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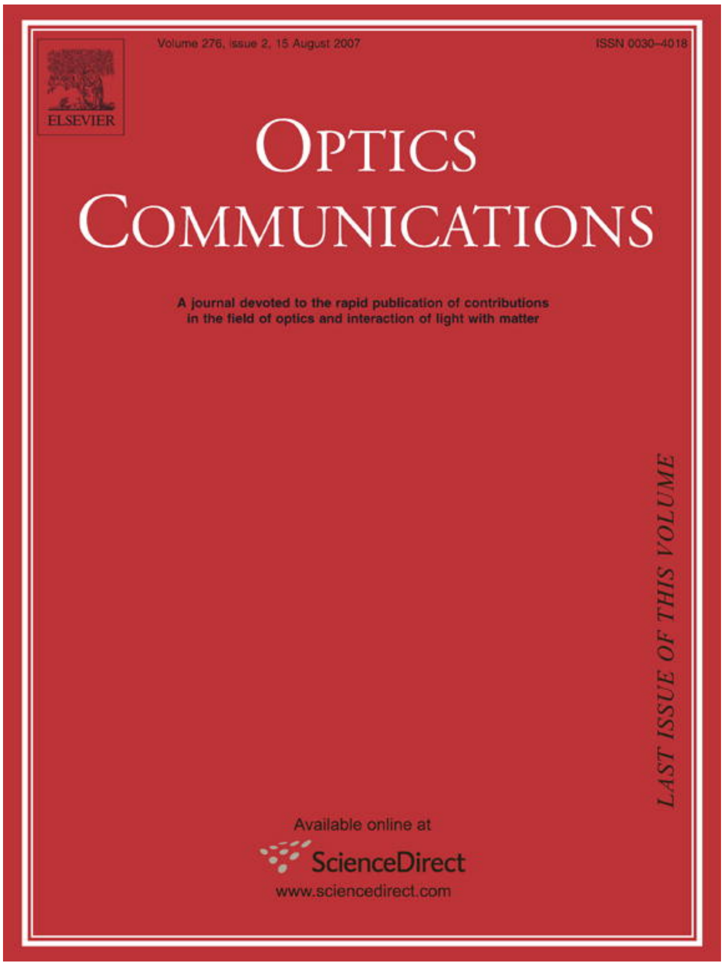

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Realization of optical limiting with a magnetic fluid film

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Abstract

In this paper, optical limiting property in a magnetic fluid film is studied. The relationship between the emergent power and the incident power is investigated experimentally and theoretically. It is found that the limiting threshold is linear with the diaphragm aperture which accord with the theoretical prediction. The external magnetic field will affect the limiting property, and increase the limiting threshold.

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Optical limiting occurs when the optical transmission of a material decreases with laser flux, which is desirable for protection of sensors and human eyes from intense laser radiation. Recently, many kinds of materials have been reported possessing the properties of optical limiting, for example, C_{60} [1], carbon nanotubes [2], gold nanorods [3] and some semiconductor nanoparticles [4–6]. In this paper, we will report the optical limiting property in a magnetic fluid.

Magnetic fluid (MF) is a kind of stable colloidal system composed of magnetic nanoparticles dispersed in a suitable liquid carrier [7]. The MF we usually use today was first synthesized in the early 1960s. The optical properties of MF have been studied intensively in recent years [8–11], and were suggested for use in optical devices, such as optical switch [12], tunable optical gratings [13,14], tunable optical fiber filters [15] and optical fiber modulator [16]. As it reported in Ref. [8], when a laser beam passes through the MF, it will make it act like a lens, and the divergence angle increase linearly with the incident power. When a diaphragm is put behind the MF, only the central part of the emergent laser, whose diameter is smaller than the diaphragm diameter, can pass through the diaphragm. Along with the increase of the incident power, the emergent power out from the diaphragm will decrease. Thus, we can form a simple optical limiting system by adding a diaphragm behind the MF.

The schematics of experimental setup for studying the optical limiting property in a MF film is shown in Fig. 1. The MF used in our experiment is olefin-based Fe_3O_4 MF, and the volume fraction is 1.26%. The MF is sealed in a sample cell made of two glass plates with a spacing of 50 μm. The sample is a thin cylinder like and the area of its cross section is much larger than the spot size of the incident laser, thereby the part far from the optical-centered axis is unaffected by the laser beam. In the experiment, a He–Ne laser with a wavelength of 632.8 nm is used. The variable attenuator is introduced in the light path to change the incident laser power on the sample. To eliminate the effect of gravitation, we put the sample horizontally, and use two reflectors to make the laser beam pass perpendicularly through the sample. If we put a screen at the far field behind the sample, we can see a laser spot on it. Along with the increasing of the incident power, the spot diameter increased and interference rings appeared. Fig. 2 displays the laser spots on the screen at different incident power.

Optical limiting is studied putting a diaphragm (instead of the screen) in the output light path (in our study, the optical path between the diaphragm and the sample is about 35 cm). When the incident power reaches to a certain

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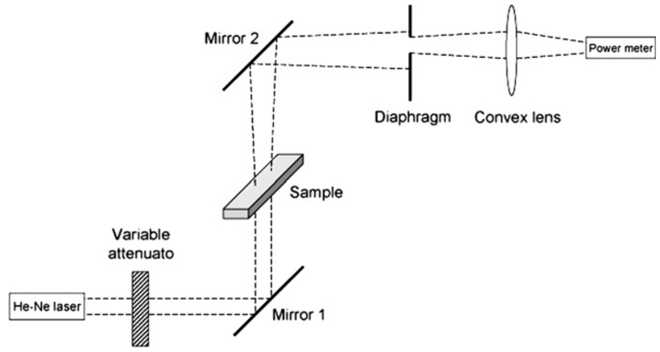

Fig. 1. The schematics of experimental setup for studying the optical limiting property in a MF film.

value, the spot diameter became larger than the diaphragm aperture, and the emergent power decreased. A power meter is put behind the diaphragm to measure the output laser intensity, and a convex lens is employed to put before the power meter to converge rays. In the experiment, a shutter is placed between the variable attenuator and mirror 1 to avoid the sample irradiated by the laser beam between two experimental data.

Fig. 3a–c shows the incident power changed with the emergent power at different diaphragm aperture, (a) 1 mm, (b) 2 mm and (c) 3 mm. We can get the limiting thresholds P_{th}, which defined as the incident power at which the emergent power begins to decrease, with different diaphragm apertures from Fig. 3 that, when $r = 1$ mm,

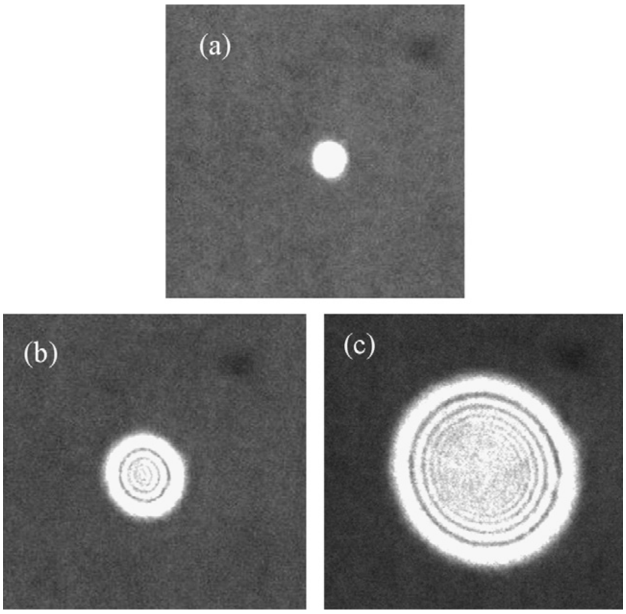

Fig. 2. Typical steady-state patterns at different incident power (a) 0.8 mW, (b) 2.9 mW and (c) 5.1 mW.

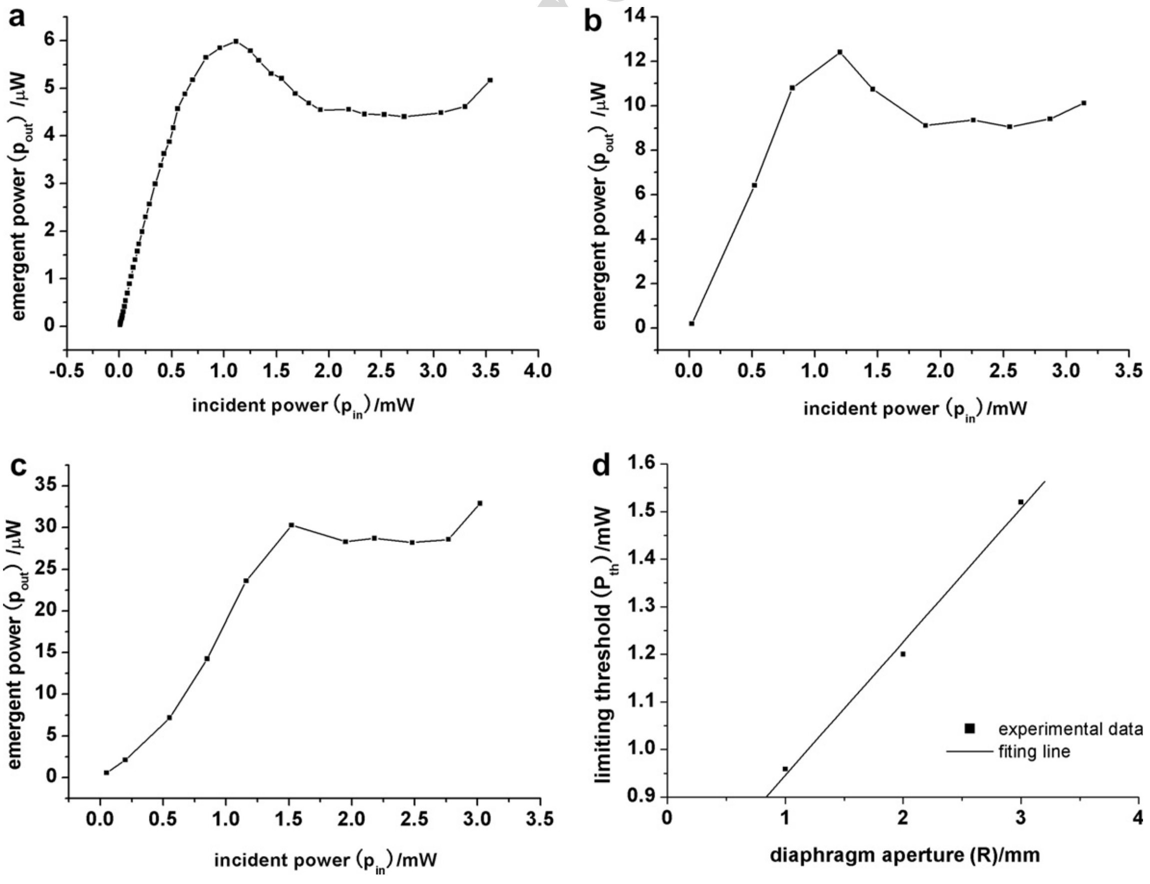

Fig. 3. Optical limiting curves of the MF with different diaphragm (a) $r = 1$ mm, (b) $r = 2$ mm, (c) $r = 3$ mm and (d) is the variation of limiting threshold with respect to diaphragm aperture for the MF.

$P_{th} = 0.959$ mW; when $r = 2$ mm, $P_{th} = 1.20$ mW; and when $r = 3$ mm, $P_{th} = 1.52$ mW. Fig. 3d shows how the limiting threshold varies with the diaphragm aperture. Evidently, the threshold is approximatively linear with the diaphragm aperture. It is shown in Fig. 3 that, when the incident power is lower than the threshold, emergent power increase linearly with the incident power. However, when the incident power is higher than the threshold, emergent power does not increase with the incident power, but decrease with it. As the incident power becomes higher, the emergent power increases again. This result accords with our study in Ref. [8], in which we concluded that the linear relationship between the divergence angle of the laser beam and the incident power is obtained in the low power range, and the convective currents happened at the high incident power will damage the linear relationship.

The maximal divergence angle (the included angle between the beam rays and the centered axis of the laser beam) of the laser beam passed through the MF can be expressed as [8]

$$\theta_{\max} \approx \frac{0.1083P}{\pi\kappa n_0 w_0}\left|\frac{dn}{dT}\right|(1 - e^{-\alpha L}) = BP, \qquad (1)$$

where w_0 is the spot radius of the laser beam on the MF (centimeter), κ and α are the thermal conductivity and the absorption coefficient of the MF. Their units are cal cm^{-1} s^{-1} k^{-1} and cm^{-1}. P is the total incident power (watts), L and n_0 are the thickness and the refractive index of the MF. T is the temperature. $\frac{dn}{dT}$ is the change of refractive index induced by the thermal expansion and concentration redistribution. So B is a constant depending on the MF and the spot size of the incident laser.

When the incident power reaches the threshold ($P = P_{th}$), the spot diameter on the diaphragm is equal to the diameter of the diaphragm aperture R. So $R = s\tan\theta_{\max}$, where s is the optical path from the sample to the diaphragm. And $\theta_{\max}$ is small enough, that we can obtain that $R \propto \theta_{\max}$. With Eq. (1) that $\theta_{\max} = BP_{th}$, we finally have $R = B'P_{th}$, where B' is a constant depending on the MF and the spot size of the incident laser. This equation shows that the limiting threshold is linear with the diameter of the diaphragm aperture and our experimental results fit well with this conclusion (see Fig. 3d).

We also made the theoretical simulation of the optical limiting curves as shown in Fig. 4, in which we used the parameter that, $\kappa = 7.56 \times 10^{-5}$ cal cm^{-1} s^{-1} K^{-1}, $\alpha = 120$ cm^{-1}, $L = 5 \times 10^{-3}$ cm, $n_0 = 1.5$ and $\omega_0 = 0.07879$ cm. It is fitted very well with our experimental results in Fig. 3.

When an external magnetic field is applied, the thermal lens effect will be suppressed [17]. The divergence angle and the transmission both decrease with the magnetic field

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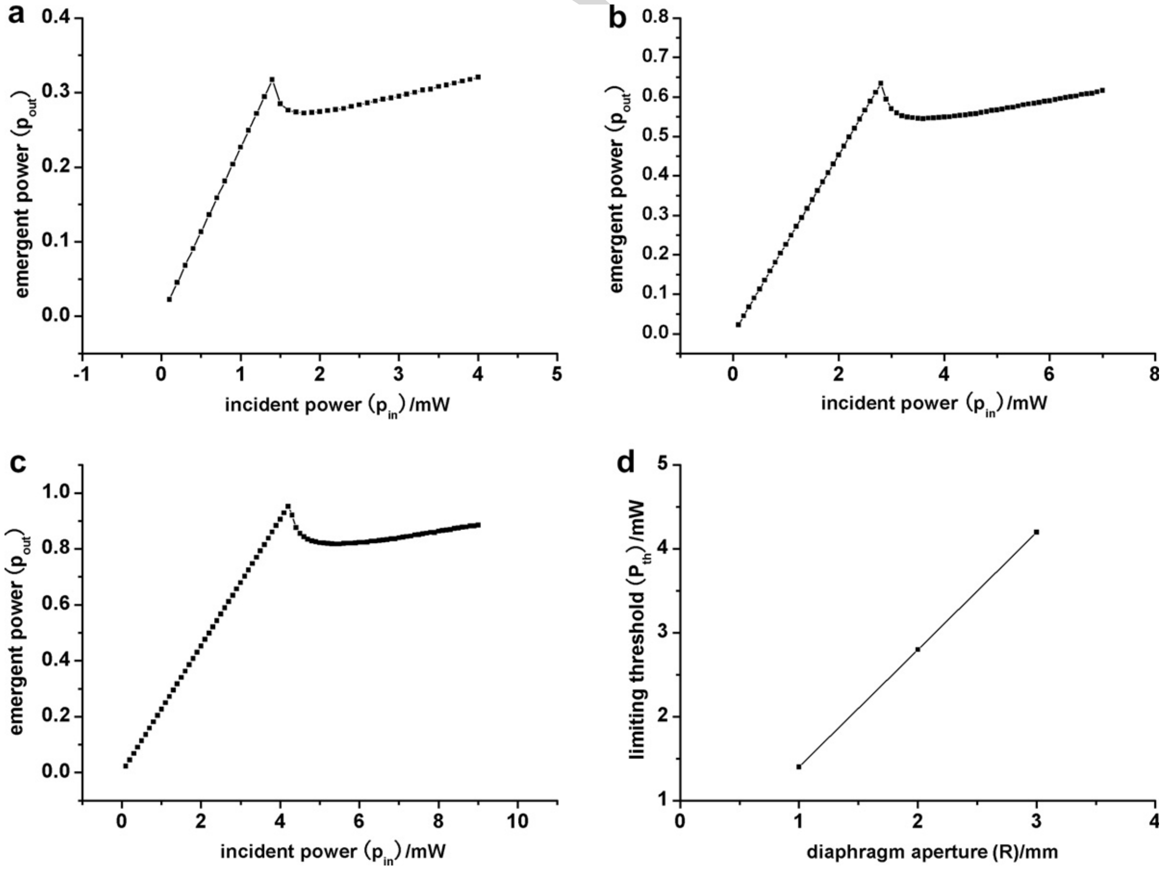

Fig. 4. Theoretical simulation of optical limiting curves of the MF with different diaphragm (a) $r = 1$ mm, (b) $r = 2$ mm, (c) $r = 3$ mm and (d) is the variation of limiting threshold with respect to diaphragm aperture for the MF (Where the emergent power is normalized).

strength monotonically. As a result, the limiting threshold power will be larger under an external magnetic field at the same diaphragm aperture, and increase with the magnetic field strength. When the external magnetic field is applied over some critical value, the phenomenon of optical limiting disappears.

In summary, we have investigated the optical limiting property in a MF film. When the incident power is larger than the limiting threshold, optical limiting appears. However, the emergent power increases again with the incident power when the incident power is too high. In addition, we obtain the conclusion that the limiting threshold is linear with the diaphragm aperture, and increase with the external magnetic field strength. The results presented in this paper maybe useful for designing the threshold-tunable optical limiter by a MF film.

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