Quantum imaging overview

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ABSTRACT

Quantum science and technology are attracting world-wide attention due to the impacts they will have on computing and communications which have no classical counterpart. However, quantum also impacts imaging and sensing. Leaving aside how new detection technologies can sense both single photons and measure their arrival time with pico-second precision, the quantum nature of light enables new types of imaging system, which again have no easy classical implementation. This is brief overview of the historical development of quantum imaging focuses on how the photon pairs created through spontaneous parametric down-conversion lead to unusual imaging systems. Referring to the work from across the global community and some work of my own group we will consider which of these imaging approaches might be considered truly quantum and which might have classical analogies. In all cases I will emphasize those systems which seem to offer practical advantage over traditional approaches giving performance benefits in terms of resolution, signal to noise or wavelength coverage.

Keywords: Quantum imaging, parametric down-conversion, single-photon detection

1. INTRODUCTION

The term quantum imaging is applied to cover a broad spectrum of systems ranging from those which are based on simply the detection of low numbers of, or single photons, those systems based on photon-pairs source to those systems which utilize squeezed state, quantum correlations or entanglement. While recognizing the rapid advances in low photon number detectors and the impact that these are having on classical imaging systems, the purpose of this paper is to examine the opportunities for sources of quantum light to enable new forms of imaging systems that have advantage over classical or traditional approaches. Spontaneous parametric down conversion (SPDC) is a process that occurs in a non-linear optical crystal where an intense pump field results in the polarization of the medium oscillating at both the driving frequency and its second harmonic. This non-linear response is the origin of frequency up-conversion that transforms, for example, an intense infrared laser beam into the equivalent beam in the green. When configured appropriately, the same crystal can also take the intense pump beam and produce two output beams of lower frequency, termed signal, and idler. These signal and idler beams are subject to various conservation laws. The conservation of energy means that the sum of the signal and idler frequencies must add to that of the pump. This conversation of energy also means that, irrespective of the diameter of the pump beam, the creation of the signal and idler photons occurs at very nearly the same time and transverse position (i.e., they are position correlated). The conservation of momentum means similarly means that the momentum of the signal and idler must add to that of the pump. This momentum conservation is nontrivial since it depends both upon the wavelengths and upon the refractive indices of the media at each of the frequencies involved, control of which ultimately defines the precise signal and idler wavelengths along with the divergence of the down converted light. The momentum conservation also implies that the signal and idler photons, despite being created at the same transverse position, have trajectories which have opposite transverse components. It is this seemingly simultaneous restriction on both position and momentum that lies at the heart of the EPR paradox[1] and the role of SPDC in investigating the "spookiness" of quantum physics. The spin angular momentum is also conserved which can lead to correlations in between the polarization states of the signal and idler photons which again has led to numerous demonstrations of quantum phenomena related to demonstrations of the Bell inequality[2]. Although all these various quantum implications are fascinating, in this paper we will consider how the various correlations can be used in imaging systems[3].

2. GHOST IMAING CLASSICAL AND QUANTUM

Within the context of using the correlations created SPDC, potentially, the first example of quantum imaging was the work of Shih and co-workers[4]. In this work the object and raster scanned detector were placed in the idler beam and signal beam respectively. In this configuration neither detector signal alone measures the spatial image information, instead the image information is only revealed from the coincident count between the two detectors. The subtlety of this experimental configuration lies in the imaging between the various planes, which is best understood with reference to geometric optics. Conceptually useful is to consider light which is projected from one of the detectors back towards the down-conversion crystal where it frequency mixes with the pump beam to

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create a new beam. This mixed light then propagates towards the other detector, and the resulting signal corresponds to the strength of the correlation as measured in the coincidence counts of the quantum experiment. To obtain a high correlation and number of different imaging configurations are possible. Firstly, both detectors can be located in the image plane of the crystal. Secondly, both detectors can be in the far-field of the crystal or thirdly, other imaging combinations providing that one detector is imaged to the other[5,6]. The non-local nature of the required measurement led to this approach being called ghost imaging. In subsequent work the scanning detector was replaced with a detector array, thereby eliminating the need to scan a detector, and hence massively reducing the required measurement time[7].

Initially, given that these ghost imaging systems relied upon correlations between pairs of photons, they were considered quantum. However, the spookiness of quantum correlation is not in the correlation itself, but that the correlation can be observed in either of two complimentary bases, e.g. that the position correlation can be observed in the image plane of the crystal and that the momentum anti-correlation can be observed in the far-field. In imaging terms this manifestation of the EPR paradox means that the image obtained from the correlation count is upright if both detectors are in the image plane of the crystal and inverted if they are both in the far-field[8,9].

More generally, although correlations at the level of single photons require SPDC or other complicated light sources, for bright, i.e. many photon, beams correlations between the spatial form of two beams are readily obtained using a beam splitter. Indeed, two such classical correlated beam can be used in a ghost imaging system where one copy illuminated an object, the transmission through which is measured using a single pixel detector and the other illuminates an imaging detector (i.e., a scanned singe pixel detector or a detector array). Once again, the signal from either detector alone does not reveal an image of the object but the product between the imaging detector and the single pixel detector summed over many different spatial patterns does reveal an image[10,11].

It is also possible to remove the beam splitter completely and use instead a spatial light modulator to create a patterned beam to illuminate an object, the correlated copy being the data file itself used to create the pattern. Initially christened as computational ghost imaging,[12] this has much in common with classical single pixel imaging[13].

One aspect of this ghost imaging that cannot be easily replicated using a beam splitter or the computational equivalent is a low photon-number imaging system where the signal and idler beams have dramatically different wavelengths meaning that the object is probed at one wavelength whereas the scanning detector is able to detect an easier to measure wavelength[14]. It is this ability to translate from wavelengths that are difficult to detect to those that are easier which is perhaps the most useful aspect of ghost imaging.

3. NON-LINEAR INTERFEROMETRY

In ghost imaging it remains the case that both wavelengths still need to be detected albeit the hard to detect wavelength requiring only a single pixel detector. This need for detection at both wavelengths can be removed by a technique called imaging with undetected photons[15], which uses non-linear interferometry based on early work by Mandel and co-workers[16].

In a traditional interferometer a beam splitter is used to create two phase correlated beams. The object is placed in one of these beams and then the beams are recombined at a second beam splitter. Interference between these beams and the presence of the object is then observed at either of the outputs from this second beam splitter. Key to interferometry is not just the splitting of one beam into two, but importantly that the input and output beams have constrained phase relationship. Similar phase relationships are also obtained between the pump, signal and idler waves incident and exiting from a non-linear crystal, but importantly the difference been that the signal and idler wave are no longer constrained to be at the same wavelength[17]. The extent to which non-linear interferometry is a fully quantum process as opposed to a complicated classical one remains a debated topic, but it does rely completely on the SPDC process and offers novel capabilities[18]

In principle there is no limit to the wavelengths that could be made visible using these nonlinear techniques, being limited only by the non-linear crystals available that are transparent at all three wavelengths and have sufficient apertures to support the required number of down-converted spatial modes (one more for every image pixel). A recent example achieves the imaging biological specimens with illumination at 4-5 microns while imaging only the non-linear interference in the near IR using a silicon-based camera[19].

4. QUANTUM ILLUMINATION

Quantum ghost imaging emphasizes the non-local nature of the detection with two separate detectors, but there are other ways to use the correlations associated with down-converted light. In SPDC, although the photons are produced in pairs if either the signal or idler beam are looked at in isolation, each exhibit intensity, shot-noise, fluctuations in the same way that any thermal source would do also. However, that the photons are produced in pairs means that these inherent noise fluctuations are perfectly correlated between signal and idler. This correlation applies to the total number of photons in the signal and idler beam and their spatial distribution, an effect that can be observed both in the many photon[20] and single photon cases[21]. Various approaches have sought to exploit this noise correlation under the umbrella term of quantum illumination[22]. The sub shot noise correlation can be exploited directly using the signal and idler beams as signal and reference where, in the absence of loss and perfect quantum efficiency, their ratio is perfectly unity irrespective of the light level[23]. Alternatively, one can seek to simultaneously exploit the spatial correlations to give sub shot noise images, but in most cases, the strength of the correlation, and hence the sub-shot noise advantage, requires low losses. Therefore, sub shot noise imaging is only available in the transmission imaging of largely transparent samples[24].

However, taking the quantum illumination approach more generally, rather than taking the ratio or difference of the signal and the refence one can perform a coincidence measurement where a signal detection is confirmed on the correlated detection of the idler (reference). Such an approach allows one to distinguish the true optical signal from the detector noise or background sources of light[25,26].

5. NEW FRONTIERS IN QUANTUM IMAGING

Undoubtedly the early days of quantum imaging were largely motivated by its non-local nature and the degree to which images themselves could highlight the EPR paradox and more recently even a Bell-type inequality[27]. More recently the focus has been on how these various techniques might lead to performance advantages. While many quantum, or quantum-inspired, approaches seem to yield modest improvements with a corresponding increase in complexity, other quantum approaches offer potentially significant change. Perhaps the most obviously of these advantages has been the wavelength transformation where the phase correlations inherent in SPDC have allowed illumination of the sample in the mid infrared while performing the detection within the wavelength bandwidth of much lower cost and more sensitive silicon-based detectors[19].

Moving beyond these advances, quantum seems set to push the imaging boundaries in other ways too. Recent work has reported on how the Hong-Ou-Mandel (HOM) dip creates the quantum equivalent to optical coherence tomography allowing depth sectioning, but in the quantum case, maybe without requiring full interferometric stability[28]. Another recent success has been the use of squeezed (sub shot noise) light to improve the sensitivity of Raman microscopy [29].

Beyond the demonstration of new approach to imaging based on new physics is the continual advance of associated commercial technologies, ranging from spatially-resolving superconducting detectors to photon counting cameras.

In all these physics and technology areas, although perhaps not having the profile of quantum computing, quantum science seems well on the way to impacting high performance imaging systems both operating in transmission mode as usually applied to microscopy and in backscatter mode as applied to stand-off imaging.

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