Experimental demonstration of an intensity minimum at the focus of a laser beam created by spatial coherence: application to the optical trapping of dielectric particles

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In trying to manipulate the intensity distribution of a focused field, one typically uses amplitude or phase masks. Here we explore an approach, namely, varying the state of spatial coherence of the incident field. We experimentally demonstrate that the focusing of a Bessel-correlated beam produces an intensity minimum at the geometric focus rather than a maximum. By varying the spatial coherence width of the field, which can be achieved by merely changing the size of an iris, it is possible to change this minimum into a maximum in a continuous manner. This method can be used, for example, in novel optical trapping schemes, to selectively manipulate particles with either a low or high index of refraction. © 2010 Optical Society of America

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The intensity distribution of a wave field in the focal region of a lens is a classical subject of physical optics [1]. One can manipulate this distribution by employing phase or amplitude masks. Recent theoretical studies showed that the state of spatial coherence of the field can also be used for this goal [2–8]. It was found, for example, that partially coherent, Gaussian-correlated beams produce a focal intensity distribution that is more spread out than that of a fully coherent beam [9]. Two studies of Bessel-correlated fields yielded the surprising prediction that it is possible to change the maximum intensity at the geometric focus into a minimum in a continuous manner [10,11]. In this Letter we discuss an experimental setup with which these predictions have been verified. Having the ability to tailor the focal intensity distribution allows one, for example, to switch from trapping high-index particles to trapping low-index particles [12].

Let us first consider a converging, monochromatic field of frequency ω emerging from a circular aperture of radius a in a plane opaque screen. The origin O of a right-handed Cartesian coordinate system is taken at the geometric focus (see Fig. 1). The field at a point $Q(\mathbf{r}')$ on the wavefront A is denoted by $U^{(0)}(\mathbf{r}',\omega)$, where $\mathbf{r}'$ is a position vector. The field at a point $P(\mathbf{r})$ in the focal region is, according to the Huygens–Fresnel principle ([13], Chap. 8), given by the expression

$$U(\mathbf{r},\omega) = -\frac{i}{\lambda}\int_A U^{(0)}(\mathbf{r}',\omega)\frac{e^{iks}}{s}\mathrm{d}^2r', \tag{1}$$

where $s = |\mathbf{r} - \mathbf{r}'|$ denotes the distance QP and λ is the wavelength of the field. [A periodic time-dependent factor $\exp(-i\omega t)$ is suppressed.]

For a partially coherent wave field, one must, apart from the field, also consider the cross-spectral density function of the field at two points $Q(\mathbf{r}_1')$ and $Q(\mathbf{r}_2')$, namely [14]:

$$W^{(0)}(\mathbf{r}_1',\mathbf{r}_2',\omega) = \langle U^*(\mathbf{r}_1',\omega)U(\mathbf{r}_2',\omega)\rangle, \tag{2}$$

where the angular brackets denote the average taken over a statistical ensemble of realizations. From Eqs. (1) and (2), it follows that the cross-spectral density function in the focal region satisfies the formula

$$W(\mathbf{r}_1,\mathbf{r}_2,\omega) = \frac{1}{\lambda^2}\iint_A W^{(0)}(\mathbf{r}_1',\mathbf{r}_2',\omega)\frac{e^{ik(s_2-s_1)}}{s_1 s_2}\mathrm{d}^2r_1'\mathrm{d}^2r_2', \tag{3}$$

where $s_1 = |\mathbf{r}_1 - \mathbf{r}_1'|$ and $s_2 = |\mathbf{r}_2 - \mathbf{r}_2'|$. The spectral density (or intensity at frequency ω) at an observation point $P(\mathbf{r})$ is given by the "diagonal elements" of the cross-spectral density function, i.e., $S(\mathbf{r},\omega) = W(\mathbf{r},\mathbf{r},\omega)$. A normalized measure of the field correlation is provided by the spectral degree of coherence, which is defined as ([15], Sec. 4.3.2)

$$\mu^{(0)}(\mathbf{r}_1,\mathbf{r}_2,\omega) = \frac{W^{(0)}(\mathbf{r}_1,\mathbf{r}_2,\omega)}{\sqrt{S^{(0)}(\mathbf{r}_1,\omega)S^{(0)}(\mathbf{r}_2,\omega)}}. \tag{4}$$

In our experiment, the cross-spectral density of the field in the entrance pupil of the lens is of the form

$$W^{(0)}(\mathbf{r}_1,\mathbf{r}_2,\omega) = S^{(0)}(\omega)J_0(\beta|\mathbf{r}_2 - \mathbf{r}_1|). \tag{5}$$

Here $S^{(0)}$ is the spectrum of the incident field, taken to be independent of position, and J_0 denotes the Bessel

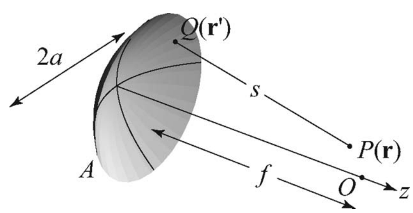

Fig. 1. Illustration of the focusing configuration.

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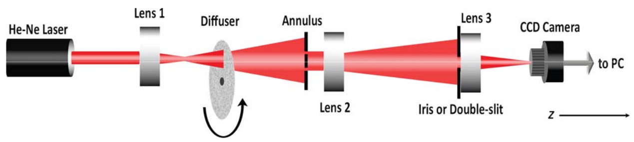

Fig. 2. (Color online) Schematic of the setup.

function of the first kind and zeroth order. The parameter β is, roughly speaking, the inverse of the coherence length. The numerical evaluation of Eq. (3) is discussed in [10,11].

Several tools, e.g., a programmable spatial light modulator, can be used to obtain a J_0-correlated field. We have chosen to create such a field using the van Cittert–Zernike theorem [14]. According to that theorem, the degree of coherence between two points in the far zone of a completely incoherent source can be expressed in terms of the Fourier transform of the intensity distribution across the source. Thus, for an incoherent annular source, the degree of coherence follows a J_0 distribution in the far zone.

The experimental setup is shown in Fig. 2. The output of a 15 mW He–Ne laser, operating at 632.8 nm, is focussed by Lens 1 onto a rotating optical diffuser. As was verified, this renders the field practically incoherent. The incoherent beam illuminates a thin annulus of inner radius 1.2 mm and outer radius 1.5 mm. The annulus is positioned in the back focal plane of a 3.7 m lens (Lens 2), which produces a J_0-correlated field in its focal plane. This field is incident on an iris of radius 2.5 mm and focused by a lens of focal length 10.6 cm (Lens 3). The focused image is captured using a CCD camera connected to a PC via a frame grabber. This provides a transverse image of the focused field. The CCD camera is mounted on top of a translator, capable of taking steps of 0.01 mm along the z axis.

The state of coherence of the far-zone field produced by the annulus was tested by replacing the iris by a series of identical double slits of width 0.172 mm and with varying slit spacing d. These pairs of slits were placed at the focus of Lens 2, and the resulting interference pattern was recorded. When the intensity at both slits is equal, the fringe visibility corresponds to the absolute value of the degree of coherence $\mu_{12}(\omega)$ of the field at the two slits ([15], Sec. 5.8.1). Figure 3 shows very good agreement between the measured values of the modulus

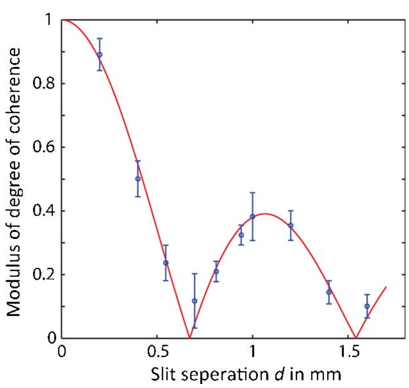

Fig. 3. (Color online) Modulus of the degree of spatial coherence of the field as a function of the slit separation d. The solid red curve indicates the theoretical prediction, and the blue circles indicate experimental values with error bars.

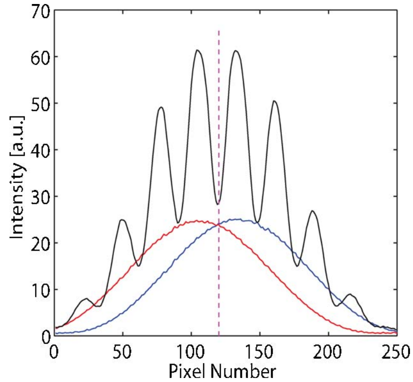

Fig. 4. (Color online) Illustration of negative correlation of the field at the two slits. At the center of the fringe pattern (vertical dashed line), an intensity minimum is observed. The blue and the red curves represent measurements with one slit covered.

of the degree of coherence and the theoretical predictions. For a slit spacing between 0.7 and 1.5 mm, the fields at the two slits are anticorrelated, i.e., $\mu_{12}(\omega) < 0$. This was verified using a slit pair with separation distance $d = 0.8$ mm. The recorded interference pattern is shown in Fig. 4. The blue and the red curves represent measurements with one of the slits covered, and the black lines show the double-slit interference pattern. At the center of the fringe pattern (indicated by the vertical dotted line), a minimum rather than a maximum is observed, confirming the predicted anticorrelation. Having thus established that the field has, indeed, the desired Bessel correlation, the slits were replaced by an iris and Lens 3 (with $a = 2.5$ mm and $f = 10.6$ cm) in order to study the focal intensity distribution. Intensity measurements in the x–y plane were made with steps of 0.1 mm along the z axis. The results are shown in Fig. 5, where the horizontal axis represents the distance of the CCD camera from Lens 3. The solid blue curve represents the theoretical prediction, while the red circles are the experimental results. Instead of a maximum, an intensity minimum is observed at the geometric focus (around 106 mm) between two intensity peaks. It is seen that the experimental results closely follow the theoretical predictions.

To observe the rotationally symmetric intensity profile in the focal plane, a set of three irises was used. The usage of irises with different radii (0.25, 0.75, and 1.2 mm) changes the spatial coherence width of the field. It is seen from Fig. 3 that, for the smallest iris, all points of

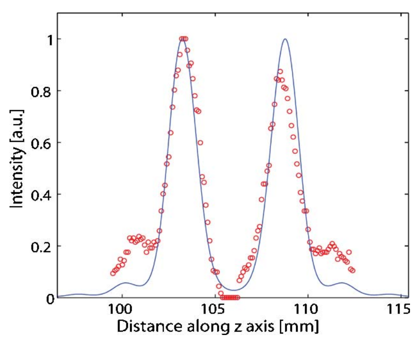

Fig. 5. (Color online) Intensity along the z axis. The solid curve represents the theoretical prediction, and the circles correspond to experimental measurements.

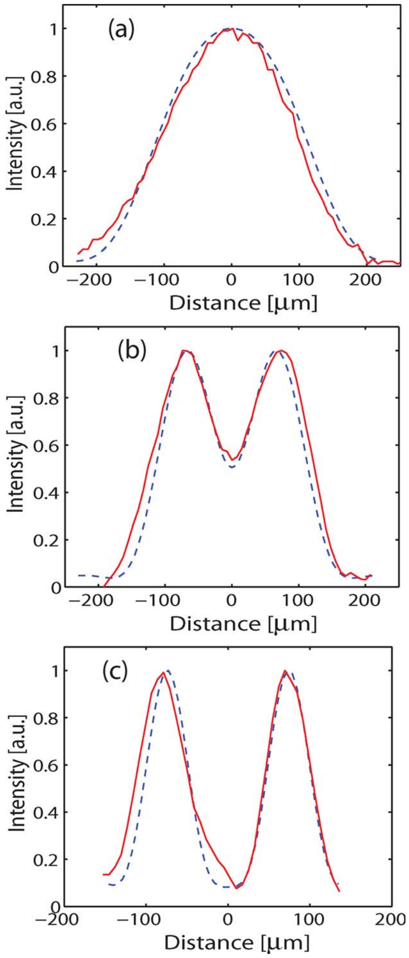

Fig. 6. (Color online) Transforming the intensity maximum in the focal plane into a minimum by varying the iris radius, (a) 0.25, (b) 0.75, and (c) 1.2 mm.

the incident field are positively correlated. For the two larger ones, both positive and negative field correlations occur. This enables us to observe the transition of the focal plane intensity from a maximum to a minimum. To maintain a Fresnel number larger than 20 in every case (to avoid the focal shift phenomenon [1,16]), Lens 3 was replaced by a lens with $f = 1$ cm. This results in a reduced separation between the maxima in the transverse direction of the order of 2 μm. Because the size of a pixel on the CCD camera is 8.6 μm, a simple magnification system was placed between Lens 3 and the camera. The results of varying the radius of the iris are shown in Fig. 6. In Fig. 6(a) the magnified intensity profile in the focal plane is shown for the case of an iris with a radius of 0.25 mm. The intensity reaches its maximum at the geometric focus (at a distance of 0 μm). Figure 6(b) depicts the gradual transition to an intensity minimum when the iris radius is increased to 0.75 mm. In Fig. 6(c) this radius is further increased to 1.2 mm, and the intensity minimum at the focus has become near zero.

In conclusion, we have shown that the focusing of a J_0-correlated field with a homogeneous intensity produces an intensity minimum at the geometric focus. The observed intensity profiles along the z axis and in the focal plane agree well with the theoretical predictions. The intensity minimum at the geometric focus can be manipulated by changing the spatial coherence width of the incident field. This is done by simply varying the aperture radius of the focusing system, and this enables us to change the intensity minimum of the focused field to a maximum, in a continuous manner. We have thus shown that, next to phase and amplitude control, there exists a fundamentally different mechanism to shape the intensity distribution in the focal region, namely, the manipulation of the state of coherence of the incident field. This approach may prove to be of value in optical tweezers and in optical trapping, where it can be used to selectively manipulate particles with either a high or a low index of refraction.

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