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On the mechanism of optical discharge stop in the tapered region of a fibre cladding

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***Abstract*.** **Two mechanisms are considered which lead to the recently discovered [E.M. Dianov, I.A. Bufetov, A.A. Frolov Opt. Lett., 29 (16), 476 (2004)] effect of optical discharge stop in the tapered region of a fibre cladding. One of the mechanisms is related to the increase in the plasma temperature in the tapered region due to heat removal weakening, while another is caused by the increase in the displacement of the inner radius of the cladding with decreasing its outer radius. It is shown that the second mechanism is more important.**

Keywords: *optical discharge stop, optical fibre.*

1. Introduction

Investigations of a damage wave produced by an optical discharge propagating in optical fibres toward laser radiation (fibre fuse effect) have attracted considerable recent attention [1 – 11]. This wave is usually initiated by local external heating or by touching a surface absorbing laser radiation with a fibre end. The wave appears due to a sharp increase of absorption in silica at a temperature of about 2000 K [1, 2, 6, 10]. The region of enhanced absorption moves toward a laser beam due to heat conduction [3, 6 – 9, 11]. Behind this region, a plasma with temperature $\sim 10^4$ K is produced, whose properties are considered in [9].

Recently, a stop of the damage wave was observed [12] in an optical fibre with a sufficiently deep groove (the so-called waist) etched in the fibre cladding. The mechanisms of this effect are considered below.

2. On rupture mechanisms of the inner layer of a fibre cladding

We explain a stop of the damage wave by drastic deformation of the inner layer of the fibre cladding caused by high pressure and by subsequent abrupt extension of the region occupied by gas and plasma. Due to expansion, the temperature of the absorbing region lowers and the absorption coefficient drastically decreases, resulting in a stop of the wave. The stop can occur even when only the inner layers of the fibre are mainly damaged, resulting in the formation of a comparatively large bubble near the waist. Of course, when the waist is narrow enough and laser power is high, the entire cladding is ruptured.

Within the framework of concepts formulated in [7 – 11], we consider two mechanisms of expansion of the inner layers of the fibre cladding. One of them is related to the increase in the plasma temperature in the tapered region of the cladding during the propagation of a thermal wave in the fibre. It is clear that heat removal from the hot fibre core is weak and, therefore, the core temperature is higher. This should lead to an increase in the plasma pressure. The second mechanism is associated with the fact that the inner radius of the cladding increases with decreasing its outer radius even at a constant pressure. Below, we consider both these mechanisms.

3. Increase in the fibre core temperature in the fibre waist

Calculations were performed based on the two-dimensional model of thermal wave propagation in cylindrical coordinates r and z developed in [8, 11]. The model includes the heat conduction equation and equation of stationary laser radiation transfer:

$$c_p(T)\rho(T)\frac{\partial}{\partial t}T(t,z,r)=\frac{\partial}{\partial z}\left[k(T)\frac{\partial}{\partial t}T(t,z,r)\right]$$

$$+\frac{1}{r}\frac{\partial}{\partial r}\left\{rk(T)\left[\frac{\partial}{\partial r}T(t,z,r)\right]\right\}+\alpha(T)I(t,z,r), \qquad (1)$$

$$\frac{\partial}{\partial z}I(z,r)=-\alpha(T)I(z,r). \qquad (2)$$

Here, z is the coordinate along the fibre; r is the coordinate along the fibre radius; $c_p(T)$ is the specific heat; I is the intensity (energy flux density) of laser radiation; $\alpha(T)$ is the absorption coefficient for laser radiation; $k(T)$ is the heat conductivity; and $\rho(T)$ is the density of matter. The intensity depends on time implicitly through temperature. It follows from calculations [7] that the radiative heat conduction can be neglected during the propagation of a thermal wave in a fibre under normal conditions [1 – 11]. The intensity distribution $I_0(r)$ of incident laser radiation over the fibre radius r was written in the form $I_0(r)=(P/\pi r_0^2)\exp[-(r^2/r_0^2)]$, where P is the specified laser radiation power and r_0 is the radius of the fibre core filled with radiation.

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Earlier in papers [8, 11], the rectangular region $0 \leqslant r \leqslant r_1, 0 \leqslant z \leqslant l$ (r_1 is the outer radius of the fibre and l is its length) was considered. It was assumed that no heat sink occurred from the fibre surface. To consider effects caused by a change in the cladding cross section, the program was modified. While the absence of a heat flux at the fibre boundary was simulated by the von Neumann conditions (the condition of the zero temperature gradient), in the calculations presented here the heat conductivity at the curvilinear fibre boundary and outside it was set zero. The results of calculations performed using these two programs differ only in a narrow region near the outer boundary of the fibre. In the von Neumann problem, isotherms are perpendicular to the boundary, whereas in the case of the zero heat conductivity the isotherms are strongly bent near the boundary and directed along it. Therefore, the choice of new boundary conditions is associated with the possibility of simulating the outer curvilinear boundary without changing the calculation scheme.

The waist of the fibre cladding had the form of a cylinder with the radius r_w. A cylinder of a larger radius r_1 formed the outer boundary of the cladding. The cylinders were jointed by the surface of a torus with the minor radius equal to the difference of their radii $r_1 - r_w$ and the larger radius equal to r_1 (Fig. 1).

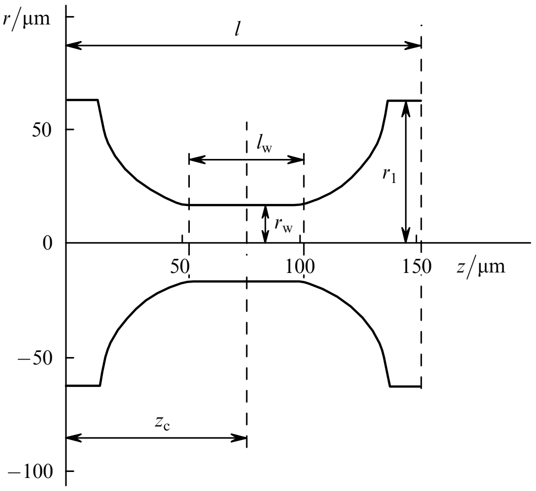

Figure 1. Longitudinal section of a tapered optical fibre used in simulations (r_w is the waist radius, r_1 is the outer radius of the fibre cladding, l is the length of the region considered, l_w is the waist length, z_c is the coordinate of the waist centre). The cladding parameters are: $l = 150$ μm, $z_c = 75$ μm, $l_w = 30$ μm, $r_w = 16.5$ μm, and $r_1 = 62.5$ μm.

The calculations show (Fig. 2a) that the temperature in the waist does increase. However, a noticeable increase in the maximum temperature T_{max} occurs only in the case of a sufficiently narrow waist with $r_w < 10$ μm (Figs 2b and 3). At the same time, a stop of the optical discharge was observed in experiments already for $r_w \approx 16.5$ μm.

Of course, the accuracy of the model used for calculations is not high enough, and the increase in the temperature in the fibre cladding waist can exceed the predicted value. In addition, the heating of external layers should enhance their plasticity. However, it is clear that the discharge stop effect can be caused not only by a weaker heat removal.

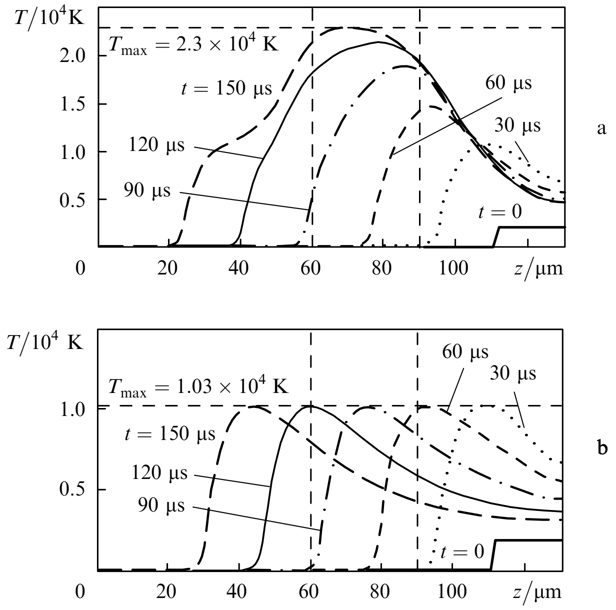

Figure 2. Temperature distribution $T(t, z, r = 0)$ over the fibre length at different instants for the laser radiation power $P = 4$ W and the radius of core filling by radiation $r_0 = 5$ μm (the laser radiation intensity $I_0 = 5.1$ MW cm^{-2}) for the waist radius $r_w = 7$ (a) and 20 μm (b). The rest of the parameters are as in Fig. 1. The vertical dashed straight lines correspond to the waist boundaries ($z_c \pm l_w/2$), the horizontal straight lines show the maximum temperature T_{max}.

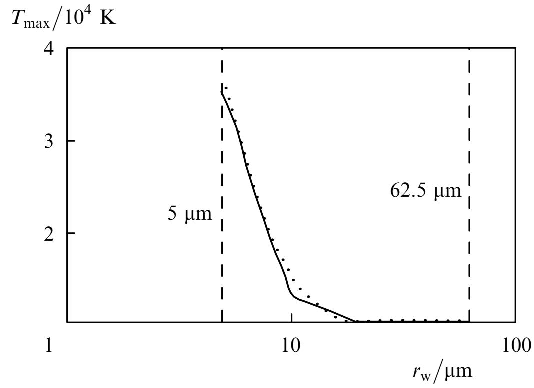

Figure 3. Dependences of the maximum temperature T_{max} on the fibre cladding waist radius r_w. The solid curve is calculations, the dotted curve is the approximation by the expression $\exp(-r_w/2.9\ \mu\text{m}) \times 1.5 \times 10^5$ K + 1.02×10^4 K. The rest of the parameters are as in Fig. 2.

4. Rupture of the inner region of a fibre caused by a large displacement of inner layers of the fibre cladding

The rupture of inner layers of the fibre can be naturally explained by a large displacement of inner layers of the cladding with decreasing the outer diameter of the cladding. Because the calculation of deformation of a cylindrical tube with a variable radius is a very challenging mathematical problem, we will use the known Lame result for the simplest case of an infinite hollow cylindrical tube inside which the pressure p is produced, while the external pressure is absent ([13], p. 35, [14], p. 339). In this case, the radial component $u(r)$ of the displacement vector is determined by the expression

$$u(r) = ar + \frac{b}{r},$$

where

$$a = p\,\frac{(1+\sigma)(1-2\sigma)}{E}\,\frac{r_0^2}{r_1^2 - r_0^2}\left(1 - \frac{R_1^2}{r^2}\right);$$

$$b = p\,\frac{1+\sigma}{E}\,\frac{r_0^2 r_1^2}{r_1^2 - r_0^2};$$

E is the Young modulus; σ is the Poisson coefficient; r_0 is the inner radius of the tube; and r_1 is the outer radius of the tube.

One can see from this expression that, when the tube thickness is small, the displacement is large even at a constant pressure. Of course, the displacement cannot be very large because the inner region should rupture at some value of the displacement. The strength of materials is analysed by using the quantity $\delta_{\rm p}$ characterising the relative lengthening during the rupture (for nonmetal materials). This is a total change in the calculated length of a sample during its rupture divided by the given calculated length ([15], p. 47). For glass, $\delta_{\rm p} = 4.5\,\%$.

Our calculations show (Fig. 4) that for $T \approx 8000$ K, the relative displacement u/r_0 achieves the critical value $\delta_{\rm p}$ when $r_1 \approx 16.5$ μm, which was observed experimentally.

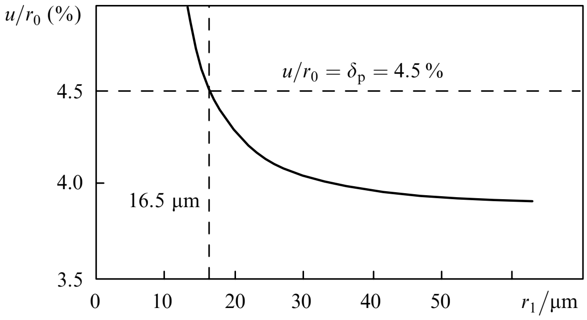

Figure 4. Calculated dependence of the relative radial component of the displacement vector of the inner part of the cladding on the outer radius of the cladding r_1 for $p = 2.8 \times 10^4$ atm ($T = 8000$ K), $r_0 = 5$ μm, $E = 87.5 \times 10^9$ Pa, $\sigma = 0.2$ [15].

It follows from the above consideration that the optical discharge stop in the fibre cladding waist can be explained by the increase in the displacement of the inner radius of the cladding with decreasing its outer radius.

5. Conclusions

We have shown that the optical discharge stop in the waist of the outer cladding of a fibre can be explained by the increase in the temperature due to a weaker heat removal and by the increase in the displacement of the inner radius of the cladding with decreasing its outer radius. The second factor seems to be more important.

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