Some topics in Quantum Imaging

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Abstract. The field of Quantum Imaging exploits the quantum nature of light and the intrinsic parallelism of optical signals to devise novel techniques for optical imaging and for parallel information processing at the quantum level (see [1] and references quoted therein). In this presentation, we will shortly discuss two topics in this area: the first is the so-called ghost imaging which, however, is not necessarily quantum; the second is the detection of faint amplitude objects with a sensitivity beyond the standard quantum limit, and in this case we are fully in the quantum domain. Both topics are related to the phenomenon of optical parametric down-conversion (PDC), in which a fraction of the pump photons of a laser beam, injected into a crystal with a quadratic non-linearity, are down-converted to a pair of signal and idler photons, with conservation of total energy and total momentum. A feature of paramount importance is that the signal and idler beams are spatially correlated both in the near field (position correlation) and in the far field (momentum correlation). The simultaneous presence of position and momentum correlation implies quantum entanglement, as it has been also observed experimentally [2].

1. Ghost Imaging

This protocol was invented by Klyshko [3] as an application of the entanglement of signal and idler photons. The signal and idler beams identify a test and a reference arm (Fig. 1). An object (e.g. a double slit in the figure) is located in the test arm. In order to obtain an image of the object, it would be necessary to use an array of detectors (e.g. a CCD camera), but one locates only a single detector in the test arm. On the other hand, one puts an array of detectors in the idler arm, but one does not get an image from this array either, because the idler photons do not interact with the object. The image of the object is obtained by detecting the coincidences between the arrival of a signal photon in the single detector and the arrival of an idler photon in one of the detectors of the array (Fig. 1). In this way, one exploits the position correlation between the signal and the idler photon. Important is also that, by simply modifying the configuration of the optical elements in the reference arm one obtains, instead of the image of the object, the Fourier transform of the intensity distribution of the object (the interference-diffraction pattern in the case of the double slit). In this case one exploits the momentum correlation between the signal and the idler photon.

The experimental demonstration of these concepts was reported in [4, 5]. With the new century, a very lively debate developed on the question whether quantum entanglement is necessary or not to realize ghost imaging (see [1] for references). Bennink et al. [6] first demonstrated experimentally that it is not necessary. The ideal configuration to realize ghost imaging
Figure 1. Scheme of ghost imaging.

Figure 2. Thermal ghost imaging.

Recently Shapiro [9] has devised a variant of thermal ghost imaging, called computational ghost imaging, which allows to get rid of the reference arm.

In the recent trend towards applications of the ghost imaging protocol, there are therefore two options. One is to use quantum entangled beams generated by PDC; in this way one has the possibility of accessing the quantum regime. The other is to use pseudo-thermal beams, which are inexpensive and easy to handle.

2. Detection of faint amplitude objects

Let us consider first the problem of the detection of a weak absorption without considering, for the moment being, the spatial distribution of the absorber. If one wants to measure absorption
with a high sensitivity, it is convenient to use the differential scheme shown in Fig. 3. The beam generated by any source is injected onto a 50/50 beam splitter, thus obtaining two classically correlated beams. The absorber is located in the path of one of the two beams, and the absorption is retrieved by measuring the difference between the photon numbers in the two beams after the absorption. The signal to noise ratio (SNR) in this measurement corresponds to the standard quantum limit (SQL) in such a measurement. Of course, the SNR can be increased by increasing the photon number in the two beams; however, if the absorber is delicate (e.g. it is a biological sample) one cannot increase the intensity arbitrarily and in this case it is convenient to be able to go beyond the SQL.

![Differential scheme for the detection of a weak absorption.](image)

The SQL arises basically from the shot-noise level (SNL) in the fluctuations of the photon number difference. Therefore PDC offers the possibility of beating the SQL, since the fluctuations in the photon number difference can be below the SNL. Precisely, in Fig. 1 one replaces the source and the beam splitter by the pump laser and the nonlinear crystal of PDC and one uses the signal and idler beams instead of the two classically correlated beams. The experimental demonstration of the possibility of beating the SNR in this way was provided in [10, 11]. Let us now consider the spatial distribution of the absorption. A natural idea is to generalize this approach to obtain the image of a weak amplitude object. In this case it is not possible to use spatially singlemode beams as those generated by the optical parametric oscillator utilized in [10, 11]. It is necessary to use spatially multimode signal and idler beams as those obtained in single-pass cavityless PDC. The experiment reported in [12] using cavityless PDC demonstrated that indeed in this way the fluctuations in the photon number difference between signal and idler can be below the shot noise level pixel by pixel, as it is necessary for the detection of a weak amplitude object with a sensitivity below the SQL.

However, the experimental setting of [12] is not appropriate for the detection of a weak amplitude object because the sub-shot-noise character arises only when the background noise of the CCD camera is subtracted. This problem has been thoroughly analyzed in [13], which demonstrates theoretically that the solution is to increase the duration of the pump pulses from the picosecond to the nanosecond range. In this regime the subtraction of the background noise becomes unnecessary, as it has been recently confirmed experimentally [14]. Now the experimental setting of [14] lends itself to the detection of faint amplitude objects.

**References**