Temperature of Optical Discharge under Action of Laser Radiation in Silica-Based Fibers

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Abstract For the first time the temperature of optical discharge was measured for a wide range of laser radiation powers. For 40W laser power the temperature reached 10⁴K, velocity of discharge propagation having increased to 10m/s.

Although the process of optical discharge propagation through the fiber under the action of laser radiation (also known as fiber fuse effect) was observed for the first time in 1987 [1], only recently the first time-resolved pictures of this process were obtained [2, 3]. High-speed photography of the discharge region showed that the shape of the plasma volume varies essentially with the power of laser radiation in the fiber. Apparently, other parameters of the discharge, such as temperature, also depend on the power of discharge maintaining radiation. The only experimental estimation of the temperature of optical discharge plasma in a fiber (to the best of our knowledge) has been performed so far in [4], where the temperature was estimated by measurement of the discharge plasma radiation spectrum. Although the radiation spectrum was essentially different from that of a blackbody, the blackbody approximation was used to evaluate the temperature, which turned out to be ~5400 K.

In this paper, measurements of discharge temperature at laser radiation powers in the range of 2 to 40 W have been carried out. Also the velocities of discharge propagation have been measured under the same conditions.

The optical discharge was driven by a CW ytterbium fiber laser with maximum output power of 100 W at the wavelength of 1072 nm. The measurement scheme is represented in Fig.1. The fiber under investigation was spliced to the laser output end, the discharge was initiated by a contact of the cleaved fiber end with a metal surface.

In all single-mode fibers under investigation the core consisted of fused silica doped with germanium dioxide. The doping level was different and mode field diameter (MFD) of laser radiation amounted to 4.0 µm (fiber 1) and 5.75 µm (fiber 2).

For temperature measurements the spectrometer USB2000 (Ocean Optics, Inc.) was used. Plasma radiation spectrum was investigated in the range of 300-1000 nm with spectral resolution of 10 nm.

Fig. 1 Top: schematic of the experiment. 1-fiber under investigation, 2-Yb fiber laser, 3,4-fiber Bragg gratings, 5-splicing points, 6-pump input, 7-spectral filters, 8-spectrometer. Bottom: picture of optical discharge propagating through the fiber. 1-most heated head part of discharge, 2- colder tail part. The optical discharge propagates from the left to the right.

In order to measure temperature of the hottest, head part (Fig.1) of optical discharge, we recorded the spectrum of plasma radiation propagating through the optical fiber towards laser source (in the same direction as the optical discharge itself does). In this case the radiation of colder plasma parts is screened by the hot plasma region. The detected plasma radiation propagated through the investigated fiber, then through the resonator of the fiber laser, and then went out of the fiber behind the high reflection Bragg grating 3 (Fig.1). Optical filters were placed in front of the spectrophotometer preventing laser pump radiation (<X=975 nm) and laser radiation itself (<X=1072 nm) from being launched into the spectrometer.

For the purpose of calibration, the radiation of a tungsten strip filament lamp of known temperature (3100 K) and emissivity was launched into the fiber under investigation and recorded by spectrometer 8 (Fig.1).

Typical shapes of plasmas spectra corrected for transmission and sensitivity of the recording channel are presented in Fig.2. In all experiments, throughout the entire range of laser radiation powers, and for both fiber types the radiation of optical discharge plasmas represented a continuous spectrum, with the shape very similar to that of a blackbody.
Fig. 2 Spectra of plasma radiation (solid lines). 1—P=38 W, fiber 1, T=10500K; 2—P=9 W, fiber 1, T=7900K; 3—P=3 W, fiber 2, T=4700K. Dashed lines—calculated blackbody spectra for corresponding temperatures.

Fig. 3 The variations of temperature (circles) and velocity of optical discharge (squares) as functions of the laser radiation intensity in the core of fiber 1 (black) and fiber 2 (gray).

We assumed the plasma temperature to be equal to the temperature of a blackbody with radiation spectrum closest to that of the plasma in the 500-800 nm range. The results of measurements of plasma temperature in optical fibers for different powers of laser radiation in the range of 2-40 W are presented in Fig. 3. The velocities of discharge propagation through the fiber, measured in the same experiments, are also presented. The measured values of temperature and velocity are plotted against laser radiation intensity averaged over mode field diameter, for radiation intensity is the value determining interaction processes of radiation with matter.

Even though the velocity data points in Fig. 3 correspond to the two different fibers, all the points almost fit one curve. The plasma temperature values are different for different fibers at the same intensity levels: the measured temperature is higher in the fiber with a smaller MFD for high enough laser intensities. This points to the presence of other parameters determining the value of plasma temperature.

In our experiments we used fibers of about 10 m long as objects of investigation. At laser radiation power level of about 40 W a Raman generation occurred in the scheme (owing to small MFD values of the fibers investigated), which set the upper limit for the range of laser radiation intensities in our experiments. Note, that the average value of intensity, indicated in Fig. 3, is approximately 2 times lower than the maximum value at the axis of the fiber (it is precisely so for modes with Gauss-distributed intensity). The experimentally obtained relation between discharge propagation velocity and plasma temperature (Fig. 4) can be used for theoretical modeling of the process.

Fig. 4 The variations of optical discharge velocity with the temperature of the discharge plasma for both types of fibers.

Conclusions
It has been shown experimentally, that the spectrum of plasma radiation of an optical discharge propagating through a silica-based fiber is close to that of a blackbody. The temperature of the plasma has been measured for various laser radiation powers in the range of 2-40 W (corresponding intensity range: 6÷300 MW/cm²) by investigating its spectrum. Plasma temperature increases steadily with the power of laser radiation launched into the fiber, and reaches 10⁴ K in the fiber with MFD=4 µm at 40 W laser power. Measured simultaneously with temperatures, the velocities of discharge propagation provide initial data for the analysis of the physical mechanisms of discharge propagation.

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