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A joint scientific session of the Physical Sciences Division of the Russian Academy of Sciences and the Joint Physical Society of the Russian Federation was held in the Conference Hall of the P N Lebedev Physics Institute, Russian Academy of Sciences, on 29 September 2004. The following reports were presented at the session:

(1) **Dianov E M, Bufetov I A** (Research Center of Fiber Optics at the A M Prokhorov Institute of General Physics, Russian Academy of Sciences, Moscow) "Fiber laser as a new breakthrough in laser physics";

(2) **I A Bufetov, E M Dianov** (Research Center of Fiber Optics at the A M Prokhorov Institute of General Physics, Russian Academy of Sciences, Moscow) "Optical discharge in optical fibers".

An abridged version of the second report is given below.

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Optical discharge in optical fibers

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The increase in the transmission efficiency of fiber-optical communication lines inevitably leads to a higher power of radiation propagating along a single optical fiber. Large number of communication channels transmitted through a single fiber, the high output power of optical amplifiers, which is required for increasing the distance between them, and utilization of erbium or Raman amplifiers of the fiber-laser radiation result in the increase of radiation power in optical fibers up to 1 W. Much higher radiation power (>1000 W) is obtained in CW fiber lasers that are used in other technical applications, in particular, in material processing. In this case, the intensity of laser radiation in the core of a single-mode optical fiber reaches values of $\sim(10^7-10^8)$ W cm^{-2} and greater .

At so high an intensity, nonlinear optical effects such as stimulated Mandelstam – Brillouin scattering or four-wave mixing may limit the possibilities of fiber-optical systems. However, there is one more effect that evidently limits the operation of optical fibers, namely, the destruction of an optical fiber under the action of optical radiation with an intensity of $\gtrsim 1$ MW cm^{-2}, provided that the process was preliminarily initiated. In the English literature, this effect is termed catastrophic damage or the fuse-effect. Indeed, the destruction of an optical fiber under the action of CW laser radiation is similar to the burning of Bickford's fuse. The term 'burning' turns out to reflect some substantial features of the process.

The first report on the destruction of single-mode silica-based optical fibers under the action of optical radiation dates back to 1987 [1]. The phenomenon is represented in Fig. 1. If laser radiation with a power on the order of 1 W is injected into a single-mode optical fiber, then under certain conditions (i.e., upon being initiated) a domain of ~ 1 μm size with bright white or blue luminescence (a small 'star') arises in the fiber core. The domain moves along the fiber towards the laser beam at a velocity of ~ 1 m s^{-1}. The temperature of the 'star' estimated from its luminescence spectrum [2] is approximately 5400 K. This estimate is probably rough; taking into account the discharge color, the actual temperature may be substantially higher.

In most cases, cavities or bubbles arise in the fiber core after the passage of the 'star'. The typical size of the cavities is a few micrometers. They can form a periodic structure along the optical fiber (see Fig. 1) or merge into a single long capillary. The waveguide properties of the fiber are totally broken in this case. Thus, long fiber segments may be destroyed. If no measures are taken after the initiation, then the whole segment of the optical fiber from the initial point to the laser will be destroyed, which may cover meters or kilometers in length.

To maintain this phenomenon, a laser radiation power of only about 1 W is sufficient. The process can be initiated in

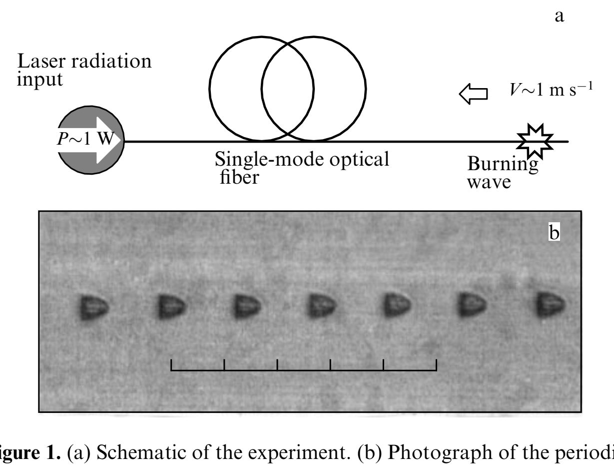

Figure 1. (a) Schematic of the experiment. (b) Photograph of the periodic cavity structure in the fiber core (LEAF optical fiber, Corning) caused by the radiation of a Nd:YAG laser with a wavelength of 1.06 μm and an output power of 4.2 W. The radiation propagates from left to right. The scale is 10 μm per division.

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various ways, for example, due to the dirt on the fiber face, the contact of the fiber end with a metal surface, or heating a piece of the fiber in an electric arc. In any case, a piece of fiber should be heated to a temperature of ~ 1000 K. In the first two initiation methods mentioned above the fiber core is heated by the absorbed laser radiation.

The destruction of optical fibers was studied in a number of papers following [1] (see [3] and review [4]). The following models were used to explain this phenomenon: radiation self-focusing in the fiber core, initiation of a chemical reaction, and the thermal mechanism of propagation [2]. The last mechanism (i.e., the discharge propagation caused by glass heating due to heat conduction) seems to agree with most of the known experimental results.

Up to now, there is no complete satisfactory explanation for cavity formation. We studied this effect in order to clarify its physical origin and determine the range of safe radiation power for operation of optical fibers. In addition, it is interesting to study the conditions of cavity formation in the fiber after the passage of the optical discharge because this effect can be used for modifying the structure of optical fibers.

If the wave is a plasma bunch possessing a temperature of $\sim 10^4$ K and propagating along the optical fiber at a velocity of ~ 1 m s^{-1} under the action of laser radiation, then it is just a slow optical burning wave or, in other words, a wave of subsonic optical discharge, which propagates due to heat-conduction energy transfer. In this case, the pressure in the optical discharge zone should be $\sim 10^4$ bar.

Recently, this fact was experimentally proven, at least qualitatively. Namely, in experiments [5] it was shown that the pressure in the core zone is so high that it can destroy the silica cladding of the optical fiber if this cladding becomes too thin. Once the cladding is destroyed, the propagation of the optical discharge stops, which can be explained by the pressure reduction in the plasma and the corresponding reduction of the absorption coefficient in the optical discharge.

It is this situation that is shown in Fig. 2. For a short (~ 2 mm) segment of a standard optical fiber, the diameter of the fused silica cladding was reduced from the standard value of 125 μm to ~ 30 μm by etching in a solution of hydrofluoric acid. While the optical discharge propagated along the fiber the plasma bunch reached the region with the reduced diameter. In this region, the cladding could not withstand the high pressure and temperature of the plasma, which resulted in the dramatic expansion of the plasma accompanied by the deformation of the silica cladding. Then the propagation of optical discharge stopped. Hence, this is a kind of protective device preserving optical fibers from the optical discharge propagation.

High pressure in the fiber core is also responsible for the 'excessive' volume emerging in this region, which results in the formation of cavities. Under a pressure of $\sim 10^4$ bar plastic deformation of solid glass occurs around the discharge domain and the glass density rises. It is known that the density of fused silica can change from 2.2 g cm^{-3} to 2.6 g cm^{-3} under the action of pressure. In the subsequent cooling, free space is left, which is observed as cavities [1].

In order to determine what factors substantially affect the parameters of fiber destruction under the action of laser radiation, we studied this phenomenon in the widest range of possible experimental conditions. The process was observed in 30 types of optical fibers differing in core material (fused silica doped with various agents: GeO_2, P_2O_5, N_2, Yb_2O_3, Nd_2O_3, Al_2O_3) under the action of radiation at wavelengths of 0.5, 1.06, and 1.48 μm. It was found that the overall picture of damages in an optical fiber depends on the core material and the mode structure of the radiation. The periodical cavity structures are mainly formed in single-mode optical fibers with large mode field diameters (greater than 5 μm) and at a radiation power noticeably exceeding the threshold value. By the threshold conditions we mean the experimental conditions under which the propagation velocity of an optical discharge wave turns to zero, i.e., the discharge stops.

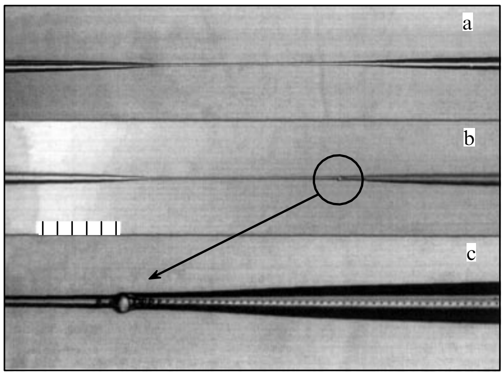

Figure 2. Cone-shaped segment of an optical fiber with a reduced thickness of silica cladding: (a) prior to the passage of the optical discharge and (b) after the passage of the discharge. The scale in (a) and (b) is 0.1 mm per division. In (c), the total frame width corresponds to 1 mm. Laser radiation is directed from left to right. The photographs were obtained without immersion.

In optical fibers with a small mode field diameter (MFD) or at a radiation power close to the threshold value, the cavities look like continuous capillaries with a diameter of ~ 1 μm located along the core axis. If several radiation modes propagate in the fiber, then irregular cavity structures are observed in the core, which often may not even have an axis of symmetry.

Studying the threshold conditions for maintaining the propagation of the destruction wave in single-mode optical fibers and measurements of the destruction wave velocity in such fibers lead us to the following conclusions.

1. The threshold conditions for the propagation of an optical discharge along a single-mode fiber can be formulated in terms of the mode field diameter of the fiber and the average intensity of the laser radiation over this diameter. These conditions are actually independent of the core material and the radiation wavelength.

2. The propagation velocity mainly depends on the intensity of laser radiation in the core and is independent of the core material.

In Fig. 3a, the threshold intensity of laser radiation needed for maintaining the propagation of optical discharge along the fiber is shown as a function of the diameter of the radiation mode field for various single-mode optical fibers and radiation wavelengths. Almost all points fit the same curve, which means that the chemical composition of the core and the radiation wavelength (in the range 1.0 – 1.5 μm) are not crucial in this process. The dependence on MFD can

[1] S I Anisimov called our attention to the fact that a similar phenomenon, albeit in a noticeably smaller scale, was observed for high-energy particles passing through metals [6].

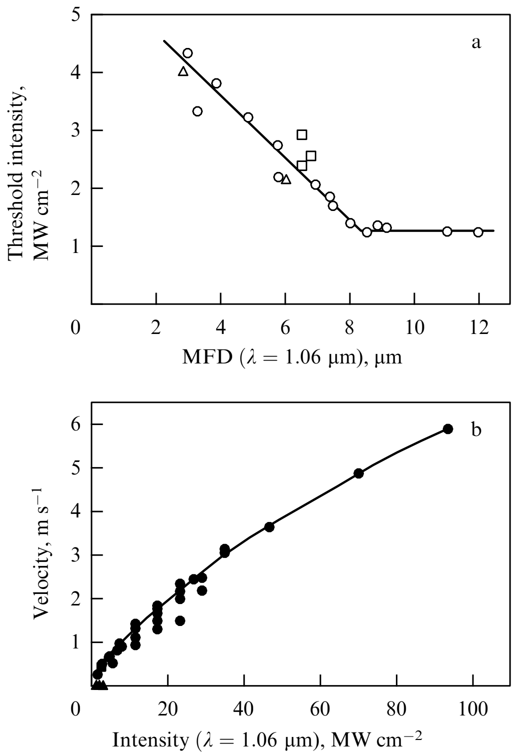

Figure 3. (a) Threshold intensity for optical fibers with (○) germanosilicate, (□) phosphosilicate and (Δ) nitrosilicate core. (b) Propagation velocity of the destruction wave in an optical fiber with a germanosilicate core versus the intensity of laser radiation.

be explained in the following way. At small values of MFD, the heat energy released in the domain near the front of the optical discharge is partly transferred towards the laser radiation due to heat conduction, thus maintaining the discharge propagation. Another part of the heat energy is transferred in the radial direction due to heat conduction and represents the loss of heat from the domain of the discharge front. At larger MFD, the role of losses is lower and at MFD > 8 μm the threshold intensity of discharge propagation stabilizes. Most probably, the threshold intensity ~ 1 MW cm^{-2} near the discharge front is determined by the condition that the absorption coefficient of laser radiation become sufficiently high in the discharge. A purely geometrical consideration yields the absorption coefficient $\sim 1/\mathrm{MFD}$.

The velocity of optical discharge propagation is shown in Fig. 3b versus the average intensity of laser radiation in the fundamental mode of the optical fiber. The experimental points correspond to the radiation wavelength 1.06 μm and three optical fibers with cores made of fused silica doped with various quantities of germanium oxide. The value of MFD in the samples was 4.7, 8.1, and 9.5 μm. Within a certain spread, all the experimental points fit the curve $V \approx 0.2 I^{0.75}$ if the threshold intensity is neglected (here, V is the velocity of propagation in m s^{-1}; I is the average intensity of laser radiation in MW cm^{-2}). The propagation velocity was found to be proportional to the radiation intensity to a power of approximately 3/4, which slightly differs from the dependence $V \sim I^{0.5}$ following from the heat-conduction description of discharge propagation [7].

Despite the importance of this effect for fiber optical communication systems and fiber laser systems, until recently there were actually no observations of optical discharge propagation along optical fibers performed with a sufficient time resolution. Experimental data concerning the relaxation of the heated domain after the passage of the optical discharge were also absent. However, it is namely during the cooling process of the heated domain that the formation of periodic cavities in the fiber core may occur, which is the most impressive feature of the phenomenon. Only recently [8], frame-by-frame recordings of the discharge propagation along an optical fiber were obtained with a time resolution sufficient for estimating the dimension of the domain occupied by the optical discharge plasma. In rapid-series photography, the discharge velocity can be found from a pair of adjacent frames. In experiments [8], it was found that the discharge velocity is constant not only at fiber segments a few dozen centimeters in length, as previous experiments have shown, but also at smaller distances, starting from 10 μm.

A photograph of optical discharge taken with a micro-objective at the exposure of 10 μs is shown in Fig. 4a. Laser radiation propagates from left to right, the radiation wavelength is $\lambda = 1.085$ μm, the radiation power is $P = 5.9$ W, and MFD $= 5.1$ μm. Illuminating the fiber with the second harmonic radiation of a CW neodymium laser one can observe the domain of luminous plasma, as well as optical inhomogeneities near the fiber core after the passage of the discharge. Color filters were chosen in such a way that the optical inhomogeneities were detected in the range of normal exposures. Under these conditions the luminous plasma looks overexposed.

The formation of cavities near the fiber core is observed not later than 20 μs after the passage of the plasma front in the case of output power $P = 1$ W, and not later than 70 μs in the case of $P = 5.9$ W. The discharge domain is followed by a dark domain with an initial diameter of 30 μm, where cavities gradually appear.

The results obtained lead one to the conclusion that the destruction of an optical fiber under the action of laser radiation is similar to the process of subsonic chemical burning and can be considered as a subsonic optical

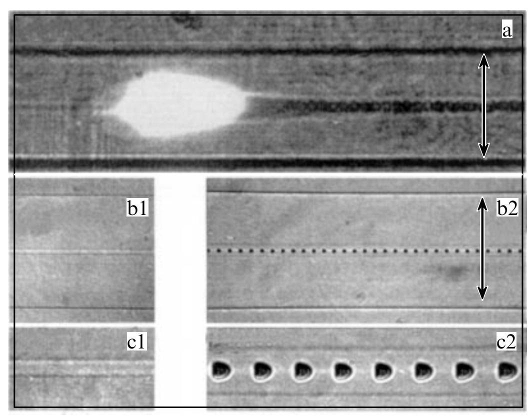

Figure 4. (a) Photograph of the optical discharge propagating along an optical fiber taken with an exposure time of 10 μs. (b) Static photographs of the same optical fiber taken at higher spatial resolution (b1) prior to and (b2) after the passage of the optical discharge. (c) Magnified image of the central part of the same fiber (c1) prior to and (c2) after the passage of the optical discharge. In (c1) one can see the core of the optical fiber, and in (c2) the structure is totally changed. The total frame width in (c1) corresponds to 40 μm and in (c2) it is 90 μ. The arrows in (a) and (b) refer to the diameter of the fiber, equal to 125 μm.

discharge in the fiber core, i.e., as a wave of optical burning. Such phenomena were studied earlier in gases [9] and glasses [10] (in the latter case only under pulsed radiation).

The propagation of the luminous domain along the fiber towards the laser radiation is the motion of a plasma bunch with a temperature on the order of 10^4 K. The principal mechanism for the propagation of the heated domain is the heat conduction, including its radiation component. The absorption of radiation at a length on the order of the diameter of the fiber core occurs in plasma of high density corresponding to the density of solid. After the passage of the discharge wave, the cooling plasma relaxes. Then, condensation and further cooling of the glass material occur. The glass becomes denser in some places (see Fig. 4, c2) and cavities arise in other places as a kind of compensation. In addition, formation of intricately shaped cavities is accompanied by the hydrodynamic motion of melt in the optical fiber. Needless to say that the role of hydrodynamics is not great in this case compared to the case of optical discharge in gases [11]. Still, it was revealed in experiments with bulk glass specimens [10].

Thus, the formation of cavities is directly related to the relaxation of the heated domain rather than to the propagation of the optical discharge wave along the fiber.

In optical fibers with a high value of Δn, the power needed to maintain the propagation of optical discharge may be lower than 300 mW at the wavelength $\lambda = 1.06$ μm and lower than 100 mW at the wavelength $\lambda = 0.5$ μm, which is dangerous for optical fibers. However, these are the threshold intensities for maintaining the optical discharge. It is implied that the discharge has been somehow initiated in the optical fiber. All the initiation methods described so far substantially differ from ordinary operating conditions for optical fibers. Without a special initiation of optical discharge, optical fibers are capable of transmitting CW laser radiation with a power density up to $(2-5) \times 10^9$ W cm^{-2} [12] and a total power in the fiber of ~ 1 kW. The threshold power values considered in this paper are needed for maintaining the propagation of optical discharge and represent the boundaries of absolute fiber stability with respect to this process.

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