areas: from scanning of sensors [1] and remote sensing [2] to nonlinear frequency doubling [3]. One example of 'random' lasers is light sources in which RDFB is due to Rayleigh scattering by natural fluctuations in the refractive index of the medium and gain is ensured by stimulated Raman scattering (SRS) in optical fibre [4]. As a rule, such lasers (RDFB lasers) range in cavity length from hundreds of metres to hundreds of kilometres. Without additional spectral selection, the emission linewidth of an RDFB laser is determined by the Raman gain profile, with allowance for the narrowing of the line to the Schawlow–Townes limit with increasing power, and ranges from 1 to 2 nm [4].

In lasers based on active fibre, use is also made of Rayleigh RDFB, ensured by long passive fibre segments ($L \approx 1-10$ km). In particular, in a study by Xu et al. [5] one of the mirrors of an erbium-doped fibre ring laser was a 5-km length of fibre, which ensured feedback. Using fibre Bragg gratings (FBGs) with different resonance wavelengths, they demonstrated two-wavelength generation. At each wavelength, single-frequency lasing was observed, with a linewidth of $\sim$1 kHz.

Since standard optical fibre has a low level of Rayleigh scattering, distributed feedback can be increased by inducing local or continuous random reflectors in the fibre, which allows the RDFB laser cavity length to be considerably reduced. In short Raman fibre lasers ($L \approx 0.5-10$ m), RDFB is ensured by either introducing random phase shifts along an FBG written throughout the fibre length [6] or writing an array of randomly spaced FBGs [7]. In the general case, single-frequency Raman generation is possible in such lasers in a certain range of output powers, but such emitters typically have low stability because of the mode competition and thermal effects. In a recent study, to ensure RDFB in an erbium-doped fibre ring laser, Deng et al. [8] also used a highly reflective (R = 93.5%) array of eight 0.75-mm FBGs with a random separation between neighbouring gratings from 2 to 8 cm. The linewidth near the SRS threshold was 0.4 pm. The low lasing threshold and the presence of discrete modes in the emission spectrum upon laser tuning were accounted for in terms of Anderson localisation.

The use of femtosecond (fs) laser modification of the refractive index for producing artificial disordered structures in fibre significantly alleviates the requirements for writing accuracy in comparison with periodic structure (FBG) inscription and allows the RDFB cavity length to be reduced by several orders of magnitude in comparison with lasers based on Rayleigh scattering by native inhomogeneities. In particular, Li et al. [9] reported a ring cavity laser with a random output coupler in the form of a structure produced in the fibre by the fs technique. The structure had the form of an array of point reflectors with a random spacing from 10 to 30 μm between neighbouring ones. The sample consisted of

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eight 1-cm-long segments, which in turn contained each 500 reflectors. To extend the refractive index modification region, the fs laser beam was scanned across the fibre axis. Thus, the random reflectors had a complex spectrum because of the formation of Fabry–Perot and Mach–Zehnder interferometers (as a result of core mode coupling and core–cladding mode coupling, respectively). Overall, the many weakly reflecting spectral filters ensured single-frequency laser operation. The laser linewidth was 2.1 kHz, and the output power was 2.9 mW.

In this paper, we report a narrow-band Er^{3+}-doped RDFB fibre laser based on two configurations of disordered structures produced using femtosecond laser writing. In a half-open cavity configuration, a 10-cm-long sample with a reflectivity of ~0.004% was used as a random reflector. In a ring cavity configuration, the structure included a sample having a reflectivity of ~0.17% and containing eight 12-cm-long reflectors, with a spacing of 40 cm between neighbouring segments. In both configurations, single-frequency laser operation was achieved. In the half-open cavity configuration, single-frequency lasing was observed at an output power up to 2.8 mW, with a laser linewidth of 18 kHz. In the ring cavity configuration, single-frequency lasing was observed over the entire range of output powers studied and the laser linewidth was 0.7 kHz.

2. Experimental

To produce compact samples with a high level of Rayleigh scattering, we used femtosecond laser modification of the refractive index [10]. From the viewpoint of structural changes in the material, the considerable increase in Rayleigh scattering in a region exposed to fs laser pulses is due to the formation of nanogratings with a typical modification zone width of ~10 nm and a period of ~100 nm [11]. The formation of nanogratings can be accounted for in terms of various mechanisms: from interference of the fs laser pulse field with the field of the electron plasma resulting from light absorption [12] to a nanoplasmonics model [13].

In this study, we used an Yb:KGW laser (Laser Conversion Pharos, 6 W) which generated 232-fs light pulses at a wavelength of 1026 nm with an energy of ~0.3 μJ at the input of the objective. The pulse repetition rate was 40 kHz. The femtosecond laser beam was focused into the fibre core [Fibercore SM1500SC(9/125)P] by a microscope objective (Mitutoyo 50X Plan Apo NIR HR, NA = 0.65). During the RDFB writing process for the ring cavity configuration, the fibre was translated by a linear positioning stage (Aerotech ABL1000) at a constant speed of 0.2 mm s^{-1}.

Under such writing conditions, the pulse density was 200 pulses μm^{-1}, which led to refractive index modification and defect formation, increasing Rayleigh scattering. The level of Rayleigh scattering was monitored with a LUNA OBR4600 high-resolution backscatter reflectometer. The total length of the written sample, consisting of eight reflectors (each 12 cm in length), was about 4 m. The spacing between neighbouring regions was varied from 40 to 50 cm, and the induced backscatter power was ~50 dB mm^{-1} relative to the power of natural scattering in Fibercore SM1500SC(9/125)P by various reflectors (Fig. 1a). The total reflectivity of the structure was 0.17% (Fig. 1b), which corresponded to natural reflection from a 20-km length of SM1500SC(9/125)P.

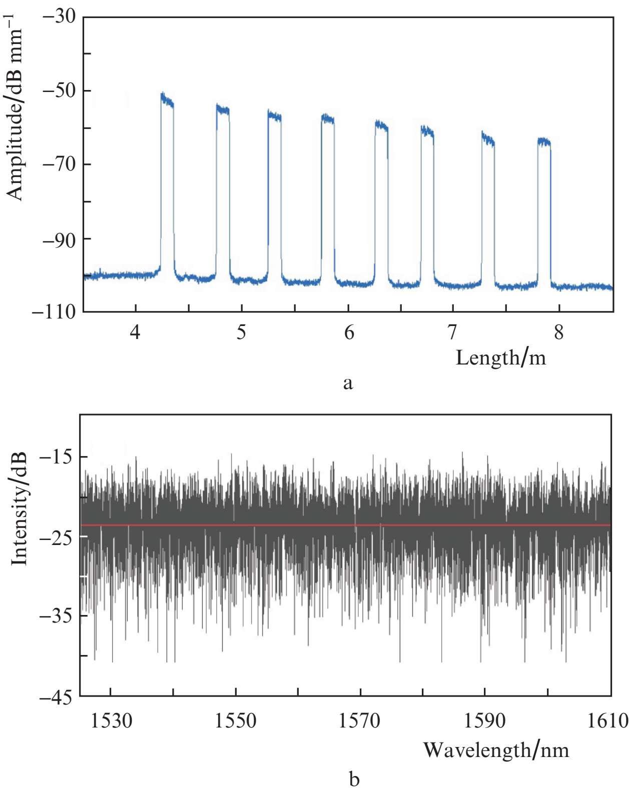

Figure 1. (Colour online) (a) Reflectogram and (b) reflection spectrum (1520–1610 nm) of an RDFB sample measured with a LUNA OBR4600 reflectometer.

An important feature of the sample was a low level of induced losses, which did not exceed 15% for each reflector. This was achieved by optimising the sample translation rate and the fs laser pulse frequency and energy. For the half-open cavity configuration, we fabricated a reflector similar to one of the reflectors in the above chain, but the induced backscatter power in a 10 cm length of SMF-28 fibre was about 40 dB mm^{-1}, its reflectivity was about 0.004%, and the loss did not exceed 15% either.

As an active medium, we used fibre fabricated at the Fiber Optics Research Center (FORC), Russian Academy of Sciences. The fibre was produced by sintering phosphate glass in a silica tube, followed by drawing. The core and cladding diameters were approximately 4.5 and 125 μm, respectively. The fibre fabrication process was described in greater detail elsewhere [14]. The fibre core was made from glass whose composition was reported previously [15, 16]. In addition to 65 mol % phosphorus oxide, the glass contained 7 mol % Al_2O_3, 12 mol % B_2O_3, 9 mol % Li_2O, and 7 mol % Re_2O_3 [17]. The erbium concentration was 1×10^{20} cm^{-3} (1.1 wt %, or 0.39 mol %, erbium oxide). In addition, the glass contained gadolinium, so that the total concentration of rare-earth ions was about 7 mol %. It is worth noting that the addition of aluminium oxide reduces the probability of clustering, which leads to cw laser operation even at a high erbium concentration. The absorption coefficients at wavelengths of 980 and 1535 nm are 0.4 and 1.4 dB cm^{-1}, respectively. The loss at a wavelength of 1300 nm is 1 dB m^{-1} and is determined primarily by the contamination of the phosphate glass in the preparation process. The small-signal gain coefficient at a wavelength of 1535 nm is 0.4 dB cm^{-1}.

We examined two cavity configurations. Scheme 1 had the form of a half-open cavity formed with the use of a highly reflective FBG with a resonance wavelength of 1535 nm, reflectivity of 90 %, and reflection bandwidth of ~65 pm. The output coupler used was a 10-cm-long RDFB structure. To minimise the loss, the output end of the pump fibre (wavelength of 980 nm and output power of ~400 mW) was fused directly to the cavity. In both configurations, the length of the active fibre was 40 cm (Fig. 2). In scheme 2, where a long RDFB structure (Fig. 1a) was incorporated into the ring cavity configuration through a circulator (as shown in Fig. 2), a semiconductor optical amplifier ensuring a broad gain band was used in addition to a fibre amplifier. The signal reflected from the RDFB structure was amplified by the semiconductor optical amplifier with a gain of ~16 dB at a wavelength of 1535 nm. An FBG with a resonance wavelength of 1536.5 nm, reflectivity of 90 %, and spectral width of 80 pm ensured spectral filtering. To prevent undesirable feedback, isolators were placed at the outputs of the experimental schemes.

The output light was divided into two channels by a coupler. The output power and spectral characteristics were measured with a Yokogawa AQ6370 optical spectrum analyser (OSA) at a spectral resolution of 20 pm. The mode composition of the output light was analysed using a Thorlabs DET08CFC photodiode (5 GHz) and Agilent N9010A radio frequency (RF) analyser. To determine the laser emission linewidth with high accuracy, we used self-heterodyne measurements [18]. One arm of the Mach–Zehnder interferometer included a 25-km-long delay line, and the other included an acousto-optic modulator (AOM) controlled by an Agilent 33250A signal generator. In addition, in linewidth measurements we obtained the beat spectrum using the radio frequency spectrum analyser.

Figure 3a shows the output power as a function of pump power. The lasing threshold was reached at pump powers of 125 and 80 mW for schemes 1 and 2, respectively. The difference in threshold pump power was due to the difference in cavity Q. At the highest pump power, ~400 mW, the output

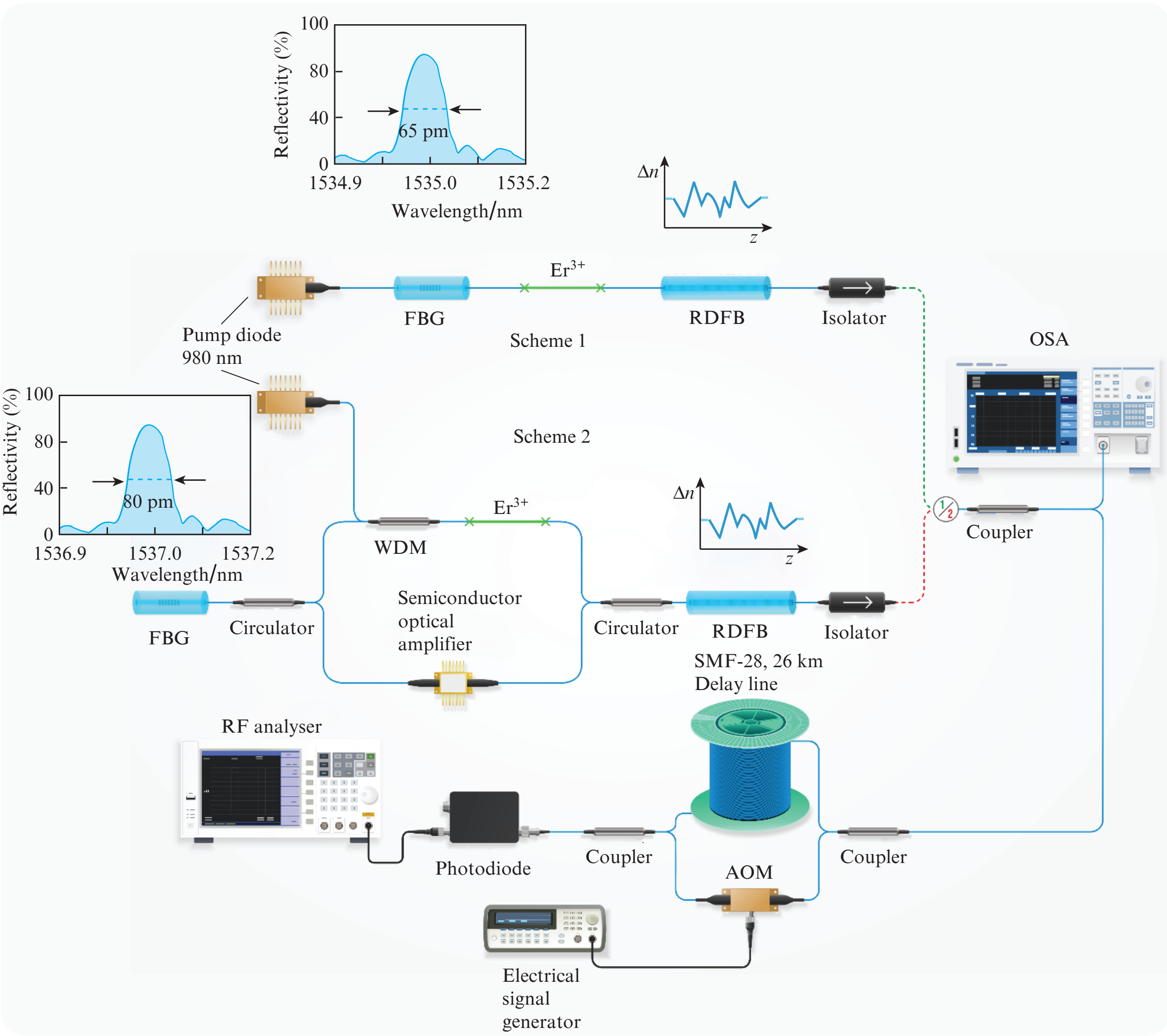

Figure 2. (Colour online) Cavity configurations used in experiments; scheme 1: half-open cavity configuration of the RDFB laser; scheme 2: ring cavity configuration of the RDFB laser and related measuring equipment.

power was 14 mW in scheme 1 and 7 mW in scheme 2. Figures 3b and 3c show lasing spectra at the highest output power: the signal-to-noise ratio was 65 dB in the ring cavity configuration and 57 dB for the half-open cavity. In both cases, the laser emission bandwidth corresponded to the instrumental function of the OSA and did not exceed 20 pm.

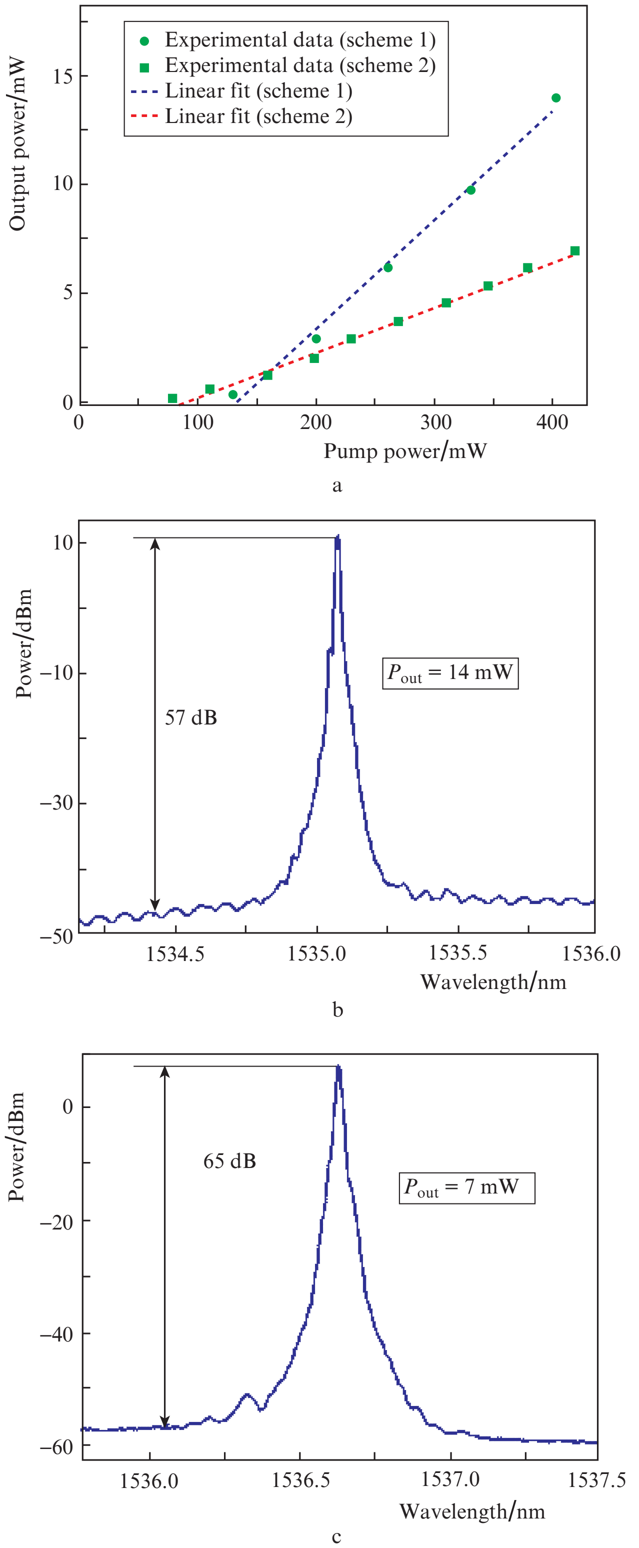

Figure 3. (Colour online) Output power as a function of pump power (a) and lasing spectra at the highest output power for schemes 1 (b) and 2 (c).

For various output powers, we measured the frequency composition of the output light. In the case of scheme 1 (Fig. 4a), single-frequency lasing was observed at output powers up to 2.8 mW. At an output power of 3 mW, intermode beat appeared at a frequency of 240 MHz, which corresponded to a spectral width of ~1.8 pm. In the case of scheme 2, the radio frequency spectrum showed no longitudinal mode beat (Fig. 4b), which corresponded to single-frequency operation.

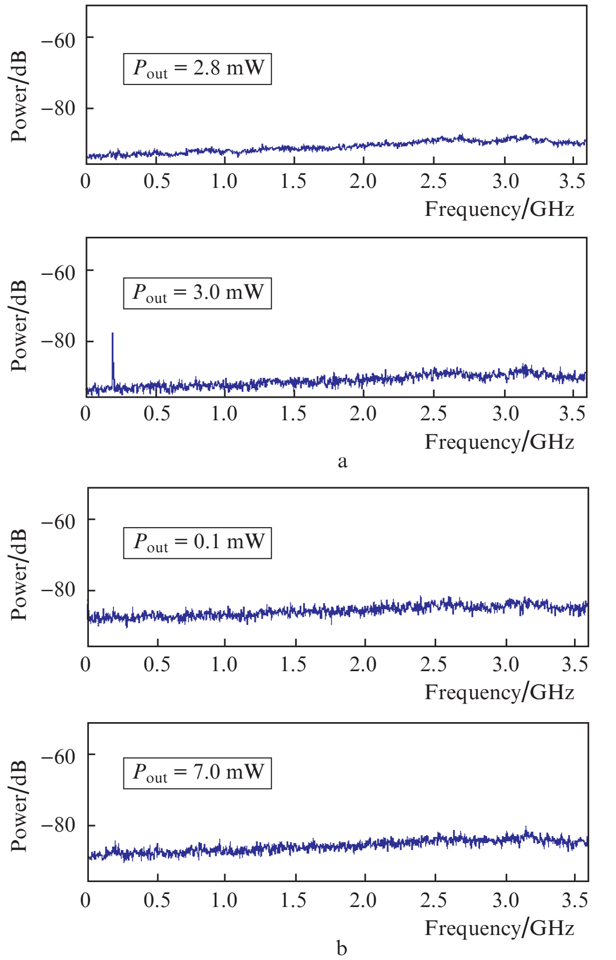

Figure 4. Radio frequency lasing spectra for (a) scheme 1 at output powers of 2.8 and 3 mW and (b) scheme 2 at the lasing threshold and the highest output power.

The relative intensity noise in the half-open cavity configuration was 88 dB Hz^{-1} at a frequency of 0.76 MHz, and that in the ring cavity configuration was 105 dB Hz^{-1} at a frequency of 0.4 MHz (Figs 5a, 5b). The insets in Fig. 5 show radio frequency beat spectra: the –20-dB linewidth was determined to be 360 kHz, which corresponded to 18 kHz FWHM for scheme 1 and 14 kHz for scheme 2 (the full width at half maximum of the emission line was about 0.7 kHz). It follows from the data obtained for scheme 2 that the spectral characteristics of the RDFB laser in this configuration compare well to those of fibre lasers with distributed feedback (DFB lasers) based on phase-shifted FBGs [19, 20]. Moreover, power characteristics of this laser surpass those of erbium-doped DFB lasers by an order of magnitude: characteristic power of the latter is ~100 μW.

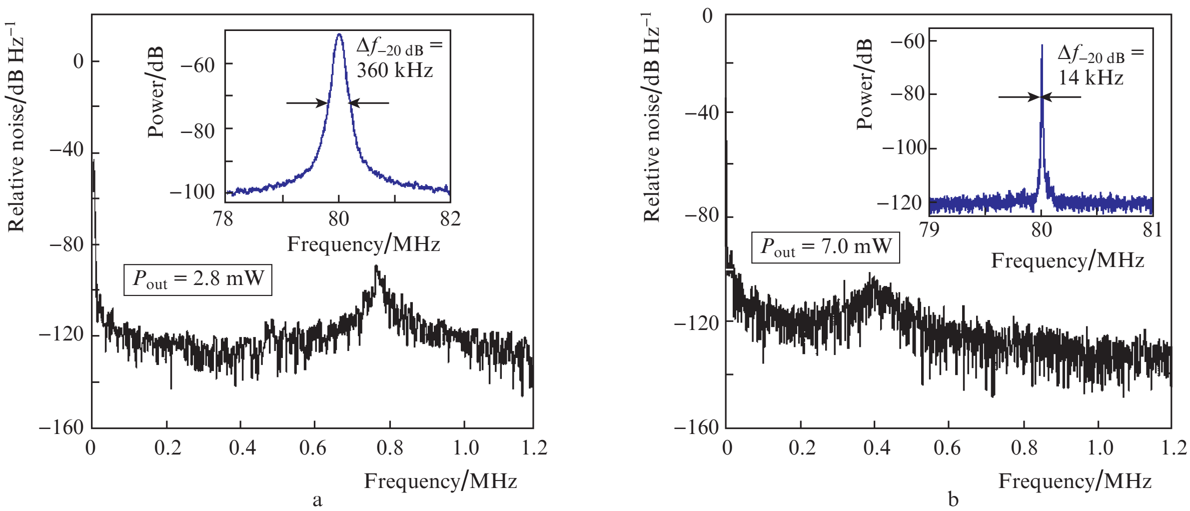

Figure 5. Relative intensity noise for schemes (a) 1 and (b) 2. Insets: radio frequency beat spectra.

3. Conclusions

Femtosecond laser modification of the refractive index allows artificial disordered structures with a high induced backscatter level to be produced in optical fibre. The requirements for the fabrication of such reflectors are markedly easier to meet in comparison with FBG inscription, and the length of the structure is several orders of magnitude smaller than that of reflectors based on natural Rayleigh scattering. The use of this type of RDFB in the erbium fibre laser configuration ensured single-frequency lasing in two configurations. In the case of the half-open cavity configuration, single-frequency lasing was observed at output powers up to 2.8 mW. The relative intensity noise was then −88 dB Hz^{-1} at a frequency of 0.76 MHz and the emission linewidth was 18 kHz. In the ring cavity laser configuration, single-frequency lasing was observed over the entire range of output powers studied. The output power was about 7 mW at the highest pump power, ~400 mW, and the signal-to-noise ratio was about 65 dB. The emission linewidth was 0.7 kHz, and the relative intensity noise at a frequency of 400 kHz was – 105 dB Hz^{-1}. Thus, the spectral characteristics of the RDFB lasers demonstrated here compare well to those of DFB erbium-doped fibre lasers [19, 20] and their power characteristics are an order of magnitude better. Moreover, the experimental procedure is considerably simpler.

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