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Investigation of heating of silica optical fibers with metal spiral by laser radiation transmitted in the core

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The thermo-optical properties of passive silica optical fibers with a metal spiral applied on their lateral polymer surface are investigated. It is shown that the heating of these optical fibers by transmitted laser radiation due to microbending losses causes a change in their temperature and electrical resistance of the metal spiral. Based on this, a simple method for measuring and real-time monitoring the output power of fiber lasers is proposed.

Keywords: fiber lasers, optical fibers, micro-bending losses, fibers with a metal spiral, optical power measurement.

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The output optical power of present-day continuous-wave fiber lasers may reach several hundred kilowatts for a multimode beam [1] and tens of kilowatts for a single-mode beam [2]. Various methods for measurement of laser radiation power at multikilowatt levels are known, but the most commonly used devices are thermal detectors. However, these methods are not suitable for continuous real-time power monitoring, which is often needed in industrial laser applications. One may divert a part of a beam with a splitter for subsequent measurement, although this, in turn, has a negative effect on the quality of the primary beam [3] and leads to uncontrollable power losses.

Ponderomotive methods [4], which are free from this drawback, are hard to implement in practice, and techniques based on the measurement of radiation scattered in fiber-optical devices [5] are inapplicable at high radiation powers due to the excitation of thermal and thermooptical effects in optical fibers.

In our earlier study [6], we have proposed a method for measurement of the power of radiation, which is transmitted along a fiber channel, involving the insertion of a sensor fiber waveguide with metallic coating into this channel. This technique is suitable for continuous measurement of the optical power of laser radiation, but has certain limitations arising due to the necessity of fine tuning of waveguide parameters, the need to insert a sensor fiber into a fiber channel, and the degradation of mechanical and optical properties of glass in such sensor fibers as a result of diffusion of metal into the bulk of silica glass coated with a metal layer.

Traditional optical fibers with a polymer coating and a metallic spiral wound round it were used in the present study to measure the optical power of fiber lasers. A copper wire 50−70 cm in length was wound tightly by hand in a spiral onto the output optical fiber of a laser radiation source. The wire diameter was 100 μm, and the winding pitch was 0.5−1 mm.

In addition to common loss mechanisms, optical fibers of this type feature bending losses induced by winding [7]. They depend on the bending magnitude and, consequently, on the winding tension. The typical spectrum for fibers with core radius $a = 12\,\mu$m is shown in Fig 1. Radiation escaping form a micro-bend region enters a silica cladding; then, since the overall absorption in a polymer cladding with a thickness of 125 μm is below 0.3% [8], it leaves the fiber and is absorbed by a metallic winding, which is heated as a result.

In order to examine the above effect, we determined the temperature of fibers with a metallic winding by measuring its electrical resistance R with a milliohmmeter. In the conditions of our experiment, this resistance depends

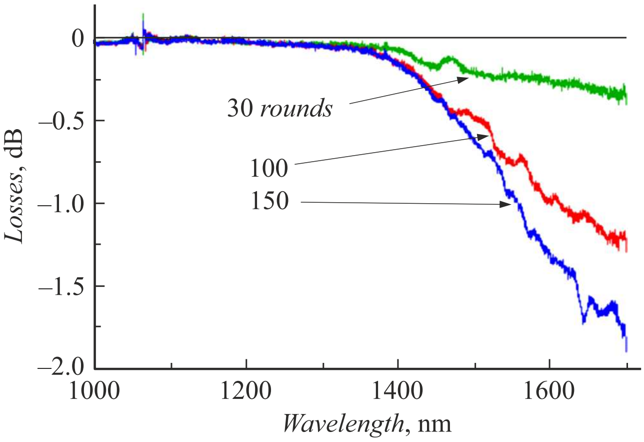

Figure 1. Spectrum of micro-bending losses in an SM fiber with a metallic winding with 30, 100, and 150 turns. Features in the region of 1070 nm are attributable to the instability of the emission spectrum of a source.

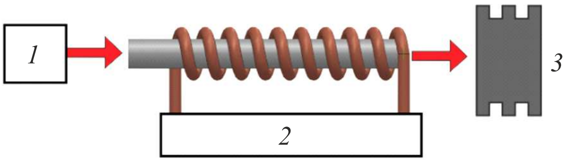

Figure 2. Schematic diagram of the experimental setup. *1* — Laser source, *2* — milliohmmeter, *3* — thermal power meter for monitoring of transmitted radiation.

linearly on temperature:

$$R = R_0\left(1 + \alpha_t \Delta T(\Delta l/l)\right).$$

Here, α_t is the thermal resistance coefficient of the metal, ΔT is the spiral temperature increment, and l and Δl are the entire length of the metal wire and the length of its wound part, respectively.

Semiconductor laser diodes with a central wavelength of 975 nm and a fiber coupler were used as a laser source in the examination of multimode (MM, $a = 300\,\mu$m, NA $= 0.22$) fibers. Single-mode (SM, $a = 12\,\mu$m) fibers were studied using a continuous-wave fiber laser with an output power up to 200 W, random polarization, and a central wavelength of 1064 nm. The schematic diagram of the experimental setup is shown in Fig. 2.

Experiments with a wire coated with a thin carbon layer, which enhances the absorption of laser radiation, and with an uncoated wire were carried out in order to determine the contribution of different loss mechanisms. The dependence of fiber heating on the power of transmitted radiation is presented in Fig. 3.

We assume that the attenuation of optical radiation in an optical fiber with a metallic spiral is governed by Bouguer law $P(z) = P_0 \exp(-\alpha z)$. Analyzing the fiber heating, one may determine radiation loss coefficient α.

When micro-bending losses occur, thermal power is released in a metallic spiral that absorbs the escaping radiation. In the general case, the spatial distribution of temperature in the studied fiber with a metallic spiral adheres to the unsteady thermal-conductivity equation with boundary conditions corresponding to convective heat exchange with the environment (Newton–Richmann law) and the fiber–winding heat exchange.

However, assuming that the Biot number for a fiber with a metallic spiral is small, we neglect the temperature distribution within it. The process of heating is then characterized by balance equation

$$P_{gener} = P_{dissip}.$$

Let P be the transmitted optical power; N be the number of winding turns; D be the copper wire diameter; L be the length of the studied fiber section; R_t be thermal resistance of the fiber (ratio of the temperature drop at the fiber–air interface to the thermal flux through it), which is determined by the kinetics of its cooling; and ΔT be the fiber temperature increment. Under steady-state conditions, convective heat dissipation power P_{dissip} is equal to thermal power P_{gener} generated in the metallic spiral. The latter depends on scattered radiation power $P\alpha L$ and fraction ND/L of scattered radiation reaching the metallic spiral and absorbed by it. Thus, we obtain

$$P\alpha ND = \Delta T/R_t.$$

It follows that the radiation loss coefficient is 0.45 and 0.7 dB/m for SM and MM fibers, respectively. A considerable deviation from the coefficients for traditional optical fibers is attributable to the contribution of micro-bending losses (see above). For an SM fiber, a loss of 0.054 dB per 100 turns is comparable to the data from Fig. 1 (with the sensitivity of an optical spectrum analyzer and the difference between windings taken into account).

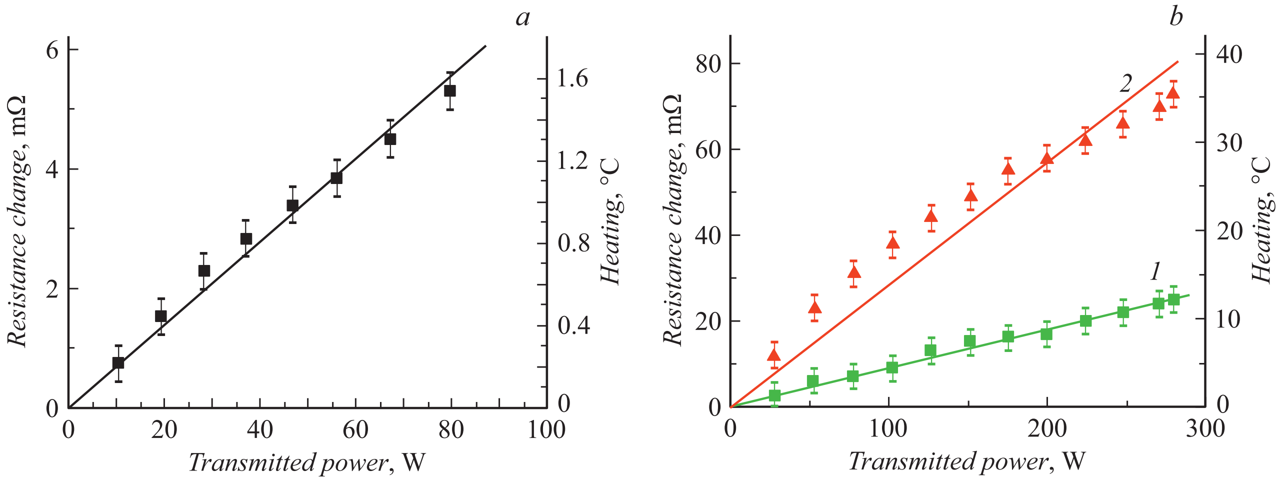

Figure 3. Dependences of the electrical resistance of a spiral and the increment of its temperature on transmitted power in an SM fiber with a carbon-coated spiral (*a*) and an MM fiber (*1* — uncoated spiral, *2* — carbon-coated spiral) (*b*). Deviations from linear dependences are probably caused by deviations from the Newton–Richmann law due to strong fiber heating.

The obtained results demonstrate the potential to measure the output radiation power of fiber lasers without any beam distortion and significant power losses. Therefore, these measurements may be performed in real time as part of a process flow.

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Conflict of interest

The authors declare that they have no conflict of interest.

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