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An Ytterbium-Doped Narrow-Bandwidth Randomly Distributed Feedback Laser Emitting at a Wavelength of 976 nm

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Abstract: All-fiber, polarization maintaining, narrow-bandwidth, Yb-doped fiber lasers with randomly distributed feedback operated near 976 nm were realized for the first time. It was shown that the laser operated in a single, longitudinal mode regime during intervals of a few seconds. At other times, the laser generated a few longitudinal modes, but its bandwidth was always below the resolution of the optical spectrum analyzer (0.02 nm). The linewidth of each single longitudinal mode of the laser was estimated to be below 20 kHz. The reasons for this observed laser behavior were discussed and methods for achieving stable, continuous wave operation in the single-longitudinal-mode regime were proposed.

Keywords: fiber laser; random distributed feedback; ytterbium-doped fiber; fiber Bragg grating; single-frequency laser

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1. Introduction

Narrow-bandwidth, ytterbium-doped fiber lasers, emitting at a wavelength near 976 nm, are attracting increasing attention due to being promising for a number of applications. Thus, narrow-bandwidth emission at the given wavelength can be required for the development of highly stable, single-frequency, ytterbium- or erbium-doped fiber lasers [1]. A wider range of applications [2–4] opens up new perspectives by doubling the radiation of such lasers (488–490 nm, blue-green radiation). In this case, the output wavelength of the laser is the same as the emission wavelength of an Ar laser, which is relatively inefficient, expensive, has a short lifetime, contains many bulk elements, and requires alignment by highly qualified personnel. Therefore, the frequency doubling of lasing at 976 nm can also be considered as an alternative to the argon laser [5–7]. Further doubling of the lasing frequency makes it possible to obtain UV radiation in the wavelength region of 244 nm [8], which is a promising source for recording fiber Bragg gratings (FBG) and lithography [9,10]. It is worth noting that existing techniques for the doubling of the frequency of a continuous wave (CW) signal require the use of narrow-bandwidth radiation (this is the case of periodically polished crystals [5–7]), or even single-frequency radiation (when doubling with the help of high-Q Fabry–Perot resonators) [8,11].

As a rule, single-frequency lasers are in high demand, the output power of which is units and even tens of watts. In general, such laser systems are built according to the MOPA (master oscillator power amplifier) principle. In this case, the manufacture of both a sufficiently narrow-bandwidth master laser and a highly efficient amplifier is a great challenge. The main problem sin the implementation of an Yb-doped fiber amplifier emitting at 976 nm are a sharp increase in amplified spontaneous emission (ASE) and the appearance of competing generation in the spectral region, with a maximum at 1030 nm with increasing pump power. To suppress radiation in the wavelength region above 1 μm, as a rule, at the stage of the implementation of the laser scheme, the length of the active fiber is reduced, which, in turn, leads to a larger fraction of the unabsorbed pump power and a relatively low total efficiency of converting the pump radiation into a signal. For this reason, specially designed active fibers are used to achieve an acceptably high pump-to-signal conversion efficiency. In particular, this goal can be achieved by introducing excessive optical losses into the spectral region of 1030 nm [12,13], or by creating fibers with an increased ratio of the area of the core to the cross-section area of the first reflective cladding [14–18].

The key element of a single-frequency laser is the master oscillator, which determines the main output characteristics (linewidth, reliability, and stability, etc.). As a master laser, it is possible to use a conventional semiconductor distributed feedback (DFB) diode. However, standard diodes have a linewidth of several MHz, and achieving a narrower linewidth requires the use of rather complex and expensive designs of such lasers. A more elegant solution is to create all-fiber, single-frequency lasers, due to their potentially higher reliability and resistance to external electromagnetic influences. When using relatively simple designs, such lasers can exhibit a narrower emission line by an order of magnitude [19]. Thus, relatively recently, the sub-kHz linewidth was demonstrated in a rather simple and reliable design of a single-frequency fiber laser [20]. The main problem of creating single-frequency fiber lasers is that, in their most common designs, namely lasers with distributed Bragg reflection (DBR) and DFB fiber lasers, the length of the active fiber is extremely short (~1 cm). This is due to the fact that the spectral distance between the longitudinal modes of the resonator must exceed the width of the reflection spectrum of the Bragg gratings. In most cases, this length of an active fiber is not enough to absorb a significant fraction of the pump, and as a result, the efficiency of such lasers is quite low. Only recent work has made it possible to improve the efficiency of such lasers by using heavily doped fibers [21,22].

The problem of creating all-fiber single-frequency lasers in the spectral region near 976 nm is that single-mode diodes emitting at a wavelength of ~915 nm are used as a pump source. The absorption of ytterbium at this wavelength is four times less than that at a wavelength of 976 nm (which is used to pump ytterbium lasers in the region of 1030–1064 and for Er-Yb single-frequency lasers), which makes it much more difficult to overcome the lasing threshold at a wavelength of 976 nm. At present, only the use of ytterbium-doped phosphate glasses has made it possible to obtain single-frequency generation in all-fiber lasers at a wavelength of 976 nm [23,24]. At the same time, the use of such fibers is by no means always acceptable for practical purposes, due to the low thermal and mechanical stability of phosphate glasses. To the best of our knowledge, single-frequency, all-fiber lasers at a wavelength of 976 nm based on silica optical fibers have not yet been realized.

The key to solving this problem may be the creation of a laser with randomly distributed feedback [25–29]. In such lasers, feedback is provided by Rayleigh reflection from an extended section of the fiber, or from an array of low-reflecting FBGs written along the length of the fiber. In the latter case, lasers are capable of generating an extremely narrow spectral line of <6 kHz in the CW mode [30,31]. The advantage of such lasers is the possibility of using the active medium itself for recording gratings, which makes it possible to significantly increase the length of the active fiber inside the resonator, thereby dramatically increasing the efficiency of the laser.

The purpose of this work was to study the particularities of creating a polarized, all-fiber laser with distributed random feedback at a wavelength of about 976 nm and to study the properties of such lasers. In particular, a random-distributed feedback laser was built using polarization maintaining elements to achieve a low-lasing threshold with only one polarization. A detailed study of the regime of laser generation and its dependence on the laser cavity length was performed. The possibility of achieving a single-frequency, single-polarization operation regime near 976 nm with a very narrow bandwidth (less than 20 kHz) for a relatively long time (few seconds) was demonstrated for the first time.

2. Materials and Methods

To develop a laser with random feedback, we used the laser design implemented in our previous work [32]. The main difference of the current work was that the circuit was implemented using polarization-maintaining optical fibers, which is necessary to achieving a single-polarization regime. For these purposes, we used the same initial preform of an ytterbium-doped fiber as in [32]. The preform was made using the modified chemical vapor deposition technique and its core was made of phosphogermanosilicate glass, which has a high photosensitivity. The concentration of ytterbium oxide corresponded to the core absorption at a level of 4 dB/m @ 915 nm. The fiber was made in the standard "PANDA" configuration—two holes were drilled into the silica preform symmetrically with respect to the core, and before drawing the fiber, two borosilicate rods were inserted into these holes. The presence of boron stress rods in the cladding created birefringence in the fiber core, which, in turn, resulted in the appearance ability of the fiber to maintain polarization. Similar to [32], weakly reflecting FBGs were recorded in the fiber directly during drawing by the use of a UV excimer laser. The estimated size of each of the recorded gratings was about 1 cm (corresponding to the width of the phase mask used to record the gratings). The distance between the recorded gratings was also about 1 cm (that is, the gratings were recorded practically without gaps between them). The estimated reflection coefficient of a single grating was about 0.05%. Due to the presence of birefringence, the reflection wavelengths of the gratings for the fast and slow axes differed and amounted to 976.25 nm and 976.5 nm, respectively (see Figure 1).

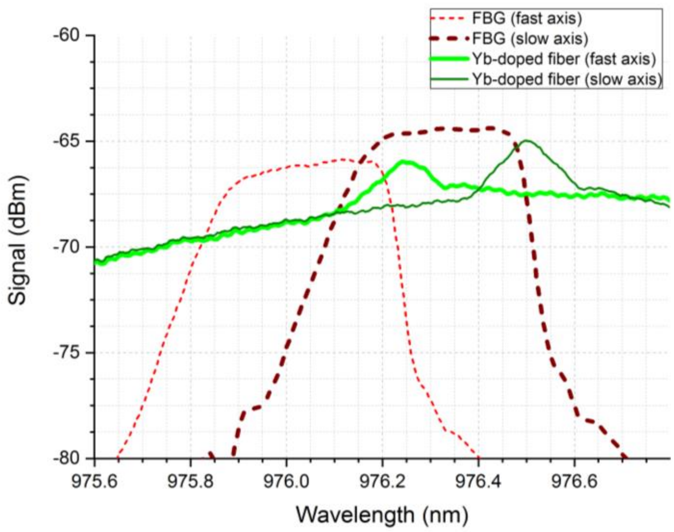


Figure 1. Reflected signal from the FBGs written in the Yb-doped fiber and from separate FBG written in polarization-maintaining fiber. Measurements were made with polarized wideband source to separately characterize fast and slow polarization in both cases. The bold lines correspond to those FBGs, which form the resonator in the realized laser operated at 976.2 nm.

The scheme of the realized laser with random feedback is depicted in Figure 2. The polarization-maintaining, ytterbium-doped fiber with a written array of FBGs (YDF-FBG-PM) was pumped by a semiconductor laser diode (pump diode), with a wavelength of 910 nm and an average power of about 200 mW, through a wavelength division multiplexor (WDM), separating the wavelengths of 910 nm and 976 nm. The 976 nm WDM port was used as the laser output and was spliced to an Isolator, which allowed only one of the polarizations to pass through.

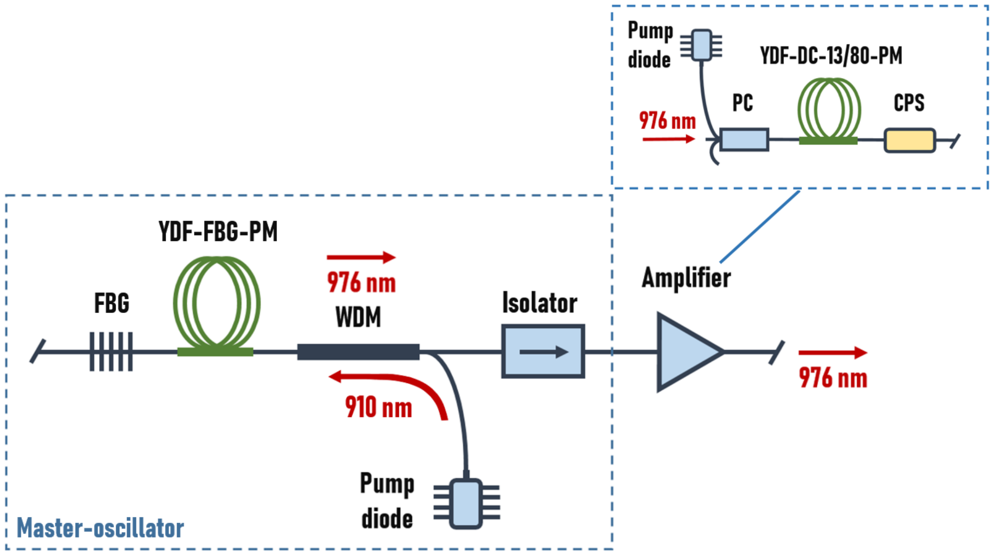


Figure 2. Schematic of a fiber laser with random feedback and a weak-signal amplifier.

A highly reflective FBG written in the polarization-maintaining fiber was spliced to the free end of the ytterbium fiber. The wavelengths corresponding to the reflection maximum of this FBG also differed for "fast" and "slow" polarizations (see Figure 1) and amounted to 975.9–976.2 nm and 976.2–976.4 nm, respectively. During the splicing, the "fast" axis of the YDF-FBG-PM was aligned with the "slow" axis of the YDF-FBG-PM. As a consequence, this made it possible to implement a high-quality resonator for the "fast" polarization of the YDF-FBG-PM—the Bragg grating for this polarization provided high reflection at wavelengths of 976.2–976.4 nm, and the array of Bragg gratings recorded in the YDF-FBG-PM provided random feedback at wavelengths near 976.25 nm. On the contrary, the "slow" polarization of the YDF-FBG-PM (with maximum reflection at 976.5 nm) was aligned to the fast polarization of the FBG (with reflection at 975.9–976.2 nm). Due to mismatch of the reflection spectrum, the quality factor of the resonator for this polarization was low, and lasing in this polarization was suppressed. As a result, conditions were created that ensured the generation of radiation in only one polarization—without the above-mentioned efforts, lasing could occur in both polarizations [33].

During the first experiment, only the master oscillator (shown in Figure 2 by a dashed rectangle) was characterized. In this case, all the free fiber ends were cleaved at an angle of about 7 degrees in order to avoid unwanted Fresnel back reflections from the corresponding ends. In the second experiment after the isolator, a weak-signal amplifier similar to that developed in [17] was placed.

3. Results

First, we studied the effect of the length of the ytterbium-doped fiber with a recorded array of Bragg gratings (YDF-FBG-PM) on the output characteristics of the developed laser. For this purpose, a 3 m long YDF-FBG-PM was gradually shortened, and for each length of the YDF-FBG-PM, the output signal spectra, oscillograms, polarization extinction ratio (PER), power, and stability for several minutes were measured. To measure the PER of the laser, two measurements of the laser radiation power at the output of the isolator were carried out—one when the slow axis of the isolator was aligned with the "fast" polarization of the YDF-FBG-PM at the output of the WDM, and the second when it was aligned with the "slow" polarization. As the fast axis of the isolator was blocked, it acted as a polarizer. This made it possible to determine the signal power propagating in the "fast" and "slow" polarization, respectively, and to determine the PER.

The main results measured with different lengths of the YDF-FBG-PM fiber are shown in Figure 3. It can be seen that the maximum output power increased with an increase in the length of the YDF-FBG-PM, which was associated with an increase in the fraction of the absorbed pump in this fiber. At the same time, with an increase in the length of the YDF-FBG-PM over 1 m, the PER deteriorated significantly. We suggest that this was due to the fact that the intrinsic reflectivity of the array of Bragg gratings recorded in the YDF-FBG-PM became sufficient for achieving efficient generation in the unwanted polarization. This assumption was partly confirmed by the measurement of the output radiation spectrum—in the long-wavelength region (976.5 nm), an additional peak began to appear, approximately coinciding with the reflection peak of the array of Bragg gratings for unwanted polarization (see Figure 4a). Moreover, the output spectra became unstable and varied with time—in Figure 4a, three spectra measured with time intervals of a few seconds are shown (signal #1, signal #2, and signal #3). It is also necessary to note that an increase in the ASE in the wavelength region of 976 nm was observed at the maximum length of the active fiber (3 m). Reducing the length of the ytterbium-doped fiber to 0.7 m led to a sharp drop in the output power to a level of less than 1 mW and an increase in the instability of the output radiation by an order of magnitude (variations in the output power over 10 min increased from 2% to 25%). Changes in the lasing wavelength within 0.1 nm were also observed with time. Apparently, with such a length of the active fiber, the available pump power was not enough to ensure stable laser generation.

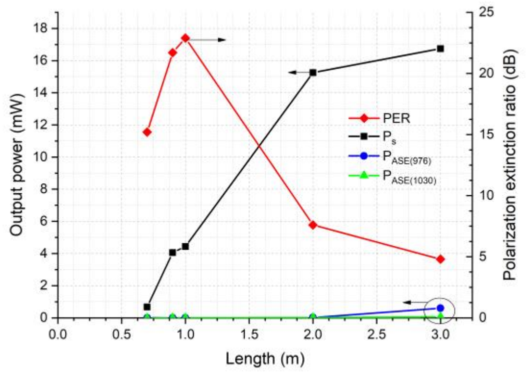
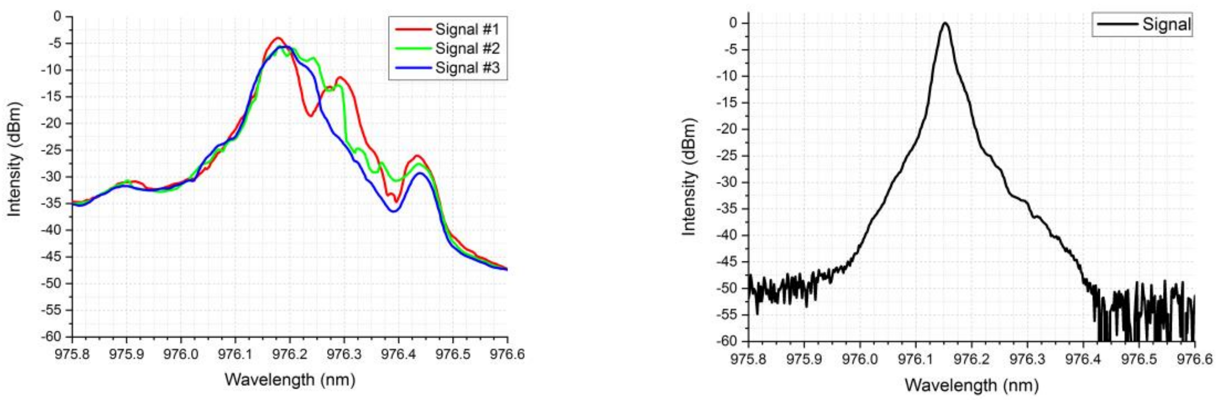


Figure 3. Dependence of the output power of the signal (P_s) at 976.2 nm, the ASE level in the wavelength region of 976 nm ($P_{ASE(976)}$) and at the wavelength of 1030 nm ($P_{ASE(1030)}$), and the PER value against the length of the ytterbium-doped fiber with the recorded array of Bragg gratings.



(**a**) (**b**)

Figure 4. Spectra of output signal for the Yb-doped fiber length of 3 m (**a**) and for the fiber length of 0.9 m (**b**) measured with optical spectrum analyzer ANDO AQ6317B.

As a result, the optimal length of the fiber was found to be in the range of 0.9–1 m—in this case, an acceptable high output power (about 4 mW) and maximum PER level were obtained. Also in this case, the most stable lasing spectrum was observed (see Figure 4b)—within the measurement error of the spectrum analyzer ANDO AQ6317B, the position of the line did not change, and the measured linewidth was 0.02 nm (by 3 dB level), which corresponded to the maximum resolution of the spectrum analyzer at the given wavelength.

In the framework of this research, we did not have the technical ability to directly measure the linewidth of the resulting laser with random feedback. However, an analysis of the oscillograms of radiation at the output of the laser was quite informative. Indeed, if we imagine the developed laser as a laser with a Fabry–Perot resonator, where one of the mirrors is a highly reflective Bragg grating, and the second is an array of weakly reflecting gratings (in the first approximation, they can be represented as one grating with a complex reflection spectrum located in the middle of the active fiber), then the spectral distance between the modes of this resonator can be estimated in orders of magnitude. Equations for the intrinsic frequency of the so-called longitudinal mode (ν_q):

$$\nu_q = \frac{c}{\mathrm{n}\cdot\lambda} = \mathrm{q}\cdot\frac{c}{2\cdot\mathrm{n}\cdot\mathrm{L}}\ ,\ \Delta\nu_q = \frac{c}{2\cdot\mathrm{n}\cdot\mathrm{L}}\ , \tag{1}$$

where c—the light speed velocity, n—the effective refractive index of the fundamental mode in the YDF-FBG-PM, λ—the wavelength of the longitudinal mode with index q, L—the resonator length, and $\Delta\nu_q$—the frequency difference between two neighboring longitudinal modes. In accordance with Equation (1), the distance between the modes can be estimated as 200 MHz for a resonator with an active fiber segment of 0.9 m (the L was taken to be ~0.45 m). The above analysis of the properties of the created resonator was based on a very rough simplification. An exact calculation of the eigenmodes of the created resonator is rather complicated, as it requires the consideration of the interference between all the FBGs (~100 items), which form the laser resonator. Nevertheless, as will be seen below, this approach made it possible to estimate, with an acceptable accuracy, the distance between the resonator eigenmodes.

The gain band of the active medium in our case had a width that was orders of magnitude greater than the distance between the longitudinal modes. However, the reflection spectrum of an array of Bragg gratings due to internal interference should have narrow reflection maxima randomly located along the spectrum that differ in intensity. Exactly within these narrow lines, lasing will develop, provided that the resonator mode falls within these maxima. At the same time, it seems very likely that there will be several modes within the maximum reflection limit of the array of Bragg gratings, which will lead to the generation of several modes. In this case, it will be possible to observe interference between the generated modes—sinusoidal modulations of the output power at half of the frequency spacing between the modes (~100 MHz, 200 MHz, 200 MHz, and so on) will appear on the oscillogram. Given the estimated distance between the modes, the presence of output power modulation when generating several modes can be observed using an oscilloscope with a bandwidth greater than the frequency difference between the modes. We used a Tektronix TDS 3054C oscilloscope with a bandwidth of 500 MHz, which made it possible to carry out these measurements.

The results of measuring the oscillograms in the developed laser with an active fiber length of 0.9 m are shown in Figure 5. It was found that the fabricated laser's significant time (about few seconds) operated in a quasi-continuous mode—(Regime 1). Periodically, this regime was switched to Regime 2 when modulation was observed with a frequency of ~100 MHz, corresponding to the beat between neighboring longitudinal modes of the resonator and even higher (~180 MHz and 280 MHz, etc.).

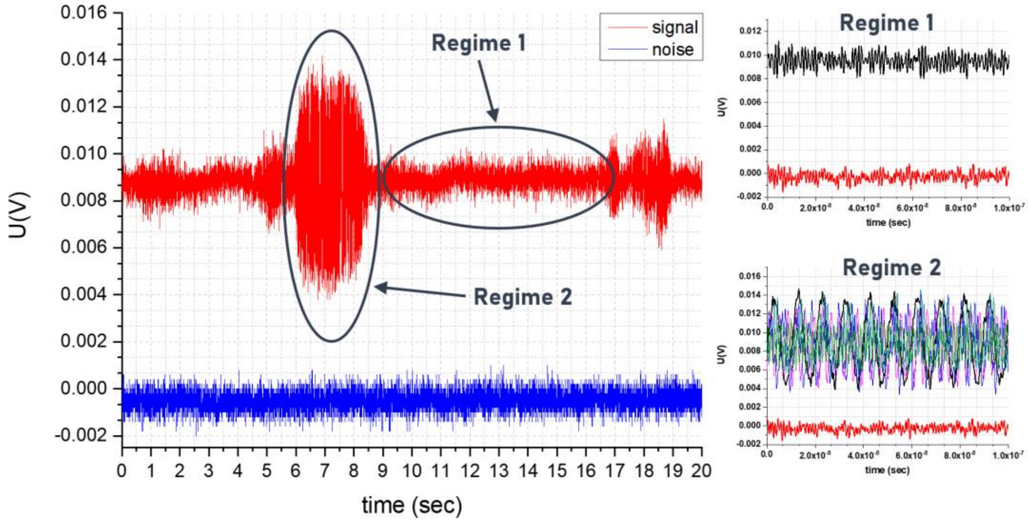


Figure 5. Signals obtained by means of an oscilloscope with the YDF-FBG-PM length of 0.9 m. Curves with different colors for Regime 2 was measured at different times to show different forms of signal, observed in the Regime 2.

The presence of a single longitudinal mode operation regime was also confirmed by the analysis of the output signal using a real-time radio frequency spectrum analyzer (KEYSIGHT EXA Signal Analyzer) with an operating broadband frequency range from 10 Hz to 3.6 GHz. Indeed, in Regime 1, there was no beating between the modes (see Figure 6a). On the contrary, very different radiofrequency spectra were observed in Regime 2—from time to time, oscillation at different frequencies appeared (see Figure 6b). In all cases, the smallest oscillation frequency was near 100 MHz (corresponding to the interference between two neighboring longitudinal modes), the next oscillation was observed at ~190 MHz (double minimum distance between longitudinal modes), and so on (~290 MHz, 300 MHz, 380 MHz, 450 MHz, 550 MHz, and 630 MHz). The exact position of each line changed over time—for example, the position of the first oscillation ranged from 98 MHz to 104 MHz. An example of such variation in a smaller spectral region is shown in Figure 6c. Such variations are a feature of lasers with random distributed feedback—the minimum distance between the longitudinal modes in such lasers is not fixed, as there is no fixed distance between the reflectors that form the laser resonator (one of the reflectors, the FBG array, is extended along the resonator). At the same time, the width of each oscillation line was extremely small—it could be seen that it was below 19 kHz (see Figure 6d). As the width of the oscillation was defined by the spectral width of each interfering longitudinal mode, we could conclude that the width of each longitudinal mode generated in our laser was below 19 kHz.

For comparison, Figure 7 shows the oscillograms of the laser with a 3 m long ytterbium-doped fiber. It can be seen that, in this case, there were no time intervals where continuous generation was observed, and the picture is noise-like, with a large number of beats at different frequencies, which indicates the generation of a large number of modes.

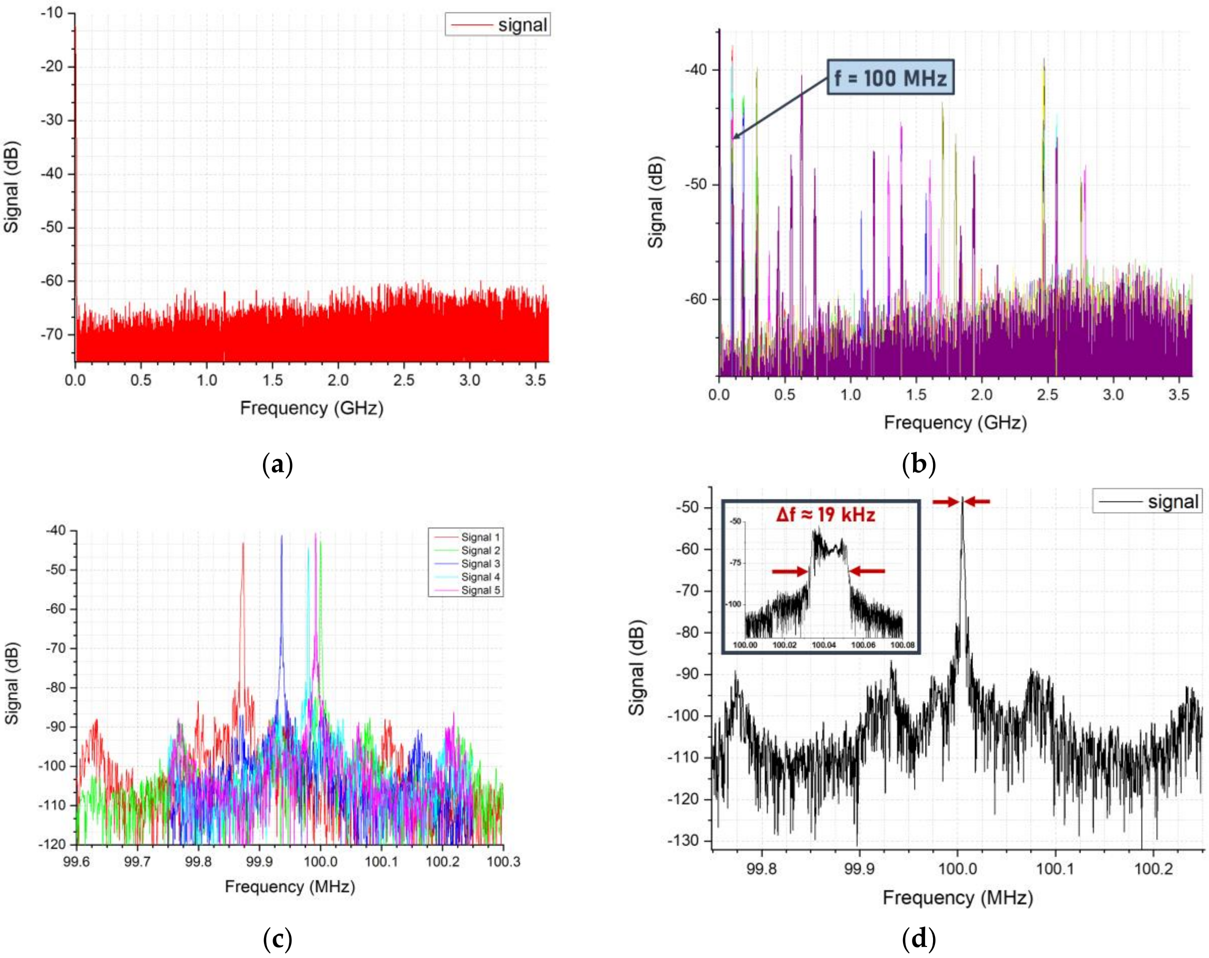


Figure 6. Radiofrequency spectra of the signal at the output of the master oscillator with YDF-FBG-PM length of 0.9 m: (**a**) Regime 1; (**b**) Regime 2 (different color corresponds to spectrums measured at different time); (**c**) variation of the position of the 100 MHz oscillation line; and (**d**) measurement of the 100 MHz oscillation bandwidth (inset—100 MHz oscillation spectrum measured in a smaller frequency range).

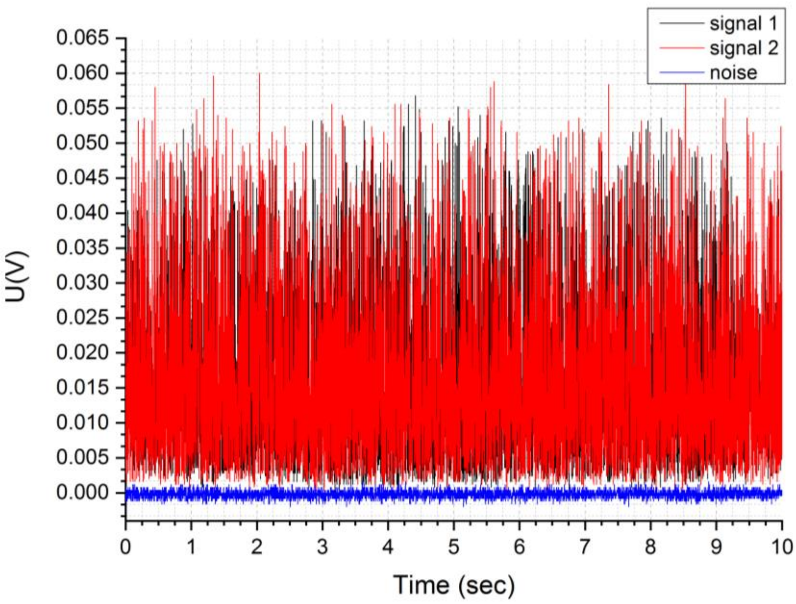
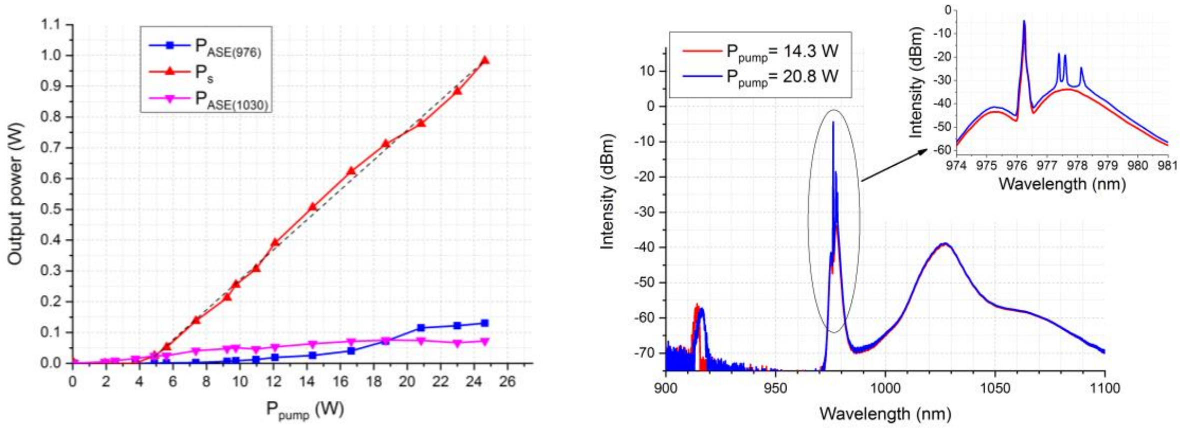


Figure 7. Graphs of signals obtained by an oscilloscope with the YDF-FBG-PM length of 3 m.

Finally, to amplify the signal, a single-stage, all-fiber, single-mode amplifier was assembled, similar to that developed in [17]. The scheme of the amplifier is shown in the inset to Figure 3, and consisted of a multi-mode pump and single-mode signal combiner (PC), multi-mode pump diode at 915 nm, YDF-DC-13/80-PM fiber available from FORC-Photonics, similar to the one developed in [17], and cladding pump striper (CPS) based on a single-mode, polarization-maintaining fiber with a core diameter of 10 µm. In the assembled amplifier, the dependence of the output power of the amplified signal on the pump power, as well as the amplified spontaneous emissions (ASE) in the wavelength regions of 976 nm and 1030 nm, was studied; the results are shown in Figure 8. An output signal power of more than 1 W was obtained, and the resulting amplification efficiency was 5.1% (it was below 1, reported in [17], due to a non-optimal signal wavelength and additional splice loss at the output of the Yb-doped fiber). It should be noted, however, that, at the maximum power, a significant level of enhanced spontaneous luminescence appeared in the spectral region near 976 nm. For this reason, the output power at the output of the first stage should be limited to 500 mW, and to achieve higher power, an additional amplification stage with a spectral filter at the input should be used—the received signal power at the output of the first stage should be sufficient for the efficient operation of a power amplifier based on special designs of ytterbium-doped fibers [12,14]. In addition, it should be noted that, to maintain the oscillation regimes described above, it was necessary to use a double-stage isolator between the master oscillator and amplifier. Otherwise, no long, single-longitudinal-mode operation regime (Regime 1) was observed—possibly due to the interference of the ASE from the amplifier and a weak signal reflected from the YDF-FBG-PM.



(**a**) (**b**)

Figure 8. (**a**) Plot of the pump power (P_{pump}) versus the power of amplified signal (P_s), power of ASE near 976 ($P_{ASE(976)}$), and power of ASE near 1030 ($P_{ASE(1030)}$) at the output of the amplifier (the dashed line is the result of a linear approximation of power efficiency); and (**b**) spectrum of the output signal for different level of pump power (P_{pump}).

4. Discussion

It should be noted that, in general, the observed regimes of the operation of the implemented laser with random distributed feedback were quite expected. Indeed, since the distance between the FBGs recorded in the ytterbium fiber could vary with temperature and tension, the fine structure of the reflection spectrum of the Bragg grating array could change over time due to temperature and mechanical fluctuations. As a consequence, the laser could switch the generation between different modes of the resonator, and, in between, the simultaneous generation of several modes. Apparently, this behavior is a feature of lasers with random feedback, since it is impossible to completely eliminate the effect of thermal fluctuations on a 0.9 m long fiber segment. The distance between the modes (about

200 MHz) led to the fact that switching occurred even with small changes in the external conditions. At the same time, it should be noted that, even in the absence of special efforts to thermally stabilize the laser (as was the case in our study), quite long time intervals of up to 10 s were observed when the laser operated presumably in the single-frequency mode. It also needs to be emphasized that the optical spectrum remained extremely narrow throughout the entire laser operation time—its position changed and the spectral width was below the resolution of the spectrum analyzer (0.02 nm) all the time, which makes the developed laser promising for most applications, as indicated in the introduction to this article. We expect that an improvement in the thermal stabilization of the developed laser could allow for a significantly longer (or even continuous wave) operation of the laser in the single-frequency regime.

Further optimization of the scheme is possible by increasing the Yb concentration in the core of the YDF-FBG-PM fiber. It would allow one to increase the pump-to-signal conversion efficiency of the designed laser and allow an increase in the output power for the fixed pump power. Alternatively, it would also make it possible to shorten the cavity length, increase the spacing between the longitudinal modes, and, in this way, increase the stability of the laser (would increase the time of the single-frequency laser operation, even without precise thermal stabilization).

It is also interesting to note that lasers with a long cavity, which generate random laser radiation, could also be interesting in some applications [26]. Moreover, lasers with a longer cavity could operate with a much higher efficiency.

5. Conclusions

With the optimal resonator configuration, stable generation was obtained at a wavelength of 976.2 nm with a spectral linewidth less than the resolution of the spectrum analyzer (0.02 nm), an output power of about 4 mW, and a polarization extinction ratio of more than 18 dB. An analysis of the time dependence of the output signal using a high-speed oscilloscope showed that, in the developed laser, it was possible to sufficiently realize long-time intervals (up to 10 s), during which, the laser supposedly operated in a single-frequency mode. The study of the dependence of the output power on the time using a fast oscilloscope made it possible to establish the operating mode of the laser—the generation of presumably single-frequency radiation and the switching of the generation between modes over the time intervals of the order of seconds. We believe that an improvement in the thermal stabilization of such a laser could provide continuous the wave generation of single-frequency radiation in the future.

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