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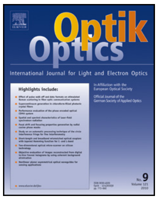

Effect of temperature on characteristics of rare earth-doped magneto-optical glass in optical current transducer application

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ABSTRACT

First, a theoretical analysis was performed on the effect of temperature and on the performance of the sensing element of rare earth-doped magneto-optical glass material that can be used in an optical current transducer application. The effect comprises two aspects: the linear birefringence and the Verdet constant. On this basis, rare earth-doped glass temperature characteristics were studied, and the experimental results indicated that the linear birefringence of rare earth-doped glass increased with increasing temperature, while its magneto-optical sensitivity decreased. Comparative experiments performed for various concentrations of rare-earth dopant in the glass revealed that changes in the dopant concentration had no significant effect on the performance of magneto-optical glass.

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1. Introduction

Due to their transducing characteristics, the existing power systems, such as electromagnetic current systems and voltage transformers, have many shortcomings that are difficult to overcome; these include high insulation requirements, large volume, high cost, narrow range of linear measurement, the presence of ferromagnetic resonance phenomenon, as well as distortion of the secondary-side output waveform due to magnetic saturation during the measurement of a short circuit current [1,2]. The above makes it difficult for electromagnetic transformers to meet the development needs of modern power systems. However, an optical current transducer (referred to as OCT) has apparent advantages. Based on Faraday's basic principles of magneto-optical rotation, OCTs have various advantages, such as small size, light weight, low cost, absence of ferromagnetic resonance problems, large linear measurement range, and broad response frequency bandwidth. Thus, optical current transducers have attracted widespread attention and have been studied by many researchers.

At the OCT's core is a magneto-optical transducing rod. For magneto-optical transducing material of this kind, it needs to be manufactured easily, have good transparency, excellent optical properties, a large Verdet constant, and weak temperature sensitivity. Currently, magneto-optical glasses are the main material type used in the research and development of Faraday magneto-optical materials. The glasses can be divided into two groups: paramagnetic and diamagnetic glasses. Paramagnetic glasses have larger Verdet constant, high magneto-optical sensitivity, and high temperature sensitivity. On the other hand, diamagnetic glasses have smaller Verdet constant as well as weaker temperature sensitivity. The Verdet constant of a diamagnetic glass is one sixth of that of a paramagnetic glass, but its nonlinear refractive index is two to eight times that of the latter [3], which limits the use of diamagnetic glasses in high-energy high-power laser devices. In addition, from temperature performance perspective, it is difficult to avoid the errors of linear birefringence caused by temperature and stress changes in diamagnetic materials [4]. Therefore, studies of paramagnetic glass performance in OCT are necessary for using this material in OCT applications.

With the rapid development of materials science in recent years, the performance of paramagnetic magneto-optical materials, which were neglected in the past, has been greatly improved. Studies have shown that the paramagnetic properties of glass are affected by various factors, such as the types of doping rare-earth ions and their concentrations, types of glass substrates, electronic transition wavelength, and temperature [5]. The magneto-optical glass doped with rare earth Tb^{+3} ions, due to its high Verdet constant and excellent optical performance, has been used in magneto-optical storage and in high-power laser systems. Because, temperature dependence of paramagnetic rare earth-doped glass is the main factor hindering its application in OCT, this study will mainly focus on the temperature characteristics of rare earth-doped magneto-optical glass in OCT.

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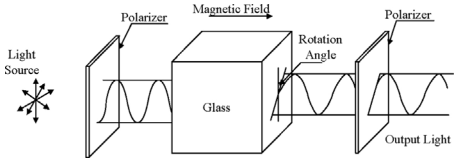

Fig. 1. Illustration of Faraday Magneto-Optical Effect.

2. Theory

2.1. Theory of Faraday magneto-optical effect

Magneto-optic current transducers utilize Faraday magneto-optical effect, which describes rotation of polarization plane that occurs when linearly polarized light travels through an optical medium along the direction of the applied magnetic field or along the direction of magnetization. Fig. 1 schematically illustrates the Faraday magneto-optical effect.

The relationship between Faraday rotation angle φ and the external magnetic field H along the direction of light propagation can be expressed as follows:

$$\varphi = VHL = V\int_L H(l)dl \tag{1}$$

where L is the distance (m) that light traveled through the magneto-optical medium, and V is the Verdet constant (rad/T • m).

According to the studies by GongQiang Liu [6], the following holds:

$$V/\chi = A(1+BT) \tag{2}$$

where $\chi = \frac{c}{T-T_p}$, A is a material-specific constant, $B = \frac{1}{\nu c - T_p}$, ν is a coefficient related to the molecular length coefficient, and c is the Curie constant.

As can be seen from Eq. (2), the Verdet constant of paramagnetic magneto-optical glass is temperature-dependent. Studies revealed that the Verdet constant of magneto-optical glass doped with Tb^{+3} Ions decreases with increasing temperature. The reason for this phenomenon is that the amplitude of electronic thermal vibration increases with increasing temperature, which enhances the hindrance of magnetic moment changes caused by the external magnetic field, weakens the paramagnetism of the glass, and thereby decreases the Verdet constant. This explanation holds at normal temperature conditions. At extremely low temperature (T = 2.03 K), the expression for the Faraday rotation angle of a magneto-optical glass doped with terbium ions becomes [7]:

$$\theta_F = a\tanh(\mu_e H/kT) + bH \tag{3}$$

where μ_e is the Bohr magneton number (mol), H is the magnetic field strength (H), T is the temperature in Kelvins (K), and both a and b are constants.

2.2. Linear birefringence of isotropic media

Considering linear birefringence, the model of light propagation in magneto-optical glass is shown in Fig. 2.

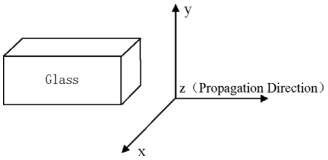

Fig. 2. Light Path with Linear Birefringence.

In this model, the z-axis is the direction of light propagation, and the x- and y-axes constitute a plane vertical to the direction of light propagation.

Linear birefringence can be expressed as:

$$\delta = \Delta n \cdot L \cdot \frac{2\pi}{\lambda} \tag{4}$$

where Δn is the difference $n_x - n_y$ of refractive indices of the sensor head in x and y directions that is caused by stress, L is the glass sensor arm length (i.e., the optical path length (m)), and λ is the incident light wavelength (nm).

It can be seen that increasing the optical path length results in an increase of the phase difference caused by linear birefringence; for this, the incident light wavelength as well as the difference of sensor head material's refractive indices should be constant.

The difference of refractive indices can be expressed as:

$$\Delta n = \Delta n_x - \Delta n_y = \frac{1}{2}(1+\nu)\cdot(p_{11}-p_{12})\cdot n^3 \cdot \frac{P}{E} \tag{5}$$

where p_{11} and p_{12} are photo-elastic coefficients of the material, ν is the Poisson's ratio of the material, P is the stress of the material (N), and E is the Young modulus (N/mm^2).

The linear birefringence per unit length can be expressed as:

$$\Delta\delta = \frac{\delta}{L} = \Delta n \frac{2\pi}{\lambda} \tag{6}$$

By substituting Eq. (5) into Eq. (6), the linear birefringence per unit length can be expressed as:

$$\Delta\delta = \frac{1}{2}\cdot\frac{2\pi}{\lambda}\cdot(1+\nu)\cdot(p_{11}-p_{12})\cdot n^3 \cdot \frac{P}{E} \tag{7}$$

where ν, p_{11}, p_{12}, and E are constants specific to the glass material, n is the refractive index of optical glass, which depends on the glass type and temperature, and the stress P is temperature-dependent as well.

3. Results

3.1. Simulation analysis

Temperature affects rare earth-doped glass in two ways: (1) the Verdet constant of the rare earth-doped glass is temperature-dependent, and (2) increasing temperature causes glass expansion, which creates thermal stress within glass packaging that in turn causes glass to change from an isotropic medium to an anisotropic medium with direction-dependent refraction indices. A phase difference is thus generated during light propagation; this phenomenon is known as temperature-induced linear birefringence.

3.1.1. Temperature dependence of Verdet constants in rare earth-doped glasses

As indicated by Eq. (1), Verdet constant directly determines the magnitude of Faraday rotation angle when the external magnetic field and the glass length are constant. According to the theory of electrodynamics, the temperature dependence of Verdet constant is as follows:

$$V(T) = A\cdot\left(1+\frac{B}{T-T_a}\right) \tag{8}$$

where T_a *is* the material's Curie temperature and A and B are material-specific constants.

Fig. 3 shows, temperature dependence of Verdet constants obtained by simulations of glass with rare earth doping ratios of 20 and 30%. For these examples, the parameters were T_a = 96.92 K, A = 32.28, and B = 245.81 for rare earth doping ratio of 20%, and T_a = 161.1 K, A = 71.34, B = 45.78 for doping ratio of 30%.

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