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Thermal treatment of silica optical fibers with CO_2-laser radiation

Теоретически и экспериментально исследовано тепловое воздействие мощного излучения CO_2 лазера на кварцевый волоконный световод. Показано, что температура световода достигает точки плавления кварца за несколько миллисекунд при мощности лазера порядка 5 Вт, в случае стандартного одномодового световода. Путем последовательного воздействия сфокусированого лазерного луча на участки световода при одновременном его растягивании, в световоде образуются перетяжки. Совместно, перетяжки образуют в световоде длиннопериодную оптическую решетку.

We investigate theoretically and experimentally the effect of high-power CO_2–laser radiation on silica optical fibers. We show that it takes several tens of milliseconds to heat the standard single–mode silica optical fiber to the fusing temperature of silica with the focused radiation of the CO_2 laser of an output power of about 5 W. A point by point exposure of the optical fiber to the focused radiation of the CO_2 laser under simultaneous axial tension results in a periodic necking of the optical fiber. Such an alteration of fiber parameters constitutes the Long Period Fiber Grating.

Ключевые слова: *волоконный световод, длиннопериодные оптические решетки, плавленый кварц, мощное лазерное излучение, CO_2 лазер.*

Introduction

The CO_2 laser is used for splicing the optical fibers, fabrication of lenses at the optical fiber tips and fabrication of optical fiber directional couplers [1]. Recently, the CO_2 laser has found a new application in the fabrication of Long Period Fiber Gratings (LPFG). The LPFG present a large interest for the optical communications. They have functions of optical filters, demultiplexors of optical signals and sensors of some physical quantities [3–15]. The LPFG can be fabricated in silica optical fibers by point-by-point exposure of fiber to the focused beam of the CO_2 laser [16–18]. Heating of small zones of the fiber almost to its fusing temperature under simultaneous axial tension results in necking phenomena – a local reduction in fiber diameter. This, in turn, locally changes the effective refractive index of the fiber core and propagation constant of the fundamental electromagnetic mode of the core. A series of several dozens or hundreds of such “necks” spaced at a period of about 200 to 300 mm (uniform or non-uniform) constitutes the LPFG. The described fabrication technique is much simpler and cheaper than alternative fabrication methods [19–23]. However, this technique is not perfect yet. Also, the theory of the interaction of high-power beam of the CO_2 laser with the optical fiber of fused quartz (silica) does not exist yet. The existing works do not describe the details of the respective fabrication facilities and operational regimes used in the writing of the LPFG. More specifically, there is no data about laser beam parameters and exposure times employed in the fabrication of the gratings. Therefore, it would be of interest to investigate theoretically and experimentally the process of heating the silica optical fibers to the fusing point of silica and the necking phenomena in the optical fibers under the exposure to the CO_2–laser radiation.

1. Mathematical model of heating the silica optical fiber with the CO2-laser radiation

Consider the focused CO_2–laser beam of a wavelength λ=10.6 μm, power P_0 and circular focus spot of a diameter D incident on a cylindrical section of the optical fiber of a length l and diameter d=2a, a is the radius of the fiber cladding (Fig. 1).

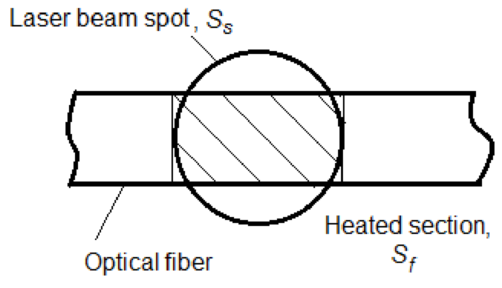


Fig 1. Problem geometry

The core and cladding of the optical fiber are of pure silica (SiO_2). The laser radiation is partially reflected at the fiber surface and the other part is completely absorbed by the material of the fiber (The penetration depth of the optical radiation of a wavelength of 10.6 μm in silica is of few microns [24]). Under these assumptions, the evolution of absolute temperature T of the heated section of the optical fiber in time, t, is governed by the following equation:

$$P_0 \eta \zeta \alpha t = E_h + E_c + E_{hc} + E_T, \quad (1)$$

η is the overall efficiency of the optical system (η=0.5), $\zeta=S_f/S_s$ is the geometrical factor, $S_f \approx 2al$ is the cross section of the heated cylindrical element of the optical fiber, $S_s = \pi D^2/4$ is the laser spot area, α_i is the integral absorptivity of the fiber section, $E_h=c_p m(T-T_0)$ is the energy spent to heat the cylindrical element of the optical fiber to the temperature T, c_p is the specific heat of silica, $m=\pi a^2 l\rho$ is the mass of the heated element of the optical fiber, ρ is the specific density of silica, T_0 is a room temperature (T_0=293 K), E_c and E_{hc} is the energy spent on convection and heat conduction, respectively, and E_T is the energy loss due to thermal radiation. Assuming that the optical fiber is in thermal equilibrium with the environment under the room temperature,

$$E_T = \sigma\varepsilon A\left(\int_0^t T^4(t)dt - T_0^4 t\right),$$

σ is the Stefan-Boltzmann constant, ε is the emissivity of silica, $A=2\pi al+2\pi a^2 =2\pi a(l+a)$ is the total area of the heated section of the optical fiber. The thermal conductivity of the substances which are in contact with the heated section of the fiber: silica and air is very low and the convection is negligible in small volumes. Therefore, the terms E_c and E_{hc} can be ignored and Eq. (1) reduced to:

$$P_0\eta\zeta\alpha t = c_p m(T - T_0) + \sigma\varepsilon A\left(\int_0^t T^4(t)dt - T_0^4 t\right). \quad (2)$$

We solved Eq. (2) numerically under different parameter combinations in order to find the exposure time required for heating the silica optical fiber to its softening and fusing temperature. In the calculations, we employed the following parameters of silica:

Table 1. Parameters of silica (SiO_2) employed in the calculations [24,25]

Specific Density, ρ	2,700 kg/m^3
Absorptivity, α	0.7 @ λ=10.6 µm
Emissivity, ε	0.7 @ λ=10.6 µm
Specific Heat, c_p	755 J/kg K
Thermal Conductivity, k	1.3 W·m^{-1}·K^{-1}
Softening Temperature, T_s	1938 K
Fusing Temperature, T_f	2270 K

2. Results of the mathematical modeling

We considered the silica optical fiber of an external diameter D of 125 µm, and a length of the heated section of the optical fiber of 125, 250 and 375 µm. These were the parameters of the single mode optical fiber (Corning SMF–28) and focusing elements available for experiments at our laboratory. The results of simulations are plotted in Fig. 2.

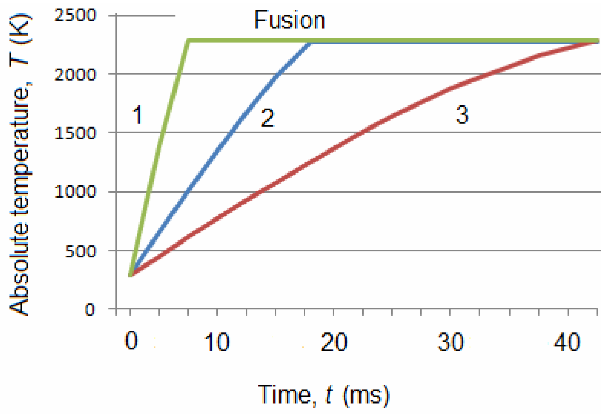


Fig. 2. Calculated absolute temperature *T* vs. time *t* for laser power P_0=2 W and various laser beam spot size *D*: 125 µm (*1*), 250 µm (*2*) and 375 µm (*3*)

Tha data in Fig. 2 show that the exposure time necessary for heating the typical silica single–mode optical fiber of an external diamter of 125 mm to its fusing temperature of 2270 K is of the order of tens of milliseconds under the moderate laser power of P_0=2 W. The required exposure time varies with beam spot size from about 9 ms to 40 ms. The exposure time would be much less with larger CO_2-laser power. But, with shorter exposure time the control of the process would be more difficult.

3. Experiment

The experimental verification of the predicted operational regimes was conducted at the arrangement which is shown schematically in Fig. 3. It consists of four principal parts: The CO_2 Laser, Focusing System, Translation Stage and Control System.

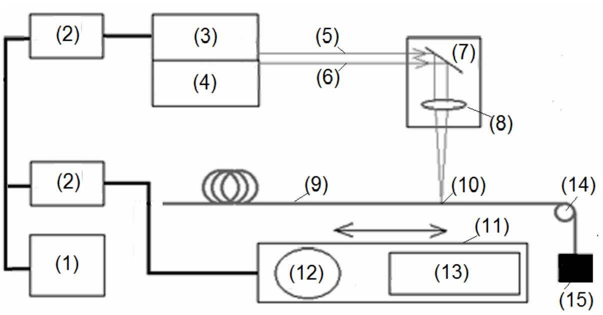


Fig.3. Layout of the experimental arrangement: (1) – Computer, (2) and (3) – Controllers, (3) - CO_2 laser, (4) – GaAs laser (visible), (5) and (6) – infrared and visible laser beams, (7) – aluminum mirror, (8) ZnSe focusing lens, (9) – silica optical fiber, (10) – CO2-laser beam spot, (11) – translation stage, (12) – DC motor, (13) – position sensor, (14) – capstan, (15) – weight

The CO_2 laser (SYNRAD J48-2W) has a sealed discharge tube. It is excited by RF current in a form of pulses of a frequency of 5 kHz which are applied to internal electrodes. The pulse width is modulated by an external controller. It allows for tuning the output laser power in a range of 0...100% of nominal value. The principal parameters of the laser are given in Table 2.

Table 2. Parameters of the employed CO_2 laser (SYNRAD J48–2W)

Maximum Output Power	25 W
Mode Quality	TEM_{00}, 95% $M^2 < 1.2$
Beam Ellipticity	<1.2
Pulse Rise Time	<150µs
Beam Diameter	3.5mm
Beam Divergence (Full angle)	4mR
Wavelength	10.57-10.63 µm
Power Stability	±5%
Polarization	Linear (vertical)

The CO_2 laser is equipped with a visible (red) GaAs diode laser which serves for the visualization of the infrared optical beam and its focal point.

The focusing system consists of a flat aluminum mirror and a ZnSe focusing lens of a focal distance *F*=36 mm.

The translation stage (Physik Instrumente M-521-DD) has a minimum incremental motion of 0.1 mm. It allows for precision positioning of the optical fiber with respect to the focal point of the CO_2–laser. The optical fiber is fixed on a special platform which is attached to the translation stage (Fig. 4). A small weight attached to the loose end of the optical fiber pulls with a force which is sufficient to extend the heated section of the fiber and produce a necking of the fiber. The operation of the CO_2 laser and translation stage is controlled by a computer via two different controllers.

The single–mode silica optical fiber (Corning SMF–28) of an external diameter of 125 µm was exposed to the focused CO2–laser beam of a spot size of 125, 250 and 375 µm. The laser operated in a single-pulse regime at a fixed output power in a range from 0.1 to 10 W. The duration of laser pulses was slowly increased from zero until the necking phenomena – a reduction in fiber diameter was observed in the heated zone of the optical fiber (Fig. 5).

The experiment confirmed the predicted character of temperature rise with time for various spot sizes shown in Fig. 2. But, it required a CO_2–laser power larger by a factor of about 2.5 with respect to its predictive value to achieve the necking of the fiber. We attribute the difference between the observed and predicted behavior to possible variation of silica properties with temperature in a very large temperature range of about 2000 K which we consider in the present work. While Refs. [25, 26] only cover the temperature range of 20 to 30 ℃.

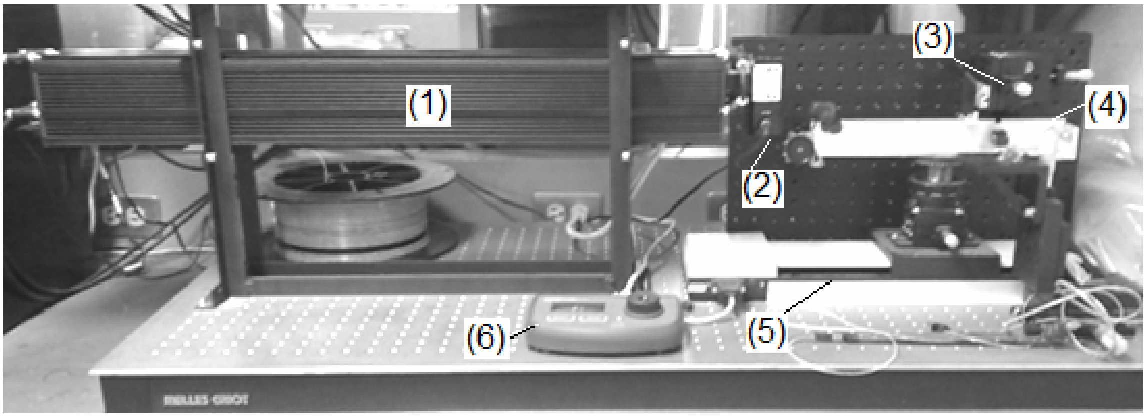
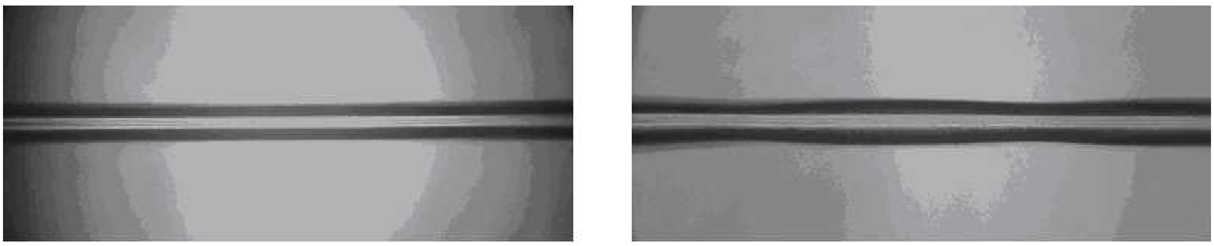


Fig.4. Experimental arrangement (General view): (1) – CO_2 laser, (2) – GaAs diode laser, (3) – focusing unit, (4) – platform with optical fiber, (6) – translation stage, (6) – laser controller



a *б*

Fig.5. The single–mode optical fiber: (*a*) before the exposure to the CO_2 –laser radiation, (*b*) – after the exposure of two zones of the fiber to focused radiation of the CO_2 laser

Conclusions

The results obtained in this work show that the exposure of a standard single–mode silica optical fiber of the coating diameter of 125 μm to the focused radiation of the CO_2 laser of an output power in the range of 2 to 5 W results in an increase of the fiber temperature to the fusing point of silica in several tens of milliseconds. The accuracy of the mathematical modeling of heating of silica to its fusing temperature requires the knowledge of physical and optical constants of silica at temperatures up to 2270 K. At present, not all of such constants are known. Experimentally, we showed that the heating of the optical fiber up to its fusing temperature under simultaneous gentle axial tension results in necking of the optical fiber. Point by point exposure of the optical fiber to the focused radiation of the CO_2 laser under axial tension of the fiber allows for the fabrication of the LPFG. Here, we have shown this only for the single mode optical fiber of standard diameter, but the theoretical model developed in this work can be applied to the optical fibers of non-standard diameter too.

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