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Generation and versatile transmission properties of ring-shaped beams based on thermal lens effect of magnetic fluids and ring-limited windows

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ABSTRACT

A simple method is proposed to generate ring-shaped beams via combining thermal lens effect of magnetic fluids and placement of ring-limited windows behind magnetic fluid samples. Far-field patterns of ring-shaped beams are simulated after the ring-limited windows. The relationship between the system parameters and the transmission parameters (describing the transmission properties of the system) are calculated and analyzed in detail. The results show that each transmission parameter is almost independent of one of the system parameters. The influence of magnetic fluid characteristic parameter on the transmission properties is also investigated. The results presented in this work may be very helpful for designing optical devices with high repeatability of performance for specific applications, such as power-tunable optical switch, optical attenuator and modulation depth amplifier.

1. Introduction

Ring-shaped beams have attracted extensive interest for a variety of applications in science and technology, such as trapping and guiding of cold atoms [1,2], manipulation of metal objects, [3] and laser writing and engraving [4]. There are several methods to generate ring-shaped beams, including rotated two or three cylindrical lens system [5,6], lens-axicon system [2], phase plate [7], multimode fibers [8], laser array [9] and computer-generated holograms [10]. However, it is usually troublesome to design and accurately operate such systems to generate ring-shaped beams. Furthermore, such methods can prove difficult when trying to finely tune the properties of ring-shaped beams (such as radiuses, widths and peak intensities).

Magnetic fluid (MF) is a kind of stable colloid composed of magnetic nanoparticles finely divided by coating particles with surface active agents dispersed in a suitable liquid carrier. Nowadays, MF is widely used for designing optical devices, such as optical switches [11], optical gratings [12,13], tunable optical capacitors [14], magnetic field sensors [15–17] and modulators [18–20]. Most of the above-mentioned applications are based on the magneto–optical properties of MF [21–23]. Research on the thermo–optical properties of MF is also conducted. Due to the strong thermal lens effect of MF [24], laser beams are converted into a series of toroidal beams after passing through the MF sample. It should be pointed out that the appearance of thermal lens effect is not only in the MF sample but also in the samples of some other materials with large thermo–optical coefficients [25,26]. Several applications and devices based on this property have been proposed, such as magnetic field sensing [27] and optical limiter [28]. If a ring-limited window is placed behind the MF sample, a ring-shaped beam is easily obtained. This will avoid utilizing a complex lens system to convert Gaussian or doughnut Laguerre–Gaussian beams into ring-shaped beams. In addition, the transmittance of the proposed configuration depends on many parameters and can be easily tuned, which can be successfully applied to design optical devices, such as power-tunable optical switch, optical attenuator and modulation depth amplifier. In this work, we will design a generation system of ring-shaped beams by employing a ring-limited window to let the specific toroidal rings pass through the system. Versatile transmission properties of the system are demonstrated by computation.

2. Generation of ring-shaped beams

When the Gaussian laser beam passes through the MF sample, the sample will absorb part of the laser beam's energy due to the relatively large absorption coefficient of MF compared to other nonmagnetic colloid. This will heat the sample non-uniformly across the cross-section of the beam assigned to the Gaussian intensity distribution of the beam. The temperature gradient along the radial direction then appears. In addition, the magnetic particle concentration within the MF sample will be redistributed

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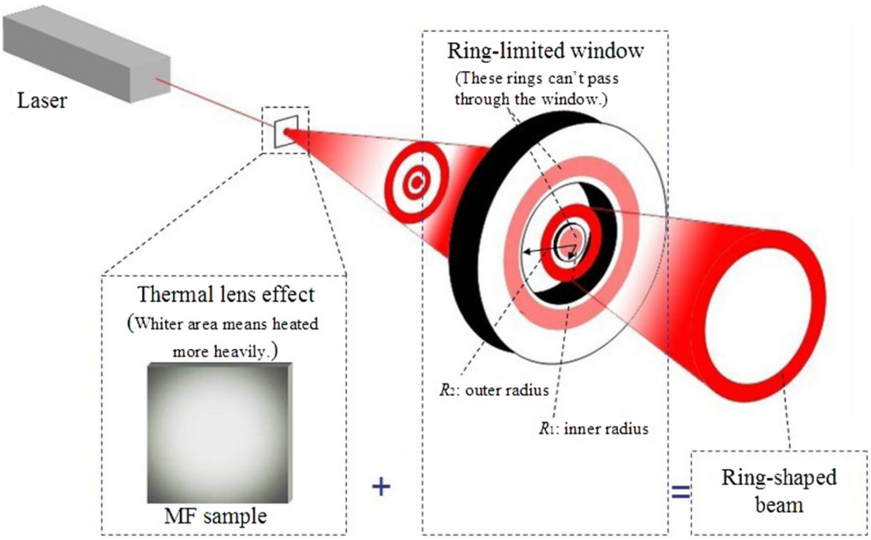

Fig. 1. Schematic of the system for generating ring-shaped beams.

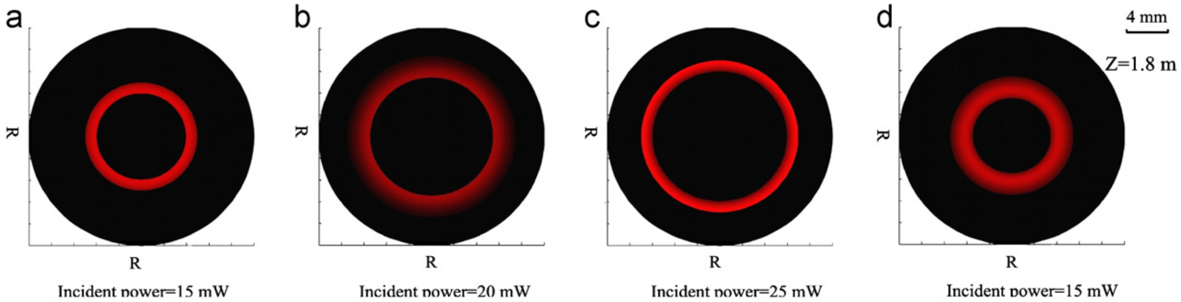

Fig. 2. Typical ring-shaped beams simulated at $Z=1.8$ m and different values of incident power, R_1 and R_2: (a) 15 mW, $R_1=4$ mm and $R_2=5$ mm; (b) 20 mW, $R_1=4.5$ mm and $R_2=7.5$ mm; (c) 25 mW, $R_1=6$ mm and $R_2=7$ mm and (d) 15 mW, $R_1=3.5$ mm and $R_2=5.5$ mm.

and assigned to Marangoni forces [29]. Both of these will contribute to creating a ‘lens’ as a result of different changes of the refractive index along the radial direction within the MF sample. Then, the output beam will be diverged into a series of beams with different output angles, which will interfere with each other behind the MF sample. The concentric rings in the far field behind the MF sample will emerge. According to the Kirchhoff diffraction integral, the intensity spatial distribution of the concentric rings is given as [28,30–32]

$$I(R,Z)=\left(\frac{k_0}{Z}\right)^2 I_0\left|\int_0^{\infty}\left\{rJ_0\left(\frac{k_0Rr}{Z}\right)\exp\left(-\frac{2r^2}{w^2}\right)\exp\left[-i(\phi_L+\phi_{NL})\right]\right\}dr\right|^2, \tag{1}$$

where R and Z are the radius in the far field and the distance between the sample and the ring-limited window. k_0, I_0 and w, respectively, are the incident laser wave vector, on-axis intensity and radius of the beam waist on the sample. J_0 is the zeroth-order Bessel function of the first kind. Φ_L and Φ_{NL} are the intensity-independent diffractive and intensity-dependent nonlinear phases respectively.

If a ring-limited window with a finely adjustable radius and width is placed behind the sample, ring-shaped beams will be obtained. Fig. 1 schematically shows the system for generating ring-shaped beams. The ring-limited window can be made by placing a light barrier in the center of an aperture. The inner and outer radiuses (R_1 and R_2) of the window and the distance between the sample and the window (Z) can be adjusted. The beams passing through the sample are changed into a series of rings. Only one or several of them can be transmitted by the window, while the central and outer rings are blocked by the limiter. By controlling the width and position of the ring-limited window, a single ring can be obtained. On the other hand, generation of ring-shaped beams with different radiuses, widths and peak intensities is also possible by properly selecting the system parameters (R_1, R_2 and Z). Fig. 2 shows several typical ring-shaped beams simulated at different parameters, wherein $Z=1.8$ m, $w=6.82\times10^{-4}$ m and $k_0=9.924\times10^{6}$ m^{-1}.

3. Versatile transmission properties

The output laser's power of the system can be written as

$$P=\int_0^{2\pi}d\theta\int_{R_1}^{R_2}I(R)2\pi Rd\,R \tag{2}$$

Combining Eqs. (1) and (2), the transmittance of the system can be obtained. For convenience, $R_0=(R_1+R_2)/2$ and $\Delta R=R_2-R_1$ are defined, which are closely related to R_1 and R_2. Fig. 3 plots the transmittance of the system as a function of incident power at different values of Z. The corresponding typical simulative transmitted patterns are shown in the insets. It is clear in Fig. 3 that the transmittance stays at zero for the low incident power range and starts to increase to a maximum when the incident power is large enough. Afterwards, the transmittance decreases and tends to approach a steady value along with some tiny fluctuations with a further increase of incident power. At low incident power, the