Gamma Irradiation Test of Ge-Doped Single-Mode Optical Fiber at Cryogenic Conditions

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Abstract—**Optical fibers are used routinely in harsh environments for signal transmission or sensing applications. Whereas the individual challenges originating from very high or very low temperatures, vacuum or ionizing radiation were extensively studied, the effects of combinations of these conditions were not investigated widely. In this paper we report on a detailed analysis of gamma irradiation tests done on Germanium-doped single-mode fibers at very low temperatures of 16 K. The drastic change in radiation response is shown with varying temperatures through measurements with discrete light sources and a spectral measurement system. To monitor the temperature in the fibers, Fiber-Bragg-Gratings (FBG) were used and their response under radiation observed. The findings will be valuable for determination of the temperature dependence of the point-defect formation as well as for specialized applications at low temperatures, such as accelerators or deep space missions.**

Index Terms—**Cryogenics, Gamma-ray effects, Fiber gratings, Optical fiber testing**

I. INTRODUCTION

IT is well known that many parameters influence the radiation response of optical fibers drastically [1], among them especially temperature. Tests at one temperature are not necessarily transferable to environments with other temperature conditions. Already 1975 Mattern et al. investigated the attenuation increase in optical fibers caused by ionizing radiation at temperatures between 217 K and 344 K [2]. Halperin and Ralph investigated the influence of temperature in bulk Ge-doped quartz between 77 K and 600 K even earlier [3]. Most of the irradiation tests on optical fibers were done in a relatively limited temperature range. Higher temperatures were investigated mostly for the installation in nuclear facilities, for example Hawn et al. presented extensive results up to 873 K [4].

At lower temperatures only very few results were published, especially below 100 K. Only three papers report on irradiation tests between 77 K and 89 K [5]-[7]. Of those Barnes and Griscom did not compare the results with data obtained at room temperature and Söderqvist included no directly comparable results.

Systematic data of radiation-induced attenuation in optical fibers as a function of temperature is only available within a limited range with lowest temperature values of 152 K and 300 K [2],[8]-[21]. West gave a review of the temperature related effects and data available at the time [22]. The temperature range covered by this existing data is mainly defined by the foreseen applications and the relevant standards, such as MIL-PRF-49291 that demands tests between 227 K and 358 K.

The purpose of this study was to extend the temperature range of systematic investigations of the temperature dependence. This is needed for modern applications in high-energy accelerators, e.g. at the Large-Hadron-Collider (LHC) at CERN, where communication and sensing applications use optical fibers at cryogenic temperatures. Also for some space mission, the combination of very low temperatures and radiation is posing a thread. Examples are ExoMars or JUICE, were the expected temperature ranges are wider than usually tested.

Up to now no comparison of radiation test data on optical fibers at room temperature and below 150 K was done except a presentation of preliminary data obtained in the framework of this project [23]. In this paper we extend those results with spectral data and results obtained with FBG at low temperature and radiation.

II. EXPERIMENTAL METHODS

A. Irradiation procedure

The irradiations were carried out at the TK1000A Co-60 facility at Fraunhofer INT produced by Isotopentechnik Sauerwein. The activity of the source was 9 TBq. The point-like radioactive pellet is placed above the optical fiber sample in a defined distance yielding a precisely determined dose rate and non-uniformity in the sample.

Dose rates around the source at various positions and distances are constantly measured with calibrated ionization chambers manufactured by PTW with ISO17025 certified traceability to national standards. Based on that, a numerical model gives dose rate, dose rate uncertainty, and non-uniformity at any given position and time.

B. Irradiation of the single-mode fiber

The fiber under test is a Corning single-mode fiber SMF28e. It is a Ge-doped single mode fiber with acrylate coating.

The measurement setup consists of three light sources, several optical switches, two power meters and a

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spectrometer. Two of the light sources are custom made SLED and LD sources with wavelengths of 1570 nm and 1312 nm, respectively, and high stability. The third source is a TQ8111 white-light source manufactured by Advantest. Optical switches by Sercalo guide the light from a selected light source to up to two samples in the irradiation chamber. Additionally a reference channel is measured by introducing a coupler. The optical power of the two discrete sources is measured with HP8153x precision power meters by Agilent. The spectral transmission of the white-light source is measured with an OceanOptics NIRquest array spectrometer. All used equipment is calibrated and traceable to national standards. A detailed description with an extensive uncertainty evaluation can be found elsewhere [21]. During the online measurements the two discrete light powers are measured one after the other followed by the respective reference channels. Every ten discrete measurements a transmission-, dark-, and reference spectrum of the fiber is taken. The whole setup is situated in a thermally stabilized measurement booth (the temperature variation during the campaign as below ±0.5°C).

The fibers are wound stress free onto Copper sample spools with a diameter of 6 cm and a width of 1 cm. The sample length was 100 m at room temperature and 1 m at cryogenic temperature of 16 K. For irradiation the radioactive pellet is ejected from its shielding position to a position directly above the center of the spool within less than 0.5 s. The total time of irradiation was 70.000 s. The samples were in a helium atmosphere inside the cryogenic chamber.

The mean dose rate in the fiber sample was 0.26 Gy(SiO$_2$)/s with an expanded uncertainty of 6%. The non-uniformity was 37%.

Online measurements are done with the sample installed at the deactivated irradiation facility before irradiation at room temperature and during the cool down phase to check the consistency and stability of the setup. Then the irradiation of about 19 h is started after which the annealing is observed at cold temperature followed by the measurement during the warming up phase.

For analysis the measurement channels are compensated with the reference channels to decrease the influence of potential drifts of the light sources.

Low temperatures were achieved with a closed-cycle cryostat, Model DE204SF manufactured by ARS. A sample chamber is mounted on the second stage of the cryostat and filled with helium exchange gas in order to ensure good thermal coupling of the fiber; the feedthroughs from the outside to the helium atmosphere in the sample chamber are designed to be at room temperature. Two cernox sensors at the second stage and inside the sample chamber monitor the temperature, as well as two Fiber-Bragg gratings within the fiber-spool. An additional head-shield coupled to the first stage of the cryostat and the outer vacuum-chamber complete the cryo-setup. The inevitable vibrations of the Gifford-McMahon type cryo-cooler did not influence the optical measurements. Neither the attenuation measurements nor the very sensitive Bragg-grating measurements show any significant effect, weather the cryo-cooler was switched on or off, or in the cooling phase. In order to avoid placing fiber feedthroughs at low temperatures, high dose rates or at the helium-vacuum boundary, all fibers are routed from the low temperature sample chamber to room temperature inside stainless steel capillaries. The crossing from the helium atmosphere to air takes place at room temperature in order to avoid strain on the fiber induced by different thermal expansion coefficients.

The irradiations at room temperature were done in the same environment as the cryo-tests, i.e. the samples were mounted onto the cryostat, the sample chamber was filled with Helium and surrounded by vacuum.

III. RESULTS AND DISCUSSION

A. *Change of transmission during cooling phase*

Fig. 1 shows the change of transmission in the sample installed inside the Helium chamber while the temperature was decreased from room temperature down to 16 K at two discrete wavelengths.

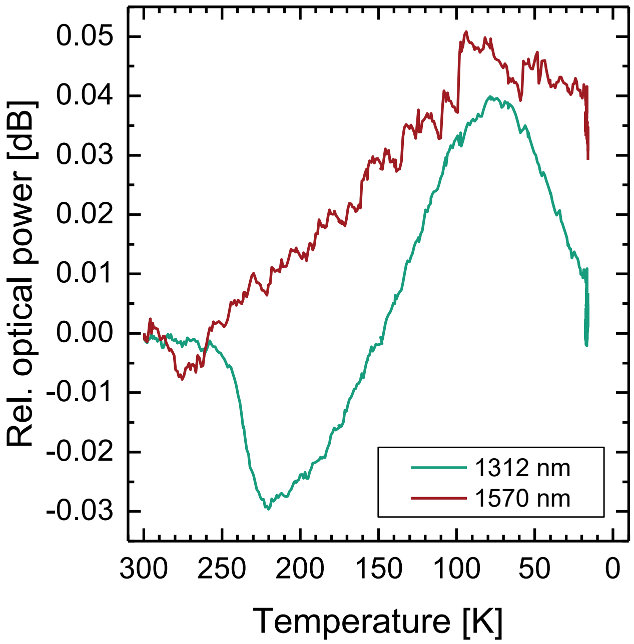

Fig. 1. Change of transmission of a commercial Ge-doped SMF during cooling down from room temperature to 16 K at 1312 nm and 1570 nm.

We observe only a slight change in transmission below ±0.5 dB which is much lower than the observed effect due to radiation later on. This confirms that the low temperature induces no mechanical or bending losses in the sample. Previous publications reported large fluctuations during the cooling of the fiber caused by microbending effects [24], which is not visible in our setup.

B. *Discrete measurements at two wavelengths*

Fig. 2 shows the radiation-induced attenuation of a commercial Ge-doped SMF at room temperature and at cryogenic conditions (16 K) at 1312 nm and 1570 nm as a function of dose.

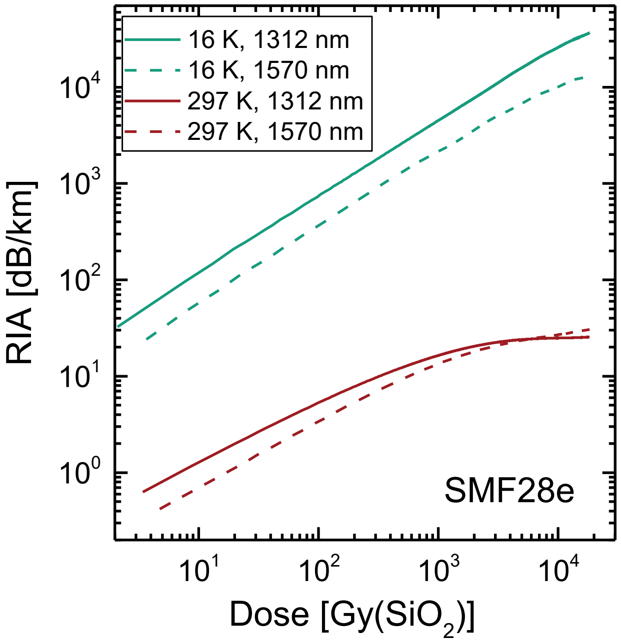

Fig. 2. Radiation-induced attenuation of a commercial Ge-doped SMF at room temperature and at cryogenic conditions (16 K) at 1312 nm and 1570 nm as a function of dose.

The RIA curves for this fiber at room temperature shown in red are in perfect agreement with previous measurements on this type of fiber, indicating that the test is not influenced by the cryostat setup. The induced losses after 18 kGy were in the range of 0.024 dB/m to 0.029 dB/m.

The same test performed on a pristine sample at 16 K, shown in green, gives much higher RIA values as expected [22]. After a total dose of 18 kGy the induced loss is 36.5 dB/m. and 12.5 dB/m at 1312 nm and 1570 nm, respectively. The loss at 1312 nm increased by more than factor of 1000 on the logarithmic dB-scale. The change in transmission is so large that any application with a fiber length in the range of a few meters or even below would not be operational any more.

C. Spectral measurements

In this section the results of the spectral measurements are shown. Even with the sample length limited to 1 m the signals soon reached the noise floor of the spectrometer. This is visible in Fig. 3. The data shown in the hatched area and at wavelengths larger than 1950 nm is not valid but limited by the dynamic range of the equipment.

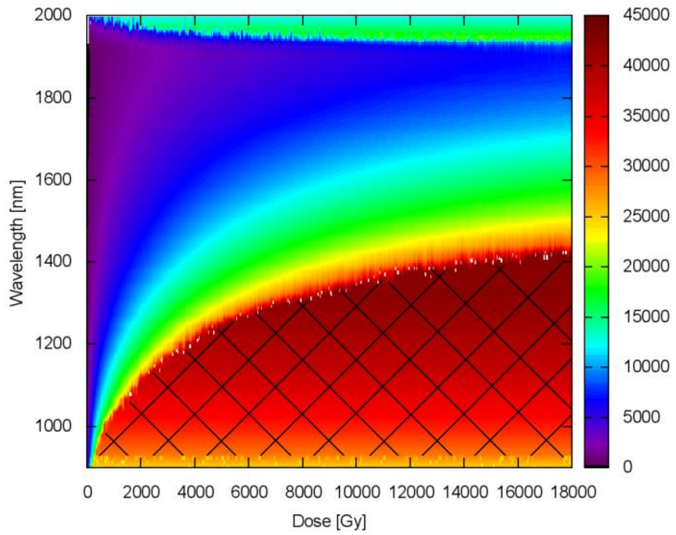

Fig. 3. Radiation-induced attenuation of a commercial Ge-doped SMF at cryogenic temperature (16 K) as a function of dose and wavelength in dB/km shown as a color plot.

The spectral plot confirms the results of the discrete measurement that the RIA is higher at 1312 nm than at 1570 nm. The RIA minimum is shifted towards higher wavelengths compared to the room temperature measurements. Whereas the minimum at 16 K is located around 1900 nm during the whole irradiation, it changes from about 1500 nm towards 1350 nm at room temperature.

The absolute values of the spectral measurement are in good agreement with the discrete measurements.

The data obtained in this project gives, for the first time, a complete view on the temperature dependent change of the RIA in a commercial SMF for cryogenic applications.

D. FBG Results

During the whole campaign two Fiber-Bragg-Gratings were interrogated with a FOS&S FBGS Scan 608 system to observe their Bragg-wavelength shift induced by the temperature change and caused by the irradiation.

In Fig. 4 the Bragg-shift as a function of temperature is shown. As expected the shift is linear down to a temperature of about 200 K, below that is becomes sub linear reaching a saturation at the lowest temperatures.

Two FBGs were implemented, one on the inside of the sample coil in direct contact with the sample spool, and the second one on the outside of the coil, in direct contact with the Helium atmosphere in the inner chamber. Since the two FBGs show the same shift we conclude that the temperature of the whole sample length was the same. Similar measurements without the inner chamber and Helium atmosphere showed significant deviations between the two indicating high difference between the inner and outer layers of the sample.

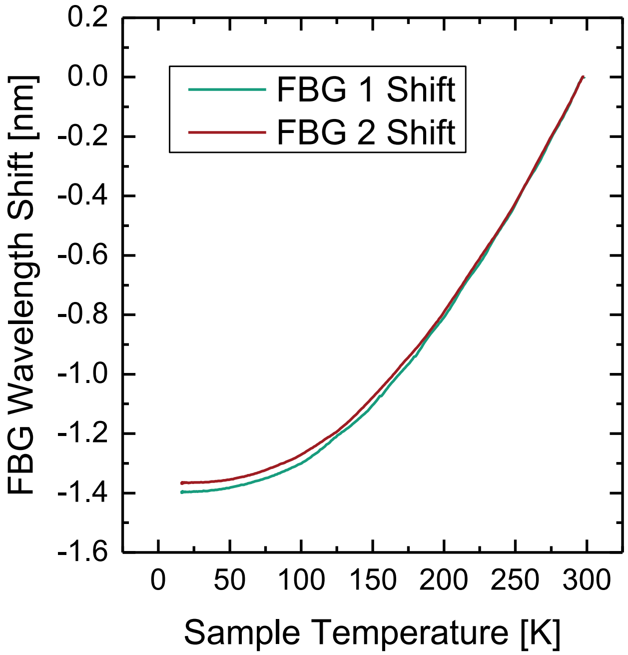

Fig. 4. Temperature-induced shift of the Bragg-wavelength while cooling down from room temperature to 16 K.

IV. CONCLUSIONS

For the first time, irradiation tests on optical fibers at 16 K were done. The direct comparison with tests at room temperature in the same experimental setup allows the analysis of the temperature on the results.

The enormous RIA increase limits the application of Ge-doped fibers at low temperatures dramatically. Even after some meters no transmission is possible.

In a follow-up project with CERN we tested the radiation-induced loss in rad-hard F-doped fibers at cryogenic temperatures. Here we observed lower temperature dependence [25].

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