Measurement of the refractive index of a magnetic fluid by the retroreflection on the fiber-optic end face

Shengli Pu,[a] Xianfeng Chen,[b] Yuping Chen, Weijun Liao, Lijun Chen, and Yuxing Xia
Department of Physics, Institute of Optics and Photonics, The State Key Laboratory on Fiber Optic Local Area Communication Networks and Advanced Optical Communication Systems, Shanghai Jiao Tong University, Shanghai 200240, China

(Received 8 December 2004; accepted 3 March 2005; published online 19 April 2005)

A simple method based on the retroreflection on the fiber-optic end face is developed to measure the refractive index of a magnetic fluid in this letter. The measuring principle, accuracy, and sensitivity of this method are analyzed theoretically, and high precision and resolution can be achieved in principle. Experimental measurements are done to investigate the concentration and temperature dependent refractive index of the magnetic fluid. The linear dependence relation is obtained for both cases. The thermo-optical coefficient of the magnetic fluid is measured to be around $-2.4 \times 10^{-4}\ {}^\circ\mathrm{C}^{-1}$. © *2005 American Institute of Physics*. [DOI: 10.1063/1.1905808]

Magnetic fluid (MF) is a kind of stable colloidal dispersion of finely divided single-domain ferromagnetic nanoparticles in a suitable liquid carrier with the aid of surfactant, which was successfully synthesized in the 1960s.[1] Since then, the phase separation, agglomeration, dynamic, and magnetic properties of MF and colloid under external magnetic field have been studied extensively.[2–5] Little research on the optical properties of MF has been done until the late part of the 20th century.[6–11] Recently, the optical properties of MF have been emphasized by many researchers and some applications to photonic devices based on MF have been set forth by some authors, for example, optical switch,[12] light modulator,[13] tunable optical grating[8,9] and coarse wavelength-division multiplexing,[14] etc.

The methods for measuring the refractive indices of liquids can be classified into refraction technique and reflection technique (including total reflection).[15,16] Refractometer, which is based on the refraction of light, is broadly used to measure the refractive indices of liquids. But only the refractive indices of transparent or translucent liquids can be measured by this method. MF has a large absorption coefficient, so reflection method must be adopted. The reports about measuring the refractive index of MF are few until the year of 2002 when Yang *et al.* found a method to measure it successfully by total reflection technique.[17] While tens or hundreds of experimental data are needed to determine the critical angle, and then the refractive index. Moreover, a prism with refractive index higher than that of the MF is indispensable to meet the condition of total reflection. Their method also requires a high level of sophisticated instrumentation and elaborate optical alignment to hold the resolution and precision of measurement. In this letter, we will develop a method to determine the refractive index of MF, which is very simple, rapid, without loss of accuracy and sensitivity, and no upper limit on the magnitude of the refractive index of the MF exists. This method is optical alignment-free and only one experimental datum with two calibration data is needed to determine the refractive index of the MF.

When the light beam is incident onto an interface between two kinds of materials with different refractive indices, a portion of light will be reflected. For the absorbing and magnetic medium, the reflectivities of electric field amplitudes (r_p and r_s) are determined by the Fresnel reflection formulas (considering the light is incident from medium 1 onto the interface between medium 1 and medium 2):[16]

$$r_p = \frac{E_p'}{E_p} = \frac{\tilde{n}_2\mu_1 \cos i_1 - \tilde{n}_1\mu_2 \cos i_2}{\tilde{n}_2\mu_1 \cos i_1 + \tilde{n}_1\mu_2 \cos i_2}, \tag{1}$$

$$r_s = \frac{E_s'}{E_s} = \frac{\tilde{n}_1\mu_2 \cos i_1 - \tilde{n}_2\mu_1 \cos i_2}{\tilde{n}_1\mu_2 \cos i_1 + \tilde{n}_2\mu_1 \cos i_2}, \tag{2}$$

where E_p and E_s are the electric field amplitudes of p polarized (parallel to the plane of the incidence) and s polarized (perpendicular to the plane of the incidence) components of the incident light, E_p' and E_s' are the corresponding reflected amplitudes; $\tilde{n}_1 = n_1 - ik_1$ and $\tilde{n}_2 = n_2 - ik_2$ are the complex refractive indices of medium 1 and medium 2, n_1 and n_2 are their real refractive indices, k_1 and k_2 are their extinction coefficients ($k = \alpha/(4\pi\tilde{\nu})$, where α, $\tilde{\nu} = 1/\lambda$ and λ are absorption coefficient, wave number, and wavelength, respectively); μ_1 and μ_2 are the relative permeabilities of medium 1 and medium 2; i_1 and i_2 are the angles of incidence and refraction.

In order to eliminate the complex assembly of optical devices and optical alignment, we use a 3 dB "X" type single-mode fiber coupler to guide the incident light to the interface between fiber core and liquid under investigation and collect the backreflected light (Fig. 1). The fiber end face is flat cleaved and the condition of normal incidence is satisfied. For visible and infrared frequencies, the relative magnetic permeability μ is to be 1.[18]

As for our experiment, medium 1 is the fiber core with $\tilde{n}_1 = n_{fc} = 1.460$ and medium 2 the MF of interest with $\tilde{n}_2 = n_{mf} - ik_{mf}$, where n_{mf} and k_{mf} are the real refractive index and the extinction coefficient of the MF, respectively. Now, the total reflectivity of light intensity R can be written in the detailed form applicable to our experiment according to Eqs. (1) and (2):

[a]Electronic mail: shlpu@sjtu.edu.cn
[b]Electronic mail: xfchen@sjtu.edu.cn

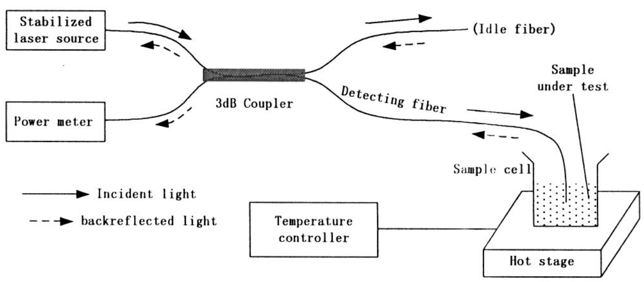

FIG. 1. Schematic diagram of experimental setup for studying the optical properties of MF.

$$R = |r_p|^2 = |r_s|^2 = \left|\frac{\tilde{n}_1 - \tilde{n}_2}{\tilde{n}_1 + \tilde{n}_2}\right| = \frac{(n_{\text{fc}} - n_{\text{mf}})^2 + k_{\text{mf}}^2}{(n_{\text{fc}} + n_{\text{mf}})^2 + k_{\text{mf}}^2}, \quad (3)$$

which is independent of the polarization state of the incident light. We can see from Eq. (3) that the refractive index of MF n_{mf} can be obtained given the values of R and k_{mf} are known. R is measured through the experiment and k_{mf} can be gotten by the relationship $k_{\text{mf}} = \alpha_{\text{mf}}/(4\pi\tilde{\nu})$. ($\alpha_{\text{mf}} = \alpha_0 c$, where α_0 is a constant and equals 9166.7 cm^{-1} for our MF[10]).

In nature, always does exist the intrinsic reflection in the experimental system. This may be assigned to the reflection from the idle fiber end face or the fusion conjunction between fibers and so on. So the actual reflected light intensity from the detecting fiber end face is undeterminable. While accurate determination of the refractive index of the sample under test requires accurate value of the reflectivity on the interface. Then, calibration procedure is necessary. Our calibration method involves measurements of the reflected light intensities when the detecting fiber tip is submerged into two samples with known refractive indices. We choose air and water as the samples for our calibration. The operating wavelength through our experiment is 1550 nm and the room temperature is 20 °C. The refractive indices of air and water can be calculated from the empirical equations given by Schmid and Penzkofer,[15] and Quan and Fry[19] to be $n_{\text{air}} = 1.000\,27$ and $n_{\text{water}} = 1.321\,91$ under one standard atmospheric pressure, respectively. The intrinsic reflection power P_0 can be achieved by the following relationship:

$$\frac{(P_{\text{water}} - P_0)S}{(P_{\text{air}} - P_0)S} = \frac{P_{\text{water}} - P_0}{P_{\text{air}} - P_0} = \frac{\left(\dfrac{n_{\text{fc}} - n_{\text{water}}}{n_{\text{fc}} + n_{\text{water}}}\right)^2}{\left(\dfrac{n_{\text{fc}} - n_{\text{air}}}{n_{\text{fc}} + n_{\text{air}}}\right)^2}, \quad (4)$$

where S is the effective sectional area of the fiber, P_{air} and P_{water} are the measured reflected powers when the detecting fiber tip is immersed in air and water, respectively. $n_{\text{air}} = \tilde{n}_{\text{air}}$ and $n_{\text{water}} = \tilde{n}_{\text{water}}$ are the refractive indices of air and water, respectively. With Eq. (4), the intrinsic reflection power P_0 can be obtained.

Similar to Eq. (4), the refractive index of MF can be derived to be

$$n_{\text{mf}} = \frac{\left[1 + \left(\dfrac{P_{\text{mf}} - P_0}{P_{\text{air}} - P_0}\right)\left(\dfrac{n_{\text{fc}} - n_{\text{air}}}{n_{\text{fc}} + n_{\text{air}}}\right)^2\right] n_{\text{fc}}}{\left[1 - \left(\dfrac{P_{\text{mf}} - P_0}{P_{\text{air}} - P_0}\right)\left(\dfrac{n_{\text{fc}} - n_{\text{air}}}{n_{\text{fc}} + n_{\text{air}}}\right)^2\right]} \pm \sqrt{\left\{\frac{\left[1 + \left(\dfrac{P_{\text{mf}} - P_0}{P_{\text{air}} - P_0}\right)\left(\dfrac{n_{\text{fc}} - n_{\text{air}}}{n_{\text{fc}} + n_{\text{air}}}\right)^2\right] n_{\text{fc}}}{\left[1 - \left(\dfrac{P_{\text{mf}} - P_0}{P_{\text{air}} - P_0}\right)\left(\dfrac{n_{\text{fc}} - n_{\text{air}}}{n_{\text{fc}} + n_{\text{air}}}\right)^2\right]}\right\}^2 - n_{\text{fc}}^2 - k_{\text{mf}}^2}, \quad (5)$$

where P_{mf} is the measured reflected power when the detecting fiber tip is immersed in the MF. Substituting P_0 getting from Eq. (4) into Eq. (5), we can get the refractive index of the MF of interest. From Eq. (5), we know that there are two calculated values of refractive index corresponding to one value of measured reflected power. While for water-based MF, its refractive index increases from the value of the refractive index of water with the concentration of the MF from zero or very diluted, so the physically relevant value must be selected.

In our experimental configuration (Fig. 1), the incident light is guided by an arm of the fiber coupler to the interface, and the reflected light is collected by the same fiber at the same location on the interface automatically. So the complex optical alignment is canceled. Furthermore, the incident light is almost normal to the interface and then the reflectivity is very insensitive to the incident angle according to Fresnel's law. Thus, small angle cleaves on the detecting fiber end due to technique deficiency does not influence the reflectivity. So measurement of the reflected power is accurate and reliable, and then the accuracy of the measurement of the refractive index is assured.

The sensitivity of this method can be gotten according to Eq. (5) and is given as

$$dn = \frac{\left(\dfrac{n_{\text{fc}} - n_{\text{air}}}{n_{\text{fc}} + n_{\text{air}}}\right)^2}{P_{\text{air}} - P_0} \cdot \frac{[(n_{\text{fc}} + n_{\text{mf}})^2 + k_{\text{mf}}^2]^2}{4 n_{\text{fc}}(n_{\text{fc}}^2 - n_{\text{mf}}^2 - k_{\text{mf}}^2)} \cdot dP, \quad (6)$$

where dP is the minimum change of power that the power meter can distinguish. For our experiment condition, the power meter is sufficient to distinguish the power change of $dP = 0.01$ dBm. It is apparent from Eq. (6) that the sensitivity for measuring refractive index depends on the sensitivity of the power meter, the refractive indices of the fiber core and the sample, and their difference. Substituting the rough refractive index of the MF and other known parameters into Eq. (6), the resolution in n_{mf} (dn) can reach the order of magnitude of 10^{-4}. In addition, a higher resolution of measurement is easy to be achieved when a higher sensitive power meter is available.

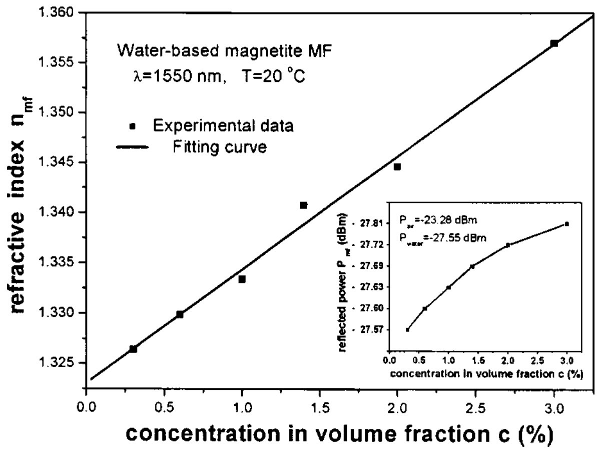

FIG. 2. Refractive index n_{mf} as a function of concentration c. The inset shows the measured reflected powers for various concentrations when the detecting fiber tip is immersed in the MF. P_{air} and P_{water} are the measured reflected powers when the detecting fiber tip is placed in the air and immersed in the water, respectively.

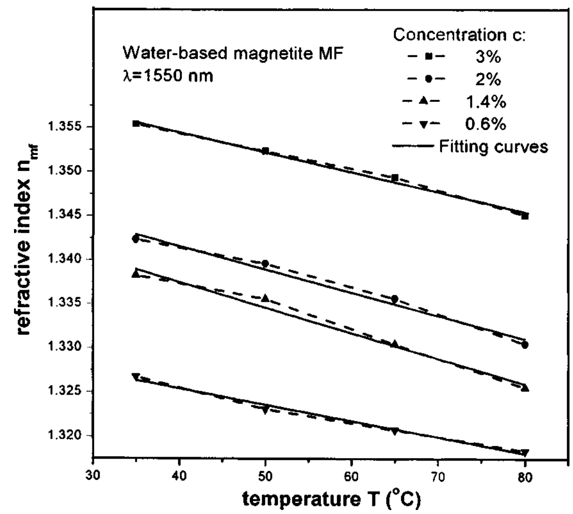

FIG. 3. Temperature dependent refractive indices of the MFs for various concentrations.

Figure 1 shows the schematic diagram of the experimental setup for measuring the refractive index of the MF. A stabilized laser is connected to one of the input ports of the coupler and emits low-power light at the wavelength of 1550 nm. The reflected light is back guided to the power meter by the 3 dB coupler. The MF is placed on the hot stage, and a temperature controller is attached to the hot stage to control the MFs temperature and study its thermo-optical characteristics. Through our experiment, the incident power on the interface is about −7.0 dBm. According to Du's and Luo's numerical calculation and our previous work, the largest temperature increase in the MF assigned to the energy of the laser is about 0.4 K.[5,6,10] So the influence of the temperature increase contributed to the laser energy on the refractive index of the MF is negligible.

Figure 2 draws the concentration dependent refractive index of the MF calibrated from the experimental data shown in the inset of Fig. 2. From Fig. 2, we can see that the refractive index of the MF increases linearly with the concentration. So it is easy to tune the refractive index of the MF by changing its concentration for some optical applications.

Thermal effect is a crucial factor as for the quality of the optical devices. Considering this aspect, we measure the refractive indices of the MFs at different temperatures for various volume fractions. Figure 3 depicts the refractive index of the MF as a function of temperature for various concentrations using the same calibration procedure as Fig. 2. As shown in Fig. 3, it is evident that the refractive index decreases with the temperature for a fixed concentration; and at a fixed temperature it increases with the concentration, which coincides with Fig. 2. The slopes of the linear fitting curves are the thermo-optical coefficients of the MF, which are about $-2.4\times10^{-4}\,°C^{-1}$.

Finally, we would like to point out that the measured refractive index is the value contributed to a small volume of the liquid in the vicinity of the fiber end face. So the spatial distribution of the refractive index of the inhomogeneous liquid can be determined. By this experimental configuration, it is easy to determine the dispersion properties of the MF or other liquids with a wavelength-tunable laser source. This method can be extended to measure other liquids whether their refractive indices are higher or lower than that of the fiber core.

In conclusion, we have measured the refractive index of the MF by the retroreflection on the fiber-optic end face successfully. Theoretical analysis shows that this method gives a high accuracy and sensitivity of measurement. In our experimental condition, the resolution of 10^{-4} in the measured refractive index of the MF is obtained. The linear dependence relation between the refractive index and the concentration or the temperature of the MF is acquired. The thermo-optical coefficient of the MF is measured to be about $-2.4\times10^{-4}\,°C^{-1}$.

This research was supported by the National Natural Science Foundation of China (Grant No. 60477016), the Foundation for Development of Science and Technology of Shanghai (Grant No. 04DZ14001), and the Program for New Century Excellent Talents in University of China.

[1]R. E. Rosensweig, *Ferrohydrodynamics* (Cambridge University Press, Cambridge, 1985).
[2]J.-C. Loudet, P. Barois, and P. Poulin, Nature (London) **407**, 611 (2000).
[3]S. A. Safran, Nat. Mater. **2**, 71 (2003).
[4]I. M. Jiang, M. S. Tsai, C. K. Lu, C. C. Shih, J. C. Chiang, and H. E. Horng, Appl. Phys. Lett. **84**, 245 (2004).
[5]W. Luo, T. Du, and J. Huang, Phys. Rev. Lett. **82**, 4134 (1999).
[6]T. Du and W. Luo, Appl. Phys. Lett. **72**, 272 (1998).
[7]S. Y. Yang, Y. P. Chiu, B. Y. Jeang, H. E. Horng, C.-Y. Hong, and H. C. Yang, Appl. Phys. Lett. **79**, 2372 (2001).
[8]H. E. Horng, S. Y. Yang, S. L. Lee, C.-Y. Hong, and H. C. Yang, Appl. Phys. Lett. **79**, 350 (2001).
[9]For a review, see H. E. Horng, C.-Y. Hong, S. Y. Yang, and H. C. Yang, J. Phys. Chem. Solids **62**, 1749 (2001), and references therein.
[10]S. Pu, X. Chen, W. Liao, L. Chen, Y. Chen, and Y. Xia, J. Appl. Phys. **96**, 5930 (2004).
[11]S. Pu, X. Chen, L. Chen, W. Liao, Y. Chen, and Y. Xia (unpublished).
[12]C.-Y. Hong, J. Magn. Magn. Mater. **201**, 178 (1999).
[13]J.-W. Seo, H. Kim, and S. Sung, J. Magn. Magn. Mater. **272–276**, e1787 (2004).
[14]Y. W. Huang, S. T. Hu, S. Y. Yang, H. E. Horng, J. C. Hung, C.-Y. Hong, H. C. Yang, C. G. Chao, and C. F. Lin, Opt. Lett. **29**, 1867 (2004).
[15]K. Schmid and A. Penzkofer, Appl. Opt. **22**, 1824 (1983).
[16]Y. Lu and A. Penzkofer, Appl. Opt. **25**, 221 (1986).
[17]S. Y. Yang, Y. F. Chen, H. E. Horng, C.-Y. Hong, W. S. Tse, and H. C. Yang, Appl. Phys. Lett. **81**, 4931 (2002).
[18]L. D. Landau and E. M. Lifshitz, *Electrodynamics of Continuous Media* (Pergamon, London, 1960).
[19]X. Quan and E. S. Fry, Appl. Opt. **34**, 3477 (1995).