Experimental Observation of Classical Subwavelength Interference with a Pseudothermal Light Source

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We report the experimental observation of classical subwavelength double slit interference with a pseudothermal light source. The experimental results are in good agreement with the theoretical simulation using the second order correlation function for the thermal light.

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Interference effects reflect the nature of waves for both classical and quantum waves. For a particle, the de Broglie wavelength depends on its mass. When two particles with the same mass combine into a whole, a molecule for example, the corresponding de Broglie wavelength reduces to half that of a single particle. Recently, a similar effect for photons, namely, quantum subwavelength interference, has drawn much attention [1–8]. For the beams generated in spontaneous parametric down-conversion (SPDC), the interference pattern created by a double slit or a beam splitter shows a subwavelength interference effect when two-photon detection is used. In comparison with massive particles, the effect has been explained by means of the photonic de Broglie wave of a multiphoton wave packet [1,2,5,7]. In further theoretical analyses, the subwavelength interference effect has been attributed to the quantum entanglement of photons [3,4]. These studies portrayed subwavelength interference as a nonclassical effect occurring in the microscopic realm.

Recently, it was shown theoretically that this effect can also exist in the macroscopic realm in which the interfering beams generated in high gain SPDC contain a large number of photons [6,9]. Furthermore, in Ref. [9], the authors found another scheme to observe double slit subwavelength interference in which a joint-intensity measurement is performed by placing two photodetectors at a pair of symmetric positions with respect to the center of the double slit. This effect occurs only in the macroscopic realm without a microscopic counterpart. Is the effect quantum or classical? The issue became clear after it was first proposed in the literature [10,11] that a thermal light source can perform ghost imaging and ghost interference, which were also formerly considered as nonclassical effects that could only be created by two-photon quantum entanglement. In Ref. [10], the authors indicated that the subwavelength double slit interference observed with joint-intensity measurement originates from the classical thermal correlation. In parallel, it has been further proved in Ref. [12] that the higher order spatial correlation of the field is responsible for the subwavelength interference and that both the entangled photon pairs generated in SPDC and thermal light possess such spatial correlation. The correlated imaging of thermal light has also been studied theoretically by other authors [13–15]. Indeed, the experimental realization of classical correlated imaging with a pseudothermal light source has already been reported [16–18].

In this Letter, we report the experimental observation of subwavelength 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 show that the thermal-like light can create an incoherent pattern in the intensity distribution and a subwavelength interference pattern in the joint-intensity observation, in agreement with the theoretical predictions.

To begin with, let us consider a coherent beam illuminating a double slit of slit width b and slit distance d. In the interference plane at a distance far from the double slit, the first order interference-diffraction pattern (also called one-photon double slit interference) is described by $G^{(1)}(x,x) = A\tilde{T}^2(kx/z)$, where function $\tilde{T}$ is the Fourier transform of the double slit function given by $\tilde{T}(q) = (2b/\sqrt{2\pi})\,\mathrm{sinc}(qb/2)\cos(qd/2)$. Thus $\tilde{T}^2(kx/z)$ 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 interference plane, we obtain the second order correlation function $G^{(2)}(x_1,x_2) = A^2\tilde{T}^2(kx_1/z)\tilde{T}^2(kx_2/z)$, which describes a two-photon double slit interference pattern. In general, $G^{(2)}(x,x)$ and $G^{(2)}(x,-x)$ may give rise to two kinds of two-photon interference: the former can be measured by a two-photon absorption detector and the latter 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 reveal no difference because $G^{(2)}(x,x) = G^{(2)}(x,-x)$. 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 that $G^{(2)}(x,x) = [G^{(1)}(x,x)]^2$. 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 signifies the coherence of the field.

Let us now 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 multimode thermal statistics. In the interference plane, the first and second order correlations are written as [10,12]

$$G^{(1)}(x_1,x_2) = A\int \tilde{T}\Big(\frac{kx_1}{z}-q\Big)\tilde{T}\Big(\frac{kx_2}{z}-q\Big)S(q)dq, \quad (1)$$

$$G^{(2)}(x_1,x_2) = G^{(1)}(x_1,x_1)G^{(1)}(x_2,x_2) + |G^{(1)}(x_1,x_2)|^2, \quad (2)$$

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

$$G^{(1)}(x_1,x_2) = AS(0)\tilde{T}\Big(\frac{k}{z}(x_1-x_2)\Big),$$
$$G^{(1)}(x,x) = AS(0)\tilde{T}(0), \quad (3)$$

$$G^{(2)}(x_1,x_2) = A^2S^2(0)\Big\{\tilde{T}^2(0) + \tilde{T}^2\Big[\frac{k}{z}(x_1-x_2)\Big]\Big\}, \quad (4)$$

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. (4), $\tilde{T}^2(2kx/z)$, shows a subwavelength interference pattern which is equivalent to the one-photon interference pattern of a coherent beam with half the wavelength. In contrast to the coherent field, the interference pattern can also be displayed in the normalized second order correlation.

The experimental setup shown in Fig. 1 is similar to that in Ref. [4] with the exception that a pseudothermal light source replaces the entangled two-photon source. The pseudothermal source is obtained by passing a focused He-Ne laser beam of wavelength 632.8 nm through a slowly rotating (0.5 Hz) ground glass disk. A double slit is placed at a distance of 15 mm from the thermal source. The two slits are separated by $d = 100\ \mu$m and have a width $b = 55\ \mu$m. The diffracted radiation is split into two beams with a nonpolarizing 50/50 beam splitter, located at a distance of 290 mm from the double slit. The transmitted and reflected beams are detected by small area (diameter 0.6 mm) Si-photodetectors D_1 and D_2, which are mounted on translation stages. The distance between the detectors

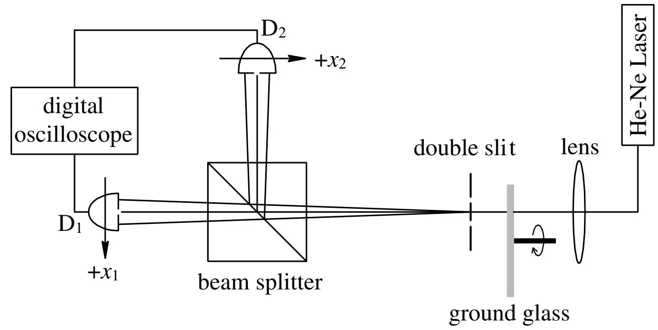

FIG. 1. Sketch of the experimental setup.

and the double slit is $z = 550$ mm. The signals from the two detectors are recorded on a digital oscilloscope (Tektronics 3012B) for the joint-intensity measurement. By measuring the average of the product of these two signals over a 2 sec interval, we obtain the average joint intensity $\langle I_1(x_1)I_2(x_2)\rangle$, where $I_1(x_1)$ and $I_2(x_2)$ are the light intensities detected by D_1 and D_2 at the positions x_1 and x_2, respectively. As a matter of fact, the joint-intensity correlation of the outgoing fields in the beam splitter is proportional to the second order correlation of the input field. For comparison, we also measured the first and second order interference-diffraction patterns of the He-Ne laser coherent light using the same experimental setup.

The experimental results are plotted in Figs. 2–4, where Figs. 2(a), 3(a)–3(c), and 4(a) show the results for thermal light, and Figs. 2(b), 3(d), and 4(b) those for coherent light. In Fig. 2 the intensity distributions of the two outgoing beams were measured. It can be seen that the incoherent thermal light produces a diffraction pattern without fringes, whereas the coherent light exhibits the well-known interference fringes. In Figs. 3 and 4, we perform the joint-intensity measurement at positions $(x,-x)$ and (x,x), respectively. For the thermal light source, the subwavelength interference patterns obtained by measuring the normalized joint-intensity correlation $g^{(2)}(x,-x) = \langle I_1(x)I_2(-x)\rangle/[\langle I_1(x)\rangle\langle I_2(-x)\rangle]$, the joint-intensity fluctuation correlation $\Delta G^{(2)}(x,-x) = \langle I_1(x)I_2(-x)\rangle - \langle I_1(x)\rangle \times \langle I_2(-x)\rangle$, and the joint-intensity correlation $G^{(2)}(x,-x) = \langle I_1(x)I_2(-x)\rangle$ are shown in Figs. 3(a)–3(c), respectively. In Fig. 4(a), the interference disappears in the correlation $g^{(2)}(x,x)$ for the thermal light. For the sake of comparison, the measured $G^{(2)}(x,-x)$ and $G^{(2)}(x,x)$ for coherent light are plotted in Figs. 3(d) and 4(b), respectively. However, the normalized correlation $g^{(2)}(x,0)$ was measured by fixing one detector at the center of symmetry and scanning the other detector along x. A similar interference pattern to that for the coherent beam is obtained, but without the subwavelength characteristic.

In the theoretical simulation we assume that the pseudothermal light has a Gaussian type spectrum $S(q) = (\sqrt{2\pi}w)^{-1}\exp[-q^2/(2w^2)]$, where w is the bandwidth of spatial frequency. Using Eq. (1), we can calculate the

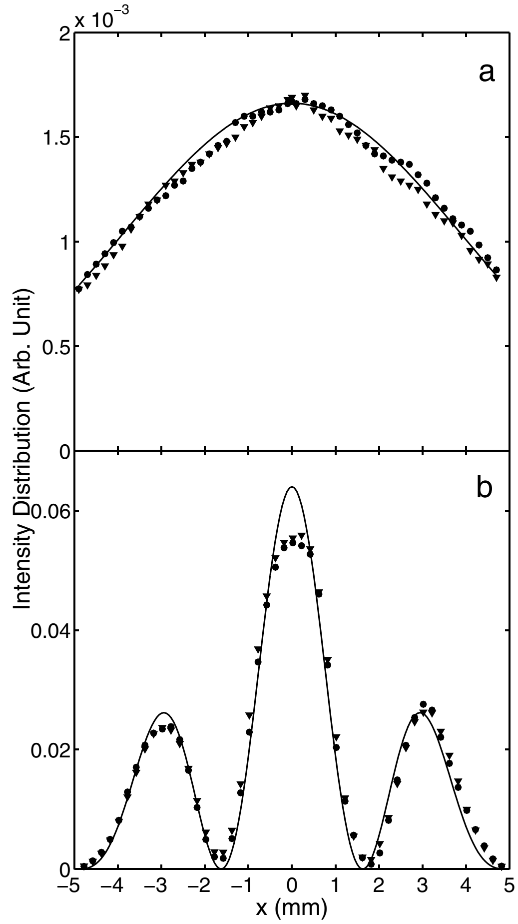

FIG. 2. Average intensity distributions of the two outgoing beams from the beam splitter for (a) the pseudothermal light and (b) the coherent light. The experimental data are indicated by triangles and circles detected by D_1 and D_2, respectively. In Figs. 2–4 the solid lines represent the numerical simulations, and the bandwidth of the thermal light spectrum is taken as $wb/(2\pi) = 0.52$.

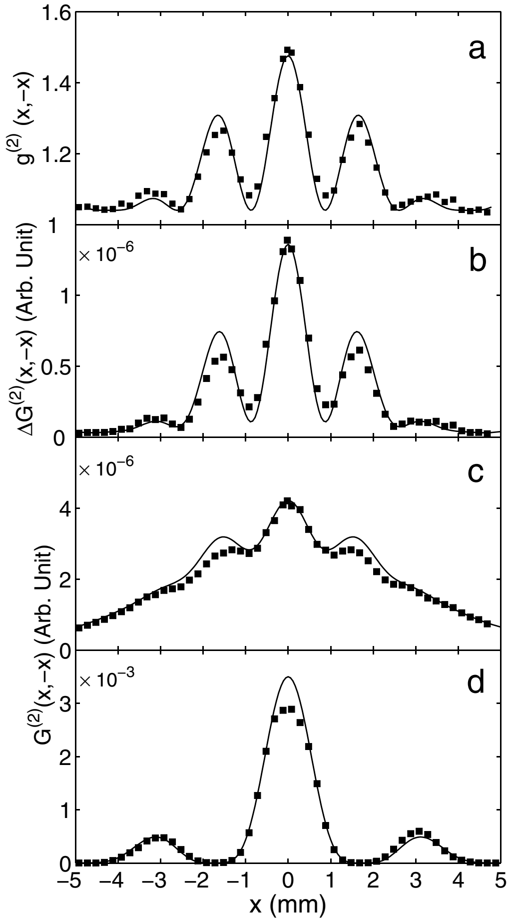

FIG. 3. Interference-diffraction patterns obtained by measuring (a) the normalized joint-intensity correlation function $g^{(2)}(x, -x)$, (b) the joint-intensity correlation fluctuation $\Delta G^{(2)}(x, -x)$, and (c) the joint-intensity correlation $G^{(2)}(x, -x)$ for the pseudothermal light. In (d) the value $G^{(2)}(x, -x)$ is measured for coherent light.

diffraction pattern as shown by the solid line in Fig. 2(a). For better fitting to the experimental data, the normalized bandwidth of the pseudothermal light is taken as $wb/(2\pi) = 0.52$, which is also applied to the theoretical simulations in Figs. 3 and 4. For ideal thermal correlation, the maximum and minimum values of the normalized second order correlation function should be 2 and 1, respectively. However, the experimental data of the interference pattern in Fig. 3(a) do not reach these values. This is because the pseudothermal source in our experiment is not perfect, and the photodetectors have a finite area. Thus, we assume a modified second order correlation function $G^{(2)}(x_1, x_2) = (1 + \delta)G^{(1)}(x_1, x_1)G^{(1)}(x_2, x_2) + |\eta G^{(1)}(x_1, x_2)|^2$, where δ and η describe the deviation from perfect thermal correlation and detection. The modification does not alter the main features of the interference patterns except for fringe magnitudes. By taking into account this modification ($\delta = 0.04$ and $\eta = 0.66$) and Eq. (1), we obtain the theoretical simulation of the interference patterns indicated by the solid lines in Figs. 3(a)–3(c) and 4(a). Therefore, the experimental data are in good agreement with the theoretical predictions. The theoretical calculations of the interference-diffraction pattern for coherent light are obtained according to the function $\tilde{T}^2(kx/z)$.

The experimental results are rather astonishing from a conventional perspective of interference. First, the interference is related to the phase of the field and light intensity does not contain any phase information. Second, the disorder of a light source may destroy the interference. This could be the reason why the discovery of the classical subwavelength effect came later than the quantum one. Reference [12] interpreted the origin of both quantum and classical subwavelength interference in terms of the spatial correlation of the field. The correlation of the transverse wave vectors can be derived by either the quantum entanglement of photons or the multimode thermal statistics. In the quantum scheme, the phase difference of the fields from the two slits to the detector is random for a

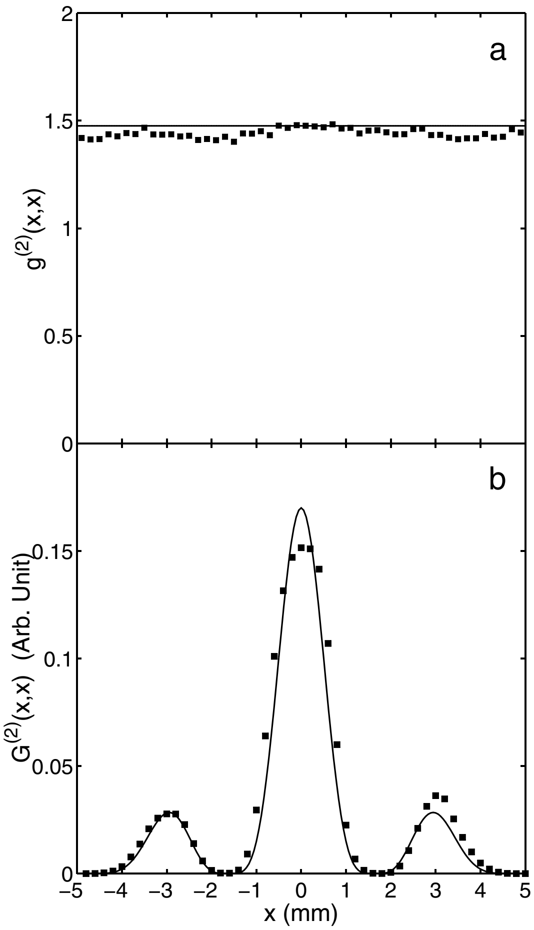

FIG. 4. Interference-diffraction patterns obtained by measuring (a) the normalized joint-intensity correlation function $g^{(2)}(x, x)$ of the pseudothermal light, and (b) the joint-intensity correlation function $G^{(2)}(x, x)$ of coherent light.

one-photon amplitude, but is well defined for a two-photon amplitude. As for the classical scheme, the phase difference of the fields at the two slits is also random in terms of the first order correlation. However, there is a definite difference of phase between the paths to detectors D_1 and D_2 from the same slit, and it is this which gives rise to interference fringes and is doubled in the expression for the intensity correlation (see Fig. 2 in Ref. [12]). In light of this, we can say that it is in fact the thermal ''disorder'' which instills the intensity correlation with certain phase information.

Enhancement of the spatial resolution of interference patterns can also be realized with coherent beams [19,20]. As a matter of fact, this enhancement is a basic feature of multiphoton measurement. Even for an ordinary interference pattern generated by a coherent beam one could measure a ''half period'' fringe by scanning the two detectors together and maintaining a distance of a half fringe interval between them. Therefore, the physics behind the term ''subwavelength interference,'' at least for the classical scheme, should refer to the statistical high order spatial correlation of the fields when each field is completely random. In this sense the present work can be regarded as a new version of the landmark Hanbury Brown and Twiss experiment [21], the full implication of which has taken an unduly long time to understand. Perhaps a better name of this effect would be Hanbury Brown and Twiss interference.

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