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Effect of proton implantation on the photosensitivity of SMF-28 optical fiber

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Abstract

Protons accelerated to multi-MeV energy have enough range in silica to reach the core of 125 μm-diameter single-mode telecommunication optical fibers located 62.5 μm under the outside surface. As a result of proton implantation, a waveguiding region appears near the end of range of the protons. After proton implantation in the core at doses of 5×10^{15} H^+/cm^2 or less the photosensitivity of proton-implanted fibers with respect to ArF excimer laser light was found to decrease. © 1999 Elsevier Science B.V. All rights reserved.

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1. Introduction

Germanosilicate optical fibers are known to be photosensitive to ultraviolet light [1,2], that is, a change in the refractive index can be induced in the fiber by its exposure to a beam of UV light. Thus, a permanent refractive index grating can be imprinted in the photosensitive core of the fiber. Many devices as currently used in industry, retroreflecting Bragg gratings and mode convertor gratings among others [3], are fabricated by this method. Ion implantation is also known to induce appreciable changes in the properties of silica-based glasses [4]. In particular, it modifies significantly the photosensitivity of both pure silica and some Ge-doped silica planar samples [5,6].

As is known, the intrinsic photosensitivity of Ge-doped silica due to the presence of germanium is characterised by an *increase* in the refractive index of this material under the effect of irradiation by UV light. It is due to the creation of different point defects and the appearence of related bands in the absorption spectrum of the material. In contrast to that, in the case of photosensitivity induced by ion implantation in pure and Ge-doped silicas, one observes a *decrease* of the refractive index of these materials when they are irradiated by a UV light beam. In this case point defects are created during ion implantation. Afterwards they may be either annihilated or transformed into

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defects of another type under the effect of a beam of UV light. As a result, absorption bands corresponding to the defects induced by ion implantation are removed or “bleached”, and the refractive index of material is therefore decreased. Hence, the intrinsic photosensitivity of Ge-doped silica and the photosensitivity induced in this material by ion implantation have opposite signs.

Standard optical telecommunication fibers are fabricated from pure and Ge-doped silicas. The possibility of modifying the photosensitivity of such a fiber locally by means of ion implantation may be interesting in view of possible applications in the fabrication of devices in fibers. Therefore, the effect of ion implantation on the photosensitivity of standard optical fibers is important. In order for implanted ions to reach the core of the fiber, protons accelerated to multi-MeV energies have been used. Our results show that a waveguiding region appears near the end of the range of protons and that if this region overlaps with the core, the photosensitivity to ArF laser light is reduced.

2. Experimental

In our experiments we have used the Corning SMF-28 single-mode telecommunication fiber. The core of the fiber has a diameter of 9 μm and is made of Ge-doped silica SiO_2:GeO_2, the concentration of GeO_2 being equal to 3 mol%. The core is embedded in a cladding of pure silica with a diameter of 125 μm. Samples of the fiber have been implanted at room temperature with 1.4 to 3.3 MeV protons.

Some of the samples were implanted by using a beam external to the vacuum chamber. In this case protons exited the vacuum system through a thin Al window and passed through 10 cm of air before reaching the fiber. The energy losses in the Al film and in the air were calculated by TRIM [7]. They are indicated in Fig. 1 and served to deduce the energy of protons incident on the fiber. Other samples were implanted in a vacuum of $\sim 10^{-6}$ Torr.

Photographs of white light transmitted through the cross-sections of optical fibers implanted at different proton energies are shown in Fig. 2(a)–(c). The bright circle at the center of each photograph corresponds to the light guided by the core of the fiber. The luminous arc across the fiber corresponds to the region where the proton implantation induced an appreciable increase in the refractive index [8]. This increase resulted in the formation of a waveguiding region under the implanted surface. The distance from the fiber surface to the induced waveguide is constant, as shown in Fig. 2(b) by the dashed circle representing the offset fiber circumference, which is represented by the white circle. The depth at which the waveguiding region is formed has been measured on photographs. It is plotted in Fig. 1 as a function of the energy of incident protons. These data are in agreement with the values of protons’ projected range R_p, as calculated by TRIM [7] and plotted in the same figure. Figs. 1 and 2 show that the most significant increase in the refractive index occurs at the end of the proton range being centered at the same depth as the nuclear stopping region. This result is in agreement with the measurements of the profile of the refraction index in proton-implanted silica fibers [8].

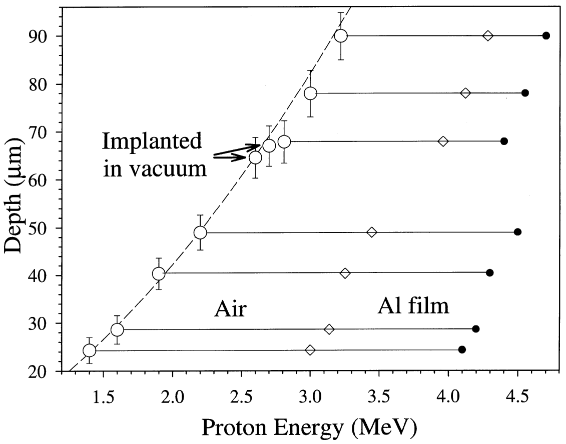

Fig. 1. The measured depth of the guiding region created by implantation vs. energy of protons incident on the fiber (○). The initial energy of protons is shown by ●, the energy of protons after passing through the Al window is shown by ◇. The horizontal lines connecting ● and ◇ with ○ show the calculated energy losses in the Al film and in the air. The dashed line represents the proton projected range calculated by TRIM.

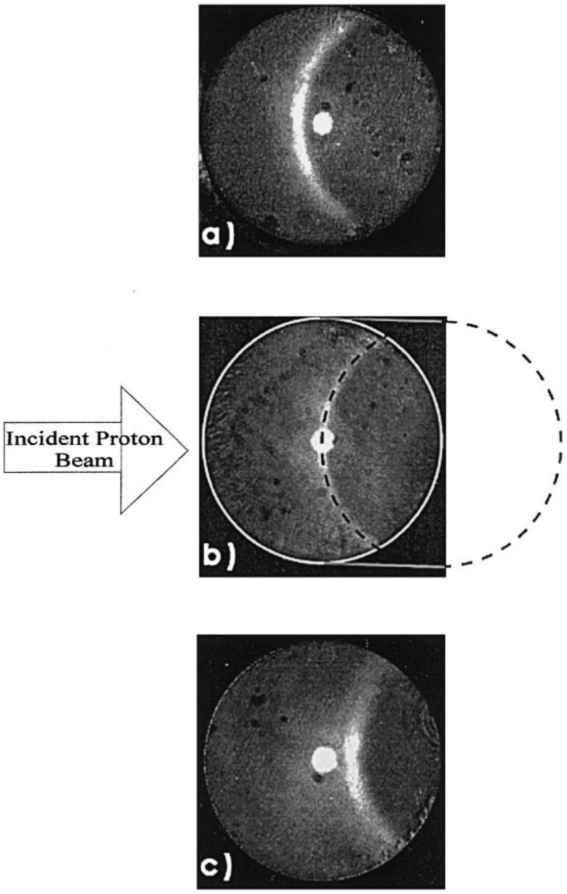

Fig. 2. Photographs of light transmitted through implanted section of fibers showing guiding in the region of increased refractive index for different energies of protons incident on the fiber. (a) $E_{\rm inc} = 2.2$ MeV. Protons did not reach the core of the fiber. (b) $E_{\rm inc} = 2.6$ MeV. Protons came to rest in the core of the fiber. (c) $E_{\rm inc} = 3.0$ MeV. Protons passed through the core of the fiber. The circles in (b) are described in the text.

In order to investigate the effect of proton implantation on the photosensitivity of the fibers, a 1 cm section in the center of a 1 m length of fiber was implanted. Three samples were implanted with 2.6 MeV protons. The projected range relative to this energy is $R_{\rm p} \approx 64.8$ μm, so that the protons came to rest in the core of the fiber (see Fig. 2(b)). The implanted fluences for 2.6 MeV H^+ implanted samples were 5×10^{14} H^+/cm^2, 1.33×10^{15} H^+/cm^2, and 5×10^{15} H^+/cm^2. The average concentrations of protons within the implanted region for these fluences were calculated to be $\sim8\times10^{17}$ H^+/cm^3, $\sim1.7\times10^{18}$ H^+/cm^3 and $\sim8\times10^{18}$ H^+/cm^3, respectively.

The photosensitivity of the implanted fibers has been examined by measuring the reflectivity of a Bragg grating imprinted in the implanted section of fiber samples by use of the phase mask technique [9]. A beam of ArF excimer laser ($\lambda = 193$ nm, 100 pulses/s, 0.35 J/cm^2/pulse) has been used. In all three samples the H^+ implantation in the core resulted in the decrease of the fiber's photosensitivity as compared to that of unimplanted fiber exposed under the same conditions (see Fig. 3 for the sample implanted at a fluence of 5×10^{15} H^+/cm^2). Also, the initial Bragg grating central wavelength in the implanted fiber of Fig. 3 is found to be 1556.6 nm, i.e. 1 nm longer than that of the unimplanted fiber. This indicates that the implantation alone increased the refractive index in the core of the fiber by 0.001. This increase seems not to be limited to the core, but rather occurs everywhere near the proton end of the range, which provides an explanation for the waveguiding effect observed in Fig. 2.

3. Discussion

Under the effect of proton implantation at fluences of 5×10^{15} H^+/cm^2 or less, the photosensitivity of SMF-28 optical fibers is found to diminish slightly. Two possible explanations for this result are to be considered. The first one is that there is an implantation-induced contribution to the photosensitivity, but this is of the opposite sign. It was shown that in pure silica and implanted Ge-doped silica the ultraviolet light induced index changes were negative and strongly correlated with bleaching of the implantation-induced absorption bands [5,10,11]. Since the net index change observed in our experiments is positive (this follows from the red shift of the Bragg grating wavelength), a small negative contribution to the UV-induced index change that is due to the implantation, would explain the observed net decrease in photosensitivity. The other possibility is that the implantation produces an overall increase in the ultraviolet absorption over the full path of

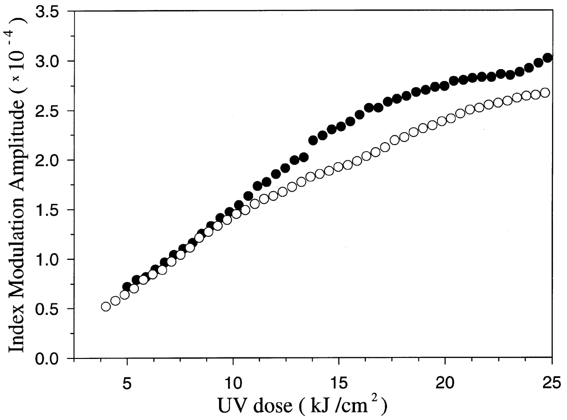

Fig. 3. The rate of refractive index change vs. UV irradiation time. Black circles (●) correspond to an unimplanted sample, white circles (○) correspond to the sample implanted at 5×10^{15} H^+/cm^2.

the protons, i.e. from the surface down to the end of range [5,10,11]. Therefore, unless the ultraviolet light used to photoimprint the grating is incident on the side of the fiber which is exactly opposite to the side from which the protons were implanted, less light would reach the core to induce refractive index changes.

Also, a third effect should be considered to be a source of possible contribution to the photosensitivity, namely the chemical effect of the presence of hydrogen [12]. When fibers similar to the ones used in our experiments are loaded with dissolved molecular hydrogen at concentrations of the order of 10^{20} H^+/cm^3, the photosensitivity to ultraviolet light is strongly enhanced. However, this effect is not found to be an important factor at the concentrations implanted here ($\sim 10^{18}$–10^{19} H^+/cm^3).

Our results show that the proton implantation is not likely to be an efficient way to load fiber cores with hydrogen for enhancing the photosensitivity because of the negative contribution arising from specific effects due to the implantation. The photosensitivity of the core is found to decrease under the conditions used. Therefore, the ion implantation in the core allows one to modify the photosensitivity of the fiber in local regions. Other effects may also make the implantation in the fiber core useful. The formation of Ge nanoclusters by implantation of high fluences of protons in bulk germanosilicate glass samples has recently been demonstrated [13,14]. Consequently, by implanting high doses of protons in fiber core through the cladding, localized regions with high optical nonlinearities could be produced in otherwise undisturbed optical fiber.

4. Conclusion

In conclusion, we have demonstrated that protons can be accurately implanted through the cladding into the core of standard telecommunications fibers. As a result, the optical properties of the fibers are modified, including a reduction of UV photosensitivity.

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