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Laser self-induced tunable birefringence of magnetic fluid

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The phenomenon of laser self-induced tunable birefringence of magnetic fluid is investigated. This phenomenon exists in magnetic fluid, no matter whether it is under an external magnetic field or not. The variation trend of the laser self-induced birefringence with the laser power follows a linear relationship. Besides, dichroism is not observed in accompany with the laser self-induced birefringence. © *2013 AIP Publishing LLC*. [http://dx.doi.org/10.1063/1.4804579]

Magnetic fluid (MF) as a kind of promising magneto-optical functional material is characterized by its various magneto-optical effects such as refractive index tunability, field dependent transmission, Faraday effect, birefringence, and dichroism.[1–4] MF attracts a lot of research interests and finds diverse applications in photonic devices, especially optical fiber devices such as sensors, modulators, filters, and switches.[5–10] Birefringence is one of the most important magneto-optical properties of MF, which is commonly used in the MF-based photonic devices.[8] There were a lot of investigations on the birefringence of MF.[3,11–15] Two main theories were proposed to explain the physical mechanisms that were responsible for the birefringence of MF. One was particle orientation theory[15] which assumed the non-spherical individual nanoparticles in the colloid rotated and aligned along the external magnetic field, and thus the MF as a whole exhibited anisotropy which caused the birefringence. The other was formation theory[13] which considered the nanoparticles formed magnetic chains or column along the external magnetic field and in turn brought about the birefringence. Further experimental investigations found the phenomenon of zero-filed birefringence of MF, in which the birefringence can be observed even in the absence of external magnetic field.[12] However, neither of the above theories could completely explain the origin of this zero-field birefringence. Later, Bakuzis proposed a dimer model to explain the phenomenon of zero-field birefringence, in which the nanoparticle chain structures were attributed to the spontaneous formation of dimers rather than monomers.[11,12] However, there were still discussions on the physical mechanisms of zero-field birefringence. Besides, the particle size, concentration, and temperature dependence of the birefringence of MF were also investigated.[14,16] The laser self-induced thermal effect on the birefringence of MF was important to the practical MF-based devices such as magneto-optical sensors and modulators.[17] Additionally, it was reported that the magnetic-field-induced birefringence was always accompanied by the dichroism, which also depended on the external magnetic field.[3,18]

In our previous works, we proposed a high-birefringence-fiber (HBF)-assisted polarimetric configuration in order to make the birefringence change of MF "visible" in the form of interference spectrum on the optical spectrum analyzer (OSA).[7] In this work, we present the phenomenon of the laser self-induced tunable birefringence of MF by taking advantage of this same configuration. This phenomenon can be observed in both the zero-field birefringence and the field-induced birefringence of MF. We also find that dichroism of MF does not occur in the zero-field birefringence but always exists in the field-induced birefringence.

The schematic diagram of the experimental setup is shown in Fig. 1. This fiber-based setup is similar to the traditional free-space setup for measuring the birefringence of MF,[14] but an extra HBF is inserted between the polarizer and the analyzer to introduce more phase difference.[7] Light from a broadband light source becomes collimated light through a single-mode-fiber (SMF) collimator, then becomes linearly polarized light through the polarizer, accumulates phase difference in turn through the HBF as well as the MF film, then produces interference fringes at the analyzer, and finally goes back through the collimator to an OSA. The anisotropic MF film can be treated as a typical birefringent material like a uniaxial crystal or a HBF with its slow axis parallel to the magnetic field direction and its fast axis perpendicular to the magnetic field direction.[18] As shown in Fig. 1, the magnetic field direction is configured to be parallel to the MF film and perpendicular to the light propagating direction. Meanwhile, the fast axis of the MF film was aligned parallelly with the slow axis of the HBF. The angle between the polarization directions of polarizer and analyzer was 90°. Hence, the relative transmittance of this polarimetric configuration can be given by[7]

$$T = e^{-(\alpha_o+\alpha_e)d} \cdot \sin^2(2\theta) \cdot [\cosh(\alpha_o - \alpha_e)d - \cos\Phi], \quad (1)$$

where θ is the angle between the polarization direction of the polarizer and the fast axis of the HBF; α_o and α_e are the absorption coefficients of the MF film which are related to the dichroism of MF; α_o is the absorption coefficient corresponding to the light polarization component parallel to the fast axis of MF film (ordinary ray) whist α_e is the one parallel to the slow axis (extraordinary ray); $\Phi = \Phi_{HBF} - \Phi_{MF}$ is the

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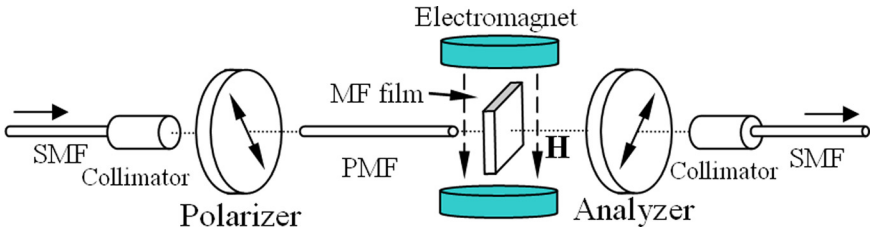

FIG. 1. Schematic diagram of HBF-assisted polarimeter.

total phase difference, where $\Phi_{HBF} = 2\pi B_{HBF} L/\lambda$ is a constant phase difference which is induced by the HBF whist the $\Phi_{MF} = 2\pi B_{MF} d/\lambda$ is a variable phase difference which is induced by the MF film; B_{HBF} and L are the birefringence and length of HBF, respectively; B_{MF} and d are the birefringence and thickness of MF film, respectively; λ is the operating wavelength of the light.

The transmission spectrum of this polarimetric configuration is an approximately periodical waveform, which is shown in Fig. 2. The peak-to-peak ratio of the transmission spectrum is affected by the item $e^{-(\alpha_o+\alpha_e)d}$. In the absence of dichroism, $\alpha_o \approx \alpha_e$, both remain constant with the external magnetic field strength; therefore, the peak-to-peak ratio remains unchanged. In the presence of dichroism, $\alpha_o \neq \alpha_e$, which increase with the external magnetic field strength; therefore, the peak-to-peak ratio will decrease accordingly. This phenomenon can be used to estimate whether α_o and α_e change distinctly or not.

The period of the transmission spectrum is dependent on the total phase difference Φ. If the condition $\Phi = 2m\pi$ (m is an integer) is fulfilled, the dip wavelengths can be obtained as

$$\lambda_m = (B_{HBF} L - B_{MF} d)/m. \tag{2}$$

Hence, the variation of the dip wavelength with the external magnetic field strength can be given by

$$\Delta\lambda_m = -\Delta B_{MF} d/m. \tag{3}$$

Equation (3) shows the variation of the birefringence of MF film can be observed by monitoring the wavelength dips of the transmission spectrum. If the birefringence increases, the wavelength dip will shift to the shorter wavelength side accordingly and vice versa.

In the experiment, the HBF used was a 70-cm-length polarization maintaining fiber (PMF), whose birefringence was about 3.3×10^{-4} (PM-1550-HP). The MF used was a water-based MF (EMG605, Ferrotec), which contained the ferromagnetic nanoparticles, Fe_3O_4, and their nominal diameters were 10 nm. The concentration of the MF was 3.9%; the saturated magnetization was 220 Oe, and the initial magnetic susceptibility was 2.96 Gs/Oe. The MF film sample was prepared simply by sealing the MF between two $22 \times 22\,mm^2$ glass slides, and its net thickness was about 30 μm. An electromagnet (EM4-HVA, Lakeshore) was employed to generate uniform static magnetic field with an accuracy of 0.01 Oe, whose strength was calibrated by a gaussmeter (Model 425, Lakeshore). The MF film was placed completely amidst the uniform field zone. The broadband light source used was an amplified spontaneous emission (ASE) source, whose spectral range was 1520–1620 nm and whose maximum power was about 200 mW. The laser power was measured with an optical powermeter. The output spectrum was monitored by an OSA (AQ6370). The central wavelengths of the collimators were 1550 nm. The polarization extinction ratios of the polarizer and the analyzer (Thorlab) were better than 40 dB. The experiment was carried out at the room temperature of 24.5 °C.

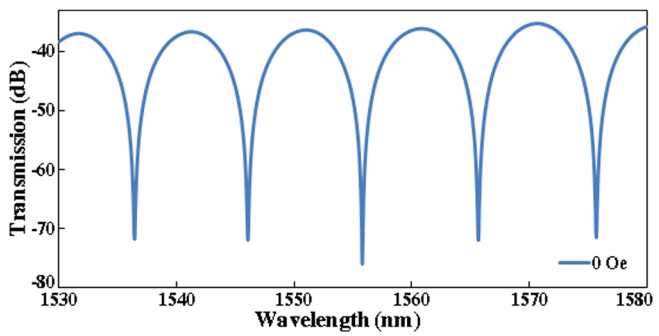

FIG. 2. Transmission spectrum of the proposed configuration.

In order to observe the laser self-induced tunable birefringence, a series of transmission spectra were recorded under zero field as the laser power was increased from 0 mW to 20 mW with an interval of about 2 mW. The laser power here was the power which actually reached the MF film. The initial overall transmission spectrum under zero field is shown in Fig. 2, which has a high peak-to-peak ratio of about 33 dB. The rightmost wavelength dip was chosen as an example for monitoring the spectral shift (Fig. 3(a)). The wavelength dip shifts to the shorter wavelength side from 1572.56 nm to 1571.22 nm totally 1.34 nm as the laser power is increased from 0 mW to 20 mW. As discussed in the principle, the wavelength-dip shift towards shorter wavelength side indicates the birefringence of MF decreases. The peak-to-peak ratio of the transmission spectrum remains almost unchanged, but the overall power level of the transmission spectrum increases due to the increase of laser power. The phenomenon of the unchanged peak-to-peak ratio indicates that dichroism of MF does not occur.

During the process of increasing laser power, every time when the laser power was suddenly increased by about 2 mW, the transmission spectrum responded immediately but shifted slowly and gradually with a declining speed. It took about 10-15 min for the spectral shift to stabilize. We consider the laser self-induced thermal effect is responsible for the variation of birefringence. When the laser passes through the MF, it will heat the MF film and creates a temperature gradient field inside the MF film; meanwhile, the nanoparticle concentration of the MF will be redistributed.[17] This phenomenon is also referred to as thermal lens effect of MF in the literatures.[17,19] The nanoparticle redistribution is due

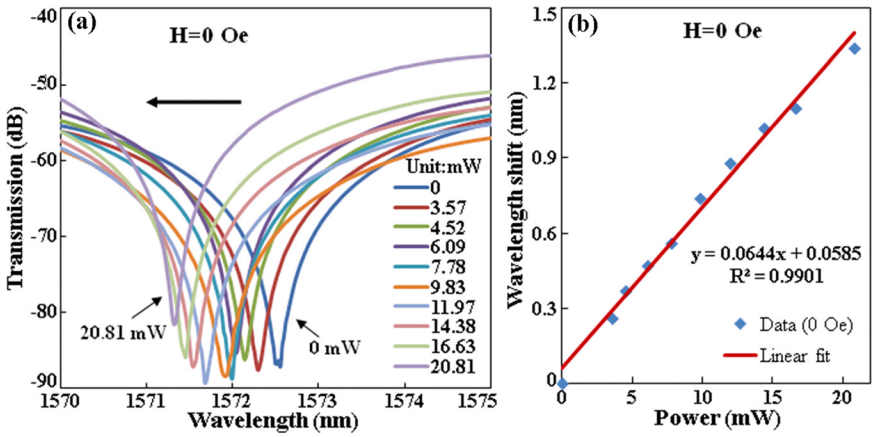

FIG. 3. (a) Transmission spectrum shifts. (b) Dip-wavelength shift with laser power under zero field.

to the Soret effect, which is a phenomenon that the nanoparticles redistribute in response to the temperature gradient.[19] As a consequence, the refractive index and birefringence of magnetic fluid will change accordingly because they are dependent on the local nanoparticle concentration.[11,20] We name this phenomenon as laser self-induced tunable birefringence of magnetic fluid. The nanoparticle concentration redistribution due to the thermal effect induced by the laser itself is carried out with the assistance of Brownian motion.[4] It will take some time for the nanoparticles to transit from the original distribution state of balance to a new one, and it took about 10–15 min for every increase of 2 mW in laser power in this experiment. Meanwhile, this laser self-induced birefringence is tuned on the base of zero-field birefringence since this experiment was carried out in the absence of external magnetic field. This zero-field birefringence are related to the presence of chain-like dimers and the orientation for the chain-like structures, which is accounted for by the spontaneous anchoring of dimers in the inner wall of the sample holder.[11,12] As the laser heats the MF, the nanoparticles gain more kinetic energy due to the laser self-induced thermal effect.[21] Subsequently, the nanoparticles with more kinetic energy enhance their spontaneous formation of orientated dimers, so the birefringence of magnetic fluid is increased. This result is also consistent with the reported experimental result.[12] The relationship between the dip-wavelength shift of the transmission spectrum and the incident laser power is plotted in Fig. 3(b). The variation trend follows a linear function. The linear fit method is applied to the data and the slope is 0.0644 nm/mW.

In order to compare the birefringence effects tuned by laser power with the one tuned by external magnetic field, a series of transmission spectra were recorded in Fig. 4(a) as the magnetic field strength was increased. The laser power was 20 mW in this experiment. As the magnetic field strength was increased from 0 Oe to 1360 Oe, the wavelength dip was also shifted to the shorter wavelength side from 1574.80 nm to 1573.69 nm totally 1.11 nm whilst the peak-to-peak ratio was decreased gradually from about 33 dB to 12 dB totally 21 dB. Compared with the result in Fig. 3(a), the significant difference is the decline of the peak-to-peak ratio. This is because in the presence of external magnetic field, the nanoparticles form magnetic chains significantly and align along the magnetic field direction.[22] The formation of the magnetic chains exhibits significant different absorption coefficients for the two beams for interference, which lead to the significant decline of the peak-to-peak ratio. However, in the case of the absence of external magnetic field, the zero-field birefringence is originated from the spontaneous formation of orientated dimers, so there is no such strong formation of magnetic chains which cause strong dichroism in MF.[12] The relationship between the dip wavelength and the external field strength is shown in Fig. 4(b). When the external magnetic field is applied on the MF film, the wavelength dip does not change until the field strength exceeds a critical field strength H_c ($H_c = 32.8$ Oe) as shown in Fig. 4(b). For the case of above H_c, the birefringence of MF increases with the external field strength linearly and rapidly (i.e., 32.8 Oe < H < 300 Oe) and then tends to be saturated gradually. As the magnetic field is applied, two major energies are responsible for the formation of the magnetic

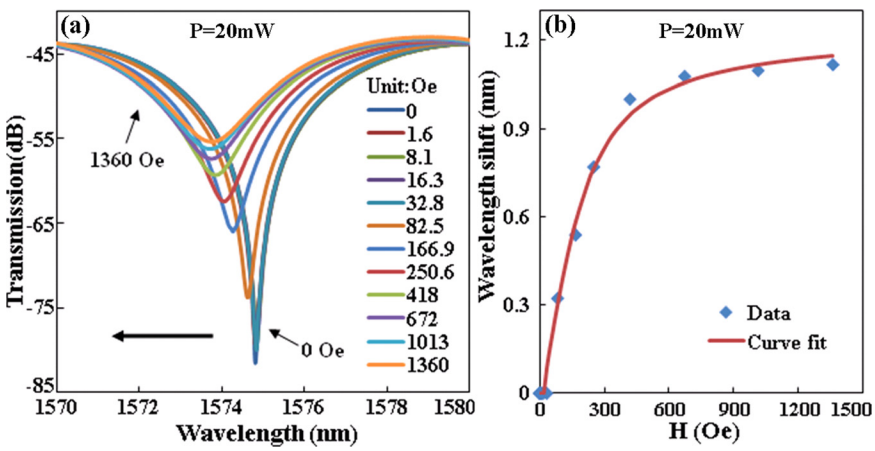

FIG. 4. (a) Transmission spectrum. (b) Dip-wavelength shift with magnetic field at a fixed laser power of 20 mW.

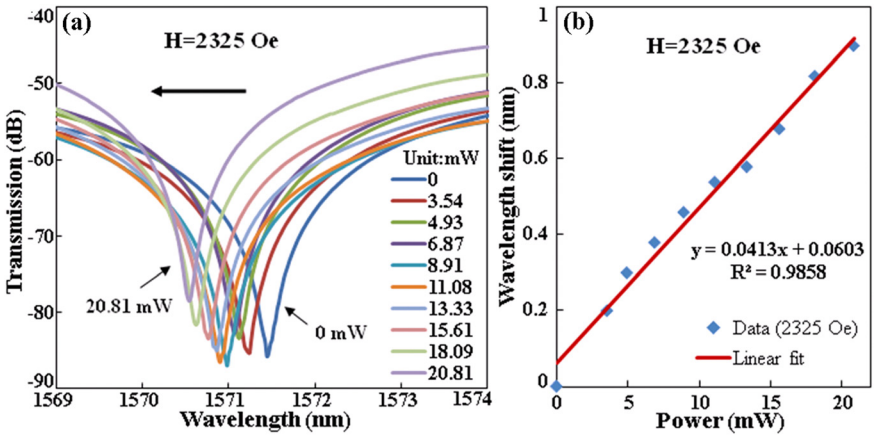

FIG. 5. (a) Transmission spectrum. (b) Dip-wavelength shifts with laser power under a fixed field strength of 2325 Oe.

columns in MF. One is the thermal energy of particles, and the other is the magnetic energy of particles. The compensation effect between the thermal energy and the magnetic energy can be described with a Langevin function.[23] With the fact that the variation in field induced-birefringence of MF with the magnetic field strength H and the temperature T is attributed to the magnetic column formation, the trend of field-induced birefringence should be similar to Langevin function.[1] Similarly, the experimental data shown in Fig. 4 are compared with Langevin-function-like B_{MF} expressed as[1]

$$B_{MF} = (B_s - B_o)\left[\coth\frac{\alpha(H-H_c)}{T} - \frac{T}{\alpha(H-H_c)}\right] + B_o, \quad (4)$$

where B_o is the initial birefringence under fields lower than the critical field H_c and B_s denotes the saturated value of the birefringence under external magnetic field. In this experiment, the birefringence became completely saturated at about $H > 1000$ Oe.

The phenomenon of laser self-induced tunable birefringence of MF under external magnetic field was also measured for comparison. The field strength was 2325 Oe, which was a deep saturation strength for this MF film according to the result in Fig. 4(b). Since the peak-to-peak ratio of the transmission spectrum declined greatly in the presence of such a strong magnetic field, the analyzer in the setup was rotated to balance the intensities of the two beams for interference so that the peak-to-peak ratio could return to its maximum value. A series of transmission spectra were recorded under external magnetic field as the laser power was increased (Fig. 5(a)). The wavelength dip shifts to the shorter wavelength side from 1571.44 nm to 1570.54 nm totally 0.9 nm as the laser power was increased from 0 mW to 20 mW. The phenomenon is similar to the one in Fig. 3(a), but the total wavelength shift range (0.9 nm) is smaller than the one in Fig. 3(a) (1.34 nm). Similarly, the relationship between the spectral shift and the laser power is a linear function (Fig. 5(b)), and the slope is estimated to be 0.0413 nm/mW, which is also smaller than the result in Fig. 3(b) (0.0644 nm/nW). The reason why the laser self-induced tunable birefringence is suppressed is due to the presence of external magnetic field. Under a stronger magnetic field, the nanoparticles in the magnetic fluid gain more enhancement in the magnetic energy of the nanoparticles. Thus, higher laser power is needed to compensate the magnetic energy making the particles to be able to reestablish the same state of balance and form the same formation structure. Therefore, it appears as the suppressing of the laser self-induced tunable birefringence.[19,21]

In conclusion, a HBF-assisted polarimetric configuration is employed to observe the phenomenon of laser self-induced tunable birefringence of MF. This phenomenon exists in MF, no matter whether it is under an external magnetic field or not. The laser self-induced birefringence is suppressed in the presence of external magnetic field. The variation trend of the birefringence change of MF with laser power follows a linear relationship. The field-induced birefringence of MF is also tested by taking advantage of the same setup for comparison, whose variation trend is a Langevin function. Another distinct difference exists in the dichroism of MF, which does not coexist with the laser self-induced tunable birefringence but is always coupled with the field-induced birefringence.

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