Phase-conjugate mirror via two-photon thermal light imaging

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We report on a two-photon imaging experiment in which a thermal light source behaves like a phase-conjugate mirror, which produces a *real* image of an object. The result offers a novel scheme of imaging and thus suggests useful applications. [DOI: 10.1063/1.2172410]

Mirrors are familiar instruments of our everyday lives: we look at mirrors to find the images of ourselves. In geometrical optics, the image produced by a mirror is usually defined as *virtual* because the image is located behind the mirror in an imaginary space. Can we have a mirror that produces *real* images? In this letter we show that such a task can be accomplished by using two-photon imaging with thermal light.

Two-photon imaging techniques appeared 10 years ago.[1] Taking advantage of quantum correlation between a pair of photons emitted by spontaneous parametric down conversion (SPDC), it was possible to split the radiation from the source into two separate paths, to put an object in one of the arms, but to recover the spatial information of the object by analyzing the conditional detection probability of a photodetector placed in the arm where there was no object. The formation of the image with radiation that never actually interacted with the object was the reason why this technique was named "ghost" imaging. Recently, a lively debate on the role of entanglement for two-photon imaging animated the community.[2,3] In particular a great deal of attention has been put on the possibility of performing two-photon imaging with classically correlated sources[3] or, after the proposal by Gatti *et al.*,[4] with thermal (or pseudothermal) radiation.[5–11]

Klyshko explained the entangled two-photon imaging in a fictitious yet fascinating way.[12] In his view, the ghost image could be understood as a two-photon geometric optical effect by using the so-called "advanced wave interpretation." Basically, the light was considered to start at one of the detectors, to propagate backwards in time until the SPDC crystal and then to propagate forward in time towards the other detector. In this interpretation, the two-photon source of SPDC is treated as a mirror.[13,14]

In this letter we experimentally show that, using Klyshko's picture, in the field of two-photon geometric optics, thermal light sources behave as phase-conjugate mirrors producing real images. The natural availability of thermal-like sources and their incoherence property suggest intriguing applications. Because the concept works for any wavelength (energy) of radiation and the formation of the image does not require any imaging lenses or equivalent imaging systems, such a method seems quite promising for imaging applications in x ray, γ ray, or other wavelengths where no effective lens is available. In particular, the existence of an actual image, not of just a "projection" or a shadow of the desired object, would allow the possibility of reconstructing a three-dimensional structure of an object by performing, layer-by-layer, two-dimensional images at different distances.

In quantum theory of photodetection, correlation measurements are governed by the second order Glauber correlation function[15]

$$G^{(2)}(t_1,\mathbf{r}_1;t_2,\mathbf{r}_2) \equiv \langle E_1^{(-)}(t_1,\mathbf{r}_1)E_2^{(-)}(t_2,\mathbf{r}_2)E_2^{(+)}(t_2,\mathbf{r}_2)E_1^{(+)} \times(t_1,\mathbf{r}_1)\rangle, \qquad (1)$$

where $E^{(-)}$ and $E^{(+)}$ are the negative-frequency and the positive-frequency field operators at space-time points $(\mathbf{r}_1,t_1)$ and $(\mathbf{r}_2,t_2)$. Ignoring the temporal part, the transverse electric field can be written as follows:

$$\mathbf{E}_i^{(+)}(\mathbf{x}_i) \propto \sum_{\mathbf{q}} g_i(\mathbf{x}_i;\mathbf{q})\hat{a}(\mathbf{q}), \qquad (2)$$

where $\mathbf{x}_i$ is a position vector in the transversal plane at the position of the detectors, $\mathbf{q}$ is the transverse component of the momentum, and $g_i(\mathbf{x}_i;\mathbf{q})$ is the Green's function associated with the propagation of the field towards the ith detector. For thermal sources the second order correlation function turns out to be[16]

$$G^{(2)}_{\text{thermal}}(\mathbf{x}_1;\mathbf{x}_2) = G_{11}^{(1)}G_{22}^{(1)} + G_{12}^{(1)}G_{21}^{(1)} \propto \sum_{\mathbf{q}} |g_1(\mathbf{x}_1,\mathbf{q})|^2 \sum_{\mathbf{q}'} |g_2(\mathbf{x}_2,\mathbf{q}')|^2 + \left|\sum_{\mathbf{q}} g_1^*(\mathbf{x}_1,\mathbf{q})g_2(\mathbf{x}_2,\mathbf{q})\right|^2. \qquad (3)$$

The second term of this equation offers the possibility of clarifying the physics behind the two-photon optical interpretation. In an analogous situation, the transverse second-order correlation function for entangled sources reads

$$G^{(2)}_{\text{SPDC}}(\mathbf{x}_1;\mathbf{x}_2) = \left|\sum_{\mathbf{q}} g_1(\mathbf{x}_1,\mathbf{q})g_2(\mathbf{x}_2,-\mathbf{q})\right|^2. \qquad (4)$$

Equation (4) readily expresses the idea behind Klyshko's interpretation: focusing on the Green's functions, the product

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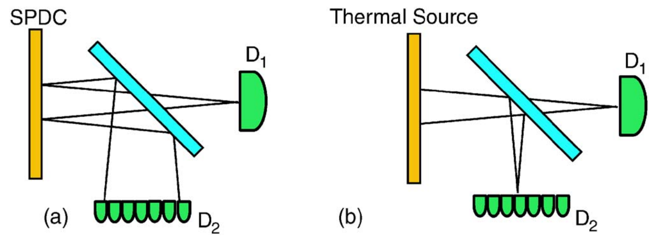

FIG. 1. (Color online) Schematic of the behavior of entangled and thermal sources for two-photon ghost imaging. Notice that if we use the advanced wave interpretation, the phenomenon can be regarded as a standard geometric optic effect in which the entangled sources (a) behave as ordinary mirrors, while thermal sources and (b) behave as phase-conjugate mirrors.

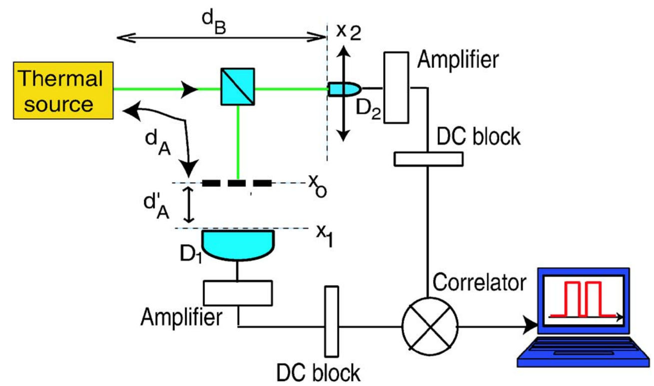

FIG. 2. (Color online) Experimental setup. The light source is a pseudothermal source obtained by focusing coherent radiation from a laser onto a rotating ground glass disk.

$g_1(\mathbf{x}_1,\mathbf{q})g_2(\mathbf{x}_2,-\mathbf{q})$ precisely represents a standard propagation of light traveling from one detector to a mirror and then being reflected to the other detector. Also for the thermal case, the second term of Eq. (3) can be interpreted similarly: the term $g_1^*(\mathbf{x}_1,\mathbf{q})g_2(\mathbf{x}_2,\mathbf{q})$ represents a standard optical effect in which light starts at one detector, is reflected by a mirror, and then arrives at the other detector. In this case, however, we are dealing with a phase-conjugated reflection. The situation is depicted in Fig. 1.

Probably the most interesting feature of such behavior of thermal sources is in the possibility of performing lensless imaging. To this end let us analyze the situation in which radiation from the thermal source is sent to two distant detectors. The object, described by the function $T(\mathbf{x})$, is at a distance d_A from the source on the path between the source of light and D_1; D_1 collects all the light transmitted by the object, while D_2 is a point-like detector scanning the plane perpendicular to the direction of the propagation of the radiation at a distance d_B from the source. In the case of perfect resolution, the Green's functions are

$$g_1(\mathbf{x}_1;\mathbf{q}) \propto \Psi\left(\mathbf{q},-\frac{c}{\omega}d_A\right)T(\mathbf{x}_1)e^{i\mathbf{q}\cdot\mathbf{x}_1},$$

$$g_2(\mathbf{x}_2;\mathbf{q}) \propto \Psi\left(\mathbf{q},-\frac{c}{\omega}d_B\right)e^{i\mathbf{q}\cdot\mathbf{x}_2}, \tag{5}$$

where $\Psi[\mathbf{q},(\omega/c)p]$ is proportional to the transfer function of the linear system and the paraxial approximation has been used,[17] ω is the light frequency, and c is the light velocity.

If the source-object and source-D_2 distances are equal ($d_A=d_B$), the second order correlation function reduces to

$$G^{(2)}_{\text{thermal}}(\mathbf{x}_1;\mathbf{x}_2) = |T(\mathbf{x}_1)|^2 + |T(\mathbf{x}_1)\,\delta(\mathbf{x}_1-\mathbf{x}_2)|^2 \tag{6}$$

and therefore, the total result considering the integral over $\mathbf{x}_1$ due to the bucket detection is

$$G^{(2)}_{\text{thermal}}(\mathbf{x}_2) = \sum_{\mathbf{x}_1} |T(\mathbf{x}_1)|^2 + |T(\mathbf{x}_2)|^2. \tag{7}$$

This result shows that, besides the first constant term, the thermal source effectively behaves like a mirror: an equal-size reproduction of the object is obtained in the plane at an equal distance from the source. Notice, however, that any generalized Klyshko's picture of the result in terms of two-photon geometric optics, only refers to the second term of Eqs. (6) and (7).[9]

It is worth discussing briefly similarities and differences of this result compared to the Hanbury-Brown and Twiss experiments.[18] The Hanbury-Brown and Twiss intensity interferometer measures two-photon correlations to deduce the angular size of the light source (distant star). All the measurements are carried out in the far field zone therefore measuring the momentum correlation of the field. In our case, instead, the second term of Eq. (6) is clearly the position-position correlation between $\mathbf{x}_1$ and $\mathbf{x}_2$ planes and therefore it is a sufficient condition for the formation of an image. The existence of the position correlation eliminates the explanation of this effect in terms of a shadow induced by the momentum correlation of the source as has happened in certain previous classical simulations.

In order to demonstrate the observation of an actual image rather than of a shadow, we operated experimentally in the near field zone and compared the in-focus measurement with an out-of-focus measurement where blurring occurs.

From a practical point of view Eq. (7) warns that an implementation of such an imaging scheme requires the development of an appropriate detection scheme. In fact for complicated objects the first term of Eq. (7) represents an overwhelming background noise term leading to poor contrast. For this reason, we measured photocurrent correlations rather than coincidence counts, as is common in previous works on correlated imaging. The background noise is basically given by the average intensities recorded at the detectors. Thus, it is only present in the dc components of the output photocurrents and can be effectively removed using a dc blocking element. On the other hand, the interesting imaging pattern can be extracted from the correlation between the beating terms in the radio-frequency components of the output photocurrents. For this reason in the experiment, the output from the photodiodes were first dc blocked and then analyzed by a standard correlation circuit.

The experimental setup is shown in Fig. 2. Radiation from a pseudothermal source[19,16] was divided in two optical paths by a beam splitter. In arm A, an object was placed at a distance $d_A=100$ mm and a bucket detector (D_1) was $d_A'=15$ mm behind it. The fact that D_1 is distant from the object further ensures that the experiment measures a point-to-point correspondence between object and imaging plane. In arm B, a point detector D_2 scanned the transverse plane at a distance $d_B=d_A$ from the source. The output photocurrents from the silicon *pin* photodiodes were first amplified and dc blocked by a passive *RC* filter and then sent to the correlation circuit composed of an rf mixer and by a low-pass filter.

The result of the measurement is shown in Fig. 3(a). The object was a double slit with slit separation 250 μm and slit

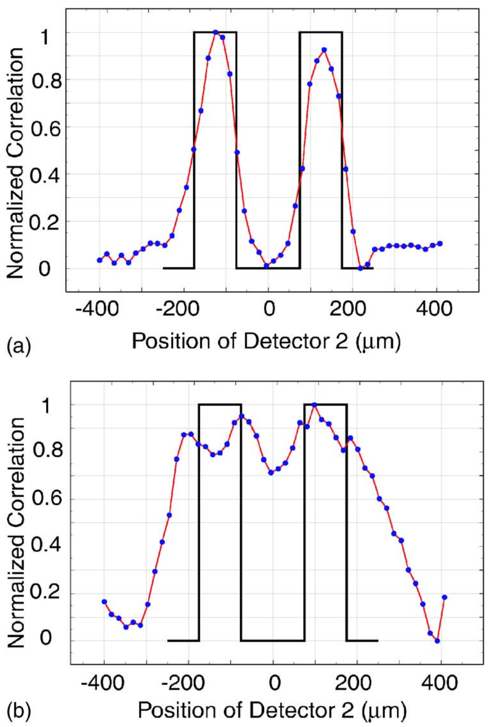

FIG. 3. (Color online) Lensless imaging: normalized correlation of the photocurrents vs transverse position of D_2. The solid black line represents the actual shape of the double slit. (a) D_2 is scanned in the "mirror" plane at $d_B=d_A$. (b) Out-of-focus measurement: D_2 is scanned in a plane for which $d_B \neq d_A$.

width 100 μm. The observations agree with the theory. The correlation measurement shows high visibility equal-size reproduction of the double slit when the distances d_A and d_B from object and image plane to the source are equal.

To further verify that the observed pattern was an image, we moved detector D_2 away from the "in-focus" condition to examine the "out-of-focus" situation. When $d_B=110$ mm, we measured a "blurred" image of the double slit. The result, reported in Fig. 3(b), clearly shows the blurring effect and confirms that in the plane at $d_A=d_B$ we have indeed observed an image.

Regarding the recent debate on ghost imaging effects, the basic question is whether or not the observation of a two-photon image with classical chaotic source means that two-photon ghost imaging is a classical effect. We have concluded exactly the opposite: the observation of ghost imaging with thermal light is a quantum two-photon interference effect. In this sense this measurement can be used to show that all two-photon correlation phenomena are essentially quantum effects. We have clarified this fundamental aspect in another letter.[20]

In conclusion we have theoretically discussed and experimentally shown the possibility of formation of high contrast two-photon imaging with thermal sources. The demonstrated method is particularly interesting because (1) it uses incoherent sources; (2) it can be implemented virtually at every wavelength; (3) thermal or chaotic sources are readily available or easily obtainable; and (4) the imaging setup does not require any optical lens or equivalent imaging system.

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