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Optical Loss of Metal Coated Optical Fibers at Temperatures up to 800°C

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Abstract—Temperature band of ordinary telecommunication optical fibers is –60...85°C. The developing fiber optic sensors which can work at higher temperatures, required to develop metal coated optical fibers. The Purpose of the work is a researching additional optical loss of copper alloy coated optical fibers which were drawn from low hydroxyl group contamination preforms at temperatures 20...800°C. It is reached that metal coated optical fiber worked at temperature 700°C for 7 hours, while the optical losses changed from 2 to 3 dB/km at the wavelength of $\lambda = 1300$ nm. It is not observed intensive growth of optical losses on hydroxyl groups at 800°C, which was observed in metal coated optical fiber when it was heated at 700°C.

Keywords: metal coated optical fiber; optical loss; temperature.

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1. INTRODUCTION

Temperature band of ordinary telecommunication optical fibers is –60...85°C. The developing fiber optic sensors which can work at higher temperatures, required to develop metal coated optical fibers [1]. In references [2–5], we investigated the influence different metal coating types (aluminum or copper) on optical loss of metal coated optical fibers up to 400°C, which showed that copper coated optical fibers have less optical loss, then aluminum coated one. In addition, we took experimental results [4], where copper coated optical fiber, which was made from quartz tube with high quantity of hydroxyl-groups (Si–OH) (MCVD technology) has high additional loss on hydroxyl-groups contamination (more 250 dB/km at the wavelength of $\lambda = 1389$ nm), at temperatures more 600°C, because of diffusion process. For comparing, at some conditions of heating, copper coated optical fiber, which was made based on Heraeus F-300 tube (FCVD technology) showed a low additional optical loss on hydroxyl-groups (~12 dB/km at the wavelength of $\lambda = 1389$ nm).

The Purpose of the work is a researching additional optical loss of copper alloy coated optical fibers at temperatures 20...800°C.

The necessity of research is due to lack of detailed information about the magnitude of optical losses in metal coated optical fibers at high temperatures more than 400°C. It was known that metal coated optical fibers at temperatures of 300–1000°C, has an irreversible increase in optical losses. But the reasons for this have not been investigated fully [6].

In the literature information on the optical losses of radiation at the metal coated optical fiber, at temperatures above 400°C, were represented by only two articles. The first article [7] was made in 1986 and concerned optical properties aluminum coated optical fiber at temperatures up to 650°C. Such fibers were made using the then available technology manufacturing preforms and quartz tubes. In second article [8], which was made in 1997, has been shown experimentally that the pure-copper coated optical fiber, can work for only a few minutes at temperatures 700...800°C, because of the rapid growth of optical losses, but the reasons for such growth of optical radiation losses were not be presented.

2. METHODS

To product such fiber we take a preform which was made on basis of quartz tube “Heraeus F-300” with low quantity hydroxyl-groups contamination 0.2...0.5 ppm [9], that equal to additional loss $\alpha =$

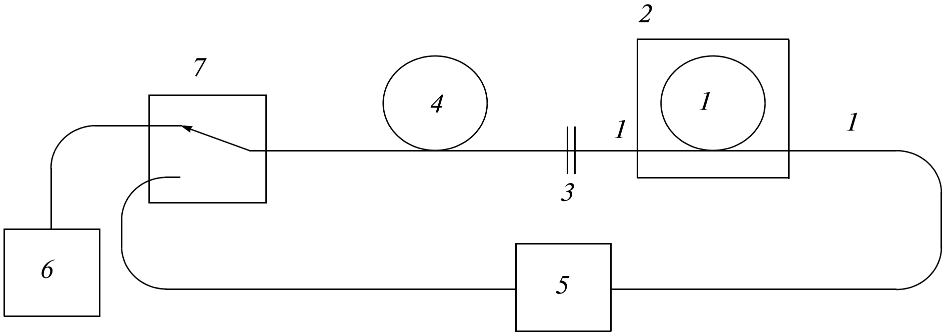

Fig. 1. The scheme of setup *1*—metal coated optical fiber; *2*—high-temperature furnace; *3*—fused connection; *4*—additional G.651 optical fiber; *5*—spectrum analyzer; *6*—optical time domain reflectometer (OTDR); *7*—optical switcher.

5...50 dB/km at the wavelength of λ = 1389 nm [10]. Germanium doped waveguide core was made by means of FCVD technology. The preform was drawn to metal coated optical fiber with such parameters: core diameter 50 μm, diameter of cladding – 230 μm, copper alloy coating thickness 20 μm. Initial loss was ~1 dB/km at the wavelength of λ = 1300 nm. Additional loss was ~1 dB/km at the wavelength of λ = 1389 nm, because of hydroxyl groups. Numeric aperture NA = 0.3. Metal coated optical fibers rewound to coil and were heated from 20 to 700...800°C for 1 hour. After temperatures 700...800°C were reached metal coated optical fibers were kept for 6.5 hours, Optical loss was measured every 30 minutes.

To product such experiment experimental setup was made. The scheme of the setup is shown on Fig. 1.

Experimental setup consisted of metal coated optical fiber (1), which was located in high-temperature furnace (2). Metal coated optical fiber was fused (3) with additional optical fiber (4) G.651 type to get fixed mode structure. Fusions of such fibers were made many times to get minimum additional loss. Optical loss were measured as by means of spectrum analyzer (5) which worked at the wavelengths of 600...1650 nm, as by means of optical time domain reflectometer (OTDR) (6) which measured backscattering loss at the wavelength of 1300 nm. Choose of measurement were made by means of optical switcher (7).

3. EXPERIMENTAL RESULTS AND DISCUSSION

Optical loss of metal coated optical fiber when it was heated up to 700°C for 1 hour was changed (see Fig. 2).

It is shown, that optical loss increased in shortwave spectrum region at the wavelength of less 800 nm and at the wavelength of λ = 1389 nm, because of hydroxyl-groups diffusion from quartz cladding to waveguide core of optical fiber. Microbending loss also changed (Fig. 3).

During of heating, optical loss also was measured by OTDR to measure backscattering loss at the wavelength of λ=1300 nm.

Microbending loss increased at temperatures 20...400°C from 1 to 4 dB/km (Fig. 3, area 1), and at temperatures 400...700°C decreased from 4 to 0.36 dB/km (Fig. 3 area 2). Microbending loss was measured by OTDR at the wavelength of λ = 1300 nm. In our opinion, the cause of microbending loss decrease at temperatures more 400°C is a recrystallization annealing of metal coating [11], which result in generation of a new structure of metal coating without defects.

It is shown on Fig. 4, at heating of metal coated optical fiber takes place increase of backscattering power (ΔP = 0.33 dB at the wavelength of λ=1300 nm), at same time optical loss decreased from 1 to 0.33 dB/km at the wavelength λ = 1300 nm. In our opinion, the cause of such backscattering power increase is an increase of fluctuation of doped material (GeO_2) in light-guide core of optical fiber [7, 12] because of heating. In addition, such backscattering power increase can be partially explained shortwave optical loss increase (less 800 nm) which was shown on Fig. 2. However, shortwave optical loss increase cannot be full described by dependence (1) [12] that indicate the presence other ways of additional optical loss and in our opinion require later investigation.

$$\alpha(\lambda) = A * \lambda^{-4}, \tag{1}$$

where A – Relay scattering coefficient $\left[\frac{dB * \mu m^4}{km}\right]$, λ – wavelength, μm.

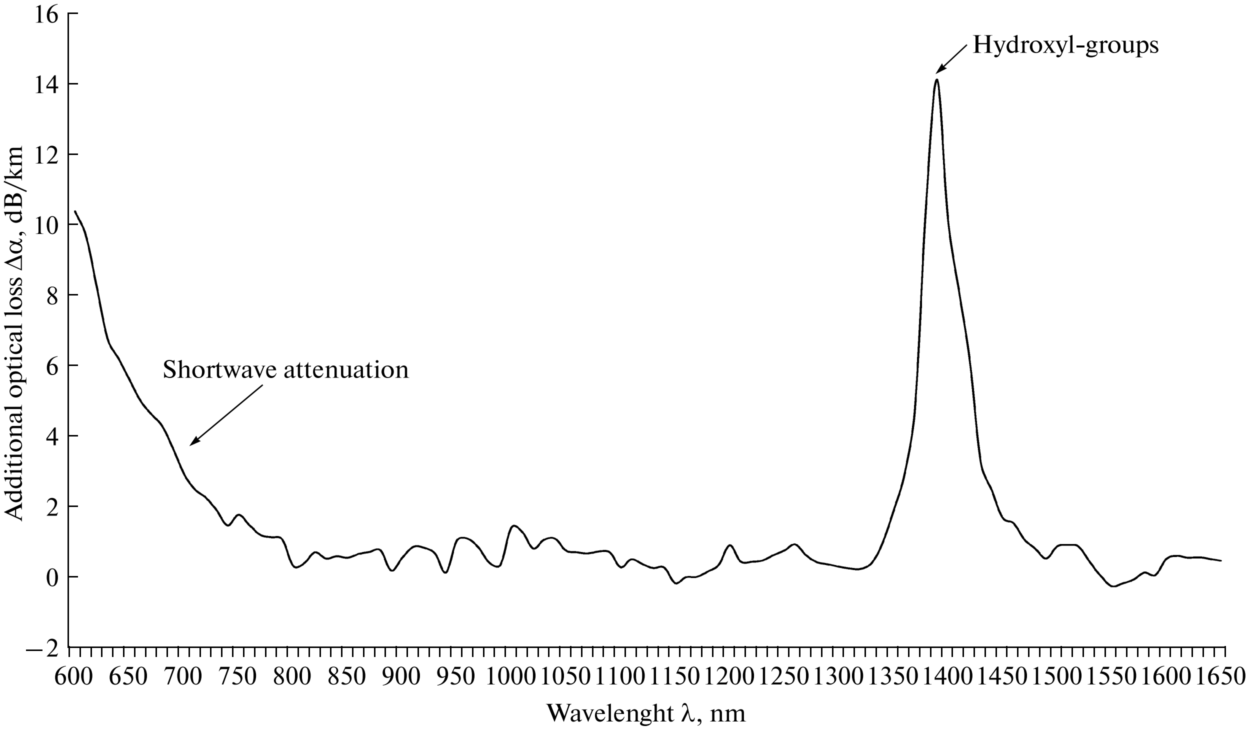

Fig. 2. Changing of optical loss at heating metal coated optical fiber from 20 to 700°C for a 1 hour

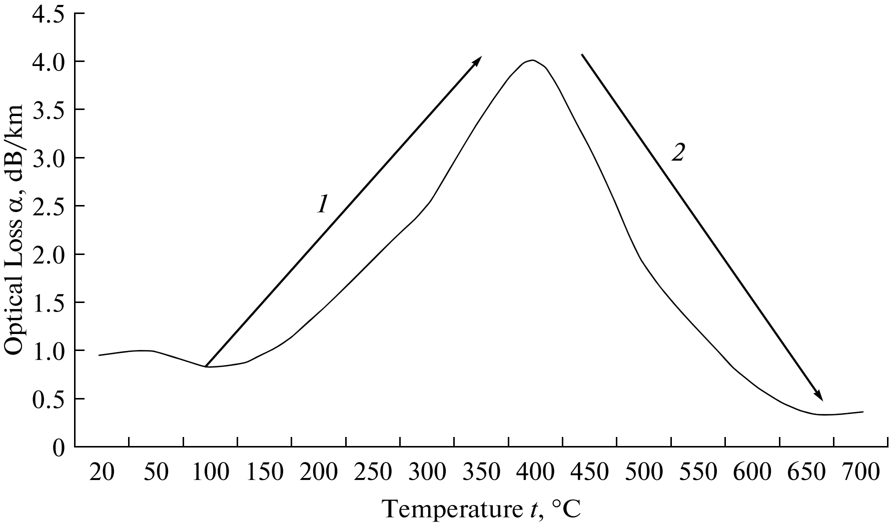

Fig. 3. Dependence of microbending loss from temperature of heating

Optical loss dependence from exposure time of metal coated optical fiber at temperature 700°C at the wavelength of λ = 1300 nm is showed on Fig. 5. It is showed, that as increasing exposure time, additional losses steadily increased at the wavelength of λ = 1300 nm.

Metal coated optical fiber optical loss at wavelengths 600...1650 nm is presented on Fig. 6. It is showed on Fig. 6, that with increasing exposure time from 4.5 to 6.5 hours as "gray loss" increase (wavelength independent loss) as hydroxyl-groups loss at the wavelength of λ = 1389 nm. If we take known correlation that hydroxyl-groups concentration of 1 ppm excites additional loss ~55 dB/km at the wavelength of λ = 1389 nm [10]. By means of last dependence we can take that additional loss of ~20 dB/km (Fig. 6 curve *1*) is equal to ~0.36 ppm of hydroxyl-groups concentration. Approximately the same hydroxyl groups con-

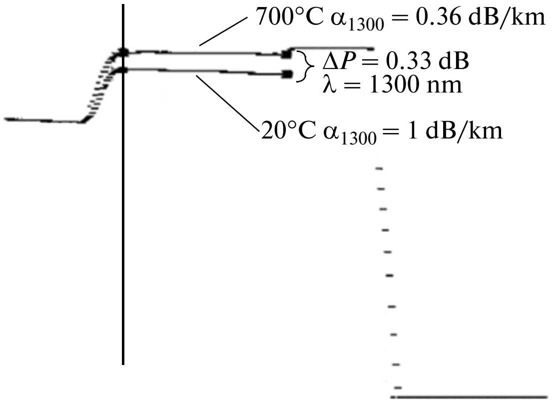

Fig. 4. Backscattering optical loss changing of metal coated optical fiber at temperatures 20 and 700°C. (The photo is from OTDR).

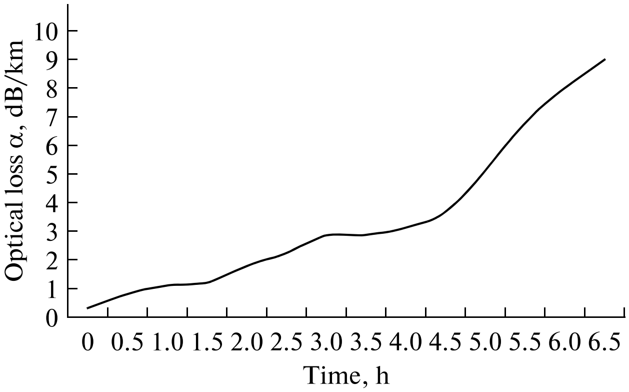

Fig. 5. Dependence of optical loss from time of exposure at temperature 700°C at the wavelength of λ=1300 nm

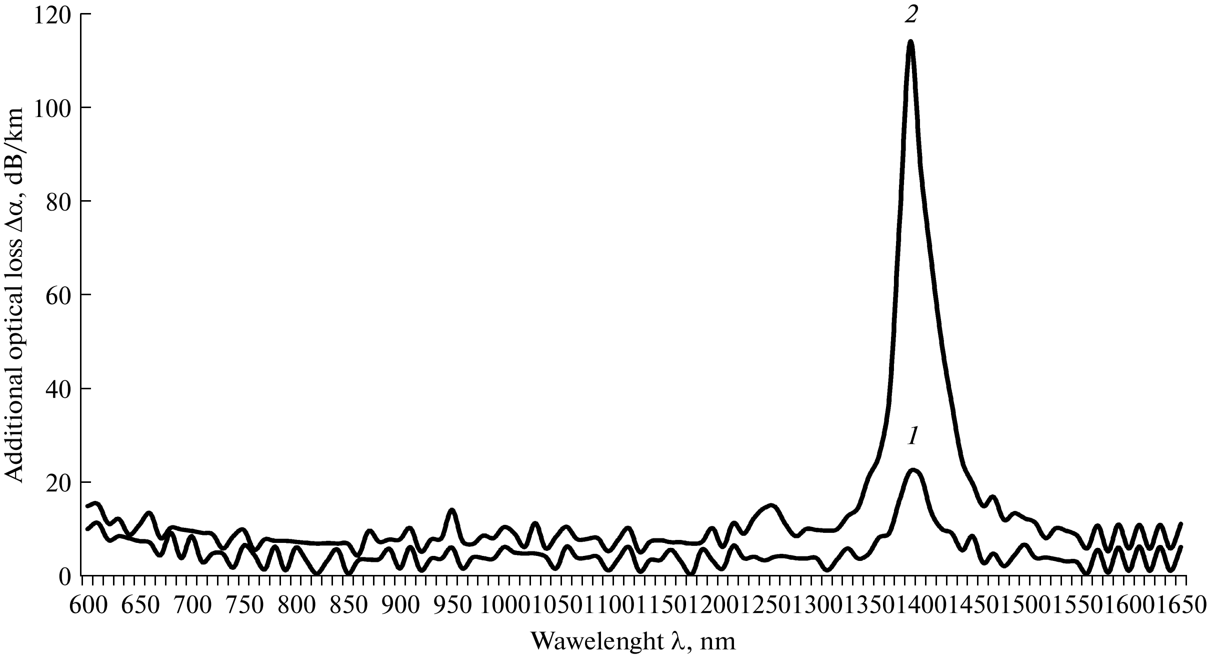

Fig. 6. Dependence of optical loss of metal coated optical fiber at heating from 20 to 700°C and keeping at 700°C for: (*1*) 4.5 hours, (*2*) 6.5 hours.

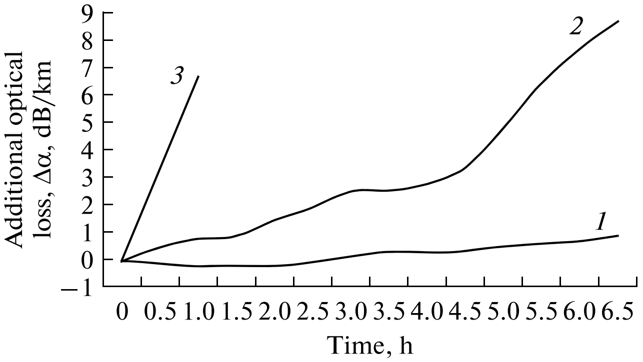

Fig. 7. Optical loss change in copper alloy coated optical fibers at the wavelength of λ = 1300 nm (*1*)—diameter 300 μm (*2*)—diameter 230 μm (*3*)—diameter 200 μm.

centration 0.2...0.5 ppm [9] it is shown in specification “Heraeus F-300” quartz tube, which was used to make such perform. Thus, we can conclude that hydroxyl-groups diffusion from cladding to core of metal coated optical fiber is a cause of optical loss increase on hydroxyl-groups after 4.5 hours at the temperature of 700°C.

Later take place optical loss excursion up to 120 dB/km at the wavelength of λ = 1389 nm (Fig. 6 curve *2*), that equal hydroxyl-groups concentration increase up to 2.2 ppm. Such hydroxyl-groups concentration increase is significantly higher than hydroxyl-groups concentration of Heraeus F-300 quartz glass [9]. In our opinion, the cause of later hydroxyl-groups optical loss increase is oxidation and depressurization of metal coating optical fiber, which excites hydroxyl-groups formation from air.

To research how optical loss depends from outer diameter of optical fiber and metal coating thickness a new metal coated optical fiber were drawn. Such fiber had parameters: optical fiber diameter core/cladding – 50/300 μm, metal coated thickness – 40 μm. One fiber was heated according to the method which described previously. It can be seen from Fig. 7 curve *1* as cladding diameter increasing as optical loss decreasing. Effective optical loss increase was 1 dB/km at the wavelength of λ = 1300 nm. For comparing, on Fig. 7 curve *2* presented optical loss change for 230 μm optical fiber and coating thickness 20 μm and on Fig. 7 curve *3* presented optical loss change for 200 μm optical fiber and coating thickness 25 μm.

It is shown, that metal coated optical fiber with diameter of 300 mm increase in the additional loss is less than optical fiber of 230 μm and even more so in optical fiber diameter 200 μm, in spite of the greater thickness of metal coating.

In addition, the metal coated optical fiber with diameter of 300 μm does not have optical loss excursion of optical losses on hydroxyl-groups after 4.5 hours of exposure, at 700°C, probably due to the greater thickness of metal coating.

Appearance of metal coated optical fiber with diameter of 300 μm after 6.5 hours of heating at the temperature of 700°C is shown on Fig. 8. It is shown that metal coated optical fiber with diameter of 300 μm are not destroyed after heating, in contrast to the metal coated optical fiber with external diameter of 230 μm and 200 μm. In addition, this optical fiber is preserved carbon sublayer (see figure 8, position 1). In order to examine the state of carbon sublayer in this heated optical fiber one turn was seized from coil and was exposed to nitric acid. Then, at the site, it could easily be removed mechanically. The real color of the carbon sublayer does not match the picture and can be described as brilliant – gray. When measuring with an ohmmeter, the electrical resistance of carbon coating after heating decreased by 10%.

Comparing the results obtained by us, it should be noted, once again, the reference [8] where presented experimental results for single-mode metal coated optical fiber with cladding of 300 μm which is at a temperature of 700°C were only a few minutes, while the optical losses reached a value of 50 dB / km at wavelengths λ = 1300 and 1550 nm, because pure-copper coating with high oxidation rate was used.

Later experiment was conducted on the study of efficiency of metal coated optical fiber at higher temperatures. According to the method described above, metal coated optical fiber diameter of 230 mm was subjected to heating, for 6 hours at temperatures 700 and 800°C (see Fig. 9).

It is shown, that additional microbending optical loss increased because of oxidation of metal coating. In this case, there is increased growth rate of the optical losses as a function of temperature. Since the magnitude of growth loss 9 dB/km at the wavelength of λ = 1300 nm at a temperature of 700°C was reached within 6.5 hours. At a temperature 800°C this level of losses has already reached within 2...2.5 hours. In addition,

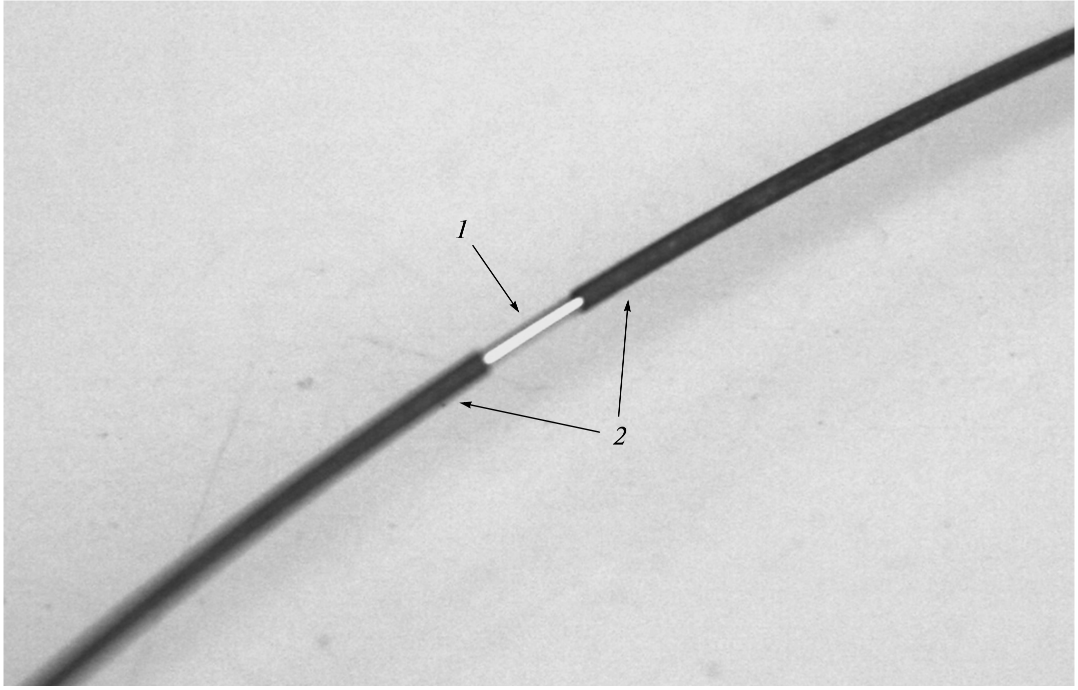

Fig. 8. Photo of appearance of metal coated optical fiber with copper alloy heated up to 700°C for 7 hours with cladding of 300 μm (*1*) – optical fiber with carbon sub layer (*2*) – oxidized copper alloy coating.

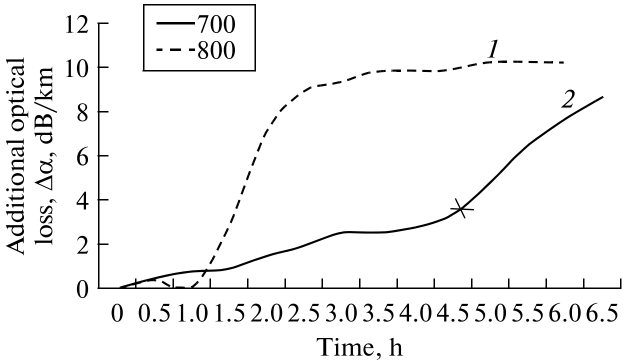

Fig. 9. Additional optical loss (λ = 1300 nm), dependent of exposure time at temperature of 800°C (*1*) and 700°C (*2*); X – point of hydroxyl-groups optical loss (λ = 1389 nm). Diameter of optical fiber is 230 μm.

when the level of losses of 9...10 dB/km at the wavelength of λ = 1300 nm was reached the growth loss almost stopped without any noticeable increase over time, which can be explained by the complete oxidation of the metal coating. We can assume that in such state metal coated optical fiber, maybe used, in place, long enough until there is physical damage of metal coated optical fiber. Just wanted to point out the initial portion of the heating (1 hour) at 800°C (Fig. 9 curve *1*) when there was no increase in optical losses. This lack of increase in losses can be explained by competition between the processes of annealing (which leads to the removal of stress) and oxidation. The kinetics of both processes depends on the temperature and the temperature increases the intensity of both processes increases.

The growth of optical losses on hydroxyl-groups at the wavelength of λ = 1389 nm was measured during the heating at 800°C. In this case, we was not observed intensive growth of optical loss on hydroxyl groups after 4.5 hours at 800°C, which was observed in metal coated optical fiber when it was heated at 700°C (Fig. 9, curve 2). This phenomenon can be explained by reaction of removing hydroxyl-groups (Si–OH) at temperatures more 700°C, according to the chemical reaction (2) [13]. It should be noted, interaction

(2), can take place at sufficient high quantity of E' centers (≡Si *) which products at high temperature and have optical loss at wavelengths $\lambda < 800$ nm [7] (see Fig. 2).

$$\equiv\text{Si}\,^* + \text{SiOH} \Rightarrow \equiv\text{Si–O–Si}\equiv +0.5\text{H}_2 \quad (2)$$

By reducing the temperature to 550°C for 10 minutes by an increase in losses of up to 24 dB/km at the wavelength of $\lambda = 1389$ nm, while the optical losses during exposure 800°C had a magnitude of ~20 dB/km at the wavelength of $\lambda = 1389$ nm.

4. CONCLUSIONS

We obtained metal coated optical fiber which showed the possibility of using such copper alloy coated optical fiber at temperatures 700°C for 4.5 hours without a significant increase in losses at the wavelength of $\lambda = 1389$ nm. With increasing exposure time of metal coated optical fiber to 6.5 hours at 700°C optical loss of up to 9 dB/km at the wavelength of $\lambda = 1300$ nm and up to 120 dB/km at the wavelength of $\lambda = 1389$ nm. Further reduction in optical loss and increase in the time of an optical fiber coated with metal at extremely high temperatures made possible by applying heat-resistant alloy and increase the diameter of optical fiber. It has been reached that metal coated optical fiber worked at temperature 700°C for 7 hours, while the optical losses changed from 2 to 3 dB/km at the wavelength of $\lambda = 1300$ nm.

Metal coating oxidation of metal coating optical fiber is the main reason leading to an increase of microbending optical loss in metal coated optical fiber at high temperatures.

In our opinion, optical properties metal coated optical fibers at high temperature require additional investigations.

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