Two-photon interference with two independent pseudothermal sources

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The nature of two-photon interference is a subject that has aroused renewed interest in recent years and is still under debate. In this paper we report the observation of two-photon interference with independent pseudothermal sources in which subwavelength interference is observed. The phenomenon may be described in terms of optical transfer functions and the classical statistical distribution of the two sources.

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Young's double-slit experiment is one of the most important experiments in the history of physics, being the earliest demonstration of the interference of wave motion. Later, it also provided powerful evidence for the wave-particle duality of light. A phenomenon of profound significance, interference is also ubiquitous in all areas of physics, but the term is by default understood to mean first-order interference, i.e., interference observed in the first-order intensity of the field in question. It was only after more than 150 years that effects due to second-order intensity correlations in optics was first considered and made use of by Hanbury Brown and Twiss in their landmark experiment [1] to measure the angular diameters of stars with an accuracy far surpassing that achievable by the Michelson interferometer because of its insensitivity to phase disturbances.

At the end of the last century the successful demonstration of two-photon interference with entangled light produced by spontaneous parametric down-conversion (SPDC) [2–8] brought to attention the question of whether two-photon interference can be considered as the interference of two distinct photons [9–12]. Recently, there has been great interest in two-photon interference with thermal light [13–20] but the nature of two-photon interference is still under debate and so deserves further research.

After Mandel *et al.* performed their famous classical first-order correlation interference experiment with two independent lasers [22,23] in the 1960s, the question of interference between independent beams became widely discussed [24–27]. In Ref. [28], a classical-like first-order interference-diffraction pattern was obtained with two independent pseudothermal light sources. Recently, nonclassical two-photon interference effects were observed with one photon coming from SPDC and the other from a weak laser source [29,30], while Kaltenbaek *et al.* succeeded in observing interference of independent photons produced by two SPDC sources [31]. However, subwavelength second-order interference was not reported. In this paper we describe the first observation of two-photon interference with two independent pseudothermal point sources which exhibited subwavelength interference.

The principle of the experiment is shown in Fig. 1. Two independent pseudothermal light sources S_A and S_B are located at two pinholes. The beams from the two pinholes pass through a beam splitter and are detected by two single-photon detectors D_1 and D_2, respectively, which can be translated in the x directions. The output signals are sent to a coincidence counter. The experiment is first performed with both sources having the same polarization and then with perpendicular polarizations.

An outline of the experimental setup is shown in Fig. 2. The stabilized He-Ne laser of wavelength 632.8 nm and length approximately 20 cm (model FS100, Beijing Fangshi Keji Co.) produces two longitudinal modes of perpendicular polarization, with a frequency difference of 1 GHz. It has been shown that two such adjacent perpendicular modes have no phase correlation and so are independent of each other [28,32]. They are separated by a 50%-50% polarizing beam splitter (PBS) so that one mode is reflected and the other transmitted by the PBS. The reflected beam passes from mirror M_2 through polarizer P_1 to mirror M_4, and is s-polarized. The p-polarized transmitted beam is reflected by mirror M_3, then passes through a half-wave plate and polarizer P_2 before being reflected by mirror M_5 to emerge parallel to the other beam. It may be converted to s-polarization by rotating the half-wave plate and polarizer P_2. The two beams are then focused by lens L at two spots A and B separated by about 1.1 mm on a ground glass plate which rotates at a speed of 12 Hz. The diameter of the spots is about 0.11 mm, so they are equivalent to two pseudo-thermal pinhole light sources. Light scattered from the two spots is then reflected by mirror M_6 and divided by a 50%-50% nonpolarizing beam splitter BS. The reflected and transmitted

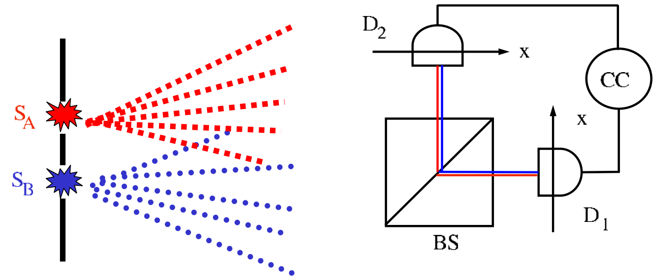

FIG. 1. (Color online) Principle of the experiment. S_A, S_B: two independent pseudothermal sources; BS: nonpolarizing beam splitter; D_1, D_2: single photon detectors; CC: coincidence counter; and x: scan direction of detectors

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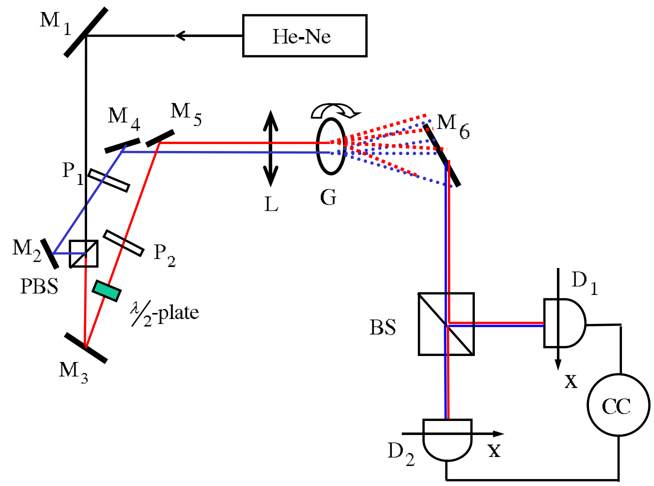

FIG. 2. (Color online) Experimental setup of interference with two independent light sources of the same polarization. M_1–M_6: mirrors; PBS: polarizing beam splitter; BS: nonpolarizing beam splitter; P_1, P_2: polarizers; L: lens (f=10 mm); and G: rotating ground glass plate (12 Hz).

beams are detected by single-photon detectors D_1 and D_2 (Perkin Elmer SPCM-AQR-13), respectively. The output pulses from the two detectors are sent to a coincidence counting circuit.

To begin with, detector D_2 was kept fixed while D_1 was scanned in the horizontal direction and the rate of coincidence counts recorded as a function of its position. As can be seen from Fig. 3(a), classical-like first-order interference-diffraction pattern can be obtained. The distance between the zeroth-order and the first-order interference peak is about 1.7 mm.

Next, when the detectors D_1 and D_2 were scanned in *opposite* directions $(x,-x)$ in steps of 0.25 mm simultaneously, the second-order interference-diffraction pattern shown in Fig. 3(b) was obtained. The distance between the zeroth-order and the first-order interference peak is about 0.85 mm, which is exactly half that of the classical case. This is very similar to the subwavelength effect, which was first predicted and observed for two-photon interference with entangled photon pairs [3,5], then was recently observed with a pseudothermal source [16,17] as well as with a single true thermal source [19].

The coincidence count rate is proportional to the second-order correlation function

$$G^{(2)}(x_1,t_1,x_2,t_2)=\langle\psi(t)|\langle\hat{E}_2(x_2,t_2)^{(-)}\hat{E}_1(x_1,t_1)^{(-)}\hat{E}_1(x_1,t_1)^{(+)}\times\hat{E}_2(x_2,t_2)^{(+)}\rangle|\psi(t)\rangle, \tag{1}$$

where $|\psi(t)\rangle$ is the state of the system, and $\hat{E}_i(x_i,t_i)^{(+)}$, $\hat{E}_i(x_i,t_i)^{(-)}$ are the positive and negative frequency field operators at time t_i at detectors $D_i(i=1,2)$ located at x_i, respectively.

We will now derive a simple explanation for this subwavelength interference with two independent sources. The

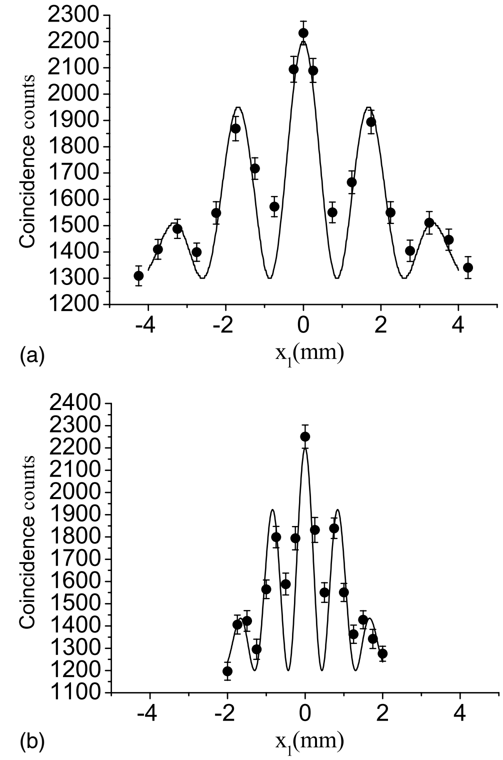

FIG. 3. Coincidence counts in 0.1 s. (a) As a function of the position of D_1 with D_2 fixed. (b) As a function of the position of detectors D_1, D_2 when they were scanned in opposite directions $(x,-x)$ simultaneously. The solid curves are theoretical plots.

transmission function of source A of the double-source function can be written as

$$T_A(x_0)=\begin{cases}1, & (d-s)/2 \leqslant x_0 \leqslant (d+s)/2\\ 0, & \text{otherwise},\end{cases} \tag{2}$$

and for source B,

$$T_B(x_0)=\begin{cases}1, & -(d+s)/2 \leqslant x_0 \leqslant -(d-s)/2\\ 0, & \text{otherwise}\end{cases} \tag{3}$$

where d is the distance between the two spots, s is their diameter, and x_0 is the distance from the central point between them.

After the beam from source A is divided at BS and detected at D_1 and D_2, the registered coincidence count is proportional to the second-order correlation function, and for Gaussian thermal fields, the relationship between the second- and first-order correlation functions $G^{(2)}$ and $G^{(1)}$ is given by [21]

$$\begin{aligned}G^{(2)}(x_1,x_2)&=\langle\hat{b}^{\dagger}(x_1)\hat{b}^{\dagger}(x_2)\hat{b}(x_2)\hat{b}(x_1)\rangle\\&=|\langle\hat{b}^{\dagger}(x_1)\hat{b}(x_2)\rangle|^2+\langle\hat{b}^{\dagger}(x_1)\hat{b}(x_1)\rangle\langle\hat{b}^{\dagger}(x_2)\hat{b}(x_2)\rangle\\&=|G^{(1)}(x_1,x_2)|^2+\langle G^{(1)}(x_1,x_1)G^{(1)}(x_2,x_2)\rangle,\end{aligned} \tag{4}$$

where $\hat{b}^{\dagger}(x_i)$ and $\hat{b}(x_i)$ are the creation and annihilation operators at detectors D_i located at (x_i), respectively.

From the Wiener-Khintchine theorem [33], the first-order spectral correlation for thermal light satisfies

$$\langle \hat{a}^\dagger(q_1)\hat{a}(q_2)\rangle = S(q_1)\delta(q_1-q_2), \quad (5)$$

where $S(q_1)$ is the spatial spectral distribution and q is the transverse wave vector of the optical field. The spectral width of thermal light can be assumed to be infinite, so $S(q_1)=1$.

For source A, we can calculate the first-order correlation function by using Eq. (5)

$$G_A^{(1)}(x_1,x_2) = \langle \hat{b}_A^\dagger(x_1)\hat{b}_A(x_2)\rangle = \int\int \tilde{H}_A^*(x_1,-q_1)\tilde{H}_A(x_2,-q_2) \times\langle \hat{a}_A^\dagger(q_1)\hat{a}_A(q_2)\rangle dq dq' = \int \tilde{H}_A^*(x_1,-q_1)\tilde{H}_A(x_2,-q_1)dq. \quad (6)$$

Here $\hat{a}_A^\dagger(q_1)$ and $\hat{a}_A(q_2)$ are the creation and annihilation operators for the source A, and $\tilde{H}_A(x_i,-q_i)$ is the partial Fourier transform of the impulse response function from the pseudothermal source A to the detectors D_i:

$$\tilde{H}_A(x_i,-q_i) = \frac{1}{\sqrt{2\pi}}\int\int h_f(x_i,x')h_A(x',x_0)dx' \exp[iq_ix_0]dx_0, \quad (7)$$

where $h_A(x',x_0)=T_A(x_0)\delta(x'-x_0)$ is the impulse response function for the upper spot of the double-source and $h_f(x_i,x')$ is the impulse response function in free space from the source to the detectors D_i. Substituting Eqs. (5) and (7) into Eq. (6), we can obtain

$$\begin{aligned} G_A^{(1)}(x_1,x_2) &= \frac{k}{2\pi z}\frac{1}{2\pi}\int\int\int T_A(x_0')T_A(x_0)\delta(x'-x_0) \\ &\quad\times \exp\left[i\left(\frac{kx_1}{z}-q\right)x_0' - i\left(\frac{kx_2}{z}-q\right)x_0\right] \\ &\quad\times dq dx_0 dx_0' \\ &= \frac{k}{2\pi z}\int_{(d-s)/2}^{(d+s)/2} \exp\left[i\frac{k}{z}(x_1-x_2)x_0\right]dx_0 \\ &= \frac{1}{\pi(x_1-x_2)}\left\{\cos\left[\frac{k(x_1-x_2)d}{2z}\right]\sin\left[\frac{k(x_1-x_2)s}{2z}\right] \right. \\ &\quad \left. - i\sin\left[\frac{k(x_1-x_2)d}{2z}\right]\sin\left[\frac{k(x_1-x_2)s}{2z}\right]\right\}, \end{aligned} \quad (8)$$

where z is the distance to the detector and λ is the wavelength of the pseudothermal light.

For the lower pseudothermal source B we obtain a similar expression but with a plus instead of a minus sign before the second term.

$$\begin{aligned} G_B^{(1)}(x_1,x_2) &= \frac{1}{\pi(x_1-x_2)}\left\{\cos\left[\frac{k(x_1-x_2)d}{2z}\right]\sin\left[\frac{k(x_1-x_2)s}{2z}\right] \right. \\ &\quad \left. + i\sin\left[\frac{k(x_1-x_2)d}{2z}\right]\sin\left[\frac{k(x_1-x_2)s}{2z}\right]\right\}. \end{aligned} \quad (9)$$

If both sources A and B have the same polarization, we can calculate the second-order correlation function from Eq. (4) to be

$$\begin{aligned} G^{(2)}(x_1,x_2) &= \langle[\hat{b}_A^\dagger(x_1)+\hat{b}_B^\dagger(x_1)][\hat{b}_A^\dagger(x_2)+\hat{b}_B^\dagger(x_2)][\hat{b}_A(x_2) \\ &\quad + \hat{b}_B(x_2)][\hat{b}_A(x_1)+\hat{b}_B(x_1)]\rangle \\ &= |G_A^{(1)}(x_1,x_2)+G_B^{(1)}(x_1,x_2)|^2 + G_A^{(1)}(x_1,x_1)G_A^{(1)} \\ &\quad\times(x_2,x_2) + G_A^{(1)}(x_1,x_1)G_B^{(1)}(x_2,x_2) + G_B^{(1)} \\ &\quad\times(x_1,x_1)G_A^{(1)}(x_2,x_2) + G_B^{(1)}(x_1,x_1)G_B^{(1)}(x_2,x_2). \end{aligned} \quad (10)$$

Here $\hat{b}_m^\dagger(x_i)$ and $\hat{b}_m(x_i)$ are the creation and annihilation operators for the source $m(m=A,B)$ at detectors D_i located at (x_i), respectively. By using Eqs. (8) and (9), the second-order correlation function when the detectors are scanned in opposite directions $(x,-x)$ can thus be written as

$$G^{(2)}(x,-x) = \left(\frac{ks}{2\pi z}\right)^2\left[1+\mathrm{sinc}^2\frac{\pi sx}{(\lambda/2)z}\cos^2\frac{\pi dx}{(\lambda/2)z}\right]. \quad (11)$$

The subwavelength interference pattern thus originates from the $(\lambda/2)$ term in Eq. (11).

However, when the beams from the two pseudothermal sources are perpendicularly polarized to each other, the second-order correlation function from Eq. (4) is

$$\begin{aligned} G^{(2)}(x_1,x_2) &= \langle \hat{b}_A^\dagger(x_1)\hat{b}_A^\dagger(x_2)\hat{b}_A(x_2)\hat{b}_A(x_1)\rangle \\ &\quad + \langle \hat{b}_B^\dagger(x_1)\hat{b}_B^\dagger(x_2)\hat{b}_B(x_2)\hat{b}_B(x_1)\rangle \\ &\quad \times\langle \hat{b}_A^\dagger(x_1)\hat{b}_B^\dagger(x_2)\hat{b}_B(x_2)\hat{b}_A(x_1)\rangle \\ &\quad + \langle \hat{b}_B^\dagger(x_1)\hat{b}_A^\dagger(x_2)\hat{b}_A(x_2)\hat{b}_B(x_1)\rangle \\ &= |G_A^{(1)}(x_1,x_2)|^2 + G_A^{(1)}(x_1,x_1)G_A^{(1)}(x_2,x_2) \\ &\quad + |G_B^{(1)}(x_1,x_2)|^2 + G_B^{(1)}(x_1,x_1)G_B^{(1)}(x_2,x_2) \\ &\quad + G_A^{(1)}(x_1,x_1)G_B^{(1)}(x_2,x_2) + G_B^{(1)}(x_1,x_1)G_A^{(1)} \\ &\quad \times(x_2,x_2). \end{aligned} \quad (12)$$

Substituting Eqs. (8) and (9) into the above equation we obtain

$$G^{(2)}(x,-x) = \left(\frac{ks}{\pi z}\right)^2\left[1+\frac{1}{2}\mathrm{sinc}^2\frac{\pi sx}{(\lambda/2)z}\right]. \quad (13)$$

For this situation we can see that the second-order correlation function is only a superposition of the Hanbury Brown and Twiss effect [1] from each pseudothermal source, and no interference pattern is observable. This was confirmed in the following experiment.

We removed the half-wave plate and adjusted the polarizer P_2 in Fig. 2 so that the two sources A and B emitted light of orthogonal polarizations. With D_2 fixed, we scanned D_1 and obtained the results shown in Fig. 4(a), while Fig. 4(b) shows the plot obtained when the two detectors were scanned in *opposite* directions $(x,-x)$ simultaneously. The

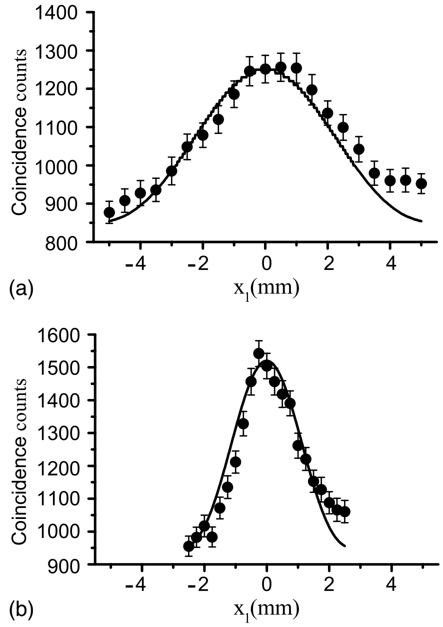

FIG. 4. Coincidence counts in 0.1 s for perpendicularly polarized beams: (a) As a function of the position of D_1 with D_2 fixed, and (b) as a function of the position of detectors D_1, D_2 when they were scanned in opposite directions $(x,-x)$ simultaneously. The solid curves are theoretical plots.

solid curves are theoretical plots calculated from Eq. (13). It is evident that there is no interference-diffraction pattern in either case.

This result would seem to be obvious from the point of view of classical first-order interference diffraction. On the other hand, from the quantum aspect when the two sources have orthogonal polarizations which photons come from which source can be distinguished and so no interference is possible. However, when the two sources have the same polarization we cannot distinguish which photons come from which source and so interference is observed. Our experimental results have thus confirmed that indistinguishability is the reason behind interference, even in the case of two sources that lack coherence in the usual sense.

Over the last few decades our understanding of interference, one of the most important concepts of physics, has advanced considerably since the days that Dirac [34] said. "Each photon then interferes only with itself. Interference between two different photons can never occur." The statement provoked widespread debate and led to a surge of experimental tests as well as philosophical argument. It is now generally agreed that Dirac's statement should be viewed in its historical content when the resolution time of photon detectors was still limited. As a way to resolve the misunderstanding, Shih *et al.* indicate that "two-photon correlation interference is the result of each pair of independent photons interfering with itself" [16], and they also maintain that two-photon interference with thermal light is not caused by the statistical correlation of the intensity fluctuations [20], even if the results can be obtained by a classical or quantum derivation. However, there is still no consensus on the actual mechanism behind this phenomena. In first-order interference it is the phase difference in the field amplitudes, caused by the different path lengths to the point of detection, that is the origin of the interference. Similarly, it is the phase difference of the two-photon amplitudes due to different paths to the two points of detection that gives rise to second-order correlation interference. Nonetheless, regardless of whether we are able to observe it or not, interference is an ever-present phenomenon of nature.

In summary, we have observed subwavelength interference with two independent pseudothermal sources, which may be helpful for understanding the nature of two-photon interference. There is still much to be explored regarding the properties of thermal light sources although they have been around for a long time. It is even conceivable that thermal light may find special applications in optical imaging and other fields because of its two-photon correlation characteristics [20,35].

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