LIGHTGUIDE FABRICATION CONTROL WITH A LASER HEATER

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The problem of controlling the diameter of a fabricated fiber with the help of an auxiliary low-power laser heater is analyzed.

Lightguides are now usually fabricated from preformed stock [1-5]. They are drawn with the help of different types of heaters: graphite furnaces, oxygen-hydrogen burners, and $CO_2$ laser radiation [1]. They must meet the following requirements: 1) the contamination of the lightguide surface must be minimum (since surface contamination reduces the lightguide strength) and 2) the variations of the lightguide diameter, which largely determine the level of optical losses in lightguides, during the drawing process must be minimized.

The purpose of this work is to analyze the possibility of controlling the diameter of the lightguide obtained with the help of an auxiliary low-power laser heater.

The use of laser heaters for drawing high-quality lightguides from stock is now quite common in world practice [2-4]. The setup described in [4] is an example. It includes a precision unit for feeding the stock, a unit for rotating the stock in order to insure uniform heating, four 100-W $CO_2$ lasers, and a unit for receiving the lightguide. The laser heater is most convenient from the viewpoint of controlling the heating; but, it does have drawbacks, namely, high-frequency perturbations are inherent. These perturbations can be caused by laser power drift fluctuations of the air flows in the comparatively small zone of the heater, etc. [5]. It is suggested that these high-frequency perturbations be compensated with the help of an auxiliary low-power laser, whose radiation is focused near the point of formation of the lightguide from the stock. In this work the dynamic response of the compensation process is studied on the basis of numerical simulation of the drawing process.

Description of the Control Loop. A diagram of the heating of the stock and the drawing of the lightguide from it as well as a diagram of the control loop are presented in Fig. 1. The radiation of the laser heater, which softens the stock, is focused into the point $z_1$ (the z axis is oriented along the draw axis). The radiation of the controlling low-power laser, which is used to compensate the high-frequency perturbations, is focused into the point $z_2$, near the point of solidification of the lightguide formed. The instability of the power sources and the thermal drift of the lasers heating the stock give rise to variations of the injected heat power in some frequency interval ($\Delta P_1(\omega)$). These variations give rise to fluctuations of the temperature on the surface of the neckdown region, near the point $z_1$ ($\Delta T_1(\omega)$) as well as at the point $z_2$ ($\Delta T_2(\omega)$). The fluctuations $\Delta T_2(\omega)$ are directly responsible for the appearance of variations in the diameter of the lightguide $\Delta d(\omega)$. We note that in the general case the frequency dependences of $\Delta P_1$; $\Delta T_1$; $\Delta T_2$ are completely different.

The temperature in the neckdown region near the point $z_1$ must be monitored with the help of any device that records the temperature distribution as well as the absolute value of the temperature, for example, a CCD array [6]. This device records $\Delta T_1(\omega)$ quite rapidly (~1 μsec). The information from this device is fed into the regulator (see Fig. 1) with the transfer function $W(\omega)$. The signal so obtained, which has the form $\Delta T_1(\omega)W(\omega)$, is fed into the input of the auxiliary heater—control laser, and its radiation is modulated in accordance with this signal:

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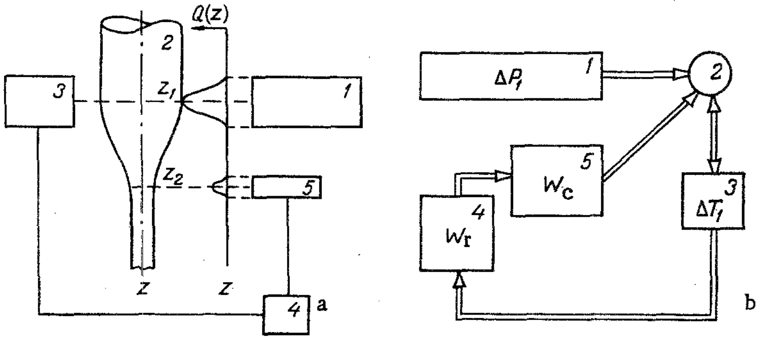


Fig. 1. Diagram of drawing of the lightguide from the stock with the help of a laser heater (a: experimental setup; b: block diagram of the control loop): 1) laser heater; 2) drawn stock; 3) thermometer in the neckdown region; 4) regulator; 5) controlling laser.

$$\Delta P_2(\omega) = \Delta T_1(\omega) W(\omega). \quad (1)$$

Assuming that the laser heater is the source of thermal noise, which must be compensated by the action of the radiation from the controlling laser, we shall synthesize a compensation system for this purpose.

Methods for Calculating the Dynamics of Heating of the Neckdown Region. We shall determine the dynamic properties of the lightguide drawing process, i.e., the dependences $\Delta T_1(\omega)$, $\Delta T_2(\omega)$, with the help of the method of numerical simulation.

We shall assume that heat transfer occurs in the neckdown region, whose shape remains constant. We shall approximate the dependence of the lightguide radius on the coordinate z as follows [7]:

$$a(z) = \frac{(a_d + a_0)}{2} + \frac{a_0}{\pi} \operatorname{arctg}\left(\frac{z - z_1}{B/2}\right). \quad (2)$$

The fused quartz glass in the neckdown region moves in accordance with the law of conservation of mass with a velocity

$$V(z) = V_0 a_0^2 / a^2(z). \quad (3)$$

The rate of drawing of the lightguides, in this case, equals

$$V_d = V_0 a_0^2 / a_d^2(z). \quad (3a)$$

Heat is injected through the surface. This means that the boundary conditions on the surface $r = a(z)$ must indicate the method of heating. Heat propagates in the stock in two ways [7]: heat transfer and, for a semitransparent material, radiation. In calculations, an effective coefficient of thermal conductivity $k(T) = k_1 + k_2(T)$, where $k_2(T)$ is a coefficient that takes into account the effect of radiation, is usually introduced. For quartz glass, for which the further calculations were performed, the coefficient k(T) can be calculated according to Rosseland's approximation [7]:

$$k(T) = k_1 + \frac{16 n^2 \sigma T^3}{3\alpha}. \quad (4)$$

We shall write the full nonstationary heat transfer equation for a coordinate system adapted to the shape of the neckdown region, taking (4) into account, as follows:

$$\frac{\partial T}{\partial t} = -u \frac{\partial T}{\partial R} - v \frac{\partial T}{\partial z} + \frac{k(T)}{\rho C_p}\left[\frac{1}{R} \frac{a_0^2}{a^2(z)} \frac{\partial}{\partial R}\left(R \frac{\partial T}{\partial R}\right) + \frac{\partial^2 T}{\partial z^2}\right] + \frac{1}{\rho C_p}\left[\left(\frac{a_0}{a(z)} \frac{\partial}{\partial R} + \frac{\partial}{\partial z}\right) k(T) \left(\frac{a_0}{a(z)} \frac{\partial}{\partial R} + \frac{\partial}{\partial z}\right) T\right]. \quad (5)$$

The radial component of the velocity of the fused quartz glass satisfies the expression

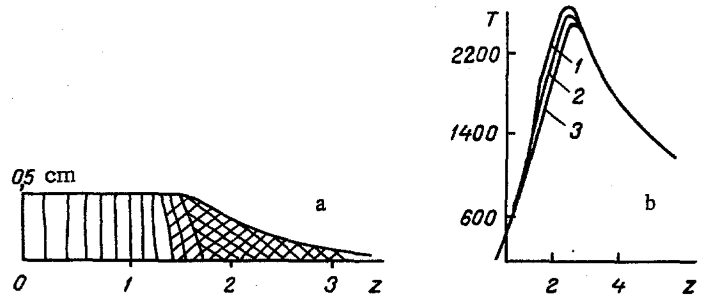


Fig. 2. Temperature distribution in the neckdown region: a) chart of isotherms (the region in which the temperature exceeds 2100 K is cross-hatched bidirectionally; the region in which the temperature varies from 1800 to 2100 K is cross-hatched unidirectionally); b) temperature on the surface of the neckdown region (1), at the center (3), and midway between the surface and the center (2). T, K; z, cm.

$$u = -\frac{R}{2}\frac{\partial V}{\partial z}.$$

We write the boundary conditions for Eq. (5) as follows:

$$\left.\frac{\partial T}{\partial R}\right|_{R=0} = 0;\ T|_{z=0} = T_\infty = 293\ \text{K};\quad \left.\frac{\partial T}{\partial z}\right|_{z=z_N} = 0,$$

$$\left.\frac{\partial T}{\partial R}\right|_{R=a_0} = \frac{1}{k(T)}\left[Q(z)(1-(a')^2)^{-1/2} + h(z)(T-T_1) + {} \right.$$
$$\left. + a'\frac{\partial T}{\partial z} + \Sigma\sigma(T^4 - T_1^4)\right] a(z)/a_0(1+(a')^2)^{-1/2}, \tag{6}$$

where $a' = da/dz$.

Thus the fact that the workpiece whose temperature equals the room temperature (293 K) enters the heating zone is taken into account. We neglect heat transfer along the formed lightguide. Absorption of laser radiation with power density Q(z) at the free boundary is taken into account; heat transfer between the surface of the neckdown region and the surrounding medium with temperature $T_1$ occurs owing to molecular heat conduction and radiation, and in addition the coefficient of heat transfer h(z) is given in [8]. The calculation is performed within the limits $0 \le z \le z_N$; $0 \le R \le a_0$; $z_N \gg z_1$ on a 10 × 60 or 25 × 100 grid with the help of an implicit, alternating-direction scheme [9].

The stationary solution for the typical regime (2B = 0.8 cm, $V_d$ = 12 m/min) was found by the method of relaxation. Figure 2 shows graphs of the isotherms in the neckdown region and graphs of the temperature distribution along the z axis for the center of the lightguide, the surface, and midway between the surface and the center.

This stationary temperature distribution was employed as the initial condition for studying the dynamic response of the system to variation of the injected heat power. Let a "dynamic shock" along the heating channel occur at the moment t = 0, i.e., the power of the laser changes by ΔP. In our calculations the degree of modulation of the laser power equalled 15%. As a result of this action thermal equilibrium breaks down in the neckdown region and the temperature in this region is redistributed. After some time $t_0$ at all points the redistribution of the temperature is completed and a new stationary state is established. In our calculations the temperature response at the point where T = 1800 K at t = 0 is determined. We have thus determined the dynamic response of the drawing system under study to an impulsive action, i.e., the transient characteristic of the system $\Delta T_2(t)$. Its Fourier transform gives the frequency characteristic $\Delta T_2(\omega)$ of the drawing system. Figure 3 shows the amplitude-frequency characteristic and $\Delta T_2(t)$ of the neckdown region, obtained by the method described above, when the drawing process is

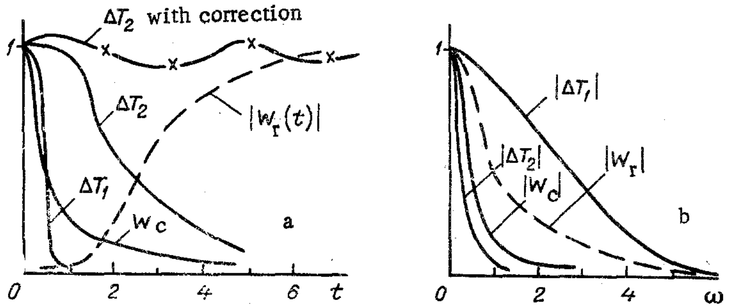


Fig. 3. Dynamic characteristics of the laser lightguide drawing system: a) transient; b) frequency. t, sec; ω, Hz.

perturbed by the injected thermal power. The transient and frequency characteristics of the drawing system for a temperature at the surface near the point $z_1$ ($\Delta T_1(t)$ and $\Delta T_1(\omega)$) are determined in an analogous manner.

The same method was employed to study the effect of a low-power controlling laser $P_2$, whose radiation is focused near the point $z_2$. It turned out that in order to compensate the 15% change in the power of the laser heater at 400 W the controlling laser must have a power of up to 50 mW. The transient and frequency characteristics of the drawing system with such an action ($W_c(t)$ and $W_c(\omega)$) are also shown in Fig. 3.

We shall make a remark concerning the determination of the characteristics $\Delta T_1(t)$ and $\Delta T_1(\omega)$. We attempted, when possible, to simulate the real drawing process together with measurement of the temperature in the neckdown region with the help of CCD array. It can record the linear size of the isothermal zone on the surface of the workpiece. We note that if the CCD array is exposed to visible radiation, then it will record not only the surface temperature, but also the volume distribution of the temperature in the neckdown region, since quartz glass is transparent in the visible region. Since the temperature gradient between the surface and the center in the hottest region is small, however, this temperature difference can be neglected. The results of numerical simulation of the drawing process permit determining how the temperature on the surface of the neckdown region near the point $z_1$ will change, and, therefore, how the surface area of the isothermal zone will change. Figure 4a shows graphs of the temperature in the hottest part of the surface of the neckdown region after the "dynamic shock" is indicated near each curve. Of course, the size of the isothermal region depends on the particular isotherm we are measuring (see Fig. 4b). In measuring the hottest zone (for example, 2650 K) this size changes very rapidly and drops to zero within fractions of a second. On the other hand, the size of the relatively cold zone (2565 K) changes slowly after the "dynamic shock," and drops to zero only over a time interval of 10 sec. Thus the speed depends on the size of the particular zone recorded, i.e., in the specific case at hand on the exposure time of the device. The dynamic characteristics, shown in Fig. 3, were obtained for the case when the temperature of the measured zone equals 2650 K.

Dynamic Characteristics of the Lightguide Drawing System. We shall discuss the basic features of the characteristics obtained. As one can see from Fig. 3, the width of the transmission band for the disturbances, entering along the laser heating channel $\Delta T_2(\omega)$, does not exceed 1 Hz. The response to the action of the controlling laser $W_c(\omega)$ is a much higher frequency process; its transmission band extends up to several Hz. This makes it possible, in principle, to control the drawing process at all frequencies at which thermal perturbations enter the neckdown region. As regards temperature measurements at the point $z_1$, as one can see from Fig. 3, the transmission band $\Delta T_1(\omega)$ for thermal perturbations in this case is comparable to the transmission band of $W_c(\omega)$, i.e., the speed of the measurements is quite high and the measurements introduce virtually no frequency distortions in the control of the lightguide drawing process.

We can now determine the form of the frequency characteristic of the regulator thus:

$$W_r(\omega) = -\Delta T_2(\omega)/(\Delta T_1(\omega)\, W_c(\omega)). \tag{7}$$

Approximating the functions $\Delta T_1$; $\Delta T_2$; $W_c$ by exponentials (as close as possible), we obtain the form of the function $W_r$ (Fig. 3, broken curves). The broken line also shows the

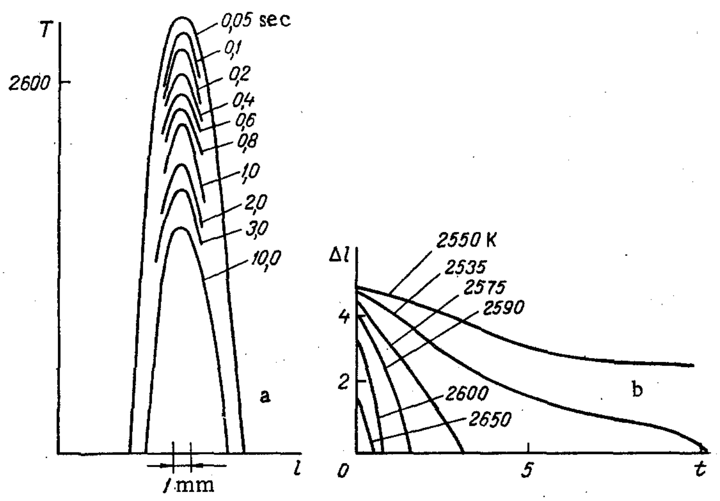


Fig. 4. Change in the temperature distribution in the neckdown region after the "dynamic shock": a) graphs of the temperature for the hottest region at different times; b) decrease in the linear size of isothermal zones. $\Delta l$, mm; t, sec.

transfer characteristic of the regulator. If at the moment t = 0 the power of the 400-watt laser heater drops by 15%, then to compensate this perturbation the temperature must be adjusted with the help of the controlling 50 mW laser, which must be switched on in accordance with $W_r(t)$.

This type of simultaneous action along two channels was simulated numerically. The result is shown in Fig. 3a (line with dots). It is obvious that compared with the change in the temperature without correction ($\Delta T_2(t)$ in the same figure) the drift in the temperature at the point $z_2$ can be reduced by an order of magnitude. Full compensation could not be realized, since the transfer functions in the formula (7) were not approximated accurately enough. Theoretically, careful selection of this approximation enables full stabilization of the temperature at the point $z_2$.

Experimental Check of the Possibility of Controlling the Lightguide Drawing Process with the Help of a Low-Power Laser Heater. For this the experimental setup shown in Fig. 1 was developed; it consisted of a laser drawing system, described in [4], with the total power of the $CO_2$ lasers equal to 400 W and a low-power controlling laser with a power of about 3 W. A CO laser of the ILGN-705 type was employed as the controlling laser. The use of a laser, radiating in the region 5-6 μm, makes it possible to heat the lightguide uniformly, since the penetration depth of the $CO_2$ laser radiation in quartz is of the order of 100 μm, i.e., an order of magnitude higher than for a $CO_2$ laser [10], and equals approximately the diameter of the lightguide. Another feature of this type of laser is that because of a number of properties of the lasing mechanism of the active medium based on CO molecules the power stability of the CO laser with a nonselective resonator is very high ($\Delta P/P \leq 1\%$) [11]. All this makes it possible to employ successfully a CO laser for controlling the lightguide diameter.

To reduce the effect of the accuracy of alignment of the laser beam relative to the lightguide at the point $z_2$ on the measurements performed, the laser beam was not focused on the lightguide, but rather it was defocused (the power density of the laser radiation was sufficient for heating the lightguide).

The spectrum of variations of the lightguide diameter as a function of the power density of the radiation of the controlling laser was measured. These measurements showed that the possibilities for controlling the lightguide diameter by the proposed method are very extensive relative to both the amplitude and frequency values of the variations of the diameter.

Organization of feedback for automatic regulation of the lightguide diameter requires the solution of the problem of precise measurement of the lightguide diameter at the point of its formation from the stock with the help of the CCD array. Existing developments in this area will make it possible to do so in the near future.

The use of a drawing control system for quartz lightguides based on an auxiliary low-power laser heater makes it possible to solve successfully the problem of transport delay in creating feedback in the circuit for measuring the deviation of the lightguide diameter from a fixed value (the heat source).

It is important to emphasize that this scheme for lightguide diameter control is also applicable to other heat sources for heating quartz stock for drawing lightguides — graphite furnaces and oxygen-hydrogen burners [1].

The beam of the controlling laser is modulated quite well and with a high frequency with the help of TsTS electrooptical ceramics.

## NOTATION

z, axis oriented along the draw axis; $z_1$, point into which the radiation from the main laser heater is focused; $z_2$, point into which the radiation of the controlling laser is focused; $\Delta P_1$, variation of the radiation power injected from the main heater; t, time; $\omega$, frequency; $\Delta T_1$, fluctuations of the temperature near the point $z_1$; $\Delta T_2$, fluctuations of the temperature near the point $z_2$; $\Delta d$, variation of the lightguide diameter; $\Delta P_2$, change in the radiation power of the controlling laser; W, $W_c$, and $W_r$, transfer functions; $a(z)$, radius of the neckdown region; $a_0$ and $a_d$, radii of the stock and lightguide; V, velocity of matter in the neckdown region (longitudinal); $V_0$ and $V_d$, rate of feeding of the stock and drawing of the lightguide; u, transverse velocity of matter; R and r, axis perpendicular to the draw axis in the coordinate systems adapted and not adapted, respectively, to the shape of the neckdown region; k(T), coefficient of thermal conductivity; n, refractive index; $\sigma$, Stefan—Boltzmann constant; $\alpha$, average absorption coefficient; $\rho$ and $C_p$, density and heat capacity; T, temperature of the material; h(z), coefficient of heat transfer; Q(z), power of the absorbed laser radiation; $z_N$, length of the working region; and 2B, width of the neckdown region.

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