Invited Paper

Quantum Imaging: Enhanced Image Formation Using Quantum States of Light

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ABSTRACT

We review recent research in the field of quantum imaging. Quantum imaging deals with the formation of images that possess higher resolution or better signal-to-noise characteristics than conventional images by making use of the coherence properties of quantum light fields. Quantum imaging also deals with indirect imaging methods such as ghost imaging, in which image information is conveyed not by a single light field but by the correlations between two separate light fields. In this contribution we concentrate primarily on recent results in the area of ghost imaging.

Keywords: quantum imaging, entangled photons, image formation

1. INTRODUCTION

Recent advances in quantum optics and in quantum information science have opened the possibility of entirely new methods for forming optical images with unprecented sensitivity and resolution. This new field of research, known as quantum imaging, has led to other breakthroughs as well, such as the possibility of imaging without interaction,[1] with enormous implications for real-world applications. Quantum imaging[2] implements ideas and techniques from the fields of quantum optics and nonlinear opticss. In addition, quantum imaging offers significant opportunities within the broader field of quantum information science because the parallelism intrinsic to image-bearing beams leads to increased information capacity. In this contribution, we concentrate on recent results in the area of ghost imaging. But we emphasize that there are many other areas of great current interest in the filed of quantum image science including single-photon imaging[3] and in the propagation of quantum states through atmospheric turbulence.[4]

2. GHOST IMAGING

Ghost imaging is an indirect imaging method that acquires the image of an object through spatial intensity correlation measurements. In a typical imaging setup (see for instance Fig. 1), two spatially correlated light fields are used. One is an object field that illuminates the object but is not spatially resolved by its detector. The other is a reference field that does not interact with the object but is spatially resolved by its detector. Then, by measuring the intensity cross-correlation function between the object and reference fields, an image can be obtained. This image is sometimes referred to as a ghost image because the photons that form the image have never physically interacted with the object being imaged. By separating the process of forming the image from that of interrogating the object, new possibilities for enhanced image formation and remote sensing are made possible. The correlations that leads to ghost imaging can be of a quantum or classical nature.[5,6] Quantum ghost imaging utilizes the spatial entanglement of biphotons generated, for instance, by spontaneous parametric down conversion (SPDC).[7,8] A different sort of ghost imaging is thermal ghost imaging, which is sometimes called classical ghost imaging, Thermal ghost imaging is achieved by using two exact copies of a spatially incoherent light field, which can be obtained for instance by passing a classical speckle pattern through a beam splitter.[9–12] Within this article we use the terms quantum and thermal in the sense defined in the previous two sentences. We note that other authors at times use these terms in somewhat different ways[13–15] Our choice of terminology is based on the simple notation that the two photons produced by parametric downconversion (PDC) are entangled

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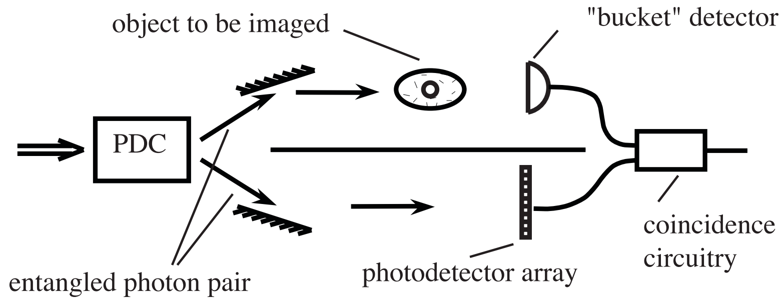

Figure 1. A typical ghost imaging setup.

in a quantum mechanical sense, whereas the nature of the correlations that occur in a speckle pattern (or more generally in any thermal light field) can be understood at a purely classical level.

The origin of image formation in thermal ghost imaging is illustrated in Fig. 2. Here we see two identical speckle patterns cast onto the object (left) and onto a photodetector array (right). For simplicity, the object is taken to be a slit in an otherwise opaque screen. The power transmitted through this slit it measured by a bucket detector. The spatial structure of the speckle pattern is measured by the imaging detector on the right. The power measured by the bucket detector is multiplied by the intensity distribution measured by the image detector, and this quantity is averaged over many realizations of the speckle pattern. In this way an image of the object is reconstructed. The object and reference fields used in ghost imaging need not have the

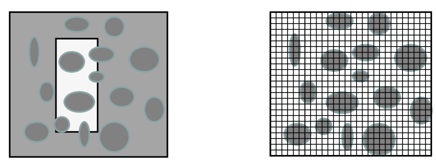

Figure 2. Statistical origin of image formation in thermal ghost imaging.

same wavelength. Indeed, nondegenerate-wavelength quantum ghost imaging has already been demonstrated experimentally,[16] although to date thermal ghost imaging experiments have been carried out only for single-frequency situations. It is natural to ask how the spatial resolution of the ghost imaging process depends on each of the wavelengths that is used. The wavelength dependence of the resolution has been studied previously for degenerate-wavelength ghost imaging[17,18] and for nondegenerate-wavelength quantum.[18]

We have recently demonstrated theoretically that nondegenerate-wavelength ghost imaging can be carried out using either classical or quantum correlations.[19] A conceptual diagram illustrating the process of nondegenerate-wavelength ghost imaging is shown in Fig. 3. We obtained analytical results which show that the resolution of nondegenerate-wavelength ghost imaging depends primarily on the wavelength of the light that illuminates the object. However, under certain specialized conditions the resolution depends also on the wavelength of the light in the reference arm. For thermal ghost imaging, the light beams in the object and reference arms can have very different wavelengths. Moreover, we found that the image resolution for the classical scheme can be higher than that for its quantum counterpart, despite the fact that the photons have the same degree of spatial correlation in the two schemes. These results are potentially important for cases in which the optimal wavelength of light that illuminates the object is very different from the optimal wavelength for the operation of the spatially resolving detector.

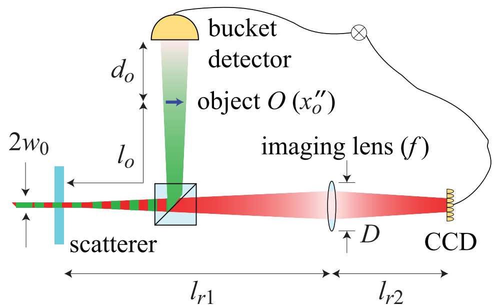

Figure 3. Geometry of two-color ghost imaging.

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