

# Measurement of photo-induced birefringence in germanosilicate fibers

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In this paper, we report a novel method for accurately measuring the photo-induced birefringence of germanosilicate fibers by using an all fiber Mach–Zehnder interferometer. The results indicate that the photo-induced normalized birefringence of C<sub>5</sub>98-302(s) germanosilicate fiber can attain 10<sup>-5</sup> and is multi-decaying-exponentially proportional to the UV exposure.

**Keywords** Mach–Zehnder interferometer, germanosilicate fibers, photo-induced birefringence

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## 1 Introduction

Since first being reported in 1978, fiber photosensitivity has been widely used for fabricating fiber gratings, which are important devices in optical fiber communication and sensor systems. The refractive index will be changed permanently in many types of doped fibers after exposure to UV radiation. However, the origin of this photosensitive character is not yet fully understood. There are two mechanisms to explain fiber photosensitivity: one is creation of color centers, and the other is structural transformation. According to the color center mechanism, the photo-induced refractive index increment is correlated with the observed absorption changes in photosensitive fibers through the Kramers–Kronig principle; while in structural transformation mechanism, changes of density and stress distribution lead to the refractive index increment [1, 2].

Nevertheless, the photo-induced refractive index change is non-isotropic, that is, photo-induced birefringence. In 1985, photo-induced birefringence of germanosilicate fibers was first discovered by Parent *et al.*, but this phenomenon did not attract much attention at that time [3]. When write fiber Bragg gratings in photosensitive fibers with UV light, photo-induced birefringence can split the transmission and reflection spectra of gratings and can thus induce undesired polarization-

mode dispersion and polarization-dependent loss, which will produce harmful effect on communication systems, especially for high-speed systems. On the other hand, photo-induced birefringence can be used to fabricate rocking filter, comb rocking filters, polarization mode dispersion compensators, and so on [4–8]. Therefore, the study on photo-induced birefringence of photosensitive fibers is needed. In 1990, photo-induced birefringence was measured with the internal writing technique and its value can attain 10<sup>-6</sup> [9]. In 1991, this result was also obtained by using external writing with UV light [10]. Ouellette *et al.* studied the photo-induced birefringence by using classical optics method, and showed that it was enhanced by increasing the Ge concentration in the core or by submitting the fiber to a thermal hydrogen treatment [11, 12]. Zhang *et al.* measured photo-induced birefringence by using a fiber loop and its value can attain 10<sup>-5</sup> [13]. A significant improvement of the research in photo-induced birefringence was theoretically analysis by use of finite-element method [14, 15].

In this paper, we propose a novel method for measuring the photo-induced birefringence of germanosilicate fibers based on an all fiber Mach–Zehnder interferometer. The experimental results show that the photo-induced normalized birefringence of germanosilicate fibers is multi-decaying-exponentially proportional to the exposure and can attain 10<sup>-5</sup>.

## 2 Theory

The experimental arrangement shown in Fig. 1 consists of a broadband light source (BBS), a fiber polarizer (FP), a polarization controller (PC), two fiber couplers used for building a Mach-Zehnder interferometer (MZI) and an optical spectrum analyzer (OSA). The two arms (1 and 2) of the MZI are made of C<sub>5</sub>98-302(s) photosensitive fibers supplied by No. 46 Institute of Information and Industry Ministry of China. Arm 1 externally exposed to UV light at 248 nm originated from a KrF excimer laser is non-isotropic. Arm 2 unexposed to UV beam can be regarded as isotropic. After passing through the FP, the light originated from BBS is transformed to be linearly polarized and the polarization can be controlled by the PC. The linearly polarized light launched into input port of MZI splits into two beams with same intensity and polarization after the 3 dB coupler 1. One beam transmits through the arm1 which can enhance the nonlinear birefringence dramatically due to the UV exposure, and then passes to 3 dB coupler 2. The other beam travels along the arm 2 to coupler 2. At the coupler 2, the beams from two arms combine and the coherent output from the MZI is directly sent to the OSA. The output spectrum is decided by the phase difference between the two arms.

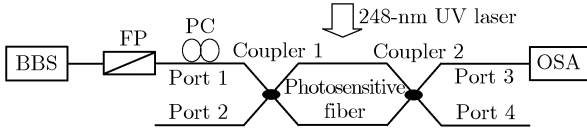


Fig. 1 Experimental setup.

We choose an orthogonal coordinate system  $(x, y, z)$  to analyze. The  $z$ -axis is directed along the longitudinal axis of the fiber, while the  $x$ -axis and the  $y$ -axis are chosen to coincide with the extraordinary and ordinary principal axes of the fiber respectively. Assuming that the angle between the direction of the linearly polarized light inputting into the port 1 of the MZI and the  $x$  axis is  $\alpha$ , after traveling through the coupler 1, the electric field can be expressed as:

$$\mathbf{E}_1 = \mathbf{E}_2 = \begin{vmatrix} A \cos \alpha \\ A \sin \alpha \end{vmatrix} \quad (1)$$

where  $A$  is the amplitude of the output light.

After passing through the arm 1, the electric field can be described as:

$$\mathbf{E}_1 = \begin{vmatrix} A \cos \alpha \cdot \exp(ikn_e l) \\ A \sin \alpha \cdot \exp(ikn_o l) \end{vmatrix} \quad (2)$$

where  $k = 2\pi/\lambda$ ,  $\lambda$  is the wavelength of the light in vacuum;  $l$  is the length of the germanosilicate fiber;  $n_o$  and  $n_e$  are the ordinary and extraordinary refractive indexes,

respectively. The electric field in arm 2 is given by

$$\mathbf{E}_2 = \begin{vmatrix} A \cos \alpha \cdot \exp[i(knl + \delta)] \\ A \sin \alpha \cdot \exp[i(knl + \delta)] \end{vmatrix} \quad (3)$$

where  $\delta$  is the phase difference caused by two different arms length,  $n$  is the refractive index of the unexposed germanosilicate fiber.

After traveling through the coupler 2, the two beams gather together and the electric field can be described as:

$$\mathbf{E} = \mathbf{E}_1 + \mathbf{E}_2 = \begin{vmatrix} A \cos \alpha \cdot \{\exp(ikn_e l) + \exp[i(knl + \delta)]\} \\ A \sin \alpha \cdot \{\exp(ikn_o l) + \exp[i(knl + \delta)]\} \end{vmatrix} \quad (4)$$

The intensity of the total light can be expressed as:

$$\begin{aligned} I &= \mathbf{E} \cdot \mathbf{E}^* \\ &= 2A^2 + 2A^2 \cdot \left\{ \cos \frac{k(n_e - n_o)l}{2} \cos \left[ \frac{k(n_e + n_o - 2n)l}{2} - \delta \right] \right. \\ &\quad \left. - \cos 2\alpha \sin \frac{k(n_e - n_o)l}{2} \sin \left[ \frac{k(n_e + n_o - 2n)l}{2} - \delta \right] \right\} \end{aligned} \quad (5)$$

The angle  $\alpha$  can be changed by rotating the PC. When  $\alpha = 0$ , we simplify Eq. (5) as

$$I = 2A^2 + 2A^2 \cos[k(n_e - n)l - \delta] \quad (6)$$

When  $\alpha = \pi/2$ , we simplify Eq. (5) as

$$I = 2A^2 + 2A^2 \cos[k(n_o - n)l - \delta] \quad (7)$$

In these two situations, the contrast of the optical spectrum also gets the highest value:

$$A_{\max} = 2A^2 \quad (8)$$

When  $\alpha = \pi/4$ , Eq. (5) turned to be

$$I = 2A^2 + 2A^2 \cos \frac{k(n_e - n_o)l}{2} \cos \left[ \frac{k(n_e + n_o - 2n)l}{2} - \delta \right] \quad (9)$$

the contrast of the optical spectrum gets the minimum

$$A_{\min} = 2A^2 \cos \frac{k(n_e - n_o)l}{2} \quad (10)$$

According to Eqs. (8) and (9), the photo-induced normalized birefringence of the germanosilicate fiber can be described as

$$B = n_e - n_o = \frac{\lambda \arccos \frac{A_{\min}}{A_{\max}}}{\pi l} \quad (11)$$

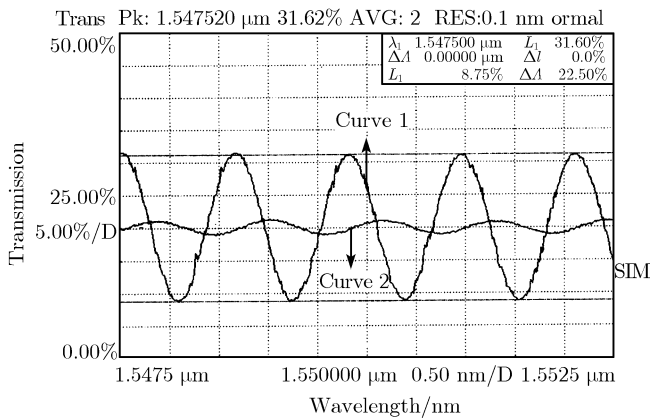
By rotating the PC, we can measure the maximum amplitude  $A_{\max}$  and the minimum amplitude  $A_{\min}$  with the OSA, then the photo-induced normalized birefringence  $B$  can be obtained.

### 3 Results and discussion

In the experiment, the spontaneous radiation emitted from an erbium doped fiber amplifier pumped by 980 nm LD is used as the BBS. The light output from the port 3 of 3 dB coupler 2 is sent to the OSA. The UV beam is first reflected by a mirror and then focused by a cylinder lens into a size of  $1.2 \times 20 \text{ mm}^2$ , so that the exposed length of C<sub>5</sub>98-302(s) photosensitive fiber is 2 cm. Working wavelength of the FP is 1550 nm. The refractive index of C<sub>5</sub>98-302(s) photosensitive fibers is 1.4623.

In order to improve the output stability, the length of the arms of MZI and the length of the fiber from the PC to MZI must be shortened as much as possible. We also avoid any bend and twist of the fiber to reduce the effect of the surroundings.

Figure 2 shows the output optical spectra from the MZI after 4100 pulses of exposure. The contrast of the optical spectrum changes periodically by rotating the PC. When  $\alpha = 0$  or  $\alpha = \pi/2$ , the contrast of the spectrum can get the maximum (curve 1). When  $\alpha = \pi/4$ , the contrast of the spectrum gets minimum (curve 2).

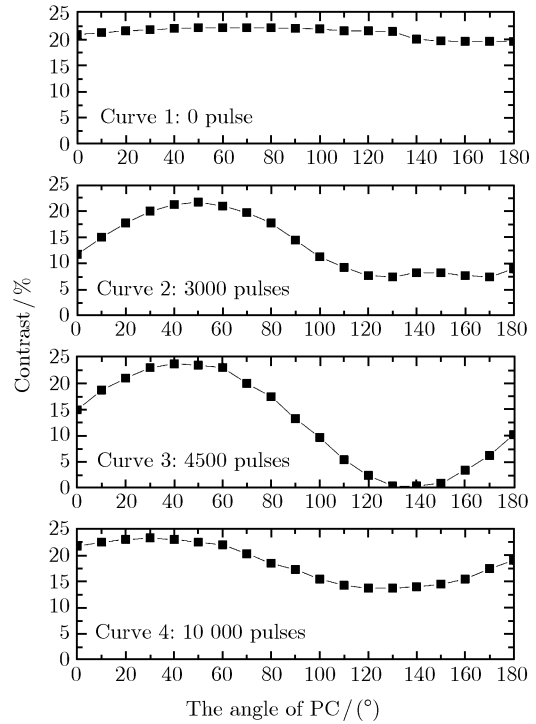


**Fig. 2** The optical spectrum output from MZI after arm1 exposed by 4100 pulses.

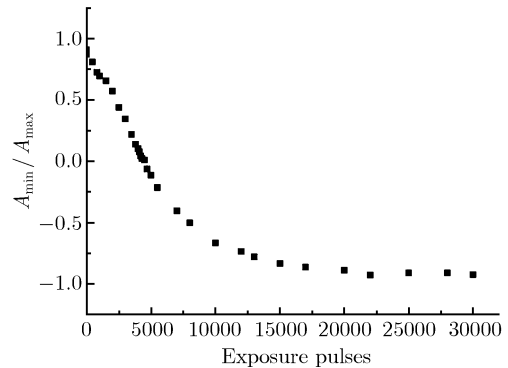
Comparison of the optical spectrum via the directions of the PC under different exposures is shown in Fig. 3. Curves 1, 2, 3, and 4 in Fig. 3 are in the cases of 0, 3000, 4500, 10 000 pulses of exposure, respectively. Curve 1 is not exactly a straight line, which indicates that the fiber is not exactly isotropic before the UV exposure. Curve 2 which is not exactly a cosine function indicates that the exposure is not intense enough so that the photo-induced birefringence is not obvious. Curve 3 and curve 4 are exactly cosine functions, which indicate that the non-isotropy of the unexposed fiber is negligible in contrast with the exposed fiber, that is, the photo-induced birefringence is very obvious.

Figure 4 shows the ratio of contrast  $A_{\min}/A_{\max}$  via the UV exposure. It has been found that:  $A_{\min}/A_{\max}$

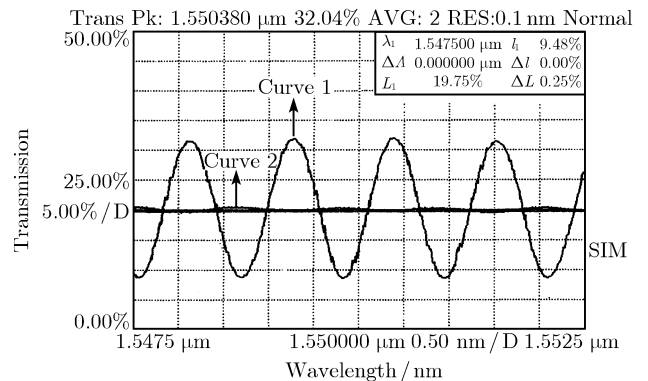
decreases gradually with the exposure at the beginning; it reaches almost zero when the exposure gets 4500 pulses ( $A_{\min}$  reaches almost zero shown as curve 2 in Fig. 5); after that, it begins to increase in negative direction.



**Fig. 3** The contrast via the direction of the PC under different exposure.



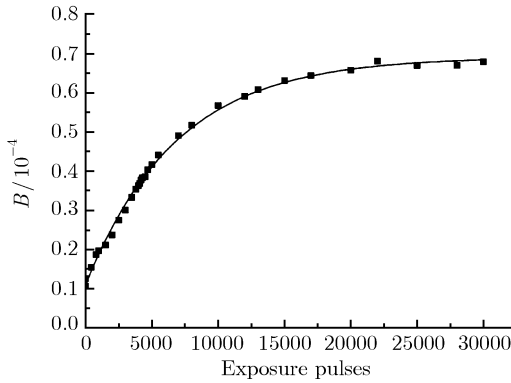
**Fig. 4** The ratio of contrast via exposure.



**Fig. 5** The optical spectrum output from MZI after arm1 exposed by 4500 pulses.

By using  $A_{\max}$  and  $A_{\min}$ , we can calculate the normalized birefringence  $B$  of the germanosilicate fiber under different exposures with Eq. (11). As an example, when the fiber is exposed to UV light for 4500 pulses: the optical spectra output from MZI after arm1 exposed by 4500 pulses are shown in Fig. 5;  $A_{\max} = 23.75\%$  (Curve 1),  $A_{\min} = 0.25\%$  (Curve 2); with the parameters  $\lambda = 1550$  nm, and  $l = 2$  cm, from Eq. (11) the calculated normal birefringence  $B$  is  $3.85 \times 10^{-5}$ .

Figure 6 shows the photo-induced normalized birefringence of the germanosilicate fiber via the UV exposure. At the beginning, the normalized birefringence increases with the UV exposure quickly. When the exposure get 4500 pulses, the normalized birefringence starts to increase slowly till it gets the saturation after about 20 000 pulses of exposure.



**Fig. 6** The normalized birefringence via exposure.

In Fig. 6, the square symbols are experimental results, and the solid line is a fitting line described by

$$B = 6.92 \times 10^{-5} - 2.91 \times 10^{-5} e^{-1.45 \times 10^{-4} t} - 2.90 \times 10^{-5} e^{-1.46 \times 10^{-4} t} \quad (12)$$

where  $t$  is UV exposure pulses. Eq. (12) indicates that the photo-induced normalized birefringence of the germanosilicate fiber is multi-decaying-exponentially proportional to the exposure, and the normalized birefringence of the can attain not more than  $6.92 \times 10^{-5}$ , which is two orders of magnitude higher than that of the communication fiber. This result coincides with the result measured by a fiber loop [13]. The measurement precision is limited by the precision of the OSA, the stability of the MZI and the BBS.

## 4 Conclusion

In this paper, we have measured the photo-induced nor-

malized birefringence of the germanosilicate fibers by using an all fiber Mach-Zehnder interferometer. We demonstrate that the photo-induced normalized birefringence of germanosilicate fiber is multi-decaying-exponentially proportional to the UV exposure. The maximum of the photo-induced normalized birefringence in the C<sub>5</sub>98-302(s) photosensitive fiber can attain  $10^{-5}$  which is two orders of magnitude higher than that of the communication fibers. In addition, the experimental setup has many advantages such as lower insertion loss, easier connection and compatibility, higher measurement precision, and so forth.

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