Nonlocal Double-Slit Interference with Pseudothermal Light

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We perform a nonlocal double-slit interference experiment with pseudothermal light. The experimental result exhibits a typical double-slit interference fringe in the intensity correlation measurement, in agreement with the theoretical analysis by means of the property of the second-order spatial correlation of field.

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Young’s double-slit experiment provided crucial evidence for the wave nature of light. The light from the two slits fell onto a screen and produced a visible pattern of light and dark parallel bands called fringes. These light and dark bands are due to constructive and destructive interference of the light coming from each slit. To create a stable interference pattern, the source of waves must be coherent in both time and space. Recently, Fonseca et al.1 reported a nonlocal double-slit interference experiment using entangled photon pairs. The signal and idler photons generated by spontaneous parametric down-conversion (SPDC) are scattered by two spatially separated apertures: none of them is a double-slit but their superposition at the same place forms a double-slit. The experimental result showed that an interference fringe appeared in the two-photon coincidence measurement whereas the individual signal and idler intensity profiles did not exhibit any fringe. The effect was attributed to the nonlocal nature of quantum interference.

Recent studies have shown that a thermal light source can play a role similar to that of a two-photon entangled source in “ghost” imaging, “ghost” interference and subwavelength interference2,3,4,5,6,7,8,9,10,11. In this paper, we report a nonlocal double-slit experiment using a pseudothermal light source. Though the source in our experiment is incoherent and does not exist any quantum entanglement, the interference effect can still be carried out by such a nonlocal double-slit.

The experimental setup shown in Fig. 1 is similar to that in Ref. [1] with the exception that a pseudo-thermal light source replaces the entangled two-photon source. The pseudothermal source is obtained by passing a focused semiconductor laser beam of wavelength 660 nm through a slowly rotating (0.002 Hz) ground glass disk. The spatial correlation of the light is separated by a 50/50 non-polarizing beamsplitter BS, which is 3.4 cm distant from the ground glass G. A1 and A2 are apertures whose superposition forms a double slit with the slit width 250 μm and the distance between two slit centers 670 μm. A1 and A2 are placed at the equal distance 4.7 cm from BS. D1 and D2 are charged-coupled-device (CCD) located at the same distance 85.3 cm from BS, and the two CCDs register the intensity distributions I1(x1) and I2(x2) across the beams.

Figure 2 shows the experimental results. Each intensity profile registered by the two CCDs does not exhibit any interference-diffraction pattern. It is clear that the source in the experiment is incoherent and random in transverse direction. Then we count the normalized intensity correlation between the two CCDs g(2)(x1, x2) = ⟨I1(x1)I2(x2)⟩/(⟨I1(x1)⟩⟨I2(x2)⟩) where one CCD scans the position while the other detects the intensity at a fixed position x = 0. We can see that the two intensity correlations, g(2)(0, x2) and g(2)(x1, 0), exhibit the double-slit interference fringes though there is no real double-slit in each arm.

The experimental results above can be explained by considering the spatial correlation properties of the thermal light. When a thermal light beam is divided into two beams, the spatial intensity correlation between them can be written as

⟨I1(x1)I2(x2)⟩ = ⟨E1∗(x1)E2∗(x2)E2(x2)E1(x1)⟩
= ⟨I1(x1)⟩⟨I2(x2)⟩ + ⟨|E1∗(x1)E2(x2)⟩|2,
(1)

⟨Ij(x)⟩ = (1/√2π) ∫ h∗j(x, x′)hj(x, x0)W(x‘ − x0)dx′dx0, (j = 1, 2)
(2)

⟨E∗(x1)E2(x2)⟩ = (1/√2π) ∫ h∗1(x1, x′0)h2(x2, x0)W(x‘ − x0)dx′dx0,
(3)

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where $h_j(x, x_0)$ ($j = 1, 2$) is the transfer function describing the field propagation in each beam, and $\tilde{W}(x' - x)$ is the first-order spatial correlation for the thermal light source.

For simplicity we consider the broadband limit for the source, i.e. $\tilde{W}(x' - x) \rightarrow \sqrt{2\pi} W_0 \delta(x' - x)$, and the symmetric arrangement of both apertures and detectors in two arms as showed in the experiment. Let $A_1(x)$ and $A_2(x)$ be transmission functions of the apertures in the two arms, their superposition forms a double-slit function

$$D(x) = A_1(x)A_2(x) = \begin{cases} 1 & (d - b)/2 \leq |x| \leq (d + b)/2 \\ 0 & \text{others} \end{cases},$$

where $b$ and $d$ are the slit width and the distance between the centers of two slits, respectively. The transfer function in each arm is given by

$$h_j(x, x_0) = \frac{k}{2\pi i\sqrt{L_0L}} \exp[ik(L_0 + L)] \int dx' A_j(x') \exp \left[ ik \left( \frac{(x' - x)^2}{2L} + \frac{(x' - x_0)^2}{2L_0} \right) \right], \quad (j = 1, 2)$$

where $L_0$ is the distance between the beamsplitter and the aperture, and $L$ the distance between the aperture and the detector. $k$ is the wave number of the beam. Thus we can calculate

$$\langle I_j(x) \rangle = \frac{W_0 k}{2\pi L} \int A_j^2(x') \, dx', \quad (j = 1, 2)$$

$$\langle E_1^*(x_1)E_2(x_2) \rangle = \frac{W_0 k}{\sqrt{2\pi L}} \exp \left[ -\frac{k}{2L} (x_2^2 - x_1^2) \right] \tilde{D} \left[ \frac{k}{L} (x_1 - x_2) \right],$$

where $\tilde{D}(q) = \langle 2b/\sqrt{2\pi} \rangle \text{sinc}(qb/2) \cos(qd/2)$ is the Fourier transform of the double-slit function $D(x)$. The intensity of each beam in Eq. (6) is independent of the transverse position due to the incoherence of the source, and in the intensity correlation (11) it gives rise to a background (the first term in Eq. (11)). However, the second term of Eq. (11) containing coherent information is now $\langle E_1^*(x_1)E_2(x_2) \rangle \sim \text{sinc}^2 \left[ \frac{L}{2\pi} (x_1 - x_2) \right] \cos^2 \left[ \frac{dL}{2L} (x_1 - x_2) \right]$. Therefore the interference fringe can be obtained in the intensity correlation measurement by scanning position in one beam and fixing a position in the other beam. The theoretical curves in Fig. 2 are in a good agreement with the experimental observation.

In summary, we have shown that the nonlocal double-slit interference can be realized with pseudothermal light. Our theoretical analysis demonstrated that two spatially separated apertures are correlated in the second-order field correlation. When the two apertures are placed at an equal distance from the beamsplitter, a typical double-slit interference pattern is obtained in the intensity correlation. Physically, this can be understood since, for the thermal light, lensless imaging can occur at the symmetric position of object with respect to the beamsplitter (9) and it causes a equivalent double-slit due to the superposition of the two apertures. We can conclude that the nonlocal double-slit interference effect should be attributed to the second-order spatial correlation of the field.

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