Methods and technique of manufacturing silica graded-index fibers with a large central defect of the refractive index profile for fiber-optic sensors based on few-mode effects

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ABSTRACT

The results of experimental study on the main technological aspects relating to a full production cycle of 50/125 μm silica multimode graded-index fibers with the central defect of the refractive index profile realized as a large dip are presented. Preform synthesis conditions for controllable implementation of the mentioned defect via MCVD method are analyzed and optimized. The effect of geometrical irregularities, induced by drawing optical fibers under the manual maintenance of the outer diameter stability, on attenuation has been explored. Applying the Weibull theory, a statistical evaluation of mechanical properties, particularly tensile strength, of the optical fibers drawn at various temperatures has been conducted.

Keywords: silica optical fiber, multimode graded-index fiber, refractive index profile defect, chemical vapor deposition, optical fiber drawing, attenuation coefficient, mechanical strength, few-mode effects

1. INTRODUCTION

Currently, silica multimode optical fibers (MMFs) with the graded refractive index (RI) profile are basic elements of compact multiport info-communication networks which connecting lines are characterized by relatively short lengths (typically up to 2000 meters, in practice – a few hundred or even dozens of meters), combining high data transmission bitrates and excellent compatibility with lasers sources[1-3].

Transition to multi-gigabit rates inevitably requires an application of coherent laser sources in optical modules of the active equipment of such networks[1, 3-5]. The latter in combination with MMF generates the regime of propagating a limited amount of guided mode components (starting from literally two to a few dozen), i.e. the few-mode regime of operation[5, 6]. The differential mode delay (DMD) parameter, caused mostly by RI profile deviations from the optimal parabolic shape, becomes the key factor defining a capability of MMF to function in the few-mode regime[1, 3-5]. For this reason, the very first generation of MMFs (categories OM1.. OM2) with technological defect in the center of the RI profile performed as a large dip, resulting in a strong manifestation of DMD effect[7-9] and consequently low bandwidth capacities, have been replaced by the new generation of MMFs (cat. OM3.. OM4) in multi-gigabit data transmission networks[5].

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On the other hand, as shown in a number of authors' papers, discussing the results of development and approbation the alternative to existing approach for registration of local and distributed external influences (for example, mechanical or temperature) in fiber-optic sensor networks operating in the few-mode regime[9-12], an application of low-loss MMFs with a strong manifestation of DMD effect may have a practical interest. This is about the analysis and comparison of 'reference' and 'current' forms of the few-mode optical signal passed through MMF with the disturbed RI profile. In this case DMD changes character of a short pulse response after formation due to the mentioned influences of additional micro- and macrobends which impact significantly mode conversion processes in optical fiber.

Over the past several decades, technological aspects of manufacturing high-performance silica graded-index MMFs have been widely investigated and demonstrated[13-17]. However, major efforts have been focused on elimination of the central defect for minimization of DMD, while much less attention has been paid to realization of MMFs with the pronounced controllable defect for maximizing DMD effect. Thus, the aim of this work consisted in experimental study of the main technological issues associated with a full production cycle of 50/125 μm silica graded-index MMFs having the explicit defect in the center of the RI profile.

2. FEATURES OF MULTIMODE GRADED-INDEX FIBER PREFORM FABRICATION PROCESS

It is known that the scheme of obtaining silica optical fiber includes two principal stages, namely, synthesis of a preform having a cylindrical form by methods of chemical deposition of silicon dioxide (SiO_2) from a gaseous phase and high-temperature transformation of such preform into a thin filament, i.e. fiber, coated with protective material[13-17]. In our case optical fiber preforms have been fabricated via the well-tried[13-15, 17-19] and mastered by the authors[20-27] MCVD (modified chemical vapor deposition) method beneficial for production of high-purity silica glass provided by isolation of a chemical reaction zone and supply lines for initial reagents from the external environment. The process is illustrated schematically in Figure 1.

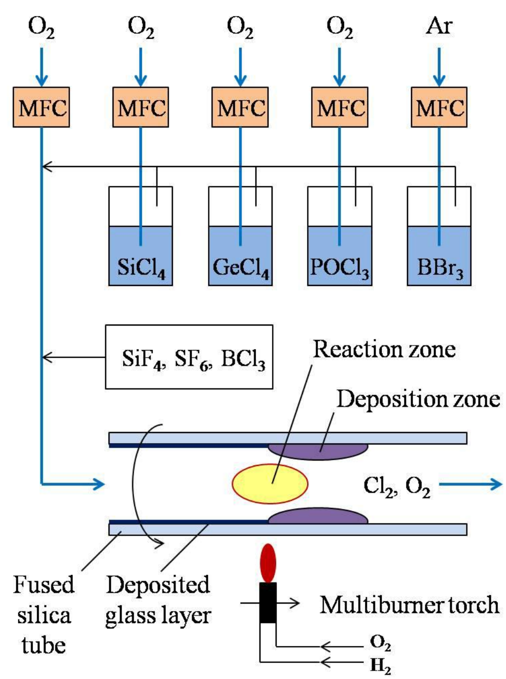


Figure 1. The process of silica optical fiber preform fabrication by the MCVD method.

The essence of the process is described below. Gas-vapor mixture which composition is formed by the supply of dry gas-carriers (oxygen or argon) regulated with the use of mass flow controllers (MFCs) through bubblers with high-volatile liquid reagents ($SiCl_4$, $GeCl_4$, $POCl_3$, BBr_3) is injected together with oxygen into the rotating silica tube. The tube is heated up to 1500 °C by the traversing with a speed of several mm/s multiburner torch. As the mixture enters the hot zone, a heterogeneous chemical reaction takes place to form submicron glassy particles that deposit on the inner surface of the tube downstream of the hot zone. The heating from the traversing torch fuses the deposited material to form a high-optical-quality glassy layer with a certain RI value. Frequently fabrication of a preform with the given RI profile is carried out by injection of gaseous fluorine-containing reagents (SiF_4, SF_6, CCl_2F_2, etc.) into the tube. After finishing the deposition and consolidation steps the tube is heated to 2000-2300 °C in order to collapse it into a rod from which optical fiber is drawn.

In this work, synthesis of graded-index MMF preforms was performed on the basis of silica tubes with low content of impurities (transition metal ions and hydroxyl groups). Deposition of glassy layers of the cladding was produced by the oxide composition P_2O_5-B_2O_3-SiO_2 with the RI almost equal to that of undoped fused silica (1.457012 at the wavelength of 633 nm). The rejection of depositing only SiO_2 particles on the inner surface of the tube was motivated by intention to reduce sintering temperature by 200-250 °C due to low glass viscosity to avoid undesirable deformation of the tube in the radial direction. The main complexity at that stage lied in matching of the flow rates of $POCl_3$ and BCl_3 to except bubble formation and RI depression.

Deposition of glassy layers of the core was carried out in the system GeO_2-P_2O_5-SiO_2 characterized by a consecutive increase of the $GeCl_4$ flow rate with respect to the fixed $SiCl_4$ flow rate in each of 40 passes of the torch. As in the previous case, co-doping with small amounts of P_2O_5 was intended to decrease the process temperature. While finishing formation of the multilayer structure, a slightly positive pressure (~ 0.01 atm) was supplied into the opposite end of the tube to prevent its early collapse by the surface tension forces.

In graded-index MMFs variation of the RI profile is described by the relation[1, 4, 28]:

$$n^2(r) = n_1^2\left(1 - 2\Delta\left(\frac{r}{a}\right)^g\right), \tag{1}$$

where n_1 – maximum value of RI at the center of a core, r – radial coordinate, a – core radius, $\Delta = \dfrac{n_1^2 - n_2^2}{2n_1^2}$ – relative difference of core and cladding RIs[28] (n_2 – cladding RI), g – profile parameter.

Considering the process of particles formation and consolidation stationary (the volume of deposited glass in each layer remains constant), it is possible to convert dependence (1) to the expression[13]:

$$V_n = V_{nt}\left(1 - 2\Delta\left(\frac{R_n}{R_0}\right)^g\right), \tag{2}$$

where V_n – flow rate of $GeCl_4$ to deposit the nth glass layer inside the tube, nt – total amount of deposited layers, R_n – distance of the nth deposited layer from the axis of a preform, R_0 – parameter defined by the tube geometry.

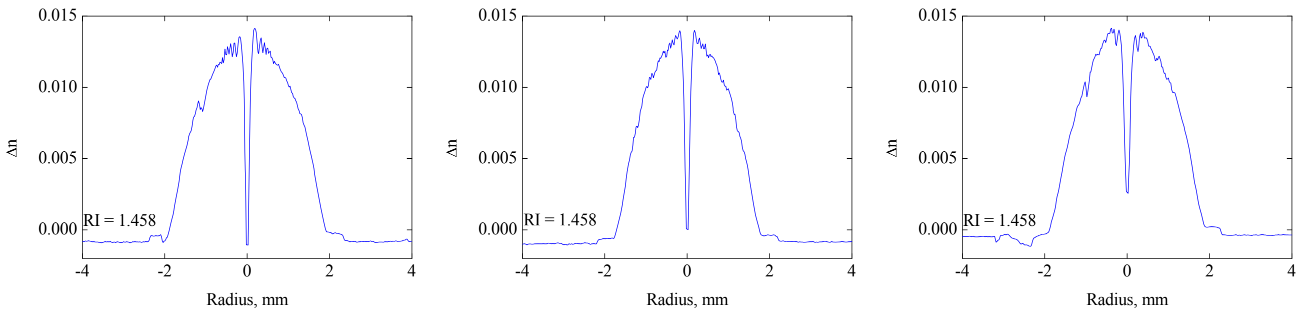
Taking into account transformation[13] $R_n = K\sqrt{nt - n}$, where K is a constant, expression (2) can be converted to the form

$$V_n = V_{nt}\left(1 - 2\Delta\left(\frac{K}{R_0}\right)^g \left(\sqrt{nt - n}\right)^g\right). \tag{3}$$

Assuming $g = 2$ (optimal parabolic shape of the RI profile that minimizes the intermodal dispersion in MMF at the wavelength near 1310 nm) and $\Delta = 0.01$ giving standard numerical aperture of 0.20, we get

$$V_n = V_{nt}\left(1 - 0.78\left(\frac{K}{R_0}\right)^2\right). \tag{4}$$

Relation (4) was taken as a basis for the selection of $GeCl_4$ and $SiCl_4$ flow rates to form the optimal graded RI profile. Figure 2 illustrates RI profiles of the first series preforms with the central defect realized as a large dip and the ratio of cladding and core diameters 2.5 (for obtaining 50/125 μm class MMFs) measured by P-101 refractometer.



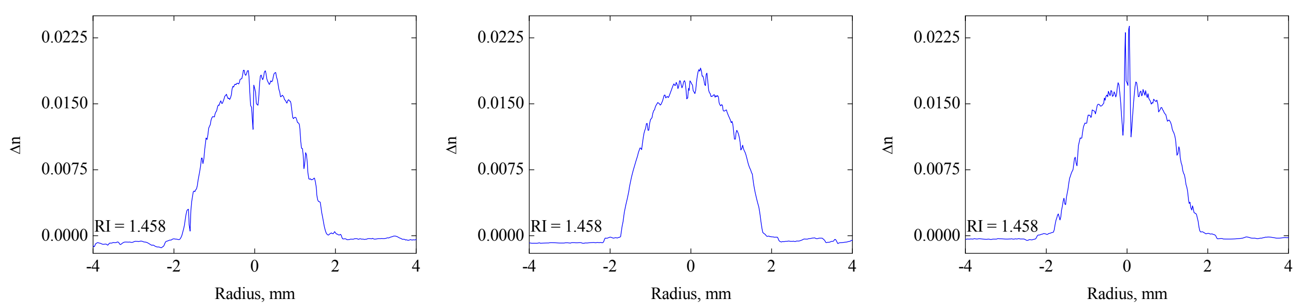
(a) (b) (c)

Figure 2. Measured RI profiles of the first series MMF preforms with the depth of the dip (a) $\Delta n_d = 0.015$, (b) $\Delta n_d = 0.014$ and (c) $\Delta n_d = 0.0115$.

According to the aim of the work, considerable attention has been paid to control of the size of the dip in the central part of the RI profile, as its depth, obviously, can enhance/weaken DMD effect depending on parameters of the transmitted few-mode optical signal[9-12]. The origin of the dip, inherent to graded-index MMFs fabricated by the MCVD method, is well studied[13, 14, 18] and caused by diffusion of germanium from the innermost glassy layer to the surface, where it is volatilized as GeO during the high-temperature collapse of the tube into a rod. So it would seem that the multilayer structure of a core defines an arbitrary manifestation of the dip which depth and transverse size can vary within rather wide limits.

However, in the first series preforms, the fine particles deposition and consolidation processes were carried out in the presence of $POCl_3$ that has led to essential decrease of inhomogeneity of the synthesized germanosilicate glass. That measure together with an accurate control over the inner tube diameter (4-5 mm) before collapse procedure contributed to obtaining of the profile in which RIs of the lowest point of the dip and the cladding have been balanced (Figure 2 (a)). The consecutive reduction of Δn_d parameter displayed in Figures 2 (b)-(c) has been realized by compensating volatile GeO evaporation in a way of supplying small amounts of $GeCl_4$ in the atmosphere of dried oxygen inside the tube during its final shrinkage.

RI profiles of the second series preforms (Figure 3) demonstrate capabilities of another approach to controlling the depth of the dip in the central part of a core, including transforming it to an alternative type of defect, i.e. peak, as shown in Figure 3 (c).



(a) (b) (c)

Figure 3. Measured RI profiles of the second series MMF preforms with the depth of the dip (a) $\Delta n_d = 0.002–0.003$, (b) $\Delta n_d \sim 0$ and (c) $\Delta n_d = –(0.004–0.005)$.

Partial (Figure 3 (a)) and almost complete (Figure 3 (b)) elimination of the dip have been implemented by etching of the inner surface of the tube which lacked GeO_2 content with gaseous fluorine-containing reagent at a high temperature followed by pre-collapsing the tube to a state when its inner diameter reduced to 3 mm. For peak formation the final collapse procedure was carried out in the conditions similar to that of the first described approach. Finally, we have succeeded not only in full compensation of GeO evaporation, but also in a local increase of RI toward the center of the profile. Based upon measurement, the RI increased on ~ 0.0065 (from ~ 1.475 to ~ 1.482 at the wavelength of 633 nm) in relation to the highest point of the parabola.

A few words should be said about a divergence of the predetermined and realized RI profiles in terms of the profile parameter g. The analysis has shown that in the first series preforms $g = 2.3$ and in the second series preforms $g = 2.4$. Apparently, this effect can be explained by the complex heat transfer kinetics and GeO_2 particle growth dynamics in the presence of various amounts of $POCl_3$. In our work, deviations from the optimal parabolic RI profile shape ($g = 2$) are insignificant, as we do not approach towards the lowest possible dispersion property.

3. INFLUENCE OF MULTIMODE GRADED-INDEX FIBER DRAWING CONDITIONS ON ITS OPTICAL AND MECHANICAL PROPERTIES

Optical fiber drawing process was performed on the specialized vertically oriented facility ('tower') equipped with the high-temperature (1900-2300 °C) furnace for softening the end of a preform to the melting point, the unit of feeding the preform with a constant speed into the hot zone of the furnace, the unit of drawing a fiber from the softened end of the preform, the unit of application an acrylate coating on the fiber to protect its outer surface against mechanical damage and the unit of winding the fiber on a spool.

Transformation of the preform having transverse dimensions of 9-10 mm and length ~ 1 m into optical fiber with the outer diameter of 125 μm was carried out in the stationary mode according to the relation[13]:

$$\left(\frac{d_p}{d_f}\right)^2 = \frac{v_f}{v_p}, \qquad (5)$$

where d_p and d_f – preform and optical fiber diameters respectively, v_f – fiber drawing speed, v_p – feed rate of a preform into the hot zone of the furnace.

Since the present work touches upon the main technological issues of fabricating graded-index MMFs with a strong manifestation of DMD effect for application as sensing elements of external influences registration in fiber-optic sensor networks operating in the few-mode regime, it seems reasonable to simulate a type of influence and study its impact on the most important from the practical point of view fiber properties.

As a result of physical influence on optical fiber, if this is not about its partial or complete destruction, new geometrical distortions of micro- and macroscopic character appear. It is typical to speak about relatively high resistance of graded-index MMFs with numerical aperture of 0.20 to macrobending, since bend-induced attenuation does not exceed 0.0015 dB/turn at the wavelength of 1310 nm for a bending diameter of 75 mm[29]. However, the situation changes drastically when dealing with distortions of much smaller size, even less than a core diameter[30, 31]. In order to study the effect of such irregularities on attenuation two series of MMFs have been drawn: 1) under the automatic maintenance of the outer diameter stability; 2) under the manual maintenance. Preforms of MMFs were characterized by the RI profile given in Figure 2 (c) which has been noted as one of the most appropriate for attainment of a strong DMD effect[32].

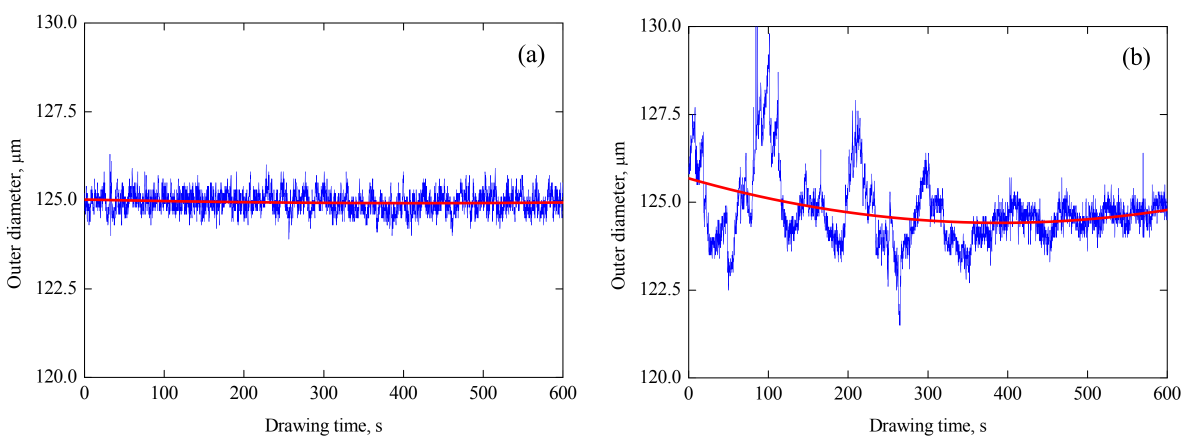


Figure 4. Indications of the outer diameter of MMFs drawn (a) under the automatic stability maintenance and (b) under the manual stability maintenance.

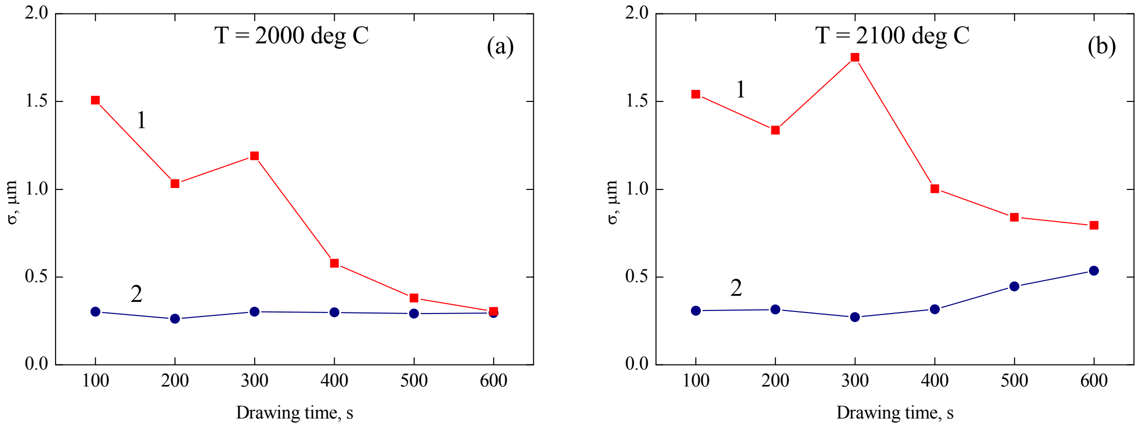


Figure 5. The standard deviation of the outer diameter of MMFs drawn at different temperatures (1) under the manual stability maintenance and (2) under the automatic stability maintenance.

As can be seen in Figure 4 (a), graded-index MMF with the large dip ($\Delta n_d = 0.0115$) in the central part of the RI profile drawn under the automatic maintenance of the outer diameter stability exhibits a narrow deviation (± 1.5 μm) from the average diameter value marked by the red third degree polynomial curve. This is less than 1.5 %, which is comparable with the performance of commercially-available analogs[29]. Moreover, the standard deviation σ weakly depends on the optical fiber drawing temperature that is confirmed by the corresponding curves in Figures 5 (a)-(b). On the other hand, the sample obtained under the manual maintenance is characterized by miscellaneous statistics: both the deviation from the average value (± 3.5 μm) and σ-parameter increase, as well as quasiperiodic oscillations provoking local peaks of the outer diameter above 130 μm appear (Figure 4 (b)). As opposed to the previous case, increase of the drawing temperature causes growth of the standard deviation (Figures 5 (a)-(b)), apparently, due to low viscosity of glass at the softened end of the preform being transformed adiabatically into optical fiber during the drawing process[13].

So using mentioned in the previous paragraphs regimes of maintaining the outer diameter stability, graded-index MMFs with two fundamentally dissimilar distributions of geometrical irregularities over a fiber length have been manufactured. After drawing the samples were transferred to the metrological control department to measure attenuation by the OTDR method[33]. The measured data are accumulated in Table 1.

Table 1. Attenuation statistics of 50/125 μm graded-index MMFs with a large dip in the center of the RI profile.

Sample	Drawing temperature, °C	Drawing regime	Length, m	Attenuation coefficient, dB/km	
				λ = 850 nm	λ = 1310 nm
A-1	2000	Automatic	500	3.685	3.844
A-2	2000	Automatic	2000	3.781	4.406
M-1	2000	Manual	500	3.967	5.966
M-2	2000	Manual	2000	4.317	7.005
A-3	2100	Automatic	500	4.400	5.101
A-4	2100	Automatic	3000	4.383	5.122
M-3	2100	Manual	500	7.059	8.190
M-4	2100	Manual	3000	8.524	10.091

According to the data presented in Table 1, a simple conclusion on increase of attenuation coefficient in the samples drawn manually as compared to the samples draw automatically can be made. Such increase is associated with additional scattering of transmitted optical power on disordered longitudinal microscopic geometrical distortions. In addition, as follows from the measurements, elevated temperatures also lead to a certain attenuation growth. A similar effect takes place in case of increasing a fiber length. The first process is induced by excessive glass softening under the conditions of low viscosity, as it was indicated earlier, and the second – by supplying a microdeformation spectrum with new high- and low-frequency components.

The spectral dependence of attenuation measured by the cutback technique[33] shows a non-distinctive for graded-index MMFs enhancement of optical absorption while moving to longer wavelengths (Figure 6).

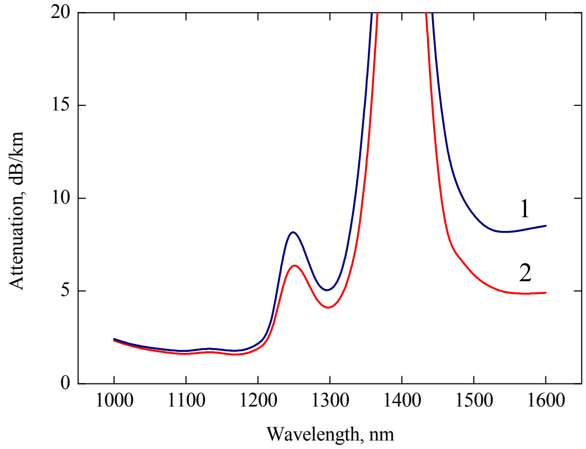


Figure 6. Spectral dependence of attenuation for the samples (1) A-3 and (2) A-1.

It can be seen from Figure 6 that optical absorption increases more pronouncedly towards lower frequencies in the sample drawn at elevated temperature. However, this time the attenuation increase is not associated with low-viscosity glass state in the hot zone of a high-temperature furnace. There are two basic physical phenomena that can explain such an irregular spectral dependence:

– the presence of P_2O_5 in the core glass which has an overtone of fundamental absorption peak at λ = 1500-1600 nm;

– the presence of B_2O_3 in the cladding glass which causes increased loss beyond 1200 nm;

– excessive content of hydroxyl groups in the silica tube diffusing to the deposited glassy layers.

Optimization of core and cladding glass compositions, as well as elaboration of technological parameters of the preform synthesis will aid in minimizing attenuation in graded-index MMFs having a defect in the central part of the RI profile presented in this paper. Low attenuation will simplify data processing in fiber-optic sensor networks based on the few-mode effects.

Several words should be said about mechanical properties of the manufactured optical fibers which define, on an equal basis with optical characteristics, their capabilities to be applied in real systems and devices. Typically, optical fibers are exploited on spools of different diameters or installed into a cable. Because of that they undergo multiple tensile and compressive stresses leading to early destruction if there is a lack of control. For this reason, developers tend to bring strength values to a level of at least 5.5-6 GPa towards acrylate-coated fibers ensuring their reliable exploitation for the period of 20-25 years[34].

From the data in Table 1, the lowest attenuation is associated with the drawing temperature of 2000 °C. However, the latter does not guarantee acceptable mechanical strength of optical fibers. By experience, it is provided at much higher temperatures due to intensive thermal treatment of a preform in the hot zone of a furnace. We have evaluated strength properties of graded-index MMFs drawn at two different temperatures.

The investigation was carried out by stretching short samples (1 m in length) with a constant speed of 200 mm/min till their break. After breaking 20-25 samples, each giving a value of tensile strength, the data were presented in terms of the Weibull distribution according to which the probability of failure F is regulated by the expression[13]:

$$F(l, \sigma_0) = 1 - \exp\left(-\sigma_0^m l\right), \tag{6}$$

converted to the form

$$\ln\ln\left(\frac{1}{1-F}\right) = m\ln(\sigma_0) + \ln(l), \tag{7}$$

where σ_0 – tensile strength, l – sample length, m – statistical parameter defined as the angle of the graph to abscissa axis.

Weibull plots for the samples A-1 and A-3 drawn at the temperatures of 2000 °C and 2100 °C respectively are given in Figure 7.

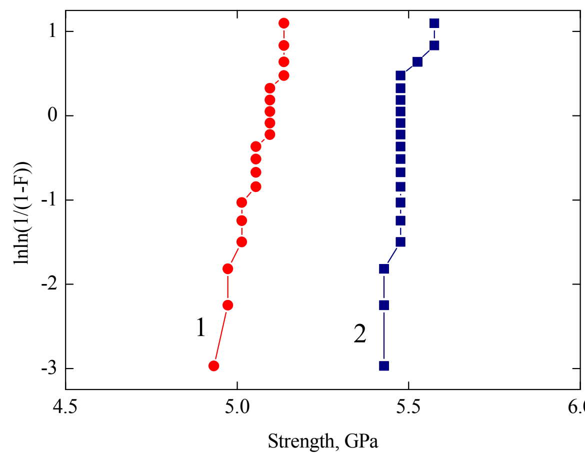


Figure 7. Weibull plots for the samples (1) A-1 and (2) A-3.

It turned out that lowering of the temperature on 100 °C degraded mechanical properties of graded-index MMFs, as the average tensile strength has decreased from 5.49 to 5.07 GPa. Although the last value is comparable with the same parameter of commercially-available silica optical fibers, it is on the lower limit of this parameter.

Thus, the next challenge lies in improvement of both optical and mechanical properties of graded-index MMFs which have a pronounced defect in the central part of the RI profile for applying them in fiber-optic sensor networks based on the few-mode effects.

4. CONCLUSION

The results of experimental study on the main technological aspects relating to a full production cycle of 50/125 μm silica multimode graded-index fibers with the central defect of the refractive index profile realized as a large dip are presented.

Preform synthesis conditions for implementation of the mentioned defect via MCVD method have been analyzed and optimized. Two approaches of controlling the depth of the dip based on compensation of GeO evaporation by injecting small amounts of $GeCl_4$ in a flow of dried oxygen inside the tube during its final collapse and high-temperature etching of depleted layers by gaseous fluorine-containing reagent have been considered and tested. The technological parameters of the process allowing to transform a dip into an alternative type of defect, i.e. peak, have been defined.

The effect of geometrical irregularities, induced by drawing optical fibers under the manual maintenance of the outer diameter stability, on attenuation has been explored. It is shown that variations of the outer diameter within the limits ± 3.5 μm lead to an increase of attenuation by 2-5 dB/km at the wavelength λ = 1310 nm as compared to analogs fabricated under the automatic maintenance of the outer diameter stability. It has been determined that in the latter case optical fibers with close to optimal parabolic refractive index profile, corresponding to numerical aperture of 0.20, and the depth of the dip 0.0115 demonstrate the attenuation in the vicinity of 5 dB/km in the second and third optical fiber telecommunication windows.

Applying the Weibull theory, a statistical evaluation of mechanical properties, particularly tensile strength, of the optical fibers drawn at various temperatures has been conducted. Based upon measurements, tensile strength of the fibers was estimated to be 5.07-5.49 GPa that is comparable with the strength properties of commercially-available silica telecom and specialty fibers.

The manufactured multimode graded-index fibers with the central defect of the refractive index profile are attractive candidates for application in fiber-optic sensor networks on the few-mode effects as sensing elements for registration of local and distributed external influences.

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