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Quantum Ghost Imaging Experiments and Mathematics

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Summary

Using a CCD camera we investigated and successfully achieved quantum ghost imaging of the stencil letters "ARL" placed in front of a photon bucket detector from photons which did not interact with the stencil letter object. We investigated the role of speckle spatial size and time scales in resolving images. The process suggests new mathematical paradigms and important applications for quantum ghost imaging .

Introduction

Because of a potential for new applications and deeper insight into quantum processes, there is enormous interest in the experimental and theoretical aspects of quantum imaging and quantum ghost imaging [1]−[8]. Quantum imaging became important after the discovery by Shih's group that entangled photons could produce quantum ghost images caused by photons that did not interact with the image mask [2] and by the JPL group that *n*-photon entanglement yields lithography which beats the diffraction resolution limit [1]. Shih's group has shown [4] that quantum ghost imaging can be interpreted in a picture by Klyshko [6] as a two-photon quantum process. In the process chaotic laser light, also termed pseudo-thermal laser light, was sent through a beam splitter. The optical radiation emanating from a beam splitter side propagated past a stenciled mask into a bucket detector. On another side of the beam splitter photons impinged on a scanning detector which, when computer processed, produced the quantum ghost image of the lettering stencil on the mask. In these cases the quantum ghost image was produced by photons that did not interact with the mask stencil or bucket detector thus raising fundamental questions regarding the physics of photons and light beams. Debate ensued on the physics of quantum ghost imaging and the advantages of entangled quantum imaging versus chaotic laser light or pseudo-thermal imaging. Entangled photon sources can achieve lower noise background, although pseudo-thermal sources are much more readily available. The experiments and interpretations of Shih's group give credence to the interpretation that even the Hanbury-Brown Twiss (HBT) astronomical imaging and the pseudo-thermal ghost imaging processes are quantum, hence the name quantum ghost imaging [3]. In this paper we report on a procedure, different from that of Shih, for performing quantum ghost imaging using a CCD camera that suggests wider applications in imaging such as medical imaging, cryptography, and enhanced detection. The work of Shih centers on nanosecond coincidence imaging using both entangled photons and pseudo-thermal laser

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sources. Other research has demonstrated pseudo-thermal quantum ghost imaging with integration times of 1ms to 3ms [7]. It would be useful for applications if quantum photon time-space correlations could be demonstrated for longer time intervals since that would widen the list of applications and reduce the cost of supporting technology. In the following we describe investigations on quantum ghost imaging on macroscopic time scales of 1ms to 10ms integration times. In addition to the timescale effect on ghost imaging we investigated the role of speckle spatial size in resolving images.

Quantum Picture Mathematical Processing and Experimental Results

Applying what was called a ”fictitious yet fascinating” [4] quantum picture explanation of the quantum ghost image by Klyshko, light propagates backward in time from a detector to the spontaneous parametric down conversion (SPDC) source and then propagates forward in time to the other detector. The Klyshko explanation [6] considers this as an advanced wave two-photon geometric optics effect. The two-photon source of the SPDC is considered to be a mirror. In analogy to SPDC sources, the pseudo-thermal sources are considered to be phase-conjugate mirrors and provide a picture which helps predict the outcome of ghost imaging.

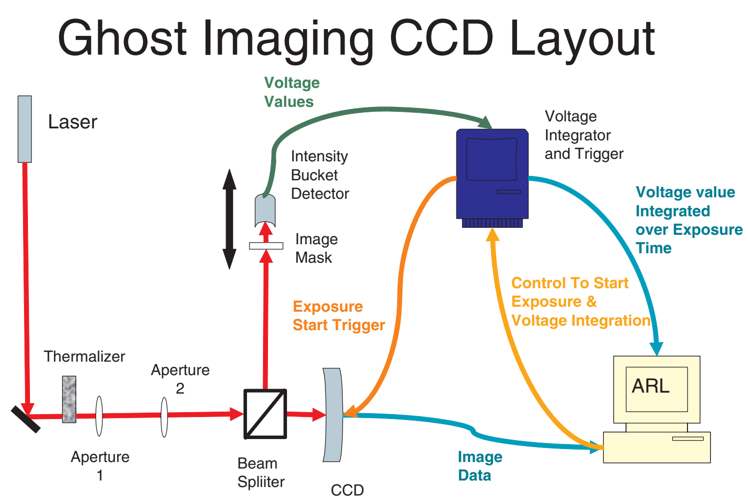

Figure 1: Quantum Ghost Imaging Experimental Setup.

Experimental Apparatus

The experimental apparatus that we used for some of the quantum ghost imaging is depicted in the schematic in Fig.1. The coherent light from the laser source transits a rotating ground glass which produces chaotic laser light or pseudo-thermal light and goes through aperture 1 and aperture 2 separated by a distance. The chaotic light travels a distance after the two apertures and intercepts a beamsplitter. It was found that the first aperture controls the speckle size and the second aperture controls the size of the outer dimension of the beam impinging on the beamsplitter. The beam is split by the beamsplitter into one beamlet entering a CCD camera and another beamlet transiting a stenciled mask and terminating in a bucket detector. Our mask stencil had the three letters "ARL". The CCD camera captures images of the speckle field at each frame. The statistics that are computed for the mean and correlations are discussed below. The instantaneous voltage from the bucket detector is integrated over the time of the CCD camera exposure using intelligent oscilloscope circuits. Each CCD speckle frame is weighted by the bucket detector interval voltage in forming mean and correlation statistics of the CCD ghost image. After sufficient CCD frames are processed the quantum ghost image of the mask stencil appears clearly in the $G^{(2)}$ correlation statistics along with a noise background. A computer controls the oscilloscope, CCD camera, timing and quantum ghost imaging calculations.

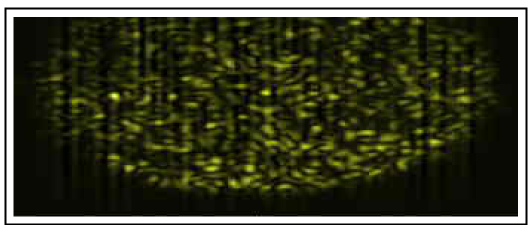

Figure 2: Instantaneous Image (.02sec) Small Speckles Image from a Large Aperture

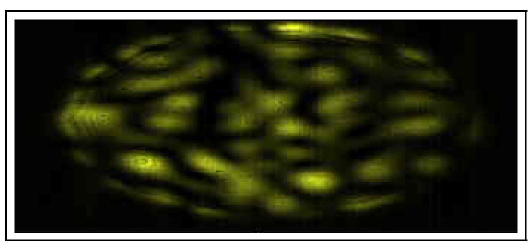

Figure 3: Instantaneous Image (.02sec) Large Speckles from a Small Aperture

Quantum Ghost Imaging Mathematics and Processing

The information received by the bucket detector and the CCD camera was processed by algorithms to calculate the ghost image functions. The mean and fluctuation intensity received by the CCD camera over N CCD shots is calculated as

$$\overline{I} = \frac{1}{N}\sum_{i=1}^{N} I_i = I_i - I_i^{'}. \tag{1}$$

The bucket detector voltage $V_{i\ bucket}$ is proportional to the photon intensity J_i received and integrated over the area of the bucket detector,

$$V_{i\ bucket} = V_i = a\int J_i(x^{'})dx^{'}. \tag{2}$$

The mean and fluctuation voltages are related by

$$\overline{V} = \frac{1}{N}\sum_{i=1}^{N} V_i = V_i - V_i^{'}. \tag{3}$$

The mean of the product of V and I over the ensemble of measurements is

$$\overline{VI} = \frac{1}{N}\sum_{i=1}^{N} V_i I_i. \tag{4}$$

The product $V_i I_i$ is given as

$$V_i I_i(x) = a\int J_i(x^{'})I_i(x)dx^{'} \tag{5}$$

$$= a\int (\overline{J}_i(x^{'}) + J^{'}(x^{'}))(\overline{I}_i(x) + I_i^{'}(x))dx^{'}. \tag{6}$$

The $G^{(2)}(x)$ correlation is readily extended to two dimensions and computed as

$$G^{(2)} = [\overline{VI}(x,y) - \overline{V}\ \overline{I}(x,y)]. \tag{7}$$

Mean and Speckle Images

Separate speckle images from the CD were captured with 1ms to 10ms second exposure. The captured images were multiplied by the time averaged bucket voltage and combined into statistical expectations. The above equations were adjusted for the sampling time intervals. The means $\overline{I}$ and the $G^{(2)}$ correlation were visualized. Laser light transiting ground glass or reflecting off of a rough surface produces speckles that are partially coherent beamlets which may vary in size. Our experiments show that we can vary the size of the speckles by controlling apertures. As expected a small aperture produces large speckles and a larger aperture produces smaller speckles as imaged on the CCD and shown in Fig. 2 and Fig. 3.

Typical mean field results show slight intensity gradients in the image, but no stencil image. $G^{(2)}$ images were calculated according to the above prescription. Fig. 4 with small speckles shows the ARL mask stencil. Very large speckles from the smallest aperture resulted in a smearing of the ARL mask stencil image to a point where the letters ran together and could not be separately identified as shown in Fig.5. These results are as expected from a complementarity point of view between the coherence of the bucket and CCD path beams and the correlation between them [7].

Figure 4: $G^{(2)}$ Image for ARL Mask Stencil and Small Speckles.

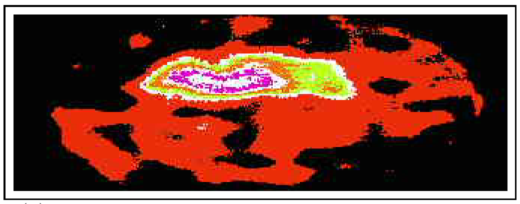

Figure 5: $G^{(2)}$ Image for ARL Mask Stencil and Large Speckles.

Concluding Remarks on Applications and Results

In the following sections we provide concluding remarks on applications to which the technology can be applied and on our experimental results and mathematical processing. Quantum imaging is a process in which a single device can produce both near field results and farfield imaging, while classical imaging would require two different devices [1]. Quantum ghost imaging can be used to perform lensless imaging such as in x-ray diffraction imaging and x-ray imaging of the human body [4]. This is important because lenses for x-rays are difficult to produce and x-ray lasers have not yet been developed. Speckle imaging can use simpler more robust equipment and can be useful in many types of imaging from military imaging to biological imaging. Quantum imaging is useful in obtaining higher resolution lithography [1]. Quantum ghost imaging can be useful in quantum cryptographic capabilities resulting in compression of the encrypted part of the message transferred [1].

Quantum ghost imaging was explored by use of a photon efficient CCD camera, a stencil mask, a bucket detector, and computer processing. ”ARL” ghost images were made from photons which had not interacted with the ARL mask stencil. The ghost images were found from the $G^{(2)}$ correlation processing of the random speckles weighted by the photon bucket detector intensity. Resolution of the imaged mask was found to be controlled by speckle size analogous to wavelets, thus presenting a new mathematical paradigm. Quantum ghost imaging has been extended to imaging over macroscopic time intervals allowing more applications. Quantum ghost imaging experiments and mathematics are useful for understanding fundamental quantum processes and for providing new applications.

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