γ -Ray-Induced Optical Attenuation in Ge-Doped-Silica Fiber Image Guides

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Abstract

Optical attenuation in fiber optic image guides comprising germanium-doped-silica-core/pure-silica-clad picture elements was investigated *in situ* (wavelength range 420-1100 nm) during ^{60}Co γ irradiation at dose rates of 1.1, 6.6, 36, and 180 Gy/h.

I. INTRODUCTION

Fiber optic image guides (IGs) are fabricated by redrawing close-packed bundles of silica-based optical fibers each comprising a core region of higher index of refraction and a concentric cladding of lower index. Typical commercial IGs feature 3,000 to 80,000 picture elements (pixels), each comprising a core filament ~ 3 to $10\ \mu\text{m}$ in diameter separated from adjacent pixels by ~ 3 to $5\ \mu\text{m}$ of cladding glass. By preserving the relative registrations of the pixels down the length of the guide, undistorted high-resolution images can be transmitted over distances ~ 100 meters. To the extent that IGs can be made sufficiently rad hard, they could be useful for remote viewing of nuclear reactors and nuclear waste repositories. Moreover, rad-hard endoscopes which could be sterilized by γ rays should find extensive application in medicine. The presumptive material system for such rad-hard IGs would be one comprising pure-silica-core pixels [1]. However, in some situations where radiation dose rates and total doses are expected to be relatively low, a germanium-doped-silica-core system may appear attractive by virtue of the high brightness and wide angle of view afforded by the larger difference in refractive index between the core and cladding. Indeed, while Ge-doped silica is known to develop strong optical absorption bands under irradiation, studies of Ge-doped-silica-core/pure-silica-clad multi-mode fibers at a wavelength of $1.3\ \mu\text{m}$ revealed that radiation-induced attenuation becomes lower at lower dose rates [2], suggestive that acceptable performance might be anticipated in some very-low-dose-rate environments such as low-level nuclear waste repositories. The present paper explores the radiation sensitivity of sections of germanium-doped-silica-core/pure-silica-clad IGs manufactured by Sumitomo Electric Industries, Ltd.

II. DESIGN OF THE EXPERIMENT

A previously-developed CCD-camera prism spectrometer [3] was adapted for *in situ* spectral measurements of optical attenuation in the visible/near-IR region (wavelength range

400-1100 nm) during and after ^{60}Co γ irradiation at room temperature. As before [3,4], light from a quartz-tungsten-halogen lamp was injected into the input ports of two Corning 1x4 couplers, the output ports of which were fusion spliced to 100/140 μm fiber pigtails. In the present case, these launch pigtails were terminated by SMA 905 connectors, as were the pigtails leading back to the spectrometer. To expand the light emanating from the connectorized pigtails to fill the larger-diameter IGs, use was made of 0.25-pitch 2-mm-diameter graded-index (GRIN) lens collimators cemented onto the polished IG ends with index-matching epoxy and retained in SMA-compatible stainless steel ferrules. Each 1x4 coupler injected spectrally identical probe light into two "sample arms" each comprising an IG segment configured as described above and two "reference arms" each consisting of a back-to-back pair of GRIN lenses and SMA hardware intervening between the launch-end and spectrometer-end pigtails. Thus, the reference arm provided a measure the light intensity I_0 which would reach the spectrometer if only the pigtails and a pair of GRIN lenses were in the optical circuit. Letting the light transmitted through the pigtails, GRIN lenses, and IG segment in the "sample arm" be denoted as I , the optical loss L (dB/km) in the IG segment can be calculated according to the relation:

$$L(\lambda) = (10,000/X) \cdot \text{Log}[C(\lambda) \cdot I_0(\lambda)/I(\lambda)], \quad (1)$$

where X is the length of the IG segment in meters, λ is the wavelength of the light, and $C(\lambda) \equiv J(\lambda)/J_0(\lambda)$ is determined from the pre-irradiation light intensities $J(\lambda)$ and $J_0(\lambda)$ transmitted by the sample and reference arms, respectively. Measurements of transmitted light intensities were accomplished as described in a companion paper [4]. Induced losses in the pigtails and GRIN lenses do not contribute to $L(\lambda)$ by virtue of placing the mated pigtail/GRIN-lens assembly of each reference arm at a position in the radiation field equivalent to that of the corresponding components in the IG sample arm.

A novel aspect of the present experiment was the simultaneous investigation of four IG segments at four widely separated dose rates. The irradiation rig consisted of an 0.77-m-diameter, 1-m-high "smoke stack" rolled from 0.8-mm-thick stainless steel which could be precisely centered above the NRL water shielded ^{60}Co γ ray source. As illustrated in Fig. 1, IG segments of lengths 3.7, 2.7, 1.8, and 0.9 m were wrapped around the stack at different heights representing iso-dose-rate locations of (top to bottom) 1.1, 6.6, 36 and 180 Gy(Si)/h, respectively, as verified by dosimetry. Of the samples delivered by the supplier, the

Figure 1. Schematic diagram of the rig used for simultaneous *in situ* optical measurements in different iso-dose-rate regions of the radiation field. In the present experiment, the top and bottom image guide segments had white jackets; the middle pair were black jacketed. For clarity, the reference-arm fiber pigtails and GRIN lens assemblies are not shown.

longest and the shortest IG segments (which were to be exposed at the lowest and highest dose rates, respectively) had white polytetrafluoroacrylate (PFA) outer coatings, while the two intermediate-length samples had black PFA coatings. It was subsequently verified that the white- and black-jacketed IGs, though nominally identical, originated in different production runs—a significant factor in interpreting the results to be described below.

III. EXPERIMENTAL RESULTS AND DISCUSSION

Pre-irradiation spectra were recorded *in situ* (i.e., with the experiment mechanically assembled in the exact configuration as it would be under irradiation). These spectra revealed (too late to change the experiment) that the GRIN lens arrangement allowed some light to be launched into the fused silica jacket or "bottle" surrounding the pixels. Although the bottle apparently contained some Fe^{2+} ions which made it less transmissive than the pixels under pre-irradiation conditions, radiation effects in the bottle still became confounded with damage in the pixels at doses below ~ 500 Gy. Also, light propagating in the relatively more rad-hard bottle made the IGs appear slightly more radiation resistant at doses greater than ~ 1 kGy than was true of the pixels alone. However, as will be alluded below and has been more extensively discussed elsewhere [5], most of these effects could be deconvolved from the data with the benefit of several post-irradiation experiments.

Figure 2 shows the spectral natures of the radiation-induced optical attenuation obtained during irradiation of the four IG segments of the present study. Some qualitative differences between the spectra of the black-jacketed IGs (Fig. 2a and b) and white-jacketed IGs (Fig. 2c and d) are apparent. Five weeks after the sample rig was withdrawn from the source, the dotted spectra were recorded by means of a different experimental arrangement, namely, by cutting the irradiated IG segments into shorter lengths and using 3-mm-dia. sapphire ball lenses in place of the (by-then severely darkened) GRIN lenses. This collimation arrangement filled only about 1/3 of the diameter of the pixel area and thus completely excluded the problem of light propagating in the bottle. Full spectra obtained in this way down to wavelengths of ~ 430 nm are shown in Fig. 3. The dichotomy between the black-jacketed and white-jacketed IGs is very clear in this figure. Because bottle effects were eliminated, this dichotomy must be ascribed to differences in the radiation responses of the pixels relating to some condition in the manufacturing process which was not controlled from one run to the next. Significantly, however, the two seemingly different spectral shapes could be fitted by using different linear combinations of the same three gaussian bands, as illustrated in Fig. 4. The Ge(1) and NBOHC bands are well known in the literature [6] (except that the NBOHC band in the present case had to be assumed to be two times broader), while the GeX band has been elucidated only recently [7]. The present results then suggest that the NBOHC and GeX bands arise from some precursor states, the numbers of which are determined by details of the manufacturing process.

Anoikin *et al.* [7] have shown that in Ge-doped-silica-core fibers the Ge(1) band (peaking at 280 nm) decays over a period of a year, while the GeX band (peaking at 475 nm) grows, perhaps in one-to-one correspondence. Although the two bands overlap to a considerable extent, the net effect at longer wavelengths can be an increase in absorption with time after irradiation. Indeed, in the present experiment the induced loss at 700 nm was observed to grow by $\sim 15\%$ in the first four days after removal of the samples from the radiation field and by $\sim 45\%$ after five weeks. This behavior implies that growth kinetics of visible-range absorption *during irradiation* must be initially linear—as opposed to the sublinear power-law behaviors commonly observed at infra-red wavelengths and associated with stretched-exponential post-irradiation decays [2].

Figure 5a and b illustrate the presently measured growth kinetics at wavelengths of 550 and 650 nm, respectively. Here, the "white" data points pertain to the white-jacketed IG segments and the black data points to the black-jacketed segments. The over-size data points represent the post-irradiation "pseudo-cut-back" measurements which excluded light running in the silica bottle. The long-dashed curves represent the presently inferred "correct" growth kinetics, i.e., initially linear with eventual saturation. High-side deviations from this canonical behavior at low doses are

Figure 2. γ -ray-induced optical loss spectra measured *in situ* for samples of Sumitomo image guide: (a) 2.71-m and (b) 1.8-m segments of black-jacketed image guide irradiated at 6.6 and 36 Gy(Si)/h, respectively; (c) 3.67-m and (d) 0.92-m segments of white-jacketed guide irradiated at 1.1 and 180 Gy(Si)/h, respectively. Dotted curves result from 5-week post-irradiation measurements of shorter portions of these segments.

Figure 3. Post-irradiation spectra (5 weeks out of source)

presumed to be due to confounding of Ge-doped-silica-pixel losses with losses in the silica bottle due to the faulty GRIN lens arrangement. In this context, it is recalled that induced losses in pure-silica-core fibers at 820 nm typically attain steady state at doses of ~ 10 -100 Gy(Si) reaching attenuation values which are higher for higher dose rates [1]. In Fig. 5b, the curves for the black-jacketed IGs cross over one another at a dose ~ 200 Gy(Si). Absent the confounding effects of light travelling in the bottle, it is inferred that (for a given IG type) the attenuation at 650 nm induced at higher dose rates should run parallel to, but *always below*, the corresponding data for lower dose rates [5]. This unusual behavior can be understood in the present case because (following [7]) at sufficiently low dose rates all Ge(1) centers would have time to convert to GeX centers *during* irradiation thus giving a higher net loss dose-for-dose at longer wavelengths than would be the case at a very high dose rate, under which condition this conversion would not have had time to take place.

Figure 4. Spectra from Fig. 3 plotted on an energy scale: (a) black-jacketed IG receiving 20 kGy(Si) (b) white jacketed IG receiving 100 kGy(Si). Thin curves are gaussian fits using previously isolated bands from ref. 7.

Figure 5. Growth curves of the γ -ray-induced optical losses measured *in situ* at (a) 550 nm and (b) 650 nm (small data points). Black and white data points correspond to black- and white-jacketed image guide segments, respectively. Over-size data points are measurements using a sapphire-ball-lens launching scheme performed five weeks after removal from the radiation field. Long- and short-dashed curves are model extrapolations of lower- and higher-dose-rate data, respectively, for the picture elements only. Deviations from the extrapolated behavior at doses below ~ 200 Gy(Si) are inferred to be a confounding effect of induced losses in the fused silica jacket or "bottle". The post-irradiation data points (oversize) are not subject to such artifacts but must be associated with the *lower-* dose-rate extrapolations.

IV. CONCLUDING REMARKS

Of all the effects determined in the present study, perhaps the most disturbing from a hardness assurance point of view is the very large variability of radiation sensitivity of the Ge-doped-silica picture elements due to currently uncontrolled aspects of the manufacturing process. Indeed, the performance of the white-jacketed IGs of the present study was inferior to that of the black-jacketed was ones by factors of ~ 3 and 5 at wavelengths of 550 and 650 nm, respectively. However, the fact that the induced losses in the spectral region ~ 400 - 700 nm do not decay with time after irradiation (and actually exhibit post-irradiation *growth* at wavelengths > 600 nm) is also an unwelcome surprise, since this implies that the use of Ge-doped-silica-core image guides in even very low-dose-rate environments may be precluded if the lifetime dose is expected to exceed a few hundred Gy(Si).

V. REFERENCES

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