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Optical imaging by means of two-photon quantum entanglement

T. B. Pittman, Y. H. Shih, D. V. Strekalov, and A. V. Sergienko
Department of Physics, University of Maryland Baltimore County, Baltimore, Maryland 21228
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A two-photon optical imaging experiment was performed based on the quantum nature of the *signal* and *idler* photon pairs produced in spontaneous parametric down-conversion. An aperture placed in front of a fixed detector is illuminated by the *signal* beam through a convex lens. A sharp magnified image of the aperture is found in the coincidence counting rate when a mobile detector is scanned in the transverse plane of the *idler* beam at a specific distance in relation to the lens.

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One of the most surprising consequences of quantum mechanics is the entanglement of two or more distant particles [1]. The classic example of a two-particle entangled state was given by Einstein, Podolsky, and Rosen (EPR) in their famous 1935 gedanken experiment [2], where the measurement of an observable on one of the particles determined the value of that observable for the other particle with unit probability. In their paper EPR pointed out that quantum mechanics allows a two-particle state where the position of each particle is undetermined, but the measurement of one particle at a certain location implies that the other must be found at a specific corresponding location. Furthermore, a similar argument holds in momentum space. This interesting nonlocal phenomenon can never be understood from a classical point of view.

A typical example of an entangled state is the two-photon state generated from spontaneous parametric down-conversion (SPDC), the nonlinear optical process in which a laser pump incident on a crystal leads to the emission of a pair of photons in an entangled state [3]:

$$|\Psi\rangle=\sum_{s,i} \delta(\omega_s+\omega_i-\omega_p)\,\delta(\mathbf{k}_s+\mathbf{k}_i-\mathbf{k}_p)|\mathbf{k}_s\rangle\otimes|\mathbf{k}_i\rangle, \quad (1)$$

where ω_j and $\mathbf{k}_j$ $(j=s,i,p)$ are the frequency and wave vector of the signal, idler, and pump, respectively. As seen in state (1), the entanglement (in $\mathbf{k}$ space) here can be thought of as the superposition of an infinite number of two-photon probability amplitudes, corresponding to the infinite number of ways the down-converted photon pairs can satisfy the phase-matching conditions [4]

$$\omega_s+\omega_i=\omega_p\,, \quad \mathbf{k}_s+\mathbf{k}_i=\mathbf{k}_p\,. \quad (2)$$

Although the momentum of each photon of the pair is undetermined, if measurement on one of the photons yields a certain momentum eigenvalue, then the other must have had a corresponding momentum eigenvalue. Therefore, in some sense this type of entanglement is more closely related to the original EPR argument than that expressed as the superposition of only two two-particle probability amplitudes, which has become so familiar since the pioneering work of Bohm [5]. In its usual usage, SPDC has proved to be a tremendously successful source of these two term Bohm-like entangled states by essentially reducing state (1) through the judicious placement of two pairs of pinholes [6,7], or two pinholes followed by spatially separated interferometers [8–12] or polarization devices [13–15]. However, by taking advantage of the whole range of momentum entanglement expressed in state (1), we have been able to perform an optical imaging experiment that demonstrates a two-photon geometrical optical effect [16].

In this experiment the signal and idler light beams emerging from the SPDC crystal are sent in different directions so that coincidence detections may be performed between two distant photon counting detectors. An aperture placed in front of one of the detectors, for example, the letters of our institution, is illuminated by the *signal* beam through a convex lens. By placing the other detector at a distance prescribed by a "two-photon Gaussian thin lens equation" and scanning it in the transverse plane of the *idler* beam, a sharp magnified image of this aperture is observed in the coincidence counting rate, even though both detectors' single counting rates remain constant.

The experimental setup is shown in Fig. 1. A 2-mm-diam beam from the 351.1-nm line of an argon ion laser is used to pump a nonlinear beta barium borate (BBO) (β-BaB_2O_4) crystal that is cut at a degenerate type-II phase-matching angle to produce pairs of orthogonally polarized signal (e-ray plane of the BBO) and idler (o-ray plane of the BBO) photons. The pairs emerge from the crystal nearly collinearly, with $\omega_s \simeq \omega_i \simeq \omega_p/2$. The pump is then separated from the slowly expanding down-conversion beam by a UV grade fused silica dispersion prism and the remaining signal and idler beams are sent in different directions by a polarization beam-splitting Thompson prism. The reflected signal beam passes through a convex lens with a 400-mm focal length and illuminates the (UMBC) aperture. Behind the aperture is the detector package D_1, which consists of a 25-mm focal length collection lens in whose focal spot is a 0.8-mm-diam dry ice cooled avalanche photodiode. The transmitted idler beam is met by detector package D_2, which consists of a 0.5-mm-diam multimode fiber whose output is mated with another dry ice cooled avalanche photodiode. Both detectors are preceded by 83-nm-bandwidth spectral filters centered at the degenerate wavelength 702.2 nm. The input tip of the fiber is scanned in the transverse plane by two orthogonal encoder drivers, and the output pulses of each detector, which are operating in the Geiger mode, are sent to a coincidence counting circuit with a 1.8-ns acceptance window.

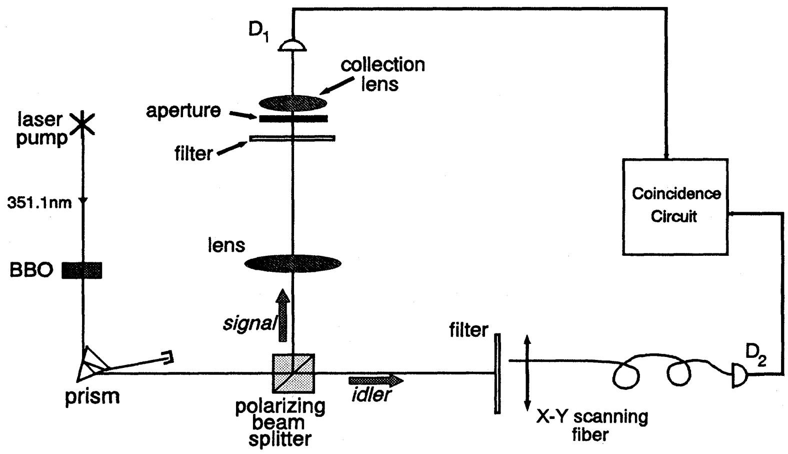

FIG. 1. Cartoon schematic (not to scale) of the experimental setup. The numbers in parentheses indicate the distances between adjacent optical devices (for simplicity, the optical distances inside the devices have been included).

By recording the coincidence counts as a function of the fiber tips's transverse plane coordinates in the idler beam, we see the image of the UMBC aperture, which is reported in Fig. 2. It is interesting to note that while the size of the aperture that was inserted in the signal beam is only about 3.5×7 mm, the observed image measures 7×14 mm. We have therefore managed linear magnification by a factor of 2. Although the transverse plane sizes of the signal and idler beams do naturally expand linearly as they propagate away from the crystal, this particular magnification value cannot be explained simply by the ratio of the distances between the detectors and the down-conversion crystal. In fact, as is seen in Fig. 1, this ratio is only slightly larger than 1:1.

However, if one considers the distances in relation to the placement of the *lens*, we see a remarkable two-photon geometrical optical effect, which is the essence of this imaging experiment. In particular, we see from Fig. 1 that the relationship between the focal length of the lens f, the aperture's distance along the optical path from the lens S, and the image plane's (i.e., fiber tip plane) optical distance from the lens (which is actually *the distance from the lens back through the beam splitter to the crystal, and then forward straight through the beam splitter to the image plane)* satisfies the Gaussian thin lens equation

$$1/S + 1/S' = 1/f. \tag{3}$$

In this experiment, we chose $S = 600$ mm, and the twice magnified clear image was found when the fiber tip was in the plane with $S' = 1200$ mm.

To understand this unusual phenomenon, we examine the quantum nature of the two-photon state produced in SPDC. We have emphasized the entanglement of the two-photon state (1) in terms of the phase-matching conditions in Eq. (2). The momentum entanglement of the photon pairs, which encourages two-dimensional correlations, is the result of the *transverse* components of the wave-vector condition

$$k_s \sin\alpha_s = k_i \sin\alpha_i, \tag{4}$$

where α_s and α_i are the scattering angles of the signal and idler photon relative to the pump beam inside the crystal. Upon exiting the crystal, Snell's law thus provides

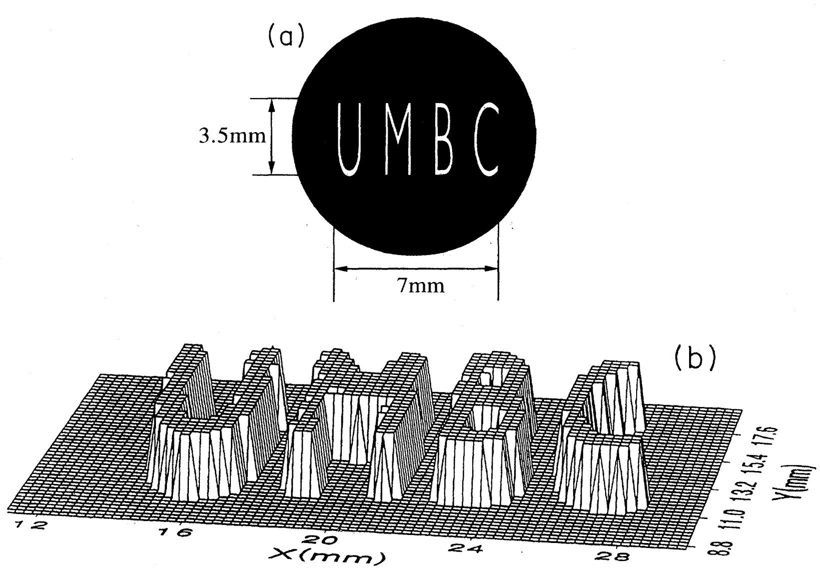

FIG. 2. (a) Reproduction of the actual aperture placed in the signal beam. Note that the size of the letters is on the order of standard text. (b) Coincidence counts as a function of the fiber tip's transverse plane coordinates. The scanning step size is 0.25 mm. The data shown is a "slice" at the half maximum value, with no image enhancement.

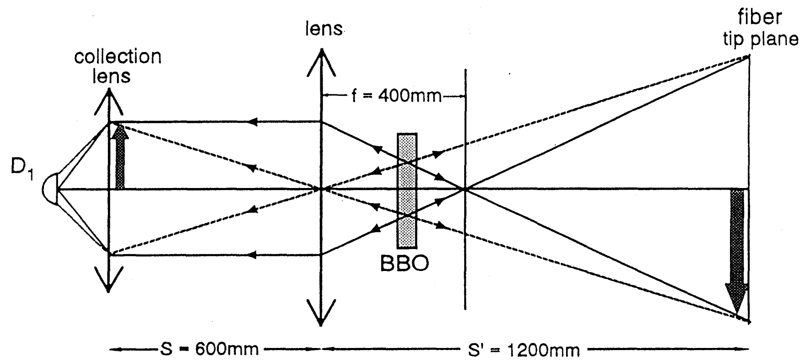

FIG. 3. Conceptual "unfolded" version of the schematic shown in Fig. 1, which is helpful for understanding the physics. Although the placement of the lens and the detectors obey the Gaussian thin lens equation, it is important to remember that the geometric rays actually represent pairs of SPDC photons that propagate in different directions.

$$\omega_s \sin\beta_s = \omega_i \sin\beta_i , \tag{5}$$

where β_s and β_i are the exit angles of the signal and idler photons with respect to the $\mathbf{k}_p$ direction. Therefore, near the degenerate frequency case the photons constituting one pair are emitted at roughly equal, yet opposite, angles. Along the lines of the EPR example, we may say that although the emission angle of each of the signal and idler photons has a considerably large uncertainty, if one is emitted at a certain angle, its conjugate must have been emitted at an equal, yet opposite angle with unit probability.

This then allows for a simple explanation of the experiment in terms of "usual" geometrical optics in the following manner: we envision the crystal as a "hinge point" and "unfold" the schematic of Fig. 1 into that shown in Fig. 3. Because of the equal angle requirement of Eq. (5), we see that the amplitudes of all photon pairs that result in a coincidence detection can be represented by *straight lines* in this unfolded version (but keep in mind the different propagation directions indicated by the small arrows diverging from the crystal in Fig. 3) and therefore the image is well produced in coincidences when the aperture, lens, and fiber tip are located according to Eq. (3). In other words, the image is exactly the same as one would observe on a screen placed at the fiber tip if the photodetector of detector package D_1 were replaced by a pointlike light source and the BBO crystal by a flat reflecting mirror.

One can see from the terms of state (1) and the conceptual rays of Fig. 3 that the entire aperture is covered by the probability amplitudes of the signal photons. Furthermore, there are many possible signal photon amplitudes that can correspond to any one specific geometric point of the aperture. However, all of their conjugate idler amplitudes are seen to reach *exactly one geometric point*, and it is precisely this point-by-point correspondence that defines an image plane in relation to the lens.

The supercorrelations of the signal and idler photons of SPDC were first observed by Burnham and Weinberg [17], who demonstrated that a fixed pinhole in the signal beam requires any pinhole in the idler beam to be located according to the phase-matching conditions in order to have any coincidence counts. Recently, further studies have provided more details about these interesting spatial correlation properties in relation to several experimental parameters [18–20]. However, in terms of the above analysis, one sees that in these types of experiments the correspondence can be more accurately thought of as a simple projection, or shadow, of the signal beam pinhole instead of an image. In fact, in our experiment removal of the lens, followed by placement of the detectors at any distance from the crystal, resulted in a completely blurred out picture, even for apertures of a much larger scale than that shown in Fig. 2(a).

In conclusion the experiment presented here, in contrast to all previous two-photon interferometric experiments, realized a quantum two-photon geometric optical effect. Whereas the classical theory of imaging is very well established, and indeed it is possible to imagine some type of classical source that could partially emulate this behavior, we have successfully performed optical imaging by means of a quantum-mechanical entangled source. By taking advantage of the two-photon state generated in SPDC, the use of a lens in the signal beam has established an image plane with the definitive point-by-point correspondence to the object (i.e., aperture) plane. The entanglement of this two-photon state is analogous to that discussed by EPR and can be used to demonstrate high-resolution imaging that can be interpreted through a "two-photon Gaussian thin lens equation."

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