Polarization in D-shaped fiber modulated by magneto-optical dichroism of magnetic fluid

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The polarization of a D-shaped fiber is modulated after immersing it in magnetic fluid (MF) and applying a magnetic field. Theoretical analysis predicts that magneto-optical dichroism of MF plays a key role in light polarization modulation. During light polarization modulation, the evanescent wave polarized parallel to the magnetic field has greater loss than its orthogonal component. Light polarization of a D-shaped fiber with a wide polished surface can be modulated easily. High concentration MF and a large magnetic field all have great ability to modulate light polarization.

Keywords: fiber optics components; polarization-selective devices; magneto-optic systems; magneto-optical materials.

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High performance fiber polarizers have been designed in recent decades using birefringent materials[1,2], metal films[3,4], and graphene[5–7]. However, because these fiber polarizers have nonadjustable extinction ratios, they act only as auxiliary components rather than sensitive devices in many applications. Liquid crystals with tunable birefringence have been found to be good candidates for optically controllable fiber polarizers[8–10]. Owing to their large refractive indices and susceptibility to temperature conditions, only a very few liquid crystals could be used for the fabrication of tunable fiber polarizers. Thus far, novel materials are still highly desired.

Magnetic fluid (MF) is a kind of new colloidal material with good magneto-optical properties[11–19]. Especially, the properties of birefringence, dichroism, and Faraday effects can be used for light polarization modulation. The D-shaped fiber is fabricated by grinding and polishing a part of the cladding of the single-mode quartz fiber. The evanescent field is exposed over the polished section. The light polarization of D-shaped fibers can be modulated by modulating this evanescent field[20–25]. In addition, if the D-shaped fiber is polished close to, but not into the core, the transmission loss can be suppressed.

In this Letter, we devote to modulating the polarization of the D-shaped fiber based on MF. Theoretical and experimental results demonstrate that the polarization of the D-shaped fiber is modulated by the magneto-optical dichroism of MF. The factors that may influence the light polarization modulation abilities are also studied, including D-shaped fiber surface width, MF concentration, and modulation magnetic field. Based on the D-shaped fiber polarization modulation, many new fiber devices or sensors can be developed.

When a magnetic field is applied to the MF, the difference of the refractive indices for the light polarized parallel and perpendicular to the magnetic field is expressed as[26]

$$\Delta n(H) = \frac{1}{2} n_1 C (X_\parallel - X_\perp)\left[1 - \frac{3}{x(H)}\coth(x) + \frac{3}{x^2(H)}\right], \tag{1}$$

where n_1 is the refractive index of the suspending medium, C is the volume fraction of magnetic nanoparticles (MNPs), $x(H)$ depends on the magnetic field H, and $X_\parallel - X_\perp$ is optical anisotropy factor:

$$X_\parallel = \frac{X_0}{1 - K_\parallel X_0}, \tag{2}$$

$$X_\perp = \frac{X_0}{1 + K_\perp X_0}, \tag{3}$$

$$X_0 = 3\frac{\varepsilon_p - \varepsilon_1}{\varepsilon_p + 2\varepsilon_1}, \tag{4}$$

$$K = \frac{v_p}{4\pi d^3} = K_\parallel/2. \tag{5}$$

Here, ε_p and ε_1 are the relative dielectric constants of the MNPs and the suspending medium, respectively. We denote v_p as the volume of the particle. d is the distance between the center of two MNPs.

Based on Eqs. (1)–(5), we know that $\Delta n(H)$ is a complex value because the relative dielectric constant of the MNPs is a complex number too. The refractive index of the MNPs is also a complex number that generally takes a value of $2.2 - 0.58j$[27]. The real and imaginary parts of $\Delta n(H)$, respectively, represent the birefringence and the dichroism of the MF, which are considered as two main magneto-optical effects. They can be used for light polarization modulation. However, the difference of the refractive indexes induced by the magneto birefringence effect of the MF is merely in the range of 0–10^{-5}, about four orders of magnitude smaller than the difference of the optical absorption coefficient $K_{\parallel} - K_{\perp}$[27]. Such weak magneto birefringence would produce very small polarization modulation for a 1 cm long D-shaped fiber. Thus, we believe that the magneto-optical dichroism of MF plays a key role in the light polarization modulation of the D-shaped fiber.

Figure 1 is the schematic diagram of light polarization modulation of the D-shaped fiber based on the magneto-optical dichroism of MF. The D-shaped fiber is immersed in the MF. If a magnetic field is applied along the x axis, MNPs could align into chains along the magnetic field. In the electric field of a light beam, an individual particle in the aggregation becomes an oscillating dipole, which interacts with its neighbors. The interaction is asymmetric, relying on the orientation of the magnetic field. As a result, on the polished surface of the D-shaped fiber, the absorption of evanescent field polarized parallel to the magnetic field is higher than that of its orthogonal component ($K_{\parallel} > K_{\perp}$), leading to the magneto-optical dichroism of the MF. Light would be polarized when passing through the D-shaped fiber.

We used AB glue to fix a single-mode quartz fiber on the grooved quartz glass. The diameters of the cladding and core of the single-mode fiber (Corning SMF-28) are 125 and 8.2 μm, respectively. The AB glue was baked at 90°C, which made the solidified AB glue hard enough for the application in an aqueous environment. Then, we polished the solidified AB glue and a portion of the fiber cladding simultaneously to fabricate a D-shaped fiber. The polished section of the fiber was about 1 cm in length. Two D-shaped fibers were prepared. Both of them showed good robustness with the protection of baked AB glue.

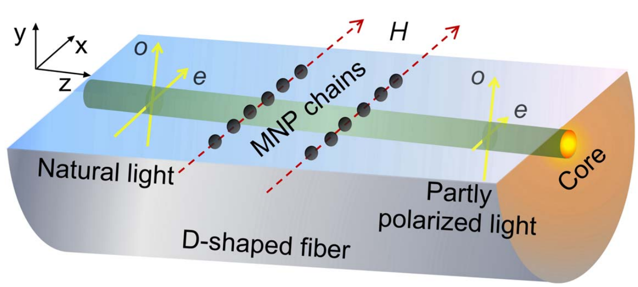

Fig. 1. Schematic diagram of light polarization modulation of the D-shaped fiber based on the magneto-optical dichroism of MF.

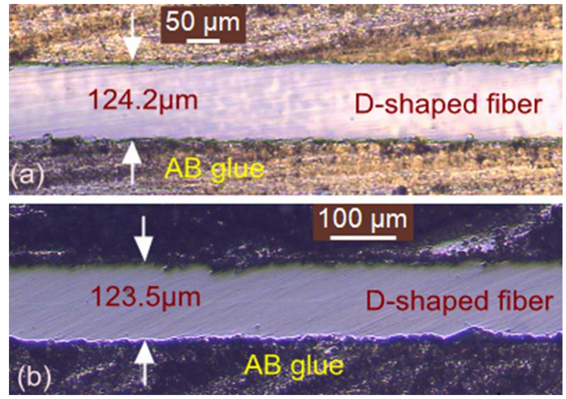

Fig. 2. Images of the polished surface of D-shaped fibers (a) A and (b) B. The widths of the polished surfaces are $d_A = 124.2$ μm and $d_B = 123.5$ μm.

Figures 2(a) and 2(b), respectively, show the polished surfaces of the employed two fibers (A and B) with widths of $d_A = 124.2$ μm and $d_B = 123.5$ μm. The corresponding thicknesses of the residual cladding of the two polished fibers are 3 and 5.6 μm, respectively.

Figure 3(a) shows the optical image of MF film in a liquid state on the D-shaped fiber. We cannot directly observe MNPs in the liquid MF film because of their small size (~10 nm in diameter). However, it is interesting to notice that we can clearly observe some random lines in the solidified MF films, as shown in Fig. 3(b). Thus, we carried out further experiments to investigate how the magnetic field can affect the alignments of these lines in the MF film. Figures 3(c) and 3(d) show the MF films solidified in the magnetic fields with different directions. It is clear that the lines have turned into orderly ones parallel to the magnetic field. The most possible reason is that the MNPs are aligned into chains that affect the generation of those lines. If a liquid MF film is concerned, we believe that MNP chains can also be generated when an external magnetic field is applied, leading to the magneto-optical dichroism of MF.

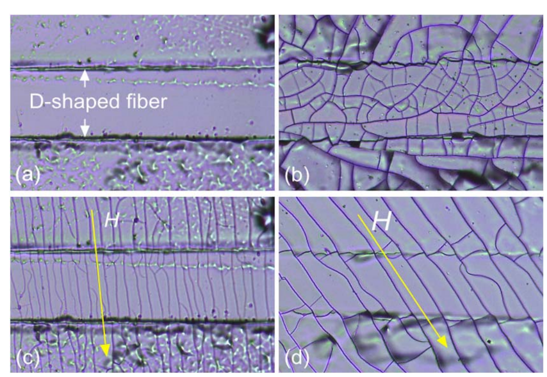

Fig. 3. Optical images of MF films on the fabricated D-shaped fiber taken by a metalloscope (Leica DM4M). (a) shows the liquid MF film. (b) is solidified MF film in the absence of the magnetic field. MF films in (c) and (d) are solidified in magnetic fields. The arrows show employed magnetic field directions.

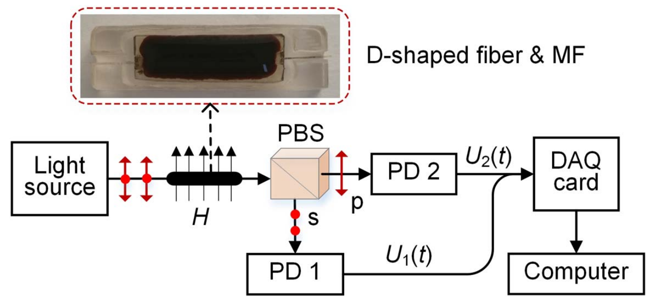

Fig. 4. Schematic diagram of the experimental setup for light polarization modulation and detection.

The schematic diagram of the experimental setup for the D-shaped fiber polarization modulation is shown in Fig. 4. The D-shaped fiber is placed in a polymethyl methacrylate box. The light from an amplified spontaneous emission light source is launched into the D-shaped fiber. A pair of electromagnets generates a magnetic field parallel to the surface of the D-shaped fiber. A polarization beam splitter (PBS), which has 30 dB extinction ratio, splits the light from the D-shaped fiber. Photo detectors (PDs) are used to detect the two orthogonal polarized lights from the PBS. A data acquisition (DAQ) card is used to convert the analog signals from the PDs into digital signals. The sampling frequency is set to be 100 Hz. The digital signals are sent to the computer for processing. The output voltages of PDs 1 and 2 are written as $U_1(t)$ and $U_2(t)$, respectively. Accordingly, the expression for the time varying polarization degree $p(t)$ is

$$p(t) = \frac{U_1(t) - U_2(t)}{U_1(t) + U_2(t)}. \tag{6}$$

$p(t)$ can be calculated in real time based on $U_1(t)$ and $U_2(t)$.

We compared the D-shaped fibers A and B to study the influence of the polished surface width of the D-shaped fiber on the light polarization modulation. The magnetic field was set to be 42 mT. Each run was 50 s. The MF was diluted with water according to the volume ratio of 1:5. Figures 5(a) and 5(b), respectively, show the time varying voltages $U_1(t)$ and $U_2(t)$ detected when testing D-shaped fiber A, while Figs. 5(c) and 5(d) are that when testing D-shaped fiber B. We notice that both $U_1(t)$ and $U_2(t)$ decrease with time in the process of applying the magnetic field, regardless of whether D-shaped fiber A or B is tested. The reason is that there exist optical absorption coefficients $K_\parallel$ and $K_\perp$ after applying the magnetic field. The decreasing speed of $U_2(t)$ is faster than that of $U_1(t)$, resulting in the magneto-optical dichroism of MF. When testing D-shaped fiber A, $U_2(t)$ decreases 2.65 dB in 50 s, while $U_1(t)$ only decreases 1.62 dB within the same period of time. As shown in Fig. 4, $U_1(t)$ and $U_2(t)$, respectively, represent the light polarized perpendicular and parallel to the magnetic field. It means that $K_\parallel$ is larger than $K_\perp$. Therefore, we can conclude that the polarization in the D-shaped fiber is modulated by the magneto-optical dichroism of the MF.

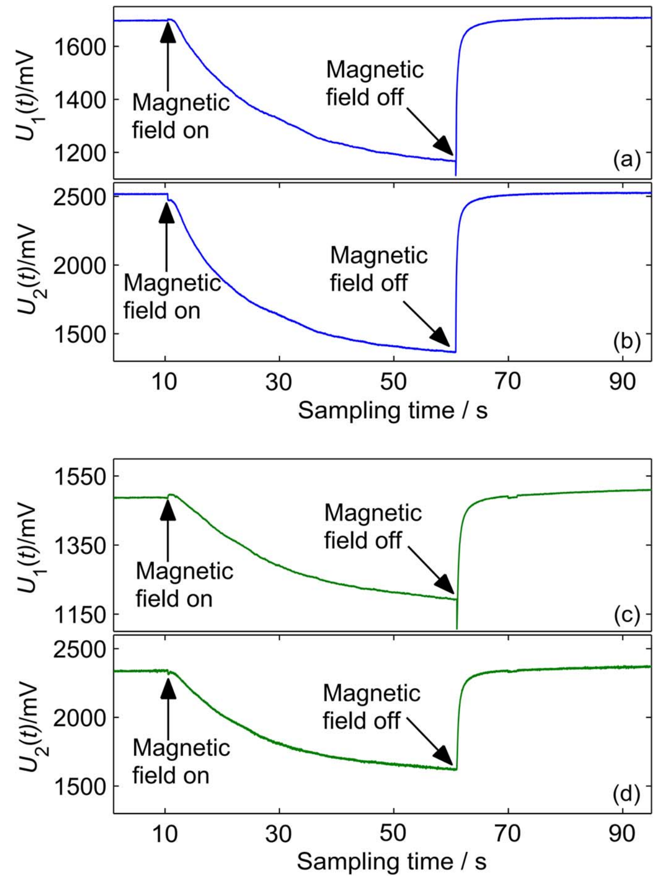

Fig. 5. $U_1(t)$ and $U_2(t)$ versus the sampling point of the DAQ card. (a) and (b) are for D-shaped fiber A. (c) and (d) are for D-shaped fiber B.

According to Eq. (6) and the data in Fig. 5, we calculate the time varying light polarization degree of the D-shaped fibers A and B. The results are shown in Figs. 6(a) and 6(b), respectively. One can see that the light

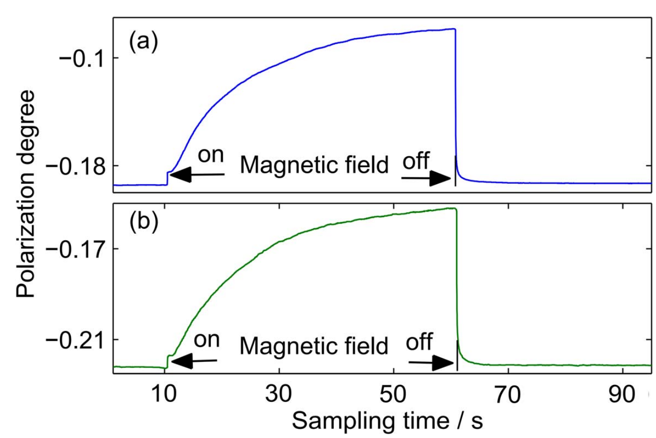

Fig. 6. Light polarization modulation when the surface widths of the D-shaped fiber are (a) 124.2 μm and (b) 123.5 μm. The magnetic field is 42 mT. The MF is diluted with water according to the volume ratio of 1:5.

polarization degree increases sharply at the time when the magnetic field is applied. Then, the change speed slows down.

We give a qualitative explanation to this phenomenon. When a uniform magnetic field is applied to the MF, the MNPs will align into chains. Under the influence of the viscous resistance of the suspending medium, the alignment process of the MNPs takes a certain amount of time. When the magnetic field is just applied, the number of MNPs participating in the arrangement is great. Therefore, the polarization degree increases rapidly. With the decrease of the number of disordered MNPs, the increased speed of polarization degree decreases.

One can also see that the polarization degree can pretty much return to the original value after removing the magnetic field for about 35 s. We attribute this phenomenon to the superparamagnetism of MF. After removing the magnetic field, the MNPs return to a disordered state under the action of thermal motion.

No matter whether the magnetic field is applied or removed, the response time of D-shaped fiber polarization modulation is relatively long. As a result, the frequency response of the polarization modulation is poor. Although the frequency response limits the utilization of this design in some applications, such as magnetic field sensing, it has very good application prospects in bio-sensing applications[18].

For D-shaped fiber A, the initial light polarization degree is −0.1945, which may derive from the birefringence of the D-shaped fiber itself. Under the action of magneto-optical dichroism of MF, the light polarization degree increases to −0.0785 when the magnetic field is applied for about 50 s. The modulation depth is 0.1160. The light polarization degree decreases back to −0.1932 after removing the magnetic field for about 35 s. A similar process of polarization modulation can also be obtained for D-shaped fiber B. However, its modulation depth is only 0.0699 when the magnetic field is applied for 50 s. The different modulation depths of Figs. 6(a) and 6(b) merely derive from the different surface width of the D-shaped fibers. It means that the polarization of the D-shaped fiber with a wide polished surface is easy to modulate.

Here, we should point out that the value of modulation depth seems to be not so good. The reason is that the thicknesses of the residual cladding of the two polished fibers are still relatively large. If a delicate polishing technique is available for fabricating a D-shaped fiber with small residual cladding, such as less than 1 μm, large modulation depth can be expected.

Then, we added the concentration of diluted MF up to the volume ratio of 1:2 for comparison of its effect on the light polarization modulation of the D-shaped fiber. After immersing D-shaped fiber A in the MF and applying the 42 mT magnetic field for about 50 s, Fig. 7 shows the time varying light polarization degree. The insets in Fig. 7 are the corresponding output voltages of PD 1 and PD 2.

Both Figs. 6(a) and 7 are obtained based on D-shaped fiber A and the 42 mT magnetic field. However, the modulation depth of the light polarization is 0.1440 in Fig. 7, which is larger than that of Fig. 6(a). This is because higher concentration MF is used in obtaining Fig. 7. Therefore, it means that higher concentration MF has greater ability to modulate light polarization. At the same time, just as shown in Figs. 5(a), 5(b), and the insets of Fig. 7, higher concentration MF also generates greater light power loss. The reason for these two phenomena is that higher concentration MF has a larger number of MNPs per unit volume, resulting in greater magneto-optical dichroism and dispersion.

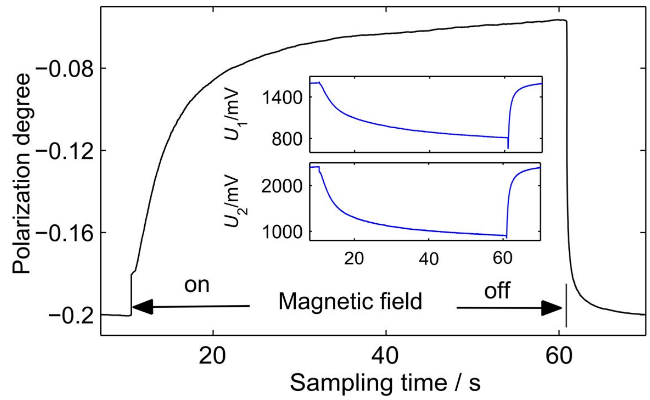

Fig. 7. D-shaped fiber light polarization modulation when the magnetic field is 42 mT, the polished surface width of the D-shaped fiber is 124.2 μm, and the MF is diluted with water according to the volume ratio of 1:2.

Finally, to study the effect of the magnetic field on the light polarization modulation of the D-shaped fiber, we carried out further experiments by increasing the magnetic field to 88 mT. The MF was also diluted with water according to the volume ratio of 1:2. After applying the magnetic field to D-shaped fiber A for 50 s, Fig. 8 shows the time varying light polarization degree and the output voltages of PDs 1 and 2.

Figures 7 and 8 are obtained based on the same D-shaped fiber and MF concentration, as well as different

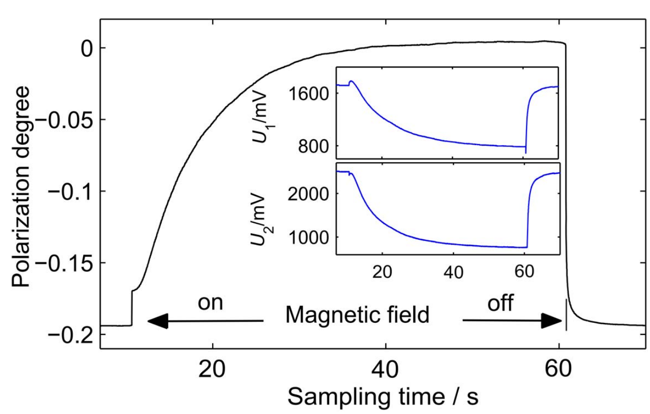

Fig. 8. D-shaped fiber light polarization modulation when the magnetic field is 88 mT, the polished surface width of the D-shaped fiber is 124.2 μm, and the MF is diluted with water according to the volume ratio of 1:2.

magnetic fields. Due to the utilization of a large magnetic field, the modulation depth of the light polarization degree in Fig. 8 is 0.1988, which is larger than that of Fig. 7. It means that a higher magnetic field has greater ability to modulate the light polarization degree. We should point out that the light polarization degree in Fig. 7 keeps increasing during the application of the magnetic field. However, in Fig. 8, the light polarization degree gets to a saturation state within 46 s. The larger modulation magnetic field can make the light polarization modulation get to a saturation state within a shorter period.

In conclusion, the polarization of a D-shaped fiber can be modulated by the magneto-optical dichroism of MF. The light polarization degree has a sudden change at the time when the magnetic field is applied or removed. Then, the change speeds all slow down. After removing the magnetic field for a period, the light polarization degree can almost return to its original value. The factors that influence light polarization modulation are also studied. We find that the D-shaped fiber with a wide polished surface, MF with a high concentration, and large magnetic field all can be utilized to produce high polarization degree. In addition, a large magnetic field can also make the light polarization modulation get to a saturation state within a short time. This fiber polarization modulator could be widely applied in physical, chemical, and biological researches.

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