Experimental Observation of Classical Sub-Wavelength Interference with Thermal-Like Light

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We show the experimental observation of the classical sub-wavelength double-slit interference with a pseudo-thermal light source. The experimental results are in agreement with the recent theoretical prediction shown in quant-ph/0404078 (to be appeared in Phys. Rev. A).

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Interference effects reflect the nature of waves, both the classical wave and the quantum wave. For a particle, the de Broglie wavelength depends on its mass. When two particles with the same mass combine into a whole, a molecular, for example, the corresponding de Broglie wavelength reduces to half of that of a single particle. Recently, a similar effect for photons, named quantum sub-wavelength interference, has drawn attention [1]- [8]. For the beams generated in spontaneous parametric down-conversion (SPDC), the interference pattern by a double-slit or a beam splitter shows a sub-wavelength interference effect in a two-photon observation. In comparison with massive particles, the effect was explained by means of the photonic de Broglie wave of a multiphoton wavepacket [1] [2] [5] [7]. In the further theoretical analysis, the sub-wavelength interference effect is attributed to a quantum entanglement of photons [3] [4]. These studies revealed the sub-wavelength interference as a non-classical effect occurring in the microscopic realm. Furthermore, it has been shown theoretically that the sub-wavelength interference effect can also exist in the macroscopic realm in which the interfered beams generated in a high gain SPDC contain a large number of photons [6] [9]. However, in Refs. [9], the authors found another scheme to observe the double-slit sub-wavelength interference in a joint-intensity measurement in which two photodetectors are placed at a pair of symmetric positions with respect to the center of double-slit. This effect occurs only in the macroscopic realm without the microscopic counterpart. Then it has been proved in Ref. [10] that the second-order spatial correlation of field is responsible for the sub-wavelength interference and that both the entangled photon pair generated in SPDC and the thermal light possess such spatial correlation. In parallel, it has been found that the thermal light source can perform the ghost imaging and interference [11]- [17], which were considered as nonclassical effects devoted by a two-photon entanglement. The discussions were stimulated by the experimental observation of ghost imaging and interference with classically correlated beams [11]. Then the authors in Ref. [12] firstly proved that the classical correlation of two beams obtained by splitting incoherent thermal radiation can perform the ghost imaging. Just recently, the experimental realization of classical correlated imaging has been reported with a pseudo-thermal light source [16] [17].

In this paper, we report the experimental observation of the sub-wavelength interference with a thermal-like light source. In a Young’s double-slit interference setup, we measure the intensity distribution and the joint-intensity distribution of a thermal-like light source at the detection plane and compare them with those of a coherent light source. The experimental results witness that the thermal-like light can perform an incoherent pattern in the intensity distribution and a sub-wavelength interference pattern in the joint-intensity observation in agreement with the theoretical predictions.

To begin with, let a coherent beam illuminate a double slit of slit width $b$ and slit distance $d$. In the interfered plane at the distance far from the double-slit, the first-order interference-diffraction pattern (also called one-photon double-slit interference) is described by $G^{(1)}(x, x) = A\overline{T}^2(kx/z)$, where function $\overline{T}$ is the Fourier transform of the double-slit function given by

$$\overline{T}(q) = \frac{2b}{\sqrt{2\pi}} \text{sinc}(qb/2) \cos(qd/2).$$

(1)

$\overline{T}^2(kx/z)$ describes an interference-diffraction pattern with the fringe-stripe interval $\lambda z/d$, where $\lambda = 2\pi/k$ is the beam wavelength and $z$ is the distance between the double-slit and the detection plane. If we perform a joint-intensity measurement in the interfered plane, however, we obtain the second-order correlation function

$$G^{(2)}(x_1, x_2) = A^2\overline{T}^2(kx_1/z)\overline{T}^2(kx_2/z),$$

which describes a two-photon double-slit interference. In general, $G^{(2)}(x, x)$ and $G^{(2)}(x, -x)$ may exhibit two kinds of observation of two-photon interference: the former is measured by a two-photon absorption detector and the latter can be carried out by a joint-intensity measurement in which two detectors are placed at a pair of symmetric positions. But for the coherent field, the two kinds of observation show no difference because

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of $G^{(2)}(x, x) = G^{(2)}(x, -x)$. Furthermore, these two kinds of two-photon interference display the same fringe-stripe interval as that for the one-photon interference due to the fact $G^{(2)}(x, x) = [G^{(1)}(x, x)]^2$. It is also well known that the normalized second-order correlation function $g^{(2)}(x_1, x_2) = G^{(2)}(x_1, x_2)/[G^{(1)}(x_1, x_1)G^{(1)}(x_2, x_2)]$ is unity which witnesses the coherence of the field.

Now, we consider one-photon and two-photon double-slit interference of a classical thermal light source, which is assumed to radiate a monochromatic chaotic beam $E(x, z, t) = \int E(q) exp[iqx] dq \times exp[i(kz - \omega t)]$, where $E(q)$ satisfies a multimode thermal statistics. In the interfered plane, the intensity distribution and the second order correlations are written as [10]

$$G^{(1)}(x, x) = A \int \bar{T}^2(\frac{kx}{z} - q)S(q) dq,$$

$$G^{(2)}(x_1, x_2) = A^2 \left\{ \int \bar{T}^2(\frac{kx_1}{z} - q)S(q) dq \int \bar{T}^2(\frac{kx_2}{z} - q)S(q) dq + \left[ \int \bar{T}(\frac{kx_1}{z} - q)\bar{T}(\frac{kx_2}{z} - q)S(q) dq \right]^2 \right\},$$

respectively, where $S(q)$ is the spatial frequency spectrum of the thermal light. In the broadband limit, these correlations can be approximately reduced to

$$G^{(1)}(x, x) = AS(0)\bar{T}(0),$$

$$G^{(2)}(x_1, x_2) = A^2 S^2(0) \left\{ \bar{T}^2(0) + \bar{T}^2[\frac{k}{z}(x_1 - x_2)] \right\},$$

respectively. It is well known that the one-photon interference of the thermal light disappears with a broadband spatial frequency. The random propagation directions wash out the interference. But the interference exists in a joint-intensity measurement even if the spatial frequency bandwidth of the thermal fluctuation is wider. In particular, when two detectors are placed at symmetric positions, $x$ and $-x$, the second term of Eq. (5), $\bar{T}^2(2kx/z)$, shows a sub-wavelength interference pattern which is equivalent to the one-photon interference of a coherent beam with half of the wavelength. In contrary to the coherent field, the interference pattern can be also displayed in the normalized second-order correlation. Figure 1 shows the second-order correlations $G^{(2)}(x, -x)$ and $g^{(2)}(x, -x)$ for both the thermal beam and the coherent beam. The double-slit parameter $d/b = 100/55$ is set so that there are three fringe-stripes in the primary diffraction range. For a moderate bandwidth of thermal light, the five fringe-stripes are observed as shown in Figs. 1b and 1d. However, as for a wide bandwidth of thermal light shown in Figs. 1a and 1d, the interference-diffraction pattern is reduced to half of that for the coherent light. In addition, the visibility of the interference pattern for $g^{(2)}(x, -x)$ is better than that for $G^{(2)}(x, -x)$ when the bandwidth is not wide enough.

The experimental setup shown in Fig.2 is similar to that in Ref. [4] with the exception of that a pseudo-thermal light source replaces the entangled two-photon source. The pseudo-thermal source is obtained by injecting a focused He-Ne laser coherent light using the same experimental setup. For comparison, we also measured the first-order and second-order interference-diffraction patterns of the two outgoing beams. It is obvious that the incoherent thermal light exhibits a diffraction pattern without fringe whereas the coherent light illustrates a well-known interference fringe. In the theoretical simulation, we assume that the pseudo-thermal light has a Gaussian-type spectrum $S(q) = (\sqrt{2\pi}w)^{-1} exp[-q^2/(2w^2)]$. Using Eq. (2), we can calculate the diffraction pattern as shown by a solid line in Fig. 3a. For better fitting to the experimental data, the normalized bandwidth of the pseudo-thermal light is taken as $wb/(2\pi) = 0.52$, which is also applied to the theoretical

the photon correlation and the photon bunching are the nature of thermal photon statistics. For the thermal light source, by measuring the normalized second-order correlation \( g^{(2)}(x, x) \) and the second order correlation \( G^{(2)}(x, x) \), we can see that the sub-wavelength interference patterns are exhibited in Figs. 4a and 4b, respectively. The fringe visibilities are 0.214 for \( g^{(2)}(x, x) \) and 0.160 for \( G^{(2)}(x, x) \). In Fig. 5a, the interference disappears in the correlation \( g^{(2)}(x, x) \) for the thermal light. For the sake of comparison, \( G^{(2)}(x, x) \) and \( G^{(2)}(x, x) \) of the coherent light are measured and exhibited in Figs. 4c and 5b, respectively. However, in Fig. 6, we measure the normalized joint-intensity correlation \( g^{(2)}(x, 0) \) by fixing one detector at the symmetric center and the result displays a similar interference pattern to the one for the coherent beam without showing the sub-wavelength effect.

The main interference features shown in Figs. 3a-5a and 6 demonstrate the theoretical predictions in Eqs. (4) and (5) which are obtained for an ideal thermal correlation with a wide bandwidth. In this case, the maximum and minimum values of the fringe pattern should be 2 and 1, respectively (see Figs. 1d and 1e). However, the pseudo-thermal source in the experiment is not perfect. In addition, the photodetectors have a finite area. Thus, we assume a modified second-order correlation \( g^{(2)}(x_1, x_2) = 1 + \delta + \eta^2 \langle I_1(x_1)I_2(x_2) \rangle / \langle I_1(x_1) \rangle \langle I_2(x_2) \rangle \), where \( \delta \) and \( \eta \) describe the deviation from the perfect thermal correlation and detection. The modification does not alter the main features of the interference patterns. By taking into account the modification, the solid lines in Figs. 3a-5a and 6 indicate the theoretical simulation of the interference patterns given by Eqs. (2) and (3). However, the theoretical calculations of the interference-diffraction pattern for the coherent light are obtained according to the function \( \widetilde{T}^2(kx/z) \).

The sub-wavelength interference is considered as an effect beating the Rayleigh diffraction limit and has prospective application in photolithography. The quantum scheme of sub-wavelength interference proposed in Ref. [4] is only proof-of-principle. The wavelength of the entangled photon pair generated in the SPDC has already been doubled from that of the pump beam. However, the intensity of an entangled photon pair is almost negligible in any practical application. The sub-wavelength interference is considered as an effect beating the Rayleigh diffraction limit and has prospective application in photolithography.

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Figure Captions

Fig. 1. Numerical simulations of the second-order correlation functions $G^{(2)}(x,-x)$ (the left side) and the normalized second-order correlation functions $g^{(2)}(x,-x)$ (the right side) for both the thermal light (a, b, d, and e) and the coherent light (c and f). The ratio between slit distance and slit width is $d/b = 100/55$. The spatial frequency spectrum $S(q)$ of the thermal light is assumed to be a Gaussian function with a bandwidth $w$. In (a) and (d) a wide bandwidth $wb/(2\pi) = 10$ is taken, and in (b) and (e) a moderate bandwidth $wb/(2\pi) = 0.52$ is taken for the thermal light.

Fig. 2. Sketch of the experimental setup.

Fig. 3. Average intensity distributions of the two outgoing beams from the beam splitter for (a) the pseudo-thermal light and (b) the coherent light. The experimental data are indicated by triangles and circles detected by D1 and D2, respectively. In Figs. 3-6, the solid lines show the numerical simulations in accordance with the experimental setup, and the bandwidth of the thermal light spectrum is taken as $wb/(2\pi) = 0.52$.

Fig. 4. Interference-diffraction patterns by measuring (a) the normalized second-order correlation function $g^{(2)}(x,-x)$ and (b) the second-order correlation function $G^{(2)}(x,-x)$ of the pseudo-thermal light, whereas in (c) $G^{(2)}(x,-x)$ is measured for the coherent light. In Figs. 4-6, the experimental data are indicated by square-dots and the modification parameters $\delta = 0.04$ and $\eta = 0.66$ are taken in the numerical simulations for the thermal light.

Fig. 5. Interference-diffraction patterns by measuring (a) the normalized second-order correlation function $g^{(2)}(x,x)$ of the pseudo-thermal light and (b) the second-order correlation function $G^{(2)}(x,x)$ of the coherent light.

Fig. 6. Interference-diffraction patterns by measuring the normalized second-order correlation function $g^{(2)}(x,0)$ of the pseudo-thermal light.
\[ G^{(2)}(X, -X) \text{(Arb. Unit)} \]

\[ X = \frac{kbx}{2\pi z} \]

\[ g^{(2)}(X, -X) \]

\[ X = \frac{kbx}{2\pi z} \]
He-Ne Laser

digital oscilloscope

beam splitter

double-slit

lens

ground glass
Intensity Distribution (Arb. Unit)

(a) 

(b) 

x(mm)
The image contains three graphs labeled (a), (b), and (c), each showing the function $g^{(2)}(x, -x)$ versus $x (\text{mm})$. The graphs are plotted in arbitrary units (Arb. Unit) and scaled by $10^{-6}$ and $10^{-3}$. The plots exhibit oscillatory behavior with multiple peaks and troughs. The x-axis represents distance in millimeters ($x (\text{mm})$) ranging from -5 to 5.
