Quality Assurance for Irradiation Tests of Optical Fibers: Uncertainty and Reproducibility

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***Abstract*—Uncertainty and reproducibility of irradiation tests of optical fibers are discussed. Estimated uncertainties are compared with consecutive measurements done over more than one year with five different single mode fibers.**

***Index Terms*—Gamma-ray effects, optical fiber radiation effects, quality assurance.**

I. Introduction

THE enhanced use of photonic technologies in radiation environments such as high-energy accelerators or space and emerging projects such as fusion reactors increase the need for irradiation tests, particularly for optical fibers. With limited budgets and therefore reduced safety margins together with high demands for the reliability of the test results, the accuracy of such measurements has to be known. Usually presentations of such test results come without a detailed uncertainty analysis or the measurement errors are only given as very general estimations.

This paper describes test and measurement procedures implemented at Fraunhofer INT for obtaining the radiation-induced loss in optical fibers caused by gamma rays. Those procedures are based on irradiation tests on optical fibers at our facilities since 1983.

Examples are presented where repeated tests of different optical fibers show the achievable reproducibility at Fraunhofer INT and confirm the uncertainty analysis. Also the influence of small temperature variation is discussed.

II. Experimental Setup

In general the described methods are derived from the respective standards, e.g., [1]–[6], or as they were discussed in earlier papers [7]–[9]. But several aspects need more attention and are discussed in greater detail here. Moreover, our experience showed that some specific recommendations are not leading to the best possible results.

A. Sample Preparation

Sample fibers are wound up onto reels of varying diameter (between 4 cm and 30 cm) and a width of 1 cm. The reels are made of aluminum of 1 to 1.5 mm thickness to serve as dose build-up layers, i.e., to achieve secondary radiation equilibrium already at the inner fiber layers. The sample preparation is done carefully with a dedicated spooling system to achieve a homogenous and stress-free sample coil. That minimizes possible microbending losses and avoids sudden attenuation changes due to mechanical relaxation processes of the fiber. This risk can be further reduced if the samples are shaken for a while before they are placed at the ^{60}Co gamma source.

The sample length is typically chosen so that the expected total radiation-induced attenuation in the sample is between 1 dB and about 5 dB, if possible. The minimum of 1 dB induced loss keeps the possible impact of noise and drifts below a few percent. On the other hand, the total induced attenuation should be kept below 5 dB to obtain homogenous light power distribution down the fiber. Otherwise possible (unavoidable) photobleaching effects could change drastically along the fiber (See Fig. 3 in [6]). For instance, if a fiber shows strong photobleaching and the total induced loss in the sample is high, the observed losses would increase along the fiber with decreasing light power, leading to an overestimation of the losses compared to those obtained at constant light power in a shorter sample [3].

If higher losses can not be avoided, the photobleaching behavior of the samples should be investigated.

Typical sample test lengths are 0.2 m to 200 m. One should note that this is not in agreement with some standards [1]–[4] that recommend or define fixed sample lengths. Considering the wide range of possible fiber types and their varying radiation sensitivity, a fixed sample length will not lead to accurate results.

Since some cladding dopands strongly affect the radiation sensitive a homogenous light distribution should be established, especially if the samples are shorter than some meters. This can be checked by comparing results obtained for different sample lengths.

If not otherwise specified, new sample spools are prepared for each test from the pristine fiber.

The samples are positioned in the irradiation area and spliced to radiation hard lead fibers of the same type. These lead fibers posses a known and low radiation sensitivity, so that the influence on the measured signal due to irradiation of a few centimeters of the lead fibers is minimized and (except for very special cases) negligible. In these special cases the known contribution of the irradiated lead fibers is subtracted.

The spool radius is measured before (inner radius r) and after the test fiber has been wound up (outer radius R) with a standard uncertainty of 0.5 mm.

Taking into account the spooling process and (under special conditions) the partly irradiated fiber leads, the combined standard uncertainty of the length of the sample l is evaluated not to exceed 2% or 2 cm, whichever is the greater. Randomly the

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length of longer fiber samples after preparation is checked again with an Optical Time Domain Reflectometer (OTDR) with a resolution of about 2 m.

B. Irradiation Facility and Dosimetry

At Fraunhofer INT most of the irradiations of optical fibers are done with the Gammamat TK1000 ^{60}Co irradiation system by *Isotopentechnik Dr. Sauerwein GmbH*. The small radioactive pellet (7 mm $\times$ 10 mm) is stored in a shielding container and can be moved into a steel tube within less than half of a second. This well-defined position is located in the center of the upright standing sample spools. That way the radius of the first layer of the fiber sample to the pellet does not vary by more than 0.5 mm.

The ejected radiation source is, except for the guiding steel tube, surrounded by open space of more than 0.5 m^3. So it is not directly enclosed in shielding material which could moderate the energy spectrum of the primary radiation and exhibit high levels of backscattering, causing inhomogeneous energy deposition and difficulties for the dosimetry. Another possible placement for the sample spools is a horizontal arrangement with the radiation source above the center of the sample spool.

By placing the sample at different distances, the dose rate can currently be varied between about 2.5 Gy/s and 0.5 mGy/s. At another available ^{60}Co source of Fraunhofer INT with similar geometry the dose rate can be further reduced by a factor of 50 for long term irradiations.

The dosimetry at is done routinely at several positions around the enabled source. The ionization chambers and corresponding electrometers are made by *Wellhöfer Dosimetrie*, Germany and *PTW Freiburg*, Germany. Both are calibrated to national standards with a relative combined standard uncertainty of less than 1%.

All obtained dose rate values at a specific distance are normalized to a reference date and a reference distance according to the inverse equation of (1):

$$G(\Delta, t) = G_r e^{-\ln 2 \frac{t-t_r}{T_{1/2}}} \frac{\Delta_r^2}{\Delta^2} \tag{1}$$

Here Δ and Δ_r are the current and reference distance, t is the current and t_r is the reference date, G and G_r are the current and reference dose rate, and $T_{1/2} = 5.2714$ a $\pm$ 0.0005 a is the half life of ^{60}Co. The mean value of such normalized values measured at various distances and over several years defines the reference dose rate for $t_r = 1990{-}01{-}01$ at $\Delta_r = 10$ cm as $G_r = 1.195$ Gy/s with a standard statistical uncertainty of 2.5% for the currently used ^{60}Co source.

The finally reported dose rate for an irradiation is determined by calculating the mean of all dose rates inside the sample volume described by the hollow cylinder with inner spool radius r, outer sample radius R and spool width H via (2) yielding the corresponding distance Δ.

$$\Delta = \sqrt{a^2 + Ha + \frac{H^2}{3} + \frac{R^3 - r^3}{3(R-r)}} \tag{2}$$

The perpendicular distance of the center of the spool to the point source is given by a. Placing Δ in (1) finally gives the mean dose rate $G(\Delta, t)$ for the irradiated fiber sample.

For the upright spool irradiations one can use $w = R - r$ and $a = H/2$, setting the pellet in the spool center. Then Δ is calculated by

$$\Delta = \sqrt{\frac{1}{12} + r^2 + rw + \frac{1}{3}w^2} \tag{3}$$

The expanded uncertainty for Δ given in cm can be approximated with the following expression:

$$\frac{U_\Delta}{\Delta} \approx 0.1 \cdot \frac{\Delta}{cm}^{-2.12} + 0.0273 \tag{4}$$

For the general case the total uncertainty for the dose rate is given by (5), shown at the bottom of the page.

The third term of (5) describes the uncertainty of the half life and the time to the reference date, that can usually be neglected. The uncertainty u_Δ for the general arrangement is a complex function of the individual uncertainties of r, R, H, and a not shown here.

C. Measurement Equipment and Procedure

The most common test setup for optical fiber tests at Fraunhofer INT is sketched in Fig. 1. The measurement equipment is located in a shielded booth which is thermally stabilized at 23.0°C $\pm$ 0.1°C. Here, as well as in the irradiation area, the temperature, humidity and ambient light are constantly monitored. Examples are shown in Fig. 2 with the seasonal temperature change in the irradiation area. A future upgrade is foreseen to regulate this temperature throughout the year to reduce these fluctuations.

The light of carefully selected highly stable LED and LD sources is adjusted with calibrated variable attenuators, e.g., HP8158B. This enables the operation of the light sources at constant power to reduce instabilities, but allows the variation of the light power in the sample. The light is then guided with a

$$u_G = G\sqrt{\left(\frac{u_{G_r}}{G_r}\right)^2 + \left(\frac{u_\Delta}{\Delta}\right)^2 + \frac{1}{T_{1/2}^2}\left((\ln 2 u_t)^2 + (\ln 2 t)^2 \left(\frac{u_{T_{1/2}}}{T_{1/2}}\right)^2\right)} \tag{5}$$

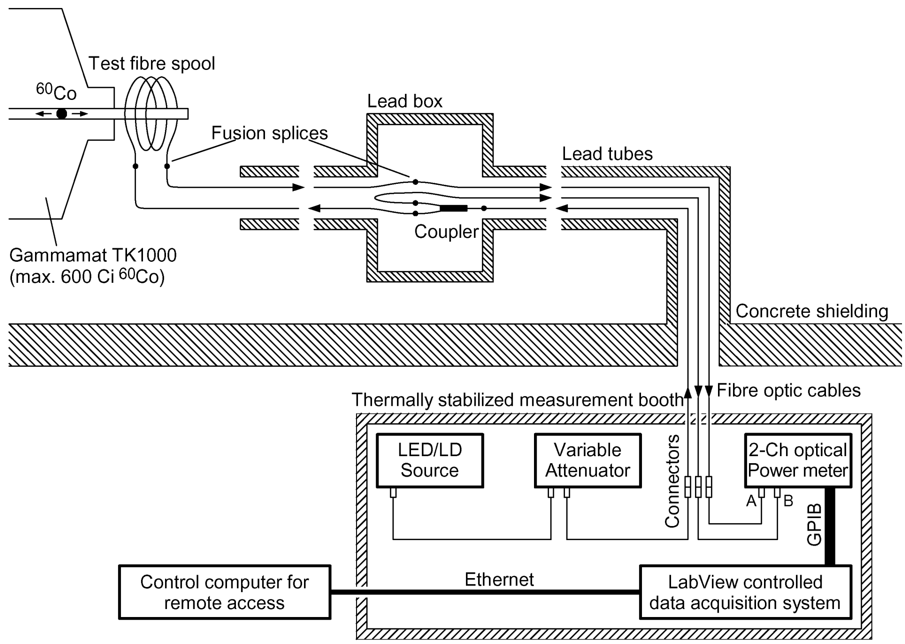

Fig. 1. Schematic of a typical experimental setup for irradiation tests of optical fibers at Fraunhofer INT.

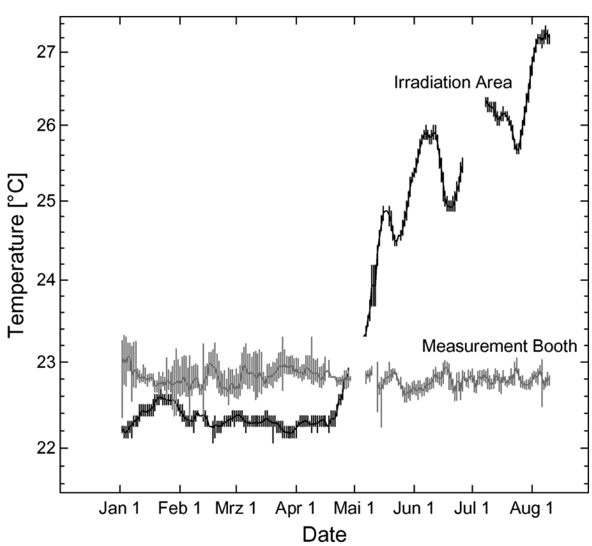

Fig. 2. Temperature monitored in stabilized measurement booth and in irradiation area with seasonal changes in 2008.

set of radiation-resistant optical cables of corresponding type to the irradiation area. Permanently installed are single-mode, graded-index and step-index fibers with core diameters between 9 μm and 200 μm. The cables are shielded with lead to guaranty long term stability. The light is split with a corresponding fiber optic coupler spliced into the light path. The couplers are, if available, mode-insensitive achromatic couplers to stabilize the output ratio and are also placed in a lead box preventing a direct exposition. One outlet is guided back and is monitored as the reference signal. The second channel is guided to the sample under test and then back to the measurement booth. There the light power is measured with calibrated high precision optical power meters, e.g., HP8153x, with different optical sensor modules.

If not otherwise specified, the attenuator is regulated to a light power between 1 μW and 10 μW in the sample according to the recommendations given in the standards [1]–[6]. However, those recommendations do not take into account the variation of power density in the fiber with the diameter. Therefore, it might be sometimes needed to adjust the light power accordingly if one compares fibers to very similar samples with a different diameter to exclude possible photobleaching influences.

Fibers for applications requiring distinctively different light powers might be tested at these levels to gain representative results.

Other setups allow the spectral measurement of the radiation-induced attenuation using white light sources and calibrated spectrum analyzers.

After the sample has been spliced into the light path, the light powers of both the reference and measurement channel are monitored for some hours to assure the stability of the setup. Usually the absolute variation of light power in both channels, mostly due to drifts of the light source, is around 0.01 dB. After compensating this by subtracting the signal of the reference channel measured in dB from the measurement signal, the typical stability is below 0.005 dB over several hours.

All test equipment is remotely controlled by dedicated software from outside of the booth. At the beginning and at the end of the irradiation the data is collected with higher frequency and lower averaging times than during the irradiation and the subsequent annealing phase. This allows following the faster processes immediately after ejecting and moving back the ^{60}Co source with proper time resolution, but minimizes noise during the rest of the measurement. The shortest periods possible for this setup are currently 0.3 s which also defines the uncertainty for the time stamp. For faster measurements, e.g., pulsed irradiations with our flash X-ray source, the light power is recorded with high-speed photo detectors.

The relative change of light power is recorded in dB, beginning already some seconds before the start. All data of the measurement channel and the reference channel is saved without any further processing with a high resolution time stamp for each data point.

D. Data Analysis

The initial light power before the test is calculated from the data measured before ejecting the ^{60}Co source for both channels and the reference channel is subtracted from the measurement channel to compensate for possible drifts of the light source. The radiation-induced attenuation A in dB/km as a function of dose D is calculated via (6)

$$A(D) = A(t \cdot G) = (A_m(t) - A_r(t)) \cdot 1000/l \qquad (6)$$

Here A_m and A_r are the relative light powers of the measurement and reference channel in decibels, l the fiber length in meters and G the dose rate calculated by (1).

Using the mean distance of the sample from the source the dose rate and its uncertainty is calculated to transfer the time scale of the data set to corresponding dose values.

All data processing is done with dedicated software leading to the radiation-induced attenuation in dB/km as a function of dose and the subsequent annealing in absolute (dB/km) and relative (% of final induced loss) values as a function of time after irradiation. As part of the data analysis the software calculates the uncertainty of the radiation-induced attenuation as described below.

III. Uncertainties

This discussion of uncertainties follows the "Guide to the Expression of Uncertainty in Measurement" (GUM) by the International Standards Organization (ISO) [10]. All information and procedures recommended in this standard cannot be described here in detail and therefore only the quantitative results will be given.

In the previous sections some individual contributions of uncertainties, such as dose rate, sample length, and drifts, were already mentioned. All uncertainty components are incorporated into a single value expressing the experimental error for each attenuation data point.

The accuracy of the optical power meters as used in our setup is specified by the manufacturer to be 0.0075 dB. The drift during the measurement is deduced from the range of values monitored in the reference channel or 0.01 dB, whichever is greater. Since this is a very conservative assumption and the drifts typically evolve and increase in magnitude with time t during the irradiation, a weighting function for this contribution is being defined by (7). Here $T = t/t_{irr}$ is the irradiation time relative to the total time of irradiation t_{irr}.

$$w(T) = (1 - 10^{-10 \cdot T})^{1/5} \qquad (7)$$

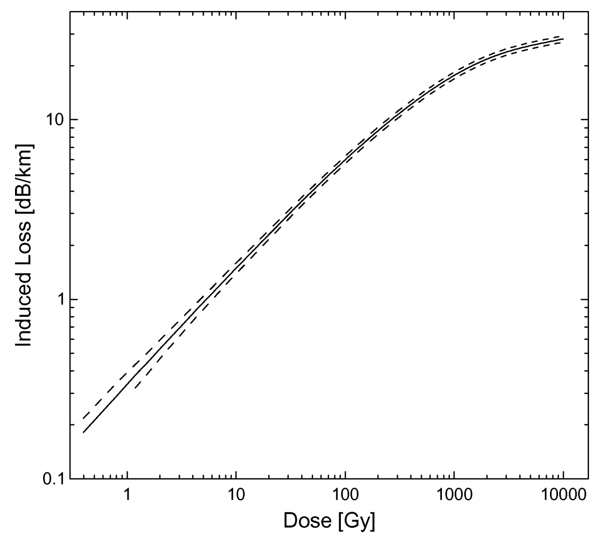

Fig. 3. Radiation-induced attenuation of a Corning SMF-28 with the calculated uncertainties shown in dashed lines ($\lambda = 1307$ nm, $\mathrm{G} = 0.20$ Gy/s, $\mathrm{t_{irr}} = 50400$ s, $\mathrm{D} = 9951$ Gy, $\mathrm{T} = 29°\mathrm{C}, \mathrm{l} = 150$ m, $\mathrm{P} = 10\ \mu$W).

This function reduces the impact in the very early part of the irradiation where the measured values are still extremely small and the nonlinearity and drift as defined above would have an exaggerated influence. On the other hand, already after 5% of the total time the uncertainties are taken into account to more than 90% of the maximum value.

Uncertainties of the dose rate and hence the dose are to be transformed into the attenuation uncertainty to provide a useful total value. Possible errors in the determination of the dose rate lead to two consequences: The first contribution is scaling of the x-axis. The abscissa values showing doses are obtained by multiplying the time by the dose rate. Uncertainties in the dose rate would compress or stretch the axis, resulting in different values of the induced loss at that point. The induced loss is correlated to the obtained dose values using the mean dose rate and the dose rate plus and minus its uncertainty. The corresponding attenuation values of the deviation pairs are subtracted. The result is the additional standard uncertainty in the attenuation and is added to the other uncertainties.

The second effect would be the direct dependence of the induced loss on the dose rate. To account for this, the functional relationship of the attenuation on the dose rate is needed, which is usually not known and typically different for different fiber types. Thus, this effect can so far not be covered in the uncertainty calculations.

We do not expect very large contributions from this second origin, since the uncertainties of the dose rates are in the order of some percent and the dose rate dependence of the induced loss is low on this scale.

As an example Fig. 3 shows the radiation-induced loss of a Corning SMF-28 fiber in double-logarithmic scale. The calculated expanded uncertainties (coverage factor $k = 2$) are shown as a function of dose with dashed lines. The expanded uncertainty of the total dose (9951 Gy) was $\pm 5.7\%$ as calculated by (5).

TABLE I
FIBER SAMPLES USED IN THE REPRODUCIBILITY TEST SERIES

Sample	Type	Core dopands	Manufacturer	Remarks
Sample A	Standard telecom SMF	Ge	Manufacturer does not want to be named	
Sample B	SMF-28e	Ge	Corning (US)	
Sample C	Standard Telecom RadHard	Ge	Draka (NL)	
Sample D	Pure Silica Core	none	Fujikura (JP)	Development sample
Sample E	Radiation resistant SMF	F	Fujikura (JP)	

The relative expanded uncertainty of the attenuation data including the dose uncertainty was determined to be $\pm 14\%$ for the very first data points and $\pm 4\%$ for higher doses. Already above 10 Gy the relative uncertainty drops below $\pm 7\%$.

IV. HOMOGENEITY

The homogeneity of an irradiation should always be given with the results to judge whether possible dose-rate variations across the sample volume might influence the interpretation. This has to be especially considered if the radiation-induced loss in the sample shows a strong dependence on the dose rate. In that case a different total result could be obtained compared to an ideal irradiation with a constant dose rate.

At Fraunhofer INT all homogeneities are given as the difference of the highest and lowest dose rate in the volume relative to the mean dose rate in the sample.

As an example the homogeneity, i.e., the variation of dose rate across the irradiated sample volume, of the measurement shown in Fig. 3 was 6.9%. It should be noted that this is higher than the reported uncertainty of the dose rate and also a possible source of dose-rate effect that can not be covered in the uncertainty analysis of the induced loss. Therefore, it is important to keep the dose rate variation across the sample as low as reasonably possible. Since this mainly depends on the geometrical setup, a careful arrangement of the irradiation source and sample is essential.

V. REPRODUCIBILITY

To confirm the uncertainty analysis a test series was performed to compare these deduced values to the reproducibility of measurements done consecutively over more than one year. The experimental arrangement was built up every time from scratch. The used light sources (always with very similar wavelength and the same light power), the power meters, and the sample spools were varied. Different technicians prepared the samples to see a possible impact of diverse handling procedures. The temperature of the whole irradiation area was $29^\circ\mathrm{C} \pm 1^\circ\mathrm{C}$ for all measurements to rule out the seasonal change of temperature. The diameter of the sample spools was reduced slightly during the test to compensate for the radioactive decay of the ^{60}Co source, leading to decreasing dose rate

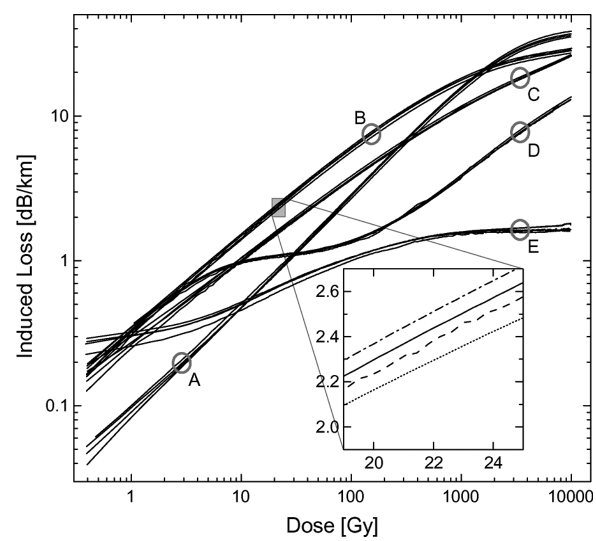

Fig. 4. Overview of all measurements done for this project. Shown are four consecutive measurements done with pristine samples of five fibers throughout one year under equal conditions.

at the same distance. So the dose rate during the whole test did not vary by more than ± 0.03 Gy/s.

In total five different single-mode fibers were tested (see Table I). Three fibers had Ge-doped cores; the other two were produced with undoped or F-doped core. Some of them were development samples provided by the manufacturers. So a wide range of SM fibers was covered. All tests were done under the same conditions: $\lambda = 1310$ nm, $\mathrm{T} = 29^\circ\mathrm{C}$, $\mathrm{G} = 0.2$ Gy/s, $\mathrm{D} \sim 10000$ Gy. The test conditions were chosen to represent a typical qualification test. Nevertheless the results of the reproducibility are representative for other test conditions at Fraunhofer INT.

The full set of data is shown in Fig. 4. It is obvious that the differences between the samples A, B, C, D, and E are much higher than those between the individual tests of the respective samples. The inset emphasizes the distinct results for each test of sample B.

As an example, one set of results for sample C is shown in Fig. 5, this time in linear scale. The irradiations were done in July 2006, October 2006, March 2007 and November 2007, and the

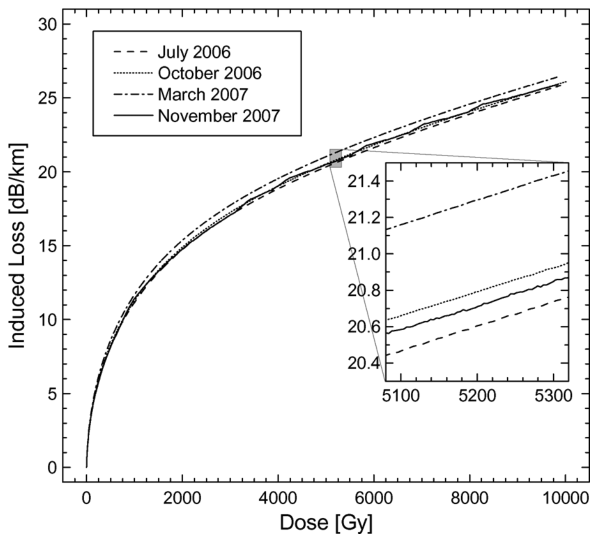

Fig. 5. Radiation-induced attenuation of a Ge-doped SM fiber measured four times under equal conditions over one year not showing the uncertainties ($\lambda =$ 1307 nm, $\mathrm{G} = 0.20\ \mathrm{Gy/s}$, $\mathrm{t_{irr}} = 50400\ \mathrm{s}$, $\mathrm{D} =\sim 10000\ \mathrm{Gy}$, $\mathrm{T} = 29^\circ\mathrm{C}$, $\mathrm{l} = 150\ \mathrm{m}$, $\mathrm{P} = 10\ \mu\mathrm{W}$).

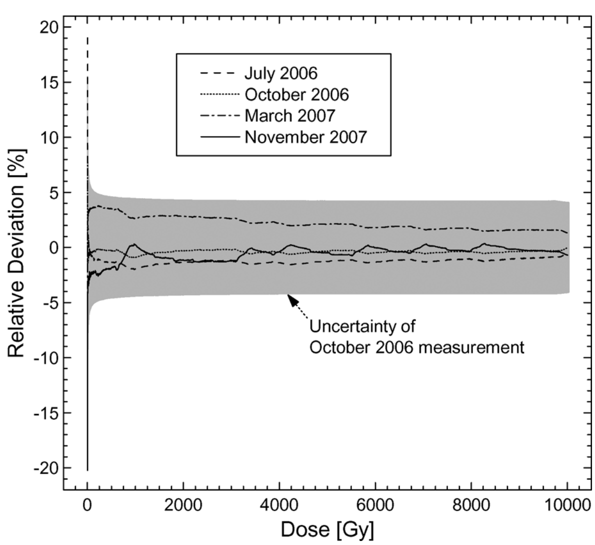

Fig. 6. Relative deviation of the data shown in Fig. 5 in comparison to the uncertainty evaluation of the data measured in October 2006.

results are compared to each other. The associated uncertainties are not plotted to emphasize the measured data.

The variation of the measured losses is in perfect agreement with the calculated uncertainties. This comparison between deviation and uncertainty is depicted in Fig. 6. The maximum deviation of the curves from each other is below ±4% except for the very first data points, whereas the calculated relative uncertainty in the test in October 2006 (shown as a gray band) is approximately ±5%.

VI. Influence of Small Temperature Change

To estimate the influence of the temperature variation during a year, similar irradiations were done also at 24°C and compared to results obtained at 29°C. Both temperatures are within the limits called "room temperature" according to [5] and could

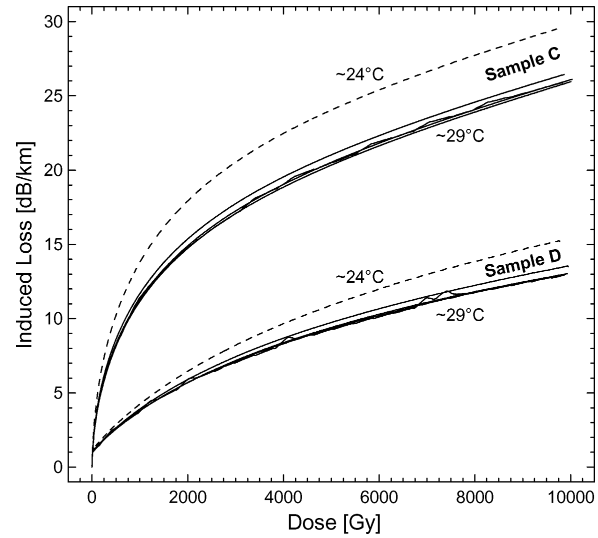

Fig. 7. Temperature dependence of radiation-induced loss for samples C and D measured at 24°C and 29°C.

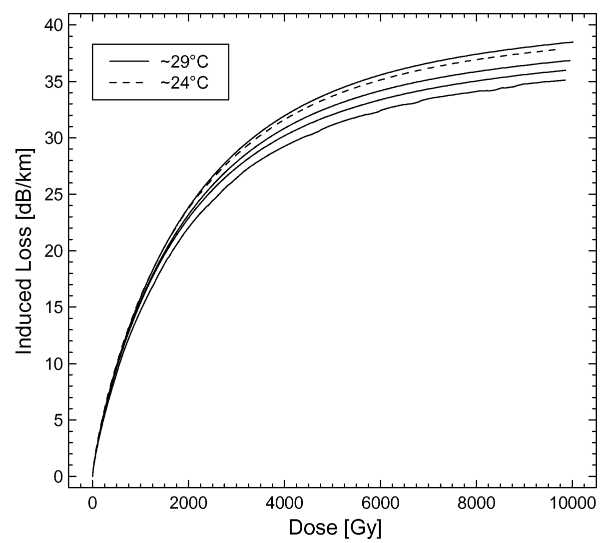

Fig. 8. Low influence of slight temperature decrease $(29^\circ\mathrm{C} \rightarrow 24^\circ\mathrm{C})$ on radiation-induced attenuation for Sample A compared to four identical measurements at 29°C.

therefore lead to the assumption that this small temperature difference is negligible. The results presented above show that we should be able to see an influence as long as the difference is clearly exceeding the corresponding uncertainty, e.g., is greater than 10%.

One example is given in Fig. 7. Here the result for an irradiation at 24°C is compared to four measurements at 29°C for the two samples C and D. All other conditions were the same. It is obvious that the temperature effect is much higher than the differences of the respective measurements at 29°C.

One should note that this was not the same for all tested fibers. For sample A, another standard commercial Ge-doped SM fiber, the temperature decrease had no notable impact as depicted in Fig. 8.

These results show that for some fibers large deviations can occur from test to test, even if the temperature is within the limits of 25°C±5°C as defined in [5] and underlines the need for exact documentation also of the precise sample temperature to be able to compare results of different irradiations.

Results from other measurements indicate effects of ∼3% to ∼6% for comparable temperature variations [11]–[13]. But these previous measurements were not investigating small temperature variations as done in this work. Since the temperature dependence was not the primary objective within this project further measurements are planned to further analyze the influence of small temperature variations, also for other fiber types.

VII. Conclusion

We presented an analysis of the test procedures of optical fibers irradiated with ^{60}Co-gammas at Fraunhofer INT. The uncertainties were discussed and examples of results confirming the reproducibility of such qualification experiments were shown. Irradiation tests of optical fibers conducted at Fraunhofer INT showed a reproducibility of about ±5% over one year. It seems therefore justified to claim that differences of more than 10% are due to test conditions or differences in the samples. Furthermore the results reduce concerns that fibers might change their radiation sensitivity over time. At least on time scales of some years one should not expect larger ageing effects in high quality telecom fibers. Finally it was shown that the temperature effects might be of importance when comparing very similar samples.

Acknowledgment

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References

[1] *Optical Fibres—Part 1-54: Measurement Method and Test Procedures—Gamma Irradiation*, IEC 60793-1-54, 2003.
[2] Standard Guide for Procedure for Measuring Ionizing Radiation-Induced Attenuation in Silica-Based Optical Fibers and Cables for Use in Remote Fiber-Optic Spectroscopy and Broadband Systems ASTM E1614-94, 2004.
[3] Procedure for Measuring Radiation-Induced Attenuation in Optical Fibers and Optical Cables NATO Nuclear Effects Task Group A/C 243, Panel IV (RSG.12), Chair: E.J. Friebele, 1992.
[4] FOTP-64: Procedure for Measuring Radiation-Induced Attenuation in Optical Fibers and Optical Cables TIA-455-64, 1997.
[5] Fibre Optic Interconnecting Devices and Passive Components—Basic Test and Measurement Procedures—Part 2-31: Tests; Nuclear Radiation EN 61300-2-31, 1995.
[6] Nuclear Radiation—Fibre Optic Guidance IEC TR 62283, 2003, Technical Report.
[7] E. J. Friebele *et al.*, "Interlaboratory comparison of radiation-induced attenuation inoptical fibers. I. Steady-state exposures," *J. Lightw. Technology*, vol. 6, no. 2, pp. 165–171, 1988.
[8] E. W. Taylor *et al.*, "Interlaboratory comparison of radiation-induced attenuation inoptical fibers. II. Steady-state exposures," *J. Lightw. Technology*, vol. 8, no. 6, pp. 967–976, 1990.
[9] E. J. Friebele *et al.*, "Interlaboratory comparison of radiation-induced attenuation inoptical fibers. III. Transient exposures," *J. Lightw. Technology*, vol. 8, no. 6, pp. 977–989, 1990.
[10] *Guide to the Expression of Uncertainty in Measurement (GUM)*, ISO/IEC Guide 98, 1995.
[11] H. Kanamori *et al.*, "Transmission characteristics and reliability of pure-silica-core single-mode fibers," *J. Lightw. Technology*, vol. 4, no. 8, pp. 1144–1150, 1986.
[12] D. L. Griscom *et al.*, "Model for the dose, dose-rate and temperature dependence of radiation-induced loss in optical fibers," *IEEE Trans. Nucl. Sci.*, vol. 41, no. 3, pp. 523–527, 1994.
[13] S. Theriault, "Radiation effects on COTS laser-optimized graded-index multimode fibers exposed to intense gamma radiation fields," in *Proc. SPIE*, 2006, vol. 6343, p. 63431Q.