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Effect of Metal Coating on the Optical Losses in Heated Optical Fibers

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Abstract—The effect of heating in air on the optical losses in metal-coated fibers has been studied. Two fibers were drawn from the same silica preform and coated by different metals (copper and aluminum). Dependences of a change in the optical losses on the temperature were measured in a 20–400°C range at a 50°C step. The optical losses of metal-coated fibers heated to temperatures below 300°C change mostly due to the microbending contribution. At temperatures above 300°C, the main contribution to increasing optical losses is due to the absorption on OH groups. It is established for the first time that the contribution to optical losses due to the OH groups is much more pronounced in Al-coated fibers than in Cu-coated ones. In addition, the Al-coated fibers exhibit growth in the optical losses above 300°C due the absorption on molecular hydrogen.

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In recent years, the development of fiber-based temperature sensors led to the need for optical fibers capable of operating at elevated temperatures as compared to the usual fibers (i.e., above 85°C and sometimes even above 500°C). It was suggested to solve this problem using metal-coated optical fibers [1]. A metal coating allows the working temperature range to be increased up to a level limited by melting of the metal. In addition, the hermetic character of a metal coating makes it possible to reach a strength level of about 13 GP (theoretical strength of silica). On the other hand, the presence of a metal coating leads to an increase in the microbending optical losses due to a difference in the linear thermal expansion coefficients (TECs) of the silica core and metal coating, which leads to a uniform increase in the spectral optical losses in multimode fibers [2, 3].

Hydroxy (OH) groups are among the main technological impurities that lead to additional optical losses at wavelengths of 0.95, 1.24, and 1.39 μm, which are derived from the main absorption wavelength at 2.72 μm [4]. As is known, the modified chemical vapor deposition (MCVD) technology, which is widely used in the production of silica fibers, involves the following factors determining product contamination with OH groups:

(i) diffusion of water vapor from ambient atmosphere to a nonhermetic technological chamber;

(ii) transfer of water vapor and molecular hydrogen from the flame of an oxygen–hydrogen burner to the quartz substrate tube;

(iii) diffusion of OH groups from the quartz tube to a light-reflecting sheath and the silica core;

(iv) transfer of hydrogen-containing impurities from the initial halides and oxygen to the substrate tube.

Mechanisms responsible for the increasing level of losses in metal-coated fibers operating at elevated temperatures have been extensively studied, but direct comparison of a change in this level for the fibers coated by different metals was not reported until now. For such a comparison, two multimode graded-index optical fibers were drawn from the same preform and then coated by different metals. The perform for drawing fibers was made of KUVI grade silica (Gus-Khrustal'nyi Plant, Russia) with a high content of OH groups (200–400 ppm) [3] and jacketed with a quartz tube (also containing a high amount of OH groups). The preform has a graded index, a numerical aperture of NA = 0.2, and $\Delta n = 0.014$. In the course of drawing, the fibers were coated sequentially with a layer of pyrolytic carbon (20 nm) and then with a 25-μm-thick deposited metal (aluminum or copper) film. The silica core diameter was 200 μm. Thus, two fiber samples were obtained with a length of about 240 m and a total diameter of 250 μm, wound into coils, and placed into an electric furnace for annealing.

The optical losses in fibers were determined using a spectrum analyzer (S15, York Co.) operating in a 800–1600 nm wavelength range. Both samples were heated in a temperature range of 20–400°C at 50°C steps, each step taking 15 min. Upon reaching 400°C, both samples were kept at this temperature for 1 h (five time steps).

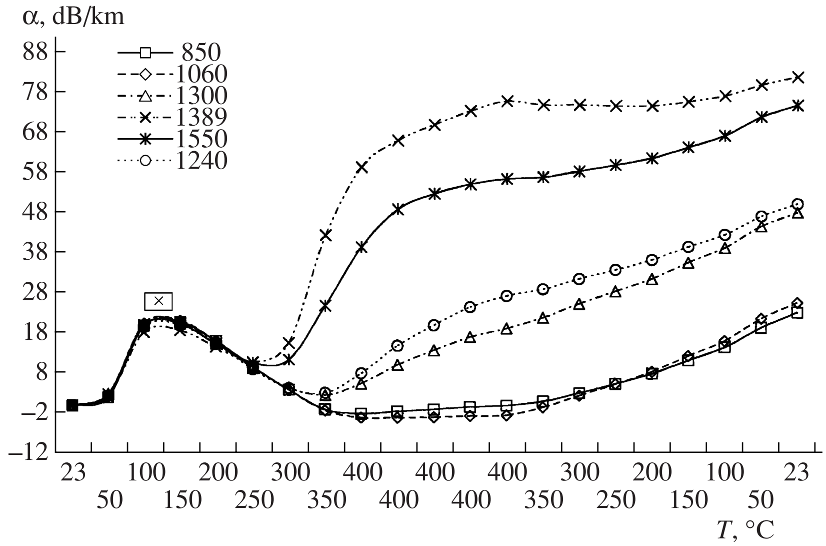

Fig. 1. Plots of the optical losses at various wavelengths in Al-coated fiber versus temperature (*X* is the characteristic temperature region).

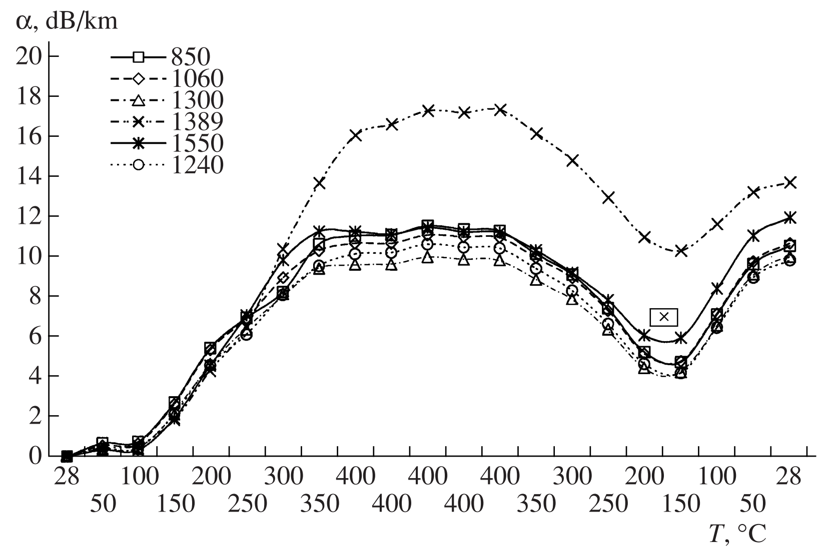

Fig. 2. Plots of the optical losses at various wavelengths in Cu-coated fiber versus temperature (*X* is the characteristic temperature region).

The initial losses at a wavelength of 1300 nm in the Cu-coated fiber were 2.4 dB/km; the initial losses in the Al-coated fiber were somewhat greater.

Figures 1 and 2 show relative changes in the optical losses at various wavelengths as functions of the temperature for Al- and Cu-coated fiber, respectively. As can be seen from Fig. 1, losses in the Al-coated fiber heated to a temperature below 300 K change mostly due to the microbending contribution. This conclusion is confirmed by the fact that α increments in the temperature interval from 0 to 250°C are independent of the wavelength, which is a characteristic feature of the microbending-induced losses [2, 3]. In the 150–200°C interval (Fig. 1, characteristic temperature region *X*) the optical losses exhibit a decrease. According to [5], this region corresponds to the recrystallization of aluminum,

At temperatures above 300°C, increasing contribution to the optical losses is due to the absorption on OH groups (λ = 1389 and 1240 nm), which reaches 75 dB/km at 1389 nm (the "tail" of the absorption band at 1.39 μm is also manifested by an increase in the absorption at 1.24, 1.3, and 1.55 μm). The magnitude of microbending-induced losses can be judged from the losses at 0.85 and 1.06 μm, which are not influenced by the losses due to OH groups. Upon termination of the heating stage, the samples were cooled to 20°C, which was accompanied by an increase in the losses due to microbending.

In the case of annealing a Cu-coated optical fiber (Fig. 2), the losses increase mostly due to the microbending contribution, the magnitude of which is also independent of the wavelength. In addition, there is a minimum of microbending-induced losses (Fig. 2, characteristic temperature region *X*). According to [5], this region corresponds to the recrystallization of copper.

At temperatures above 300°C, the losses on Cu-coated fiber also exhibit a growth due to OH groups (1389 nm), which reach a maximum of 18 dB/km at 400°C (with allowance for the microbending contribution). The microbending contribution can be traced by a change in the optical losses at 0.85, 1.06, 1.3, and 1.55 μm.

The data in Fig. 1 show that the Al-coated fiber is characterized by a more pronounced growth in the optical losses on OH groups (above 70 dB/km at 1389 nm). In contrast, the Cu-coated fiber (Fig. 2) exhibits a rather insignificant increase in the losses (not exceeding 6 dB/km at 1389 nm).

The obtained experimental results were mathematically processed with allowance for the well-known fact [6] that the ratio of the intensity of losses at 1.39 and 1.24 μm is 23 : 1. On the other hand, the absorption peak due to molecular hydrogen also occurs at 1.24 μm. Using experimental data to calculate the difference $\Delta\alpha$ [dB/km] defined as follows:

$$\Delta\alpha = \alpha_{1240} - \frac{\alpha_{1389}}{23}, \quad (1)$$

where α_{1240} are the optical losses at 1240 nm, we conclude that the absorption on hydroxy ions alone corresponds to $\Delta\alpha \sim 0$, while in the presence of hydrogen $\Delta\alpha > 0$.

Figure 3 shows the plots or relative losses, from which it can be seen that Cu-coated fiber has $\Delta\alpha \sim 0$, while the Al-coated fiber is characterized by a growth in $\Delta\alpha$ at temperatures above 350°C. We believe that this is evidence for an increase in the concentration of molecular hydrogen in the latter sample. The content of molecular hydrogen can be estimated using published data on the dependence of additional losses $\Delta\alpha(H_2)$ in a hydrogen-saturated fiber on the hydrogen pressure and fiber temperature, which can be expressed as follows [7, 8]:

$$\Delta\alpha(H_2) = A(\lambda)\exp\left(\frac{8670\ \mathrm{J/mol}}{RT}\right), \quad (2)$$

where $A(\lambda)$ is the spectral dependence of these losses. For $\lambda = 1.24$ μm, we have $A(1.24\ \mu\mathrm{m}) = 0.27$ dB/(atm bar) and, hence, $\Delta\alpha = 1.27$ dB/km at $T = 400$°C. Since the magnitude of additional losses in our experiments was ~19 dB/km (Fig. 3), the equivalent external pressure must be ~15 bar. In this case, the concentration of molecular hydrogen according to [8] is ~7.5 × 10^{18} mol/cm^3 or ~2800 ppm, which is much greater than the concentration of hydroxy ions in the volume of the substrate tube of the initial preform.

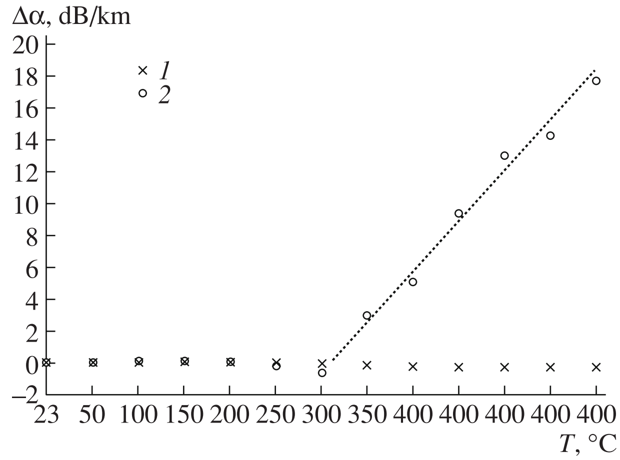

Fig. 3. Plots of the difference of losses $\Delta\alpha$ versus temperature for (*1*) Cu-coated and (*2*) Al-coated silica fibers.

In conclusion, we have studied the spectral variation of optical losses in Al- and Cu-coated silica fibers heated in air up to 400°C. It is established that the heating of an Al-coated fiber, in contrast to the Cu-coated one, leads to (i) a significant increase in the contribution of losses caused by the absorption on hydroxy ions at $\lambda = 1.39$ and 1.24 μm and (ii) the appearance of an additional absorption at $\lambda = 1.24$ μm, which is apparently caused by the presence of molecular hydrogen. It should be noted that a qualitatively similar behavior was observed for many samples. In order to elucidate the factors responsible for this anomaly, additional investigations are in progress.

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