# Generation of adjustable partially coherent bottle beams

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The experimental realization of partially coherent bottle beams is reported in this paper. It is shown that by controlling the coherence of the incident light we can generate the adjustable partially coherent bottle beams. The generated bottle beams may have applications in atom optics, and optical tweezers, etc..

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Recently there have been growing interests in the generation of a bottle beam, in which actually is a dark focus surrounded by regions of higher light intensity[1−8]. Such bottle beam has applications in optical tweezers and atom optics, e.g., in atom guiding, atom trapping etc[8]. In the early stage of research of atom optics, a focused red-detuned Gaussian laser beam is the first chosen scheme to trap cold atoms (or molecules). The optical dipole traps rely on the force experienced by the atoms in a far-detuned radiation field, and the atoms are confined where the intensity takes its maximum[9]. This limits the trap lifetime and moreover, as the atoms spend most of their time in a strong radiation field, energy levels are deeply disturbed by the ac stark effect. Another optical dipole trap scheme is based on a bottle beam[8]. It has been demonstrated that a bottle beam is an efficient scheme for trapping the cold atoms, in which the radiation field is detuned to the higher frequency side of an atomic transition, so that it is possible to confine the atoms in low intensity regions. Long trap coherence times and very little perturbations on hyperfine atomic levels can be achieved in blue-detuned optical dipole traps. We notice that almost the generated bottle beams are spatially completely coherent. The design and fabrication of the diffraction elements or optical systems for generation of bottle beams are well understood, but there are little attempts for generation of the partially coherent bottle beams, although it has been proved that the partially coherent light has advantages over the spatially completely coherent light[10−12]. It has been shown that the partially coherent light suffers less harmful effect, such as low sensitivity to the speckle etc, therefore the partially coherent bottle beams may have advantages over their counterparts of completely spatial coherence. In this letter we introduce a scheme for generating adjustable partially coherent bottle beams by use of spatial coherence effect.

The scheme for generating partially coherent bottle beams is shown in Fig. 1, in which a He-Ne laser delivers a Gaussian beam of wavelength $\lambda = 632.8$ nm, and the Gaussian beam is focused by a lens onto a rotating ground glass. The beam profile on the ground glass is Gaussian, i.e.,

$$I(\rho) = I_0 \exp\left(-\frac{2\rho^2}{w_0^2}\right), \tag{1}$$

where $I_0$ is a positive constant, denoting the on-axis intensity; $\omega_0$ is the beam width of the beam on the ground glass; $\rho$ is the module of the position vector $\boldsymbol{\rho}$ on the plane of the ground glass. We measured the beam width, and obtained $\omega_0 = 0.15$ mm. The light from the rotating ground glass can be viewed to be spatially incoherent. Based on van Cittert Zernike theorem, after propagating the distance $d$ in free space, the light reaching at an axicon becomes partially coherent[13]. The partially coherent bottle beams can be generated by the focusing of partially coherent light with the axicon-lens system. $z_0$ is the distance between the axicon and a focusing lens $L_2$. A charge coupled device (CCD) connecting to a computer is used to record the resultant bottle beams.

The degree of coherence of the partially coherent light on the axicon can be evaluated by van Cittert Zernike theorem as[13]

$$\mu(\Delta\mathbf{r}) = \frac{\int_0^\infty \exp(-\frac{2\rho^2}{w_0^2}) J_0(k\frac{\Delta\mathbf{r}}{d}\rho)\rho \mathrm{d}\rho}{\int_0^\infty \exp(-\frac{2\rho^2}{w_0^2})\rho \mathrm{d}\rho}, \tag{2}$$

where $J_0(\cdot)$ is the Bessel function of order zero. After straight calculus calculation, we can obtain

$$\mu(\mathbf{r}_1 - \mathbf{r}_2) = \exp\left[-\frac{(\mathbf{r}_1 - \mathbf{r}_2)^2}{2\sigma^2}\right], \tag{3}$$

where

$$\sigma = 2d/(kw_0) \tag{4}$$

is the effective coherent length. $\mathbf{r}_1$ and $\mathbf{r}_2$ are two position vectors on the axicon plane, and $\Delta\mathbf{r} = \mathbf{r}_1 - \mathbf{r}_2$. It is found from Eqs. (3) and (4) that degree of coherence of the partially coherent light in front of the axicon plane is of Schell-model type, the effective coherent length is dependent upon the wave number $k$, the beam width of the focused Gaussian beam on the ground glass, and the distance between the ground glass and the axicon. From Eq. (4), we find that the effective coherent length $\sigma$ is proportional to $d$ and inverse proportional to $w_0$. This indicates that the increase of $d$ (or the decrease of $w_0$) can result in the increment of $\sigma$. This may provide us a

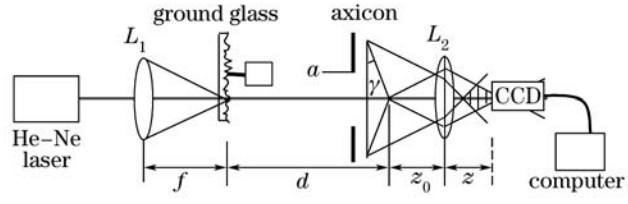


Fig. 1. Experimental setup for generating partially coherent bottle beams. A lens $L_1$ is employed to focus a Gaussian beam delivered from a He-Ne laser onto a rotating ground glass, and the scattering light in incident an aperture axicon, and focused by a lens $L_2$. $f_1$=35 mm, $\gamma$=2°, $a$ is the radius of the limiting aperture. $w_0$=0.15 mm.

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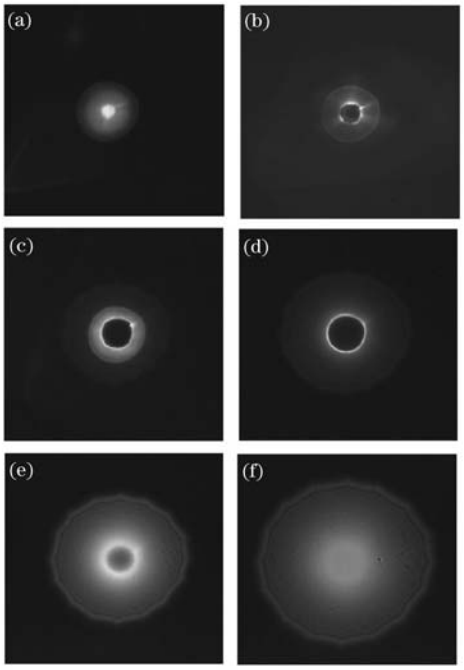


Fig. 2. Transverse intensity distribution across six positions of the focused region, showing that the partially coherent bottle beam was achieved. $f_1$=35 mm, $f_2$=35 mm. $w_0$=0.15 mm, $d$=142.8 cm, $\lambda$=0.6328 $\mu$m (resulting in the effective coherence length 1.9 mm). $\gamma=2^\circ$, $z_0$=31.5 mm, $n$=1.458, $a$=10 mm. The distances between the lens and the observed positions are (a) 30.0, (b) 31.5, (c) 33.0, (d) 34.5, (e) 36.0, and (f) 37.5 mm, respectively.

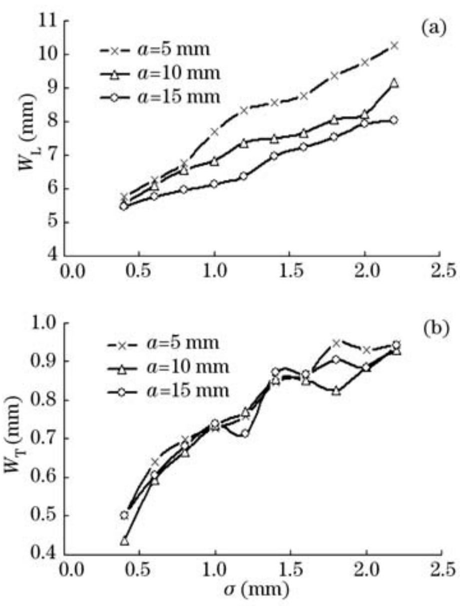


Fig. 3. (a) Longitudinal width $W_L$ and (b) transverse width $W_T$ of the bottle beam as functions of the spatially coherent length ($\sigma$) of the incident partially coherent light for three radii of the limiting aperture. $\lambda$=0.6328 $\mu$m, $w_0$=0.15 mm, $\gamma=2^\circ$, $f_1 = f_2 = 35$ mm, $z_0 = 300$ mm.

facile approach to change the spatial coherence of the incident partially coherent light, so that to achieve adjustable partially coherent bottle beams.

Figure 2 presents the transverse intensity distribution at six different $z$ planes, in which the partially bottle beam is produced. It is shown that the partially coherent bottle beam, the dark focus surrounded by regions of higher intensity, has been achieved. As we know, the partially coherent light is less sensitive to speckle, therefore the generated partially coherent bottle beam possesses advantage over the completely coherent one.

The size of the generated partially coherent bottle beam is an important parameter. In Fig. 3, we plot the longitudinal width $W_L$ (Fig. 3(a)) and the transverse width $W_T$ (Fig. 3(b)) of the bottle beam as a function of the spatially coherent length ($\sigma$) of the incident partially coherent light at three different limiting aperture radii. It is shown that both the longitudinal width $W_L$ and the transverse width $W_T$ increase with the increment of $\sigma$. It is also shown that the larger limiting aperture results in larger longitudinal width. From Fig. 3(b), we may find that the transverse width $W_T$ seems to be independent of the limiting aperture. This property can be found by ray-trace method of the geometrical optics, as given in Ref. [14]. This may provide us an approach to change the desired shape of the bottle beam.

In conclusion, we have experimentally generated partially coherent bottle beams. It is shown that by controlling the coherence of the incident light we can generate the adjustable partially coherent bottle beams. The generated bottle beams may have applications in atom optics, and optical tweezers, etc..

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