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Transient optical phenomenon in ferrofluids

Chintamani Pai^{a*}, M. Shalini^b, Radha S.^a

^aDepartment of Physics, University of Mumbai, Vidyanagari, Santacruz (E), Mumbai 400098, India

^bUM-DAE CBS, University of Mumbai, Vidyanagari, Santacruz (E), Mumbai 400098, India

Abstract

In this paper, we report the experimental observation of diffraction patterns in a ferrofluid comprising of Fe₃O₄ nanoparticles in hexane by a 10 mW He-Ne laser beam. An external dc magnetic field (~1.7 kG) was applied perpendicular to the beam. Transient phenomenon in diffraction patterns is studied with and without magnetic field. Diffraction patterns showed a variation in both zero and applied magnetic field. This provides some information of non-linear optical properties and magneto-optical effects. Laser beam passed through a sample establishes refractive index gradient modifying the original Gaussian beam of the laser. Analysis of transient diffraction patterns can be used to study the parameters of ferrofluid like viscosity and thermal conductivity. This gives a new insight to understand the dynamics of the magnetic fluid and its potential use for the development of ferrofluid based sensors.

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Keywords: Thermal lensing, ferrofluid, diffraction pattern.

Nomenclature

n	refractive index of a liquid
T	temperature (K)
c	concentration (mg/ml)
r	radial distance from optical center of laser beam (mm)
z	distance variable in the direction of transmission of laser beam (mm)
t	time (ms)
D	mass coefficient
D _T	thermal coefficient
w ₀	waist beam radius of laser
k	thermal conductivity of a liquid
ρ	density of a liquid
c _p	heat capacity of a liquid

1. Introduction

Research in ferrofluids has been very active since its invention by NASA in 1965. Ferrofluids are colloidal suspensions made up of magnetic particles. Each tiny particle is coated with a surfactant to prevent aggregation. Over the years

* Corresponding author. Tel.: +91-9773597589; fax: +0-000-000-0000 .

E-mail address: chintupai@gmail.com

researchers working in the field of ferrofluids, have come up with diverse applications using ferrofluids. Behavior of ferrofluid under the influence of magnetic field has made it useful for several industrial and scientific applications [1-7]. These applications include ferrofluidic seals, dampers, speakers, heat transportation as well as magnetically guided drug delivery systems. There have been past studies probing the interaction of laser with ferrofluids. Optical transmission and scattering studies involving ferrofluids show their potential application to develop sensors [8-12]. Optical transmission studies of ferrofluids in external magnetic field have applications in developing magnetically tunable optical limiters, switches and optical gratings.

When a laser beam passes through a section of a liquid causing heating, it establishes a refractive index gradient. Due to this gradient, spatial phase modulation of laser beam occurs, causing it to self-focus or self-defocus. This phenomenon, termed as thermal lensing, has been studied by different groups [13-17]. Diffraction patterns due to thermal lensing has been observed in dispersions of carbon nanotubes [13-14], metallic nanoparticles [15] and in nematic liquid crystals [16]. Motivation for our study arises from earlier work on ferrofluids where extinction in the transmitted intensity of laser beam was observed in applied magnetic field [18-19]. In the current paper we explore the transient optical response of ferrofluids by studying the thermal lensing phenomenon.

1.1. Thermal lensing and ferrofluids

Gordon et al. have carried out a theoretical work on the interaction of laser with liquid samples [20]. Many papers have reported the thermal lens induced diffraction patterns in ferrofluid samples [21-25]. The phenomenon of diffraction due to thermal lensing is illustrated in figure 1a. Transmission of laser passing through a liquid sample establishes a refractive index gradient that depends upon the intensity of the incident laser beam. Laser transmission causes a local heating in a liquid, because of which thermal and concentration diffusion of particles occur. The self-defocusing or self-focusing nature of the thermal lens is determined by the change in refractive index being positive or negative, as shown in figure 1(b).

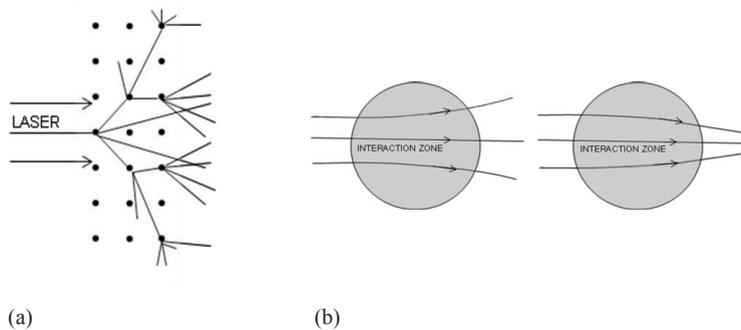


Fig. 1. Illustration of thermal lensing in a liquid leading to (a) diffraction pattern and (b) formation of thermal lens with self-defocusing effect or self focusing effect.

1.2. Interaction of laser with liquid samples

Diffraction patterns arising because of thermal lensing are studied in different conditions of varying carrier liquid, particle concentration, magnetic field etc. Following equations govern local heating caused by a laser in a liquid sample resulting in spatial phase modulation of a laser beam [20, 24, 25].

$$\delta n(r, z) = \left(\frac{\partial n(r, z)}{\partial T} \right) \delta T + \left(\frac{\partial n(r, z)}{\partial c} \right) \delta c \tag{1}$$

The refractive index gradient δn in the above equation has two components: due to thermal diffusion and other due to concentration gradient established within the sample liquid. Further, the temperature distribution arising due to local heating is given by,

$$\Delta T(r, t) = \frac{A w_o^2}{8k} \left\{ \exp i \left(- \frac{2r^2}{w_o^2} \right) - \exp i \left(- \frac{2r^2}{8 \left(\frac{k}{\rho c_p} \right) t + w_o^2} \right) \right\} \tag{2}$$

In the equation (2), temperature distribution profile $\Delta T(r, t)$ is a function of radial distance from optical center r and time t respectively. Due to above temperature distribution, there is a mass flux given by the following equation,

$$\frac{\partial c}{\partial t} = D\Delta c + D_T \nabla [c(1-c)\nabla T] \quad (3)$$

Based on the above equations, it is quite clear that temperature distribution within a liquid sample takes some time to attain equilibrium. Finally after equilibrium, steady state solution is of the form,

$$\Delta T(r) = \frac{Aw_o^2}{8k} \left\{ \ln \left(\frac{2\gamma a^2}{w_o^2} \right) - \frac{2r^2}{w_o^2} \right\} \quad (4)$$

Where γ and a are constants as discussed by Gordon et al [20]. In the present paper, we report the temporal dynamics of diffraction pattern in the transient regime based on the development of temperature profile till it reaches a steady state. This has been done in zero and applied magnetic field for a ferrofluid sample.

2. Experimental set-up

The transient response analysis has been carried out on a ferrofluid comprising of Fe_3O_4 nano particles (40 nm) in Hexane that was prepared by a chemical co-precipitation method. He-Ne laser beam (10 mW, 633 nm) was passed through a cuvette (path length 1 mm) containing a sample of ferrofluid (30 mg Fe_3O_4 per ml Hexane) in an experimental arrangement as shown in Fig 2(a). The transient diffraction pattern was studied by initiating the response using a manual shutter both in absence and presence of a magnetic field. In case of a magnetic field, a square wave pulse (40 sec) of magnetic field strength (~ 1.7 kG) was applied perpendicular to the direction of a beam. Diffraction patterns formed on a screen placed at about 200 cm from the sample were recorded by using CCD camera followed by video and image processing.

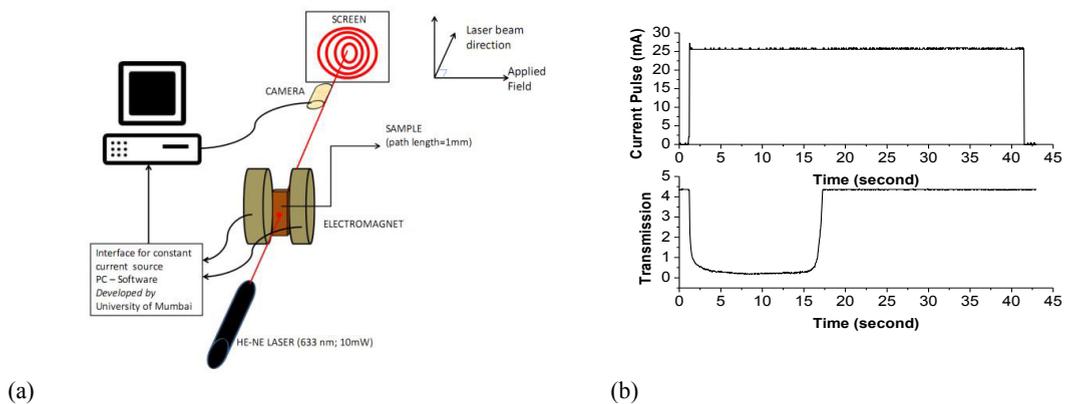


Fig.2. (a) Experimental set-up (b) Graph showing a square wave pulse and corresponding transmitted intensity.

In case of a magnetic field, the transient was studied after the recovery of transmitted intensity. The square wave pulse applied to magnet power supply and the response of the ferrofluid is shown in Figure 2 (b).

3. Results and discussion

In case of zero magnetic field, the transient diffraction pattern starts as a spot and develops gradually over a time duration (~700 ms) and then stabilizes. The diffraction pattern also develops a compression in the vertical direction. In applied magnetic field ~1.7 kG, the transient diffraction pattern again starts as a spot and develops gradually over a time duration (~700 ms) and stabilizes. However, a distinct difference in the pattern as compared to that in the absence of field is observed. Diffraction pattern remains nearly circular in the vertical direction. Figure 3 shows temporal variation in diffraction patterns arising due to transient thermal response in both zero as well applied magnetic fields. In both cases, it was observed that laser beam undergoes self-defocusing due to thermal lensing.

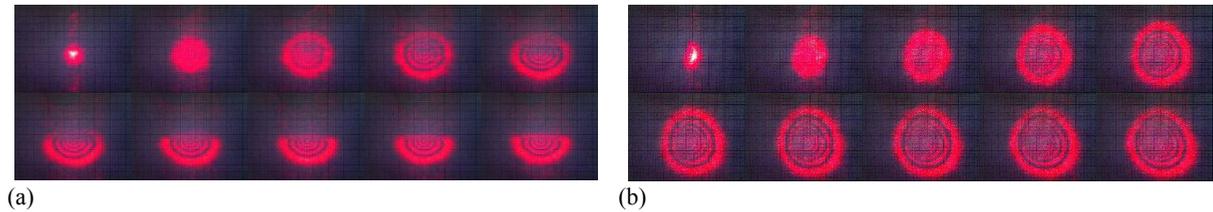


Fig.3. Set of images (from top left to right) showing temporal evolution (~70 ms interval) of diffraction patterns (a) Without magnetic field (b) With magnetic field.

Local heating causes a change in refractive index by setting up thermal diffusion and concentration gradient of particles. As laser starts heating up the ferrofluid instantaneously, it takes finite time for achieving dynamic equilibrium. Due to thermal conductivity and diffusion there will be a refractive index gradient which gets established in the medium. Nature of the refractive index gradient due to local heating is such that Gaussian laser beam undergoing transmission creates an interference pattern.

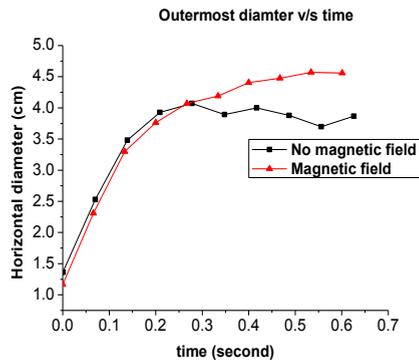


Fig.4. Variation in outermost diameter versus time in case of zero and applied magnetic field

With time, the influence of gravity having slower response time starts compressing diffraction patterns in vertical direction. Earlier reports have shown such vertically compressed patterns [13]. This paper reported that when the sample is kept in a horizontal position, no such compression has been observed (diffraction patterns appear in form of circular rings). The similar compression in diffraction patterns observed, when the sample is kept in vertical position, in zero magnetic field, is thus due to gravity effects. In the presence of applied magnetic field, compression of diffraction patterns is not observed over same time duration suggesting that magnetic field compensates the effect of gravity. Since applied magnetic field is known to have an effect or orienting the nano-particles, forming chains of nano-particles [26-29] within ferrofluid, gravity effect is reduced, resulting in better circular diffraction patterns. Our studies corroborate that chain formation taking place in presence of magnetic field, affects the transient response of the sample, resulting in circular diffraction patterns.

4. Conclusion

As Laser transmission through ferrofluid sample causes a local heating, evolution of diffraction patterns shows a definite thermal response time and correspondingly, changes in refractive index gradient. This relates to a thermal response of ferrofluid sample. Significant difference in transient diffraction patterns with and without magnetic field is observed. Time taken by diffraction patterns to attain final stability can be useful to differentiate ferrofluid samples having different viscosities, thermal conductivities and particle size. Number of rings observed and diameter of diffraction patterns with time can provide the information regarding the change in refractive index during the transient regime. This has potential application in developing ferrofluid based sensors and analyzing particle diffusion in small time scales.

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