Optik 168 (2018) 590–597

Contents lists available at ScienceDirect

Optik

journal homepage: www.elsevier.de/ijleo

Original research article

Random sources generating far fields with ring-shaped array profiles

Zhenzhen Song [a,*], Zhengjun Liu [b], Jingfei Ye [a], Qiongge Sun [c], Shutian Liu [d,*]

[a] School of Physics and Optoelectronic Engineering, Nanjing University of Information Science & Technology, 210044, China
[b] Department of Automation Measurement and Control, Harbin Institute of Technology, 150001, China
[c] Beijing Institute of Space Mechanics and Electricity, Beijing, 100094, China
[d] Department of Physics, Harbin Institute of Technology, 150001, China

ARTICLE INFO

Article history:
Received 10 March 2018
Accepted 11 April 2018

Keywords:
Coherence
Statistical optics
Spectral density

ABSTRACT

We introduce a class of planar random source generating ring-shaped array profiles in the far field. The model for spatial correlation function of this new source is composed by the Fourier transform of the Laguerre-Gaussian array function with circular symmetry. The analytical expressions for the spectral density (average intensity) in free space and atmospheric turbulence are derived. The effect of the source parameters on the propagation properties are investigated in detail. Numerical results show that the source can produce a ring-shaped optical array profile consisting of dark-hollow-shaped or Gaussian-like-shaped beamlets at some distance, and then keep shape-invariant for long distances in free space. The number of rings, the position of beamlets, and other features can be conveniently controlled by changing the initial source parameters. In addition, increasing the relative separation distance of each beamlet or decreasing the radius of beamlets can reduce the turbulence-induced degradation.

1. Introduction

Optical fields with spatially array profiles are of popular interest motivated by its potential applications, chiefly to optical imaging and optical manipulation for particles [1,2]. Up to now, a multitude of experimental and theoretical techniques have been investigated for generating optical lattices [3–15], including the interference of laser beams [9,10], phase-only modulation implemented by a spatial light modulator (SLM) [11–13], Fourier-filtering operation of phase patterns [14], and fractional Talbot phase-only modulation [15].

It is well known that, for a planar and quasi-homogeneous Schell-model source, the far-field intensity distribution is proportional to the two-dimensional Fourier transform of the source correlation function [16]. This reciprocity relation provides an effective approach to build the model of random sources, which can generate prescribed far-field intensity distribution, by devising the source spatial correlation structure [17]. A number of partially coherent spatial sources were introduced, such as multi-Gaussian Schell-model (MGSM) sources for tunable flat far-fields [18–22], Laguerre-Gaussian Schell-model (LGSM) sources for dark-hollow far-fields [23], fractional multi-Gaussian-correlated Schell-model (FMGSM) sources for cusped far-fields [24], multi-sinc Schell-model (MSSM) sources for multi-ring or optical array far-fields [25], Gaussian Schell-model array (GSMA) sources for optical array far-fields [26], multi-Gaussian Schell-model sources for ring-shaped far-fields [27],

* Corresponding authors.
E-mail addresses: szz@nuist.edu.cn (Z. Song), stliu@hit.edu.cn (S. Liu).

https://doi.org/10.1016/j.ijleo.2018.04.083

radial Gaussian Schell-model (RGSM) sources for ring-shaped optical array far-fields [28]. The propagation of the beams generated by these partially coherent sources in the turbulence has also been investigated [29–35]. Due to the special initial coherence properties, the influence of the turbulence on these beams is less than the conventional Gaussian Schell-model (GSM) beams.

In a recent publication [35], a novel class of partially coherent sources of Schell-model type, generating ring-shaped beam arrays with rectangular symmetry in the far field, was introduced. As an extension, we propose a new type random source with circularly symmetric multi-ring-shaped array far-fields in this paper. The spatial correlation function of the source is devised based on a Fourier transform of a radial Laguerre-Gaussian array function. We derive the analytical expression of the spectral density (average intensity) in free space and atmospheric turbulence, and analyze its propagation properties. The optical array profiles and the position of beamlets can be flexibly adjusted by the initial source parameters. The far-field beamlet shape can be either dark-hollow or Gaussian-like profile according to particular parameters, which is also different from RGSM sources [28].

2. Light source model

Suppose that a stationary and scalar source is located in the plane $z = 0$ and generates a beam-like field propagating into the positive half-space $z > 0$. The second-order statistical properties of the light source can be described by the cross-spectral density (CSD) function $W_0(\mathbf{r}_1, \mathbf{r}_2)$ at two arbitrary spatial positions $r_1 = (x_1, y_1)$ and $r_2 = (x_2, y_2)$ in the source plane (where the dependence on frequency was omitted for conciseness). Due to the superposition rule, a function $W_0(\mathbf{r}_1, \mathbf{r}_2)$ is a genuine CSD if it can be written in the following integral form [17]

$$W_0(\mathbf{r}_1, \mathbf{r}_2) = \int p(\upsilon) K_0^*(\mathbf{r}_1, \upsilon) K_0(\mathbf{r}_2, \upsilon) d^2\upsilon, \tag{1}$$

where $p(\upsilon)$ is an arbitrary nonnegative and Fourier transformable function, $K_0(\mathbf{r}, \upsilon)$ is an arbitrary integral kernel, and the asterisk stands for complex conjugate. For Schell-model sources, the kernel $K_0(\mathbf{r}, \upsilon)$ must have a Fourier-like structure as [17]

$$K_0(\mathbf{r}, \upsilon) = \tau(\mathbf{r}) \exp(-i\mathbf{r} \cdot \upsilon), \tag{2}$$

where $\tau(\mathbf{r})$ is an complex amplitude profile function. Hence, the Schell-model CSD leads to

$$\begin{aligned} W_0(\mathbf{r}_1, \mathbf{r}_2) &= \tau^*(\mathbf{r}_1)\tau(\mathbf{r}_2)\tilde{p}(\mathbf{r}_1 - \mathbf{r}_2) \\ &= \tau^*(\mathbf{r}_1)\tau(\mathbf{r}_2)\mu(\mathbf{r}_1 - \mathbf{r}_2), \end{aligned} \tag{3}$$

where the source spectral degree of coherence (DOC) $\mu = \tilde{p}$, and the tilde represents the Fourier transform.

In order to generate a far field with ring-shaped array profiles, we set the following form for the function $p(\upsilon)$:

$$\begin{aligned} p(\upsilon) = \frac{\delta^{2n+2}(N+1)NM}{2^{2n+3}\pi n!} \sum_{q=1}^{N}\sum_{j=1}^{qM} \left[p_H\left(\upsilon_x - \frac{qR\cos\varphi_j}{\delta}, \upsilon_y - \frac{qR\sin\varphi_j}{\delta}\right)\right. \\ \left. + p_H\left(\upsilon_x + \frac{qR\cos\varphi_j}{\delta}, \upsilon_y + \frac{qR\sin\varphi_j}{\delta}\right)\right], \end{aligned} \tag{4}$$

with

$$p_H\left(\upsilon_x, \upsilon_y\right) = \left(\frac{\upsilon_x^2 + \upsilon_y^2}{\delta^2}\right)^n \exp\left[-\frac{\delta^2\left(\upsilon_x^2 + \upsilon_y^2\right)}{2}\right], \tag{5}$$

where δ is the coherent length, n and R are positive real constants, N and M are positive integers, $\upsilon = \left(\upsilon_x, \upsilon_y\right)$, $\varphi_j = \pi j/qM + \theta$, θ is the additional phase. In fact, $p_H\left(\upsilon_x, \upsilon_y\right)$ is the function associated with a LGSM beam defined in [23]. So function $p(\upsilon)$ is manifestly non-negative, and represents a family of multi-ring shaped array profiles with dark-hollow-shaped beamlets, and the radius of each beamlet depends on the parameter n. The number of rings and the beamlets is related to the parameters N and M. The parameter R can be regarded as a weight coefficient to enlarge the radius of all rings by the same proportion.

For our purpose, the amplitude profile function $\tau(\mathbf{r})$ can be chosen at will, and we set it to be a Gaussian with the beam width σ, i.e.

$$\tau(\mathbf{r}) = \exp\left(-\frac{\mathbf{r}^2}{2\sigma^2}\right). \tag{6}$$

Substituting Eqs. (4)–(6) into Eq. (3), and applying the following formulae [36]

$$\left(x^2 + y^2\right)^n = \sum_{m=0}^{n} \binom{n}{m} x^{2n-2m} y^{2m}, \tag{7}$$