Dynamic performance of magneto-optical Bi-substituted rare-earth iron garnet

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The dynamic performances of magneto-optical Bi-substituted rare-earth iron garnet (BIG) under different external magnetic fields and at different frequencies are experimentally studied. The measurement data indicate that the Faraday rotation angle is almost proportional to the external magnetic field when the garnet is far less saturated, while there is good switch performance when it is saturated. The higher the working frequency is, the larger the saturation magnetic field and the phase delay of Faraday angle relative to the field. The saturation fields and the phase delays at different frequencies are measured. The dynamic performance of the BIG determines the performance of BIG-based optical devices. To get the better performance of such devices, the garnets with small dampness and large stiffness should be chosen elaborately.

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Bi-substituted rare-earth iron garnet (BIG) is a kind of magneto-optical (MO) materials that are widely used in optical attenuator, switch, modulator, and isolator in optical fiber communication systems or in optical sensor in optical sensing fields because of its high transmission ratio and large Faraday rotation coefficient. In potential applications, the dynamic response of these devices is one of the key parameters to evaluate their performances because most of the devices work in dynamic state. MO garnet is the key part in these devices. The garnet's dynamic performance determines the dynamic response of these devices. In previous works, many researches are focused on the garnet's optical transmission ratio spectrum, temperature performance, micro-mechanism of Faraday effects, and influence of different substitutions on Faraday effects[1−4]. However, the dynamic performance of garnets is rarely reported. In this paper, we report the dynamic performance of a kind of BIG at low and high frequencies in detail. The result can be a reference when designing such devices.

In the experiment, laser diode (LD) whose central wavelength is 1550 nm is used. Laser light transmits through a polarizer, a Faraday rotator, an analyzer, and then is received by an optical detector (Agilent 81637B). The relative angle between the polarization planes of polarizer and the analyzer is set 45°. The Faraday rotator consists of one piece of BIG and an electrical coil surrounding the BIG. Voltage output from a function generator (Kenwood FG-273A) is supplied to the coil to provide the BIG magnetic field. The voltage on the coil and that from the optical detector are recorded by an oscilloscope (Tektronix TDS210), and further processed by computer. The BIG (Mitsubishi corp., Japan) can generate 45° maximum Faraday angle. The saturation field of the BIG is $70 - 120$ Oe. The impedance of the function generator is about 50 Ω, and the resistance of the coil is 40 Ω, inductance is 2.41 mH. The coil is with the inner diameter of 4 mm, outer diameter of 10 mm, length of 8 mm, and 780 windings. The experimental setup is schematically shown in Fig. 1.

The frequency response of the coil should be considered at first since it provides the BIG an AC magnetic field. When the signal's frequency is not very high, we can consider the resistance and inductance of the coil. Figure 2 shows the voltage amplitude (U_m), current amplitude (I_m), and phase delay (θ) of current relative to voltage of the coil at different frequencies when the AC voltage is sinusoidal. It can be seen that the voltage on the coil and the phase delay increase with the increase of frequency, while current decreases inversely.

In this experiment, Faraday angle ϕ is determined by output voltage from the optical detector, expressed as

$$\phi = \frac{1}{2}\sin^{-1}\left(1 - \frac{2U_d}{U_m}\right), \qquad (1)$$

where U_d is the output voltage, U_m is the value when $\phi = -45°$.

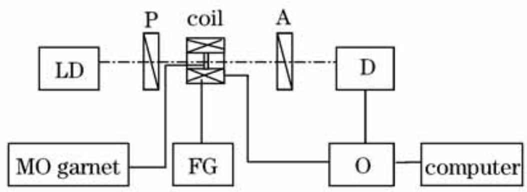

Fig. 1. Schematic diagram of the experimental setup. *P*: polarizer; *A*: analyzer; *D*: optical detector; FG: function generator; *O*: oscilloscope.

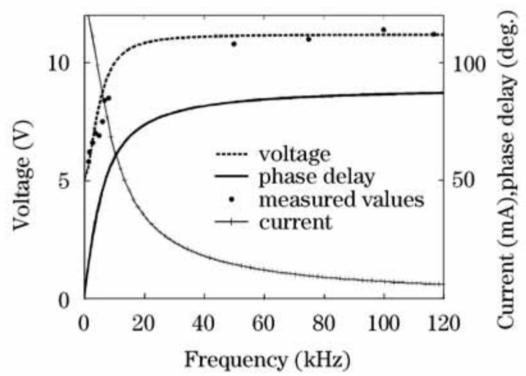

Fig. 2. Frequency dependence of I_m, U_m, and θ.

The variation of Faraday angle due to the variation of U_d is

$$|\Delta\phi| = \left|\frac{\Delta U_d}{U_m \cos 2\phi}\right|. \quad (2)$$

As the current I and the Faraday angle ϕ are proportional to magnetic field H and magnetization M[5,6], respectively, curve I-ϕ is similar with hysteresis curve H-M. It is reasonable to measure curve I-ϕ because people always need to control the Faraday angle by controlling the current in practical applications. At 1.23 Hz, the voltage waveforms from the oscilloscope and calculated curve I-ϕ at different current amplitudes are shown in Fig. 3. When the current is less than 12 mA, the BIG is far less saturated, ϕ is almost proportional to I, as shown in the inset in Fig. 3(a). When the current becomes greater, ϕ is no longer proportional to I. hysteresis appears, as shown in Fig. 3(b). When I_m = 56 mA, the BIG is fully saturated, as shown in Fig. 3(c). The deeper the saturation degree, the more obvious hyesteresis is observed. In Fig. 3(a), the middle value of the Faraday angle is not 0°. This is because the BIG is used to make optical switch initially. When the BIG works in non-saturation state, the influence of remnant magnetism inside the BIG is obvious, which makes the Faraday angle rotate about 12° in prior. The calculated curve $I - \phi$ is not very smooth when ϕ approaches ±45°. It is because that when ϕ approaches ±45°, any small variation of U_d, which may be resulted from electrical noise, ground noise, magneto-electrical noise, thermal noise, or environmental noise, will lead to great calculation error $\Delta\phi$ according to Eq. (2). In the experiment, U_m is 190 mV, the noise drift is about 5 mV. When U_d changes from 190 to 185 mV, ϕ changes from 45° to 35.6°, which agrees with the curve I-ϕ in Figs. 3(b) and (c).

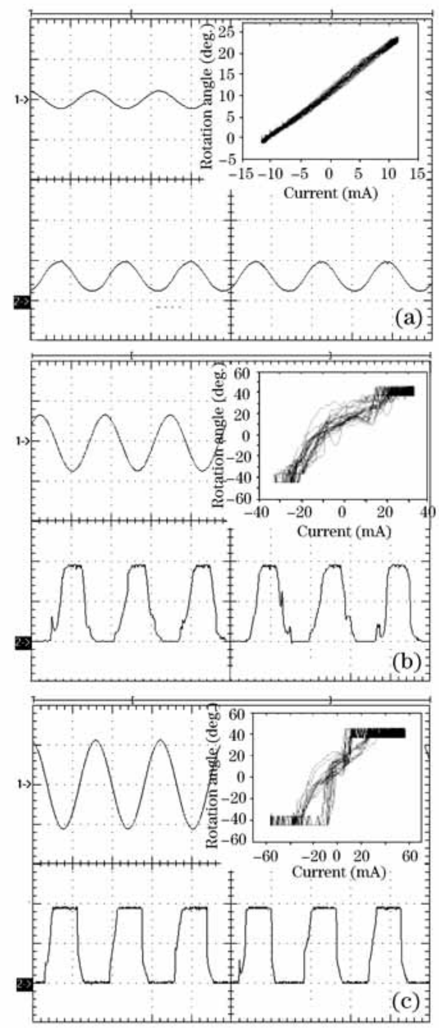

Fig. 3. Voltage waveforms from oscilloscope at 1.23 Hz. 1: the voltage on coil; 2: the output voltage from the optical detector. Insets are the I-ϕ curves. (a) I_m = 12 mA; (b) I_m = 33 mA; (c) I_m = 56 mA.

The saturation currents at different frequencies are shown in Fig. 4. The saturation current (magnetic field) increases gradually with the increase of frequency. More than 80 mA is needed at 6.3 kHz while only about 50 mA at low frequency.

As Faraday angle is synchronous with the output voltage from the optical detector absolutely, the phase delay of Faraday angle relative to the voltage on coil is equal to the phase delay of the output voltage from the detector relative to the voltage on coil, as shown in Fig. 5. From Fig. 2, the phase delay of current relative to voltage on coil can be calculated. Then the phase delay of Faraday angle relative to current can be obtained, which equals to the difference of above two phase delays, as shown in Fig. 6. The upper fitting curve in Fig. 6 represents the phase delay of Faraday angle relative to the voltage on coil, and the lower represents the phase delay of current relative to the voltage on coil. The difference between them is the phase delay of Faraday angle relative to

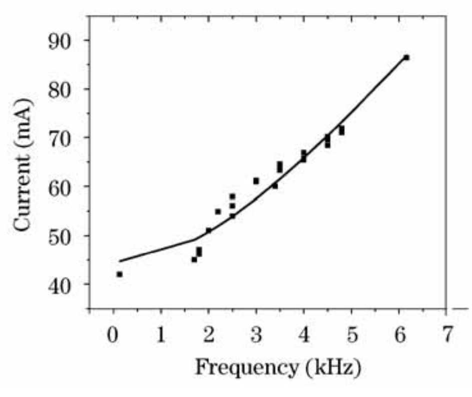

Fig. 4. Dependence of saturation current with frequency.

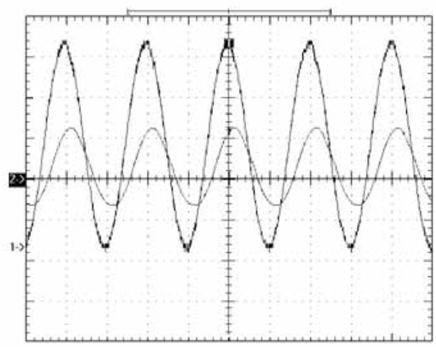

Fig. 5. Voltage waveforms at 995 Hz. The greater is on the coil, the smaller is from optical detector.

Table 1. Properties of Three Kinds of Magneto-Optic Thick Films[4]

	Film 1	Film 2	Film 3
Composition	$(BiY)_3Fe_5O_{12}$	$(BiTb)_3(FeGa)_5O_{12}$	$(BiTb)_3(FeGa)_5O_{12}$
Film Thickness (μm)	60×2	100× 2	320
A (J/m)	3.7× 10^{-2}	3.0× 10^{-2}	2.5× 10^{-2}
M_s (kA/m)	143	56	28
K(J/m^3)	1.4×104	4.5×103	4.7×103
Stripe Width (μm)	7	12	50
Damping	Low	High	High
Faraday Rotation at 1.3 μm (deg.)	27	27	45

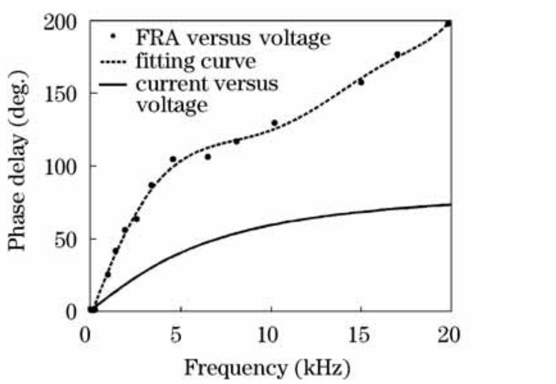

Fig. 6. Phase delays of Faraday angle versus current at different frequencies. FRA: Faraday rotation angle.

current. It is obvious that the phase delay of Faraday angle increases as the frequency goes up.

In the experiment, the saturation current (magnetic field) and the phase delay of Faraday angle relative to magnetic field increase with the increase of frequency. It indicates that at higher frequency, greater saturation magnetic field is needed, and larger phase delay is got. It is because that Faraday rotation strongly depends on the displacement of the domain walls inside the garnet. The motion of domain walls under AC magnetic field meets the equation[4]

$$m\ddot{x} + \beta\dot{x} + \kappa x = 2\mu_0 H M_s, \qquad (3)$$

where x is the displacement of domain walls, m is the effective mass of the domain walls per unit area, β is the viscous damping coefficient, κ is the wall stiffness coefficient, μ_0 is the permeability in vacuum, H is the applied magnetic field perpendicular to MO garnet, and M_s is the saturation magnetization.

Assuming a sinusoidal AC magnetic field with radial frequency ω is applied to the garnet, the phase delay of displacement relative to the field is

$$\gamma = \mathrm{arctg}\frac{\omega\beta}{\kappa - m\omega^2}. \qquad (4)$$

The amplitude of the displacement is

$$x_m = \frac{2\mu_0 H_m M_s}{\sqrt{(\kappa - m\omega^2)^2 + (\omega\beta)^2}}, \qquad (5)$$

where H_m is the amplitude of magnetic field.

Obviously, there are similar performances of phase delay and amplitude of Faraday angle in AC magnetic field, which leads to the variations of saturation field and phase delay of Faraday angle at different frequencies.

In optical switches based on garnets, the hysteresis should be as small as possible so that the switch follows the variation of signals. But due to the frequency limitation, the optical switch that can work well at low frequency, probably cannot be saturated at higher frequency, and cannot work well as a result. Also, the switch cannot respond to the variation of signal due to the existence of phase delay. Thus optical switch is actually frequency limited. When the garnet is used in current or magnetic field sensors due to the variation of saturation field and phase delay its responsivity and response time are different at different frequencies, which lead to the measurement error and affect the accuracy of the sensors.

According to Eq. (4), to reduce the influence of phase delay, the garnet with small β/m and large κ/m is needed. If neglecting the difference of m, the garnet with small dampness and large stiffness should be chosen. Table 1 lists the properties of three kinds of MO thick films. It can be found that the first kind of garnet is with less dampness and larger stiffness. It is more suitable to make optical switches or sensors. The relationship of κ with the parameters in the table is: $\kappa = \left[\frac{\mu_0}{4\pi}\right]^{3/2} \frac{(1.7)^{3/2} M_s^3}{\left[(AK)^{1/2} L\right]^{1/2}}$, where L is the thickness of garnet.

In conclusion, we have studied the dynamics of a kind of BIG under different magnetic fields and at different frequencies. The experiment indicates that, with the increase of working frequency, the saturation magnetic field and the phase delay of Faraday angle relative to magnetic field increase. This results from the motion of domain walls inside the garnet. This dynamic performance of the garnet affects the dynamic response of such optical devices that are based on garnets, and arouses the measurement error of optical sensors. To reduce the influence of the dynamic performance, the suitable MO garnet should be chosen to make the variations of phase delay and amplitude of saturation magnetic field at different frequencies as small as possible.

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