Quantum Electronics **38** (5) 441 – 444 (2008)

INTERACTION OF LASER RADIATION WITH MATTER. LASER PLASMA

PACS numbers: 42.81.– i; 52.50.Jm
DOI: 10.1070/QE2008v038n05ABEH013751

Propagation of an optical discharge through optical fibres upon interference of modes

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Abstract. **The propagation of an optical discharge (OD) through optical fibres upon interference of LP_{01} and LP_{02} modes is studied. Under these conditions after the OD propagation through the fibre, the formation of an axially-symmetric group sequence of voids with a spatial period equal to that of mode interference (200 – 500 μm depending on the parameters of the fibre) is observed. The groups of voids are formed near the sections of the fibre with a minimal diameter of the intensity distribution of laser radiation. Large spaces between voids in the fibre have allowed us to measure accurately the difference Δn of refractive indices of the fibre core and cladding and distribution of dopants in different cross sections of the fibre after the OD propagation. A substantial increase in Δn (up to ten times) is observed. Approximately half this increase is caused by compression and densification of the fibre material after the propagation of the optical discharge.**

Keywords: *optical discharge, optical fibre, interference of modes, change in the refractive index, fused silica.*

Upon propagation of an optical discharge (OD) in a silica fibre under the action of laser radiation, a change in a number of parameters of the fibre core [such as the refractive index profile $\Delta n(r)$, distribution of dopants, etc.] is observed and voids (caverns) of different shape in the core are produced [1 – 3]. However, important details of this complicated process, such as mechanisms of radiation absorption, mass and heat transfer in the OD region, process of formation of voids (although some progress has been recently made here [4]), still remain unclear. To obtain new experimental data on the propagation of the optical discharge in optical fibres, we studied for the first time in this paper its propagation under conditions of a periodic change in the radial distribution of the laser radiation intensity $I(r)$ in the fibre core. The necessary modulation of $I(r)$ in the fibre has been achieved due to the interference of propagating modes. The found peculiarities of the OD propagation under such conditions and the use of fibres with a relatively large core diameter (~ 10 μm) have allowed us to measure in detail and reveal a number of properties in the change in $\Delta n(r)$ and distribution of dopants in the core of optical fibres after the OD propagation.

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Received 1 November 2007
Kvantovaya Elektronika **38** (5) 441 – 444 (2008)
Translated by I.A. Ulitkin

To initiate and maintain the OD propagation in an optical fibre, we used a single-mode 1.07-μm ytterbium fibre laser with a linewidth of $\Delta\lambda = 0.5$ nm. In the majority of experiments on the OD propagation, we used an optical fibre (denoted below as OF2) with a core doped with germanium oxide and fluorine, with a W-index profile ($\Delta n_{max} \approx 2 \times 10^{-3}$) and 12-μm field diameter of the LP_{01} mode (at the laser radiation wavelength). The initial profile $\Delta n(r)$ and the profiles of germanium [$C_{Ge}(r)$] and fluorine [$C_F(r)$] concentrations are presented in Fig. 1. Although this fibre is a single-mode one, at small distances from the splicing point with the fibre of the fibre laser, the propagation of leaky LP_{11}, LP_{02} and LP_{21} modes is observed in it. In our experiments, the LP_{11} and LP_{21} modes were not excited due to the cylindrical symmetry of the optical scheme of radiation coupling.

The interference of LP_{01} and LP_{02} modes leads to the periodic modulation of the intensity distribution $I(r)$ along the fibre core: at a distance of ~ 340 μm the shape of $I(r)$ changes from a single peak of diameter 7 μm (at the $1/e^2$ level) to a ring with the internal and external diameters of 17 and 5 μm (these values are the results of calculations). In this case, the maximal laser radiation intensity in the mentioned sections changes approximately by 7.8 times (at a constant power).

The experiment was performed as follows (Fig. 2a). The output single-mode optical fibre (OF1) of the fibre laser was spliced to the optical fibre OF2. After initiating the OD (by touching the output end of the fibre to the metal plate), it propagated in OF2 with the characteristic average velocity ~ 1 m s^{-1} and stopped after the laser switching off.

Figure 2b presents typical damages in the core of the fibre OF2 in our experiments, which differ substantially from similar damages in single-mode fibres known from other papers (see, e.g., [1, 2]). Large spaces (~ 100 μm) between voids (in usual single-mode fibres they are equal to ~ 10 μm) are observed. On a part of the fibre OF2 at a distance up to 5 mm from the splicing point OF1/OF2, the interference of modes leads to the formation (Fig. 2b) of a large-scale periodic structure of groups of voids (LSPSV), whose period $\Delta L \approx 340$ μm is close to the calculated period of the interference pattern. At larger distances from the point of radiation coupling (where the LP_{02} mode is already

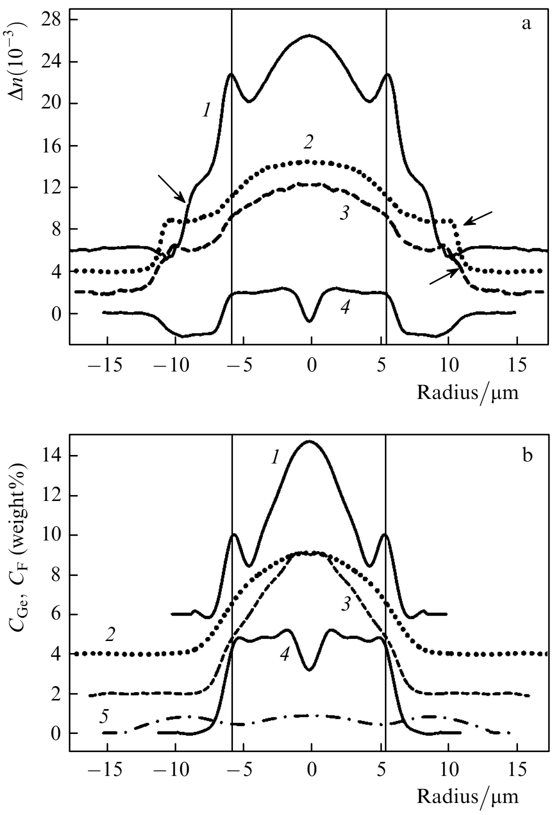

Figure 1. Profiles of the refractive index (a) and distribution of Ge and F concentrations (b) in different sections of the optical fibre OF2. Curves (*1–3*) correspond to fibre sections (*1–3*) presented in Fig. 2b, curve (*4*) – to the parameters of the initial fibre OF2 before the OD propagation, curve (*5*) shows the initial distribution of fluorine. To avoid overlapping, curves (*1–3*) are displaced up on the vertical axis by two units of the scale with respect to each other, curves (*4*) and (*5*) are not displaced.

absent) a periodic sequence of voids of diameter ~ 5 μm separated by ~ 10 μm, which is often observed in single-mode fibres, is produced in the fibre OF2.

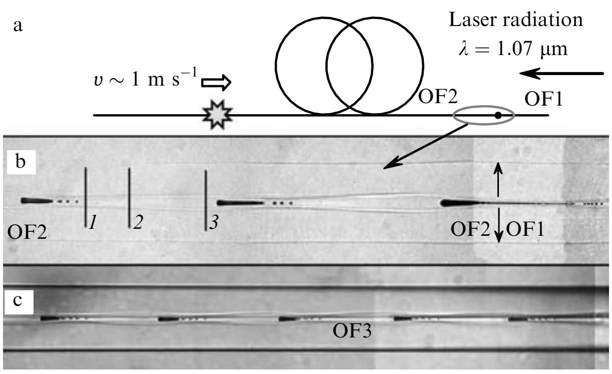

Figure 2. Scheme of the experiment (a) and the view of the fibre OF2 after the OD propagation near the splicing point OF1/OF2 (the laser output power is $P = 3$ W) (b). Vertical arrows define the plane of fibre welding and show the diameter of their reflecting cladding (125 μm). Digits (*1–3*) denote the fibre sections, for which distributions $\Delta n(r)$ and $C_{\mathrm{Ge}}(r)$ are presented in Fig. 1; (c) – LSPSV in the fibre OF3 at a distance of 1 m from the splicing point OF1/OF3 ($P = 4.4$ W); the diameter of the fibre cladding is 125 μm, the laser radiation propagates from the right to the left and the OD propagates in the opposite direction at ~ 1 m s^{-1}.

By replacing in the same experiment OF2 by OF3 maintaining the propagation of both LP_{01} and LP_{02} modes (OF3 parameters: germanosilicate optical fibre with the profile $n(r)$ close to rectangular, $\Delta n \approx 6 \times 10^{-3}$, the core diameter $d_c = 12$ μm), the distance Λ at which the LSPSV was observed, increased by three orders of magnitude: $\Lambda \approx 4$ m, $L = 240$ μm (Fig. 2c). The value of L was independent of the laser power in the range from 2 to 20 W. At distances from the point of coupling single-mode laser radiation to the fibre OF3 larger than Λ, the LSPSV gradually transforms to a uniform (with a period of ~ 10 μm) sequence of voids similar to those appearing after the OD propagation in a single-mode fibre (Fig. 3e, on the left). Note that a picture similar to that in Fig. 2c was apparently observed in [3], but the reasons of its formation have not been discussed by the authors.

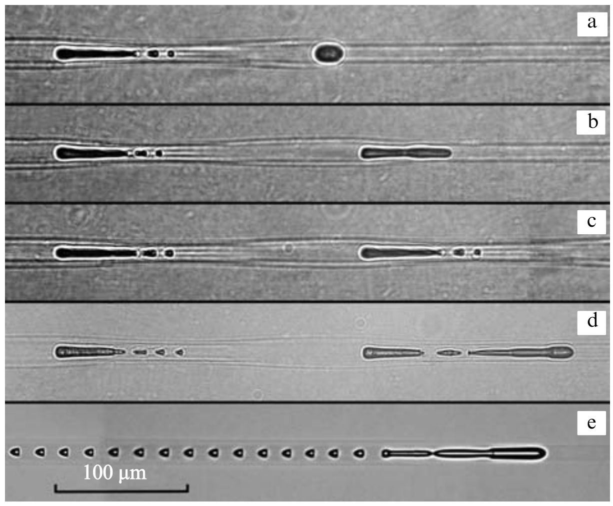

Figure 3. View of damages of the fibre OF3 in the vicinity of the OD stopping, which propagates under the action of two-mode radiation from a fibre laser upon its rapid switching off (less than 5 μs). Frames (a–c) correspond to experiments for the output power of $P = 2.2$ W [the frame (c) coincides with (a) but is displaced by the value of the LSPSV period], frames (d) and (e) are taken at $P = 4.4$ W; frames (a–d) correspond to experiments performed at a distance of about 1.5 m to the splicing point of fibres OF1/OF3, for the frame (e) this distance is equal to 20 m. Radiation propagates from the right to the left and the scale is the same for all the frames.

All these features can be explained by the interference of LP_{01} and LP_{02} modes whose period can be readily calculated by using known relations of the parameters of optical fibres (see, e.g., [5]). Thus, the period of the interference pattern for the fibre with a rectangular profile $\Delta n(r)$ is

$$L = \frac{\lambda}{\Delta n (b_1 - b_2)},$$

where b_1 and b_2 are normalised indices of propagation of LP_{01} and LP_{02} modes, respectively. The value L substantially depends on the wavelength. The function $L(\lambda)$ for the fibre with a rectangular profile $\Delta n(r)$ and parameters close to those of OF3 is presented in Fig. 4. The calculated value of L (for $\lambda = 1.07$ μm) is close to the LSPSV period in the fibre OF3. The use of a relatively nonmonochromatic (in our case, $\Delta\lambda \approx 0.5$ nm) source leads to the blurring of the interference patters. The calculated dependence of the fibre length $\Lambda(\lambda)$, on which the interference pattern can be observed for $\Delta\lambda \approx 0.5$ nm, is also presented in Fig. 4. At $\lambda = 1.07$ μm, Λ is ~ 4 m, which agrees with the experiment. Note also the presence of the minimum on the dependence $L(\lambda)$ whose existence leads to the appearance of the resonance maximum on the dependence $\Lambda(\lambda)$. One can say that in this case we deal with the zero of the intermode dispersion.

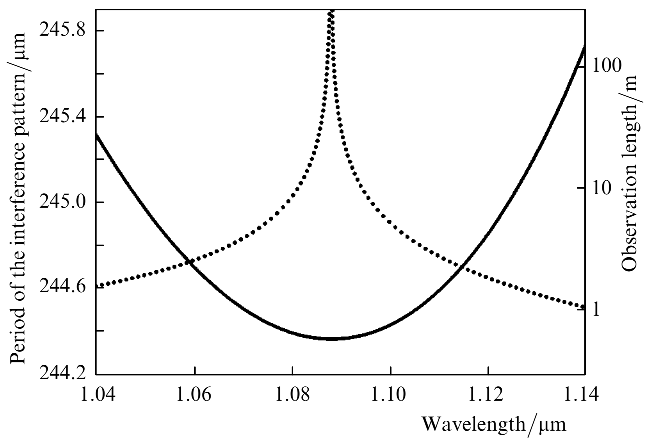

Figure 4. Calculated wavelength dependences of the period of the interference patterns for LP_{01} and LP_{02} modes (solid curve) and observation length of the interference of these modes (dashed curve) in the fibre OF3.

To observe the interference of modes at larger distances, it is necessary either to decrease the laser linewidth or tune the laser wavelength closer to the resonance one, which is about of 1.088 μm for OF3. In one of the experiments we replaced the fibre laser by the solid-state Nd : YAG laser with a significantly narrower emission band ($\Delta\lambda < 0.1$ nm). This allowed us to increase the LSPSV observation length in the fibre to 20 m. Note that a number of factors, for example, a change in the fibre parameters over the length can lead to a decrease in the LSPSV observation length.

A large distance between groups of voids (the value of L was in the range from 200 to 500 μm in different fibres under study) allowed the measurement of $\Delta n(r)$ and distribution of dopants in different sections of the damaged fibre without reducing the accuracy of measurements due to the influence of voids close to the measuring point (unlike [3], where such measurements were performed for the first time). To measure $\Delta n(r)$, we used a S14 Profiler (York Technology) and to measure the germanium and fluorine concentrations, we employed a JSM 5910LV scanning electronic microscope with an X-ray spectrum analyser (Oxford Instruments). In all cases, the distance between the measuring point on the cleaved face of the fibre and the nearest void was no less than 100 μm. Figure 1 presents the results of these measurements for three sections of OF2 located along the OD propagation within one period and corresponding to the minimal [section (*1*)], intermediate [section (*2*)] and maximal [section (*3*)] diameters of the laser radiation intensity distribution.

We have found a considerable change in the profiles $\Delta n(r)$ and $C_{Ge}(r)$ in all sections of the fibre though which the OD propagated. Changes in the distribution of the fluorine concentration after the discharge propagation have not been fixed [apparently, due to a comparably low (~ 0.5 weight %) accuracy of measurements]. A substantial increase (by 3–10 times) in the maximal value of Δn_{max} has been observed in different sections.

In all cases an increase in the concentration of germanium C_{Ge} on the fibre axis and a disappearance of a void in the centre of $\Delta n(r)$ and $C_{Ge}(r)$ profiles typical for fibres manufactured by using the MCVD technology takes place. The evaporation of the core material to the gaseous state (in the vicinity of the OD the temperature and pressure achieve $\sim 10^4$ K and $\sim 10^4$ atm [6]) followed by the thermal relaxation (in this case the cooling front in any section of the fibre moves mainly from the side surface to the centre) leads to the enrichment of the paraxial region of the core with a low-melt component – germanium oxide (as during the process of zone melting). Similarly, the value of C_{Ge} changes along the fibre axis. The highest weight concentration of germanium is observed in sections (*1*) and (*3*) (8.7 % and 7.0 %, respectively) located substantially closer to the produced voids than section (*2*), where the maximal value of C_{Ge} is approximately equal to the initial one (5.1 %).

The comparison of profiles $\Delta n(r)$ (Fig. 1a) measured in sections (*1–3*) (Fig. 2b) with the initial refractive index profile caused by the presence of GeO_2 (Fig. 1b; contribution to Δn due to doping with fluorine is neglected here because it apparently does not exceed 2×10^{-3}) shows that in these section only the upper part of the profile $\Delta n(r)$ can be explained by the contribution of germanium (the approximate estimate of the change in the refractive index due to doping with germanium: $\Delta n_{Ge} \approx 1.15 \times 10^{-3} C_{Ge}$ [weight %]). The rest part of Δn ($\sim 3.5 \times 10^{-3}$ and higher), which approximately coincides with the amplitude of drastic changes in Δn on side faces of the profile (denoted by arrows in Fig. 1a), is caused by other reasons. Obviously, this increase in Δn is caused by the compression and densification of the silica in the region of the fibre core after the OD propagation under the action of high pressure and temperature. This hypothesis is confirmed by the fact that after thermal annealing in the torch flame these jumps of the refractive index disappear.

The comparison of the profile $\Delta n(r)$ in sections (*1–3*) with the photographs of these sections similar to those in Fig. 2, but in an expanded scale, show that dark lines on the photographs with the sections coincide with the regions of a drastic change in the refractive index (see also [6, 7]). Thus, the lines most remote from the fibre axis mark a boundary of the OD interaction on the fibre material and, at least, qualitatively show a change in the $I(r)$ distribution along the fibre. Taking this into account and by using Figs 2 and 3 we can conclude that the groups of voids observed in the LSPSV experiments are formed near the sections of the fibre with the minimal diameter $I(r)$.

The dependences $\Delta n(r)$ and $C_{Ge}(r)$ presented in Fig. 1 and corresponding to section (*1*) differ by the presence of side maxima whose position is marked by vertical solid lines. Outside the region restricted by these lines, the profile $C_{Ge}(r)$ (*1*) almost coincides with the initial profile (*4*). Inside this region the concentration of germanium is lower at its external boundary and higher at the centre. In our opinion, this fact indicates that the high-temperature region of the OD in this section occupies only a part of the core doped with germanium, which has lead to the redistribution of the GeO_2 dopant inside this region, i.e. to the enrichment of the paraxial region with a low-melt component GeO_2, which results in the formation of side maxima upon cooling-down the heated region from the periphery to the centre.

The results of the experiments on stopping the OD in [4] show that when it propagates in the fibre for constant $I(r)$ over the cross section in the region occupied by the discharge, the density of the material is lower than the initial density of the silica. This results in the fact that after a sudden switching off of the laser radiation and thermal relaxation of the discharge region, an elongated cavity of length up to ~ 100 μm is formed in its place in the fibre core, which is often divided into several parts. The results of similar experiments [4] performed by us for the case of propagation and stopping of the OD upon interference of two modes in the fibre OF3 are presented in Fig. 3 (frames a – d). Here as in [4], after a sudden switching off of laser radiation (within ~ 5 μs), the formation of a cavern at the point of the OD stopping is observed but the shape of this cavity substantially depends on the diameter of the distribution $I(r)$ at the point of the discharge stopping. When the OD stops in the fibre section of diameter $I(r)$ close the maximal one, this region after cooling down takes the shape of a ball of diameter ~ 14 μm (Fig. 3a). The cavern of quite a different shape is formed if the OD is stopped in the section with the minimal diameter $I(r)$ (Fig. 3b, on the right) or somewhat further (Fig. 3d, on the right). For comparison, the shape of the cavern formed in the waist (in the vicinity of the minimal diameter) $I(r)$ is shown in Fig. 3c if the OD does not stop. We can obviously state that the shape of the OD region during the propagation changes (at least, qualitatively) similarly to the shape of the cavern formed at the spot of the OD after the thermal relaxation as is shown in Fig. 3.

Therefore, we have demonstrated in this paper for the first time that the propagation of the optical discharge under conditions of a periodic change in the radiation intensity distribution over the fibre diameter leads to the formation of a large-scale periodic structure of voids in the core after the discharge propagation. In this case the groups of voids are formed near the sections of the fibre with the minimal diameter of the intensity distribution.

Changes in the profile $\Delta n(r)$ are caused both by changes in the profile $C_{Ge}(r)$ and the compression and densification of the silica in the region of the fibre core. After the discharge propagation the profile $C_{Ge}(r)$ changes in the cross section and along the fibre, which is caused by processes similar to those in the process of zone purification. The corresponding choice of the fibre parameters allows one to obtain periodic sequences of voids in the fibre with the specified period in the range from 10 to 1000 μm due to the propagation of the optical discharge.

Acknowledgements. The authors thank V.F. Khopin and A.N. Gur'yanov for their help in the experiments and useful discussions.

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