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Communication

Distributed Bragg Reflector Laser Based on Composite Fiber Heavily Doped with Erbium Ions

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Abstract: A distributed Bragg reflector (DBR) laser with a specially designed, heavily Er^{3+}-doped composite fiber of a length as short as 1.8 cm is demonstrated. The DBR laser, pumped by a 980 nm laser diode with power of up to 370 mW, generates single-frequency radiation at a wavelength of 1535 nm with a narrow instantaneous linewidth of <100 Hz and a high output power of 2 mW. The obtained Er^{3+}-doped fiber laser parameters pave the way toward a broad range of practical applications from telecommunications and sensing to scientific research.

Keywords: fiber laser; fiber Bragg gratings; distributed Bragg reflectors; composite erbium fiber; single-frequency regime; narrow linewidth

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1. Introduction

Single-longitudinal-mode (SLM) fiber lasers are widely used in a broad range of applications such as coherent telecommunications [1], sensing with a high spatial resolution [2,3], Rayleigh backscattering reflectometry [4] and high-resolution spectroscopy [2]. Distributed feedback (DFB) fiber lasers are the most popular among them and provide stable single-frequency generation due to the spectral filtering in a laser cavity formed by a fiber Bragg grating with a pi-phase shift inscribed in the core of the active fiber [5–7]. The fabrication of a phase-shifted FBG with an overall length of ≥5 cm is quite a challenging task in comparison with uniform FBG inscription, considering the precise spatial position and amplitude of the phase shift to be created during the inscription process. For these reasons, elaborated phase masks with phase shifts in the structure or complicated point-by-point inscription techniques are used for the inscription process via continuous UV radiation [7] and femtosecond (fs) laser pulses [8], respectively. Aside from DFB fiber lasers, it is possible to achieve single-frequency generation with comparable output parameters using a distributed Bragg reflector (DBR) laser scheme characterized by a short cavity with an active fiber between two long, uniform FBGs [9]. For example, an SLM fiber laser based on active an Er^{3+}/Yb^{3+} co-doped fiber was demonstrated, emitting at 1560 nm with an output power of up to 200 mW and a spectral width of 2 kHz [10]. A reduction in the cavity length of a DBR laser based on an Er^{3+}/Yb^{3+} active fiber to 2 cm in length was achieved in [11], in which one FBG was replaced by a dielectric mirror, allowing for laser generation at 1535 nm with an output power of up to 300 mW and a spectral width of 1.6 kHz.

However, the development of a DBR fiber laser with single-frequency generation based on an Er^{3+} active fiber is difficult task owing to the low absorption cross-sections of Er^{3+} active ions and a clustering problem in the case of a high concentration of Er^{3+}

ions, which results in a pulsed regime of laser generation. To avoid these disadvantages, a specially designed Er^{3+}-doped composite was developed [12]. The measured gains at the wavelength of 1535 nm were about 1.6 dB/cm and 3.1 dB/cm for fibers with the erbium oxide concentrations of 1 wt% and 3 wt%, respectively [13]. Owing to a high radiation absorption in the case of the 3 wt% active fiber, an extremely short DFB fiber laser with a 5 mm long cavity was demonstrated through the use of a point-by-point femtosecond laser inscription technique of a pi-phase shifted FBG [14]. Moreover, using a 1 wt Er^{3+} active fiber in a DFB laser configuration with a cavity length of 5 cm, single-frequency generation lasing at 1559.5 nm with a output power up to 3 mW at a pump power of 320 mW was demonstrated [15].

In this work, we present the results of the development of a DBR laser with an Er^{3+} active fiber with a high concentration of active ions (3 wt%) in a cavity as short as 2 cm formed by two mirrors: a less reflective FBG inscribed in the active fiber core and a highly reflective dielectric multilayer mirror deposited on the fiber end face. A single-frequency lasing regime is observed in the whole pump power range (up to 370 mW) with the instantaneous laser linewidth of ~100 Hz at a maximum output power of 2.05 mW. To the best of our knowledge, the DBR Er^{3+}-doped fiber laser developed here has a record short cavity length of 1.8 cm, resulting in spectral and output power parameters favorable for a wide range of applications.

2. Experiment

The optical fiber used as an active medium for the DFB lasers was produced via a rod-in-tube technique, using a phosphate glass rod and a silica tube and then drawing the preform. The process of manufacturing the fiber is described in detail in papers [16,17]. To fabricate the core, we used glass of the same composition as the glass used in [16,17]. In addition to 65 mol% of phosphorus oxide (PO_2), this composition contained 7 mol% of Al_2O_3, 12 mol% of B_2O_3, 9 mol% of Li_2O, and 7 mol% of RE_2O_3. The concentration of erbium oxide in the initial glass was about 1.2 mol% (3 wt% erbium). The core diameter of the active fiber amounted to 3.6 µm, which corresponded to a mode field diameter of 4.34 µm. The peak absorptions were about 1.25 dB/cm and 3.65 dB/cm at a pump wavelength of 980 nm and an output radiation wavelength of 1535 nm, respectively. Thus, due to the high concentration of active ions, $N \approx 1.6 \times 10^{20}$ cm^{-3}, the fiber gain coefficient was as high as $g \approx 3.1$ dB/cm at a lasing wavelength of 1535 nm. At such a high concentration of active ions, ion clustering usually occurs, leading to pulsed laser generation [18,19]. A high phosphorus concentration in the core of the composite fiber reduced the clustering effect so that the overall concentration of clusters decreased to ~8% [14], which is significantly lower than cluster concentration in commercial active fibers with lower concentrations of ions. For example, the cluster concentration in the Er-doped active fiber Er-80 amounts to 14% at a lower ion concentration ($N = 3.7 \times 10^{19}$ cm^{-3}).

The highly reflective dielectric mirror used in the DBR laser cavity was deposited via magnetron sputtering on the active fiber end face [20]. The mirror consisted of 15 quarter-wavelength layers of $H(LH)_7$ with a high refractive index, $nTiO_2 \approx 2.4$ (H, titanium oxide TiO_2), and a low refractive index, $nSiO_2 \approx 1.47$ (L, SiO_2), resulting in reflection coefficient of >99% at 1.55 µm and a total thickness of ≈ 3.2 µm. The reflection coefficient at a pump wavelength of 980 nm amounted to 20%. An FBG with a narrow spectral bandwidth inscribed via a femtosecond laser point-by-point technique [8] was used as an output coupler with a reflection wavelength of ≈1535 nm, a reflection coefficient of 98%, a spectral bandwidth of ≈60 pm and a length of 1.5 cm. The required length of the active fiber for CW laser generation depends on the gain coefficient at the output radiation wavelength and the total losses in the cavity:

$$gL = T_{FBG} + T_{dm} + \alpha_L + \ln(1 - \alpha_{splice}), \quad (1)$$

where L is the length of the active fiber, and g is the gain coefficient, which was estimated to be 3.1 dB/cm at a wavelength of 1535 nm. T_{FBG} and T_{dm} are the losses of the FBG and dielectric mirror deposited on the fiber tip, respectively. The value of the passive loss α in the fiber, measured at a wavelength of 1300 nm, was about 4–5 dB/m [13]. Due to the difference in the mode field diameter (MFD) between the SMF-28 and the composite fiber, the splicing losses α_{splice} amounted to ≈50%. Despite the high total losses, the minimum fiber length required for the CW laser generation was estimated to be ≈1 cm. In the experiment, the length of the active fiber was 1.8 cm, taking into account that an FBG with a length of 1.5 cm results in a total resonator length of 3.3 cm.

The experimental scheme of the DBR laser is shown in Figure 1. The DBR fiber cavity was pumped by a single-mode laser diode with a wavelength of 980 nm and an output power of up to 370 mW through the 980/1.550 nm wavelength division multiplexer (WDM). The laser wavelength and output power were measured using a Yokogawa AQ6370 Optical Spectrum Analyzer (OSA) with a resolution of 20 pm. An Agilent N9010A Radio Frequency (RF) spectrum analyzer and a Thorlabs DET08CFC 5 GHz photodiode were used to measure the relative intensity noise (RIN). A Mach-Zehnder interferometer (MZI) was utilized to determine both the instantaneous laser linewidth and the spectral width at longer time intervals of ~100 µsec. One of the MZI arms contained a 25 km fiber, and the other arm contained an acousto-optic modulator (AOM) controlled by an Agilent 33250A signal generator with a carrier frequency of 80 MHz. The beat signal was measured with a Thorlabs DET08CFC photodiode and a LeCroy WavePro 725Zi-A/5 GHz oscilloscope with FFT function, which allowed for the waveforms and RF spectra of the signal to be measured.

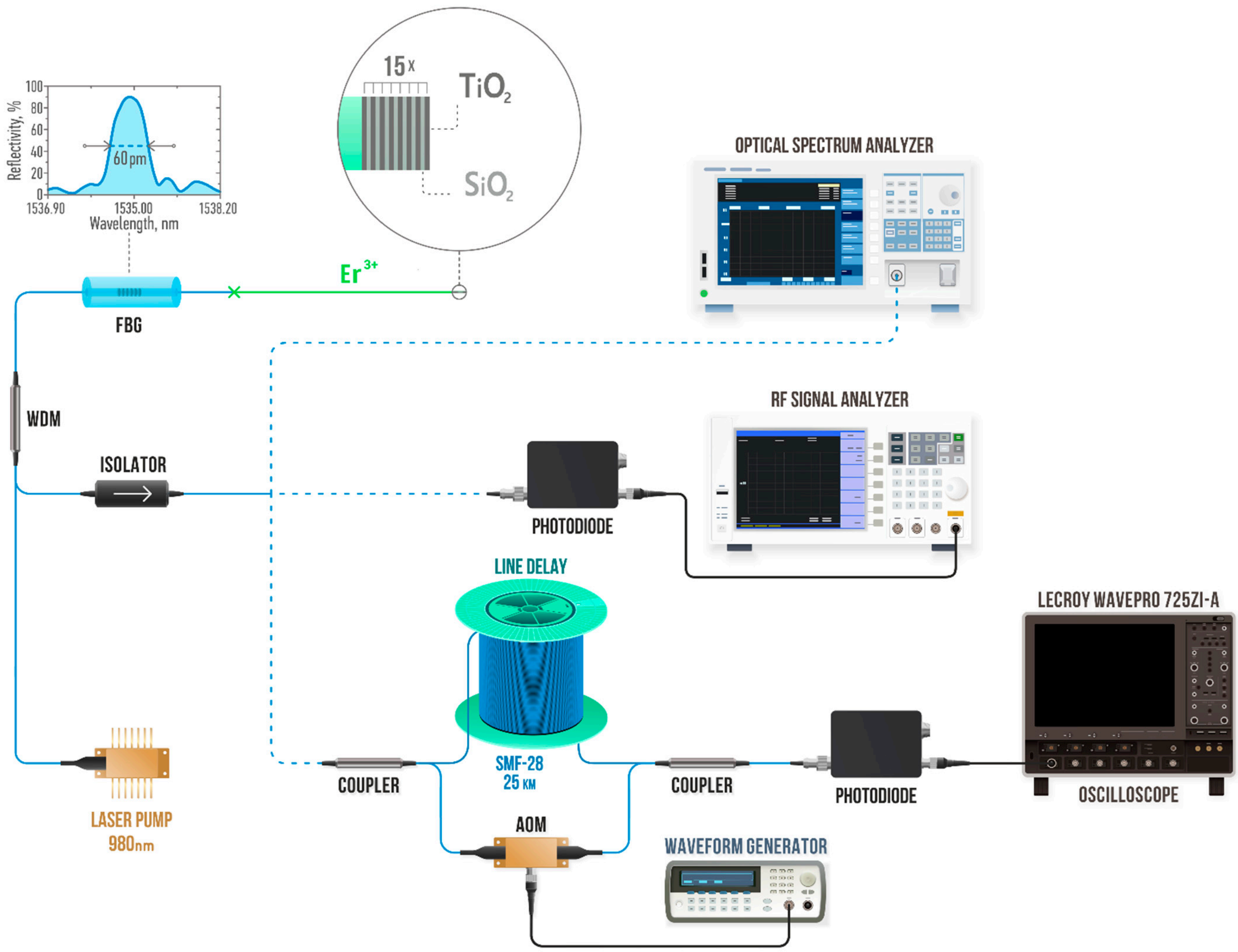

Figure 1. Experimental setup.

3. Results and Discussion

Figure 2a shows the measured output power as a function of the pump power. The threshold for generating radiation with a wavelength of ≈1535 nm was reached at a pump power of 140 mW. The high value of the threshold power can be explained by the losses of splicing between the active fiber and the single-mode fiber with the FBG. The output power reached 2.05 mW at a maximum pump power of 370 mW, which corresponds to a differential efficiency of η ~0.85% and significantly exceeds this value for typical Er^{3+} DFB lasers [21].

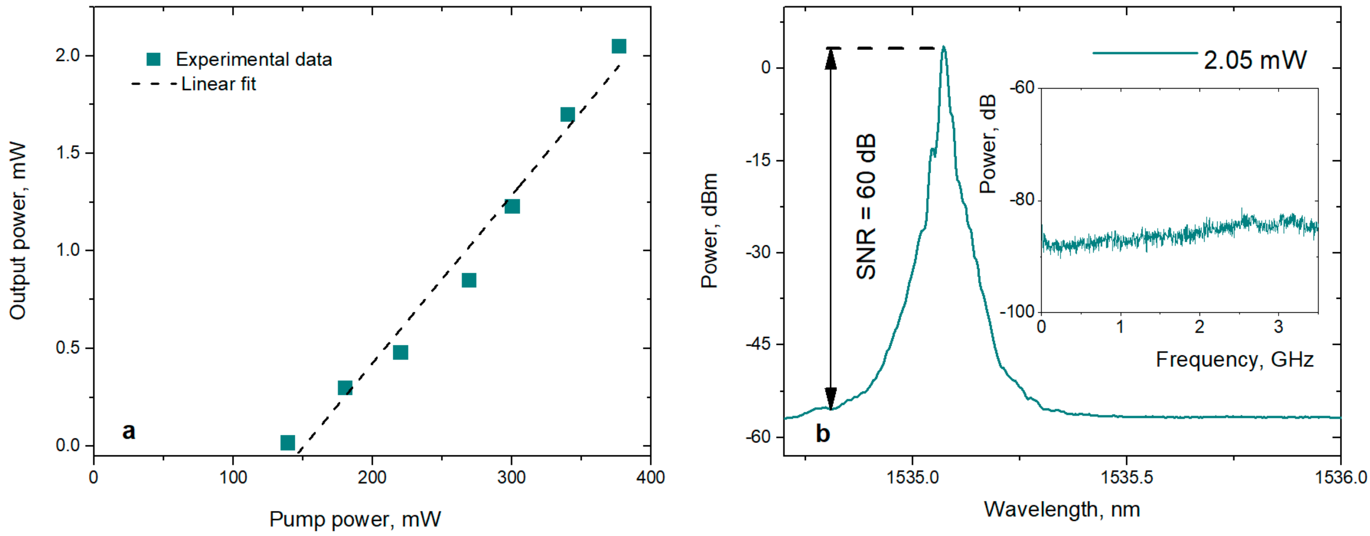

Figure 2. (**a**) The measured output power as a function of pump power; (**b**) output laser radiation spectrum at maximum output power; inset: RF spectrum of radiation.

Figure 2b shows the optical spectrum of the output radiation at maximum output power: the spectral width at the half-maximum of 20 pm corresponds to the OSA instrumental function, and the signal-to-noise ratio is 60 dB. The RF spectrum at the maximum output power presented in the inset of Figure 2b reveals no longitudinal mode beat peaks in the frequency range up of to 3.6 GHz (≈28 pm at 1535 nm), thus confirming the regime of single-frequency generation.

The measured level of the RIN was −90 dB/Hz at 527 kHz, which is a typical value for this type of laser without external active stabilization. Using the technique of beat waveform processing described in [22–24], the frequency noise spectrum was obtained (see Figure 3b). The value of the instantaneous laser linewidth was determined by the level of white noise, S_0, and was $\Delta v = \pi S_0 \approx 94$ Hz [25]. The relatively high value of the instantaneous linewidth was determined by the high power level of the spontaneous noise [26], which depends on the concentration of active ions in the fiber [27]. The self-heterodyne technique was used to determine the laser linewidth at the delay line time interval [28]. Figure 3c shows an RF beat signal with a width of 110 kHz at a level of −20 dB, which corresponds to the laser linewidth of 5.5 kHz for the Lorenz profile. Therefore, the obtained spectral characteristics of the proposed DBR-laser are comparable with the spectral characteristics of typical Er^{3+} DFB lasers but with a significant excess of output power.

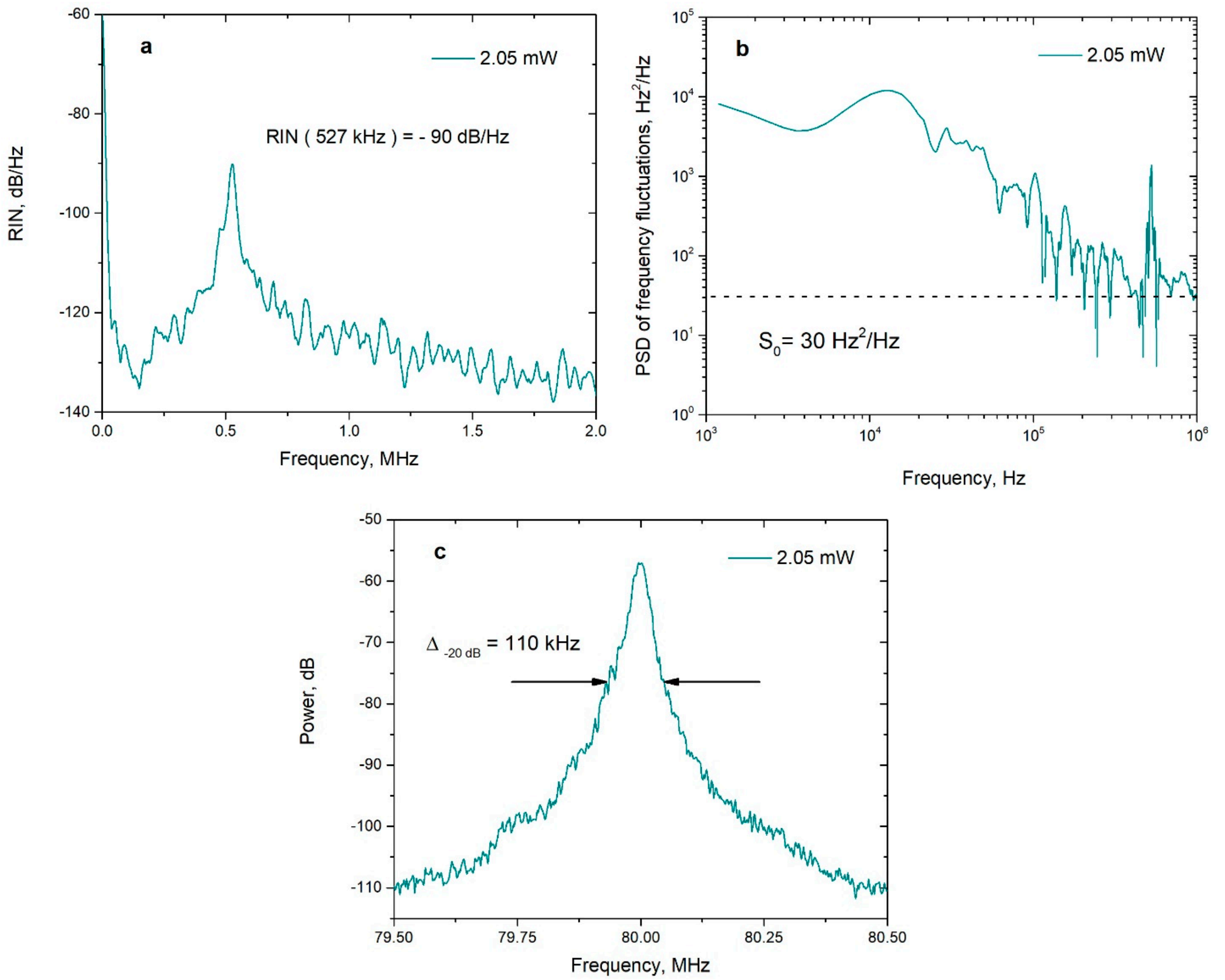

Figure 3. (**a**) Relative intensity noise measured at the maximum output power of the laser; (**b**) PSD of frequency fluctuations; (**c**) RF beating spectra obtained via heterodyne.

4. Conclusions

Thus, based on a heavily Er-doped fiber with a gain coefficient of ≈3.1 dB/cm, a DBR fiber laser has been developed with a record short active fiber length of 1.8 cm. A significant shortening of the cavity length was achieved through the use of a dielectric, highly reflective thin-film mirror deposited on the end face of the active fiber. In combination with the FBG, the total length of the structure was 3.3 cm. Due to the broad free spectral range of the obtained short laser cavity, a single-frequency regime was observed in the entire lasing power range with a maximum output power of 2 mW. The signal-to-noise ratio was at least 60 dB, as measured by the OSA, with an optical bandwidth resolution of 20 pm, and the peak of the RIN was observed at a frequency of 527 kHz; the peak amplitude value corresponded to −90 dB/Hz. The measured instantaneous linewidth of the laser at maximum output power was 100 Hz, and the width measured over a time interval of ~100 µs was 5.5 kHz. In addition, the use of a broadband dielectric mirror makes it possible to easily tune the generation wavelength via the compression/tension of the output FBG.

The characteristics of the developed compact DBR fiber laser presented herein open the path for applications in telecommunications, sensing, metrology, and scientific research in which compact and stable narrowband laser sources with tuning options are required [2].

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