Generation of a hollow laser beam by a multimode fiber

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A simple method to generate a hollow laser beam by multimode fiber is reported. A dark hollow laser beam is generated from a multimode fiber and the dependence of the output beam profile on the incident angle of laser beam is analyzed. The results show that this hollow laser beam can be used to trap and guide cold atoms.

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Hollow laser beams can be used to trap and guide atoms[1], create optical trap[2] and confine cold atoms[3]. This kind of beams can also be used to manipulate micro-subject. Hollow blue-detuned laser beams, which provide radial confinement, are particularly interesting and versatile for the construction of atomic dipole traps. There are many methods to generate hollow laser beams, such as evanescent wave[4,5], computer-generated hologram[6,7], holey fiber[8], axicon[9,10], resonators with diffraction optical elements[11] and so on[12]. The method of the evanescent wave can produce very powerful dipole trap near the face of medium. But the interaction region is speckle (micron degree) and is limited by the shape of medium. The computer-generated hologram or axicon is hardly fabricated and the core of the beam generated by this method is not completely dark. The holey fiber to generate hollow beams has the low coupling efficiency of 50%. The method of inserting the diffraction optical elements into laser resonator may change all the optical system. So this method to generate hollow beam is limited in application. In the present study, we use a simple method to generate a hollow laser beam based on commercial multimode fibers. The multimode fiber is easy to be obtained and has as high as 80% coupling efficiency. The hollow beam from multimode fiber has completely dark core and such dark core hollow beam is useful in guiding and trapping cold atoms.

Our experimental setup is shown in Fig. 1. A laser diode (LD) with total power of 5.2 mW is focused by a lens L with focal length of 60 mm, and the incident angle θ between the laser beam and the axis of the fiber can be changed during the experiment. The focusing beam is collimated by a collimation lens (CL) with focal length of 4.5 mm before being coupled into the fiber, the length of fiber is 2 m. The output beam patterns are observed and recorded at 5 mm away from the end of the fiber by charge coupled device (CCD) arrays.

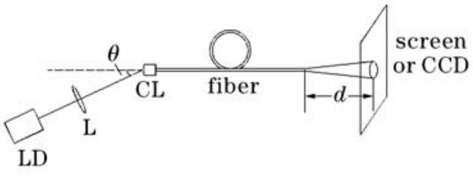

Fig. 1. Experimental scheme.

The output patterns observed by CCD arrays for different incident angles are shown in Fig. 2. We first adjust the incident angle of the laser beam to match the axis of the fiber. At this position the output beam is a disk shape as shown in Fig. 2(a). Changing the incident angle θ of the laser beam leads to a series of different patterns of the output beam. When the incident angle is $\theta = 0.6°$, a dark spot appears at the center of the pattern of the output beam. The size of the dark spot increases when the incident angle increases. At the angle of 1.19°, the diameter of the dark spot at the center is comparable with the width of the ring, which gives an

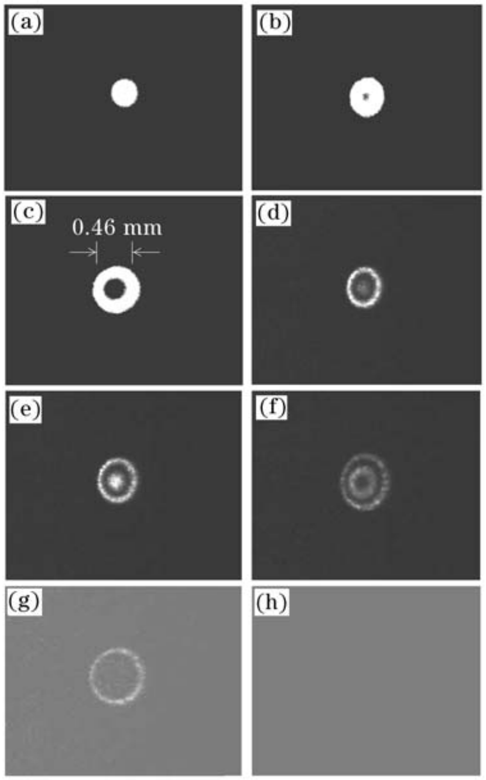

Fig. 2. Different output beam patterns for the different input angles with (a) 0°, (b) 0.6°, (c) 1.19°, (d) 1.31°, (e) 1.42°, (f) 1.59°, (g) 1.62°, (h) 2.78°, respectively.

almost perfect hollow beam, as shown in Fig. 2(c). When the angle increases further there is a misty light spot in the ring core and intensity of the output beam becomes dimmer. There is a bright spot at the center of the ring as the angle is increased to 1.42°. The double ring appears at 1.59° as shown in Fig. 2(f), and the pattern is changed into a ring again at 1.62°. Finally there is no output at the angle larger than 2.78°. When the incident angle increases, the coupling efficiency for the total output power decreases. The coupling efficiencies are 91%, 80%, 87%, 78%, 56%, 19%, 13%, 0% corresponding to Figs. 2(a)—(h) respectively.

These phenomena can be explained by the transmission of laser beam in a parabolic index of the multimode fiber core. The refractive index distribution of parabola fiber is described as

$$n(r)^2 = n_1^2[1 - 2\Delta(r/a)^2], \qquad r < a, \tag{1a}$$

$$n(r)^2 = n_{\mathrm{cl}}^2, \qquad r > a, \tag{1b}$$

where r is the radial coordination, n_1 is the refractive index of the fiber core, a is the radius of the fiber core, $\Delta = (n_1^2 - n_{\mathrm{cl}}^2)/(2n_1^2)$, and n_{cl} is the index of cladding.

The transition of the ray in the fiber obeys the ray equation. There are two kinds of rays in the fiber. One is the meridian ray and the other is the skew ray. The meridian ray travels in the meridian plane and the meridian plane is all the section crossing with the axis of the fiber and being vertical to the fiber wall. In the experiment, the laser transition in the fiber is meridian ray. From the ray equation we can get the radial kinetic equation of meridian ray as[13]

$$g(r) = n^2(r) - \bar{I}^2/r^2 - \bar{n}^2, \tag{2}$$

where $\bar{I}$ is the angular ray constant and $\bar{n} = n(0)\cos(\pi - \theta)$ is the index constant. When $\bar{n}$ satisfies the condition of $n_{\mathrm{cl}}^2 < \bar{n}^2 < n_1^2$ and r is in the range of $0 \le r \le a$, there will be two extreme points r_{g1} and r_{g2} which are the solution of $g(r) = 0$. So the ray should be confined in the annulus of $r_{g1} \le r \le r_{g2}$. This is the reason that we got annulus output in the experiment. We can get

$$\arccos 1 < \theta < \arccos \frac{n_{\mathrm{cl}}}{n_1}. \tag{3}$$

With the parameters of a typical multimode fiber used in the experiment: $a = 0.3$ mm, $n_1 = 1.457$, $n_{\mathrm{cl}} = 1.440$, Eq. (3) should be $0 < \theta < 8.59°$. But in the experiment there is no output under the condition of $\theta > 2.78°$. One possible reason is that the laser power is low (milliwatt degree). The other possible reason is that the off-axis rays will travel relatively a much longer distance and encounter more reflections than the axis rays. Each reflection incurs loss and gives a fixed attenuation per length, so the rays at larger angles will attenuate more. Then we cannot get any result when $\theta > 2.78°$.

Figure 3 is the experimental result of the far field intensity distribution with ring intensity profile at the incident angle of 1.19°. Figure 3(a) is the intensity distribution recorded by the CCD array, Fig. 3(b) is the corresponding output beam pattern, and the dot of Fig. 3(c) is the intensity distribution profile along the x axis through the center of the ring, and the solid curve is the fitting results using a double Gaussian function. We find that the intensity distribution of the ring is asymmetry and the core of ring is completely dark. When the incident beam has an angle with the axis of the multimode fiber, the intensity of laser beam in the fiber is asymmetry, which is partially kept at the output. This problem can be solved by inputting two beams at the incident angles of θ and $-\theta$, respectively.

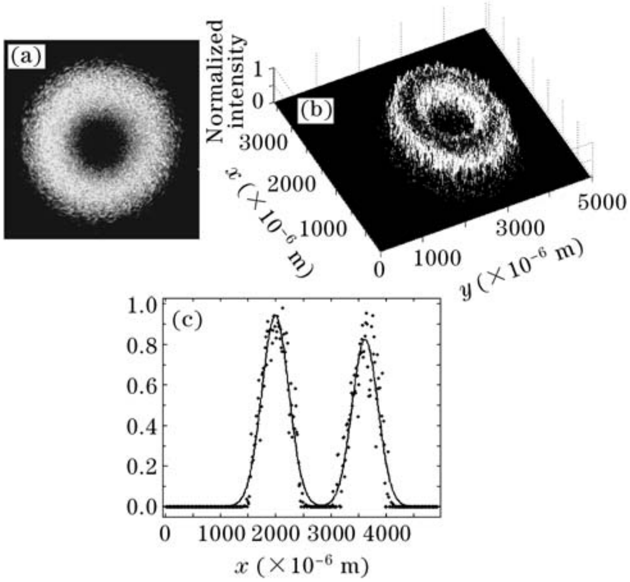

Fig. 3. Far field intensity distribution of the ring beam. (a) The picture of the beam; (b) x-y plane intensity distribution of the beam; (c) x axis intensity distribution.

In the experimental setup, the far field divergence angle of the output beam is 0.126 rad. In order to build an optical trap or an atom guide, we insert two lenses with short focal length of 4.5 and 30 mm in the path of hollow laser beams. Assuming that the distance between the end of the fiber and the first lens is d_1 and separation between two lenses is d_2, by adjusting the distances d_1 and d_2, we can get different diameter rings. For example, when $d_1 = 4.5$ mm and $d_2 = 60$ mm, we get 15-mm-long parallel hollow beam with diameter of 1.30 mm and the darkness size 1.01 mm. Such parallel hollow laser beams are very helpful in our optical molasses experiment. We use the hollow laser beam together with the moving molasses technique to move the cold atomic cloud from the cooling region to the probing region. The hollow beam can reduce the cold atom diffusion and increase the signal-to-noise ratio. We will add such hollow beam in our next optical molasses experiment.

In summary, we used a simple method to generate a hollow laser beam based on a commercial multimode fiber. A Gaussian laser beam transition in a multimode fiber can be translated into a double Gaussian hollow beam whose inner region is completely dark. Such hollow beams can be used to build optical traps for atoms and tweezers for manipulation of micro-objects. And it also can be used as an atom lens or guiding atom. In addition, hollow laser beams with appropriate polarization patterns can generate optical vortices.

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