

# Radiation-Resistant Single-Mode Optical Fibers

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*Loss of silica-based optical fibers increases when they are exposed to radiation. We have developed a fluorine-doped core single-mode optical fiber, which complies with ITU-T G.652.B and has excellent radiation-resistant characteristics compared with pure silica core single-mode fiber. Although the increase in radiation-induced loss of the conventional pure silica core single-mode fibers with the condition  $1 \times 10^6$  R/h and 60 min is approximately 25 dB/km at 1310 nm wavelength, the loss of the fluorine-doped core single-mode fibers with the same condition is approximately 5 dB/km at 1310 nm wavelength. In addition to the excellent radiation-resistant characteristics, we have confirmed that the fiber has an excellent loss recovery characteristic after irradiation.*

## 1. Introduction

Optical fiber transmission systems are widely used in present telecommunications because optical fibers have a large bandwidth and low loss and are not influenced by the electromagnetic induction, and their use can reduce the size and weight of optical fiber cables. Moreover, the demand for data transmission in the high radiation environment is large. Therefore, research and development on radiation-resistant optical fibers has been conducted for more than 20 years<sup>1)</sup>. When optical fiber is exposed to radiation, a colored center is formed because of the defect that exists in the fiber, there is absorption loss, and the transmission characteristic deteriorates. In particular, it is known to result in optical absorption in an ultraviolet and a visible region by defects that occur in the dopant such as germanium generally used to control the refractive index profile, the optical fiber manufacturing process, and the remaining impurities<sup>2)</sup>.

In the research of the radiation-resistant characteristics of silica-based optical fibers, research on large core optical fiber with step index profile and pure silica core glass was the main trend<sup>3-5)</sup>. In large core fiber with pure silica core where the radiation-resistant characteristics of the silica glass optical fiber depend on the concentration of OH and chlorine content, and the process of manufacturing core glass, the radiation-resistant characteristics of the optical fiber with high OH content are reported to be excellent<sup>6)</sup>. Nevertheless, further improvement of transmission capacity is needed when using it under the radiation environment in nuclear plants, reprocessing facilities, etc. The demand of large core optical fibers with the

graded index (GI) profile and single-mode optical fibers for high capacity has become larger; thus the need for boron and fluorine co-doped fibers, fluorine-doped fibers, and germanium-doped fibers with GI profile has been reported<sup>7)</sup>. Furthermore, pure silica core single-mode optical fibers with high transmission capacity and good radiation-resistant characteristics have also been reported.

However, in research fields such as accelerators where in recent years the aim has been to experiment on high-energy physics, there is an increasing demand for optical fibers with a large transmission capacity and an improved radiation-resistant characteristic. The fibers are 1.3- $\mu$ m optimized optical fibers that have excellent radiation-resistant characteristics and are compliant with the international standard ITU-T G.652.B. Although OH content is effective for the improvement of the radiation-resistant characteristics, the concentration of OH content in 1.3- $\mu$ m optimized optical fibers should be low, the so-called "low-OH type," because OH content has a very large absorption loss at 1.38  $\mu$ m wavelength. However, the fiber with low-OH core glass is inferior to the fiber with high-OH content, the so-called "high-OH type," in terms of radiation-resistant characteristics. It has been reported that radiation resistance was improved by fluorine doping to the core by the evaluation of a large core fiber<sup>8)</sup>.

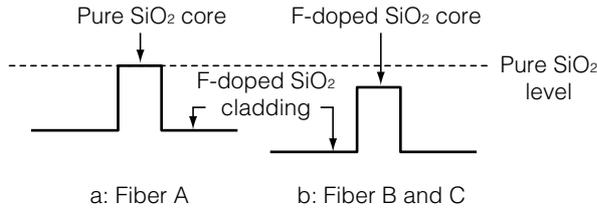
In this paper, we report that the radiation-resistant characteristic of single-mode optical fibers is greatly improved by optimizing the fluorine concentration added to the core glass.

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**Table 1. Parameters of sample fibers.**

Fiber No.	Material		OH content of core glass (ppm)	Manufacturing process for core glass	Fluorine content (wt%)		$\Delta n^*$ (%)	Core diameter ( $\mu\text{m}$ )	Cladding diameter ( $\mu\text{m}$ )
	Core	Cladding			Core	Cladding			
A	SiO <sub>2</sub>	F-SiO <sub>2</sub>	< 1	Plasma method	0	1.4	0.35	8.3	125
B	F-SiO <sub>2</sub>	F-SiO <sub>2</sub>	< 1	VAD method	0.2	1.6	0.35	8.3	125
C	F-SiO <sub>2</sub>	F-SiO <sub>2</sub>	< 1	VAD method	0.8	2.2	0.35	8.3	125

\*: Relative refractive index difference

**Fig. 1. Refractive index profiles of sample fibers.**

## 2. Design and characteristics

### 2.1. Fiber design

Figure 1 shows the refractive index profiles of the fibers that we fabricated. Figure 1(a) shows the refractive index profile of Fiber A with pure silica core glass, Fig. 1(b) shows that of Fibers B and C with fluorine-doped core glass. The parameters of all fibers are shown in Table 1.

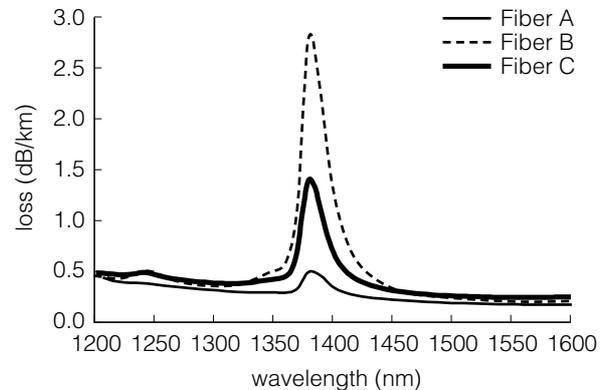
The OH content of the core glass for Fiber A is less than 1 ppm, the core glass is fabricated by the plasma method, and fluorine is not added to the core glass. The OH contents of core glass for Fibers B and C are less than 1 ppm, and fluorine concentrations are adjusted by the amount of the fluorine in Vapor Axial Deposition (VAD) method. The fluorine concentrations of Fibers B and C are 0.2 wt% and 0.8 wt%, respectively. The three optical fiber preforms are fabricated using the Outside Vapor Deposition (OVD) method. High concentration fluorine was added to the cladding of Fibers B and C as compared to Fiber A, as shown in Table 1, to keep the relative refractive index difference between the core and cladding of all fibers similar.

### 2.2. Fiber characteristics

The characteristics of the fibers fabricated for trial purposes and the loss spectra of the fibers are shown in Table 2 and Fig. 2. All characteristics of the three fibers are similar except for transmission loss. The transmission loss at 1.31  $\mu\text{m}$  wavelength of Fibers B and C are slightly higher than that of Fiber A. In particular, increased loss of Fiber B, influenced by the tail of the OH absorption loss at 1.38  $\mu\text{m}$  wavelength, is observed. The loss increases with little wavelength dependency, which is a dominant factor of the transmission loss of Fibers B and C, and thus it is thought

**Table 2. Characteristics of sample fibers.**

Characteristic	Recommended value in ITU-T G.652.B	Fiber A	Fiber B	Fiber C
Loss (dB/km) @1310 nm	$\leq 0.4$	0.33	0.35	0.38
Loss (dB/km) @1550 nm	$\leq 0.35$	0.18	0.21	0.25
PMD (ps/ $\sqrt{\text{km}}$ )	$\leq 0.2$	0.1	0.1	0.1
MFD ( $\mu\text{m}$ ) @1310 nm	8.6-9.5 $\pm 0.7$	8.6	8.6	8.7
Cladding diameter ( $\mu\text{m}$ )	125.0 $\pm 1.0$	125.0	125.0	125.0
Core concentricity error ( $\mu\text{m}$ )	$\leq 0.8$	0.2	0.3	0.2
Cladding noncircularity (%)	$\leq 2.0$	0.5	0.4	0.4
Cutoff wavelength ( $\mu\text{m}$ )	$\leq 1.26$	1.24	1.24	1.22
Zero-dispersion wavelength (nm)	1300-1324	1308	1308	1309
Zero-dispersion slope (ps/nm <sup>2</sup> /km)	$\leq 0.093$	0.081	0.081	0.079

**Fig. 2. Loss spectra of sample fibers.**

that the main cause of the loss increase is a structural imperfection loss. An influence of the fluorine-doping process to the core glass is thought to be the cause.

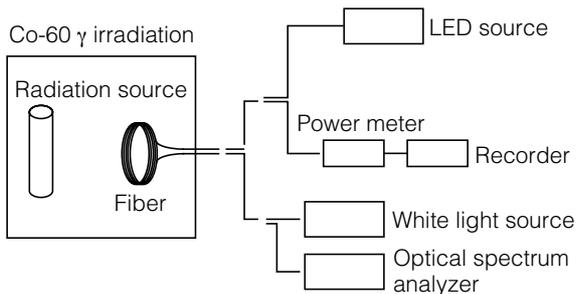


Fig. 3. Schematic diagram of experimental apparatus.

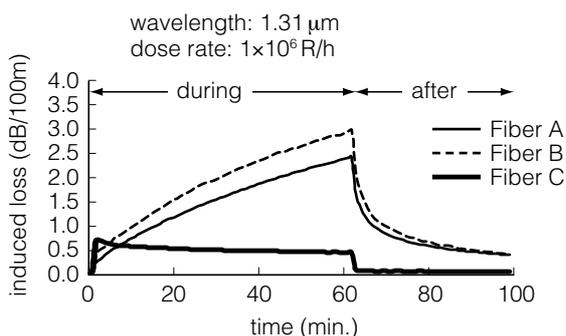


Fig. 4. Time response curves of radiation-induced loss.

It is important that these radiation-resistant optical fibers comply with the standard of normal single-mode optical fibers because they are used for data communications. All fibers fabricated for trial purposes meet ITU-T G.652.B; thus, it is possible to use these fibers the same as standard single-mode optical fibers.

### 3. Radiation-resistant characteristics

#### 3.1. Measuring method

Radiation-induced loss of the optical fibers during irradiation of the  $\gamma$  line was measured by two ways using LED source and optical spectrum analyzer. Figure 3 shows the schematic diagram of the measurement system. Each fiber length irradiated was 100 m. Radiation-induced loss increase of the optical fibers was continuously measured using LED at 1.31  $\mu\text{m}$  wavelength during and after irradiation. The three levels of dose rate were  $1 \times 10^5$ ,  $5 \times 10^5$ , and  $1 \times 10^6$  R/h; the radiation-induced loss and the loss recovery characteristics were measured during and after irradiation. The dose-rate dependency and the recovery characteristics of the induced loss by the radiation of the optical fibers were investigated using these measurements.

#### 3.2. Radiation-induced loss increase and loss recovery

Figure 4 shows the time-response curves of the radiation-induced loss at 1.31  $\mu\text{m}$  wavelength during

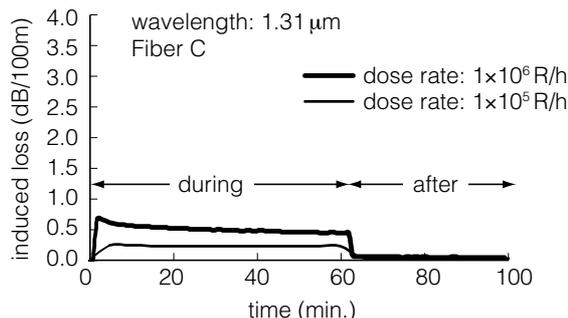


Fig. 5. Dose-rate dependency of radiation-induced loss.

and after irradiation. The irradiation condition was a dose rate of  $1 \times 10^6$  R/h with an exposures time of 60 min. The induced losses of Fiber A with pure silica core glass and Fiber B with the 0.2 wt% fluorine-doped core glass increase according to the length of exposure time. As observed, although large induced loss, as shown in Fiber C, occurred for a short time after the start of the irradiation, the induced loss increase gradually became lesser in spite of the irradiation. This is because fluorine accelerates the defect recovery by focusing on the energy of the  $\gamma$  line; thus, the so-called radiation hardening effect occurs.

Though this results in higher induced loss of Fiber B with the fluorine-doped core than that of Fiber A, it is thought to be influenced by the difference in the production method for the core material. It can be said that there is little effect of the suppression of the induced loss by the radiation in fluorine concentration of 0.2 wt% as a result. Although the increase in radiation-induced loss of Fiber A at the condition  $1 \times 10^6$  R/h and 60 min is approximately 25 dB/km at 1310 nm wavelength, the loss of Fiber C at the same condition is approximately 5 dB/km at 1310 nm wavelength. Moreover, it has been confirmed that this fiber has an excellent loss recovery characteristics after irradiation in a very short time. It is thought that fluorine has a similar effect as the OH content fills up the nonbonding defect in the fiber.

Figure 5 shows the dose-rate dependency of the induced loss in Fiber C. The measurement condition was dose rates of  $1 \times 10^5$  R/h and  $1 \times 10^6$  R/h at 1.31  $\mu\text{m}$  wavelength and the exposure time was of 60 min. As the dose rate increased, the induced loss increased. The recovery characteristic of this level was confirmed regardless of the dose rate.

#### 3.3. Radiation-Induced Spectral Loss

Figure 6 shows the induced loss spectra from 600 nm to 1300 nm of Fibers B and C when a dose rate of  $1 \times 10^5$  R/h was irradiated for 30 min. The induced loss spectrum of Fiber B was large, and the spectrum was not obtained accurately at the wavelength of 650

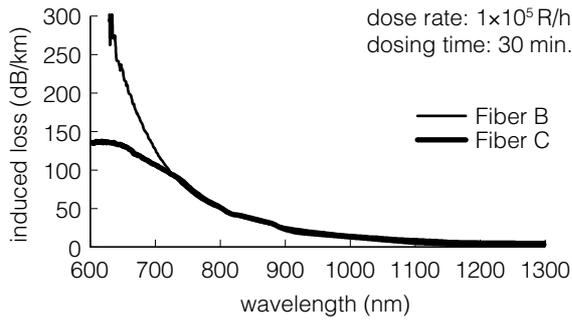


Fig. 6. Radiation-induced loss spectra.

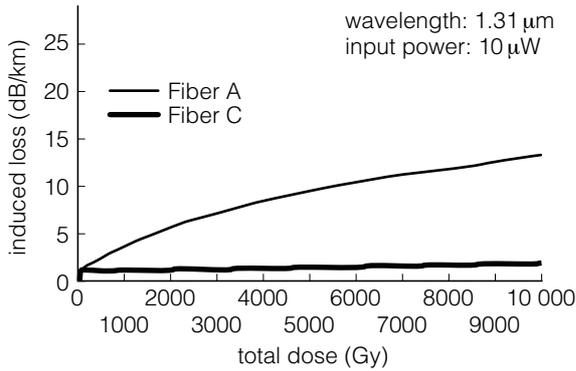


Fig. 7. Large dose radiation characteristics.

nm or less. It is confirmed that the induced loss below 700 nm of Fiber B is larger than that of Fiber C, as shown in Fig. 6. This is thought to have been influenced by the defect of E' with a center absorption loss of 215 nm. In Fiber C, it is presumed that the defect in the glass will be blocked by increasing the fluorine concentration, to suppress the loss increase by the radiation. On the contrary, the little absorption peak is seen at around 630 nm in Fiber C. The influence is thought to be due to the defect of nonbridging oxygen hole center (NBOHC), which is one of the color centers in the fused silica.

### 3.4. Large-dose irradiation characteristics

Figure 7 shows the dose dependency of induced loss of Fibers A and C. The measurement wavelength is 1.31  $\mu\text{m}$ . The induced loss of Fiber A with pure  $\text{SiO}_2$  core showed a tendency to increase with an increase in total irradiation, and the induced loss of approximately 13 dB/km was confirmed in a total dose of  $10^4$  Gy. On the contrary, although the induced loss of Fiber C with 0.8 wt% fluorine-doped core showed immediate saturation in the low-dose area, the large induced loss was not seen afterwards. The induced loss was approximately 2 dB/km in Fiber C in a total dose of  $10^4$  Gy. From this result it was confirmed that the effect of the addition of fluorine to the core was high.

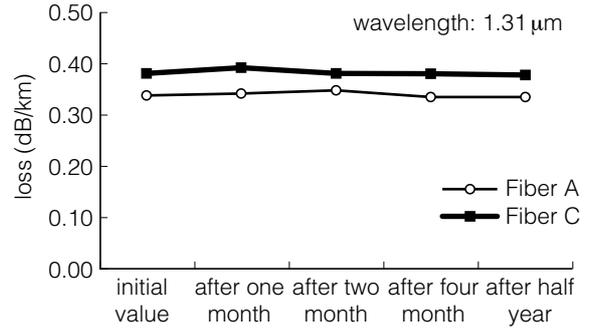


Fig. 8. Long-term stability of loss on Fiber A and C.

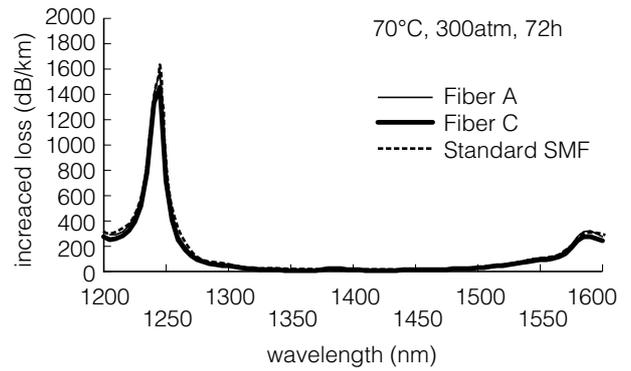


Fig. 9. Loss changes of sample fibers after hydrogen treatment.

## 4. Reliability

Although the method of adding hydrogen to the fiber for the improvement of the radiation-resistant characteristics is known, there might be a problem in the stability of the characteristics because hydrogen easily separates from the fiber. However, there is no characteristic change by the change in the concentration of hydrogen for Fibers A, B, and C because they were not treated with hydrogen. The change in the optical characteristics because of the change in the refractive index profile and the change of a long-term transmission loss have been discussed previously at length while discussing the fluorine-doped core optical fiber. Next, the transmission loss and MFD of Fibers A and C were measured for half a year to confirm the stability of the characteristics. Figure 8 shows the result of the measurement. It is confirmed that these fibers remain inert and stable over a long period of time. Moreover, MFD did not change beyond  $0.1 \mu\text{m}$  from an initial value and it conformed within the measurement error.

Furthermore, to confirm the influence of the hydrogen characteristics by fluorine doping the core, the change in the transmission loss of three fibers, Fibers A and C and a standard germanium-doped core single-mode optical fiber, was measured before and after the hydrogen treatment. Figure 9 shows the loss change of the fibers after hydrogen treatment. The

**Table 3. Test result of mechanical properties.**

Evaluation item	Measurement condition	Standard (unit)	Fiber A	Fiber C
Dynamic tensile force <sup>*1</sup>	-	0.7-2.0 (N/mm)	1.0	0.8
Coating stripping force <sup>*2</sup>	Maximum/average at room temperature	1-8.9/1-5 (N)	4.0/2.1	4.4/2.2
Dynamic fatigue value <sup>*3</sup>	Two-point bending	>18	19	19

\*1 : Reference Standard

\*2 : IEC60793-1-32, GR-20

\*3 : IEC60793-1-33, GR-20

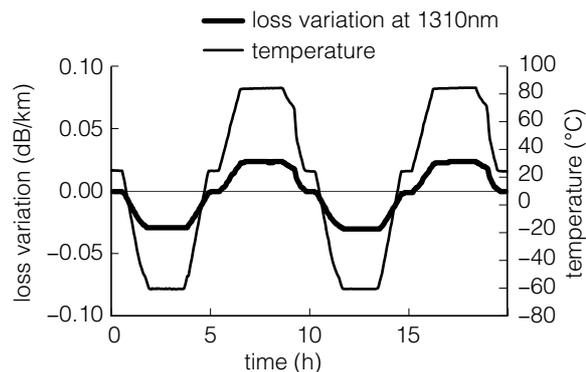
hydrogen treatment condition was 70°C and 300 atm pressure for 72 hours. It was confirmed that the result was almost equal for the three fibers, and there was not much difference in the hydrogen characteristics by the fluorine doping though the tendency for a slightly low loss change of Fiber C with fluorine doping core was shown.

Further, the test results of mechanical properties are shown in Table 3. The dynamic tensile force and the coating stripping force of fibers depend on the resin coating and fiber drawing conditions, and the values of the Fibers A and C were almost the same as standard transmission optical fibers. Moreover, it was confirmed that dynamic fatigue values of Fibers A and C were almost the same as that of the standard optical single-mode fibers. Figure 10 shows the loss variation of Fiber C during heat cycles. The loss variation at -60°C and +85°C were -0.02 dB/km and +0.01 dB/km, respectively. The loss fluctuation of Fiber C at the varying temperature was 0.03 dB/km; although this was a slightly high fluctuation compared to that of the standard germanium-doped core fiber, it was thought to be a negligible change. The temperature dependence of this loss is thought to be dependent on the slightly high initial loss of this fiber.

From the above-mentioned results, it can be concluded that there is no reliability difference caused by fluorine doping.

## 5. Conclusion

It was confirmed that an excellent radiation-resistant characteristic could be obtained by 0.8 wt% fluorine doping of the core of a 1.3- $\mu\text{m}$  optimized single-mode optical fiber used under the radiation environment as compared to the pure silica core optical fiber. In addition to conforming to international standard ITU-T G.652.B, it was confirmed that the radiation-

**Fig. 10. Loss variation during heat cycles on Fiber C.**

induced loss of our developed fiber was decreased to 5 dB/km at 1310 nm wavelength from that of 25 dB/km of conventional pure silica core fiber at 1310 nm wavelength with the radiation condition of  $1 \times 10^6$  R/h and 60 min. Moreover, it is confirmed that the fiber has an excellent loss recovery characteristic after irradiation for a short time. We are now planning to fabricate radiation-resistant optical fibers having improved radiation-resistant characteristic and low initial loss by optimization of the concentration of fluorine and fabrication methods.

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