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Optical discharge propagation along hollow-core optical fibres

A.N. Kolyadin, A.F. Kosolapov, I.A. Bufetov

Abstract. **Propagation of an optical discharge along a revolver hollow-core optical fibre under the action of laser radiation is observed for the first time. As a source of radiation, a repetitively pulsed Nd : YAG laser with an average power up to 4 W, generating nanosecond trains of picosecond pulses, is used. After initiating an optical discharge, a motion of plasma formation along the optical fibre towards the laser beam at an average velocity of about 1 m s^{-1} is observed. It is revealed that a quasi-periodic destruction structure of the fibre capillary reflective cladding with a period of about 170 μm is formed in the process of optical discharge propagation. The results obtained show that the optical discharge propagation observed in our experiments represents a process of periodic picosecond pulse excitation of a light detonation wave in the air filling the core. As a result, during the action of a train of nanosecond laser pulses, the optical discharge moves along the fibre with a velocity in the range from 100 to 10 km s^{-1}.**

Keywords: *revolver fibre, hollow-core fibre, optical discharge, light detonation.*

1. Introduction

As the power of laser radiation propagating along optical fibre increases, a number of nonlinear phenomena (for example, stimulated Brillouin scattering, Raman scattering, four-wave mixing) arise, which limit the power of transmitted radiation. There is another clearly nonlinear effect that obviously restricts the capabilities of optical fibres, namely the effect of fibre destruction under the action of high-intensity radiation. This effect was first discovered in silica fibres [1, 2] and was named the 'fuse-effect' in the English-language literature. A considerable number of works are dedicated to studying this effect (see review [3] and references therein). It turned out that this effect represents a motion with a velocity from 1 to 10 m s^{-1} of brightly glowing optical discharge (OD) along the core of silica fibre (i.e., the motion of a plasma formation supported by optical radiation) with a temperature of ~10^4 K. The OD propagation leads to the destruction of the waveguide properties of fibre, since a sequence of voids which scatter laser radiation is formed in the optical fibre after the OD propagation. The OD propagation under the action of cw laser radiation was observed in the range of radiation intensities of $10^6 - 10^9$ W cm^{-2} in the core. Physical mechanism that determines the OD propagation in this case is the heat-conducting energy transfer from the OD hot region to the cold core material towards the laser radiation flux. Therefore, in the specified range of intensities, the OD propagation process is similar to the process of slow chemical combustion [4].

With an increase in the laser radiation intensity in the silica core to values greater than 10^9 W cm^{-2}, another (detonation) regime of OD propagation is realised [5]. In this case, the energy release zone moves together with a shock wave along the fibre towards the laser radiation, as in the case of chemical detonation. The shock wave propagation is supported by laser radiation absorption that occurs on the wave front. In this case, the OD motion velocity is much higher than that in the slow heat-conducting regime, and reaches about 3 km s^{-1}. When using repetitively pulsed lasers with an average power of several watts, the average OD velocity turns out equal to ~1 m s^{-1}. The propagation of an optical detonation wave in fibre is accompanied by the development of cracks in its glass and a complete destruction of the fibre standard diameter (125 μm). The destruction pattern after the OD wave passage was successfully recorded in [5] only using a special silica-glass fibre with an enlarged cladding diameter of 600 μm. The cracks formed in this fibre did not reach the outer surface, and the fibre retained its shape.

In optical fibres made of glasses with low glass transition temperatures, such as chalcogenide and fluoride glasses for the mid-IR range, the OD under the action of a radiation power of ~1 W is not supported. Nevertheless, the fibre destruction under the action of laser radiation takes place and has a nature of thermochemical decomposition of the fibre material throughout its cross section [6]. Threshold powers and destruction intensities for such fibres are approximately an order of magnitude lower than those of silica glass. Hereinafter, the threshold value of the destruction process is understood as the radiation power (intensity) corresponding to a zero propagation velocity of the destruction wave (see [7]).

One of the possibilities of increasing the threshold power of OD propagation proved to be the use of silica-glass fibres with a microstructured cladding [8]. The presence of air-filled capillaries near the solid-state core of the fibre provides an additional opportunity to increase the OD volume with a corresponding decrease in its density and laser radiation absorption coefficient, and, as a consequence, an increase by about an order of magnitude in the threshold radiation intensity to maintain the OD.

The development of silica hollow-core fibres has opened new prospects for transmission of high-power laser radiation. Currently, the production of optical cables based on the fibres

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A.N. Kolyadin, A.F. Kosolapov, I.A. Bufetov Fiber Optics Research Center, Russian Academy of Sciences, ul. Vavilova 38, 119333 Moscow, Russia; e-mail: iabuf@fo.gpi.ru

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designated for transmission of ultrashort high-power laser pulses has been started by the industry (see, for example, [9]). These fibres also have certain characteristic values of power and radiation intensity, exceedance of which triggers the destruction process [10, 11]. In particular, in the course of transportation of nanosecond pulses along hollow-core fibres (Kagome-type fibre), fibre destruction was observed in several experiments (see [11]) at the radiation intensities of about 10^{10} W cm^{-2} in the core, after which a destruction wave propagated along the fibre at a velocity of $\sim$5 cm s^{-1}. It was shown in [12] that pulses with a duration of $\sim$100 fs and intensity up to 10^{11} W cm^{-2} could be transported along the hollow-core fibre (revolver-type fibre) for a distance of 10 m without any degradation in the pulse parameters. In this case, the fibre destruction threshold was not reached.

Studying the processes occurring during the destruction wave propagation along the hollow-core fibres (HCFs), on the one hand, expand our knowledge on the radiation interaction with matter in relevant conditions, and on the other, makes it possible to use the obtained information in the development of more advanced optical fibres. In this work, we present for the first time a study on the process of destruction of a hollow silica glass fibre, with a core filled by the air at atmospheric pressure, under the action of high-intensity laser radiation after initiation of an optical discharge in the hollow core.

2. Experimental setup

In our experiments with the OD propagation along a HCF, two types of revolver-type HCFs [revolver fibre (RF)] were used: RF1 and RF2 [13]. Their cross sections and dimensions are shown in Fig. 1 and indicated in the caption thereto. The RF feature is that its reflective cladding has a relatively simple structure and consists of one layer of capillaries which can both touch each other (RF1) and be located at a certain distance (RF2). Both fibres were designed in such a way that the wavelength of the laser radiation source (1064 nm) fell within the fibre transparency zone.

A single-mode Nd:YAG laser (Antares, Coherent) was used as a laser radiation source. It was operating in the following regimes: continuous generation with an output power up to 10 W (regime 1); repetitively pulsed generation of nanosecond pulses due to Q-switching of the resonator having an average output power up to 7 W (pulse duration τ_p = 130 ns at the 0.5 level, repetition rate ν_p = 1200 Hz) (regime 2); Q-switching regime similar to regime 2, but with additional mode locking (regime 3). As a result, the generated radiation consisted of nanosecond trains of picosecond pulses (NTPPs): the train duration was 130 ns, the duration of picosecond pulses (PPs) was τ_p = 100 ps at the repetition rate ν_p = 76 MHz (13 ns period, Fig. 2), filling the envelope of nanosecond pulses with the same parameters as in regime 2. The average power reached 5 W. We were able to initiate the OD propagation along the fibre only in the case when the laser was operating in regime 3.

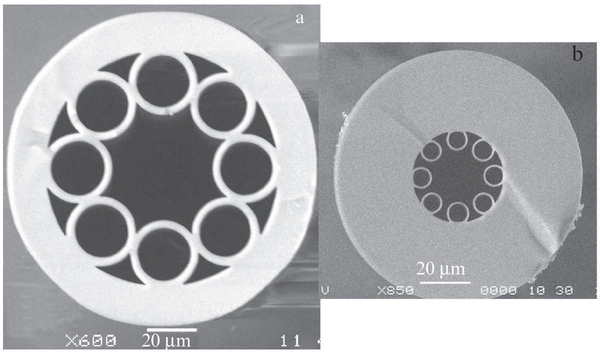

Figure 1. Images of (a) RF1 and (b) RF2 cross sections. Basic geometrical dimensions (RF1/RF2) are as follows: external diameter of the support tube, 125/100 µm; hollow core diameter, 42/20 µm; inner diameter of the support tube, 93/36 µm; capillary wall thickness in the reflective cladding, 3.1/0.8 µm; wall thickness of the supporting tube, 16/32 µm.

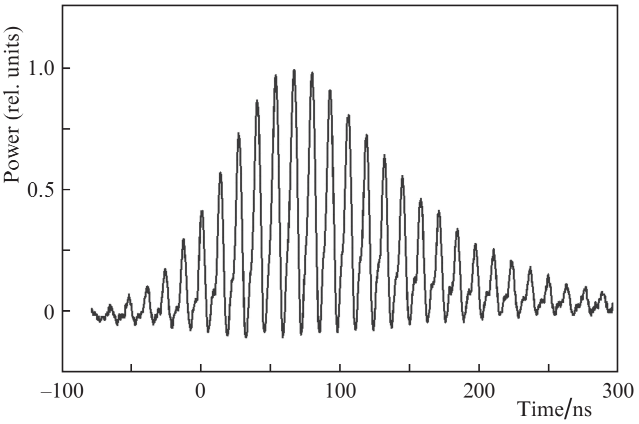

Figure 2. Oscillogram of the nanosecond train of picosecond laser pulses (regime 3), consisting of a sequence of pulses with a duration of 100 ps following with a period of 13 ns. Actual duration of the picosecond pulses on this oscillogram is not displayed due to frequency limitations of the radiation detector.

The experimental scheme is shown in Fig. 3. Laser radiation was launched through a lens (*1*) into the core of the RF, which represented silica glass structure coated with polymeric cladding (its cross section is shown in Fig. 1). By adjusting the position of the RF input end face, maximum value (up to 80%) of the laser radiation launch efficiency into the RF hollow core was attained, which was monitored using a power meter (*7*). In a number of experiments, the polymeric cladding in the RF region 3 was removed in order to place this region into an immersion liquid and to observe the OD propagation using a microscope (*4*). The image was recorded by a camera (*5*), whose shutter was open during the entire time of OD motion within the camera view field. In addition, the overall pattern of OD propagation was recorded by a TV-camera (*6*) with a frequency up to 240 fps. After initiation of an OD (*9*) near the output end face of fibre (*8*), this OD started to move at velocity V along an air-filled fibre core (*2*). The arrow indicates the OD propagation direction.

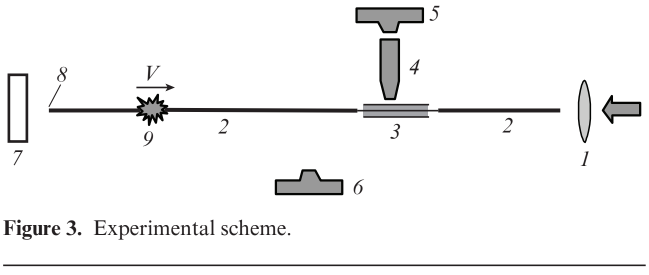

Figure 3. Experimental scheme.

3. Experimental results

An average laser radiation power at the RF output during the OD initiation was about 4 W for RF1 and about 2 W for RF2. At the same time, maximum average power of nanosecond pulses at the RF1/RF2 output was 16/8 kW, while at the maxima of picosecond pulses it reached 2.0/1.0 MW. This corresponds to the following intensities of laser radiation on the axis of the RF1/RF2 core: average intensity over the NTPP, $2.4\times10^9/5.2\times10^9$ W cm^{-2}; maximum picosecond pulse intensity, $3.2\times10^{11}/7.0\times10^{11}$ W cm^{-2}.

The length of the fibre section into which radiation was coupled ranged from 35 to 70 cm. Radiation with the above parameters passed along the RF without any significant disturbances. Therefore, as in the majority of studies on OD propagation (see, for example, [7]), the discharge was specially initiated. In these experiments, with the aim of OD initiation, a plane absorbing metal surface was brought in parallel to the RF output end face. Plasma formed on such a target started to absorb the laser radiation propagating along the RF core. As a result of energy transfer from the plasma at the target, the ionisation of air molecules in the fibre occurred, and these molecules, in turn, began to absorb laser radiation, which triggered the OD propagation along the fibre. A similar, but much larger-scale process of OD initiation in a glass tube with a diameter of 7 mm, exceeding by 2.5 orders of magnitude that of the RF, was experimentally observed in [14] (see Fig. 7 in [14]).

All the experiments were performed when the laser was operating in the NTPP regime. After launching laser radiation with a power of 4 W and 2 W into RF1 and RF2, respectively, an optical discharge was initiated and began to propagate along the fibre at an average velocity of $\sim$1 m s^{-1}. This OD represented a spot, brightly glowing in the visible wavelength range and moving along the fibre towards the laser radiation. Despite the fact that the laser operated in a pulsed regime, while the NTPP duration constituted about 10^{-4} of the time between them, the OD moved along the fibre with an approximately constant average velocity being a result of averaging over several periods between the NTPPs. It is of interest that by order of magnitude this velocity turns out approximately equal to the velocity of OD motion along the standard silica-glass solid-core fibres under the action of cw laser radiation of the same average power [15].

Figure 4a presents a set of 15 consecutive superimposed (overexposed relative to the OD brightness) frames taken by the camera (*6*) (Fig. 3) in the experiment with RF1. These frames determine the OD position every 25 ms. Figure 4b shows the time dependences of the distance travelled by the OD in fibres RF1 and RF2. Despite the significant difference in the diameters of fibre cores, the average velocities of OD propagation along RF1 and RF2 proved to be close: they constituted 1.0 m s^{-1} for RF1 and 0.91 m s^{-1} for RF2.

The consequences of OD passage along RF1 and RF2 were substantially different. In the case of RF1, the silica structure of the fibre was completely destroyed after the OD passage, and its fragments were held together only by the polymer cladding. In the case of RF2 having a twice as thick support tube (see Fig. 1), the fibre was externally preserved as a whole.

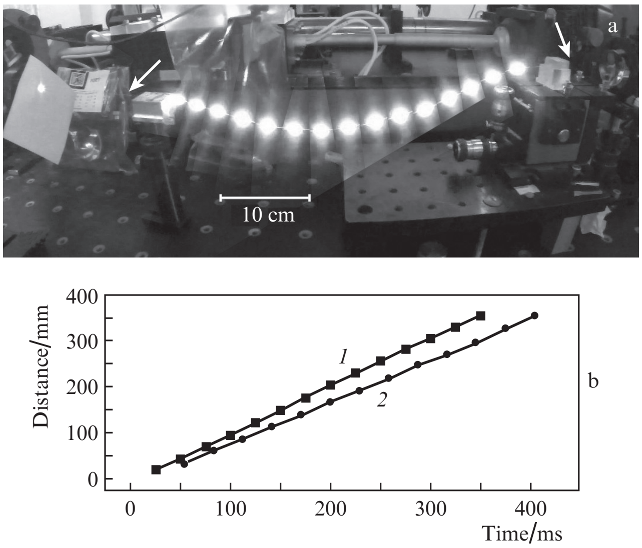

Figure 4. (a) OD propagation along RF1: 15 superimposed OD frames taken at intervals of 25 ms (the point of laser radiation input into RF1 is shown on the- right, and the point of OD initiation is shown on the left), and (b) time dependence of the distance travelled by the OD along (*1*) RF1 and (*2*) RF2 (initial points of reference are chosen arbitrarily).

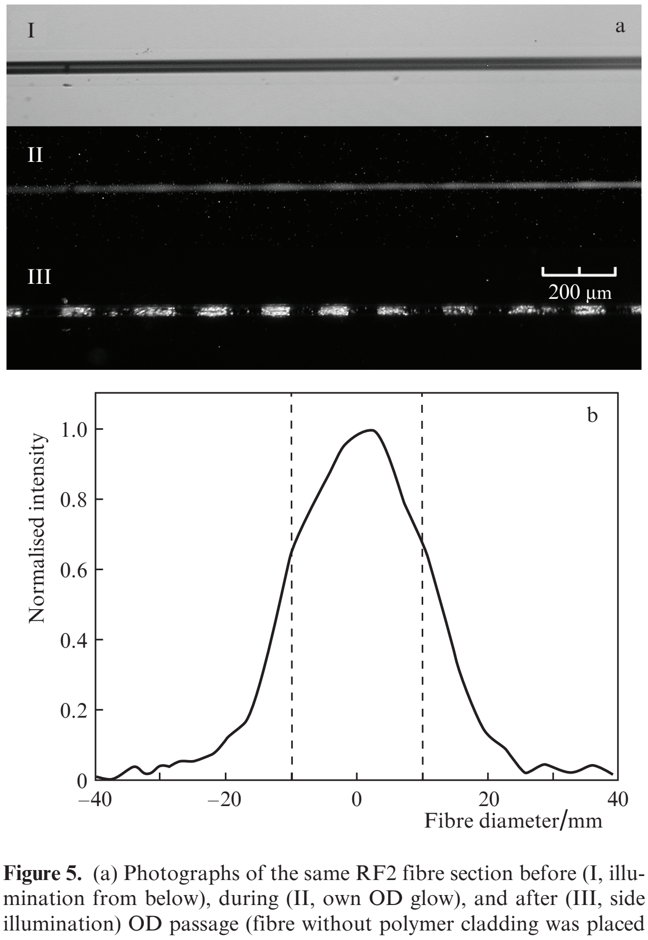

Figure 5. (a) Photographs of the same RF2 fibre section before (I, illumination from below), during (II, own OD glow), and after (III, side illumination) OD passage (fibre without polymer cladding was placed into immersion liquid), and (b) intensity distribution of OD plasma radiation in the RF2 cross section, measured according to the densitogram of frame II. Dashed lines indicate the boundaries of the RF2 hollow core.

Figure 5a shows photographs of the same RF2 section before, during, and after the OD passage along the fibre, taken by means of the camera (*5*) (see Fig. 3). Before the OD passage, the fibre was homogeneous in length (frame I). The integral-in-time photograph of the OD plasma glow (frame II) indicates that the OD in the section under consideration continuously propagated over the RF2 hollow core. The position of the OD glow region relative to the fibre core is illustrated by the dependence of the OD glow intensity on the coordinate along the fibre diameter (Fig. 5b). The photograph taken after the OD passage (frame III) recorded the destructions of the RF2 reflective cladding, representing a quasi-periodic structure with a period of about 170 μm. Herewith, within this period, areas with significant destructions (light) alternate with those less damaged (dark).

Figure 6 shows enlarged photographs of such areas (I.1 and II.1), and also photographs of the RF2 fibre cleavages, taken after the OD passage along the destroyed and less destroyed sections (I.2 and II.2). A preserved structure of the capillaries of reflective cladding is observed in Fig. 6 (II.2), whereas it is completely absent in Fig. 6 (I.2).

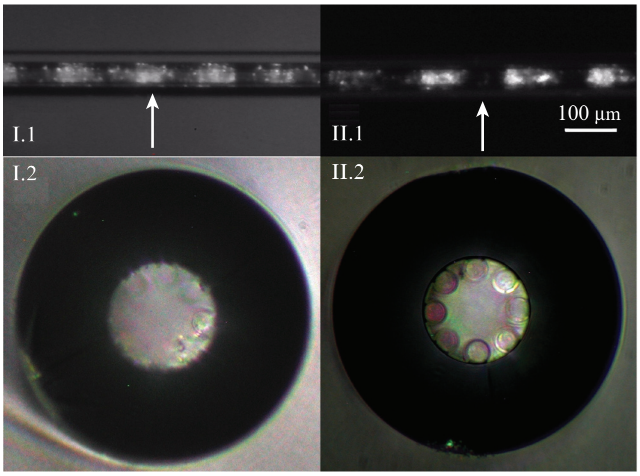

Figure 6. RF2 fibre after the OD passage: (I.1, II.1) side view, cleavage points are indicated by arrows; (I.2, II.2) photographs of the fibre cross section, corresponding to the places indicated in I.1, II.1. Photographs I.1 and II.1 were made without immersion and therefore the vertical scale differs from the horizontal scale specified for I.1 and II.1. In I.2 and II.2, the outer diameter of the fibre is 100 μm.

4. Results and discussion

The continuous OD propagation along a hollow fibre with an average velocity of ~1 m s^{-1} under the action of a periodic sequence of NTPPs, having been observed in our experiments, is actually a combination of the motion of a light detonation wave along the fibre during each PP, the motion of a decaying shock wave (SW) between the PPs, the plasma discharge relaxation within a millisecond time interval [16] between the NTPPs, and the breakdown of relaxing plasma by one of the first PPs of the next NTPP. After that the process is repeatedly continued. A similar process is implemented in conventional fibres with a silica-glass core under the action of a sequence of nanosecond laser pulses [5].

The following should be said regarding the start of the OD motion, with the arrival of each subsequent NTPP (after the first, when the OD is initiated by a metal surface). The optical breakdown threshold in the air is about 10^{11} W cm^{-2} at the neodymium laser wavelength and atmospheric pressure [17]. Such intensities were attained at the PP maxima in our experiments, but optical breakdown never occurred. Thus, we did not reach the optical breakdown threshold in a hollow fibre under our conditions. However, after the OD initiation in all our experiments, it passed along the entire available fibre length. Possible reasons for a reliable OD 'restart' after millisecond intervals between the NTPPs are the known effect of lowering the optical breakdown threshold in gas with increasing pressure [18] and an increase in the light wave electric field at the edges of capillary fragments in the destruction region.

The areas of complete destruction of the capillaries of reflective cladding in RF2 (Figs 5 and 6) correspond apparently to the areas of SW propagation with the maximum pressure jump at the wave front, i.e., to the propagation of a light detonation wave under the PP action and immediately after its termination. The average distance between the destruction areas is ~170 μm (Figs 5 and 6), and the SW passes it for 13 ns (PP period), which makes it possible to estimate the average velocity of OD propagation between the PPs as 13 km s^{-1}.

According to the estimate, the OD propagation velocity provided the OD is considered as a light detonation wave [4, 19, 20] during the PP action (at an energy in the single PP of ~0.1 mJ) constitutes ~160 km s^{-1}. In some approximation, it is possible to describe the propagation of a powerful shock wave along a hollow fibre after PP termination as a solution of the model one-dimensional problem on strong explosion [21]. If we assume that the energy of a single PP is released instantly in the cross section of a hollow fibre, then after 100 ps (PP duration), the SW velocity in this approximation would constitute ~100 km s^{-1}, and after 13 ns (the distance between PPs) it would attain 20 km s^{-1} (the estimated average velocity of SW propagation for the indicated time interval is about 30 km s^{-1}). Thus, the approximation of the one-dimensional problem on a strong explosion in our case is correct in the order of magnitude; however, the OD velocity turns out overrated up to three times. Apparently, this is a consequence of the difference between the cross sections of the hollow fibre and the tube with a diameter equal to the core diameter (that approximation was used in the estimates), and the neglect of energy losses due to the destruction of cladding capillaries and heating of the outer tube of the capillary.

If we assume that, under the action of the PP with an intensity exceeding one-half of the intensity of the most powerful PP in the NTPP, the OD travels for a distance of ~170 μm (see Fig. 5), and the OD is independently initiated by each PP of this type, then the average velocity of OD motion would constitute ~2 m s^{-1}, which represents a good estimate for the observed value of $V \approx 1$ m s^{-1}. A lower average velocity of OD propagation compared to this estimate can be observed due to the fact that the OD is only initiated by the PPs, the intensity of which exceeds one-half of the maximum.

Thus, in the present work we have observed for the first time the OD propagation along a hollow-core RF under the action of repetitively pulsed radiation from a neodymium single-mode laser. The data on the average velocity of OD propagation and the destruction pattern of the fibre reflective cladding allow us to conclude that the discharge propagation process consists of the process of propagation of the optical detonation wave (under the action of a PP with an intensity of ~10^{11} W cm^{-2}), the motion of a high-power SW between PPs (period of 13 ns), and the SW relaxation between the NTPPs during a time interval of about 1 ms, with subsequent initiation of a detonation wave by the next PP.

The obtained results show that the destruction velocity of the hollow-core fibres in the transportation of high-peak and average-power radiation can reach kilometres per second and be accompanied by the complete fibre destruction. Exclusion of the possibility of accidental OD initiation extends the range of operating powers and radiation intensities of the fibre systems with a hollow core. On the other hand, the use of hollow optical fibres makes it possible to carry out model experiments on the propagation of various types of combustion (slow, i.e., heat-conductive, and detonative) in one-dimensional geometry (along the tube).

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