Nuclear Engineering and Technology 56 (2024) 685–687

Contents lists available at ScienceDirect

Nuclear Engineering and Technology

journal homepage: www.elsevier.com/locate/net

Technical Note

Irradiation damage and recovery in gold-coated fiber optics

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ARTICLE INFO

Keywords:
Radiation damage
Fiber optic
Recovery

ABSTRACT

Fiber optic cables are used extensively for remote monitoring in applications under extreme conditions, such as at high temperatures or in ionizing radiation fields. When high temperature fiber optic cables were subjected to gamma irradiations, there was a significant loss in transmission at wavelengths < 350 nm after only 1 minute of irradiation. Negligible recovery of the fiber optic transmission with time was observed over 2 years, but the irradiation damage was almost completely reversed by high temperature annealing at 400 °C.

1. Introduction

Fiber optics function by transmitting light through thin, transparent cables to deliver high-performance optical signals over long distances. These fibers have a wide range of applications for remote *in-situ* monitoring of systems and solutions using analytical methods like UV-visible spectroscopy and Raman spectroscopy. Remote monitoring is essential in applications in extreme environments, like those associated with ionizing radiation. These environments can be natural, like in outer space, or manufactured, like in high energy physics facilities, such as the Large Hadron Collider, or nuclear facilities, such as nuclear reactors or hot cells [1]. These types of environments are of particular interest as they are not safe for personnel due to multi-component ionizing radiation fields. However, radiation may influence the performance of fiber optic cables used for remote monitoring by changing their optical, chemical, and mechanical properties. There are a large variety of fiber optics available commercially, and the extent of radiation damage received by each fiber is different depending on the fiber materials, manufacturing processes, and the radiation conditions, including temperature, nature of radiation, total dose, dose rate, and environment [1].

2. Materials and methods

High temperature fiber optic cables rated for temperatures up to 700 °C of 25 cm length (Part # SFS440) were procured from Molex LLC (formerly known as Fiberguide Industries, Lisle, IL, USA). The fibers consist of a 400 μm diameter high-OH pure silica core surrounded by a 440 μm diameter fluorine-doped silica cladding, coated in a 510 μm diameter gold-sheath and an outer Silverflex braided fiberglass cladding. The fiber materials chosen were pure and fluorine-doped silica, which have been demonstrated to exhibit the highest radiation resistance in past studies [2]. The cables are silver soldered with a SubMiniature version A (SMA) connector on either end, and rated for transmission in the 190–1250 nm range.

The fibers were irradiated in air in a Foss Therapy Services Inc. (Pacoima, CA, USA) Model 812 ^{60}Co Irradiator at the Center for Radiation Chemistry Research at Idaho National Laboratory. The approximate dose rate over the entire fiber length was determined relative to the aqueous Fricke dosimeter and corrected for the radioactive decay of cobalt-60 ($\tau_{1/2} = 5.27$ years; $E_{\gamma1} = 1.17$ MeV and $E_{\gamma2} = 1.33$ MeV) with no further corrections used for differences in the material densities.

An Agilent Technologies, Inc. (Santa Clara, CA, USA) Cary 60 UV-Vis spectrophotometer with fiber optic coupler was used to evaluate the transmission of the fiber optic cables at set time periods throughout the irradiation, scanning from 1100 to 190 nm with a scan rate of 300 nm/min. A Cary 5000 UV-Vis-NIR spectrophotometer with fiber optic coupler was used to examine the fiber optic transmission recovery from time and heating. The fiber was scanned from 1200 to 200 nm at 600 nm/min. All scans of the fiber optics were repeated in triplicate, by disconnecting and reconnecting from the fiber optic coupler between replicates to account for any changes in absorbances due to the fiber connections.

Fiber recovery by heating was performed within an argon glovebox in a Thermo Fisher Scientific (Waltham, MA, USA) Thermolyne benchtop muffle furnace (Part: FB1415M).

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https://doi.org/10.1016/j.net.2023.11.004
Received 22 August 2023; Received in revised form 26 September 2023; Accepted 2 November 2023

3. Results and discussion

Fig. 1 shows the change in fiber optic cable absorbance with gamma irradiation time at a dose rate of 47.4 ± 0.7 Gy min^{-1} over the wavelength range of 190–350 nm. Within a minute at this dose rate, the transmission in the ultraviolet region of the spectrum was significantly impacted. At wavelengths from 350 – 1100 nm however, no change in transmission was observed after 100 minutes of irradiation, corresponding to a total absorbed dose of 4.74 kGy.

This loss of transmission, or radiation-induced absorption (RIA) in a glass under gamma irradiation is explained by the formation of color centers in the fiber core by electrons or holes trapped in defects in the glass [3,4]. The color center bands are primarily observed in the ultraviolet region, consistent with the loss of transmission observed at wavelengths < 350 nm in this work. Here, the primary defect peak in Fig. 1 seems to be centered around 214 nm, or 5.8 eV. This absorption band has been observed in the past from X-ray [5], gamma [6], neutron [7], and heavy ion irradiations [8]. This band has been well-characterized with electron spin resonance spectroscopy and is attributed to E' centers forming in the silica [2,9,10]. An E' center is made up of an unpaired electron in a dangling tetrahedral orbital of a silicon atom bonded to only three oxygens in the glass [11]. After 100 minutes of irradiation, it appears that a second less intense characteristic band is also appearing in Fig. 1 at 258 nm, or 4.8 eV. This absorption band has been the subject of some debate [12,13], but is likely caused by non-bridging oxygen hole centers (NBOHCs) [2], which correspond to a silicon atom being bonded to an oxygen atom with an unpaired electron, or dangling bond [10].

Fiber optic cables damaged by 1.4 ± 0.2 MGy of gamma irradiation were left at room temperature for up to 2 years with no improvement in their transmission or change in the observed RIA. Identical irradiated fibers underwent varied heat treatments in triplicate, and the recovery of their transmission was studied. Fig. 2 shows the observed average recovery after 24 hours at a given temperature. As seen in Fig. 2, fibers heated to 80 °C did not show significant recovery and fibers heated to 200 °C showed only marginal improvement after 24 hours. Fibers which were heated to 300 °C showed some improvement in the ultraviolet range after 24 hours, but did not fully recover. However, essentially complete recovery of the fiber optic transmission was obtained by heating to 400 °C for 24 hours. Note that the small jump observed in the spectrum at 350 nm is simply an artifact from the instrument switching lamps. The exact recovery of a given material is expected to depend on its composition and fabrication process [3], but 24 hours at 400 °C post-irradiation appears sufficient to thermally bleach the defects out of the glass.

These observations are highly relevant to the use of fiber optics for remote monitoring in extreme environments. This work shows that the fibers can be successfully used under irradiation at wavelengths greater than 350 nm for long periods of time. To minimize radiation damage and use fiber optics in the ultraviolet region in radiation environments, more advances are required in the development of radiation-resistant fibers. An appropriate solution may include using particular dopants in the fiber core that prevent color centers from forming, advanced pretreatments for the fibers prior to irradiation, or developing a lightweight cladding that can shield the fiber from radiation damage. Simultaneous heating to bleach the defects in the fiber during irradiation has yielded mixed results [14,15]. Depending on the fiber doping, this treatment can decrease the RIA by facilitating defect recombination, or increase the RIA by favoring the generation of other types of defects [14].

4. Conclusions

This study has irradiated gold-coated fiber optics rated for high temperatures and studied their radiation-induced damage and recovery with heat treatment by optical transmission. Significant damage in the UV range occurred within a minute of irradiation at 47.4 Gy min^{-1}. Heat treatments of the damaged fibers post-irradiation showed effectively complete recovery after 24 hours at 400 °C. These results suggest that for use in the UV range, further advances in fiber optic composition or processing must be developed to avoid damage from the radiation field.

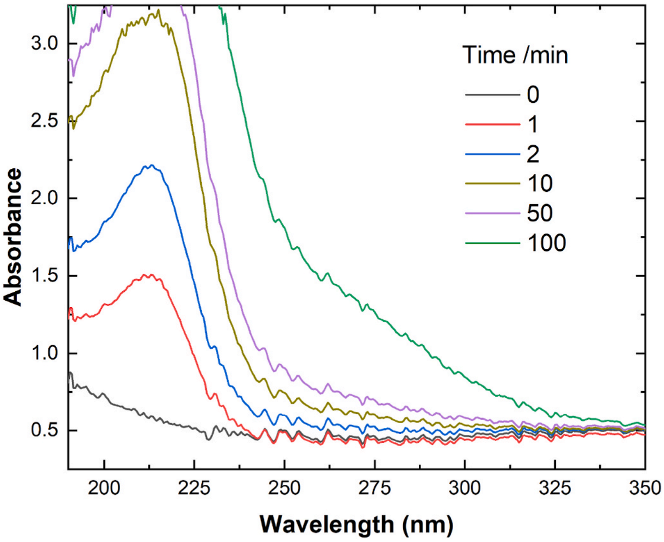

Fig. 1. Change in the fiber optic absorbance with gamma irradiation at a dose rate of 47.4 Gy min^{-1}.

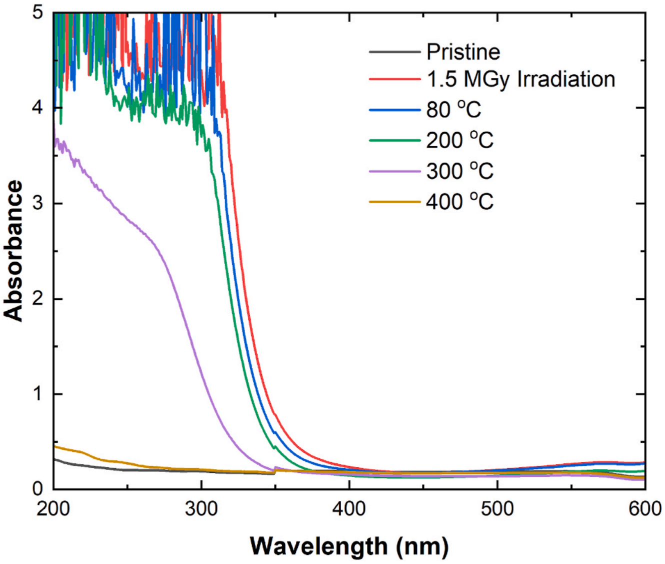

Fig. 2. Recovery of the irradiated fiber optic after 24 hours at a given temperature.

Declaration of competing interests

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Acknowledgements

This work is supported through the INL Laboratory Directed Research & Development (LDRD) Program under DOE Idaho Operations Office Contract DE-AC07-05ID14517.

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