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Broadband superluminescent erbium source with multiwave pumping

Andrey B. Petrov [a,b,*], Regina Gumenyuk [c], Mikhail S. Alimbekov [d], Pavel E. Zhelezov [d], Nikita E. Kikilich [a,b], Artem S. Aleynik [a,b], Igor K. Meshkovsky [a,b], Konstantin M. Golant [e], Yuri K. Chamorovskii [e], Maxim Odnoblyudov [f], Valery Filippov [f,g]

[a] *Saint-Petersburg National Research University of Information Technologies, Mechanics and Optics, Russia*
[b] *Light Guide Photonics Institute, Kronverkskiy pr. 49, Saint-Petersburg, 197101, Russia*
[c] *Laboratory of Photonics, Tampere University of Technology, Korkeakoulunkatu 3, FI-33720, Tampere, Finland*
[d] *Technopark "Mordovia", Lodygina 3, 430034, Saransk, Russia*
[e] *Kotel'nikov Institute of Radio Engineering and Electronics, Mokhovaya 11, bld.7, 125009 Moscow, Russia*
[f] *Peter the Great St. Petersburg Polytechnical University, Polytechnicheskaya ul.29, 195251 St. Petersburg, Russia*
[g] *Ampliconyx Ltd., Lautakatonkatu 18, FI-33580, Tampere, Finland*

A R T I C L E I N F O

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A B S T R A C T

We demonstrate the superbroad luminescence source based on pure Er-doped fiber and two wavelength-pumping scheme. This source is capable to provide over 80 nm of spectrum bandwidth with flat spectrum shape close to Gaussian distribution. The corresponding coherence and decoherence lengths were as small as 7 μm and 85 μm, correspondingly. The parameters of Er-doped fiber luminescence source were explored theoretically and experimentally.

1. Introduction

The broadband superluminescent optical sources (SFS) are necessary for high-precision fiber-optic gyroscopes (FOGs) production of navigation accuracy class, which is a sensor of angular velocity in inertial space (Sagnac interferometer). FOGs, which are capable of measuring angular velocity at the level of 10^{-2}–10^{-3} °/h, are sensitive to the slightest external and internal disturbances and unstable effects, which leads to parasitic effects. The parasitic effects, which have the greatest influence on a resolution reduction of FOG include: the Rayleigh backscattering [1], the transformation of polarization modes in the optical elements [2], the nonlinear Kerr effect [3], the Shupe effect [4], the stress-induced T-dot effect and the back-reflection at the junction of the optical elements [5]. To minimize these spurious effects, the optical radiation of the SFS must have small coherence and decoherence lengths, which is possible to achieve by increasing of the spectrum width and the approximation of its shape to the Gaussian-shape [6]. The coherence and decoherence lengths are inversely proportional to the spectrum bandwidth according to the following formula [7]:

$$L_c = \sqrt{\frac{2\ln(2)}{\pi n}}\frac{\lambda^2}{\Delta\lambda}, \tag{1}$$

$$L_{dc} = \frac{\lambda^2}{\Delta\lambda_{FWHM}}, \tag{2}$$

where $\Delta\lambda_{FWHM}$ is the full width at the half-maximum of the source intensity spectrum, λ is a wavelength and n is refractive index.

This work is devoted to the design of the erbium doped fiber source (EDFS) with an extremely small coherence and decoherence lengths. EDFS allows to generate optical radiation stable in time with a broadband spectrum, which is close to Gaussian-shape, therefore, these sources have a small coherence length with reported value at the level of 0.8 (less than 1 mm) and decoherence at the level of 0.03 [8].

Accordingly, using EDFS as a broadband source in the FOG allows to reduce the error in the output signal [9]. Developers and researchers usually increase the width of the spectrum without considering its shape. However, for the FOG interferometer, the shape is also important, as well as decoherence length. For example, in [10], the two-sided pumping scheme was used at 980 nm with a 1530/1550 nm WDM splitter for smoothing the output spectrum. However, the width of the obtained spectrum is only 23 nm, while semiconductor broadband sources allow to obtain a spectrum width of more than 60 nm. In [11], two erbium-doped fibers with different concentrations of erbium were used. Based on the results of the preliminary simulation of the fiber

* Corresponding author.
E-mail address: 79602507133@yandex.ru (A.B. Petrov).

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Table 1
Simulation results.

Pump wavelength, nm	Spectrum width, nm	Central wavelength, nm	Pump power, mW	Fiber length, m
976	37.5	1530.74	2.3	4
1534	37–38	1572	100–300	20.5–23.5
976 + 1534	75	1557–1595	60–90	18–25

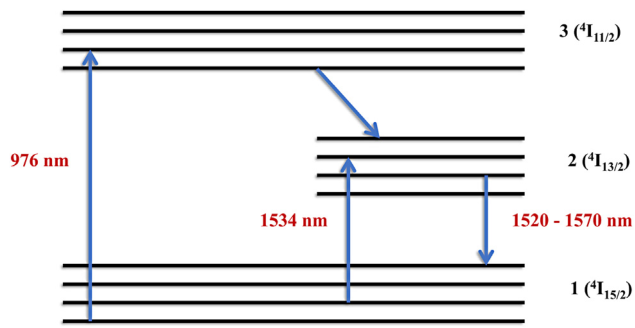

Fig. 1. Three-level diagram of Er ions in Er:glass fiber.

length and pump power, a spectral width of 65 nm was achieved. Pumping was carried out at a wavelength of 980 nm in the forward and backward directions. However, the coherence length of the obtained spectrum is too large.

Another configuration of the broad EDFS source was presented by W. Huang et al. [12]. In the reported setup erbium doped fiber without pumping was added in front of the WDM splitter. This addition to the EDFS scheme made it possible to increase the efficiency of the source due to the use of inverse radiation of amplified spontaneous emission (ASE). The width of the spectrum was 52.6 nm.

The currently available methods of achieving of minimum coherence length of EDFA have several disadvantages, which include changing of the shape of the spectrum i.e. increase of its difference from the Gaussian-shape by increasing of its width, which creates additional peaks in a function of coherence length, thereby increasing of the decoherence length [7].

In this paper we propose a practical solution of coherence length reducing. This method consists of building of a double-side pumping scheme with two different pump sources based on Yb-free Er-doped fiber. This fiber is well known candidate for long-wavelength gain extension due to the near four-level nature of the energy transition [13]. The first pump source counter-pumps to the energy level $I_{13/2}$ at wavelength 1534 nm, that is greater than the main absorption peak 1530 nm (Fig. 1) [14]. It allows to eliminate the sharp peak of luminescence at the wavelength of 1530 nm and flatten the spectrum. The second pump source cooperate-pumps at the wavelength of 976 nm to the energy level $I_{13/2}$ via the energy level $I_{11/2}$, contributing to the short-wave span of the total spectrum of luminescence in the wavelength span of 1520–1620 nm, assuming that the sufficient amount of fiber. Adjusting the power of the pump sources operated at 976 nm and 1534 nm allows to control the shape and width of the total spectrum of luminescence to achieve a superior spectrum broadening.

2. Modeling

Initially, the proposed EDFS was simulated in the program ≪Gain Master Simulation Tool≫ from company Fibercore. In terms of prototype fiber the fiber Fibercore I-25 (980/125), which has absorption 35–45 dB/m at the wavelength of 1531 nm and numerical aperture 0.23–0.26, was chosen in the model. This fiber had similar characteristics to the fiber used in our experiment.

The simulation results, which revealed the dependence of spectrum bandwidth of amplified spontaneous emission (ASE) on the fiber length and power of pump lasers at the wavelength of 976 nm and 1534 nm separately and simultaneously, are shown in Table 1. The pump power level was chosen at such rate to reach the maximum of the desired characteristics (spectrum width and spectrum flatness) in the particular fiber length. The Fig. 2 shows the simulation spectra in the case of two wavelengths pumping scheme for different active fiber lengths and the maximum spectrum bandwidth approaches the value about 75 nm.

From the simulation data we can make a conclusion that in order to achieve broadband and smooth spectrum of EDFS it is necessary to use simultaneously two pump sources at the wavelengths 976 and 1534 nm.

3. Materials and methods

In the experiment we have examined two types of specially developed Yb-free Er-doped fibers fabricated and supplied by Kotel'nikov Institute of Radio Engineering and Electronics (Russian Academy of Science, Moscow). These Er-doped alumina–silica-core/pure-silica cladding fibers were drawn from preforms synthesized by the SPCVD process [15] (and references therein). The fibers had standard 125 μm outer diameters and were polymer coated.

The only difference in design between two fiber samples is various Er contents in the core glass and as a consequence different absorption coefficients at 976 nm pump wavelength Absorption spectra of the fibers are presented in Fig. 3. The absorption coefficients of type 1 (Er15) and type 2 (Er100) fibers at 976 nm wavelength amount to 15 dB/m and 100 dB/m respectively. The core diameter of Er15 is 11 μm, and cut-off wavelength is 1325 nm. Whereas, Er100 is characterized by 7 μm of the core and cut-off wavelength at 1350 nm.

The choice of Yb-free Er-doped fibers was determined by the near four-level nature of the energy transition encouraged by the efficient resonance pumping at 1530 nm [16]. Excitation at 1530 nm stimulates the electronic transitions between the lower-lying energy levels of the excited manifolds $I_{13/2}$ and upper sub-levels of the Stark manifolds $I_{15/2}$. This results in incorporation of more energy level transitions, what positively affects on the spectrum broadening.

4. Experiment

To investigate luminescence properties of the active fibers we consider the several setups with different pumping schemes similar, which were used in the simulation (Fig. 4): short-wavelength, long-wavelength and dual-wavelength pumping schemes. The short-wavelength pumping scheme includes 976 nm single-mode pump laser diode (PLD) with maximum pump power of 200 mW (Fig. 4a). The 976 nm laser diode pumps Er-doped fiber via wavelength division multiplexer (WDM). One port of WDM is used as output port (output backward), another is covered by antireflection gel (AR gel). The in-line fiber pigtailed isolator prevents back reflection from the forward output port and eliminates lasing. Long-wavelength pumping scheme incorporates by tunable 1534 nm laser (NKT Photonics), which directly pumps Er-doped fiber without any dichroic mirror (Fig. 4b). This scheme does not required isolator since the lasing threshold was not achieved. The third scheme is dual-pumping shown in Fig. 4c. It combines short- and long-wavelength-pumping setups. The tunable NKT Photonics laser at 1534 nm is used for cooperate-pumping, and the PLD at 976 nm is used for counter-pumping. The length of the active fiber is chosen to optimize spectrum width and varies in the different schemes.

The results obtained in short-wavelength pumping scheme for Er15 and Er100 are shown in Fig. 5. The optimum lengths of active fibers