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# Reciprocity of Faraday effect in ferrofluid: Comparison with magneto-optical glass

Shibin Wang*, Caixin Sun, Lin Du, Chenguo Yao, Yong Yang

*State Key Laboratory of Power Transmission Equipment & System Security and New Technology, Chongqing University, Chongqing 400030, China*

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ABSTRACT

The transmission light intensity method is carried out on a classical platform to study the reciprocity of Faraday effect in water-based $Fe_3O_4$ ferrofluid and its diluents. Setting the polarization direction of the analyzer at an angle of 45° to that of the polarizer, the switchable DC magnetic field and the alternating magnetic field are imposed to ferrofluid. The ferrofluid film is replaced by magneto-optical glass for contrastive experiments. The results indicate that ferrofluid is different with magneto-optical glass. Even though the direction of magnetic field is reversed, the rotation direction of the polarized light does not change for ferrofluid. The theoretical model of magneto-optical rotation was used to describe the origin of the reciprocity of Faraday effect in ferrofluid and the non-reciprocity in magneto-optical glass. These findings suggest that the magnetic moments of nanoparticles in ferrofluid tend to the same orientation with the magnetic field because of the rotation of particles.

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## 1. Introduction

A magnetic field along the direction of propagation of polarized light in a solid or liquid medium causes rotation of the plane of polarization, known as Faraday effect. The related researches have promoted the applications of magneto-optical media in electric current measurement [1,2], magnetic field sensing [3] and light intensity adjustment [4]. Among the many studies, it's an interesting topic to study the relationship between the rotation direction of the polarized light and that of the magnetic field. Previous studies in solid magneto-optical materials have demonstrated that the rotation direction of the polarized light only depends on the magnetic field direction, and despite of the propagation direction of the light [5]. That is so-called non-reciprocity of Faraday effect for solid magneto-optical materials. A back-reflected fiber-optic current sensor has been demonstrated based on the non-reciprocity of Faraday rotation in single-mode sensing fiber [6]. It could restrain the influence of birefringence on measurement and improved the sensitivity of response [7] or enhanced the anti-interference ability [8]. Fang and Claus presented the intensity-based reciprocity-insensitive structure (IRIS) to compensate the birefringence and the power loss influences in the fiber-based current sensors [9].

For the liquid-phase magneto-optical materials, Donatini et al. [10] found that Faraday effect of ferrofluid $Fe_2CoO_4$ in dibutylphthalate (DBP) is non-reciprocal. When the direction of steady magnetic field is reversed, the values of rotation angle are symmetrical in relation to the origin. This property has been tested repeatedly for four ferrite ferrofluids (including water-based $Fe_3O_4$ ferrofluid) in visible-near infrared spectrum [11,12]. However, we found that the rotation direction of Faraday effect in water-based $Fe_3O_4$ ferrofluid does not change even though the direction of magnetic field reverses. By comparing with solid-phase magneto-optical glass, the Faraday rotation of ferrofluid is reciprocal.

The paper is organized as follows. In Section 2, we describe the experiment materials and the platform. The experiment results are presented in Section 3. The theoretical analysis is prompted in Section 4, and in Section 5, we summarize the main findings.

## 2. Materials and methods

Water-based ferrofluid was prepared by chemical co-precipitation method [13,14]. The magnetite particles were treated with oleic acid, which acted as a surfactant. The synthesized nanoparticle shapes were obtained from the atom force microscope (AFM) micrograph using an IPC-208B microscope. Proper amount of ferrofluid containing about 31.2% particle mass concentration was mounted on a gold plate and dried in ambient air. The AFM picture is shown in Fig. 1. The diameter of magnetic particles in ferrofluid is estimated as about 8 nm by topographic observation. No significant agglomeration is observed. Structural information is obtained using a Rigaku D/max-3c diffractometer. The ferrofluid specimen was placed in a dish and dried at room temperature, and then grounded into powder for the X-ray diffraction (XRD). The XRD picture is shown in Fig. 2. The diffraction pattern for the

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* Corresponding author. Tel.: +86 023 62563152; fax: +86 023 62563152.
*E-mail address:* wsb@cqut.edu.cn (S. Wang).

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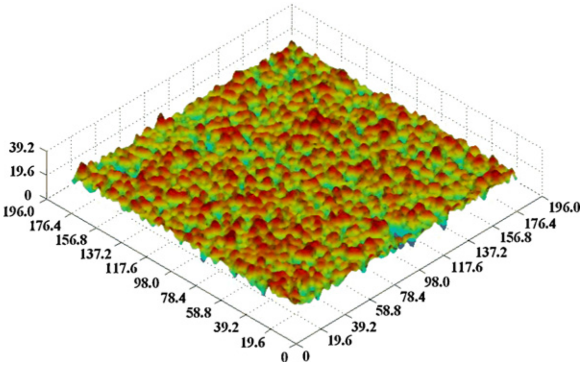

**Fig. 1.** Atom force microscope (AFM) micrograph of magnetic nanoparticles in ferrofluid (unit: nm).

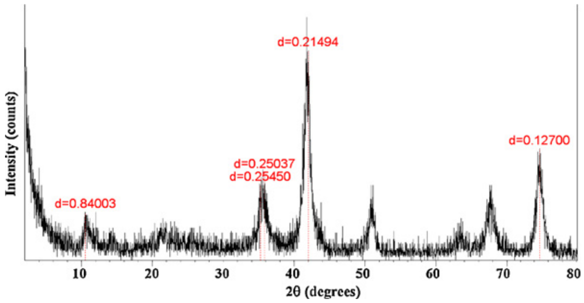

**Fig. 2.** X-ray diffraction (XRD) spectrum of magnetic nanoparticles in ferrofluid.

specimen clearly shows sharp diffraction peaks corresponding to magnetite. The sample film was made by ferrofluid injected into a liquid cell (Fig. 3), which contains two pieces of $CaF_2$ windows and a piece of polytetrafluoroethylene (PTFE) gasket. When ferrofluid is injected into the gap between two pieces of $CaF_2$ windows by the injection hole, original air in gap is supplanted through the exhaust hole. The thickness of PTFE gasket is 6 μm, which is equal to the thickness of the ferrofluid film. As the material used in the contrastive experiments, cylindrical magneto-optical glass is MR3-2 (made by Xi'an Aofa Optoelectronics Technology Inc.), with the diameter of 10 mm and the height of 3 mm.

Fig. 4 shows the schematic diagram of the experimental platform, which is a classical arrangement and widely used in the studies of Faraday effect for magneto-optical media. The monochromatic light emitted from the laser diode propagates along the *x*-axis and the wavelength is 650 nm, power is 5 mW. A polarizer is used to convert the randomly polarized light into linearly polarized light. The orientation of the linearly polarized light rotates an angle after the light has passed through the ferrofluid film because of Faraday effect. Then an analyzer oriented 45° with the polarizer converts the orientation variation of the polarized light into intensity variation of the light, and then this output is sent to a photodetector. The reason of using the analyzer is that photodetector can only detect the intensity of light, rather than the orientation of polarization. The output exporting from the photodetector is converted into digital signal by a data acquisition card and transferred to a computer. The direction of magnetic field in air gap of C-type electromagnet is always perpendicular to the ferrofluid film and parallel to the direction of the polarized light. The environmental temperature during the test is kept constant at 298 K.

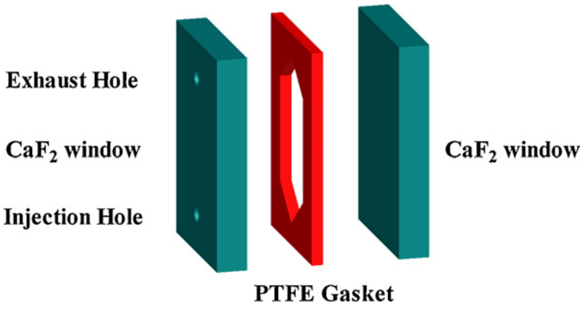

**Fig. 3.** Construction of the liquid cell.

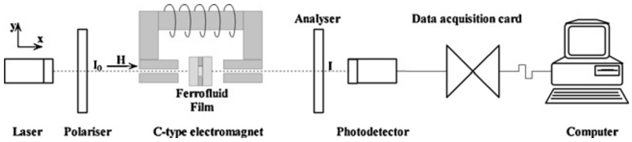

**Fig. 4.** The schematic diagram of the experimental platform. The direction of magnetic field ***H*** is same or opposite with the direction of the direction of light propagation. $I_0$ is the intensity of the polarized light transmitted from the polarizer and *I* is the light intensity from the analyzer.

When the excitation current is applied into the coil of C-type electromagnet, a modulation magnetic field is generated in the air gap. The direction of DC magnetic field is reversed by changing the direction of the excitation current. So, the direction of magnetic field is same or opposite with the direction of light propagation along the *x*-axis. The intensity of magnetic field can be regulated by the amplitude of electric current. As for the AC magnetic field, the direction is altered periodically in air gap. Similarly, the amplitude of magnetic field can be modulated by the amplitude of electric current. A slice of magneto-optical glass is used to replace the ferrofluid film for the contrastive experiments.

## 3. Results

### 3.1. Switchable DC magnetic field

The ferrofluid film is placed in the center of air gap of C-type electromagnet. The following steps are implemented during the experiment. Firstly, DC is applied into the coil of C-type electromagnet. The direction of magnetic field is designated as the positive when it is same with the propagation direction of the polarized light. A clockwise rotation is regarded as the positive rotation angle when viewing towards the light source. Secondly, the direction of DC is changed and the magnetic field turns to be negative as the direction of field is opposite with the light propagation. The intensity of the transmission light is measured when modulating the amplitude of the excitation current. Finally, ferrofluid with the mass concentration of 20%, 10% and 5% is conducted in turn. All of the results are shown in Fig. 5.

It is clearly demonstrated in Fig. 5 that (1) the intensity of the transmission light increases with the intensity of the magnetic field, no matter the field direction is same or opposite with the light propagation; (2) the intensities of the polarized light have the same maximum value for the positive and the negative field. All different concentration ferrofluids obey above descriptions, i.e. it has no influence for the direction of the magnetic field on the relationship between the intensity of the polarized light and the intensity of the magnetic field.

Replacing the ferrofluid film with magneto-optical glass, similar steps are carried out repeatedly and the results are shown in Fig. 6.

There is a huge difference between magneto-optical glass and ferrofluid as modulated by switchable DC magnetic field. It can be seen from Fig. 6 that when the field direction is same with the light propagation, the light monotonously intensity increased with the magnetic field. Contrarily, the light intensity decreased with

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