

# Interference from a nonlocal double-slit through one-photon process

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**Abstract:** In this paper, we report an interference experiment in which a spatially incoherent light source illuminates two spatially separated apertures, whose superposition at the same place forms a double-slit. The experimental result exhibits a well-defined interference fringe solely through intensity measurements, in agreement with the theoretical analysis by means of the first-order spatial interference of the incoherent light. Consequently, the nonlocal double-slit interference with thermal light should be attributed to the first-order spatial correlation of incoherent field.

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## 1. Introduction

In classical optics, interference is implemented through intensity observation in a detection plane where two or more light beams are superposed. This is regarded as the first-order or one-photon interference. Recently, it has been shown that interference phenomena may occur through intensity correlation measurements or two-photon coincidence measurements even if the first-order interference disappears, such as "ghost" imaging, "ghost" interference, subwavelength interference and nonlocal double-slit interference [1–5]. These effects, regarded as the second-order or two-photon interference, manifest nonlocal features since an entangled two-photon source is involved. As an example, in the nonlocal double-slit interference, a pair of signal and idler photons generated by spontaneous parametric down conversion 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 [5]. Though each intensity profile of the signal and idler beams does not exhibit any fringe, an interference pattern can be observed in the two-photon coincidence measurements of the two beams. These effects were attributed to the nonlocal character of the quantum entanglement. Recent theoretical and experimental results demonstrated that the similar second-order interference effects to the above can be performed by using a thermal light source [6–24]. Gao et al. [24] demonstrated that the interference from a nonlocal double-slit can be performed through the intensity correlation measurements of thermal light. The similarity between the two-photon entangled source and the thermal light source arouses different physical explanations, such as quantum vs. classical interpretation, to the nature of the second-order correlation of thermal light [25, 26]. There is still no consensus so far, and hence new experimental results would be helpful to reach the proper understanding.

## 2. Experimental results

In contrast to common knowledge that irregular phase distribution of an incoherent source shall degrade interference pattern in intensity observation, Zhang et al. first demonstrated that a spatially incoherent light source is capable of obtaining the coherence information through just the intensity distribution itself [27]. Here we report such an experiment in which the nonlocal double-slit interference can also be implemented through one-photon process. As sketched in Fig. 1, the experimental setup is very similar to the recent proposal [27] on the first-order interference effect in an unbalanced interferometer using spatially incoherent light source, but with a nonlocal double-slit replacing the real double-slit. The source field is divided into two parts by the beamsplitter BS<sub>1</sub>: one illuminates aperture A<sub>1</sub> in path 1 and the other illuminates aperture A<sub>2</sub> in path 2. BS<sub>2</sub> is a 50/50 beamsplitter, where the interference of the two fields may occur. Aperture A<sub>1</sub>, a wire with a diameter of  $L_1 = 0.2$  mm and aperture A<sub>2</sub>, a slit with a width of  $L_2 = 0.4$  mm, are placed at the equal distance  $z_0 = 1$  cm from BS<sub>1</sub>, and their superposition at the same position forms a double-slit of slit width  $b = 0.1$  mm and

spacing  $d = 0.3$  mm. The distance between the aperture and charge-coupled device (CCD) camera is  $z_1 = 38$  cm, and the two arms of the interferometer have the same optical path. A lens of focal length  $f = 19$  cm is set in the middle of path 2, so aperture  $A_2$  and the CCD screen are located in the two focal planes of lens  $L$ . The equal-optical-path condition can assure that one photon interferes with itself after passing through the two arms. However, there are different diffraction configurations in the two arms and it is the key in the present scheme since balanced interferometer washes out the information of the object [27].

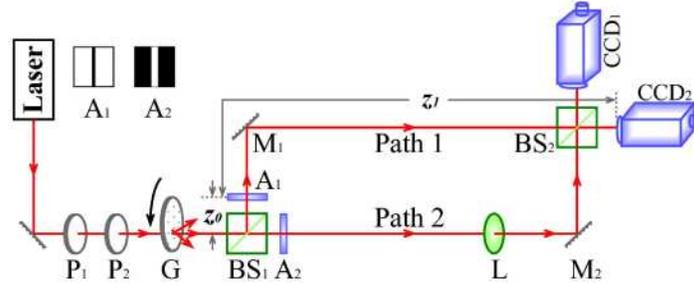


Fig. 1. Experimental scheme of an unbalanced interferometer using an incoherent light source. The interferometer is formed by two mirrors,  $M_1$  and  $M_2$ , and two beamsplitters,  $BS_1$  and  $BS_2$ . Polarizer  $P_1$  and Glan prism  $P_2$  are used for modulating the light intensity, and  $G$  is a rotating ground glass disk in the middle of path 2, where  $A_2$  and CCD camera are located at the two focal planes of lens  $L$ .

In the experiment we first use a pseudo-thermal light source as incoherent source, which is formed by passing a He-Ne laser beam of wavelength 632.8 nm through a slowly rotating (0.005 Hz) ground glass disk  $G$ . A huge number of speckles illuminating the object have the average size about 0.01 mm, which is much smaller than that of the apertures. 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 observe the interference patterns at the two outgoing ports of the beamsplitter  $BS_2$ , which are recorded by either of two CCD cameras. As the ground glass rotates slowly, the interference patterns in the detection plane fluctuate randomly. However, if we average over a number of frames, a well-defined interference pattern emerges [27]. Experimental results are shown in Fig. 2, where (a) and (b) are the average intensity patterns  $\langle I_1 \rangle$  and  $\langle I_2 \rangle$  registered by  $CCD_1$  and  $CCD_2$ , respectively. We will show in the next section that the fringes fit well the Fourier spectrum of a double-slit, modulated by a quadratic phase factor. Since the interference terms at the two outgoing ports have a phase shift  $\pi$  due to the reflection and transmission of the beamsplitter, the two fringes are complementary. For a 50/50 beamsplitter, the difference and sum of the two patterns gives the net interference pattern and the intensity background, as shown in Figs. 2(c) and 2(d), respectively. As a matter of fact, the homogeneous intensity background in Fig. 2(d) verifies the incoherence of the source.

To further demonstrate above effect, a true thermal light source should be taken into account. We replace the pseudo-thermal light source in Fig. 1 by a Na lamp of wavelength 589.3 nm with an illumination area of  $10 \times 10$  mm<sup>2</sup>. In this case, the coherence time of the Na lamp is much shorter than the responses time of the CCD camera, so the interference patterns can appear directly on the CCD screen, as shown in Fig. 3. The patterns are similar to that in Fig. 2, except for the slightly different spacings, owing to the different wavelengths of the two sources.

To confirm whether the interference patterns above are related to the spatial incoherence, we may compare them with the results obtained in the same interferometer using coherent light. We simply remove the ground glass in Fig. 1. The experimental results are shown in Fig. 4, where the interference patterns are stationary and completely different from that in Figs. 2 and 3.

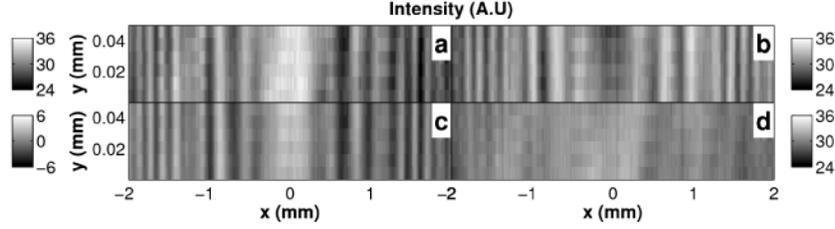


Fig. 2. Experimentally observed interference patterns in the scheme of Fig. 1. (a) and (b) are interference patterns (averaged over 2000 frames) registered by CCD<sub>1</sub> and CCD<sub>2</sub>, respectively; (c) and (d) are their difference and summation, respectively.

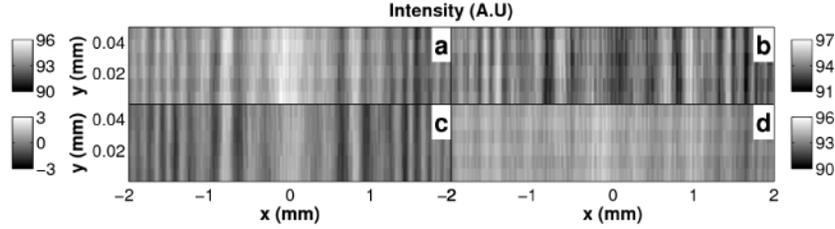


Fig. 3. Same as in Fig. 2 but with a Na lamp replacing the pseudo-thermal light source in the scheme of Fig. 1.

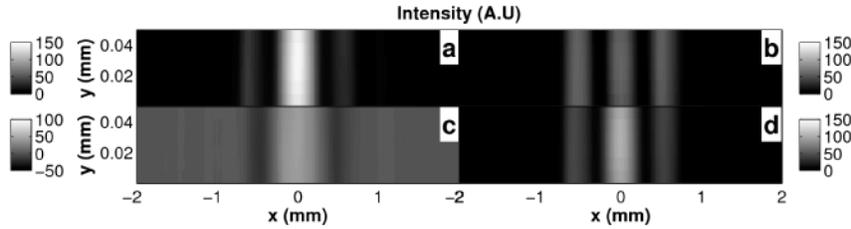


Fig. 4. Same as in Fig. 2 but the ground glass disk is removed in the scheme of Fig. 1.

### 3. Theoretical analysis

We now present the theoretical explanation for the experimental results. Let  $E_s(x)$  and  $E_j(x)$  be the source field at BS<sub>1</sub> and the field of path  $j(=1,2)$  at the recording plane, respectively, and  $x$ , the transverse position across the beam. The field diffraction in path  $j$  is described as

$$E_j(x) = \int h_j(x, x_0) E_s(x_0) dx_0, \quad (1)$$

where the impulse response function  $h_j(x, x_0)$  of path  $j(=1,2)$  is written as [24]

$$h_1(x, x_0) = \frac{k}{2\pi i \sqrt{z_0 z_1}} \exp[ik(z_0 + z_1)] \int A_1(x_1) \exp\left[\frac{ik}{2z_0}(x_1 - x_0)^2 + \frac{ik}{2z_1}(x - x_1)^2\right] dx_1, \quad (2a)$$

$$h_2(x, x_0) = \frac{k}{2\pi i \sqrt{z_0 f}} \exp[ik(z_0 + 2f)] \int A_2(x_2) \exp\left[\frac{ik}{2z_0}(x_2 - x_0)^2 - \frac{ik}{f} x x_2\right] dx_2. \quad (2b)$$

$k$  is the wavenumber of the beam;  $A_1(x) = 1 - \text{rect}(x/L_1)$  and  $A_2(x) = \text{rect}(x/L_2)$  are designated as the transmission functions of the two apertures, respectively, and their product  $D(x)$  is a double-slit function with slit width  $b = (L_2 - L_1)/2$  and spacing  $d = (L_2 + L_1)/2$ ,

i.e.,  $D(x) = A_1(x)A_2(x) = \text{rect}[(x-d/2)/b] + \text{rect}[(x+d/2)/b]$ . The propagation of the mutual coherence in the interferometer is given by

$$\langle E_i^*(x_1)E_j(x_2) \rangle \propto \int h_i^*(x_1, x_0)h_j(x_2, x_0') \langle E_s^*(x_0)E_s(x_0') \rangle dx_0 dx_0'. \quad (3)$$

The intensity patterns at the two outgoing ports of the interferometer are obtained to be

$$\langle I_{1,2}(x) \rangle = \langle E_1^*(x)E_1(x) \rangle + \langle E_2^*(x)E_2(x) \rangle \pm [\langle E_1^*(x)E_2(x) \rangle + \text{c.c.}], \quad (4)$$

where  $\langle E_j^*(x)E_j(x) \rangle$  and  $\langle E_1^*(x)E_2(x) \rangle$  stand for the intensity pattern in path  $j$  and the interference term, respectively.

For a spatially incoherent light source, the first-order field correlation function satisfies  $\langle E_s^*(x_0)E_s(x_0') \rangle = I_s \delta(x_0 - x_0')$ , and the interference term is written as

$$\begin{aligned} \langle E_1^*(x)E_2(x) \rangle &\propto I_s \int h_1^*(x, x_0)h_2(x, x_0)dx_0 \\ &= \frac{I_s k}{2\sqrt{2\pi}f} \exp\left[-\frac{ikx^2}{4f}\right] \int A_1^*(x_1)A_2(x_1) \exp\left[-\frac{ikx_1^2}{4f} - \frac{ikxx_1}{2f}\right] dx_1 \\ &\approx [I_s k / (2\sqrt{\pi}f)] \exp[-ikx^2/(4f)] \tilde{D}[kx/(2f)], \end{aligned} \quad (5)$$

where  $z_1 = 2f$  has been used. The approximation in the last step is valid when the size of the double-slit is much less than the area of the diffraction pattern, and the Fourier transform of the double-slit function  $D(x)$  is deduced as  $\tilde{D}(q) = (2b/\sqrt{2\pi}) \sin c(qb/2) \cos(qd/2)$ . Obviously, Eq. (5) is equivalent to the result that a real double-slit is set at the position of aperture  $A_2$  in the interferometer [27]. However, the two intensity distributions,  $\langle E_1^*(x)E_1(x) \rangle$  and  $\langle E_2^*(x)E_2(x) \rangle$ , are homogeneous. Figure 5 shows the numerical simulation of Eq. (5), fitting well with the experimental results in Fig. 2, apart from minor asymmetry. Any misalignment in the optical system may cause the asymmetry in the interference pattern.

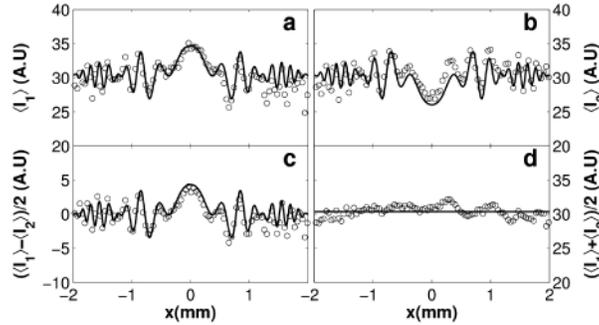


Fig. 5. One-dimensional interference patterns corresponding to that of Fig. 2. Experimental data and theoretical simulation are given by open circles and solid lines, respectively.

As for the spatially coherent light, it has  $\langle E_s^*(x_0)E_s(x_0') \rangle = E_s^*(x_0)E_s(x_0')$ , and the first-order correlation function Eq. (3) is separable as

$$\langle E_i^*(x_1)E_j(x_2) \rangle \propto \int h_i^*(x_1, x_0)E_s^*(x_0)dx_0 \times \int h_j(x_2, x_0')E_s(x_0')dx_0'. \quad (6)$$

As a result, there is no joint diffraction between the two arms to form an effective double-slit. For simplicity, we assume the Gaussian intensity distribution with a plane wave front for the

laser beam, i.e.,  $E_s(x_0) \sim \exp(-x_0^2/\sigma^2)$ , where  $\sigma$  characterizes the spot size. Using Eq. (6) and Eq. (4), we calculate 1D interference patterns in Fig. 6. As we expected, the net interference pattern in Fig. 6 (c) corresponds to the product of the diffraction fields of the two apertures, and the intensity background in Fig. 6 (d) coincides with the sum of the two diffraction patterns of  $A_1$  and  $A_2$ . No information about the double-slit can be obtained when  $A_1$  and  $A_2$  are illuminated coherently. The theoretical curves are in a good agreement with the experimental results for the coherent light case of Fig. 4. A slight mismatch of some side-peaks comes from our simple laser model in the theoretical simulation.

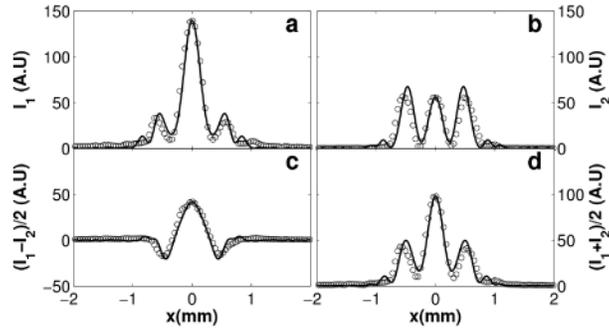


Fig. 6. One-dimensional interference patterns corresponding to that of Fig. 4. Experimental data and theoretical simulation are given by open circles and solid lines, respectively. The spot size of the laser beam is taken as  $\sigma = 0.8$  mm.

#### 4. Summary

In summary, we have demonstrated that the interference of a nonlocal double-slit can be realized through one-photon process. Our theoretical analysis showed that two spatially separated apertures can be joined together in the first-order field correlation of spatially incoherent light. The previous experiment on the nonlocal double-slit interference with thermal light relies on intensity correlation measurements. Physically, the second-order field correlation of thermal light is decomposable into the first-order correlations, one of which, the modulus of the first-order cross field correlation at two positions, i.e.,  $\left| \langle E_1^*(x_1) E_2(x_2) \rangle \right|^2$ , records the interference. In essence, the nonlocal double-slit interference with thermal light should be attributed to the first-order field correlation of incoherent light. However, the second-order field correlation of entangled photon pair cannot be degraded into the first-order ones, and hence the corresponding nonlocal double-slit effect and other quantum imaging are based on the true second-order interference.

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