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# Average intensity and spreading of partially coherent model beams propagating in a turbulent biological tissue

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ABSTRACT

For Gaussian beams with three different partially coherent models, including Gaussian-Schell model (GSM), Laguerre-Gaussian Schell-model (LGSM) and Bessel-Gaussian Schell-model (BGSM) beams propagating through a biological turbulent tissue, the expression of the spatial coherence radius of a spherical wave propagating in a turbulent biological tissue, and the average intensity and beam spreading for GSM, LGSM and BGSM beams are derived based on the fractal model of power spectrum of refractive-index variations in biological tissue. Effects of partially coherent model and parameters of biological turbulence on such beams are studied in numerical simulations. Our results reveal that the spreading of GSM beams is smaller than LGSM and BGSM beams on the same conditions, and the beam with larger source coherence width has smaller beam spreading than that with smaller coherence width. The results are useful for any applications involved light beam propagation through tissues, especially the cases where the average intensity and spreading properties of the light should be taken into account to evaluate the system performance and investigations in the structures of biological tissue.



## 1. Introduction

With the development of imaging technology in the biological tissue including optical coherence tomography (OCT) [1–3], the propagation of optical beams through a biological tissue [4–14] is a subject of considerable importance which has received more and more attention from researchers.

As an important approach to provide quantitative guidance for disease diagnosis or screening, the average intensity and spreading of signal light play key roles in biophotonics research [4]. Based on the experimental results of intensity measurement, Wu et al. [5] indicated that the unified Mie and fractal model of cell light scattering provides an accurate interpretation of the scattering spectra measured from intact cells in suspension and culture and quantitative information about cellular structural features and organization can be deduced from this unified model from wavelength- and angular-resolved light scattering spectroscopy. Biological tissue is a very complex system in which the light is strongly scattered in propagation due to the spatial fluctuation of its refractive index. Schmitt and Kumar have measured and analyzed statistical properties of the refractive-index variations in specimens of biological tissue and they found that spatial correlations quantitatively similar to those produced by atmospheric turbulence [6]. Based on this model of power spectrum of refractive-index variations in biological tissue, Gao made lots of efforts to explore the changes of coherence and the state of polarization of optical beams propagating through a biological tissue [7–11]. The unified theory of coherence and polarization for random electromagnetic beams was employed to analyze the change of

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coherence due to the fluctuations of the index of refraction of tissue [12]. Xu and Alfano utilized the fractal continuous random media to model visible and near-infrared light scattering by biological tissue and cell suspensions [13]. For an improvement of the model based on a continuous refractive index variation presented in [6], Sheppard proposed a fractal model of light scattering in biological tissue and cells based on K-distribution, the range of allowable power laws was extended into the subfractal regime [14].

As an optical beam propagates through the turbulent biological tissue, it will experience random deflections due to refractive turbulence. As a result, the average intensity of beam will decrease and the beam width will increase as a result of the effect of diffraction [15]. For stochastic electromagnetic vortex beams propagation through the turbulent biological tissues, the spectral density, the spectral degree of coherence and the spectral degree of polarization were investigated in detail [16]. The analytical formulae of anomalous hollow beams (AHBs) propagating through the turbulent biological tissues based on the extended Huygens-Fresnel integral formula and the irradiance and spreading properties of AHBs in turbulent biological tissues were studied numerically in [17]. Some published computational papers [18,19] have suggested that the intensity and spreading of beams with partially coherent sources are less sensitive to the effects of turbulence than fully coherent ones. Evidence shows that choosing the appropriate partially coherent model beam is one of the most effective methods to reduce the influence of turbulence on the laser beams propagating through the random medium [20,21]. However, to the best of our knowledge, the intensity and spreading of partially coherent model beams propagating through a turbulent biological tissue have not been studied.

In this paper, we put forward a model of average intensity for GSM, Laguerre-Gaussian Schell-model (LGSM) and Bessel-Gaussian Schell-model (BGSM) beams, spreading of LGSM and BGSM beams propagating in the biological tissue turbulence on the basis of the fractal model the of the refractive index power spectrum of fluctuations in biological turbulent tissue.

The paper is organized as follows, in Section 2, we derive the expressions of average intensity for GSM, LGSM and BGSM beams in turbulent biological tissue. The spreading of partially coherent model beams through turbulent biological tissue is given in Section 3. The numerical simulations and analysis are given in Section 4. Finally, conclusions are given in Section 5.

## 2. Average intensity of partially coherent beams propagating in a turbulent biological tissue

The cross-spectral density function (CSDF) of GSM, LGSM and BGSM random fields at the planar source surface can be written as [20]:

$$W^{(0)}(\boldsymbol{\rho}_1,\boldsymbol{\rho}_2;\omega)=\exp\left(-\frac{\boldsymbol{\rho}_1^2+\boldsymbol{\rho}_2^2}{4\sigma_s^2}\right)\mu^{(0)}(\boldsymbol{\rho}_2-\boldsymbol{\rho}_1;\omega), \tag{1}$$

where $\boldsymbol{\rho}_1$ and $\boldsymbol{\rho}_2$ are two-dimensional position vectors at the source plane (the notation for a partially coherent beam propagating through a turbulent biological tissue is shown in Fig. 1), $\sigma_s$ is the rms width of the source, $\omega$ is the angular frequency, $\mu^{(0)}$ is the spectral degree of coherence of the source for GSM, LGSM, BGSM beams and takes the following form [20,21]:

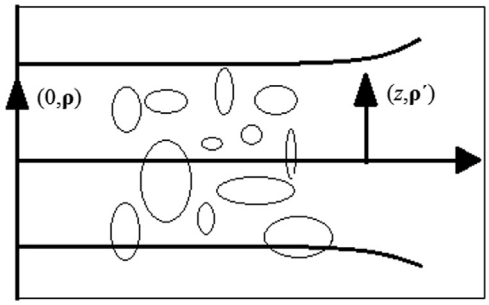


**Fig. 1.** Notation for a partially coherent beam propagating through a turbulent biological tissue.

$$\mu_G^{(0)}(\boldsymbol{\rho}_2-\boldsymbol{\rho}_1;\omega)=\exp\left(-\frac{|\boldsymbol{\rho}_2-\boldsymbol{\rho}_1|^2}{2\sigma_\mu^2}\right), \tag{2}$$

$$\mu_L^{(0)}(\boldsymbol{\rho}_2-\boldsymbol{\rho}_1;\omega)=\exp\left(-\frac{|\boldsymbol{\rho}_2-\boldsymbol{\rho}_1|^2}{2\sigma_\mu^2}\right)\mathrm{L}_n\left(\frac{|\boldsymbol{\rho}_2-\boldsymbol{\rho}_1|^2}{2\sigma_\mu^2}\right), \tag{3}$$

$$\mu_B^{(0)}(\boldsymbol{\rho}_2-\boldsymbol{\rho}_1;\omega)=\exp\left(-\frac{|\boldsymbol{\rho}_2-\boldsymbol{\rho}_1|^2}{2\sigma_\mu^2}\right)\mathrm{J}_0\left(\beta\frac{|\boldsymbol{\rho}_2-\boldsymbol{\rho}_1|}{2\sigma_\mu^2}\right), \tag{4}$$

where $\beta$ and $\sigma_\mu$ are real constants, $\mathrm{J}_0(\cdot)$ is the zeroth-order Bessel function of the first kind, and $\mathrm{L}_n(\cdot)$ is the $n$-order Laguerre polynomial and $n$ is the order of Laguerre polynomial. Eq. (2) corresponds to the collimated beam.

The condition on the LGSM and BGSM sources for beamlike field generation is the same as that for the classic GSM source [20]:

$$\frac{1}{4\sigma_s^2}+\frac{1}{\sigma_\mu^2}\ll\frac{2\pi^2}{\lambda^2}, \tag{5}$$

with $\lambda$ being the wavelength of the source.

According to the extended Huygens-Fresnel principle, upon propagation from the source plane to any plane with $z>0$ and by the paraxial approximation, the CSDF takes the form [15]

$$W(\boldsymbol{\rho}_1',\boldsymbol{\rho}_2',z;\omega)=\frac{k^2}{(2\pi z)^2}\iint W^{(0)}(\boldsymbol{\rho}_1,\boldsymbol{\rho}_2;\omega)\exp\left[-\mathrm{i}k\frac{(\boldsymbol{\rho}_1'-\boldsymbol{\rho}_1)^2-(\boldsymbol{\rho}_2'-\boldsymbol{\rho}_2)^2}{2z}\right]\times\langle\exp[\Psi^*(\boldsymbol{\rho}_1,\boldsymbol{\rho}_1',z;\omega)+\Psi(\boldsymbol{\rho}_2,\boldsymbol{\rho}_2',z;\omega)]\rangle_a\,\mathrm{d}^2\boldsymbol{\rho}_1\mathrm{d}^2\boldsymbol{\rho}_2 \tag{6}$$

where $\boldsymbol{\rho}_1'$ and $\boldsymbol{\rho}_2'$ are two-dimensional position vectors at the output plane, $k=2\pi n_0/\lambda$ is the wave number of light, with $n_0$ being the background refractive index, $\Psi^*(\boldsymbol{\rho}_1,\boldsymbol{\rho}_1',z;\omega)$ represents the random part of the complex phase of a spherical wave propagating in biological tissue turbulence, the asterisk stands for the complex conjugate, and $\langle\cdot\rangle_a$ denotes the ensemble average of in biological tissue turbulence.

The last term in above integrand can be given by the expression [15]:

$$\langle\exp[\Psi^*(\boldsymbol{\rho}_1,\boldsymbol{\rho}_1',z;\omega)+\Psi(\boldsymbol{\rho}_2,\boldsymbol{\rho}_2',z;\omega)]\rangle_a$$