Results in Physics 16 (2020) 102832

Contents lists available at ScienceDirect

Results in Physics

journal homepage: www.elsevier.com/locate/rinp

Continuous-wave operation of an erbium-doped short-cavity composite fiber laser

A.A. Rybaltovsky[a,b,*], O.V. Butov[a], S.A. Vasiliev[b], I.A. Nechepurenko[a,c], O.N. Egorova[d], S.L. Semjonov[b], B.I. Galagan[d], B.I. Denker[d], S.E. Sverchkov[d]

[a] Kotelnikov Institute of Radioengineering and Electronics of RAS, 11-7, Mokhovaya Str., Moscow 125009, Russia
[b] Fiber Optics Research Center of the Russian Academy of Sciences, 38 Vavilov Street, 119333 Moscow, Russia
[c] Dukhov Research Institute of Automatics, 22 Suschevskaya, Moscow 127055, Russia
[d] Prokhorov General Physics Institute of the Russian Academy of Sciences, 38 Vavilov Street, 119991 Moscow, Russia

ABSTRACT

In the paper we investigate the characteristics of a short-cavity fiber laser based on a new silica fiber with a composite erbium-doped phosphosilicate core without additional co-doping with ytterbium. For the first time, the operation of such laser in the continuous-wave lasing mode with 1490-nm pump is shown. The laser operation in the self-Q-switching mode, changing to the continuous-wave mode with increasing the pumping power, is demonstrated.

Introduction

Development of a high-quality narrow-band laser source for the spectral range of 1.5–1.6 μm is of great interest for telecommunications, metrology, spectroscopy, fiber-optic sensors, scientific and some other applications. Single-frequency erbium-doped fiber lasers, constructed either following the classic Fabry-Perot scheme or as distributed feedback lasers (DFB) with a cavity length of only a few centimeters and a spectral bandwidth of less than 10 kHz, have great prospects for the applications as simple, compact and relible signal or reference sources. However for most applications the long-term stability of the single-frequency laser output parameters is required, which implies operation of the laser in a strictly continuous-wave (CW) operation mode. The problem of the spontaneous pulsing of erbium-doped fiber lasers is well known [1–4]. The phenomenon is associated with up-conversion effects in erbium ion clusters existing in the glass network [4].

To solve the erbium clustering problem, as well as to increase the pump efficiency of erbium-doped fiber lasers, co-doping of the glass with ytterbium is often used. This allows reducing the concentration of erbium (and thus clusterization level) in the fiber core, keeping the pump efficiency high enough for short-cavity lasers [5,6]. Unfortunately, this approach has some inherent drawbacks. Co-doping with ytterbium ions can cause the amplified spontaneous emission (ASE), which leads to a significant decrease of the laser efficiency and to parasitic lasing in the region of 1 μm. [7,8]. Thus, development of stable and efficient CW single-frequency fiber lasers requires active fibers with high-concentration of non-clustered erbium ions in the core with no ytterbium co-doping. This can be done using glass materials providing better solubility of erbium ions. Phosphate glass or heavily phosphorus-doped silica glass are known to be the promising materials to satisfy these requirements [9]. However, the fibers made of these glass types are difficult to produce and are not well compatible with standard fibers and telecommunication components. Composite erbium-doped fiber, developed recently on the base of heavily phosphorus-doped silica glass [10], satisfies most of the aforementioned requirements. The main aims of this paper were to develop a short-cavity single-frequency fiber laser (DBR laser) using this composite fiber as an active medium as well as to study the operation properties of this laser.

Experiment and results

The cavity of the DBR laser was formed by two Bragg gratings fabricated directly in the composite single-mode erbium-doped phosphosilicate fiber. Spectral and waveguiding characteristics of the fiber are given in [10]. The key feature of the fiber is the ultra-high phosphorus oxide concentration (24 mol%) in the silica based core. This was achieved with rod-in-tube technique of fiber fabrication where phosphate glass rod and silica tube were used as initial components. The absorption of erbium ions in the fiber at 976 and 1490 nm was ~0.4 dB/cm [10], whereas the peak absorption (at 1535 nm) achieved 1.4 dB/cm. Due to phosphorus in the core, the fiber, being H_2-loaded, possesses photosensitivity at 193-nm irradiation sufficient for inscribing effective Bragg gratings [11]. The fiber was H_2-loaded at a temperature

* Corresponding author.
E-mail address: rybaltovsky@yandex.ru (A.A. Rybaltovsky).

https://doi.org/10.1016/j.rinp.2019.102832
Received 11 October 2019; Received in revised form 22 November 2019; Accepted 22 November 2019
Available online 27 November 2019

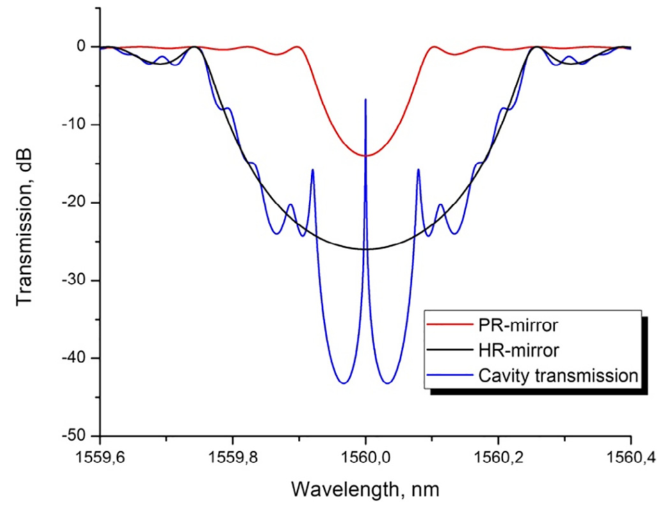

Fig. 1. Calculated transmission spectra of the Bragg gratings and the spectrum of DBR fiber laser cavity (blue line) composed by these gratings (see details in text).

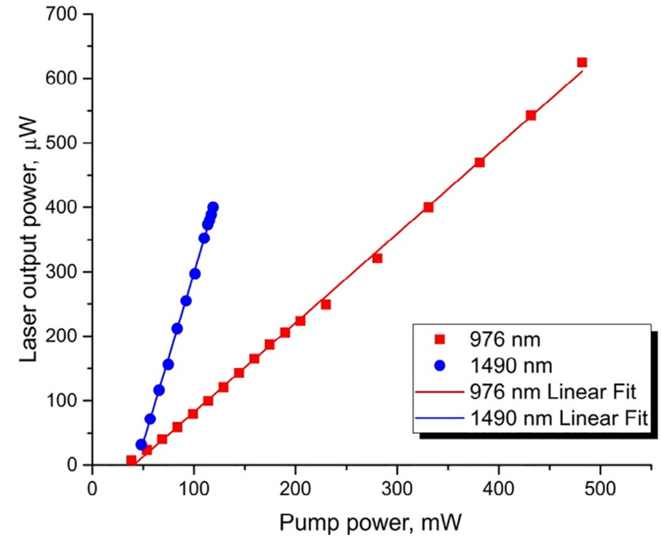

Fig. 3. The laser output power as a function of the pump power for two pump wavelengths used in the experiments.

of 90 °C and a pressure of 12 MPa during 24 h. The Bragg gratings were then inscribed through a uniform phase mask with a period of 1072 nm by pulsed 193-nm radiation of the Coherent COMPexPro ArF-excimer laser with the pulse repetition rate of 10 Hz and the pulse energy density of 200 mJ/cm^2. The configuration of the laser cavity (gratings' parameters and the distance between them) was chosen based on the amplifying properties of the active fiber and pumping conditions. At the ends of a short composite fiber section a highly reflecting (HR) grating with a length of L_{HR} = 5 mm and an output partially reflecting (PR) grating with a length of L_{PR} = 10 mm were inscribed. The gratings had reflection coefficients R_{HR} = 99.8% (~26 dB) and R_{PR} = 96% (~14 dB), respectively. The distance between the inner edges of the gratings was 9 mm. Fig. 1 shows the calculated transmission spectra of the gratings as well as the spectrum of the cavity composed of them. The difference in the transmission of the center and side peaks by more than 10 dB indicates that the resulting DBR laser cavity should support single frequency lasing.

The prepared DBR composite fiber laser was tested using two single-mode pumps at 976 and 1490 nm. The pump sources were connected to the DBR laser through a fiber wavelength division multiplexers (WDM) according to the backward pumping scheme described in detail elsewhere [4,12]. The pump power P_P and the output power of the DBR laser P_L were measured using a JDSU OLP-55 power meter. We used a high-speed photodetector and a Tektronix DPO4102B oscilloscope with a maximum bandwidth of 1 GHz to study the temporal characteristics of the output laser radiation. Fig. 2a shows the lasing spectra measured using a Yokogawa 6370D optical spectrum analyzer with a resolution of 0.016 nm at 1490-nm pump. The shape of the laser radiation spectrum (a central narrowband peak) shows that the laser generates in the single frequency mode near the lasing thresholds. The single-frequency laser operation was also confirmed with an VitaWave FPI SCC-750 scanning confocal interferometer with a free-dispersion region of 750 MHz, allowing the longitudinal modes of the laser cavity to be analyzed. With an increase of the pumping current, two orthogonally polarized radiation modes appear in the spectrum, the spectral distance between them being 20 pm. The polarization splitting of the laser radiation was verified and confirmed with the help of Glan prism polarizer, which allowed us to distinguish both polarization states separately. At the maximum power of our 976-nm pump source only (~480 mW) a second longitudinal cavity mode was observed in the laser spectrum, being located approximately 0.08 nm aside of the main emission line.

The bandwidth of the laser radiation was measured by means of the self-heterodyne scheme illustrated in detail in [13] using a 50 km delay line. Fig. 2b shows the radio frequency spectrum of the resulting beats, measured at 40-mW pump power. Having the spectrum and using the approach described in [14] we estimated the bandwidth of single

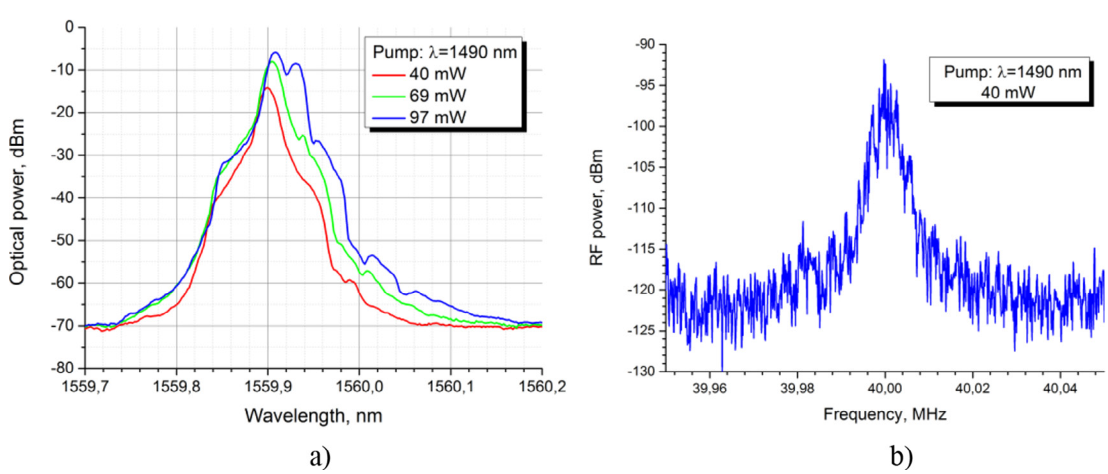

Fig. 2. The emission spectra of the DBR laser at various pump power at the wavelength of 1490 nm (a) and the radio frequency spectrum measured at 40-mW pump (b).

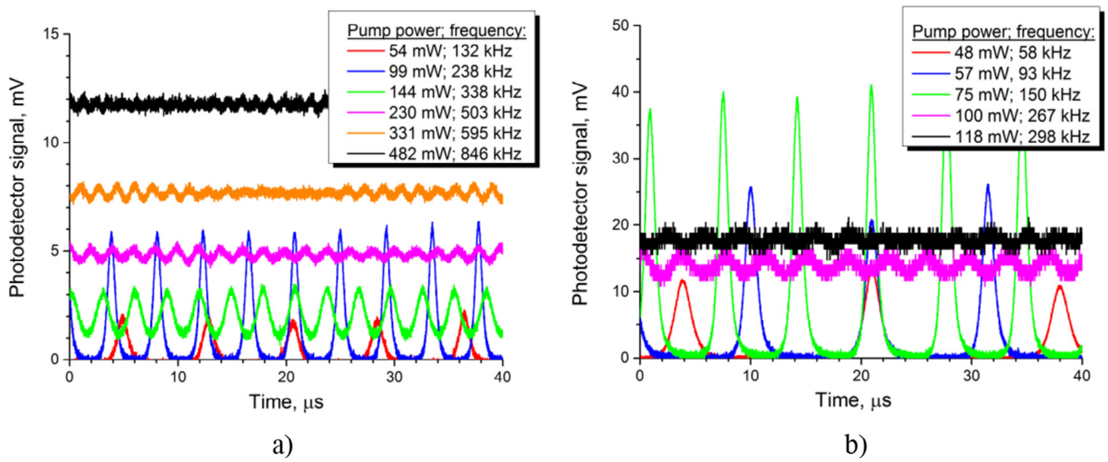

Fig. 4. The time dependence of the DBR laser radiation intensity at various pump power at the wavelengths of 976 (a) and 1490 nm (b).

frequency emission of the DBR fiber laser which occurred to be less or equal to 4 kHz.

Fig. 3 shows the dependences of the laser output power on the pump power for both pumps we used in the experiments. As seen the lasing thresholds are approximately equal and amount to about 30–40 mW pump power. However, the slopes of the curves (laser power efficiency) depend on the pump wavelength and differ by more than 3.5 times (0.52% and ~0.14% with pump at 1490 nm and 976 nm, respectively). Significant difference in the lasing efficiency cannot be explained by the difference in the pumping wavelengths only, i.e. pump-emission energy gap. Apparently, the excited state absorption (ESA) of Er^{3+} ions and related up-conversion processes during pumping at a wavelength of 976 nm can mainly contribute to the difference [15,16].

Fig. 4 shows the time dependence of the DBR laser radiation at various pump power at wavelengths of 976 nm (Fig. 4a) and 1490 nm (Fig. 4b). At low pump power the DBR laser operates in a pulse mode, the pulse repetition rate and pulse duration being uniquely dependent on the pump power. With the increase of pump power the pulsations in the output laser emission become less pronounced and finally the laser emits almost CW radiation. These temporal properties and transitional behavior of the laser emission correspond well to the theory described in detail in [4]. Note that the nature of the temporal dependence of the laser emission is different for different pump wavelengths. At 976-nm pump with respect to 1490-nm pump the peaks have higher frequency (see legends of the figure) but lower magnitude and the transition to the CW regime is less abrupt.

Conclusion

Comparative study of the spectral and temporal characteristics of a DBR composite-fiber laser emission pumped at two wavelengths 976 and 1490 nm has been carried out. A composite erbium-doped (ytterbium-free) phosphosilicate fiber was used as an active fiber medium of the laser. For the first time the CW emission of a short-cavity DBR erbium-doped fiber laser was observed at a wavelength of 1490 nm. Comparison of the two pumps we used showed that the lasing efficiency is much higher (~3.5 times) at pump with longer wavelength. In our opinion the difference can be explained by the effect of up-conversion processes enhanced at 976-nm wavelength pump. The operation of the laser in a self-Q-switch mode at low pump power and the gradual transition to CW mode with the growth of the pump power have been demonstrated.

Funding

The work was carried out within the framework of the state task and partially was supported by the Russian Foundation for Basic Research: RFBR 17-07-01388 A.

CRediT authorship contribution statement

A.A. Rybaltovsky: Conceptualization, Investigation. **O.V. Butov:** Investigation, Writing - review & editing, Funding acquisition. **S.A. Vasiliev:** Validation, Software, Writing - review & editing. **I.A. Nechepurenko:** Methodology, Formal analysis. **O.N. Egorova:** Investigation, Resources. **S.L. Semjonov:** Supervision. **B.I. Galagan:** Resources. **B.I. Denker:** Project administration. **S.E. Sverchkov:** Resources.

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.

References

[1] Loh WH, de Sandro JP. Suppression of self-pulsing behaviour in erbium-doped fiber lasers with resonant pumping: experimental results. Opt Lett 1996;21(18):1475–7.
[2] Kir'yanov AV, Il'ichev NN, Barmenkov YuO. Excited-state absorption as a source of nonlinear thermo-induced lensing and self-Q-switching in an all-fiber Erbium laser. Laser Phys Lett 2004;1(4):194–8.
[3] Skvortsov MI, Wolf AA, Dostovalov AV, Vlasov AA, Akulov VA, Babin SA. Distributed feedback fiber laser based on a fiber Bragg grating inscribed using the femtosecond point-by-point technique. Laser Phys Lett 2018;15:035103.
[4] Smirnov AM, Bazakutsa AP, Chamorovskiy YK, Nechepurenko IA, Dorofeenko AV, Butov OV. Thermal switching of lasing regimes in heavily doped Er3+ fiber lasers. ACS Photonics 2018;5:5038–46.
[5] Spiegelberg C, Geng J, Hu Y, Kaneda Y, Jiang S, Peyghambarian N. Low-noise narrow-linewidth fiber laser at 1550 nm. J Lightwave Technol 2004;22(1):57–62.
[6] Xu SH, Yang ZM, Liu T, Zhang WN, Feng ZM, Zhang QY, et al. An efficient compact 300 mW narrow-linewidth single frequency fiber laser at 1.5 µm. Opt Express 2010;18(2):1249–54.
[7] Nilsson J, Alam S-U, Alvarez-Chavez JA, Turner PW, Clarkson WA, Grudinin AB. High-power and tunable operation of erbium-ytterbium co-doped cladding-pumped fiber lasers. IEEE J. Quantum Electron 2003;39:987–94.
[8] Sobon G, Kaczmarek P, Antonczak A, Sotor J, Abramski KM. Controlling the 1 µm spontaneous emission in Er/Yb co-doped fiber amplifiers. Opt Express 2011;19:19104–13.
[9] Egorova ON, Semjonov SL, Velmiskin VV, Yatsenko YuP, Sverchkov SE, Galagan BI, et al. Phosphate-core silica-clad Er/Yb-doped optical fiber and cladding pumped laser. Opt Express 2014;22(7):7625–30.
[10] Rybaltovsky AA, Egorova ON, Zhuravlev SG, Galagan BI, Sverchkov SE, Denker BI, et al. Distributed Bragg reflector fiber laser directly written in a composite fiber manufactured by melting phosphate glass in a silica tube. Opt Lett 2019;44(14):3518–21.
[11] Rybaltovsky AA, Sokolov VO, Plotnichenko VG, Lanin AV, Semenov SL, Gur'yanov AN, Khopin VF, Dianov EM. Photoinduced absorption and refractive-index induction in phosphosilicate fibres by radiation at 193 nm. Quantum Electron 2007;37(4):388–92.

[12] Butov OV, Rybaltovsky AA, Bazakutsa AP, Golant KM, Vyatkin MYu, Popov SM, et al. 1030 nm Yb3+ distributed feedback short cavity silica-based fiber laser. J Opt Soc Am B 2017;34(3):A43–8.
[13] Richter LE, Mandelburg HI, Kruger MS, McGrath PA. Linewidth determination from self-heterodyne measurements with subcoherence delay times. IEEE J Quantum Electron 1986;QE-22:2070–4.
[14] Ip E, Kahn JM, Anthon D, Hutchins J. Linewidth measurements of MEMS-based tunable lasers for phase-locking applications. IEEE Photonics Technol Lett 2005;17(10):2029–31.
[15] Barmenkov YO, Kir'yanov AV, Guzmán-Chávez AD, Cruz José-Luis, Andrés Miguel V. Excited-state absorption in Erbium-doped silica fiber with simultaneous excitation at 977 and 1531 nm. J Appl Phys 2009;106:083108.
[16] Kir'yanov AV, Barmenkov YO, Guzmán-Chávez AD. Er^{3+} excited-state absorption in an Erbium-doped silica fiber at the wavelengths 1490–1580 and 978 nm. Laser Phys 2008;18(11):1251–6.