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Two-color correlation between intensity fluctuations in atmospheric turbulence

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ABSTRACT

The correlation between intensity fluctuations generated by two varying wavelengths through a turbulent medium is investigated, where the influences arising from source correlation and perturbation of atmosphere are mainly emphasized. It is demonstrated that the correlation between intensity fluctuations can be enhanced or reduced by modulating the difference of two incident wavelengths. For shorter wavelength, the correlation between intensity fluctuations is stronger at the far field. In addition, in the case of single wavelength, a relationship $\lambda_1 z_1 = \lambda_2 z_2 = \lambda_n z_n$ holding in free space could be found, from which the distance where the peak value occurs may be inferred. However, it can be destroyed by increasing the strength of atmosphere.

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1. Introduction

The correlation between intensity fluctuations, closely related to the famous Hanbury Brown–Twiss experiment that was firstly conducted and analyzed in the 1950s [1–3], has gained increasing attention in recent years. Since it deals with the problem of high-order moment of the electric field, measuring the correlation holds promise for numerous applications in various areas. Apart from being originally introduced to determine the angular diameters of stars [4], it has been proved to play a major role in neutrino physics [5], quantum optics [6], and in the characterization of rough surfaces [7], as well as the ghost imaging, a subject has begun to attract more interest [8–12].

Most of the previous studies have assumed that the random fluctuations in the electric fields obey the Gaussian statistics. Based on this assumption, the correlation between intensity fluctuations has a simplified form by using Gaussian moment theorem. It is revealed that for scalar stochastic beams, the correlation between intensity fluctuations can be defined by the square of the cross-spectral density function [13,14]. And for stochastic electromagnetic beams, it is given by the sum of the squares of the elements of the cross-spectral density matrix [15–17]. It should be pointed out that turbulence is an unavoidable factor in practical optical applications, such as remote sensing or telescope observation. When the beam propagates through atmospheric turbulence, however, the fluctuations in the electric field may no longer be governed by the Gaussian statistics [18]. Those results obtained under the assumption that the random fluctuations in the electric fields obey the Gaussian statistics are not applicable to the case of atmospheric turbulence, where the statistic properties of the propagating beam can be quite complex, and is in fact a topic of current research.

It is also worth pointing out that there is another restriction on the recently published works on the correlation between intensity fluctuations, i.e., the lights in two response arms have the same wavelength, being monochromatic or quasi-monochromatic. However, the ghost imaging, which strongly depends on the correlation between intensity fluctuations, with two different wavelengths has been recently reported to produce some results distinctly different from that with single wavelength [19,20], which shows the significant influence of varying incident wavelengths to some extent. In this paper, we will concentrate on the modulation of the correlation between intensity fluctuations, based on the difference of incident wavelengths and the strength of turbulence.

2. Correlation between intensity fluctuations generated by two wavelengths through atmospheric turbulence

Two approaches can be used to make the incident beams correlated. One is to produce the same amplitude modulation by using a spatial light modulator (SLM) [19] and the other is phase modulation using two different SLMs [20]. The proposed experimental scheme for measuring the correlation between intensity fluctuations is shown in Fig. 1, where the latter approach has been involved. The two beams with the same phase distribution in the output plane of SLM are spatially incoherent but in a correlated

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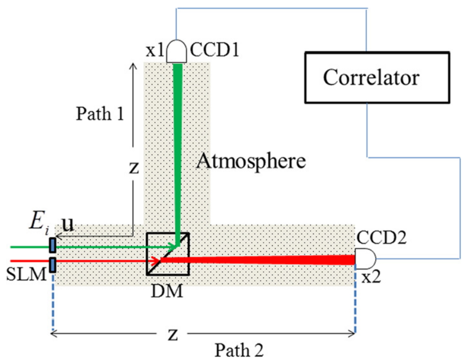

Fig. 1. The schematic for correlation between intensity fluctuations with two-wavelength in atmospheric turbulence. DM: dichroic mirror; SLM: spatial light modulator.

manner. Then, the fluctuations of intensity detected by two CCDs are correlated, after the two beams traveling the same propagation distance in atmospheric turbulence. In the proposed paper, it is assumed that the temporal behavior of the source is able to be suppressed and the detectors have slow response.

To study the properties of correlation between intensity fluctuations, let us begin by briefly reviewing the main results about the theory for following analysis. The fluctuation in intensity of a field $E(x)$ at a point is governed by

$$\Delta I(x) = I(x) - \langle I(x) \rangle, \tag{1}$$

where the angular brackets denote the time average in the detector, and $I(x)$ means the instantaneous intensity.

The correlation between intensity fluctuations at the two different detectors is characterized by [19]

$$\begin{aligned} C(x_1, x_2) &= \langle \Delta I_1(x_1) \Delta I_2(x_2) \rangle = \langle I_1(x_1) I_2(x_2) \rangle - \langle I_1(x_1) \rangle \langle I_2(x_2) \rangle \\ &= \langle E_1^*(x_1) E_1(x_1) E_2^*(x_2) E_2(x_2) \rangle \\ &\quad - \langle E_1^*(x_1) E_1(x_1) \rangle \langle E_2^*(x_2) E_2(x_2) \rangle, \end{aligned} \tag{2}$$

where $E_a(x_a)$, $a = 1, 2$ is the field evaluated at the CCD in each path and the star denotes the complex conjugate.

According to the extended Huygens–Fresnel integral, the output fields passing through atmospheric turbulence can be expressed as [21]

$$\begin{aligned} E_a(x_a) = {} & \left(\frac{-i}{\lambda_a z} \right)^{1/2} \exp(2i\pi z/\lambda_a) \int \mathrm{d}u \, E_{ia}(\lambda_a, u) \\ & \times \exp\left[\frac{i\pi}{\lambda_a z} (x_a - u)^2 \right] \exp\left[\phi_a(u, x_a) \right], \end{aligned} \tag{3}$$

where $E_{ia}(\lambda_a, u)$ is the field at the output plane of SLM, and $\phi_a(u, x_a)$ denotes the random phase correlation term due to the turbulence.

Recalling that the input fields are taken to be independent quasi-monochromatic lights and the spatial correlations impressed by the SLM obey Gaussian statistics. Hence, the electric fields at the output plane of SLM satisfy the relationship

$$\begin{aligned} & \langle E_{i1}(u_1) E_{i1}^*(u_1') E_{i2}(u_2) E_{i2}^*(u_2') \rangle \\ & \quad = \langle E_{i1}(u_1) E_{i1}^*(u_1') \rangle \langle E_{i2}(u_2) E_{i2}^*(u_2') \rangle \\ & \qquad + \langle E_{i1}(u_1) E_{i2}^*(u_2') \rangle \langle E_{i2}(u_2) E_{i1}^*(u_1') \rangle. \end{aligned} \tag{4}$$

Inserting Eqs. (3) and (4) into Eq. (2), the correlation can be reorganized as

$$\begin{aligned} C(x_1, x_2) = {} & \frac{1}{\lambda_1 \lambda_2 z^2} \int \mathrm{d}u_1 \mathrm{d}u_1' \mathrm{d}u_2 \mathrm{d}u_2' W(u_1, u_1', u_2, u_2') \\ & \times \exp\left\{ \frac{i\pi}{\lambda_1 z} \left[(x_1 - u_1)^2 - (x_1 - u_1')^2 \right] \right\} \\ & \times \exp\left\{ \frac{i\pi}{\lambda_2 z} \left[(x_2 - u_2)^2 - (x_2 - u_2')^2 \right] \right\} \\ & \times \langle \exp\left[\phi_1(u_1, x_1) + \phi_1^*(u_1', x_1) \right] \rangle_m \\ & \times \langle \exp\left[\phi_2(u_2, x_2) + \phi_2^*(u_2', x_2) \right] \rangle_m, \end{aligned} \tag{5}$$

where the subscript m implies that the average is taken over the ensemble of statistical realizations of the turbulent medium and the last two terms representing the phase correlation can be well approximated as [22,23]

$$\begin{aligned} & \langle \exp\left[\phi_a(u_1, x_1) + \phi_a^*(u_2, x_2) \right] \rangle_m \\ & \quad \cong \exp\left\{ -\left[(u_1 - u_2)^2 + (u_1 - u_2)(x_1 - x_2) + (x_1 - x_2)^2 \right] / \rho_a^2 \right\}, \end{aligned} \tag{6}$$

where $\rho_a = (0.55 C_n^2 k_a^2 z)^{-3/5}$ measures the coherence length of a spherical wave propagating in the turbulent medium and C_n^2 is the structure parameter of the refractive index.

And the spatial cross-correlation function of the lights in the plane of SLM is supposed to take the form

$$\begin{aligned} W(u_1, u_1', u_2, u_2') = {} & \exp\left(-\frac{u_1^2 + u_1'^2 + u_2^2 + u_2'^2}{4\sigma^2} \right) \\ & \times \exp\left[-\frac{(u_1 - u_2')^2 + (u_2 - u_1')^2}{2\delta^2} \right], \end{aligned} \tag{7}$$

where σ and δ refer, respectively, to the transverse size and correlation length of the source.

On substituting from Eqs. (6) and (7) into (5), it follows immediately that

$$\begin{aligned} C(x_1, x_2) = {} & \frac{1}{\lambda_1 \lambda_2 z^2} \int \mathrm{d}u_1 \mathrm{d}u_1' \mathrm{d}u_2 \mathrm{d}u_2' \\ & \times \exp\left(-\frac{u_1^2 + u_1'^2 + u_2^2 + u_2'^2}{4\sigma^2} \right) \\ & \times \exp\left[-\frac{(u_1 - u_2')^2 + (u_2 - u_1')^2}{2\delta^2} \right] \\ & \times \exp\left\{ \frac{i\pi}{\lambda_1 z} \left[(x_1 - u_1)^2 - (x_1 - u_1')^2 \right] \right\} \\ & \times \exp\left\{ \frac{i\pi}{\lambda_2 z} \left[(x_2 - u_2)^2 - (x_2 - u_2')^2 \right] \right\} \\ & \times \exp\left[-\frac{1}{\rho_1^2} (u_1 - u_1')^2 - \frac{1}{\rho_2^2} (u_2 - u_2')^2 \right]. \end{aligned} \tag{8}$$

By taking integrations with respect to u_1, u_1', u_2, u_2', one finds that the final analytical expression is readily calculated

$$\begin{aligned} C(x_1, x_2) = {} & \frac{\pi^2}{\lambda_1 \lambda_2 z^2 \sqrt{a_1} \sqrt{a_1'} \sqrt{a_2} \sqrt{a_2'}} \\ & \times \exp\left\{ -\frac{\pi^2 x_1^2}{\lambda_1^2 z^2} \left[\frac{1}{a_1} + \frac{1}{a_1'} \left(1 - \frac{1}{a_1 \rho_1^2} \right)^2 \right] \right\} \\ & \times \exp\left\{ \frac{1}{4a_2} \left[\frac{i\pi x_1}{a_1' \lambda_1 z \delta^2} \left(1 - \frac{1}{a_1 \rho_1^2} \right) - \frac{2i\pi x_2}{\lambda_2 z} \right]^2 + \frac{b^2}{4a_2'} \right\}, \end{aligned} \tag{9}$$

where

$$a_1 = \frac{1}{4\sigma^2} + \frac{1}{2\delta^2} - \frac{i\pi}{\lambda_1 z} + \frac{1}{\rho_1^2},$$

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