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Correlation of Intensity Fluctuations for Scattering of a Partially Coherent Plane-Wave Pulse

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Abstract: We derived analytical expressions for the correlation of intensity fluctuations of a partially coherent Gaussian Schell-model plane-wave pulse scattered by deterministic and random media. Our results extend the study of correlation of intensity fluctuations at two space points for scattered stationary fields to that at two time points for scattered non-stationary fields.

Keywords: coherence and statistical optics; scattering; partially coherent; pulse

1. Introduction

Scattering is of great importance in physics, astronomy, chemistry, meteorology, biology, and in other fields. Scattering of electromagnetic fields from a medium which fluctuates both in space and in time has been studied extensively in recent years [1–9]. The scattering medium may be deterministic or random, continuous or discrete. The inverse problem, i.e., the problem of finding the properties of the object from the statistical properties of the scattered field, is of considerable interest [10–13].

Non-stationary light fields, also named stochastic optical pulses or partially coherent pulses, exhibit partial coherence spectrally and temporally, and have attracted much attention due to their important roles in optical telecommunications, optical imaging, fiber optics, etc. The study of partially coherent pulses has been developed from conventional Gaussian correlation function to nonconventional correlation functions. There has been substantial work on the propagation and scattering of partially coherent pulses [14–18].

Correlation of intensity fluctuations, i.e., the Hanbury Brown-Twiss effect, was first introduced to determine the angular diameter of radio stars [19]. Recently, there have been several attempts to study the correlation of intensity fluctuations at two space points of the scattered field, and it was found that information about the scattering potentials of deterministic and random media may be obtained from the measurement of the correlation of intensity fluctuations [20–22]. In the present paper, we considered correlation of intensity fluctuations at two time points of the scattered field for a partially coherent Gaussian Schell-model plane-wave pulse. We derive analytical expressions for the correlation of intensity fluctuations of a partially coherent Gaussian Schell-model plane-wave pulse scattered by deterministic and quasi-homogeneous random media.

2. Correlation of Intensity Fluctuations

We begin with a brief review of correlation of intensity fluctuations in the space-time domain at two space-time points, say ($\boldsymbol{r}_1$, t_1) and ($\boldsymbol{r}_2$, t_2) [23,24]. The intensity fluctuations are defined by the formula:

$$\langle \Delta I(\boldsymbol{r}_j, t_j) \rangle = I(\boldsymbol{r}_j, t_j) - \langle I(\boldsymbol{r}_j, t_j) \rangle \ (j = 1, 2), \tag{1}$$

where:

$$I(\boldsymbol{r}_j, t_j) = E^*(\boldsymbol{r}_j, t_j) E(\boldsymbol{r}_j, t_j), \tag{2}$$

is the instantaneous intensity of the field $E(\boldsymbol{r}_j, t_j)$. The asterisk denotes the complex conjugate and the angular bracket denotes the ensemble average. Then the correlation of intensity fluctuations at two space-time points ($\boldsymbol{r}_1$, t_1) and ($\boldsymbol{r}_2$, t_2) has the form:

$$\langle \Delta I(\boldsymbol{r}_1, t_1) \Delta I(\boldsymbol{r}_2, t_2) \rangle = \langle I(\boldsymbol{r}_1, t_1) I(\boldsymbol{r}_2, t_2) \rangle - \langle I(\boldsymbol{r}_1, t_1) \rangle \langle I(\boldsymbol{r}_2, t_2) \rangle. \tag{3}$$

We note that the first term on the right-hand side of Equation (3) is the fourth-order correlation function. Assuming that the field fluctuations obey Gaussian statistics and the first moment of the field $E(\boldsymbol{r}_j, t_j)$ is zero, the fourth-order correlation function can be expressed in terms of second-order moments by the Gaussian moment theorem:

$$\begin{aligned} \langle I(\boldsymbol{r}_1, t_1) I(\boldsymbol{r}_2, t_2) \rangle \quad &= \langle E^*(\boldsymbol{r}_1, t_1) E(\boldsymbol{r}_1, t_1) \rangle \langle E^*(\boldsymbol{r}_2, t_2) E(\boldsymbol{r}_2, t_2) \rangle \\ &+ \langle E^*(\boldsymbol{r}_1, t_1) E(\boldsymbol{r}_2, t_2) \rangle \langle E^*(\boldsymbol{r}_2, t_2) E(\boldsymbol{r}_1, t_1) \rangle \\ &= \langle I(\boldsymbol{r}_1, t_1) \rangle \langle I(\boldsymbol{r}_2, t_2) \rangle + |\Gamma(\boldsymbol{r}_1, \boldsymbol{r}_2, t_1, t_2)|^2. \end{aligned} \tag{4}$$

On substituting from Equation (4) into Equation (3) we obtain for the correlation of intensity fluctuations the formula:

$$\langle \Delta I(\boldsymbol{r}_1, t_1) \Delta I(\boldsymbol{r}_2, t_2) \rangle = |\Gamma(\boldsymbol{r}_1, \boldsymbol{r}_2, t_1, t_2)|^2, \tag{5}$$

where $\Gamma(\boldsymbol{r}_1, t_1, \boldsymbol{r}_2, t_2)$ is the mutual coherence function of the field. Its normalized version:

$$\frac{\Gamma(\boldsymbol{r}_1, \boldsymbol{r}_2, t_1, t_2)}{\sqrt{\Gamma(\boldsymbol{r}_1, \boldsymbol{r}_1, t_1, t_1)}\sqrt{\Gamma(\boldsymbol{r}_2, \boldsymbol{r}_2, t_2, t_2)}} = \frac{\Gamma(\boldsymbol{r}_1, \boldsymbol{r}_2, t_1, t_2)}{\sqrt{\langle I(\boldsymbol{r}_1, t_1) \rangle \langle I(\boldsymbol{r}_2, t_2) \rangle}} = \gamma(\boldsymbol{r}_1, \boldsymbol{r}_2, t_1, t_2), \tag{6}$$

is the complex degree of coherence of the field. From Equations (5) and (6) it follows that:

$$\frac{\langle \Delta I(\boldsymbol{r}_1, t_1) \Delta I(\boldsymbol{r}_2, t_2) \rangle}{\langle I(\boldsymbol{r}_1, t_1) \rangle \langle I(\boldsymbol{r}_2, t_2) \rangle} = |\gamma(\boldsymbol{r}_1, \boldsymbol{r}_2, t_1, t_2)|^2. \tag{7}$$

The term on the left-hand side of Equation (7) may be defined as the normalized correlation of intensity fluctuations of the field. This formula shows that the normalized correlation of intensity fluctuations is equal to the squared modulus of the degree of coherence at two space-time points ($\boldsymbol{r}_1$,t_1) and ($\boldsymbol{r}_2$,t_2).

3. Correlation of Intensity Fluctuations of a Partially Coherent Plane-Wave Pulse Scattered by Deterministic and Random Media

We began by considering a temporally partially coherent Gaussian Schell-model plane-wave pulse incident upon a linear scatterer, which occupies a finite domain D. In the space-time domain, the temporal coherence function of the pulses takes the form [14,15]:

$$\Gamma(t_1, t_2) = \Gamma_0 \exp[-\frac{t_1^2 + t_2^2}{2T^2} - \frac{(t_1 - t_2)^2}{2T_c^2} - i\omega_0(t_1 - t_2)], \tag{8}$$

where ω_0 is the central frequency of the pulse, T denotes the pulse duration, and T_c describes the temporal coherence length of the pulse. The cross-spectral density function of the pulses in the space-frequency domain can be readily determined by employing the Fourier transform [14,15], which yields:

$$W(\omega_1,\omega_2) = W_0 \exp[-\frac{(\omega_1-\omega_0)^2+(\omega_2-\omega_0)^2}{2\Omega^2} - \frac{(\omega_1-\omega_2)^2}{2\Omega_c^2}], \tag{9}$$

where $W_0 = \Gamma_0 T/2\pi\Omega$ and the spectral width Ω and the spectral coherence width Ω_c of the pulses are connected to the temporal parameters by the equations $\Omega^2 = 1/T^2 + 2/T_c^2$ and $\Omega_c = T_c\Omega/T$.

Suppose that the incident pulses propagate in a direction specified by a real unit vector $\boldsymbol{s}_0$ (as shown in Figure 1), the cross-spectral density function of the incident light at a pair of points, specified by position vectors $\boldsymbol{r}_1$ and $\boldsymbol{r}_2$, is given by the formula:

$$\begin{aligned} W^{(i)}(\boldsymbol{r}_1',\boldsymbol{r}_2',\omega_1,\omega_2) &= W_0 \exp[-\tfrac{(\omega_1-\omega_0)^2+(\omega_2-\omega_0)^2}{2\Omega^2} - \tfrac{(\omega_1-\omega_2)^2}{2\Omega_c^2}] \\ &\times \exp[i(k_2\boldsymbol{s}_0\cdot\boldsymbol{r}_2' - k_1\boldsymbol{s}_0\cdot\boldsymbol{r}_1')], \end{aligned} \tag{10}$$

with $k_i = \omega_i/c_i$ (i = 1, 2) and c being the speed of light in vacuum.

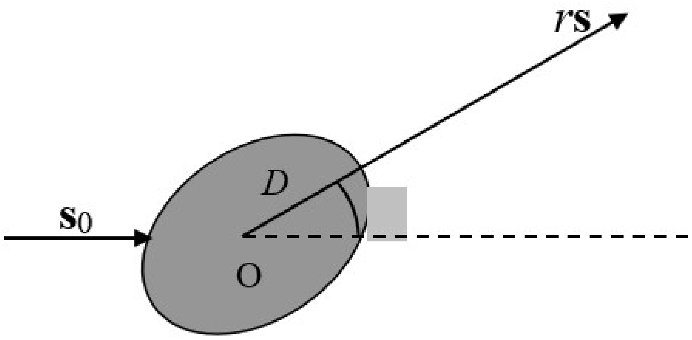

Figure 1. Scattering problem geometry. $\mathbf{s}_0$ and $\mathbf{s}$ represent the incident and scattering directions, respectively. θ is the scattering angle, and D is the domain the scatterer occupies.

We assumed that the medium is a weak scatterer, so that the scattering may be analyzed within the accuracy of the first-order Born approximation. The scattering potential of the medium, at a point specified by a position vector $\boldsymbol{r}_i'$ within the scatterer, is characterized by $F(\boldsymbol{r}_i',\omega_i)$. The resonance frequencies of the medium, i.e., the frequencies of its atomic or molecular transitions, were assumed not to lie within the spectral brand of the incident light. Thus, over the effective frequency range of the incident light, the scattering potential may be approximated by $F(\boldsymbol{r}_i',\omega_0)$.

For a deterministic medium, the scattering potential $F(\boldsymbol{r}_i',\omega_0)$ is a well-defined function of position. The cross-spectral density function of the scattered light in the far zone, at two points specified by position vectors $r\boldsymbol{s}_1$ and $r\boldsymbol{s}_2$, is given by the approximate far-zone formula

$$\begin{aligned} W^{(s)}(r\boldsymbol{s}_1,r\boldsymbol{s}_2,\omega_1,\omega_2) &= \int_D\int_D W^{(i)}(\boldsymbol{r}_1',\boldsymbol{r}_2',\omega_1,\omega_2)F^*(\boldsymbol{r}_1',\omega_0)F(\boldsymbol{r}_2',\omega_0) \\ &\times \tfrac{1}{r^2}\exp[ir(k_2-k_1) - i(k_2\boldsymbol{s}_2\cdot\boldsymbol{r}_2' - k_1\boldsymbol{s}_1\cdot\boldsymbol{r}_1')]d^3\boldsymbol{r}_1'd^3\boldsymbol{r}_2'. \end{aligned} \tag{11}$$

For a random medium, the scattering potential is, of course, a random function of position. The correlation function of the scattering potential at a pair of points, specified by position vectors $\boldsymbol{r}_1'$ and $\boldsymbol{r}_2'$ in the scattering medium, is defined by the formula:

$$C_F(\boldsymbol{r}_1',\boldsymbol{r}_2',\omega_0) = \langle F^*(\boldsymbol{r}_1',\omega_0)F(\boldsymbol{r}_2',\omega_0)\rangle, \tag{12}$$

where the angle brackets denote the average value taken over the ensemble of random medium realizations. We then obtain the formula:

$$\begin{aligned} W^{(s)}(r\mathbf{s}_1, r\mathbf{s}_2, \omega_1, \omega_2) &= \int\limits_D \int\limits_D W^{(i)}(\mathbf{r}_1', \mathbf{r}_2', \omega_1, \omega_2) C_F(\mathbf{r}_1', \mathbf{r}_2', \omega_0) \\ &\times \frac{1}{r^2} \exp[ir(k_2 - k_1) - i(k_2 \mathbf{s}_2 \cdot \mathbf{r}_2' - k_1 \mathbf{s}_1 \cdot \mathbf{r}_1')] d^3\mathbf{r}_1' d^3\mathbf{r}_2'. \end{aligned} \tag{13}$$

The mutual coherence function of the scattered field is obtained by taking the inverse Fourier transform of the cross-spectral density function, which gives:

$$\begin{aligned} \Gamma^{(s)}(r\mathbf{s}_1, r\mathbf{s}_2, \omega_1, \omega_2) &= \int \int_{-\infty}^{+\infty} W^{(s)}(r\mathbf{s}_1, r\mathbf{s}_2, \omega_1, \omega_2) \\ &\times \exp[i(\omega_1 t_1 - \omega_2 t_2) d\omega_1 d\omega_2. \end{aligned} \tag{14}$$

We now illustrate our analysis by two examples. Suppose first that the pulse is incident on a deterministic spherical scatterer centered at the point $\mathbf{r}_c = (0,0,d)$, occupying a finite domain D, with a three-dimensional (soft) Gaussian potential:

$$F(\mathbf{r}, \omega_0) = C_0 \exp[-\frac{x^2 + y^2 + (z-d)^2}{2\sigma^2}], \tag{15}$$

where C_0 and σ are positive constants, which are independent of position but may depend upon ω. Given the properties of the scatterer and those of the incident field, we may use Equations (7), (10), (11), (14), and (15) to give the following expressions for the intensity statistics. The average intensity of the scattered field is:

$$\begin{aligned} &\langle I^{(s)}(r\mathbf{s}, t) \rangle \\ &= \frac{(2\pi)^3 C_0^2 \sigma^6 \Gamma_0 T}{r^2 \sqrt{(1+4\sigma^2 \sin^2\frac{\theta}{2}(1/T^2+2/T_c^2)/c^2)(T^2+4\sigma^2\sin^2\frac{\theta}{2}/c^2)}} \\ &\times \exp\left[-\frac{(t-(2d\sin^2\frac{\theta}{2}+r)/c)^2}{T^2+4\sigma^2\sin^2\frac{\theta}{2}/c^2} - \frac{\omega_0^2}{[c^2/(4\sigma^2\sin^2\frac{\theta}{2})+(1/T^2+2/T_c^2)]}\right], \end{aligned} \tag{16}$$

and the normalized correlation of intensity fluctuations (NCIF) has the form:

$$\begin{aligned} &\frac{\langle \Delta I^{(s)}(r\mathbf{s},t_1) \Delta I^{(s)}(r\mathbf{s},t_2) \rangle}{\langle I^{(s)}(r\mathbf{s},t_1) \rangle \langle I^{(s)}(r\mathbf{s},t_2) \rangle} \\ &= \exp\left[-\frac{(t_1-t_2)^2}{\frac{T_c^2}{T^2}[1+4\sigma^2\sin^2\frac{\theta}{2}(1/T^2+2/T_c^2)/c^2][T^2+4\sigma^2\sin^2\frac{\theta}{2}/c^2]}\right], \end{aligned} \tag{17}$$

where θ is the angle between the observation direction and the incident direction, i.e., $\mathbf{s} \cdot \mathbf{s}_0 = \cos\theta$. Equations (16) and (17) give the analytical expressions for the average intensity and NCIF of the scattered field. The simple relationships make it easy to derive σ of the medium if we get the intensity, or the correlation of intensity fluctuations which can be performed by Hanbury Brown-Twiss measurements. We calculated in Figures 2 and 3 the normalized intensity and the NCIF of the scattered partially coherent Gaussian Schell-model plane-wave pulses for different values of σ of the deterministic spherical scatterer, respectively. The calculation parameters are $T = 15$ fs, $T_c = 10$ fs, $\lambda = 800$ nm, $\omega_0 = 2.36$ rad/fs and $t = \frac{r}{c}$. One finds from Figures 2 and 3 that the normalized intensity and the NCIF of the scattered partially coherent Gaussian Schell-model plane-wave pulse are closely related to σ of the deterministic spherical scatterer, which may be useful in studying the inverse problem. Figure 2 shows that the scattering becomes more directional when σ increases. And Figure 3 shows that the NCIF increases with the increase of σ.

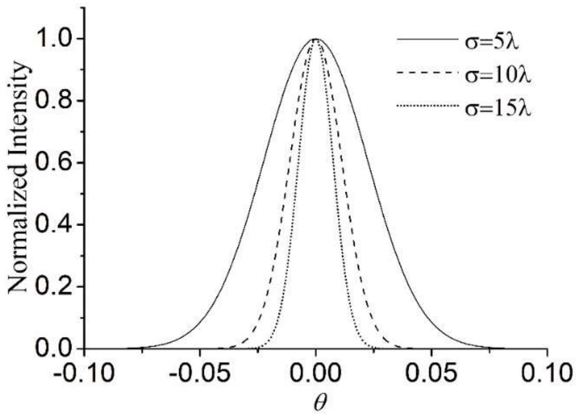

Figure 2. The normalized intensity of the scattered partially coherent Gaussian Schell-model plane-wave pulse versus θ for different values of σ of the deterministic spherical scatterer.

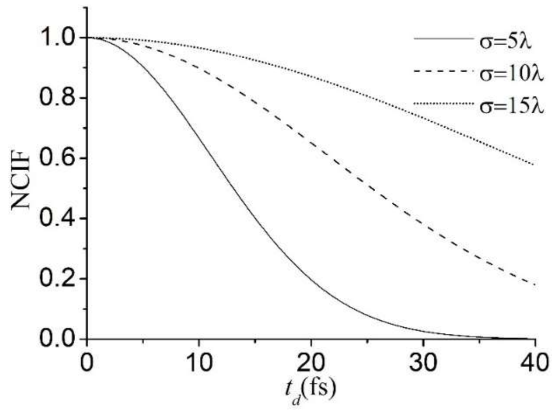

Figure 3. The normalized correlation of intensity fluctuations (NCIF) of the scattered partially coherent Gaussian Schell-model plane-wave pulse versus $t_d = t_2 - t_1$ for different values of σ of the deterministic spherical scatterer with $\theta = 0.5$.

Next, let us suppose that the pulse is incident on a quasi-homogeneous random medium. The correlation function of the scattering potential of such a medium has the form:

$$C_F(\boldsymbol{r}'_1, \boldsymbol{r}'_2, \omega_0) = C_R(\boldsymbol{R}', \omega_0) C_r(\boldsymbol{r}', \omega_0) = C_0 \exp\left[-\frac{(\boldsymbol{R}')^2}{2\sigma_R^2} - \frac{(\boldsymbol{r}')^2}{2\sigma_{\boldsymbol{r}}^2}\right], \tag{18}$$

where C_0, σ_R, and σ_r are positive constants with $\sigma_R \gg \sigma_r$. The function $C_R(\boldsymbol{R}', \omega_0)$ varies much more slowly with $\boldsymbol{R}' = (\boldsymbol{r}'_1 + \boldsymbol{r}'_2)/2$ than the function $C_r(\boldsymbol{r}', \omega_0)$ varies with $\boldsymbol{r}' = \boldsymbol{r}'_2 - \boldsymbol{r}'_1$. It follows from Equations (7), (10), (13), (14), and (18) that the average intensity and the NCIF of the scattered field are given by the expressions:

$$\begin{aligned}
&\langle I^{(s)}(r\boldsymbol{s}, t)\rangle \\
&= \frac{(2\pi\sigma_R\sigma_r)^3 C_0 \Gamma_0 T}{\sqrt{(T^2 + 8\sigma_R^2 \sin^2\frac{\theta}{2}/c^2)(1 + 2\sigma_r^2 \sin^2\frac{\theta}{2}(1/T^2 + 2/T_c^2)/c^2)}} \\
&\times \exp\left[-\frac{(t - r/c)^2}{(T^2 + 8\sigma_R^2 \sin^2\frac{\theta}{2}/c^2)^2}\right. \\
&\left. + \frac{\omega_0^2}{(1/T^2 + 2/T_c^2)(1 + 2(1/T^2 + 2/T_c^2)\sigma_r^2 \sin^2\frac{\theta}{2}/c^2)}\right],
\end{aligned} \tag{19}$$

$$\begin{aligned}&\frac{\langle \Delta I^{(s)}(r\mathbf{s},t_1)\Delta I^{(s)}(r\mathbf{s},t_2)\rangle}{\langle I^{(s)}(r\mathbf{s},t_1)\rangle\langle I^{(s)}(r\mathbf{s},t_2)\rangle}\\ &= \exp\left[-\frac{(t_1-t_2)^2}{\frac{(T^2+8\sigma_R^2\sin^2\frac{\theta}{2}/c^2)(1/(1/T^2+2/T_c^2)+2\sigma_r^2\sin^2\frac{\theta}{2}/c^2)}{(T^4/(T_c^2+2T^2)+(4\sigma_R^2-\sigma_r^2)\sin^2\frac{\theta}{2}/c^2)}}\right].\end{aligned} \tag{20}$$

It follows from the analytical expressions Equations (19) and (20) that for a quasi-homogeneous random medium, one can also derive σ_R and σ_r from both the average intensity and the NCIF of the scattered field. Figures 4 and 5 illustrate the normalized intensity and the NCIF of the scattered partially coherent Gaussian Schell-model plane-wave for different values of σ_R and σ_r of the quasi-homogeneous random medium separately. Other calculation parameters are the same as those in Figures 2 and 3. It is shown that σ_R and σ_r of the quasi-homogeneous random medium determine both the average intensity and the NCIF together; however, the effect of σ_r is more apparent than that of σ_R. Figure 4 shows that the scattering becomes more directional when σ_R or σ_r increases. Figure 5 shows that the NCIF increases as σ_r increases or σ_R decreases. In applications, the troposphere and confined plasmas sometimes can be modeled as quasi-homogeneous random media.

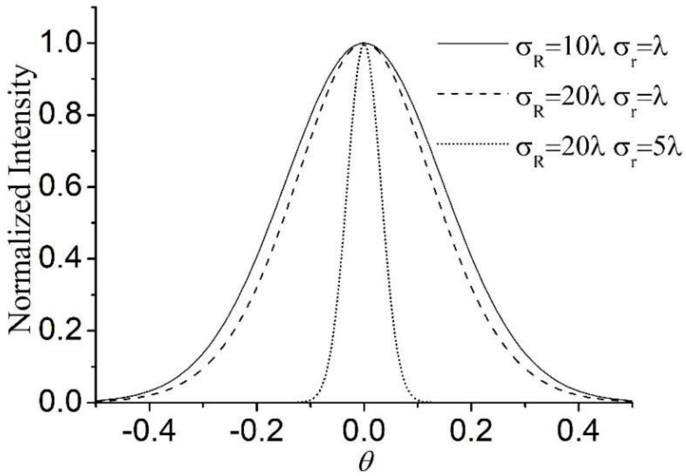

Figure 4. The normalized intensity of the scattered partially coherent Gaussian Schell-model plane-wave pulse versus θ for different values of σ_R and σ_r of the quasi-homogeneous random medium.

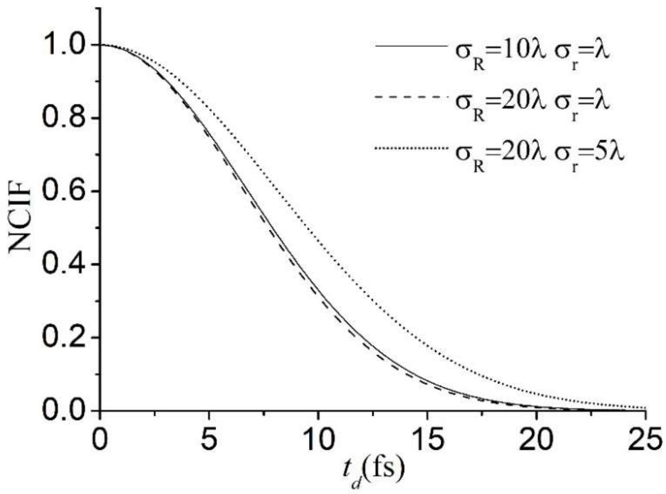

Figure 5. The NCIF of the scattered partially coherent Gaussian Schell-model plane-wave pulse versus $t_d = t_2 - t_1$ for different values of σ_R and σ_r of the quasi-homogeneous random medium with $\theta = 0.5$.

4. Summary

We have derived analytical formulas for the average intensity and the normalized correlation of intensity fluctuations for the scattered field of a partially coherent Gaussian Schell-model plane-wave pulse. We considered two typical scattering objects, a deterministic spherical scatterer and a quasi-homogeneous random medium. Our study extended the research of correlation of intensity fluctuations at two space points of the scattered stationary fields to that at two time points of scattered non-stationary fields.

Author Contributions: Y.Z. (Data curation, Writing-original draft, Methodology); C.D. (Formal analysis, Writing review and editing); L.P. (Project administration, Writing-review and editing), Y.C. (Project administration, Writing-review and editing).

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References

1. Wolf, E.; Foley, J.T. Scattering of electromagnetic fields of any state of coherence from space-time fluctuations. *Phys. Rev. A* **1989**, *40*, 579–587. [CrossRef]
2. Van Dijk, T.; Fischer, D.G.; Visser, T.D.; Wolf, E. Effects of Spatial Coherence on the Angular Distribution of Radiant Intensity Generated by Scattering on a Sphere. *Phys. Rev. Lett.* **2010**, *104*, 173902. [CrossRef]
3. Tong, Z.; Korotkova, O. Theory of weak scattering of stochastic electromagnetic fields from deterministic and random media. *Phys. Rev. A* **2010**, *82*, 033836. [CrossRef]
4. Gbur, G. Designing directional cloaks from localized fields. *Opt. Lett.* **2015**, *40*, 986–989. [CrossRef]
5. Wang, Y.; Yan, S.; Kuebel, D.; Visser, T.D. Dynamic control of light scattering using spatial coherence. *Phys. Rev. A* **2015**, *92*, 013806. [CrossRef]
6. Li, J.; Chang, L. Spectral shifts and spectral switches of light generated by scattering of arbitrary coherent waves from a quasi-homogeneous media. *Opt. Express* **2015**, *23*, 16602–16616. [CrossRef]
7. Wang, Y.; Kuebel, D.; Visser, T.D.; Wolf, E. Creating von Laue patterns in crystal scattering with partially coherent sources. *Phys. Rev. A* **2016**, *94*, 033812. [CrossRef]
8. Wang, T.; Wu, H.; Ding, Y.; Ji, X.; Zhao, D. Changes in the spectral degree of coherence of a light wave on scattering from a particulate medium. *Opt. Commun.* **2016**, *381*, 210–213. [CrossRef]
9. Hurwitz, E.; Gbur, G. Optically switchable directional invisibility. *Opt. Lett.* **2017**, *42*, 1301–1304. [CrossRef]
10. Zhao, D.; Korotkova, O.; Wolf, E. Application of correlation-induced spectral changes to inverse scattering. *Opt. Lett.* **2007**, *32*, 3483–3485. [CrossRef]
11. Lahiri, M.; Wolf, E.; Fischer, D.G.; Shirai, T. Determination of Correlation Functions of Scattering Potentials of Stochastic Mediafrom Scattering Experiments. *Phys. Rev. Lett.* **2009**, *102*, 123901. [CrossRef] [PubMed]
12. Wu, H.; Pan, X.; Zhu, Z.; Ji, X.; Wang, T. Reciprocity relations of an electromagnetic light wave on scattering from a quasi-homogeneous anisotropic medium. *Opt. Express* **2017**, *25*, 11297–11305. [CrossRef] [PubMed]
13. Zhao, D.; Wang, T. Direct and inverse problems in the theory of light scattering. *Prog. Opt.* **2012**, *57*, 261–308.
14. Pääkkönen, P.; Turunen, J.; Vahimaa, P.; Friberg, A.T.; Wyrowski, F. Partially coherent Gaussian pulses. *Opt. Commun.* **2002**, *204*, 53–58. [CrossRef]
15. Lajunen, H.; Vahimaa, P.; Tervo, J. Theory of spatially and spectrally partially coherent pulses. *J. Opt. Soc. Am. A* **2005**, *22*, 1536–1545. [CrossRef]
16. Ding, C.; Cai, Y.; Korotkova, O.; Zhang, Y.; Pan, L. Scattering-induced changes in the temporal coherence length and the pulse duration of a partially coherent plane-wave pulse. *Opt. Lett.* **2011**, *36*, 517–519. [CrossRef]
17. Ding, C.; Cai, Y.; Zhang, Y.; Pan, L. Scattering-induced changes in the degree of polarization of a stochastic electromagnetic plane-wave pulse. *J. Opt. Soc. Am. A* **2012**, *29*, 1078–1090. [CrossRef]
18. Tang, M.; Zhao, D.; Zhu, Y.; Ang, L.K. Electromagnetic sinc Schell-model pulses in dispersive media. *Phys. Lett. A* **2016**, *380*, 794–797. [CrossRef]

19. Wu, G.; Visser, T.D. Correlation of intensity fluctuations in beams generated by quasi-homogeneous sources. *J. Opt. Soc. Am. A* **2014**, *31*, 2152–2159. [CrossRef] [PubMed]
20. Xin, Y.; He, Y.; Chen, Y.; Li, J. Correlation between intensity fluctuations of light scattered from a quasi-homogeneous random media. *Opt. Lett.* **2010**, *35*, 4000–4002. [CrossRef]
21. Jacks, H.C.; Korotkova, O. Intensity–intensity fluctuations of stochastic fields produced upon weak scattering. *J. Opt. Soc. Am. A* **2011**, *28*, 1139–1144. [CrossRef]
22. Kuebel, D.; Visser, T.D.; Wolf, E. Application of the Hanbury Brown–Twiss effect to scattering from quasi-homogeneous media. *Opt. Commun.* **2013**, *294*, 43–48. [CrossRef]
23. Wolf, E. *Introduction to the Theory of Coherence and Polarization of Light*; Cambridge University Press: New York, NY, USA, 2007.
24. Mandel, L.; Wolf, E. *Optical Coherence and Quantum Optics*; Cambridge University Press: New York, NY, USA, 1995.