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Experimental investigation of the factors influencing temperature dependence of radiation-induced attenuation in optical fiber

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The effects of transmission wavelength, total dose and light source power on temperature dependence of radiation-induced attenuation (RIA) in Ge–P co-doped fibers were investigated. Three fibers irradiated up to total dose of 100 Gy and 10,000 Gy were used as test samples. A test system for temperature dependence of RIA was built up. The influence of transmission wavelength, total dose and light power on temperature sensitivity and linearity of RIA in three irradiated fibers were researched. The test results show that temperature sensitivity and linearity of RIA in optical fibers could be improved by adjusting total dose and selecting transmission wavelength. The light source power does not have obvious influence on temperature sensitivity and linearity. The Ge–P co-doped fiber at 850 nm transmission wavelength with higher total dose is a very promising candidate for fiber-optic temperature sensor.

1. Introduction

Optical fibers are increasingly used in temperature monitoring, which have unique advantages such as immunity to electromagnetic interferences, high stability, durability against harsh environments [1,2]. Some studies indicate that the RIA is mainly caused by the radiolytic electrons and holes trapping point defects in optical fibers, namely the absorption of color centers [3,4]. Light transmission in optical fibers exposed to radiation environment is strongly affected by the color centers formed in fibers. Some absorbing defects have already been studied in detail [5–7]: Ge(1), Ge(2), GEC, GeE′ with regard to Germanium-related defects, POHC, P1, P2 and P4 defects with regards to Phosphorus-related defects, and NBOHC, POR, SiE′ and Self-Trapped-Hole (STH) defects. Borgermans et al. indicates that the optical absorption increases with increasing temperature during irradiation in phosphorous doped fibers [8]. The inverse temperature dependence in P-doped fibers can be explained by the phosphorus oxygen hole center (POHC) transforming into P1 center [9,10]. In [11], it is the first time that the temperature dependence of the color center absorption is proposed as an important factor influencing the RIA behavior of post-irradiation fibers besides the thermally driven color center generation, conversion and annealing process. According to these phenomena, the temperature dependence of RIA is further researched.

In order to better apply the optical fiber in complex radiation environment and utilize temperature dependence of RIA for temperature sensor, the factors influencing temperature dependence of RIA in optical fiber are investigated. The radiation-induced attenuation [12–16] in optical fibers depends largely on core–clad composition, fiber design along with different radiation parameters like radiation source, total dose and operating parameters like temperature, transmission wavelength. In [17], it has been mentioned that the color centers absorption impacting the RIA at 1310 nm in Ge–P co-doped fiber exhibits monotonic and remarkable temperature dependence, which makes an effective contribution to RIA temperature dependence of the fiber. In this paper, we have examined the temperature dependence of RIA in Ge–P co-doped optical fibers after accelerated and sufficient annealing under different experimental conditions. The effects of transmission wavelength, total dose and light source power on the sensitivity and linearity of RIA in optical fiber has been studied. The stable and monotonic temperature dependence of RIA in optical fibers can be potentially applied for temperature measurement.

2. Experiments

In the paper, three Ge–P co-doped fibers with the same length, which are commercial off-the-shelf (CTOS) optical fibers made in China were chosen. The three fibers are Ge doped (∼4 mol%) and P doped (∼1%) in core. And the cladding and coating diameters of them are 80 μm and 165 μm. The fibers F1 and F2 are produced with a loss constant of 2.55 dB/km at 850 nm, and the sample F3 is produced with a loss constant of 0.8 dB/km at 1310 nm. The fiber F1 had been irradiated up to a total dose of 100 Gy by a ^{60}Co gamma radiation source, while F2 and F3 were irradiated to 10,000 Gy. After irradiation, the fibers were initially annealed at room

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temperature for a few weeks, and then at 70 °C to accelerate annealing process until the variation of attenuation can be neglected at 60 °C. Thus, most of the color center defects which are unstable below 60 °C were annealed and conversed. Table 1 lists main parameters of the test optical fibers.

The test system for temperature dependence of RIA is shown in Fig. 1. A white light source with a wide output spectrum was used to test absorption spectra. The Super luminescent diodes (SLD) operating at 850 nm and 1310 nm respectively were used. The output optical beam of light source was separated into two paths. One was used for reference to compensate for the variation of light intensity, and the other was used for interrogation signal. The optical power meter was used to monitor optical signal. The attenuation of the optical fiber can be computed according to Eq. (1).

$$A'(T) = -10\lg\frac{P_T(T)}{P_R(T)} \tag{1}$$

$P_R(T)$ and $P_T(T)$ are the values of the optical power measured in the reference and test paths, respectively.

In order to reduce the effect of other factors in test path, the experimental data were normalized by the data measured at 20 °C. Then the relative attenuation of fiber can be calculated by

$$A(T) = -10\lg\frac{P_T(T)}{P_R(T)}\frac{P_R(20)}{P_T(20)} \tag{2}$$

$P_R(20)$ and $P_T(20)$ are the values at 20 °C of the optical power measured in the reference and test paths, respectively.

The temperature inner the chamber was measured by standard temperature meter with an accuracy of ±0.5 °C and a resolution of 0.0625 °C. Temperature measurement range was controlled continuously from −40 °C to 60 °C.

The radiation induced absorption spectra of three experimental fibers from 800 nm to 1520 nm were measured with an optical spectrum analyzer (OSA).

Finally, the temperature sensitivity and linearity of RIA in the irradiated optical fibers were analyzed based on radiation induced absorption spectrum, transmission wavelength, total radiation dose and light source power. Table 2 shows all experiments in the paper.

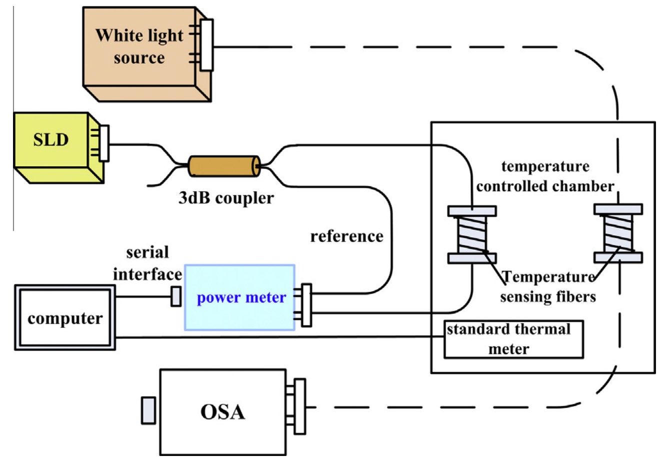

Fig. 1. Experimental setup.

Table 2
The list of all experiments.

Investigation content	Test fiber	Test content	Light source
Temperature dependence	F1, F2, F3	Radiation induced absorption spectra from 800 nm to 1520 nm	White light source
Effect of transmission wavelength	F3	RIA at 850 nm and 1310 nm	SLD (850 nm and 1310 nm)
Effect of total dose	F1, F2	RIA at 850 nm	SLD (850 nm)
Effect of light power	F2, F3	RIA at 850 nm	SLD (850 nm)

3. Results and discussion

The radiation induced absorption spectra of optical fibers are important for selection of the suitable transmission wavelength for evaluation of RIA temperature dependence. As a comparison, the absorption spectra of three fibers before irradiate and after irradiate were measured at −40 °C, −20 °C, 0 °C, 20 °C, 40 °C and 60 °C from 800 nm to 1520 nm, respectively.

The fiber loss spectrum of the fibers without irradiation is shown in Fig. 2. It can be seen that the loss of optical fibers before irradiation is not monotonic and remarkable temperature dependence within the scope of the test.

Fig. 3 illustrates that the temperature dependence of RIA in three irradiated fibers is stable and wavelength-dependent. Because the temperature dependent color center absorption does not change the number and kinds of color center, and it is a reversible process [11]. The loss of optical fiber and the loss variation caused by temperature after irradiation are more an order of magnitude than the fiber without irradiation.

In [11], the P1 color center absorption spectrum is compressed with increasing temperature. Thus, we infer that the absorption spectrum of other color centers may have the same characteristic. As the absorption bands of many radiation-induced defects are in the ultraviolet (UV) and visible ranges and can extend to near infrared region, the RIA at shorter wavelength should be more sensitive to temperature, which is identical with our experimental results.

Table 1
Main parameters of test optical fibers.

Fiber ID	Core composition	Operating wavelength (nm)	Total dose (Gy)
F1	Ge, P	850	100
F2	Ge, P	850	10,000
F3	Ge, P	1310	10,000

3.1. The effect of transmission wavelength

It is well known that the magnitude of radiation-induced attenuation is dependent on the wavelength of the transmitted light. In our study, the temperature dependence of RIA was observed from radiation induced absorption spectra of the test fiber F3. Then the effect of transmission wavelength on temperature dependence of the fiber F3 was studied at 850 nm and 1310 nm, respectively.

The spectra of the fiber F3 around 850 nm and 1310 nm are enlarged, and the spectra measured are normalized by the spectrum measured at 20 °C to observe the temperature dependence of RIA. Fig. 4 illustrates the smoothed RIA spectra in the fiber F3 at six different temperatures around 850 and 1310 nm. As shown in Fig. 4, the RIA round 850 nm and 1310 nm has significant and monotonic temperature dependence. Compared with the spectra measured around 1310 nm, it can be seen that the variation of RIA around 850 nm with temperature is more an order of magnitude larger than the variation of attenuation around 1310 nm.