Improvement in Radiation Resistivity of Pure Silica Core Image Guides for Industrial Fiberscopes

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Improvement in Radiation Resistivity of Pure Silica Core Image Guides for Industrial Fiberscopes

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To improve radiation resistivity of pure silica core image guides for industrial fiberscopes used for remote visual inspection in nuclear environments, the effects of dopants in the core materials were evaluated. Then the limitation in using the image guide with improved radiation resistivity under severer environments exceeding the scope of the experiments were assessed by the method to evaluate radiation-induced degradation quantitatively. The results have revealed that an appropriate doping amount of F in core glass improves radiation resistivity of image guides better than OH. To clarify the mechanism for the effect of F, further experiments to analyze the structural defects in silica glass are still being carried out.

1. Introduction

Industrial fiberscopes incorporating a pure silica core image guide, which is a coherent multiple optical glass fiber bundle with high purity silica glass core for remote visual inspection, was developed as an application of optical communication technologies ten years ago. Since then, superior radiation resistivity and color fidelity of high purity silica glass have extended the use of fiberscopes to remote visual inspection and monitoring in nuclear environments, where the inspection using the conventional image guides made of multi-component glass is impossible. With the extensive use for remote monitoring of nuclear installations and the widening reputation for practical effects, the demand for the image guides with improved radiation resistivity is increasing for use in severer nuclear environments.

Our researches have found that radiation resistivity of image guides mostly depends on core glass material. For improvement, we conducted the experiments to find a more effective dopant in the core glass material. Then we assessed the

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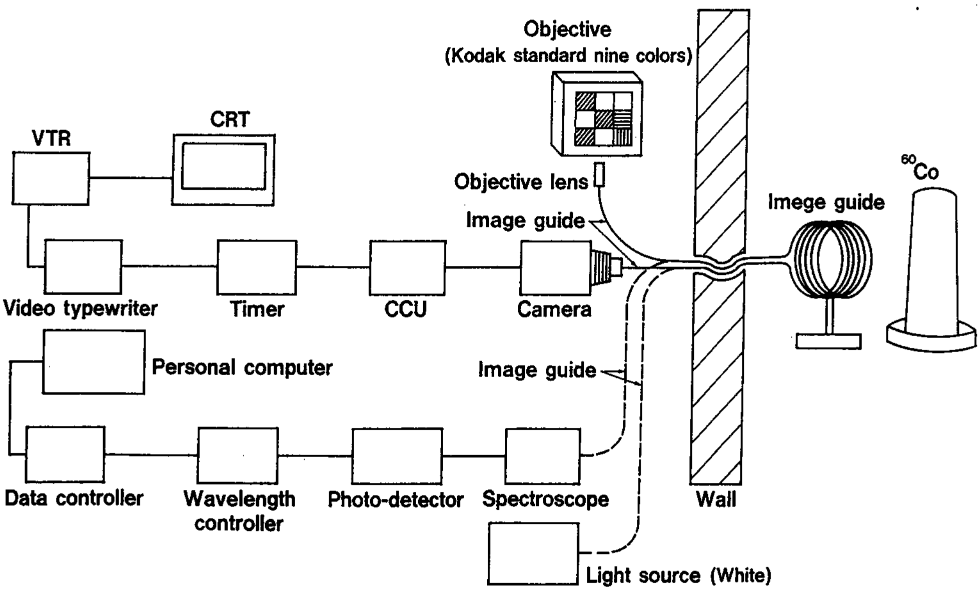

Fig.1 Irradiation test diagram

Table 1 Image guide samples and conditions for irradiation tests

Image guide	Core material			Preform structure	Number of pixels	Core packing density (%)	Irradiation test conditions			
	Cl content (ppm)	OH content (ppm)	F content (ppm)				Dose rate (C/kg/h)	Total dose (C/kg)	Irradiated length (m)	Measurement temperature
A	Free	Free	3,000	Three -layer	3,000	32	5.16 (2×10^{4}R/h)	2.58×10^{2} (10^{6}R)	10	R.T
							5.16×10 (2×10^{5}R/h)	2.58×10^{3} (10^{7}R)	5	
B	Free	100	Free				5.16 (2×10^{4}R/h)	2.58×10^{2} (10^{6}R)	10	
							5.16×10 (2×10^{5}R/h)	2.58×10^{3} (10^{7}R)	5	

limitation in using the image guide with improved radiation resistivity under severer environments exceeding the scope of the experiments, using the method for quantitative evaluation of radiation-induced degradation in picture quality which we already established.

2. Experiments

Figure 1 shows the experimental set-up using ^{60}Co as the irradiation source. Table

1 summarizes the image guide core compositions and testing conditions. The irradiation was conducted for 50 hours. The image guides were multiple fiber image guides in which each pixel with high purity silica glass core is coherently aligned and fused.

For the experiments, two core materials were selected: Cl-free, OH-free and F-containing core (No. A) and Cl-free, OH-containing and F-free core (No. B). While many papers have reported the influence of Cl and OH ions on radiation resistivity of pure silica core optical fibers$^{1)}$, it was reported that an image guide with Cl-free, OH-rich core material has good radiation resistivity.$^{2)}$ On the basis of our earlier finding that less OH content in Cl-free core glasses lead to better radiation resistivity$^{3)}$, we selected a core material with an OH content as low as 100 ppm and subjected it to the experiments to compare the effects of F and OH in suppressing radiation-induced degradation.

3. Results

Spectral loss increases in the image guides by gamma-ray irradiation at the dose rates of 2×10^4 R/h and 2×10^5 R/h were measured *in-situ*. The results are shown in Figs. 2 to 5. For both dose rates, the image guide (No. A) has better radiation resistivity. In particular, the difference in the absorption peaks around 480 nm and

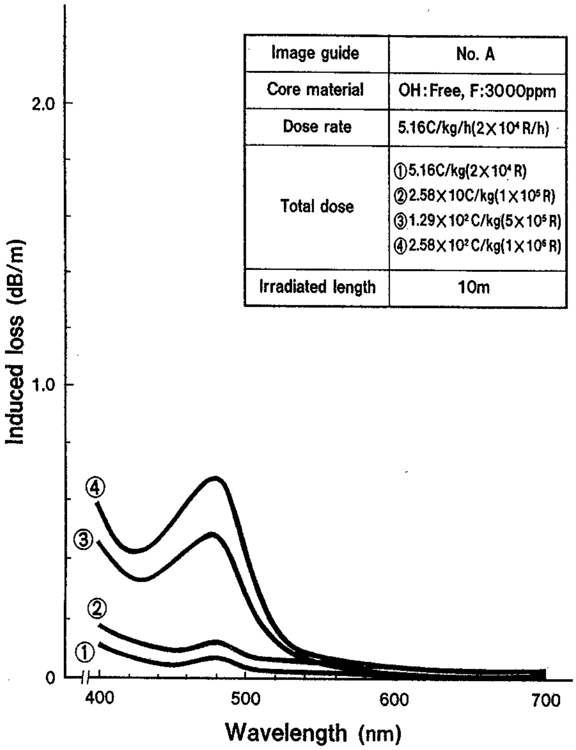
Image guide	No. A
Core material	OH: Free, F: 3000ppm
Dose rate	5.16C/kg/h(2×10^4 R/h)
Total dose	①5.16C/kg(2×10^4 R) ②$2.58\times10$C/kg(1×10^5 R) ③$1.29\times10^2$C/kg(5×10^5 R) ④$2.58\times10^2$C/kg(1×10^6 R)
Irradiated length	10m

Fig.2 Total dose dependence of *in-situ* radiation-induced losses

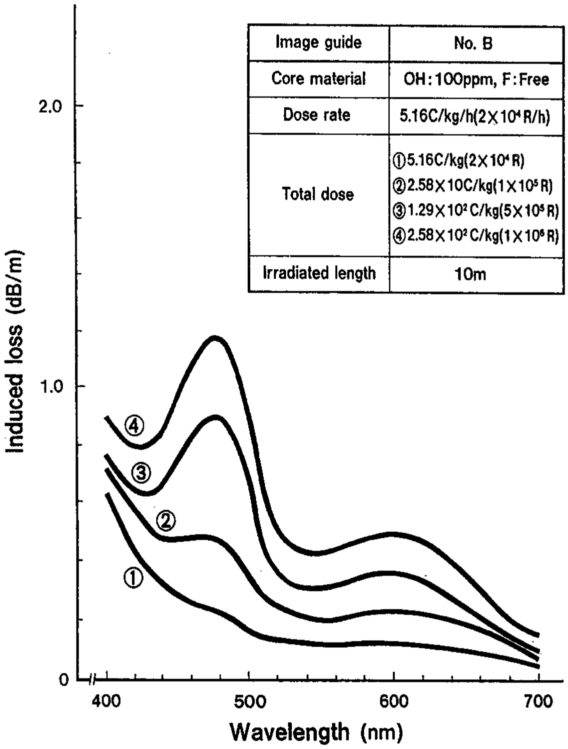

Image guide	No. B
Core material	OH:100ppm, F:Free
Dose rate	5.16C/kg/h(2×10^4 R/h)
Total dose	①5.16C/kg(2×10^4 R) ②$2.58 \times 10$C/kg(1×10^5 R) ③$1.29 \times 10^2$ C/kg(5×10^5 R) ④$2.58 \times 10^2$ C/kg(1×10^6 R)
Irradiated length	10m

Fig.3
Total dose dependence of *in-situ* radiation-induced losses

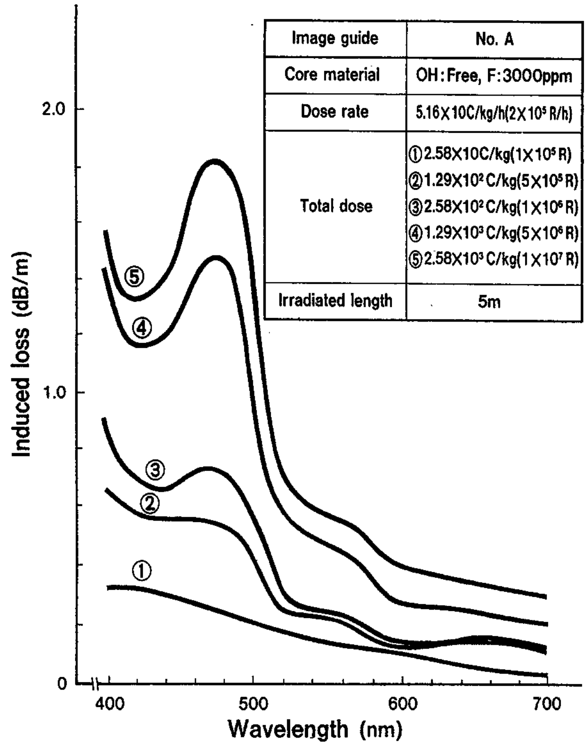

Image guide	No. A
Core material	OH:Free, F:3000ppm
Dose rate	5.16×10C/kg/h(2×10^5 R/h)
Total dose	①$2.58 \times 10$C/kg(1×10^5 R) ②$1.29 \times 10^2$ C/kg(5×10^5 R) ③$2.58 \times 10^2$ C/kg(1×10^6 R) ④$1.29 \times 10^3$ C/kg(5×10^6 R) ⑤$2.58 \times 10^3$ C/kg(1×10^7 R)
Irradiated length	5m

Fig.4
Total dose dependence of *in-situ* radiation-induced losses

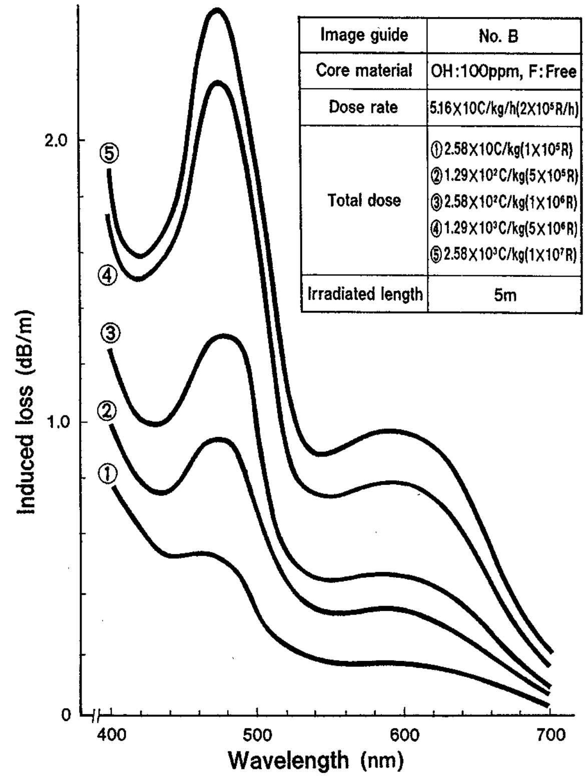

Fig.5 Total dose dependence of *in-situ* radiation-induced losses

610 nm are noticeable, and under higher doses, the difference becomes clearer. The absorption peak around 610 nm is found in the results with image gude (No. B) only. This peak is attributable to the presence of OH.

In evaluating the radiation-induced degradation in image guides, the use of which is visual inspection, degradation in picture quality observed by human eyes is the most important factor. The losses in output power, particularly in the wavelengths from 510 nm to 610 nm, have great weights in the degradation perceived by human eyes. On the contrary, the influence of the losses from 400 nm to 440 nm and from 680 nm to 700 nm is negligible, since these wavelengths correspond to the ends of visible wavelength range. As we already reported,[4] the measurement results were callibrated with spectral luminous efficiency, and average visual radiation-induced losses, representing the radiation-induced degradation perceived by human eyes, were obtained. Comparison of the average visual radiation-induced losses in the two image guides more clearly shows the effect of F in suppressing the radiation-induced degradation.

To assess the radiation-induced losses and the durability under the total doses higher than the experimental conditions, the relation between the average visual radiation-induced loss of the image guide (No. A) and the total dose was plotted and extrapolated as shown in Fig. 6, where the equation, $\log L = a \log R + b$ was obtained. The average visual radiation-induced loss is larger at a higher dose rate under the

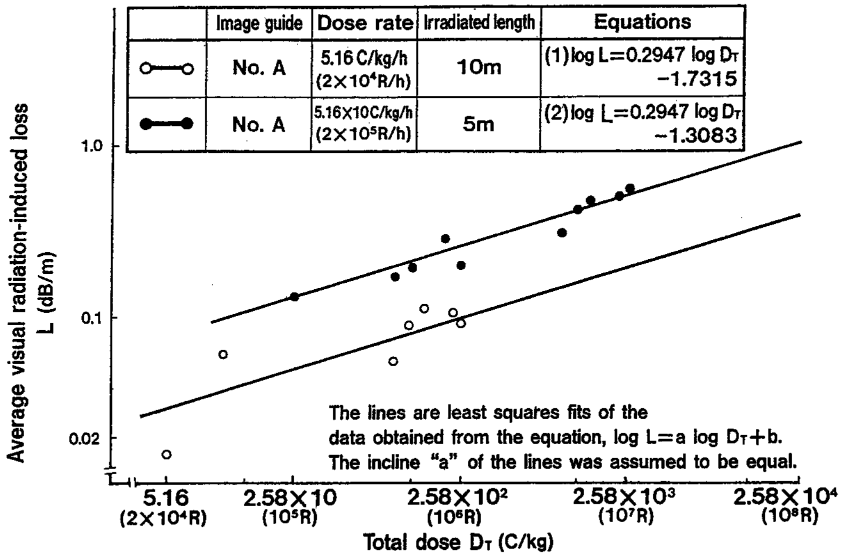

Fig.6 Dependence of *in-situ* average visual radiaiton-induced losses on total dose

Table 2 Maximum allowable total doses for a specific irradiation length(C/kg) (Image guide: No. A)

Average visual induced losses Lℓ (dB)(at400~700nm)	Dose rate (C/kg/h)	Irradiated length ℓ (m)					
		1m	2m	5m	10m	20m	30m
3dB (Output power ratio ≈ 50%)	5.16 (2×10⁴R/h)	3.12×10⁷ (1.21×10¹¹R)	2.97×10⁶ (1.15×10¹⁰R)	1.33×10⁵ (5.14×10⁸ R)	1.26×10⁴ (4.89×10⁷ R)	1.20×10³ (4.66×10⁶ R)	3.04×10² (1.18×10⁶ R)
	5.16×10 (2×10⁵R/h)	1.12×10⁶ (4.33×10⁹ R)	1.09×10⁵ (4.22×10⁸ R)	4.85×10³ (1.88×10⁷ R)	4.62×10² (1.79×10⁶ R)	4.41×10 (1.71×10⁵ R)	1.11×10 (4.31×10⁴ R)
4dB (Output power ratio ≈ 40%)	5.16 (2×10⁴R/h)	8.28×10⁷ (3.21×10¹¹R)	7.89×10⁶ (3.06×10¹⁰R)	3.51×10⁵ (1.36×10⁹ R)	3.35×10⁴ (1.30×10⁸ R)	3.20×10³ (1.24×10⁷ R)	8.05×10² (3.12×10⁶ R)
	5.16×10 (2×10⁵R/h)	3.04×10⁶ (1.18×10¹⁰R)	2.89×10⁵ (1.12×10⁹ R)	1.29×10⁴ (5.00×10⁷ R)	1.23×10³ (4.76×10⁶ R)	1.17×10² (4.53×10⁵ R)	2.94×10 (1.14×10⁵ R)
5dB (Output power ratio ≈ 30%)	5.16 (2×10⁴R/h)	1.77×10⁸ (6.85×10¹¹R)	1.68×10⁷ (6.52×10¹⁰R)	7.51×10⁵ (2.91×10⁹ R)	7.15×10⁴ (2.77×10⁸ R)	6.81×10³ (2.64×10⁷ R)	1.72×10³ (6.66×10⁶ R)
	5.16×10 (2×10⁵R/h)	6.48×10⁶ (2.51×10¹⁰R)	6.17×10⁵ (2.39×10⁹ R)	2.76×10⁴ (1.07×10⁸ R)	2.61×10³ (1.01×10⁷ R)	2.49×10² (9.66×10⁵ R)	6.30×10 (2.44×10⁵ R)
7dB (Output power ratio ≈ 20%)	5.16 (2×10⁴R/h)	5.55×10⁸ (2.15×10¹²R)	5.26×10⁷ (2.04×10¹¹R)	2.35×10⁶ (9.11×10⁹ R)	2.24×10⁵ (8.67×10⁸ R)	2.13×10⁴ (8.26×10⁷ R)	5.39×10³ (2.09×10⁷ R)
	5.16×10 (2×10⁵R/h)	2.03×10⁷ (7.86×10¹⁰R)	1.93×10⁶ (7.48×10⁹ R)	8.62×10⁴ (3.34×10⁸ R)	8.20×10³ (3.18×10⁷ R)	7.79×10² (3.02×10⁶ R)	1.97×10² (7.64×10⁵ R)
10dB (Output power ratio ≈ 10%)	5.16 (2×10⁴R/h)	1.86×10⁹ (7.20×10¹²R)	1.77×10⁸ (6.85×10¹¹R)	7.89×10⁶ (3.06×10¹⁰R)	7.51×10⁵ (2.91×10⁹ R)	7.15×10⁴ (2.77×10⁸ R)	1.81×10⁴ (7.00×10⁷ R)
	5.16×10 (2×10⁵R/h)	6.81×10⁷ (2.64×10¹¹R)	6.48×10⁶ (2.51×10¹⁰R)	2.89×10⁵ (1.12×10⁹ R)	2.76×10⁴ (1.07×10⁸ R)	2.61×10³ (1.01×10⁷ R)	6.60×10² (2.56×10⁶ R)

※1 Lℓ means in-situ average visual radiation-induced losses in the whole wavelength region from 400 to 700nm considering spectral luminous efficiency.

same total dose. Table 2 summarizes the maximum allowable total doses (D_T) for the image guide (No. A) in a specific irradiated length to give a specific average visual radiation-induced loss (*Ll*) at the dose rates of 2×10⁴ R/h and 2×10⁵ R/h, respectively. When the image guide is irradiated over the length of 5 m and its limit in average visual radiation-induced loss for practical use is 4dB over the whole length, for example, it is usable under total doses up to 3.51×10⁹ C/kg (1.36×10⁹ R) at a dose rate of 2×10^4 R/h. With the same conditions at a dose rate of 2×10^5 R/h, it is usable under total doses up to 1.29×10^4 C/kg (5.00×10^7 R).

4. Discussion

Many authors have reported the effects of Cl and OH ions doped in high purity silica glass core optical fibers and image guides on radiation resistivity and stated that Cl-free and OH containing (in some hundreds ppm) silica glass core gives good radiation resistivity.[2] It has also been reported that F doping in high purity silica core generally degrades radiation resistivity.[5]

Our experimental results[6], on the contrary, have revealed that an appropriate doping amount of F in core glass improves radiation resistivity of image guides far better than OH.

To clarify the mechanism for the effect of F, further experiments to analyze the structural defects in silica glass are still being carried out. In our opinion, the highest electronegativity of F gives the largest difference in electronegativity between Si and F among those between Si and all elements, and/or the bonding energy between Si and F (135 kcal/mol) is higher than those between Si and H (76 kcal/mol), between Si and Cl (94 kcal/mol), and Si and O (108 kcal/mol). Accordingly the unpaired electron of Si is so strongly attracted by F atoms that the bond between Si and F have difficulty in breaking even when irradiated by gamma rays and that the defects by gamma rays are not easily formed.

5. Conclusion

For remote visual inspection and monitoring of installations using fiberscopes under severer nuclear environments, we investigated improvement in radiation resistivity of high purity silica glass core image guides. An image guide with Cl-free, OH-free and F-containing core glass material (No. A) and an image guide with Cl-free, OH-containing and F-free core material (No. B) were compared for radiation-induced degradation at the dose rates of 2×10^4 R/h and 2×10^5 R/h. The results have revealed that the image guide No. A has much better radiation resistivity and that, in visible wavelengths, F has better effects in suppressing radiation-induced degradation in pure silica glass than OH, which was reported to have good effects. We assume, however, that the range of appropriate amount of F content to suppress radiation-induced degradation exists. Then the limitation in using the image guide with improved radiation resistivity under severer environments exceeding the scope of the experiments was assessed, by using the method for quantitative evaluation of radiation-induced degradation in picture quality which we already established.

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