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A PICOSECOND FIBER LASER BASED ON A TAPERED YTTERBIUM FIBER WITH THE LOW BIREFRINGENCE

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Abstract. This paper presents the results of the experimental study of a fiber laser connected according to the MOPA scheme, where a power amplifier was made of an ytterbium double-clad tapered spun fiber with low intrinsic birefringence. A peak output power of 160 kW with the average power of 160 W has been achieved at 1040 nm wavelength, 50 ps pulse duration and its repetition frequency of 20 MHz; the laser beam quality parameter and the mode-spot diameter being 1.15 and 35 μm, respectively. The values of azimuth, ellipticity and degree of polarization of the output radiation were found; their little sensitivity to the pump power was demonstrated. This research was the next important step in the development of high-power picosecond fiber lasers technology.

Keywords: ytterbium spun tapered fiber, picosecond fiber laser, intrinsic birefringence

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ПИКОСЕКУНДНЫЙ ИМПУЛЬСНЫЙ ВОЛОКОННЫЙ ЛАЗЕР НА ОСНОВЕ КОНИЧЕСКОГО ИТТЕРБИЕВОГО ВОЛОКНА С НИЗКИМ СОБСТВЕННЫМ ДВУЛУЧЕПРЕЛОМЛЕНИЕМ

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Аннотация. В работе приведены результаты экспериментального исследования волоконного лазера, построенного по схеме задающего генератора и усилителя мощности, изготовленного из иттербиевого конического spun-волокна с двойной оболочкой и малой величиной собственного двулучепреломления. На длине волны 1040 нм при длительности импульсов 50 пс и частоте повторения 20 МГц достигнута пиковая выходная мощность 160 кВт при средней мощности 160 Вт. Параметр качества лазерного пучка $M^2 = 1{,}15$, диаметр модового пятна – 35 мкм. Определены значения азимута, эллиптичности и степени поляризации выходного излучения и продемонстрирована их слабая зависимость от мощности накачки. Проведенное исследование стало следующим важным шагом в развитии технологии мощных пикосекундных волоконных лазеров.

Ключевые слова: иттербиевое коническое волокно, пикосекундный волоконный лазер, активное spun-волокно, собственное двулучепреломление

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Introduction

The technology of high-power picosecond fiber lasers has been developing rapidly over the past decade [1]. They are widely used in materials processing, medicine and lithography. Such lasers are typically made by the Master Oscillator Power Amplifier scheme (MOPA). Such a scheme includes a master oscillator generating low-power laser pulses with good spatiotemporal coherence, and a chain of optical power amplifiers increasing the pulse energy to the required level.

The main problem limiting the peak output power of such a system is the occurrence of undesirable nonlinear effects in the active fiber of the last amplifier stage. To overcome the limitations imposed by these effects, active optical fibers of special types are used. These include, for example, fibers with large mode area (LMA), low aperture and large spot size (up to 14 μm [2]), microstructured fibers [3], 3C fibers (chirally-coupled-core) [4], anisotropic tapered fibers with large mode area [5]. A characteristic of a high-power fiber laser, which is important for coherent combination or nonlinear wavelength conversion, is stable output polarization.

The most common technical solution available for overcoming these limitations are fibers with large intrinsic anisotropy [6]. However, while this approach is successful for passive fibers, a number of negative phenomena begin to arise in the case of active fibers. When exciting radiation is pumped into the cladding, part of it is absorbed and heats the fiber (the so-called quantum defect), leading to a change in internal stresses in the fiber and unpredictable distortions of its birefringence [7, 8]. As a result, the polarization state of laser radiation changes.

To solve this problem, it was proposed to use active fiber with small intrinsic birefringence [9], namely, a spun fiber, for which this parameter is usually about 10^{-8} rad/m.

The first picosecond lasers with an average output power of up to 70 W and mode field diameter of 26 μm, built according by the MOPE scheme, were experimentally studied in [9–12], using spun fiber as the last amplifier. Using spun fiber with spin pitch from 7.5 to 30 mm made it possible to obtain the output polarization that was an order of magnitude more stable than in the case of active optical fibers with large intrinsic anisotropy.

Furthermore, it was found in [10, 11] that the state of polarization of light at the output of active tapered fiber with strong anisotropy significantly depends on the power of the pump radiation injected into the cladding. The authors of these papers observed a significant drift in the polarization state of radiation at the output of an amplifier with a PANDA-type tapered fiber (a customized polarization-maintaining fiber). The ellipticity and azimuth of the fiber changed by tens of degrees even at the input pump power of 20 W. At the same time, high stability of output polarization was demonstrated in [11] for an amplifier with spun fiber with low intrinsic birefringence at the same input pump power of 20 W, without any measures to stabilize the temperature of the fiber.

Our study is aimed at further developing the technology of high-power picosecond fiber lasers using active tapered fiber with small intrinsic birefringence as the last amplifier stage. The article is aimed at increasing the peak and average radiation power in this type of laser, also considering its polarization characteristics and their dependence on the power of the injected pump radiation and its operating time.

Spun tapered double-clad fiber (sT-DCF)

We used sT-DCF fibers in the experiments, manufactured at the Fryazino Branch of the Kotelnikov Institute of Radioengineering and Electronics of the Russian Academy of Sciences (Fryazino, Moscow Oblast, Russia) [9]. The optical fibers were drawn from a preform doped with ytterbium ions Yb^{3+}, which had a step-index core, using a technology similar to that used for spun passive [13] and active tapered [9–13] fibers. During the extraction process, the workpiece was fed into a high-temperature furnace at a speed variable in time according to a given law, which was necessary to form an optimal longitudinal profile [14]. The profile of the fiber prepared is shown in Fig. 1. The angular rotation velocity of the preform was also varied during fiber drawing in the range of 200–300 rpm.

The ratio of the diameters of the core, the first and the second claddings was 1.0:12.7:15.9, and the numerical apertures of the shells were 0.13 and 0.27, respectively. The in-core absorption was 850 dB/m at a wavelength of 976 nm. Two segments were cut off from the first cladding, which made it possible to reduce the proportion of helical modes that do not pass through the core of the fiber. A photograph of the wide end of the fiber is also shown in Fig. 1. Note that this is a standard method for increasing pump absorption in active fibers [15].

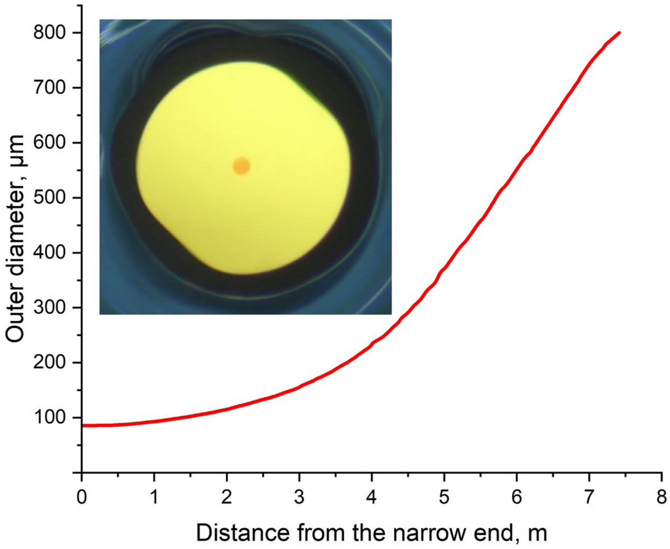

Fig. 1. Profile of fiber considered. Graph of variation in diameter of second cladding along the length of sT-DCF fiber is given.
Inset: photograph of wide end of the fiber

Thus, the diameter of the outer glass cladding changed smoothly from 85 to 800 μm, and the diameter of the core from 5.3 to 50.3 μm, so that only the fundamental mode was excited in the narrow end of the tapered fiber. The total length of the fiber was 7.5 m, the spin pitch was 30 mm. A reflective coating with a low refractive index (numerical aperture of 0.53) was applied to the outer surface of the fiber, with a protective acrylate coating then applied over it.

The value of intrinsic birefringence (the difference in the propagation constants of eigenmodes) for this sT-DCF fiber was

$1.45\cdot10^{-8}$ rad/m; the latter was determined experimentally by the Jones method [11, 16–18].

Experimental setup

A prototype of a fiber laser was assembled by the MOPA scheme, using the prepared optical fibers as the gain medium of the last amplifier stage (Fig. 2).

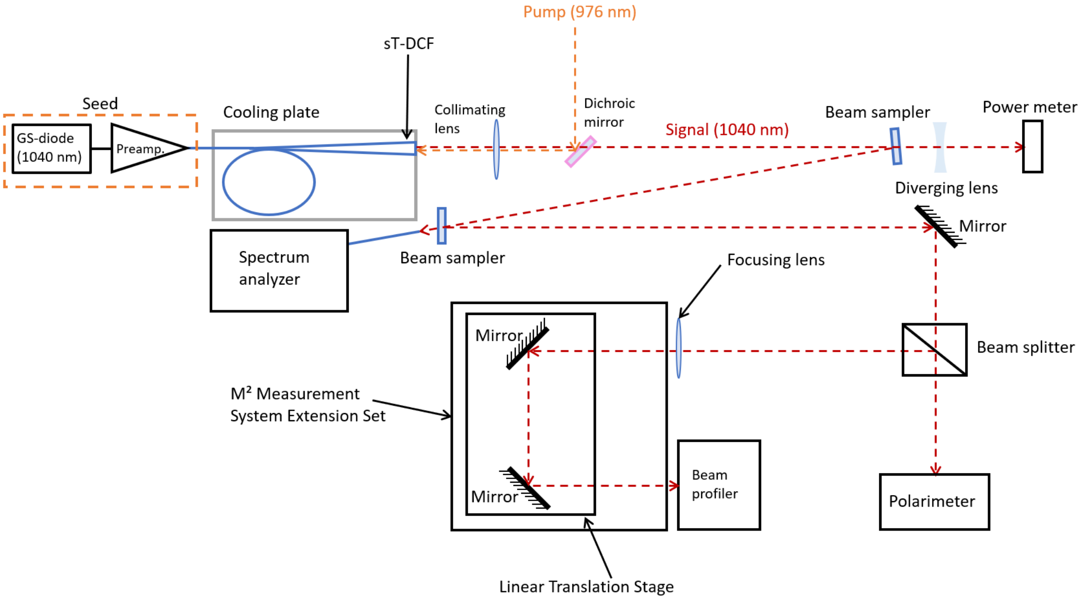

Fig. 2. Layout of fiber laser prototype for studying the parameters of its radiation

A commercially available laser diode with a fiber output (GS-diode) was used as the master source, emitting linearly polarized light with a wavelength of 1040 nm; the repetition rate of 50 ps pulses was equal to 20 MHz. Radiation with a power of about 1 MW was pre-amplified to an average power of about 100 MW while maintaining a spectral linewidth of 50 pm (Fig. 3), after which it was injected into the core of the narrow end of the active sT-DCF.

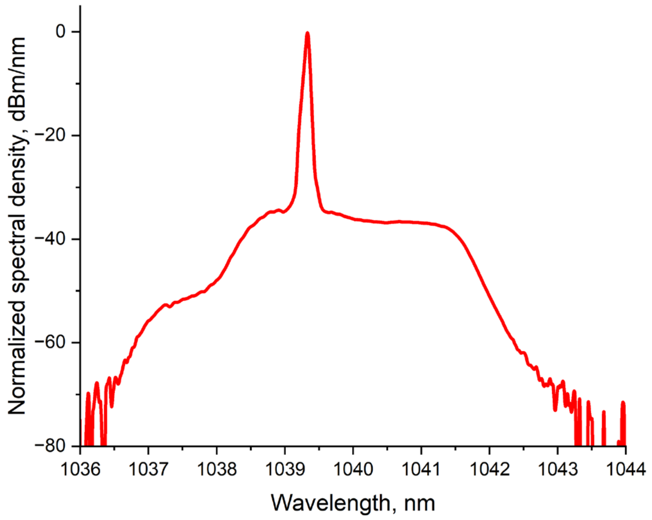

Fig. 3. Spectral density of master laser emission

The active fiber was pumped using a system of two laser diodes emitting at a wavelength of 976 nm and combined by means of a fused fiber-optic coupler. Pump radiation was injected into the cladding of the wide end of the fiber using a dichroic mirror and an aspherical lens. The entire active fiber was located on a special cooled plate so as to reduce the temperature gradient inside the gain medium and avoid thermal damage to the fiber.

The output power, radiation spectrum, beam quality and polarization characteristics of radiation (degree of polarization, ellipticity and azimuth) were constantly monitored during the laser's operation. The Ophir L1500W-SH power meter (Ophir Optronics, Israel), Ando optical spectrum analyzer (AAATesters, USA), Thorlabs M2MS-BC106VIS/M beam analyzer and

Thorlabs PAX1000IR2/M polarimeter (Thorlabs, USA) were used. If it was necessary to measure the divergence of the output beam, the focusing lens in front of the entrance slit of the beam analyzer was removed. The maximum range of displacements of the linear translation stage located inside the analyzer was 100 mm.

Experimental results

The gain parameters of MOPA. Fig. 4 shows the dependence of the output power of the fiber laser on the pump power injected into the wide end of the active spun fiber. The efficiency of the pump radiation conversion of the amplifier we manufactured reached 63%. The average output power in pulse mode (duration of 50 ps, repetition rate of 20 MHz) was 160 W for an input pump power of 270 W, the peak output power was 160 kW.

The average power was limited solely by the available pump power. The conversion efficiency did not decrease with increasing pump power.

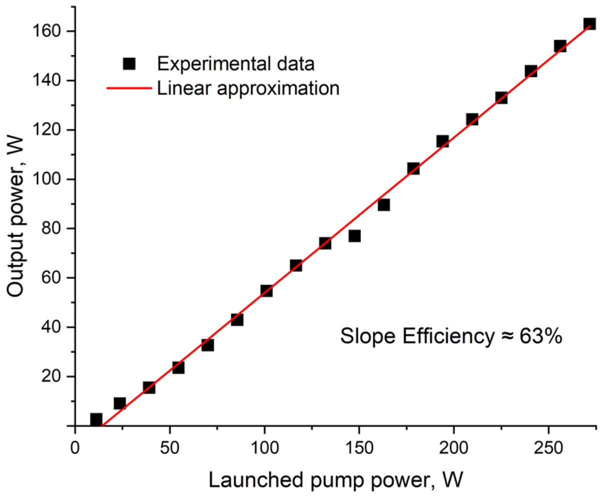

Fig. 4. Experimental dependence of average output power of amplifier (fiber laser) (symbols) on pump power and its linear approximation (solid red line)

The mode field diameter (MFD) was determined by measuring the divergence of the output beam, using the following ratio for the diffraction-limited divergence [19]:

$$\mathrm{MFD} = 4\lambda / \pi\Theta, \tag{1}$$

where λ is the wavelength, Θ is the divergence of the beam.

The measured MFD for the used tapered spun fiber was 35 μm.

The laser radiation spectra obtained at different amplified signal powers are shown in Fig. 5. As follows from the experimental results, the contribution made by radiation outside the spectral range of the master laser increases with an increase in the output signal power. It is caused by self-phase modulation and four-wave mixing.

We studied the shape of the caustics, as well as its cross sections in the near and far fields (Fig. 6). The above results, as well as the high beam quality ($M^2 < 1.3$) (Fig. 7) indicate the predominance of the fundamental mode inside the active tapered fiber.

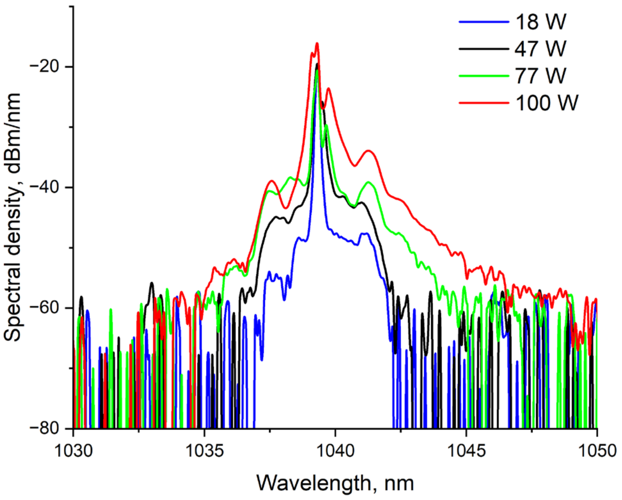

Fig. 5. Laser emission spectra at different values of average output power of amplified signal

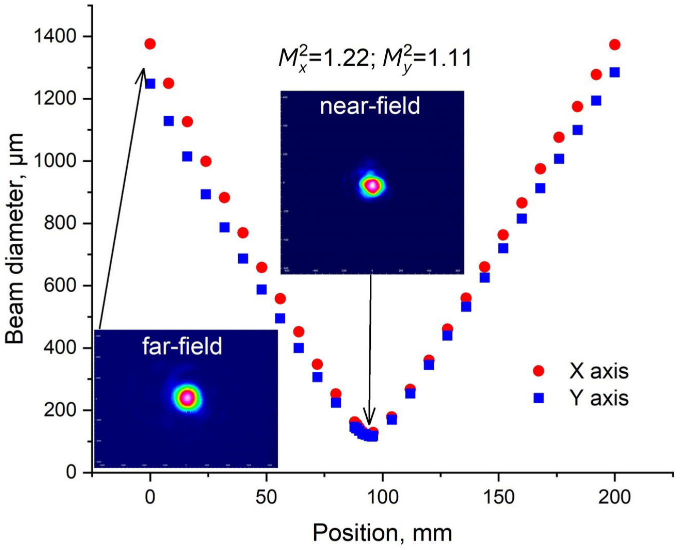

Fig. 6. Dependences of mode field diameter (measured by the 4-sigma method (ISO Standard)) on distances along two axes between the focusing lens and the beam analyzer.
Insets: photographs of the far and near fields

Polarization state of output radiation. The polarization states of laser radiation at different output power levels are shown on the Poincarй sphere (Fig. 8). Similar analysis was carried out in [10, 11] but for small values (25 W) of the pump power injected into cladding shell of active tapered spun fiber. Pump radiation with a power of up to 270 W was injected in this study, causing changes in the polarization state with an increase in output radiation power.

To study the long-term stability of the polarization state at the output of the amplifier with spun fiber, we conducted a two-hour test at constant output power of 125 W (Fig. 9).

The standard deviation for azimuth, ellipticity and degree of polarization was approximately 0.4°, 0.5° and 1.5%, respectively. This result indicates a high temporal stability of the polarization state of the amplifier considered. The smooth change in the dependences, only amounting to a few degrees, is caused by the instability of water temperature cooling the fiber during the experiment.

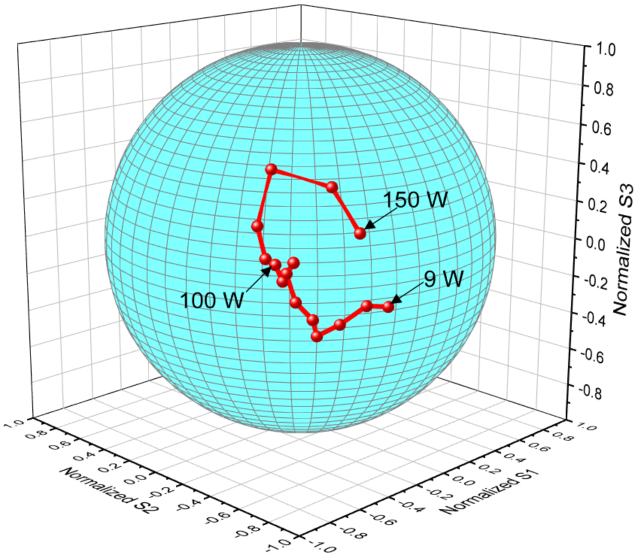

Fig. 8. Representation of polarization states of output radiation at different power levels on the Poincaré sphere

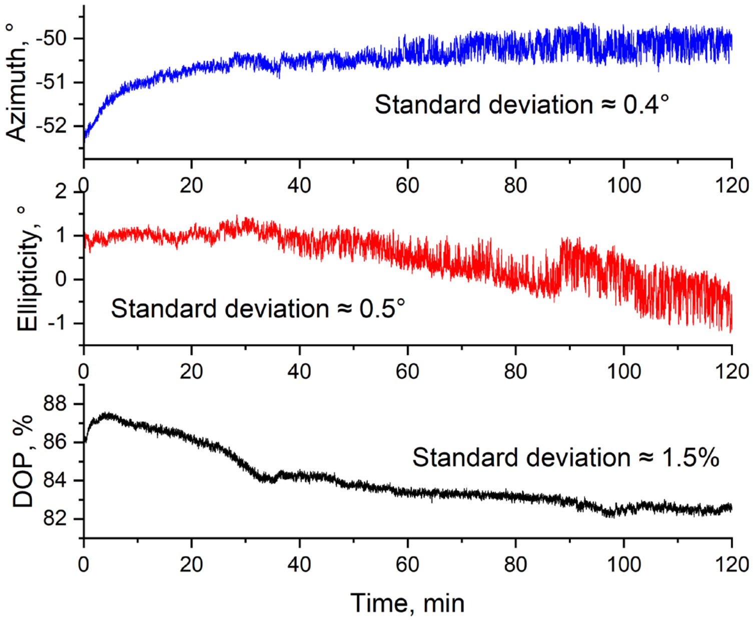

Fig. 9. Results of two-hour test for polarization characteristics of output radiation of amplifier with active tapered spun fiber.
Drifts are shown for azimuth (upper graph), ellipticity (central graph) and degree of polarization (lower graph).
Signal power during the experiment was 125 W

Discussion and conclusions

We considered double-clad active tapered ytterbium-doped spun fiber with low intrinsic birefringence ($1.45 \cdot 10^{-8}$ rad/m) with large mode field diameter (35 μm). The longitudinal change in the core diameter is an effective measure for suppressing stimulated Mandelstam–Brillouin scattering [20]. The large spot size makes it possible to increase the threshold for Raman scattering. Thanks to the appropriately selected geometry of the fiber, namely, the variable diameter along its length and large diameter of the core at the wide end, using an active tapered fiber in a power amplifier allowed to significantly increase the threshold for the appearance of nonlinear effects and achieve simultaneously high values of both average and peak output power. The low intrinsic birefringence of the tapered spun fiber ensured high stability of the output state of polarization with varying pump power.

As a result of the conducted study, we presented a fiber laser based on active tapered spun fiber, designed by the MOPA scheme, generating radiation with a peak power of 160 kW at a wavelength of 1040 nm, an average output power of 160 W in pulsed mode and an output beam quality of $M^2 \approx 1.15$. The linewidth at the level of −3 dB was about 0.2 nm with an average output power of 100 W with an optical pulse duration of 50 ps and a pulse repetition rate of 20 MHz.

It is important to note that one of the significant results of this study, compared with those published earlier (see, for example, [9–12]), is that stable polarization of output radiation was achieved for a powerful (160 W) amplifier with active fiber. Moreover, the dependence of output polarization state on the injected pump power was obtained at pump power values significantly higher than in [9–12], up to 270 W. In addition, the dependences of fiber parameters such as azimuth and ellipticity on the injected pump power were experimentally recorded.

The conducted study takes the next important step in the development of high-power picosecond fiber laser technology.

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