Initial and radiation-induced loss in holey optical fibres

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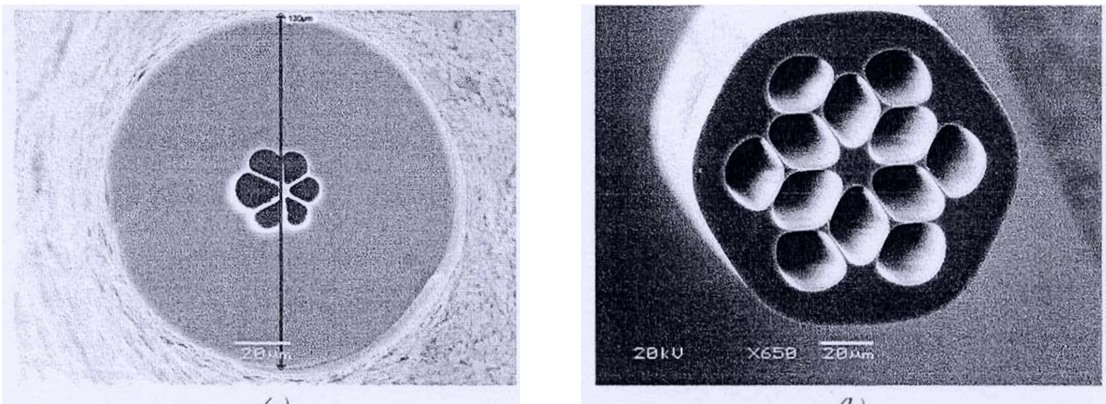
Abstract: Initial and radiation-induced loss spectra are analyzed in three multimode holey fibres with a high-OH KU-1 silica core. A fibre with an optimized cross-section is shown to have no leakage loss. A high concentration of gamma-radiation-induced non-bridging oxygen is argued to be due to a high cooling rate during fibre drawing.

1. Introduction

At present, so-called microstructured optical fibres are being intensively developed and investigated. Different types of such fibres are known [1]. In microstructured (holey) fibres investigated in this paper, light is guided in a silica core owing to a lower refractive index of the cladding containing air holes (Fig. 1).



(a) (b)

Fig.1. Cross-sections of the holey fibres constructed with the help of an electron microscope: fibre #1 (a), fibres #2 and #3 (b).

We investigate initial and radiation-induced loss spectra in holey fibres. The objective of the initial loss investigation is optimization of the structure of the fibre cross-section. Interest in radiation-induced loss is due to a number of promising applications of fibre optics in the nuclear industry: e.g., plasma diagnostics in thermonuclear reactors [2] and transmission of image from nuclear installations [3]. For such applications, sufficient transparency of the fibre should be ensured in the presence of nuclear radiation in the visible spectral region.

Earlier it was established that the precursors of radiation-induced non-bridging oxygen hole centre (NBOHC) which is the main source of radiation-induced absorption in the visible region [4] arise during the perform fabrication process [5]. The latter consists in depositing an F-doped silica cladding on an undoped silica rod (plasma outside deposition process, POD) [6]. Fibres produced without depositing an F-doped cladding and drawn with a light-reflecting polymer coating exhibit a much lower concentration of radiation-induced NBOHC than POD fibres [5].

Preforms of holey fibres are also fabricated without depositing a light-reflecting glass cladding; therefore, it would be natural to assume that the concentration of radiation-induced NBOHC in holey fibres will be much less than in POD fibres.

To our knowledge, only one paper has been devoted to radiation resistance of holey fibres [7]. The kinetics of the induced loss growth at λ=1.55 μm in the process of γ-irradiation has been investigated in that paper. We investigate, for the first time, radiation-induced absorption in holey fibres in the spectral range 400-900 nm.

2. Fibre Samples and Experiments

Three holey fibres (Fig. 1) were produced for this study from KU-1 silica rods (the hydroxyl concentration in KU-1 silica is ~800 ppm, the chlorine concentration, ~80 ppm). In fabricating the preform of fibre #1, a specially prepared rod was jacketed with a Suprasil F-300 silica tube of Heraeus (Fig.1. a). This silica features a low hydroxyl content (~0.2 ppm) and a high chlorine content (~1200 ppm). The thickness of the glass bridges separating the holes in fibre #1 was 140 nm. Fibres #2 and #3 were drawn from one and the same perform (Fig.1. b) and differed in the thickness of the glass bridges, which amounted to ~760 nm in fibre #2 and ~650 nm in fibre #3. No outer tube was used in preparing the perform of fibres #2 and #3. All the three fibres were multimode.

On measuring the initial loss spectra, the fibres were subjected to γ-irradiation from a cobalt source. For the sake of comparison, a POD fibre with a KU-1 silica core was irradiated simultaneously with the holey fibres under the same conditions (dose, dose rate, and temperature). The POD fibre had a core diameter of 100 μm and an F-doped silica cladding 12 μm in thickness. On completion of the irradiation, optical loss spectra were measured, and by subtracting the initial loss spectra, the induced loss spectra were constructed.

In the first experiment, the holey fibre #1 and the POD fibre were irradiated (dose of 0.94 MGy, dose rate of 2.04 Gy/s). The post-irradiation losses were measured 1 day after finishing the irradiation. In the second experiment, the holey fibres #2 and #3 were irradiated together with the POD fibre (dose of 1.31 MGy, dose rate of 2.63 Gy/s). The post-irradiation losses were measured 4-5 hours after finishing irradiation. In the both experiments the fibres were irradiated at room temperature.

3. Results and Discussion

The initial loss spectra are shown in Fig. 2. The loss in fibre #1 is noticeably larger than in the POD fibre. The loss rises with decreasing wavelength, when it approaches the width of the bridges, and with increasing wavelength (e.g. see region 1500-1600 nm), when the depth of penetration of the tails of the mode fields into the bridges increases. These facts testify that the loss in fibre #1 is mainly due to light leakage through the glass bridges between the holes. We also notice two bands of unknown nature at 410 and 690 nm (the bands at about 730, 880, 950, 1120, 1270 and 1370 nm are caused by hydroxyl vibration [8]).

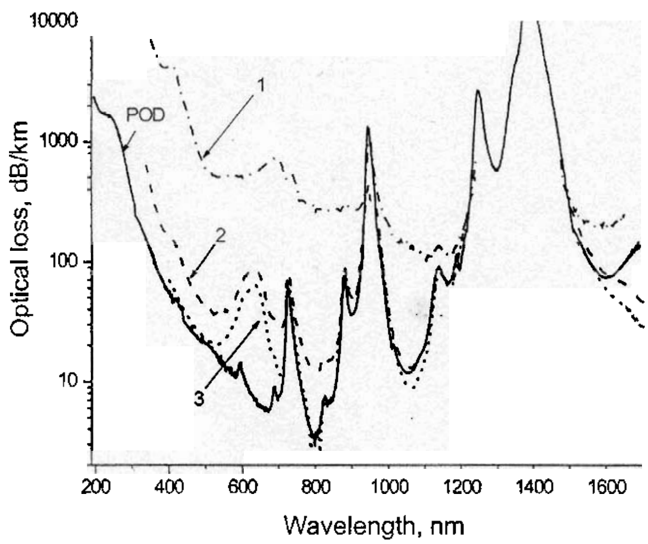


Fig.2. Initial loss spectra in the fibres.

The losses in fibres #2 and #3 are significantly lower than in fibre #1. Fibre #3 demonstrates virtually no leakage loss, which follows from comparing its loss spectrum with that of the POD fibre. Moreover, in the region λ>1600 nm, where the POD fibre exhibits some loss associated with mode field penetration through the cladding into the polymer coating, fibre #3 (as well as fibre #2) have lower losses. Thus, the presence of the second layer of holes in the cladding (Fig.1. b) preventing light leakage through glass bridges allows complete suppression of leakage loss in multimode holey fibres in both short- and long-wavelength regions, provided the thickness of the glass bridges is sufficiently small (~ 650 nm in the case of fibre #3). The fact that fibre #2 shows some leakage loss is, in our opinion, due to somewhat larger thickness of the bridges.

Fibres #2 and #3 exhibit the 630 nm absorption band associated with NBOHC. (Fig. 2). This band is indicative of too high a cooling rate during the fibre drawing process. It was previously established [9] that the formation probability and concentration of the drawing-induced NBOHC in high-OH-silica-core F-doped silica-cladding fibres go up with increasing the cooling rate. The cooling rate is determined by the drawing speed and the fibre mass per unit length [9]. The holey fibres #2 and #3 featured a mass per unit length ~ 2 times lower than standard hole-free fibres with the cladding diameter of 125 μm (see Fig.1. b). Therefore, under normal drawing regimes, the core of fibres #2 and #3 cooled down faster than in the case of hole-free fibres and holey fibre #1, which mass per unit length is not so small.

Figs. 3 and 4 show the radiation-induced loss spectra. The shape of the radiation-induced loss spectrum of fibre #1 (Fig. 3) is determined by Cl-associated colour centres [10]. These centres show up as monotonically decreasing absorption with wavelength, its peak lying in the UV region. The emergence of these colour centres is explained by using a high-Cl tube in manufacturing the perform of fibre #1. The intensity of the radiation-induced NBOHC band in fibre #1 is 3 times lower than that in the POD fibre. By comparing the induced loss spectrum in fibre #1 and the data of papers [4,11] one may to assume that the radiation-induced NBOHC in fibre

#1 also arose owing to the chlorine impurity either in the core or in the glass of the bridges in the vicinity of the core. The microscopic mechanism of the formation of radiation-induced NBOHC due to chlorine is discussed in [11].

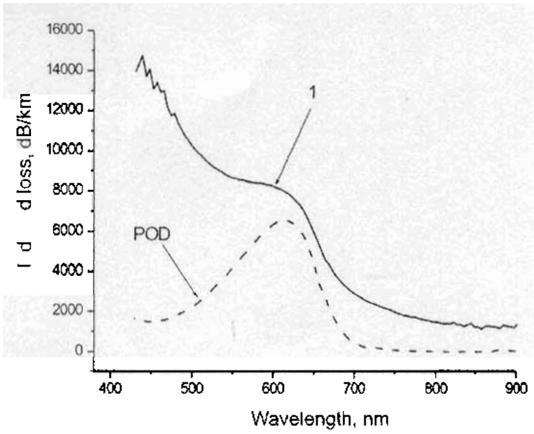


Fig.3. Induced loss spectra in holey fibres #1 and in the POD fibre measured 1 day after γ –irradiation (0.94 MGy, 2.04Gy/s).

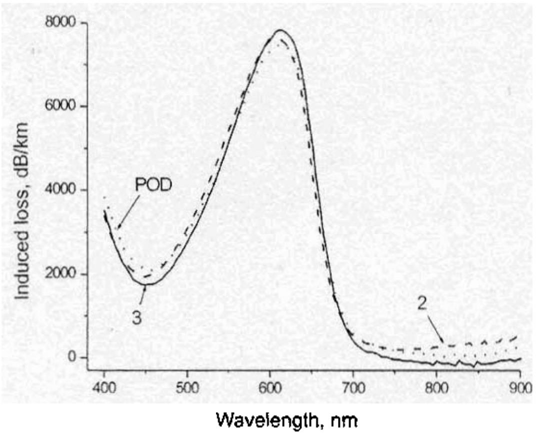


Fig.4. Induced loss spectra in holey fibres #2, #3 and in the POD fibre measured 4-5 hours after finishing the irradiation (1.31 MGy, 2.63Gy/s).

The intensity of the radiation-induced 630 nm band in fibres #2 and #3 turned out to be virtually the same as in the POD fibre (Fig. 4). The precursors of radiation-induced NBOHC in these holey fibres arose during fibre drawing. According to [12], the formation probability of the precursors of radiation-induced colour centres (including NBOHC) and the concentration of the precursors increase with increasing the fibre drawing temperature. Obviously, the higher is the cooling rate, the lower is the probability of subsequent thermal decay of the precursors.

The formation probability of the drawing-induced precursors of radiation-induced NBOHC in fibre #1 was not so high owing to a much larger mass per unit length as compared to fibres #2 and #3 (Fig. 1). It should also be noted that the drawing speed of fibre #1 was 2.4 times lower than that of fibres #2 and #3, and the drawing temperature of fibre #1 was 100 °C lower.

Thus, reduction of radiation-induced absorption in the visible spectral region in holey fibres with a silica core requires increasing the fibre mass per unit length or decreasing the cooling rate during the drawing process. This can be achieved by jacketing the holey perform with a low-Cl tube. The cooling rate can also be reduced by decreasing the speed and the temperature of the drawing process.

4. Conclusion

Suppression of the excess initial loss in multimode holey fibres requires optimization of the fibre cross-section. It has been found that the presence of only one layer of holes surrounding the core does not ensure the absence of leakage loss even in the case of very thin silica bridges. It has also been found that in the presence of two layers of holes it is possible to optimize the thickness of the bridges to obtain a virtually zeroth leakage loss.

A holey fibre fabricated using a high-Cl jacketing tube has demonstrated strong radiation-induced absorption due to Cl-associated colour centres. The holey fibres fabricated without using an outer tube have featured a high concentration of radiation-induced non-bridging oxygen hole centre with a band at 630 nm. The precursors of this colour centre arose, in our opinion, at the stage of fibre drawing owing to a high cooling rate. The possibility to reduce radiation-induced absorption in the visible spectral region in holey fibres to a level lower than that in POD fibres remains an open question and requires increasing the fibre mass per unit length, optimization of the drawing regimes (decreasing the speed and temperature of the drawing process), and abandonment of the high-Cl tube application in preparing the perform.

5. References

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