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The quality of temporal ghost imaging over optical fiber

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ABSTRACT

By exploiting the duality between light propagation in space and time, temporal ghost imaging (TGI) over optical fiber is investigated theoretically and numerically. The analytical expression of the point spread function (PSF) of TGI is derived. The effects of the optical fiber length, group-velocity dispersion (GVD) coefficient and effective width of the incident pulse on TGI over optical fiber are studied by using classical temporally incoherent non-stationary pulsed light. Based on simulation results, we find that for different dispersion, high quality TGI can be obtained by using appropriate optical fiber length and effective width of the incident pulse. Our results can be used to choose the optimal parameters in the design of realistic TGI system over optical fiber.

1. Introduction

Ghost imaging uses correlation measurement between light transmitted through an object and the spatially resolved intensity pattern of the incident light to reconstruct the ghost-image of the original object [1]. The interesting aspect of this technique is that information about the spatial distribution of the object is retrieved through the intensity correlation measurement, by scanning transversely the point-like detector located at the reference arm, although the beam in this arm never interacts with the object to be imaged. Pittman et al. first realized ghost imaging using a two-photon entangled source [2,3]. A few years later, it was observed that ghost imaging did not necessitate nonlocal correlations of entangled photons but could be realized with classical, mutually correlated light beams [4–9].

Note that more and more attention has been paid to temporal ghost imaging (TGI) due to its novel peculiarities and its wide application. Very recently, Ryczkowski et al. performed the experiment of TGI which achieved temporal resolution at the picosecond level and was insensitive to the temporal distortion that may occur after the object [10]. By taking into account the space-time duality in optics [11], it was readily expected that the temporal counterpart of conventional ghost imaging was in existence. In fact, temporal ghost diffraction with entangled photons was shown both theoretically and experimentally in view of pulse shaping [12,13]. In 2010, Setälä et al. presented TGI using long classical plane-wave pulses and proved that the intensity correlation was given by the fractional Fourier transform of the temporal object [14]. In recent years, it has also been proved theoretically that the same phenomenon could be reproduced with classical partially coherent optical pulses on the basis of the fourfold analogy between the quantum entanglement and the classical coherence in the space and time domains [15]. This analogy was derived from Wolf equations that the two-photon probability amplitudes satisfied and Wolf equations could govern the propagation of classical second-order coherence functions in the space and time domains [16–18]. In 2016, Dong et al. theoretically and experimentally explored the way to realize long distance quantum ghost imaging (QGI) over optical fibers [19].

Image quality is the most important factor to characterize an imaging system. There are many works to study the quality of ghost imaging in the spatial domain, while the corresponding work in TGI over optical fiber is quite rare, especially the effects from the properties of optical fiber on TGI are not discussed. In this paper, we theoretically investigate the quality of TGI over optical fiber with classical temporally incoherent non-stationary pulsed light. The analytical expression describing the point spread function (PSF) of TGI is firstly derived. The quality of TGI is dependent on the width of PSF. Based on numerical simulation, we quantitatively analyze the quality of TGI over optical fiber. It is shown that the shorter optical fiber length and wider incident pulse can lead to high quality TGI under different dispersion.

2. Theoretical model

The geometry of TGI over optical fiber is illustrated in Fig. 1. In general, the source is assumed as classical temporally incoherent

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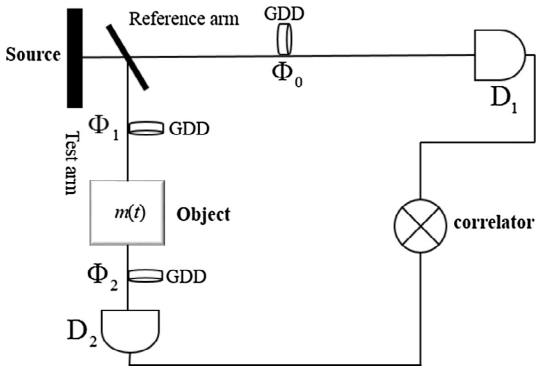

Fig. 1. Geometry of TGI over optical fiber.

non-stationary pulsed light whose correlation time is zero. The source is split into two mutually correlated beams which are directed to the reference and test arms. In the reference arm, the beam propagates in a dispersive medium and is detected by a fast detector which does not see the temporal object to be characterized. In the test arm, the other beam travels in a dispersive medium, then directly illuminates the temporal object to be imaged, and the transmitted pulse is collected by a slow detector which does see the object but without resolving its temporal structure. The detectors are employed to measure the instantaneous intensities at the end of both arms. The temporal characteristics of this object are obtained by the correlation between intensity fluctuations in the two arms.

In this TGI system, the temporal object $m(t)$ is a temporal modulator with a deterministic variation and is represented by nonreturn to zero (NRZ) code which is shown in Fig. 2. The common dispersive medium is signal-mode fiber characterized by the group-delay dispersion (GDD) parameters. The GDD parameters of optical fibers are described through the form $\Phi_i = \beta_i d_i,\ i = (0, 1, 2)$, where β_i is the group-velocity dispersion (GVD) coefficient, and d_i denotes the length of signal-mode fiber.

Suppose that, the incident pulse from the initial source is the Gaussian form and it is classical temporally incoherent non-stationary pulsed light. The source of this kind may be characterized by

$$\Gamma_0(t_1', t_2') = \langle E_0(t_1')E_0^*(t_2')\rangle = exp\left[-\frac{{t_1'}^2 + {t_2'}^2}{T^2}\right]\delta(t_2' - t_1'), \qquad (1)$$

where the positive constant T represents the effective width of the pulse, $\delta()$ denotes the Dirac delta function, and $\langle \ldots \rangle$ denotes the statistical average.

Both arms consist of a cascade of linear elements whose effect on the field is contained in the kernels function. In fact, the kernel function is the transmission function in the optical fiber channel, which can also be regarded as the unit impulse response function

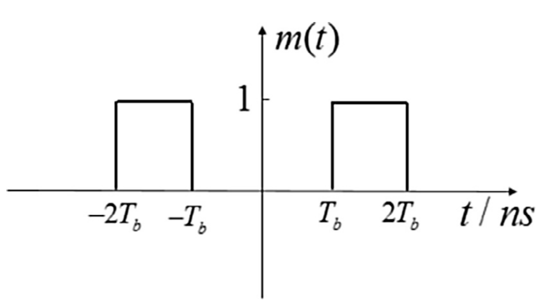

Fig. 2. The signal waveform pattern of the temporal object.

of the system. So the kernels $K_1(t_1, t_1')$ for the reference arm and $K_2(t_2, t_2')$ for the test arm are given, respectively, by the expressions [20]

$$K_1(t_1, t_1') = \sqrt{\frac{i}{2\pi\Phi_0}}exp\left[-i\frac{(t_1' - t_1)^2}{2\Phi_0}\right], \qquad (2)$$

$$K_2(t_2, t_2') = \sqrt{\frac{i}{2\pi\Phi_1}}\sqrt{\frac{i}{\Phi_2}}\int dt\, m(t) \times exp\left[-i\frac{(t - t_2')^2}{2\Phi_1}\right]exp\left[-i\frac{(t_2 - t)^2}{2\Phi_2}\right], \qquad (3)$$

here, $m(t)$ denotes the temporal object to be imaged, the specific signal waveform of the temporal object is rectangular shape with symbol interval T_b.

After the propagation of the pulse, the intensity distribution in the test or reference detector is

$$I_j(t_j) = \int dt_1' dt_2' \Gamma_0(t_1', t_2') K_j^*(t_j, t_1') K_j(t_j, t_2'), \qquad (4)$$

where $j = 1, 2$. The information about the temporal object can be extracted from the correlation between the intensity fluctuations in two detectors [20]

$$G(t_1, t_2) = \langle I_1(t_1) I_2(t_2)\rangle - \langle I_1(t_1)\rangle\langle I_2(t_2)\rangle = \left|\int dt_1' dt_2' \Gamma_0(t_1', t_2') K_1^*(t_1, t_1') K_2(t_2, t_2')\right|^2. \qquad (5)$$

In fact, the temporal object satisfies the following conditions [21]

$$\langle m(t) m^*(t')\rangle = m(t) m^*(t'). \qquad (6)$$

Substituting Eqs. (1)–(3), Eq. (6) into Eq. (5), we can obtain the correlation function of intensity fluctuation $G(t_1, t_2)$ as

$$\begin{aligned} G(t_1, t_2) &= \frac{1}{4\pi^2\Phi_0\Phi_1\Phi_2}\int dt_1' dt_2' dt dt' \langle m(t) m^*(t')\rangle \\ &\times exp\left[-\alpha({t_1'}^2 + {t_2'}^2)\right] \\ &\times exp\left[i\beta_{11}\left[(t_2' - t_1)^2 - (t_1' - t_1)^2\right]\right] \\ &\times exp\left[i\beta_{12}\left[(t' - t_1')^2 - (t - t_2')^2\right]\right] \\ &\times exp\left[i\beta_{13}\left[(t_2 - t')^2 - (t_2 - t)^2\right]\right] \\ &= \frac{1}{4\pi^2\Phi_0\Phi_1\Phi_2}\int dt_1' dt_2' dt dt' m(t) m^*(t') \\ &\times exp\left[-A{t_1'}^2 - B{t_2'}^2 - Ct_1' - Dt_2'\right] \\ &= \frac{2\beta_{11}\beta_{12}\beta_{13}}{\pi\sqrt{\alpha^2 + (\beta_{11} - \beta_{12})^2}}\int dt |m(t)|^2 exp\left[-\frac{(t - \frac{\beta_{11}}{\beta_{12}}t_1)^2}{\Delta_{PSF}^2}\right], \end{aligned} \qquad (7)$$

where $\alpha = 2/T^2, \beta_{11} = 1/2\Phi_0, \beta_{12} = 1/2\Phi_1, \beta_{13} = 1/2\Phi_2, A = \alpha + i\beta_{11} - i\beta_{12}, B = \alpha - i\beta_{11} + i\beta_{12}, C = -2t_1 i\beta_{11} + 2t' i\beta_{12}$, and $D = 2t_1 i\beta_{11} - 2ti\beta_{12}$.

Integrating over t_2, temporal ghost-image is given by

$$G(t_1) = \int dt_2 G(t_1, t_2) = \frac{2\beta_{11}\beta_{12}\beta_{13}}{\pi\sqrt{\alpha^2 + (\beta_{11} - \beta_{12})^2}}\int dt |m(t)|^2 exp\left[-\frac{(t - \frac{\beta_{11}}{\beta_{12}}t_1)^2}{\Delta_{PSF}^2}\right], \qquad (8)$$

from (8), the PSF of TGI over optical fiber [22–24] is

$$h(t, t_1) = \frac{\pi}{\sqrt{2\alpha}\beta_{12}\Delta_{PSF}}exp\left[-\frac{(t - \frac{\beta_{11}}{\beta_{12}}t_1)^2}{\Delta_{PSF}^2}\right], \qquad (9)$$