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Change of coherence of light produced by tissue turbulence

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ABSTRACT

The coherence is an important property of the light that can be explored to realize very high sensitive measurements in many applications. In this work, the unified theory of coherence and polarization for random electromagnetic beams will be employed to analyze the change of coherence due to the fluctuations of the index of refraction of tissue. To the best of our knowledge, for the first time the expression for calculating the change of the mutual coherence function of a random, wide-sense stationary, electromagnetic beam propagating along the z direction due to the tissue turbulence is given. The results can be used to estimate the distribution of the mutual coherence function across a plane normal to the direction of propagation at a distance z from the incident plane. It can also be employed to calculate the change of the mutual coherence function with propagation distance. Thus the results are useful for any applications involved light beam propagation through tissues, especially the cases where the coherence and polarization properties of the light field should be taken into account to evaluate the system performance.

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1. Introduction

Tissue is a very complex system in which the light is strongly scattered in propagation due to the spatial fluctuation of its refractive index. The amplitude of the light backscattering from living tissue is then very weak. Thus to effectively measure the backscattered light from a depth beneath the surface for generating optical sectional images and obtaining characteristics of tissue, many low-coherence interferometry-based imaging techniques have been proposed, in which the very short coherence length of a light source with large bandwidth has been explored in several arrangements of optical paths to realize measurements of the positions of the reflectors or backscatterers within tissue because of their high detection sensitivity and high resolution, including optical coherence tomography (OCT) [1–3]. In these arrangements, only the light backscattered from live tissue that is of some degree of coherence with the light reflected from the reference mirror contributes to the measured signal. These techniques then have very high detection sensitivity and depth resolution [4]. The coherence of light beam also influences the light field distribution in the focal region and resolution of the system [5,6].

Usually, the coherence of light can be divided into two categories. One is the temporal coherence which is mainly determined by the bandwidth of the light source. The other is the spatial coherence which is affected by the correlation properties of the light field in the source plane and the turbulence of the medium [7].

It is a well-known fact that when propagating in free space, the coherence of light may change due to the correlation that exists between the light fields at two space-time points in the source plane [7]. For the propagation of the light in a random medium, the spatial correlation of the refractive index of the medium can also lead to the change of the coherence of the light [8–13]. In this work, we will concern ourselves with analysis of the changes of the spatial coherence of the light propagating in tissues.

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We will use the mutual coherence function (MCF) as a measure of the spatial coherence of the light beam. MCF is the cross-correlation of the optical fields separated by a distance ρ in a plane normal to the direction of propagation. The MCF determines the signal-to-noise ratio (SNR) of an optical heterodyne detector and the limiting resolution obtainable along the beam path in the medium [14,15]. The effect of the decrease of the MCF due to the light scattering by large tissue components on the SNR of an OCT system has been analyzed [16,17].

Due to the fact that the tissue constitutes have sizes spanning a range from much smaller than a wavelength to the diameter of a cell (2–50 μm) and there is no clear boundaries between these components, the effects of tissue structures on the coherence of the light beam are complex. It has been shown that the MCF of the light beam can be influenced by the tissue turbulence [12,13]. Although the 2×2 cross-spectral density correlation matrix of the beam at any cross-section perpendicular to the direction of propagation of the beam was derived in Refs. [12,13], the formula for calculating the change of the MCF with propagation distance was not given. While the decrease of MCF due to the multiple small angle forward scattering of the large particles in tissue has been analyzed [16,17], the effects of the isotropic scattering by very small tissue structures such as the protein macromolecules have not been considered. The experimental data showed that the submicron tissue structures dominate the single backscattering of light from bulk tissues [18,19].

In this work, effects of tissue turbulence on coherence of light propagating through or scattered from it are analyzed. We will use the unified theory of coherence and polarization for random electromagnetic beams to analyze the change of coherence due to the fluctuations of the index of refraction of tissue. To the best of our knowledge, the explicit expression for calculating the change of the MCF due to the turbulence is given for the first time.

2. The theory

2.1. Change of coherence with tissue turbulence

Consider a random, wide-sense stationary, electromagnetic beam propagating along the z direction. Following Wolf, we choose mutually orthogonal x- and y-axes perpendicular to the z-direction and use $\{E_i(\vec{r},\nu)\}(i=x,y)$ to represent the statistical ensemble of the spectral component of frequency ω of the fluctuation electric field at a point $\vec{r}$ in space. All the second-order coherence properties, including the spectral density, the spectral degree of the coherence and the spectral degree of polarization, can be defined by using a 2×2 cross-spectral density matrix [8,9,12]

$$\overleftrightarrow{W}\equiv[W_{ij}(\vec{\rho}_1,\vec{\rho}_2,z;\nu)]=[\langle E_i^*(\vec{\rho}_1,z;\nu)E_j(\vec{\rho}_2,z;\nu)\rangle] \quad (i=x,y;j=x,y) \tag{1}$$

where the asterisk denotes the complex conjugate and the subscripts i, j label Cartesian components of a typical realization $\mathbf{E}(\vec{\rho},z;\nu)$ of the electric field in two mutually orthogonal directions perpendicular to the direction of propagation of the beam (the z-direction) (see Fig. 1).

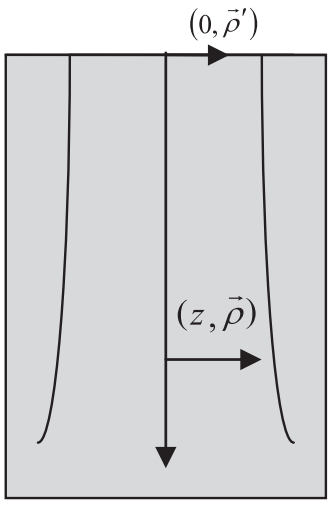

Fig. 1. The notation relating to propagation of a beam through tissue.

The method of measuring the four elements of this matrix has been described by Roychowdhury and Wolf [20].

According to the generalized Wiener–Khintchine theorem, the mutual coherence function $M(\vec{r}_1,\vec{r}_2,\tau)$ of the electric field at points Q_1 and Q_2, specified by position vectors $\vec{r}_1=(\vec{\rho}_1,z)$ and $\vec{r}_2=(\vec{\rho}_2,z)$ in a statistically stationary electromagnetic beam which propagates close to the z-direction, and the cross-spectral density function form a Fourier transform pair and may be expressed as [7]

$$M(\vec{r}_1,\vec{r}_2,\tau)=\int_0^\infty W(\vec{r}_1,\vec{r}_2,\nu)e^{-j2\pi\nu\tau}d\nu \tag{2}$$

where τ represents the difference between the two time instants t_1 and t_2 at which the correlation between the light vibrations at the two points Q_1 and Q_2 is being considered.

As pointed out previously, the MCF of the light will change because of the spatial correlation of the refractive index of tissue. Because its variations in tissue are generally small, the refraction index of tissue can be written as a sum of its mean $\langle n(\vec{r})\rangle$ and a spatially varying part $\delta n(\vec{r}),n(\vec{r})=\langle n(\vec{r})\rangle+\delta n(\vec{r})$, where $\langle\delta n\rangle=0$. The spatial correlation of the refractive index is defined as

$$B_n(\vec{r})=\langle n(\vec{r}_1)n^*(\vec{r}_2)\rangle=\langle n\rangle^2+\langle\delta n(\vec{r}_1)\delta n(\vec{r}_2)\rangle, \tag{3}$$

where $\vec{r}=\vec{r}_2-\vec{r}_1$. Assuming that the tissue is statistically space homogeneous and isotropic, the spatial correlation B_n is then only dependent on $r=|\vec{r}|$ [21–23]. The Fourier transform of the spatial correlation function, $\Phi_n(K)$, is known as the spectral density of the index of refraction fluctuations. For a variety of mammalian tissues such as human skin, $\Phi_n(K)$ is given by [23]

$$\Phi_n(K)=\frac{4\pi\langle\delta n^2\rangle L_0{}^2(\varsigma-1)}{(1+K^2L_0{}^2)^\varsigma}, \tag{4}$$

where L_0 is the outer scale of the refractive-index inhomogeneity size and in the range of 4–10 μm, the parameter ζ is related to the fractal dimension of the tissue and has a mean value of 1.41 for tissue and is an indication of the classical turbulent behavior of tissue, $\langle\delta n^2\rangle$ is the variance

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