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Changes in the degree of polarization of random electromagnetic GSM vortex beams in biological tissues

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ABSTRACT

Based on the Huygens-Fresnel principle, the analytic expressions of the cross-spectral density matrix elements of the random electromagnetic Gaussian Schell model (GSM) vortex beams in biological tissues are derived, and used to study the changes in the on-axis degree of polarization $P(0, 0, z)$, one point degree of polarization $P(\rho, \rho, z)$ and two points (generalized) degree of polarization $P(0, \rho, z)$ of random electromagnetic GSM vortex beams. The results show that with the increment of the propagation distance z, the bigger C_n^2 is, the earlier appearance of the inflexion points in $P(0, 0, z)$ and $P(\rho, \rho, z)$ are, but the changes in $P(0, \rho, z)$ are related to the propagation distance. The smaller σ_{xy} is, the greater σ_{yy} is, the more smooth the change curves of $P(0, 0, z)$, $P(\rho, \rho, z)$ and $P(0, \rho, z)$ are. Besides, the difference values between σ_{xx} and σ_{yy} also influence the changes in $P(0, 0, z)$, $P(\rho, \rho, z)$ and $P(0, \rho, z)$. On the same conditions, the changes in $P(0, \rho, z)$ are more complicate than those in $P(\rho, \rho, z)$, and the changes in $P(\rho, \rho, z)$ are more complex than those in $P(0, 0, z)$.

1. Introduction

The emergence and applications of laser promote the development of biomedical photonics in life science. The propagation characteristics of laser in the medium are closely related to the optical parameters of the medium, which leads to that it is significant to research the transmission law of laser in the biological tissue in order to effectively and accurately obtain the optical parameters of the biological tissues [1–4]. We also know that it is difficult to study the propagation properties of laser in biological tissue because of the complexity and security of biological tissue [5]. However, due to people's burning desire to the better life quality, it becomes an urgent demand to investigate the propagation properties of laser in biological tissues, and thus a great number of theoretical and experimental researches relevant to the tissue optics have been developed. In 1996 Schmitt et al. pointed that the spatial correlations in the refractive indices of different tissues have similar properties and can be described mathematically by a model that resembles the classical Kolmogorov model of atmospheric turbulence, and reported the power spectrum model of mammalian tissue [6]. Based on the power spectrum model of mammalian tissue and the unified theory of coherence and polarization [7], numerous studies have been devoted to investigating the propagation characteristics of random electromagnetic beams passing the biological tissues. For instance, the changes in polarization state of isotropic random electromagnetic beams on the optical axis passing biological tissues have been studied [8,9]. The effect of the upper dermis of human on the mutual coherence function of a random electromagnetic beam also

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has been investigated [10]. The effects of the biological tissue turbulence on the average intensity and scintillation index of random Gaussian beams have been discussed in the numerical simulations [11] and so on.

The vortex beam is named to the singular beam endowed with the screw wave-front dislocations, topological charge and optical vortex. Much interest has been exhibited recently in vortex beam owning to its attractive applications in optical communications [12–14], quantum information and entanglement [15–18], optical manipulation and trapping of small particles [19–23], optical parametric oscillator [24,25], biological tissues [26,27] and so on. As far as we know, a great number of researches are concerning the non-vortex beams propagating through biological tissues, while that referred to the vortex beams is scarce. The influence of both the topological charge and the correlation length of the beam on the propagation of stochastic electromagnetic vortex beams have been studied by employing the unified theory of coherence and polarization [26]. On the other hand, the spectral degree of polarization is regarded as the important optical parameter of beams, and its change is directly related to the optical properties of media. The measurement and estimation of the spectral degree of polarization becomes an important subject to investigate the structure and function of biological tissues.

In the present paper, the analytical expressions of the cross-spectral density matrix elements for the GSM vortex beam with topological charge $m = \pm 1$ through biological tissue are derived based upon the extended Huygens-Fresnel principle and the unified theory of coherence and polarization. The relationship between the changes in the on-axis degree of polarization $P(0, 0, z)$ between the structure constant of the refractive-index C_n^2 of the biological tissues, the spatial correlation length (σ_{xy} and σ_{yy}) and the wave length λ of random electromagnetic GSM vortex beams, and the propagation distance z has been discussed in detail, respectively. The same things also have been performed to the one point degree of polarization $P(\rho, \rho, z)$ and two points degree of polarization $P(0, \rho, z)$ of the random electromagnetic GSM vortex beam.

2. Theoretical model

The cross-spectral density matrix of random electromagnetic vortex beams at the source plane $z = 0$ is expressed as [28]

$$\leftrightarrow W(\mathbf{s}_1, \mathbf{s}_2, 0) = \begin{pmatrix} W_{xx}(\mathbf{s}_1, \mathbf{s}_2, 0) W_{xy}(\mathbf{s}_1, \mathbf{s}_2, 0) \\ W_{yx}(\mathbf{s}_1, \mathbf{s}_2, 0) W_{yy}(\mathbf{s}_1, \mathbf{s}_2, 0) \end{pmatrix}, \tag{1}$$

where

$$W_{ij}(\mathbf{s}_1, \mathbf{s}_2, 0) = < E_i^*(\mathbf{s}_1, 0) \cdot E_j(\mathbf{s}_2, 0) > \quad (i, j = x, y) \tag{2}$$

where E_x and E_y denote the two components of the electric field. $\mathbf{s}_l \equiv (s_{lx}, s_{ly})$ $(l = 1, 2)$ is the two-dimensional position vector at the source plane $z = 0$.The asterisk and angle brackets stands for the complex conjugate and ensemble average, respectively.

The elements $W_{ij}(\mathbf{s}_1, \mathbf{s}_2, 0)$ of the cross-spectral density matrix of random electromagnetic GSM vortex beams at the source plane are expressed as [29]

$$W_{ij}(\mathbf{s}_1, \mathbf{s}_2, 0) = A_i A_j B_{ij} \left[s_{1x}s_{2x} + s_{1y}s_{2y} + i\,\mathrm{sgn}(m) s_{1x}s_{2y} - i\,\mathrm{sgn}(m) s_{2x}s_{1y} \right]^{|m|} \times \exp\left(-\frac{\mathbf{s}_1^2 + \mathbf{s}_2^2}{w_0^2} \right) \exp\left[-\frac{(\mathbf{s}_1 - \mathbf{s}_2)^2}{2\sigma_{ij}^2} \right] \tag{3}$$

where A_i is the amplitude of the electric field-vector component E_i, B_{ij} are correlation coefficients between two components E_i and E_j, w_0 is the waist width, σ_{ij} is related to the spatial correlation length. Sgn (m) denotes the sign function; m specifies the topological charge, and in the following we take $m = +1$. For $m = 0$, Eq. (3) reduces to those of random electromagnetic GSM vortex-free beams,

$$W'_{ij}(\mathbf{s}_1, \mathbf{s}_2, 0) = A_i A_j B_{ij} \exp[-\frac{s_1^2 + s_2^2}{w_0^2}] \exp[-\frac{(\mathbf{s}_1 - \mathbf{s}_2)^2}{2\sigma_{ij}}]. \tag{4}$$

Based on the extended Huygens-Fresnel principle [30], the elements of cross-spectral density matrix of random electromagnetic GSM vortex beams propagating through biological tissue can be expressed as

$$W_{ij}(\boldsymbol{\rho}_1, \boldsymbol{\rho}_2, z) = (\frac{k}{2\pi z})^2 \iint d^2\boldsymbol{\rho}_1 \iint d^2\boldsymbol{\rho}_2 W_{ij}(\mathbf{s}_1, \mathbf{s}_2, 0) \times \exp\left\{ -\frac{ik}{2z}[(\boldsymbol{\rho}_1 - \mathbf{s}_1)^2 - (\boldsymbol{\rho}_2 - \mathbf{s}_2)^2] \right\} < \exp[\psi^*(\boldsymbol{\rho}_1, \mathbf{s}_1) + \psi(\boldsymbol{\rho}_2, \mathbf{s}_2)] >, \tag{5}$$

where the ρ_1 and ρ_2 is the position vector at the z plane, the relationship between the wave number k and the wave length λ is $k = 2\pi/\lambda$, $\psi(\rho, s)$ denotes the random part of the complex phase due to the turbulence and can be written as [31]

$$\langle \exp[\psi^*(\boldsymbol{\rho}_1, \mathbf{s}_1) + \psi(\boldsymbol{\rho}_2, \mathbf{s}_2)] \rangle \cong \left\{ -\frac{1}{\rho_0^2}[(\boldsymbol{\rho}_1 - \boldsymbol{\rho}_2)^2 + (\boldsymbol{\rho}_1 - \boldsymbol{\rho}_2)(\mathbf{s}_1 - \mathbf{s}_2) + (\mathbf{s}_1 - \mathbf{s}_2)^2] \right\}, \tag{6a}$$

where

$$\rho_0 = 0.22\left(C_n^2 k^2 z\right)^{-1/2}, \tag{6b}$$