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Spatial correlation properties of apertured partially coherent radially polarized beams in turbulent atmosphere

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ABSTRACT

Based on the extended Huygens–Fresnel integral, the analytical formulae for the cross-spectral density matrix of the partially coherent radially polarized beams diffracted at a circular aperture in turbulent atmosphere are derived. The unapertured and free-space cases can be viewed as the special cases of our general result. By using the degree of coherence formula, the spatial correlation properties of the apertured partially coherent radially polarized beams in turbulent atmosphere are studied. The analyses indicate that the spatial correlation of the apertured partially coherent radially polarized beams are more affected by the atmospheric turbulence with the larger structure constant, the smaller truncation parameter, the larger coherence length, and the farther propagation distance.

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1. Introduction

Radially polarized beams have attracted growing interest in recent years due to their unique properties and important applications in electron acceleration, optical trapping, optical data storage, laser cutting, material processing, dark-field imaging, and elimination of thermally induced birefringence effects [1–8]. Various methods for generating radially polarized beams have been developed and applied either by polarization conversion arrangements outside a laser cavity [9–11], or by specially designed polarization-selective elements inside a laser resonator [12–14].

The propagation characteristics of various laser beams through turbulent atmosphere have been extensively studied due to their wide applications in free-space optical communication, atmospheric imaging systems and remote sensing [15–21]. The average intensity distributions and polarization properties of completely coherent radially polarized beams in turbulent atmosphere have been discussed [16]. The propagation properties of partially coherent radially polarized beams in turbulent atmosphere have also been demonstrated [17–19]. The spatial correlation properties of partially coherent flat-topped beams and apertured partially coherent beams through atmospheric turbulence have been analyzed [20,21]. To the best of our knowledge, the spatial correlation properties of the apertured partially coherent radially polarized beams in turbulent atmosphere have not been examined. In this paper, by using the extended Huygens–Fresnel integral, the analytical expressions for the cross-spectral density matrix of the partially coherent radially polarized beams diffracted at a circular aperture propagating in turbulent atmosphere are derived, and their spatial correlation properties are discussed in detail.

2. Propagation of partially coherent radially polarized beams diffracted at a circular aperture in turbulent atmosphere

In the Cartesian coordinate system, assuming that a circular aperture with radius a is located at the source plane $z=0$, the electric field of a completely coherent radially polarized beam just behind the aperture reads as [22,23]

$$E(x_0, y_0, 0) = \frac{\sqrt{2}E_0}{w_0} \exp\left(-\frac{x_0^2 + y_0^2}{w_0^2}\right) t(x_0, y_0)(x_0 e_x + y_0 e_y) \tag{1}$$

$$t(x_0, y_0) = \begin{cases} 1 & x_0^2 + y_0^2 \le a^2 \\ 0 & otherwise \end{cases} \tag{2}$$

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where $\mathbf{e}_x$ and $\mathbf{e}_y$ are the unit vectors in the x and y directions, respectively. w_0 is the waist width of Gaussian beam, E_0 is an amplitude constant, and $t(x_0, y_0)$ denotes the window function of the aperture. Within the framework of the paraxial approximation, the longitudinal component of the electric field compared with the transverse component can be negligible [24]. Thus, we do not consider the longitudinal component of the electric field here.

The cross-spectral density matrix for the radially polarized beams diffracted at a circular aperture has the form

$$W(\boldsymbol{r}_1, \boldsymbol{r}_2, z) = \begin{bmatrix} W_{xx}(\boldsymbol{r}_1, \boldsymbol{r}_2, z) & W_{xy}(\boldsymbol{r}_1, \boldsymbol{r}_2, z) \\ W_{yx}(\boldsymbol{r}_1, \boldsymbol{r}_2, z) & W_{yy}(\boldsymbol{r}_1, \boldsymbol{r}_2, z) \end{bmatrix} \tag{3}$$

where

$$W_{\alpha\beta}(\boldsymbol{r}_1, \boldsymbol{r}_2, z) = < E_\alpha^*(\boldsymbol{r}_1, z) E_\beta(\boldsymbol{r}_2, z) > \tag{4}$$

α,β=x,y, $\boldsymbol{r}_1 = (x_1, y_1)$ and $\boldsymbol{r}_2 = (x_2, y_2)$ are the position vectors at the receiver plane. The asterisk stands for the complex conjugate and the angle brackets represent an ensemble average over the medium statistics. By using Eqs. (1)–(4), the elements of cross-spectral density matrix for the apertured partially coherent radially polarized beams at the source plane $z = 0$ can be expressed as

$$W_{\alpha\beta}(\boldsymbol{r}_{01}, \boldsymbol{r}_{02}, 0) = \frac{2E_0^2 \alpha_{01} \beta_{02}}{w_0^2} \exp\left(-\frac{r_{01}^2 + r_{02}^2}{w_0^2}\right) t^*(x_{01}, y_{01}) t(x_{02}, y_{02}) g_{\alpha\beta}(\boldsymbol{r}_{01}, \boldsymbol{r}_{02}) \tag{5}$$

where $\boldsymbol{r}_{01} = (x_{01}, y_{01})$ and $\boldsymbol{r}_{02} = (x_{02}, y_{02})$ are the position vectors at the source plane. The complex degree of spatial coherence $g_{\alpha\beta}(\boldsymbol{r}_{01}, \boldsymbol{r}_{02})$ is supposed to be [22,25,26]

$$g_{\alpha\beta}(\boldsymbol{r}_{01}, \boldsymbol{r}_{02}) = \exp\left[-\frac{(\boldsymbol{r}_{01} - \boldsymbol{r}_{02})^2}{\sigma_{\alpha\beta}^2}\right] \tag{6}$$

where $\sigma_{\alpha,\beta}$ is the mutual coherence length (when $\alpha \neq \beta$) or auto-coherence length (when $\alpha = \beta$).

On the basis of the extended Huygens–Fresnel integral [17,27], the elements of cross-spectral density matrix for the apertured partially coherent radially polarized beams propagating in turbulent atmosphere are given by

$$\begin{aligned} W_{\alpha\beta}(\boldsymbol{r}_1, \boldsymbol{r}_2, z) &= \left(\frac{k}{2\pi z}\right)^2 \int_{-\infty}^{\infty}\int_{-\infty}^{\infty}\int_{-\infty}^{\infty}\int_{-\infty}^{\infty} W_{\alpha\beta}(\boldsymbol{r}_{01}, \boldsymbol{r}_{02}, 0) \\ &\times \exp\left[-\frac{ik}{2z}(\boldsymbol{r}_1 - \boldsymbol{r}_{01})^2 + \frac{ik}{2z}(\boldsymbol{r}_2 - \boldsymbol{r}_{02})^2\right] \\ &\times < \exp[\psi(\boldsymbol{r}_{01}, \boldsymbol{r}_1, z) + \psi^*(\boldsymbol{r}_{02}, \boldsymbol{r}_2, z)] > dx_{01} dy_{01} dx_{02} dy_{02} \end{aligned} \tag{7}$$

where k is the wavenumber, and the ensemble average term is [27]

$$\begin{aligned} &< \exp[\psi(\boldsymbol{r}_{01}, \boldsymbol{r}_1, z) + \psi^*(\boldsymbol{r}_{02}, \boldsymbol{r}_2, z)] > \\ &= \exp\left[-\frac{(\boldsymbol{r}_{01} - \boldsymbol{r}_{02})^2 + (\boldsymbol{r}_{01} - \boldsymbol{r}_{02})(\boldsymbol{r}_1 - \boldsymbol{r}_2) + (\boldsymbol{r}_1 - \boldsymbol{r}_2)^2}{\rho_0^2}\right] \end{aligned} \tag{8}$$

where $\rho_0 = (0.545 C_n^2 k^2 z)^{-3/5}$ is the coherence length of a spherical wave propagating in turbulent atmosphere, C_n^2 is the structure constant of the refractive index and describes the turbulence level. It is noted that a quadratic approximation of the Rytov's phase structure function is used in derivation of Eq. (8).

In order to obtain the analytical expressions, the aperture function is expanded as the sum of complex Gaussian functions with finite terms [28]:

$$t(x_0, y_0) = \sum_{n=1}^{N} A_n \exp\left[-\frac{B_n}{a^2}(x_0^2 + y_0^2)\right] \tag{9}$$

where the complex constants A_n and B_n are the expansion and Gaussian coefficients, respectively, which can be obtained by optimization computation. The study showed that the method of the finite complex Gaussian expansion of the aperture function can provide satisfactory results in the Fraunhoffer and Fresnel regions except for the extreme near-field (<0.1 times the Fresnel distance) [28], and this method has been widely used [21,29,30].

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