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Quantum Ghost Imaging by Measuring Reflected Photons

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Summary

A new type of imaging, Quantum ghost imaging, is described that is based on the measurement of photons reflected from an object . A CCD array is placed facing a chaotic light source and gated by a photon counting detector that simply counts all randomly reflected photons from an object. A "ghost" image of the object is then observed in the gated CCD. This interesting demonstration is not only useful for practical applications, such as x-ray lensless imaging, but is also important from a fundamental point of view. It further explores the nonclassical two-photon interference nature of thermal light ghost imaging.

Introduction

Quantum ghost imaging is a new type of imaging. The first two-photon imaging experiment was demonstrated by Pittman et al. in 1995[1]. The experiment was named "ghost imaging" due to its nonlocal feature. The key physics demonstrated in that experiment may not be the "ghost." The original purpose of the experiment was to study and test the two-particle EPR[2] correlation in position and in momentum for an entangled two-photon system[3]. Experiments of ghost imaging[1] and ghost interference[4] stimulated the foundation of quantum imaging in terms of multi-photon geometrical and physical optics. Entangled multi-photon systems were introduced to lithography for sub-diffraction-limited imaging[5].

Quantum imaging has so far demonstrated two peculiar features: (1) reproducing ghost images in a "nonlocal" manner, and (2) enhancing the spatial resolution of imaging beyond the diffraction limit. Both the nonlocal behavior observed in the ghost imaging experiment and the apparent violation of the uncertainty principle explored in the quantum lithography experiment are due to the two-photon coherent effect of entangled states, which involves the superposition of two-photon amplitudes, a nonclassical entity corresponding to different yet indistinguishable alternative ways of triggering a joint-detection event in the quantum theory of photodetection [6]. The nonlocal superposition of two-photon states may never be understood classically. In 2004, Gatti et al.[7] proposed ghost imaging by replacing entangled state with chaotic thermal radiation. A question about ghost imaging is then naturally raised: Is ghost imaging a quantum effect if it can be simulated by "classical" light? Thermal light ghost imaging is based on the second-order spatial correlation of thermal radiation. In fact, two-photon correlation of thermal radiation is not a new observation. Hanbury-Brown and Twiss (HBT) demonstrated the second-order spatial correlation of thermal light in 1956 [8]. Differing from entangled states, the maximum correlation in thermal radiation is 50%, which means

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33% visibility of intensity modulation at most. Nevertheless, thermal light is a useful candidate for ghost imaging in certain applications[9][10].

The HBT experiment was successfully interpreted as statistical correlation of intensity fluctuations. In HBT, the measurement is in the far-field (Fourier transform plane). The measured two intensities have the same fluctuations while the two photodetectors receive the same mode and thus yield maximum correlation

$$\langle I_1 I_2 \rangle = \bar{I}_1 \bar{I}_2 + \langle \Delta I_1 \Delta I_2 \rangle. \tag{1}$$

When the two photodetector receive different modes, however, the intensities have different fluctuations, the measurement yields $\langle \Delta I_1 \Delta I_2 \rangle = 0$ and gives $\langle I_1 I_2 \rangle = \bar{I}_1 \bar{I}_2$. One type of the HBT experiments explored the partial (50%) spatial correlation $\langle I_1 I_2 \rangle \sim 1 + \delta[(\boldsymbol{\rho}_1 - \boldsymbol{\rho}_2)(\Delta\theta)]$ of the thermal radiation field, where $\boldsymbol{\rho}_j$ is the transverse coordinate of the jth photodetector and $\Delta\theta$ is the angular size of the source. This result has been applied in Astronomy for measuring the angular size of stars. Although Eq. (1) gives a reasonable explanation to the far-field HBT phenomena, the classical theory of statistical correlation of intensity fluctuations is very limited. First, it fails to provide an adequate interpretation for ghost imaging of entangled states. The visibility of ghost image of entangled two-photon state is 100% which means a 100% correlation, i.e., $\langle I_1 I_2 \rangle \sim \delta(\boldsymbol{\rho}_1 - \boldsymbol{\rho}_2/m)$, where m is the magnification factor of imaging. If one insists on Eq. (1), the mean intensities $\bar{I}_1$ and $\bar{I}_2$ must be zero. Otherwise Eq. (1) leads to non-physical conclusions. The measurements, however, never yield zero mean values of $\bar{I}_1$ and $\bar{I}_2$ in any circumstances. Second, Scarcelli et al. recently demonstrated a lens-less "near-field" ghost imaging of chaotic radiation [9] and pointed out that the theory of statistical correlation of intensity fluctuations does not work for that experiment. Differing from HBT in which the measurement is in the far-field, Scarcelli's experiment is in the near-field. In the near-field, for each point on the detection plane, a point photodetector receives a large number of (N) modes in the measurement. The ratio between joint-detections triggered by "identical mode" and joint-detections triggered by "different modes" is N/N^2. For a large N, the contributions from "identical mode" is negligible and thus $\langle \Delta I_1 \Delta I_2 \rangle = 0$, as we know that different modes of chaotic light fluctuate randomly and independently. Therefore, the classical idea of statistical correlation of intensity fluctuations will not work in the multi-mode case. Scarcelli et al. provided a successful alternative interpretation in terms of quantum theory of two-photon interference[3]. However, the concept of two-photon superposition is not restricted to the entangled states. It is generally true for any radiation, including "classical" thermal light. Unfortunately, this concept has no counterpart in the classical electromagnetic theory of light.

We report a new experimental study of near-field thermal light ghost imaging

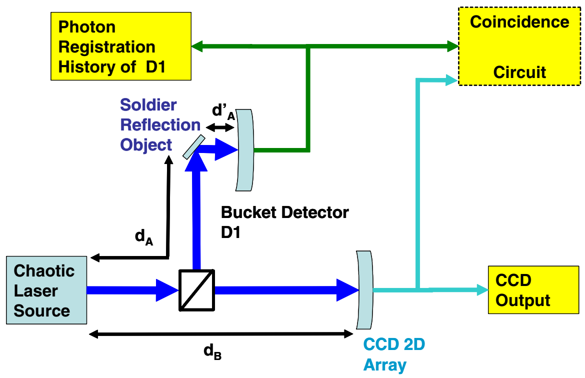

Figure 1: ARL ghost image experiment schematic

to provide further experimental evidence and theory supporting the quantum theory of ghost imaging[11]. This experiment reports the first set of two-photon images captured by a 2D photon counting CCD array by means of joint-detection with another photon counting detector. Interestingly, the CCD array was not "looking" at the object. Instead it was the other photon counting detector that simply counted all randomly reflected and scattered photons from the surface of the object. This demonstration is useful for practical imaging-sensing field-applications.

Experiments and results

Figure 1 is the schematic setup of the experiment. Radiation from a chaotic pseudothermal source [10] is divided into two paths by a non-polarizing beam splitter. In arm A, an object, such as an Army soldier model, was illuminated by the light source at a distance of $d_A = 450mm$. A "bucket" photodetector, D_1, was used to collect and to count the photons that were reflected from the surface of the object. In arm B a 2-D photon counting CCD array was placed a distance of $d_B = d_A = 450mm$ from the source. The CCD array was facing the light source instead of facing the object. The "bucket" detector was simulated by using a large area silicon photodiode for collecting photons reflected from the object. A triggering pulse from a PC was used to synchronize D_1 and the CCD array for two-photon joint-detection.

The chaotic light was simulated by transmitting a laser beam through a lens and through a rotating ground glass phase screen. Figure 2 reports the two-photon image of the Army soldier model. Although the image quality needs to be improved, it is clear what the object is. The poor quality of the image is mainly due to the low photon flux of the reflection.

To ensure that the new experimental setup is equivalent to that of historical ghost imaging experiments we have performed a similar measurement. Figure 3 reports a two-photon image of an "ARL" stencil mask. In this measurement, the bucket detector D_1 was placed behind the "ARL" stencil mask, collects and counts

Figure 2: Ghost image of an Army soldier model

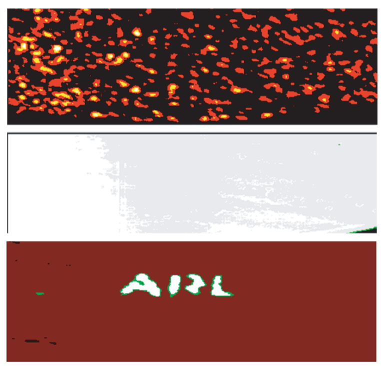

Figure 3: Ghost image of "ARL" stencil. Upper Fig.: Single frame CCD output. Middle Fig.: Averaged CCD output. Lower Fig.: CCD-D1 joint-detection

the photons that have passed through the "ARL" letters. The result shows a high fidelity reproduction of the letters "ARL". However, when the CCD was moved away from $d_B = d_A$, the images were blurred, indicating that it is an image and not a "projection shadow".

Theory and analysis

The Army soldier in Fig. 2 is an image by any standard meaning, except the image exists in joint-detection only. Mathematically, a ghost image is the result of a convolution between the aperture function (amplitude distribution function) of the object $A(\boldsymbol{\rho}_o)$ and a δ-function like second-order correlation function $G^{(2)}(\boldsymbol{\rho}_o, \boldsymbol{\rho}_i)$

$$F(\boldsymbol{\rho}_i) = \int_{obj} d\boldsymbol{\rho}_o A(\boldsymbol{\rho}_o)\, G^{(2)}(\boldsymbol{\rho}_o, \boldsymbol{\rho}_i) \tag{2}$$

where $G^{(2)}(\boldsymbol{\rho}_o, \boldsymbol{\rho}_i) \simeq \delta(\boldsymbol{\rho}_o - \boldsymbol{\rho}_i/m)$, $\boldsymbol{\rho}_o$ and $\boldsymbol{\rho}_i$ are 2-D vectors of the transverse coordinate in the object plane and the image plane, respectively, and m is the magnification factor. The δ-function characterizes the perfect point-to-point relationship between the object plane and the image plane. If the image comes with a constant background, as in this experiment, the second-order correlation function $G^{(2)}(\boldsymbol{\rho}_o,\boldsymbol{\rho}_i)$ in Eq. (2) must be composed of two parts

$$G^{(2)}(\boldsymbol{\rho}_o,\boldsymbol{\rho}_i) = G_0 + \delta(\boldsymbol{\rho}_o - \boldsymbol{\rho}_i/m) \tag{3}$$

where G_0 is a constant. The value of G_0 determines the visibility of the image. Examining Eq. (3), one may connect it with the $G^{(2)}$ function of thermal radiation

$$G^{(2)} = G_{11}^{(1)} G_{22}^{(1)} + |\, G_{12}^{(1)}\,|^2 \tag{4}$$

where $G_{11}^{(1)} G_{22}^{(1)} \sim G_0$ is a constant, and $|G_{12}^{(1)}|^2 \sim \delta(\boldsymbol{\rho}_1 - \boldsymbol{\rho}_2)$ represents a nonlocal position-position correlation. Although the second-order correlation function $G^{(2)}$ is formally written in terms of $G^{(1)}$s, the physics are completely different. $G_{12}^{(1)}$ is usually measured by one photodetector representing the first-order coherence of the field. In Eq.(4), $G_{12}^{(1)}$ is measured by two independent photodetectors at distant space-time points and represents a nonlocal EPR correlation. Differing from phenomenological intensity-intensity correlation, the quantum theory of joint photodetection (Glauber's theory) [6] indicates the physical origin of the phenomenon. The theory gives the probability of a specified joint photodetection event and allows us to identify the superposed probability amplitudes. Simplified to 2-D $G^{(2)} = Tr[\hat{\rho} E^{(-)}(\boldsymbol{\rho}_1) E^{(-)}(\boldsymbol{\rho}_2) E^{(+)}(\boldsymbol{\rho}_2) E^{(+)}(\boldsymbol{\rho}_1)]$, where $E^{(-)}$ and $E^{(+)}$ are the negative and positive frequency field operators at space-time coordinates of the photodetection event and $\hat{\rho}$ represents the radiation density operator. $E_j^{(+)}(\boldsymbol{\rho}_j) \propto \sum_{\boldsymbol{\kappa}} g_j(\boldsymbol{\kappa};\boldsymbol{\rho}_j)\,\hat{a}(\boldsymbol{\kappa})$ where $\hat{a}(\boldsymbol{\kappa})$ is the annihilation operator for the mode corresponding to $\boldsymbol{\kappa}$ and $g_j(\boldsymbol{\rho}_j;\boldsymbol{\kappa})$ is the Green's function associated with the propagation of the field from the source to the jth detector [10]. Eq. (5) indicates a two-photon superposition.

$$G^{(2)}(\boldsymbol{\rho}_1,\boldsymbol{\rho}_2) = \sum_{\boldsymbol{\kappa},\boldsymbol{\kappa}'} \left| g_2(\boldsymbol{\kappa};\boldsymbol{\rho}_2) g_1(\boldsymbol{\kappa}';\boldsymbol{\rho}_1) + g_2(\boldsymbol{\kappa}';\boldsymbol{\rho}_2) g_1(\boldsymbol{\kappa};\boldsymbol{\rho}_1) \right|^2 . \tag{5}$$

The superposition happens between two different yet indistinguishable Feynman alternatives that lead to a joint photodetection: (1) photon $\boldsymbol{\kappa}$ and $\boldsymbol{\kappa}'$ are annihilated at $\boldsymbol{\rho}_2$ and $\boldsymbol{\rho}_1$, and (2) photon $\boldsymbol{\kappa}'$ and $\boldsymbol{\kappa}$ are annihilated at $\boldsymbol{\rho}_2$ and $\boldsymbol{\rho}_1$. The interference phenomenon is not, as in classical optics, due to the superposition of electromagnetic fields at a local point of space-time. It is due to the superposition of $g_2(\boldsymbol{\kappa};\boldsymbol{\rho}_2) g_1(\boldsymbol{\kappa}';\boldsymbol{\rho}_1)$, and $g_2(\boldsymbol{\kappa}';\boldsymbol{\rho}_2) g_1(\boldsymbol{\kappa};\boldsymbol{\rho}_1)$, the two-photon amplitudes. Completing the normal square of Eq. (5), $\sum_{\boldsymbol{\kappa}} |g_1(\boldsymbol{\kappa};\boldsymbol{\rho}_1)|^2 \sum_{\boldsymbol{\kappa}'} |g_2(\boldsymbol{\kappa}';\boldsymbol{\rho}_2)|^2 = G_{11}^{(1)} G_{22}^{(1)}$

corresponds to G_0, the other term corresponds to $|G_{12}^{(1)}(\boldsymbol{\rho}_1,\boldsymbol{\rho}_2)|^2$ which gives the EPR δ-function of position-position correlation. The Green's function from the radiation source to the transverse planes at d_A and $d_B = d_A$ for Fig. 1 is:

$$g_1(\boldsymbol{\kappa};\boldsymbol{\rho}_o) \propto \Psi\left(\boldsymbol{\kappa}, -\frac{c}{\omega}d_A\right)e^{i\boldsymbol{\kappa}\cdot\boldsymbol{\rho}_o},\ g_2(\boldsymbol{\kappa};\boldsymbol{\rho}_i) \propto \Psi\left(\boldsymbol{\kappa}, -\frac{c}{\omega}d_B\right)e^{i\boldsymbol{\kappa}\cdot\boldsymbol{\rho}_i} \tag{6}$$

where $\Psi(\omega d/c)$ is a phase factor representing the optical transfer function of the linear system under the Fresnel near field paraxial approximation, ω is the frequency of the radiation field, and c is the speed of light. Substituting Eq. (6) into $|\sum_{\boldsymbol{\kappa}} g_1^*(\boldsymbol{\kappa};\boldsymbol{\rho}_1)g_2(\boldsymbol{\kappa};\boldsymbol{\rho}_2)|^2$ at $d_A = d_B$,$|\int d\boldsymbol{\kappa}\, g_1^*(\boldsymbol{\kappa};\boldsymbol{\rho}_1)g_2(\boldsymbol{\kappa};\boldsymbol{\rho}_2)|^2 \simeq |\delta(\boldsymbol{\rho}_o+\boldsymbol{\rho}_i)|^2$. Substituting this δ-function together with the constant G_0 into Eq. (2), an equal sized lens-less image of $A(\boldsymbol{\rho}_o)$ is observed in the joint-detection between the CCD array and the photon counting detector D_1. Image visibility is determined by G_0.

Conclusion

Our ghost experiment based on measuring reflected photons is successfully interpreted as the result of two-photon interference. The two-photon interference results in a point-point correlation between the object plane and the image plane and yields a ghost image of the object by means of joint photodetection. This experiment is useful for imaging-sensing field-applications and for the fundamental understanding of quantum nonlocality and multi-photon superposition.

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