Temperature dependence of radiation-induced attenuation of optical fibers

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Received April 25, 2012; accepted June 20, 2012; posted online September 28, 2012

We investigate the temperature dependence of radiation-induced attenuation (RIA) at 1 310 nm for a Ge/P co-doped fiber after a steady-state γ-ray irradiation. A γ irradiation facility ^{60}Co source is used to irradiate the fiber at a dose rate of 0.5 Gy/min, satisfying a total dose of 100 Gy. The test temperature ranges from –40 to 60 °C by 20 °C, and the RIA of the fiber is obtained using a power measuring device. The experimental result demonstrates that RIA exhibits a steady, monotonic, and remarkable temperature dependence after approximately 48 h of accelerated annealing at 70 °C. The optical fiber irradiated with a high dose and annealed sufficiently can be used as a temperature sensor.

OCIS codes: 060.2310, 350.5610, 120.6780, 060.2370, 060.2400.

doi: 10.3788/COL201210.110604.

The recent advancements in photonic technologies have provided new applications for optical fibers involving radiation environment, such as fibre optic gyroscope (FOG)[1,2] and fiber optics amplifiers[3,4] in space. The presence of highly energetic radiation in this environment, however, may induce additional optical attenuation greatly. Radiation-induced attenuation (RIA) is primarily caused by the trapping of radiolytic electrons and holes at defect sites in the fiber, i.e., formation of color centers[5,6]. In addition, a number of studies have indicated that the RIA of an optical fiber is sensitive to temperature[7,8]. Various studies have demonstrated that RIA decreases with increasing temperature, with the exception of fibers containing phosphorus (P)[9]. This phenomenon is mainly because of thermal annealing of color centers, which eliminates more of the damage at an elevated temperature[10]. For a P-doped fiber, researchers have considered this exception by transforming the phosphorus oxygen hole center (POHC) into the P1 center[11,12].

In this letter, the temperature behavior of the RIA of a Ge/P co-doped fiber after steady-state γ-ray irradiation and a series of annealing treatments was tested to demonstrate the temperature dependence of color center absorption. Our tests only considered the temperature, avoiding the influence of other factors, such as radiation dose and dose rate.

Only one type of fiber was studied in our experiments, Ge/P co-doped both in core and cladding. The cladding and coating diameters of this fiber were 80 and 165 μm. This 300-m-long fiber was produced with a loss constant of 0.8 dB/km at 1 310 nm.

Our experiments involved three steps. First, the temperature behavior of the fiber loss was tested in two temperature cycles before irradiation to compare the RIA temperature effect. Second, the tested fiber was subjected to radiation to satisfy a total dose of 100 Gy, and then set aside for approximately 4 d at room temperature for primary annealing. Two temperature cycling tests were conducted for the RIA temperature characteristic testing, in which the test condition was the same as the initial conditions. Finally, the fiber underwent an accelerated annealing process at 70 °C, which was 10 °C higher than the maximal test temperature, until the attenuation variation was less than 0.005 dB in the last 5 h. The annealing process was approximately 48 h. In addition, the RIA temperature performance was tested after the annealing process.

Every temperature behavior test for each step included two temperature cycling tests. The scheme of each temperature cycling is described in Fig. 1. Each cycling test started and ended at 25 °C. Temperature control was achieved using an electric heating oven, whose uncertainty of temperature control was better than ±0.5% in the whole tested range from –40 to 60 °C.

The experimental setup shown in Fig. 2 was developed

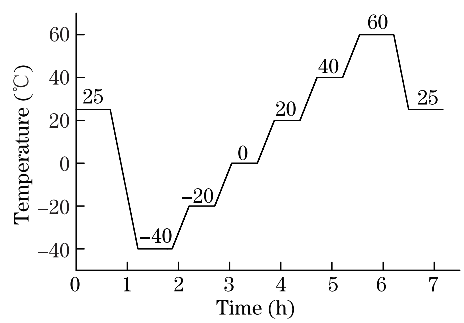

Fig. 1. Cycling setting for the temperature behavior tests of the fiber.

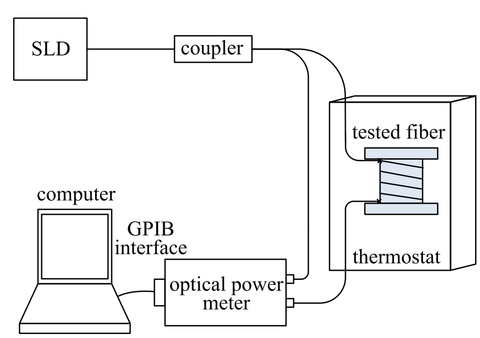

Fig. 2. Experimental setup for measuring the attenuation of the fiber in temperature cycling tests.

to measure the loss or attenuation of the fiber. A super luminescent diode (SLD), operating at 1 310 nm, was used as the light source, and its output optical signal was split into 2 paths by a 2×2 coupler. The interrogation signal power was approximately 20 μW. Both optical signals from the tested fiber and the reference were measured using a multichannel optical power meter. The attenuation $A(t)$ of the fiber can be calculated by

$$A(t) = -10 \lg \frac{P_{\mathrm{T}}(t)}{P_{\mathrm{R}}(t)}, \quad (1)$$

where $P_{\mathrm{T}}(t)$ and $P_{\mathrm{R}}(t)$ are the measured powers of the tested fiber and reference, respectively. RIA was then computed by

$$\mathrm{RIA}(t) = A(t) - A_0, \quad (2)$$

where $A(t)$ and A_0 denote the real-time attenuation and fiber loss before irradiation, respectively.

The γ irradiation facility ^{60}Co source at Peking University was used to irradiate the fiber at a dose rate of 0.5 Gy/min. The process was conducted at the natural temperature of the irradiation room.

The temperature behavior of the tested fiber loss before irradiation is shown in Fig. 3(step 1), in which the loss curve evidently slightly fluctuates with temperature. The maximal variation in the attenuation in the temperature cycling tests was approximately 0.014 dB, i.e., 0.047 dB/km, which was considerably lower than the ordinary fiber loss, –0.8 dB/km. This slight temperature effect is often ignored in a general application.

The relationship between the fiber RIA and temperature in the two different periods of annealing (steps 2 and 3) are illustrated in Figs. 4 and 5. A small gap was observed between the RIA at the starting stages of the two cycles in Fig. 4, approximately 0.025 dB. This condition indicates that some kind of unstable color center contributes slightly to the RIA annealed in the previous cycling test, possibly at the higher temperature stages (>25 °C).

By contrast, the RIA of the fiber in step 3 was almost the same as the initial for identical temperature stages (Fig. 5), after approximately 48 h of accelerated annealing at 70 °C. This phenomenon confirms that any thermal annealing or translation of color centers corresponding to RIA at 1 310 nm scarcely appears in the test process, demonstrating that at least one type of steady color center correlated with the permanent RIA in the entire tested temperature range. This RIA temperature-dependence suggests that the optical absorption of color centers is temperature-dependent.

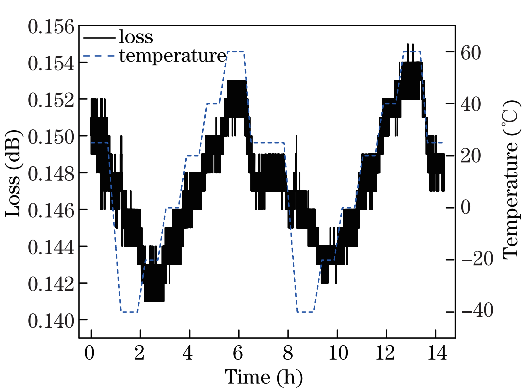

Fig. 3. Temperature behavior of the tested fiber before irradiation (step 1).

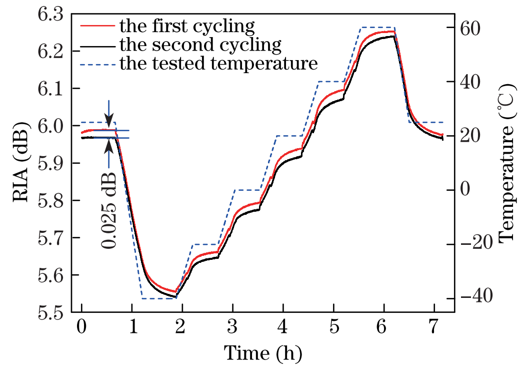

Fig. 4. RIA temperature-dependence after primary annealing at room temperature (step 2).

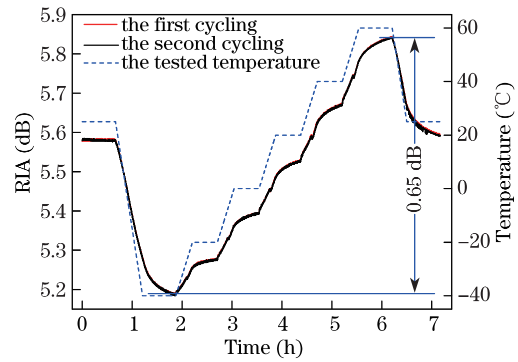

Fig. 5. RIA temperature-dependence after accelerated annealing of 48 h at 70 °C (step 3).

In the tested Ge/P co-doped fiber, Ge- or P-related defects contributed to the RIA at 1 310 nm. P1 centers were steady in the range from –40 to 60 °C and considered responsible to almost the entire RIA at 1 310 nm in P co-doped fibers[13]. The co-doping with Ge may induce Ge(1) centers contributing to the RIA of the tested wavelength[14]; however, the induced absorption band of Ge(1) was unmeasurable at 1 310 nm in the present low-dose (100 Gy) experiment[15]. Several causative UV absorption centers may exist, forming the so-called UV-absorption tail. This tail strongly decreases with increasing wavelength, and the RIA at 1 310 nm caused by the UV-absorption tail in the P-doped fibers is less than one order of magnitude than the P1 centers[8]. Several annealing defects in step 2 may be related to the UV-absorption tail. Therefore, the temperature effect of RIA in our experiment was possibly caused by the temperature dependence of P1 center absorption.

The RIA increased monotonically with increasing temperature and nearly linearly for every single cycling test in Fig. 5 (step 3). The RIA variation caused by temperature was approximately 0.65 dB in the entire temperature range from –40 to 60 °C, notably higher than the loss change before irradiation (0.014 dB). The average temperature sensitivity was approximately 0.0065 dB/°C for the 300-m-long test fiber, irradiated at a dose of 100 Gy. A temperature variation greater than 2 °C using the fiber may be achieved. This condition implies that the temperature dependence of the color-center absorption is monotonic and remarkable. Our curve in Fig. 5 was not smooth mainly because of the excessively long fiber and limited test condition. If exposed to more than 100 Gy radiation, such as 1 000 Gy, the tested fiber can have higher temperature sensitivity as RIA increases. Hence, the fiber irradiated with a high dose and annealed sufficiently can be used as a temperature sensor.

In conclusion, the RIA temperature effect for a Ge/P co-doped fiber in two different periods of annealing after irradiation are presented and compared with the temperature behavior of the attenuation of the fiber before irradiation. The color center absorption influencing the RIA at 1 310 nm for the Ge/P co-doped fiber exhibits monotonic and remarkable temperature dependence, providing an effective contribution to the RIA temperature effect of the fiber. A temperature sensor can be fabricated using this type of fiber after having the fiber irradiated at a high dose and annealed sufficiently. However, further work is needed to investigate the RIA temperature behavior of other kinds of fiber with different dopants. The feasibility of temperature sensing using the color-center temperature dependence should also be studied.

This work was supported by the National Natural Science Foundation of China (No. 61007040). We would also like to thanks Professors Li Jiuqiang and Sun Deliang for their help in the irradiation experiments.

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