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Optics Communications 260 (2006) 383–397
OPTICS COMMUNICATIONS
www.elsevier.com/locate/optcom

Analytic design of an anamorphic optical system for generating anisotropic partially coherent Gaussian Schell-model beams

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Received 15 June 2005; received in revised form 7 October 2005; accepted 26 October 2005

Abstract

The analytic design of anamorphic optical system for transforming the coherent Gaussian beam of a He–Ne laser to a partially coherent Gaussian Schell-model beam with an anisotropic cross-section and an anisotropic degree of coherence is described. Design equations are formulated and some design examples are presented.

PACS: 42.15.Eq; 42.25.Kb

Keywords: Anamorphic optical system; Partial coherence; Gaussian Schell-model beam; Degree of coherence

1. Introduction

Coherence is the physical property of light wave that is most closely related to interference and diffraction phenomena. In view of applications of diffraction and interference, light waves can be classified with respect to their degree of coherence. Most light waves are partially coherent. However, laser-generated light waves have highly coherent properties in time and space. Partially coherent light sources such as light emitting diodes and excimer lasers are widely used not only in display systems but also in lithography systems for the fabrication of semiconductors. A great deal of information is available concerning theoretical aspects as well as practical applications related to partially coherent light waves and related technologies [1,2]. Moreover, research and development on optical structures and devices for managing partially coherent light waves have kept pace with the development of partially coherent light sources [3–8].

On the other hand, controlling the coherence property of light waves is an important issue due to the fact that the general characteristics of diffraction and interference can be seriously affected by the coherence of light wave. The careful consideration and management of partially coherent light wave are important for applications of displays, lithography, and diffractive optics. The inherent speckle contamination problem associated with laser display systems has recently been treated through managing the coherence of the scanning laser beam [9].

In this paper, a method for forming Gaussian Schell-model (GSM) beams [10–13] with specific coherence characteristics using a complete coherent He–Ne laser was investigated. Controlling the coherence property of the generated GSM beam is also discussed. In addition, since typical partially coherent lasers such as excimer lasers that are used in material processing, have anisotropic cross-sections and an anisotropic degree of coherence, it would be more meaningful to manage the GSM beam so as to have anisotropic coherence characteristics. Simulating such anisotropic GSM beams using a He–Ne laser

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0030-4018/$ - see front matter
doi:10.1016/j.optcom.2005.10.065

would be useful in research and development related to partially coherent light sources as excimer lasers. This study would be useful for addressing the speckle reduction problem in laser display systems.

The objective of this paper is the design of anamorphic optical system for generating a GSM beam with an anisotropic cross-section and an anisotropic degree of coherence function. Analytic design equations of the targeted anamorphic optical systems are proposed based on an analysis of the propagation of the GSM beams through first order optical systems, as studied by Lin and Cai [10]. This paper is organized as follows. In Section 2, Lin's formula of the propagation of GSM beams through the first order optical system is reviewed. In Section 3, the variable separation of an orthogonal anamorphic system is discussed. In Section 4, the design and analysis of the proposed anamorphic optical system is described. In Section 5, some design examples are presented. In Section 6, a conclusion and final remarks are presented.

2. Propagation of the GSM beams through the first order optical system

The statistical characteristics of light waves varying with spatial and temporal randomness can be described by the cross-spectral density [1,2]. The cross-spectral density indicates the degree of the correlation between optical fields at two separated points, r_1 ($r_1 = (r_{x1},r_{y1})$) and r_2 ($r_2 = (r_{x2},r_{y2})$) in the transverse x–y plane perpendicular to the optical axis (z-axis), which takes the product form of the spectral density and the normalized degree of coherence. For a fixed temporal frequency, the cross-spectral density of the light wave $\Gamma(r_1,r_2)$ is defined as

$$\Gamma(r_1, r_2) = [S(r_1)]^{1/2}[S(r_2)]^{1/2}G(r_1, r_2), \tag{1}$$

where $S(r_{1,2})$ is spectral density function and $G(r_1,r_2)$ is expressed by $g(r_2,r_1)\exp(-\mathrm{j}\phi(r_1,r_2))$. $g(r_2,r_1)$ and $\phi(r_2,r_1)$ denote the degree of coherence and the effective phase difference between optical fields at positions r_2 and r_1, respectively. When the spatial distribution follows a wide-sense stationary (WSS) distribution on the transverse plane, the degree of coherence depends on only the distance between r_1 and r_2. This type of statistical model for a light wave is called the Schell model. If a light wave with a fixed temporal frequency follows the Schell model and has the property such that its spectral density and degree of coherence are represented, respectively, by Gaussian functions for $r_{1,2}$ and $|r_1 - r_2|$, the light waves are called GSM beams [1,4]. In addition, a partially coherent twisted anisotropic GSM beam is a generalized beam structure having the additional phase term $\phi(r_1,r_2)$ [10–16]. The cross-spectral density of the GSM beam then takes the form

$$\Gamma(r_1, r_2) = [S(r_1)]^{1/2}[S(r_2)]^{1/2}g(r_2 - r_1)\exp(-\mathrm{j}\phi(r_1, r_2)), \tag{2}$$

where $S(r_{1,2})$ and $g(r_2 - r_1)$ are given, respectively, by:

$$S(r_{1,2}) = \left(\frac{A}{2\pi}\right)\frac{1}{\det\sigma_s}\exp\left[-\frac{1}{2}r_{1,2}^{\mathrm{T}}(\sigma_s^2)^{-1}r_{1,2}\right], \tag{3}$$

$$g(r_2 - r_1) = \exp\left[-\frac{1}{2}(r_2 - r_1)^{\mathrm{T}}(\sigma_g^2)^{-1}(r_2 - r_1)\right]. \tag{4}$$

Here, the exponent terms in Eqs. (3) and (4) are represented by the quadratic form expression, and $(\sigma_s^2)^{-1}$ and $(\sigma_g^2)^{-1}$ are referred to as the transverse spot width matrix and the transverse coherence width matrix, respectively. These are real symmetric matrices, and their physical dimensions are the inverse square of the distance. The effective phase difference of the cross-spectral density, $\phi(r_1,r_2)$, is given as

$$\phi(r_1, r_2) = \frac{k}{2}(r_1 - r_2)^{\mathrm{T}}K(r_1 + r_2), \tag{5}$$

where k is the wave number equal to $2\pi/\lambda$ and λ is the operating wavelength. K is a real matrix defined as

$$K = R^{-1} + \mu J, \tag{6}$$

where R^{-1} is called the wavefront curvature matrix and has transpose symmetry. The constant, μ, is the twist factor, and J is a transposed antisymmetric matrix as

$$J = \begin{bmatrix} 0 & 1 \\ -1 & 0 \end{bmatrix}. \tag{7}$$

In the light wave model defined above, the functional forms of $S(r_{1,2})$ and $g(r_2 - r_1)$ can be considered to be an anisotropic Gaussian function having an anisotropic quadratic form with its own principal axes in its exponential term [10,15,16]. It is not necessary for the principal axes of $S(r_{1,2})$ and $g(r_2 - r_1)$ to be equal to each other. In addition, it is not necessary for the principal axes of the wavefront curvature matrix R^{-1} existing in the phase term of the cross-spectral density to be equal to those for $S(r_{1,2})$ and $g(r_2 - r_1)$.