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Non-local correlation interference with pseudo-thermal light

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ABSTRACT

We report an experimental demonstration of non-local correlation interference with a pseudo-thermal light source. The experimental results show denser and sparser interference effects compared to classical interference. Our experimental result suggests that denser lithography and imaging can also be achieved with correlation method.

1. Introduction

People recognized the wave nature of light since Thomas Young's double-slit experiment. From then on, how to improve the resolution of optical equipment is a heated topic. In the recent decades, correlation measurement provided a remarkably useful method to take this burden. In 1995, Shih et al. achieved ghost imaging and interference with quantum entangled sources generated by a spontaneous parametric down conversion process in a nonlinear crystal [1,2]. With the same method, sub-wavelength interference was achieved, which significantly improved the resolution of double-slit diffraction [3]. In 1999, Choi et al. demonstrated the images with noiseless optical amplification process in a KTP crystal [4]. When people were delighted at the advantages of quantum source, ghost imaging and diffraction were achieved with thermal light source [5–16]. After the first realization of correlation images with classical light source by Boyd's group, people began to discuss the relationship between the quantum source and classical source in ghost imaging [8,10,13]. Meanwhile, the quality of imaging was discussed in detail in Refs. [9,17]. On the other hand, Granot et al. studied the sub-wavelength spatial solutions with nonlocal Kerr effect in 1999, Fonseca et al. studied the nonlocal de Broglie wavelength of a two-particle system in 2000, Scarcelli et al. studied the two-photon interference with thermal light, and Gao et al. demonstrated an interference experiment of non-local double-slit in 2008 [18–21]. Similar effects were reported in different systems [22–26]. Although, these works have shown the characters of resolution breaking and non-locality with coincidence or correlation measurement, there is no report about denser or sparser sub-wavelength non-local interference to our knowledge.

In this paper, we carry out a non-local double-slit experiment with pseudo-thermal light. Second-order correlation calculation method and experimental setup are applied as in Ref. [21]. With different ways of measurement, we can get denser sub-wavelength and sparser interference patterns. We hope that our work can deepen the cognition of correlation measurements and can be used in super resolution imaging.

2. Theoretical analysis

The experimental setup is shown in Fig. 1. A He–Ne laser beam with wavelength $\lambda = 632.8$ nm impinges on a slowly rotating ground glass (GG) with a rotating frequency of 5×10^{-5} Hz to form the pseudo-thermal light source. Then, the quasi-thermal light is separated by a 50/50 nonpolarizing beam splitter (BS), and one beam passes through an object T_a in the up arm, and the other one passes through T_b in the down arm. Two charge-coupled devices (CCDs), D_1 and D_2, register the intensity distributions $I_1(x_1)$ and $I_2(x_2)$. Since the source is spatially incoherent, it is clear that the average intensity distribution of the diffraction field in each arm is homogeneous.

We now consider the intensity correlation measurement in this scheme. For simplicity, our discussion will be restricted to one dimension, but it is straightforward to extend the analysis to two dimensions. Let $T_a(x_a)$ and $T_b(x_b)$ be the transmittance function describing the two objects, separately. The impulse response

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functions from the thermal light source (GG) to detectors D_1 and D_2 are, respectively, expressed as

$$h_1(x_1, x_0) = \frac{k\exp\left[ik(z_{01} + z_1)\right]}{i2\pi\sqrt{z_{01}z_1}} \int dx_a T_a(x_a) \exp\left[\frac{ik}{2z_{01}}(x_a - x_0)^2 + \frac{ik}{2z_1}(x_1 - x_a)^2\right], \tag{1}$$

$$h_2(x_2, x_0) = \frac{k\exp\left[ik(z_{02} + z_2)\right]}{i2\pi\sqrt{z_{02}z_2}} \int dx_b T_b(x_b) \exp\left[\frac{ik}{2z_{02}}(x_b - x_0)^2 + \frac{ik}{2z_2}(x_2 - x_b)^2\right], \tag{2}$$

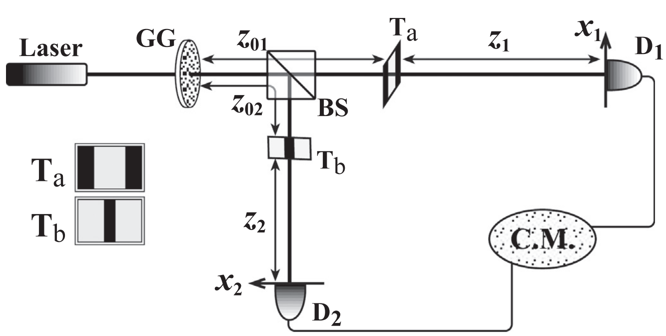

Fig. 1. Experimental setup of the non-local correlation interference. GG is a ground glass and BS is a 50/50 non-polarizing beam splitter. T_a and T_b are the objects. D_1 and D_2 are two CCDs. Correlation measurement (C.M.) is employed in this experiment. The insets demonstrate the shapes of the objects in the two arms.

where k is the wave number. z_{01} and z_1 are distances from object T_a to the source and D_1 plane, respectively. z_{02} and z_2 are distances from object T_b to the source and D_2 plane, respectively. x_1 and x_2 are transverse coordinates on the planes of T_a and T_b, respectively.

The normalized intensity correlation between the two CCDs can be written as

$$g^{(2)}(x_1, x_2) = \frac{\langle I_1(x_1)I_2(x_2)\rangle}{\langle I_1(x_1)\rangle\langle I_2(x_2)\rangle} = 1 + \frac{\left|\langle E_1^*(x_1)E_2(x_2)\rangle\right|^2}{\langle I_1(x_1)\rangle\langle I_2(x_2)\rangle}, \tag{3}$$

where $E_i(x_i)(i = 1, 2)$ is the field in the plane of D_i.

The cross correlation term can be described as

$$\langle E_1^*(x_1)E_2(x_2)\rangle = \int dx_0 dx_0' h_1^*(x_1, x_0)h_2(x_2, x_0')\langle E_0^*(x_0)E_0(x_0')\rangle, \tag{4}$$

where $E_0(x_0)$ is the field of the source, and is spatially complete incoherent that

$$\langle E_0^*(x_0)E_0(x_0')\rangle = I_0\delta(x_0 - x_0'), \tag{5}$$

where I_0 is a constant with the same dimension to the light intensity. For simplicity, we set $z_{01} = z_{02}$, $z_1 = z_2 = z$, then the first-order field correlation between the two fields $E_1(x_1)$ and $E_2(x_2)$ is obtained to be

$$\langle E_1^*(x_1)E_2(x_2')\rangle = I_0 \int dx_0 h_1^*(x_1, x_0)h(x_2, x_0) \propto \exp\left[-\frac{ik}{2z}\left(x_1^2 - x_2^2\right)\right] \int dx T(x)\exp\left[\frac{ik}{z}\left(x_1 - x_2\right)x\right], \tag{6}$$

where $T(x) = T_a^*(x)T_b(x)$. Apparently, the cross correlation term in Eq. (6), demonstrates a Fourier transformation of a combined target $T(x)$.

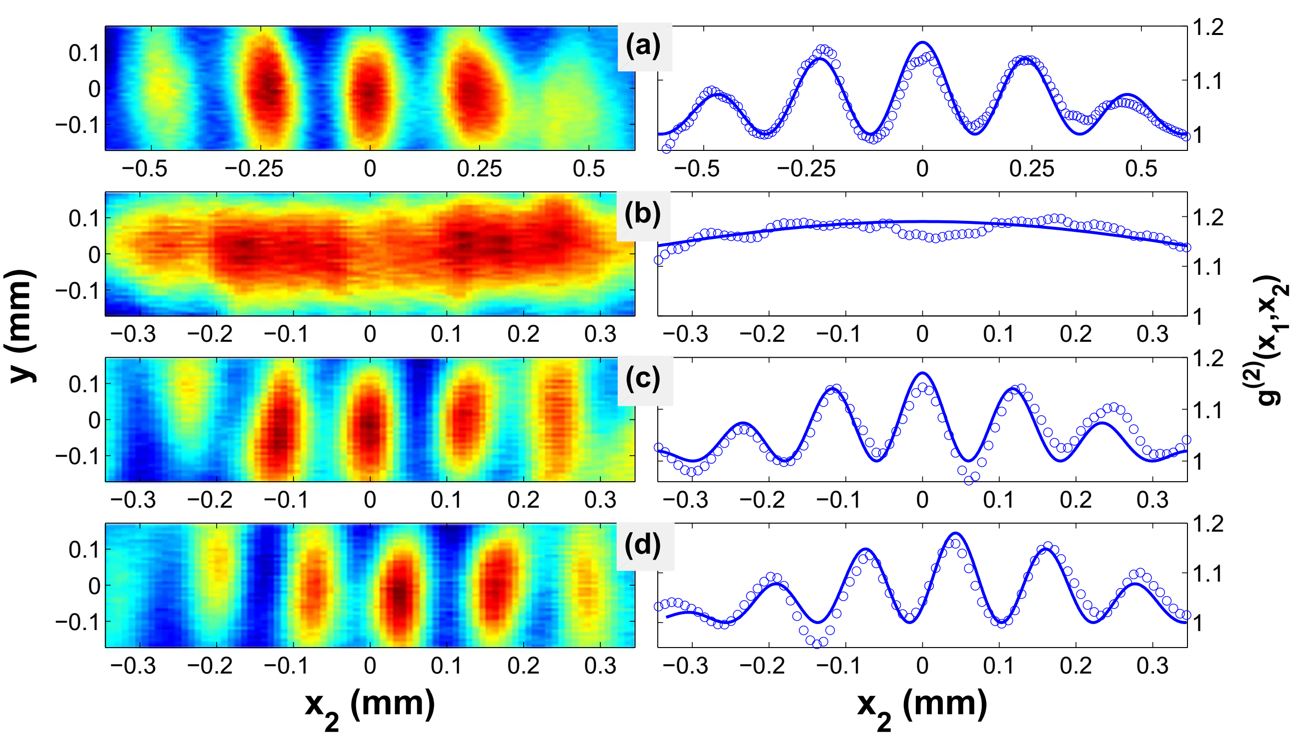

Fig. 2. Experimental results of non-local correlation measurement. We set $x_1 = 0$ in (a), $x_1 = x_2$ in (b), $x_1 = -x_2$ in (c) and $x_1 = -(x_2 - 86\ \mu m)$ in (d). Left and right columns correspond to the 2D and 1D results, respectively. In the right column, the open circles are experimental data and the solid lines are theoretical curves.