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Suppressing the thermal lens effect by magnetic-field-induced mass transfer and phase separation in a magnetic fluid

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A method for suppressing the thermal lens effect in a magnetic fluid is proposed in this letter. When an external parallel magnetic field is applied, the thermal lens effect is weakened, and the degree of the divergence of the laser beam after passing through the magnetic fluid decreases. By experimental measurement and theoretical analysis, we assign this phenomenon to two physical mechanisms: the magnetic-field-induced mass transfer and phase separation in the magnetic fluid. With this method, the quality of the magnetic-fluid-based potential photonic devices can be improved. © *2005 American Institute of Physics*. [DOI: 10.1063/1.1996841]

Thermal lens effect originates from the heat energy absorbed by the material when a laser beam passes through.[1–3] In a pure liquid or solid, this heat changes the refractive index of the material contributed to the thermal expansion. While in a binary liquid mixture, the change of refractive index is usually assigned to the Soret effect, which dominates over the thermo-optical effect.[4,5] Many researchers have proposed the applications of thermal lens effect and the typical examples are the absorption coefficient measurement,[6] thermal diffusivity measurement,[7] and electric current sensors.[8] Marcano O. *et al.* have measured the absorption coefficients of liquids and solids as small as 10^{-8} cm^{-1} successfully by this effect.[9]

Magnetic fluid is a kind of stable colloid consisting of magnetic nanoparticles coated with surfactant and dispersed in a liquid carrier.[10] The phase separation, dynamic, and magnetic properties of magnetic fluid and colloid have been researched extensively.[11–24] Lately, with the dramatic development of photonic devices, the optical properties of magnetic fluid have been emphasized,[25–29] and its applications are extended to optics.[30–32] The thermal lens effect in a magnetic fluid is very notable and may be harmful to some pragmatic applications due to the divergence of the laser beam. Recently, Liberts *et al.* have proved that the thermal lens effect in the magnetic fluid can be suppressed by applying electric field.[33] In their experiment, high electric voltage is needed to produce a suitable electric field and the diffraction patterns become labyrinthine after applying the electric field. In this letter, we bring forward a new method for suppressing the thermal lens effect. By this means, we can control the divergence of laser beam and improve the quality of potential magnetic-fluid-based photonic devices.

The sample we use to study is liquid paraffin-based magnetite magnetic fluid with volume fraction of 1.26%. Because of the strong absorption of the magnetic fluid, thin film sample made by sealing the magnetic fluid into two parallel glass plates is used to study.[34] A 1.447 mW single mode He–Ne laser with a wavelength of 632.8 nm is employed. Figure 1 shows the layout of our experiment for studying the suppression of thermal lens effect in the magnetic fluid. A special electromagnet is introduced to the light path to generate a uniform horizontal magnetic field in the sample region. The strength of the magnetic field is adjusted by tuning the magnitude of the supply current. To eliminate the gravity effect, the sample is placed horizontally and the laser beam passes through the sample vertically by two mirrors. The emergent rays are divergent because of thermal lens effect and imagined on the screen. A charge-coupled device video camera is applied to photograph the diffraction patterns on the screen and the signals are transferred to the personal computer by an analog-to-digital converter. The transmitted light powers at different field strengths are measured by a power meter.

In the absence of magnetic field, the thermal lens diffraction patterns are observed on the screen several seconds after the shutter is open when the transferring of the magnetic particles in the magnetic fluid reaches a quasisteady state. When the magnetic field is applied, we can observe the reduction of the diffraction patterns and the transmitted light becomes dim. Figure 2 displays the typical quasisteady diffraction patterns at different applied magnetic field strengths: (a) 0, (b) 31.0, (c) 46.5, and (d) 88.2 Oe. We can see from Fig. 2 that both the diameters of the diffraction patterns and

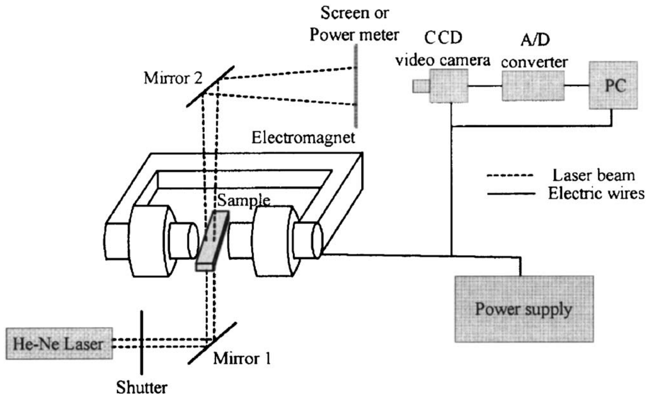

FIG. 1. Experimental layout for studying the suppression of thermal lens effect in a magnetic fluid by applying an external parallel magnetic field. The strength of the magnetic field is adjusted by tuning the magnitude of the supply current. The transmitted light powers at different field strengths are measured by a power meter.

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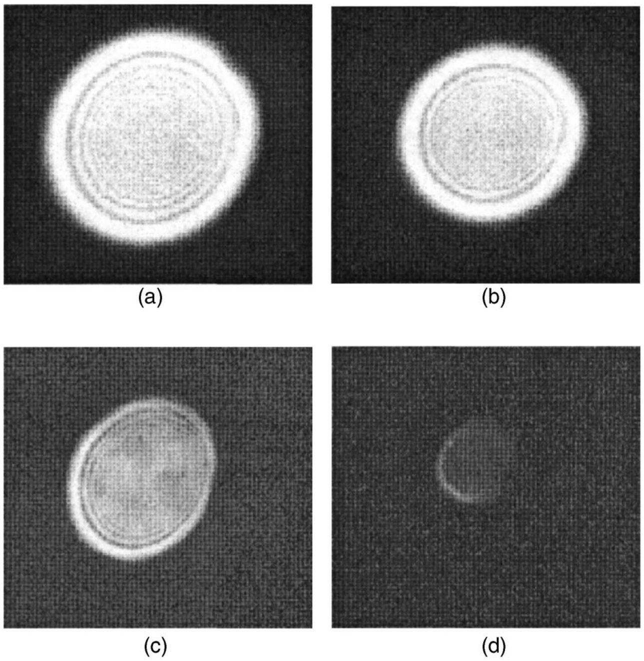

FIG. 2. Typical quasisteady diffraction patterns at different applied magnetic field strengths: (a) 0, (b) 31.0, (c) 46.5, and (d) 88.2 Oe.

the optical transmission decrease with the applied magnetic field strength.

The divergence angle θ is defined as the included angle between the outmost ray and the central ray of the laser beam after passing through the sample, which can be calculated by $\theta = \arctan[(R - r_0)/L]$. Where R and r_0 (about 0.79 mm in our experiment) are the radii of the diffraction patterns on the screen and the laser beam on the sample, respectively; L is the distance between the sample and the screen. The divergence angle θ as a function of applied magnetic field H is plotted in Fig. 3. The inset of Fig. 3 shows the relationship between the magnetic field strength and the applied current I.

It is shown in Fig. 3 that the divergence angle θ decreases with the magnetic field strength monotonically. In the low magnetic field region, the decrease is not obvious, while the decrease tends to saturate in the high magnetic field region.

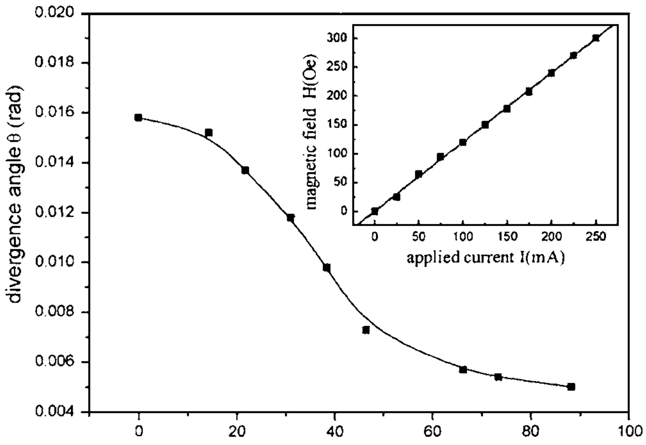

FIG. 3. Divergence angle θ as a function of applied magnetic field H. The inset shows the relationship between the magnetic field strength H and the applied current I.

By detailed analysis, we assign this phenomenon to two physical mechanisms, which degenerate the concentration gradient within the magnetic fluid: (1) Magnetic-field-induced mass transfer by additional magnetic body force on the magnetic particles; (2) magnetic-field-induced phase separation by the competition between the magnetic energies and the thermal energies of the magnetic particles.

In the presence of applied magnetic field, the magnetic body force arising from the magnetization of the magnetic particles exists in the magnetic fluid. Because the magnetization is temperature- and concentration-dependent, we rederive the magnetic body force density including these two factors. The magnetic body force density under the nonisothermal condition follows as

$$\mathbf{f}_m = -\nabla\left\{\mu_0 \int_0^{H'} [\partial(M\nu)/\partial\nu]_{H'} dH'\right\} + \mu_0 \mathbf{M}\cdot\nabla\mathbf{H}', \tag{1}$$

where $\mathbf{M}$ is the magnetization, $\mathbf{H}'$ the local magnetic field within the magnetic fluid, μ_0 the permeability in vacuum. $\nu = 1/\rho$ is the specific volume of the magnetic fluid and ρ is its mass density. The first term of Eq. (1) is due to the magnetization and magnetostriction of the magnetic fluid, while the second term is called Kelvin body force density $\mathbf{f}_k$ contributed to the magnetic field gradient within the magnetic fluid.

The direction of the external magnetic field $\mathbf{H}$ is parallel to the magnetic fluid thin film surface in our experiment. According to the boundary conditions of electromagnetic field, we can get the magnetic field in the magnetic fluid $\mathbf{H}' = \mathbf{H}$. Because $\mathbf{M}$ is parallel to $\mathbf{H}'$ within the magnetic fluid and $\mathbf{H}$ is uniform spatially, $\mathbf{f}_k = 0$ can be obtained. Now, Eq. (1) is reduced to

$$\mathbf{f}_m = -\nabla\left\{\mu_0 \int_0^{H} [\partial(M\nu)/\partial\nu]_{H} dH\right\}.$$

The small magnetic field is used in our experiment, so $\mathbf{M} = \chi(T,c)\mathbf{H}$ and $\chi(T,c)$ is the magnetic susceptibility of the magnetic fluid that follows Curie's law $\chi(T,c) \propto c/T$, where c and T are the concentration and temperature of the magnetic fluid, respectively. We can attain $\chi(T,c) \propto \rho/T$ with $\rho \propto c$. With these relationships, our calculation[35] shows that

$$\mathbf{f}_m \propto \frac{\mu_0 H^2 (\rho/T)^2 (\nabla T/T - \nabla\rho/\rho)}{\partial\rho/\partial T}. \tag{2}$$

Our previous work[34] reveals that T decreases with the transverse distance from the centered optical axis r, while ρ increases with r because of Soret effect. So both ∇T and $-\nabla\rho$ are radial inward. Taking account the negative value of $\partial\rho/\partial T$, we can know that the magnetic body force is radial outward according to Eq. (2).

It is also shown from Eq. (2) that the magnetic body force density $\mathbf{f}_m$ equals zero in the absence of magnetic field. So the quasisteady state is founded some time after the shutter is open. When the external magnetic field is applied, the magnetic body force occurs within the magnetic fluid, which is proportional to the square of the magnetic field strength. This breaks the initial quasisteady state and a new equilibrium state is established by the outside transferring of mass. The larger the magnetic field strength, the larger the magnetic body force. Moreover, the magnetic body force within

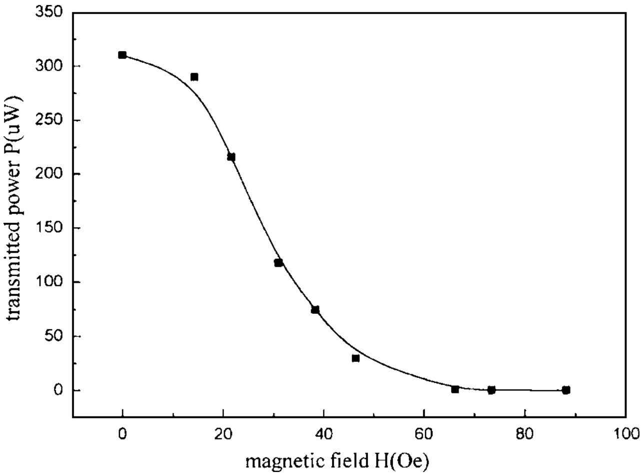

FIG. 4. Optical transmission as a function of magnetic field.

the magnetic fluid is inhomogeneous spatially with respect to *r*. This force degenerates the concentration gradient established by the laser-induced temperature field, and so the refractive index gradient is degenerated. Because the divergence angle is proportional to the refractive index gradient,[34] the divergence of the laser beam is suppressed. And then the suppression of thermal lens effect happens.

When the external parallel magnetic field is applied over some critical value, the magnetic energies of the magnetic particles exceed their thermal energies and the magnetic particles agglomerate to form chains. Yang *et al.* have proved that the magnetic-field-dependent optical transmission originates from the agglomeration of the magnetic particles that reduces the area of the liquid phase.[36] The larger the magnetic field strength, the more the chains are formed, and the fewer the area of the liquid phase, so the transmission is inversely proportional to the magnetic field strength. In order to verify the existence of agglomeration, we use a power meter to measure the transmitted powers after the laser passing through the sample at different magnetic field strengths. The optical transmission as a function of magnetic field is depicted in Fig. 4.

It is shown in Fig. 4 that the transmitted power decreases with the magnetic field strength. This decrease is contributed to the phase separation in the magnetic fluid. When the magnetic field increases, more chains are formed in the magnetic fluid thin film. This reduces the area of liquid phase and then the optical transmission.

It is well known that the thermal lens effect in a magnetic fluid is due to the laser beam induced configuration of the magnetic particles.[34] When the agglomeration exists, the phase separation degenerates the heat-induced configuration of the magnetic particles. So the thermal lens effect is suppressed. Moreover, the degree of phase separation increase with the magnetic field strength so the larger the magnetic field, the deeper the suppression. This phenomenon is observed in our experiment. It is worth pointing out that the phase separation does not occur when the magnetic field strength is below some critical value and it saturates at some high magnetic field as shown in Fig. 4 so the suppression should have the analogous trend. This is proved in our experiment and the result is shown in Fig. 3.

In conclusion, a new method for suppressing the thermal lens effect has been observed by the experiment in this letter. The physical mechanisms of this phenomenon are assigned to the magnetic-field-induced mass transfer and phase separation competitive with the heat-induced configuration of concentration within the magnetic fluid. The method can be used to control the divergence of the laser beam to improve the quality of the potential magnetic-fluid-based photonic devices.

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