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High-order nonuniformly correlated beams

Dan Wu [a,b], Fei Wang [b,*], Yangjian Cai [b]

[a] Wenzheng College of Soochow University, Suzhou 215104, China
[b] College of Physics, Optoelectronics and Energy & Collaborative Innovation Center of Suzhou Nano Science and Technology, Soochow University, Suzhou 215006, China

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ABSTRACT

We have introduced a class of partially coherent beams with spatially varying correlations named high-order nonuniformly correlated (HNUC) beams, as an extension of conventional nonuniformly correlated (NUC) beams. Such beams bring a new parameter (mode order) which is used to tailor the spatial coherence properties. The behavior of the spectral density of the HNUC beams on propagation has been investigated through numerical examples with the help of discrete model decomposition and fast Fourier transform (FFT) algorithm. Our results reveal that by selecting the mode order appropriately, the more sharpened intensity maxima can be achieved at a certain propagation distance compared to that of the NUC beams, and the lateral shift of the intensity maxima on propagation is closed related to the mode order. Furthermore, analytical expressions for the r.m.s width and the propagation factor of the HNUC beams on free-space propagation are derived by means of Wigner distribution function. The influence of initial beam parameters on the evolution of the r.m.s width and the propagation factor, and the relation between the r.m.s width and the occurring of the sharpened intensity maxima on propagation have been studied and discussed in detail.

1. Introduction

Spatial coherence is one of the important properties in optical fields, and plays a significant role in affecting the propagation characteristics of light beams as well as the performance in some practical applications such as image system and free-space optical communications [1–4]. According to optical coherence theory, the spatial coherence properties can be characterized by two-point cross-spectral density (CSD) functions in space-frequency domain [1]. However, one can't choose the mathematical models for the CSD functions arbitrarily due to the fact that CSD function must satisfy the non-negative-definiteness and hermiticity conditions. In 2007, Gori and Santarsiero derived a sufficient condition to ensure that the theoretical models for the CSD functions are genuine and physically realizable [5]. Since then, a variety of partially coherent beams with different coherence properties including multi-Gaussian correlated Schell-model beams, Hermite-Gaussian correlated Schell-model beams and Laguerre-Gaussian correlated Schell-model beams, etc., have been proposed theoretically [6–12]. Owing to their particular coherence properties, these beams exhibit peculiar propagation features, capable of producing various kinds of far-filed beam profiles such as ring shape, flat-top and beam arrays, which is very useful in beam shaping, optical trapping and manipulation [13,14]. Meanwhile, several experimental setups have been established to generate these partially coherent beams [15–17]. The progress of this subject can be found in the reviewed article [18]. On the other hand, considerable attention has been paid to propagation of the partially coherent beams with different coherence properties through atmospheric turbulence [19–23]. It was found that the scintillation index of the multi-Gaussian correlated Schell-model beams is much lower than that of the conventional partially coherent beams, i.e., Gaussian-Schell model (GSM) beams propagation through the turbulence, which has a potential application in free-space optical communications and remote sensing.

Of particular interest is the NUC beams whose spatial coherence distribution is spatially varying [24]. Such beams display two extraordinary propagation characteristics, i.e., the lateral shift of the intensity maxima and "auto-focusing" phenomena during free-space propagation, which is quite different from those for Schell-model beams whose spatial coherence is only dependent on the difference of two specified points. The evolution of the spectral density and the scintillation index of the NUC beams in turbulent media were explored [25–28]. It was shown that the NUC beams not only have lower scintillation but also higher intensity compared to GSM beams, making them an ideal candidate for information carriers in free-space communications. The study of

* Corresponding author.
E-mail address: fwang@suda.edu.cn (F. Wang).

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the NUC beams was further extended to vector and temporal case [29–32]. Recently, Hyde et al. reported an efficient method for experimental generation of the scalar or vector NUC beams by using of a phase-only spatial light modulator (SLM) [33].

In this paper, we have extended the conventional NUC beams to the more general class of partially coherent beams with spatially varying correlations, named high-order nonuniformly correlated (HNUC) beams. In this extension, The NUC beams can be considered as a special case for the new introduced HNUC beams. The evolution of the spectral density of the HNUC beams for selected mode orders on free-space propagation has been studied through numerical examples. Furthermore, we derived the simple analytical expressions for the second-moments such as r.m.s width and propagation factors, of the HNUC beams during free-space propagation with the help of the Wigner distribution function (WDF). Based on the derived expressions, the evolutions of the r.m.s width and the propagation factor of the HNUC beams on propagation have been investigated in detail. Some useful and interesting results are presented.

2. Theoretical model for high-order nonuniformly correlated beams

Suppose that a partially coherent beam-like field is statistically stationary, at least in wide sense, propagating along z axis. In space-frequency domain, The CSD function of the HNUC beams in the source plane ($z = 0$) is written as

$$W_0(x_1, x_2, 0) = \exp\left(-\frac{x_1^2 + x_2^2}{2\omega_0^2}\right)\mu(x_1, x_2, 0), \tag{1}$$

with

$$\mu(x_1, x_2, 0) = \exp\left[-\frac{\left((x_2 - x_0)^m - (x_1 - x_0)^m\right)^2}{\omega_c^{2m}}\right], \tag{2}$$

where function $\mu(x_1, x_2, 0)$ denotes the spectral degree of coherence (SDOC). ω_0 is the beam waist size in the source plane; ω_c and x_0 are two real constants. The quantity ω_c is a measure of spatial coherence of the beam. The parameters ω_0, ω_c and x_0 may depend on the angular frequency ω of the beams. The dependence of the CSD function and other derived quantities on ω will be omitted throughout the paper. m represents the mode order. For $m = 1$, Eq. (1) reduces to the expression for a GSM beam, while it becomes NUC beams which was introduced by Lajunen and Saastamoinen when $m = 2$ [24]. We referred the HNUC beams that the mode order is a positive integer number and larger than 2. Such beams can be regarded as the general form of one class of the partially coherent beams with spatially varying correlations. As shown in Eq. (1), we only consider the beam depending on one transverse dimension x for simplicity. The generalization of the results to two-dimensional case is straightforward, just writing the CSD function $W_0 = (x_1, x_2, y_1, y_2, 0) = W_0(x_1, x_2, 0)W_0(y_1, y_2, 0)$ where $W_0(y_1, y_2, 0)$ has the same form with $W_0(x_1, x_2, 0)$ in place of x_1 and x_2 with y_1 and y_2, respectively.

We plot in Fig. 1 the contour graphs of the SDOC of the HNUC beams for several selected mode orders in the source plane and the corresponding cross-lines ($x_2 = 0$) of the SDOC (see in Fig. 1 (g) and (h)). For comparison, the contour graphs and cross-lines of the SDOC of the GSM beam ($m = 1$) and the NUC beam ($m = 2$) are also plotted in Fig. 1. The parameters used in calculation are chosen to be $\omega_c = 0.5$ mm and $x_0 = 0$. One finds that the SDOC of the GSM beam is position independent and the cross-line at any fixed position x_2 are of Gaussian profile, as expected. When $m \geq 2$, the distributions of the SDOC of the beams are spatially varying. With the increase of order m, the pattern of SDOC in the central region becomes more flattened and similar with the rectangular shape. The field of HNUC beams in the region $|x - x_0| < \omega_c$ can assume to be completely coherent approximately, i.e., the values of SDOC of two arbitrary points in this region are nearly unit. While the field out of the region $|x - x_0| < \omega_c$ is nearly incoherent, except for the two points $(x, -x)$ where they are completely coherent for even order. Therefore, we can divide the HNUC beams with larger mode order two parts from the point view of their coherence property. One is completely coherent in the region $|x - x_0| < \omega_c$, and another is completely incoherent out of region $|x - x_0| < \omega_c$, except for the pair of points $(x, -x)$ for even order.

To be a physically realized or genuine beam, it suffices to that the CSD function of partially coherent beams has the representation of the form [5]

$$W_0(x_1, x_2, 0) = \int p(v)H^*(x_1, v)H(x_2, v)dv, \tag{3}$$

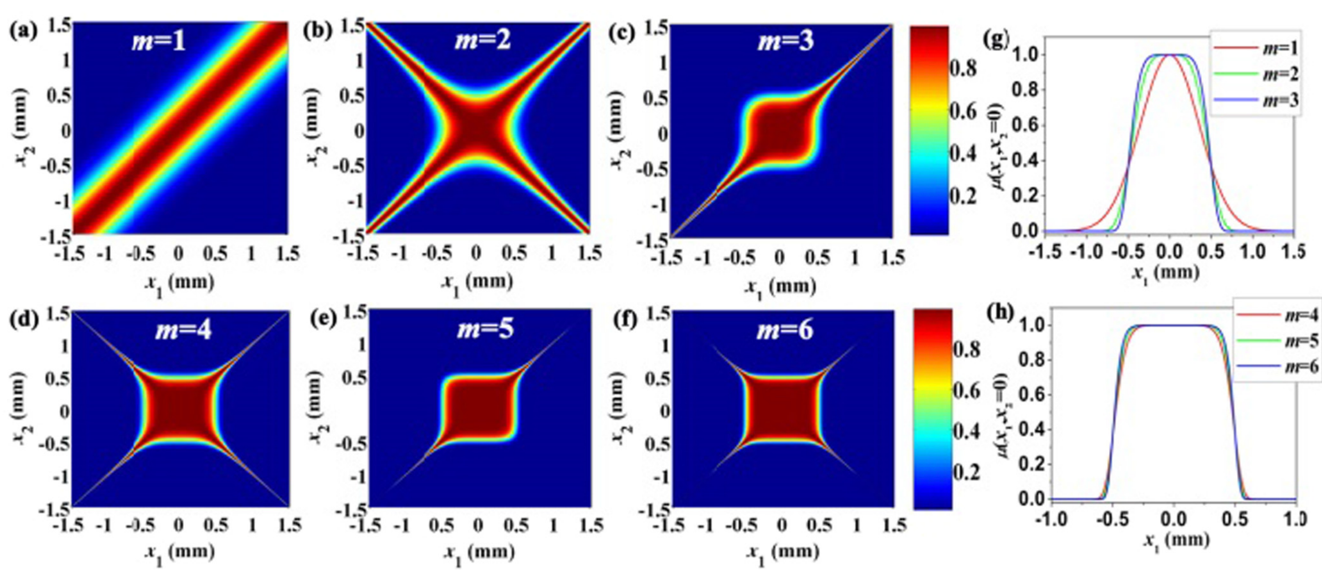

Fig. 1. Contour graphs of the SDOC of (a) a GSM beam, (b) a NUC beam and (c)–(f) HNUC beams for different mode order. (g)–(h) The corresponding cross-line plot ($x_2 = 0$). The parameters used in the calculation are $\omega_c = 0.5$ mm, $x_0 = 0$.