GENERATION OF PARTIALLY COHERENT OPTICAL TRAP FOR ATOM TRAPPING

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Abstract: Atom trapping through optical beams is a great area of current research. In this paper, we demonstrate particle trapping scheme using partially coherent optical bottle beam. The partially coherent optical bottle beams are produced by using different combinations of annular aperture and lens. The scheme is based on our recent experimental studies for partially coherent bottle beams.

1. INTRODUCTION

The use of neutral atoms for quantum information processing is a topic of great research interest. The quantum states of single atom can be manipulated by first localizing them in tightly confining traps. In the early stages of research in the field of atom optics, a focused red-detuned Gaussian laser beam was the first scheme chosen to trap cold atoms (or molecules) [1]. Optical dipole traps are based on the force experienced by the atoms in a far detuned radiation field. This scheme limits trap lifetime as the atoms are confined in the region where the intensity reaches its maximum. Since the atoms spend most of their lifetime in strong radiation field, the energy levels of the atoms are very much disturbed by the ac Stark effect.

To overcome the problems in atom trapping using red detuned focused Gaussian laser beam, blue detuned laser beam was used. Here, atoms are confined in the region where the intensity is minimum thus sometimes referred as dark trap. One of the examples of blue detuned laser beam is bottle beam. A bottle beam is a special kind of optical beam in which the dark focus is surrounded by the regions of higher intensity [2]. The dark trap (bottle beam or blue detuned laser beam) has several advantages over the bright trap (red detuned laser beam). For instance, in the dark trap, the atoms (or other trapped particles) are held in the area of low intensity and therefore scatter fewer photons when compared to a bright trap of the same depth. It significantly decreases the atomic heating and decoherence rates. In addition, the trap induced ac Stark shifts are also minimized.

Various approaches have been demonstrated so far to generate bottle beams, using elements such as special phase mask [3], amplitude mask [2] and a bimorph adaptive mirror [4], by focusing two identical Gaussian beams with opposing radii of curvature using an interferometer [5] and by focusing of super Gaussian beams using lens axicon system [6]. All these techniques are applicable for the generation of spatially completely coherent bottle beams. Meanwhile, some investigations emphasize that the partially coherent light has advantages over spatially completely coherent light due to their low sensitivity to speckle, etc. [7-9]. Until now, few papers have dealt with the potential applications of partially coherent light in atom optics and optical tweezers [7-9]. Recently, some interesting studies have been carried out for the generation of partially coherent optical bottle beams both theoretically [10] and experimentally [11, 12]. Partially coherent bottle beam might have potential applications in particle trapping and to design optical tweezers. In this paper, we discuss the experiment and demonstrate mechanism to control the shape and size of the dark focus of bottle beam. The proposed scheme is cost effective and realizable. It may have potential applications in particle trapping of different sizes.

2. EXPERIMENTAL SETUP

The experimental setup to generate the partially coherent optical trap is shown in Fig. 1. The source S was a 5mW He-Ne laser which gives a Gaussian beam of wavelength \( \lambda = 632.8 \text{ nm} \). The Gaussian beam was focused by a lens L on to a rotating ground glass diffuser D, which makes the light spatially incoherent. A set of different lenses and apertures referred as lens aperture system (LAS) was placed at a distance \( d \) behind the rotating glass diffuser. After propagating a distance \( d \) in free space, the light incident on the lens aperture system plane (LASP) of LAS becomes partially coherent, and the degree of coherence of the light on LASP was evaluated by using van Cittert-Zernike theorem [19]. The schematic diagram of the LAS is shown in the inset of Fig. 1. The LAS consists of an annular aperture \( A_n \), a circular aperture \( A \) and two convex lenses \( L_1 \) and \( L_2 \) of focal lengths \( f_1 \) and \( f_2 \) respectively. Both the annular aperture and the circular aperture were made on photographic films. Each component of LAS was placed on-axis. The central obstruction \( \varepsilon \) of the annular aperture can be expressed as the ratio of \( b_o \) to \( a_o \): \( 0 < \varepsilon < 1 \), where \( b_o \) is the inner radius and \( a_o \) is the outer radius of the annular aperture. In this study, to change the central obstruction of the annular aperture, the outer radius was kept fixed (equal to 0.6mm), while the inner radius...
radius was varied. After passing through the annular aperture, the partially coherent light was focused by lens \( L_1 \) of focal length \( f_1 \).

\[
\tilde{L} = 3.832 \left( \frac{c f}{\omega a_s} \right),
\]

where, \( c \) is the speed of light, \( f \) is the focal length of the lens, \( \omega \) is the angular frequency of the incident beam and \( a_s \) is the outer radius of the annular aperture.

At the back focal plane of the lens \( L_1 \), a circular aperture \( A \) of radius \( a = 0.5 \) mm was placed to filter the zeroth order Bessel beam. The Bessel beam was then focused by the lens \( L_2 \) of focal length 15 cm. The aperture of the lens \( L_2 \) was kept much larger than the beam radius of the Bessel beam so that the diffraction by the lens aperture could be neglected. The spectral degree of coherence of the partially coherent beam in front of the lens \( L_2 \) can be expressed \([7, 10]\) as

\[
\mu^{(0)}(r_1 - r_2, \omega) = \frac{1}{1 - \varepsilon^2} \text{Besinc}[k|r_1 - r_2|b] - \frac{\varepsilon}{1 - \varepsilon^2} \text{Besinc}[k|r_1 - r_2|b]
\]

Here, \( \text{Besinc}(u) = 2J_1(u)/u \) and \( J_1(u) \) is the Bessel function of order unity, while parameter \( \varepsilon \) and \( b \) are two positive constants representing the spatial coherence properties of the partially coherent beam. \( k = \omega/c \) is the wave number associated with angular frequency, \( \omega \).

Theoretically, it has been demonstrated that intensity distribution in a focused field is dependent both on the intensity and on the spectral degree of coherence. It has also been discussed that if the spectral degree of coherence of the incident light is Bessel-correlated, local minima of intensity at the geometrical focus is generated \([16]\). Thus, desired intensity distribution could be achieved by modulating the spectral degree of coherence of the incident light. Since the incident light on the lens \( L_2 \) is Bessel correlated field whose spectral degree of coherence is given by Eq. (2), local minima of intensity is generated at its geometrical focus, thus forming optical beam with dark focus. At the back focal plane of the lens \( L_2 \), a CCD connected to a computer was used to record the generated partially coherent optical bottle beam.

### 3. RESULTS

The dark focus of the generated partially coherent bottle beam may act as an optical trap for trapping particles. Experimentally generated partially coherent optical bottle beams (dark optical trap) for different effective correlation lengths are shown in Fig. 2. The figure shows that how the size of the dark focus of the generated bottle beam changes with change in the effective correlation length of the light incident on the lens \( L_2 \). Thus optical traps of different sizes could be generated by changing the effective correlation length of the incident beam.
using different lenses $L_1$ of different focal lengths. In our study we used lenses of focal lengths $f_1 = 15, 20, 25$ and 30cm respectively. Other experimental parameters were $\lambda = 632.8\text{nm}$, $f_2 = 15\text{cm}$, $\varepsilon = 0.5$ and $a_e = 0.6\text{mm}$. Not only does the size but also the shape of the dark focus changes with the effective correlation length. It can be visualized from Fig. 2 that for smaller values of the effective correlation length, the shape of the dark focus is somewhat spherical. As we increase the effective correlation length, the longitudinal size of the dark focus increases rapidly than the transverse size, thus making the dark focus elliptical. The variation in the size of the optical trap with the change in the focal length of the lens $L_1$ (in turn change in the effective correlation length) is shown in Fig. 2(a)-(d).

It is found that the central obstruction of the annular aperture used in LAS also has significant impact on the size of the dark focus of the partially coherent bottle beam. By using the annular apertures of different central obstruction, different sizes of dark focus of the bottle beam could be produced, thus producing different sizes of optical traps. To study the effect of the central obstruction of the annular aperture, the annular apertures of different central obstruction were used. The observations were repeated for different $\varepsilon$, i.e. for $\varepsilon = 0.4, 0.5$ and 0.6 respectively. The effective correlation length was varied and the longitudinal width ($W_L$) and the transverse width ($W_T$) of the dark focus of the generated partially coherent bottle beam were measured. The other experimental parameters remain the same.

To exhibit the concept, the longitudinal width ($W_L$) and the transverse width ($W_T$) of the dark focus of the generated partially coherent bottle beam are plotted against the effective correlation length for each annular aperture.

Fig. 3 illustrates the dependence of the longitudinal width of the dark focus on the effective correlation length for the annular apertures of different central obstructions. It is evident from the figure that longitudinal width increases as the effective correlation length increases. Apart from it, as we increases the size of the central obstruction, the longitudinal width of the dark focus also increases.

Fig. 4 shows the variation of the transverse width of the dark focus with the effective correlation length for different central obstruction of the annular aperture. It shows that the transverse width of the dark focus also increases with the effective correlation length but the central obstruction of the annular aperture does not affect the transverse width significantly. The analysis reveals that the central obstruction of the annular aperture has significant impact on the longitudinal width of the dark focus while the transverse width remains almost unaffected with the change in the central obstruction of the annular aperture.

This is comparatively a simple approach to control the shape and the size of the dark focus of the bottle beam than other techniques. Thus, by changing the effective correlation length of the incident beam and the central obstruction of the annular aperture, dark partially coherent optical trap of different sizes could be produced. These types of optical traps may have number of applications in science and engineering.

**4. CONCLUSION**

In this study, experimental results of generation of partially coherent optical bottle beam are presented. The dark focus of the bottle beam may act as a dark trap for trapping particles. The size of the dark focus might be controlled by modulating the effective correlation length of the incident light as well as by
changing the central obstruction of the annular aperture. The scheme might provide a simple approach to generate dark optical traps of different sizes to trap different particles.

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REFERENCES


