Beyond classical limits by exploiting quantum light : a short review of INRIM results

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Abstract. Quantum properties of light and, in particular, quantum correlations have recently disclosed the possibility of realising protocols addressed to overcome limits of classical imaging, a field collectively christened quantum imaging. In particular quantum correlations between twin beams represent a fundamental resource for these studies. Here we present three experimental applications of these properties.

1. Introduction

Quantum properties of the optical field represent a resource of the utmost relevance for the development of quantum technologies, allowing unprecedented results in disciplines ranging from quantum information and metrology [1,2,3] to quantum imaging [4,5].

A very interesting example is offered by the possibility of overcoming measurement limits pertaining classical states. In this proceedings we review three achievements that could have relevant practical application one concerning the imaging, the other the detection of weak objects by exploiting the quantum correlations of parametric down conversion (PDC) emission and split thermal light.

2. Sub shot noise quantum imaging

The principle of the first technique (see Fig.1), dubbed sub shot noise quantum imaging, is to take advantage of the correlation in the noise of two conjugated branches of PDC emission for imaging a weak absorbing object, otherwise lost in the noise. The image of the object, eventually previously hidden in the noise, could be restored [5,6,7,8] by subtracting the noise measured on one branch from the image of a weak object obtained in the other branch

When operating under shot noise this method allows in principle a full reconstruction of the absorption pattern of an object with a sensitivity superior to that available with classical techniques at the same illumination level. In order to reach this goal, in view of important practical application, one should obtain a very high level of spatial quantum correlation, that requires a precise characterization/control of speckles structures and high quantum detection efficiency.

The degree of correlation is quantified by the figure of merit $\sigma = < \delta^2 (N_i-N_s)> / <N_i+N_s>$, N_i and N_s being the photon number measured in correlated pixels, whose theoretical value, in term of the transmission of the optical channel η (including the quantum efficiency of the detector) for PDC it is $1-\eta$. Thus, in principle, in an ideal situation, it can approach zero, while in classical case it is larger than 1. Thus, for $\sigma<1$, one is allowed beating the performances of the analogous differential classical scheme, while when $\sigma<0.5$, one is allowed beating every classical scheme (the best classical scheme is still the direct illumination with a shot noise limited source).

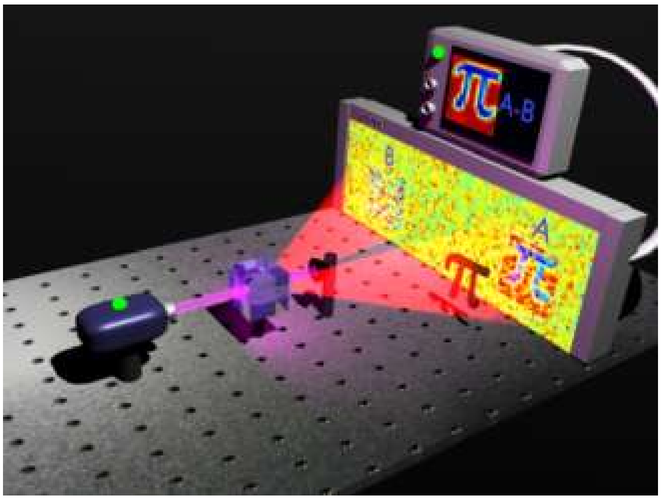

Figure 1. Simplified schematic of the set-up for imaging under shot noise level.

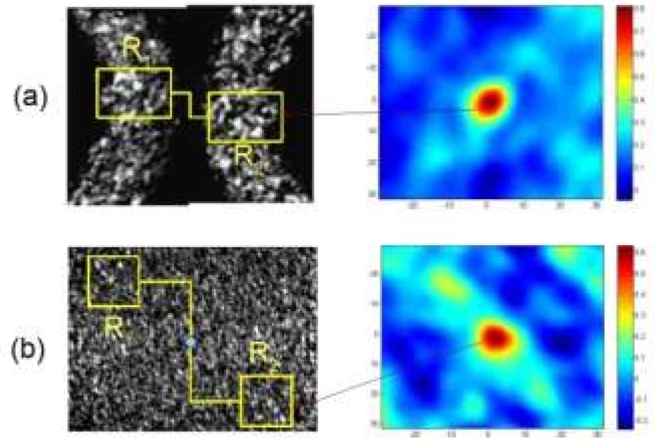

Figure 2. Example of correlations in noise pattern in twin beams, with (a) and without (b) an interference filter. In the second raw we report the cross correlation function.

Our experimental set up consisted of a 355 nm laser beam that, after a spatial filtering, pumped a type II BBO crystal producing PDC. After eliminating the UV beam, one correlated beam crossed a weak absorbing object and it was addressed to a CCD array. The other beam (reference) was directly addressed to another area of CCD camera.

After a study on the speckle structure of twin beams and their control [9,10] (Fig.2), in a first phase we have evaluated the capability to reach a sub shot noise level (σ <0.5). Our results clearly demonstrated this achievement, see Fig.3.

Since this preliminary step showed that we had achieved the regime needed for obtaining a higher sensitivity respect to every classical imaging, we have then inserted a weak absorbing object on the optical path of the signal beam, a titanium deposition on glass with a uniform absorption 5%.

In order to verify the theoretical predictions we collected a large number of frames (about 1200) and grouped the frames in classes with respect their value of σ. Fig.4 compares the performances of SSNQI with classical schemes for a single shot picture.

A quantitative statistical analysis of the advantages of the SSNQI is shown in Fig.5 , where we report the ratio R of the quantum to the classical Signal to Noise Ratio (SNR) plotted in terms of the average correlation degree σ of the data set: the SSNQI has, as expected, a clear advantage when σ<0.5 with respect to the direct classical imaging, and is definitely better than differential classical imaging for σ < 1. For the best achieved values of the correlation degree in the quantum regime, we obtain an improvement of the SNR larger than 30% compared with the best classical imaging scheme and more than 70% better than the differential classical scheme.

These results clearly demonstrate the potentialities of quantum systems for overcoming the classical limits of measurements, paving the way to further future developments in this sense.

Furthermore, they prompt for further developments of this scheme for reaching levels interesting for commercial applications, in measurements concerning photosensible samples (as, for instance, biological or thin films samples).

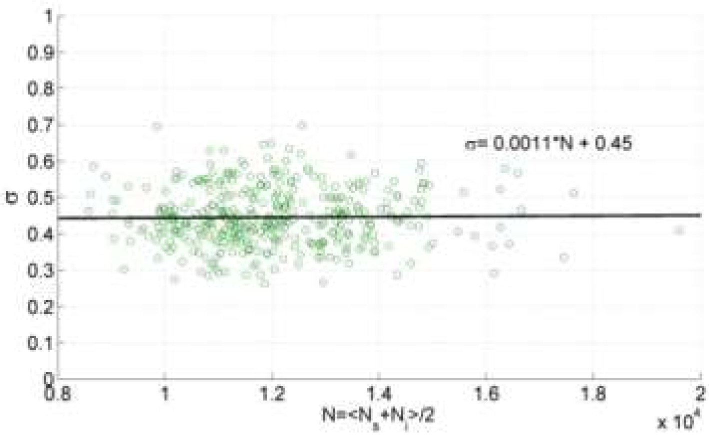

Figure 3. The degree of correlation. The degree of correlation $\sigma = \langle \delta^2 (N_i - N_s) \rangle / \langle N_i + N_s \rangle$ is plotted in function of the average number of photons of the single beam. One can observe how it is always largely under the classical limit 1, and on average under 0.5: this represents the condition for realising an advantageous quantum imaging.

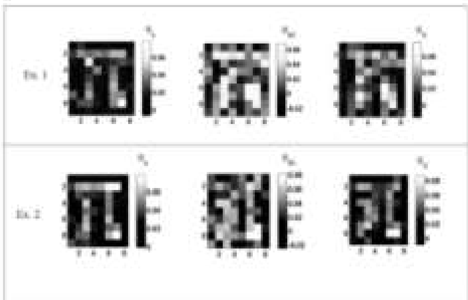

Figure 4. Example of the imaging of a weak absorbing object, a π, with quantum imaging (left) compared with two classical schemes (direct and differential).

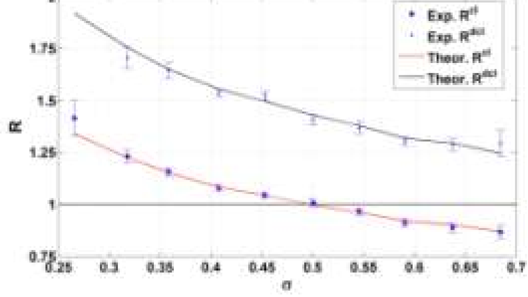

Figure 5. Ratio of signal to noise ratios in SSNQI and differential (black curve) and direct (red curve) classical protocols.

3. Toward quantum illumination

The principle of the second technique, dubbed quantum illumination, is to take advantage of the correlation in the noise of two conjugated branches of PDC emission for detecting the presence of a weak absorbing object, otherwise lost in a preponderant thermal background.

In particular in [3] Lloyd demonstrated, expanding some previous theoretical ideas [11,12,13], that the use of entanglement can in principle improve the possibility of detecting an object hidden in a background. This idea was then further elaborated in [2], where it was shown that quantum illumination may offer a significant performance gain respect to optimum reception coherent-state systems, and in [14], where it was demonstrated that the quantum protocol advantages are significant in multi- photon regime. Finally, application to secure quantum key distribution was proposed in [15]. However, these works did not specify a feasible model for the detection apparatus. An attempt in this sense was then presented in [16] where two detectors were proposed: one based on an optical parametric amplifier and an ideal photon-counter, the other based on the use of phase conjugation followed by balanced dual detection. Nevertheless, both the schemes are of very difficult experimental realisation, limiting their applicability.

Here, we explore the capability of a quantum illumination scheme and realize it in a more realistic characterized by a dominant and unknown background, severe losses, and when the receivers are photo-counting detector available nowadays. We present preliminary data demonstrating that the use of simple second order correlation measurements of the joint photon numbers distribution already suffices in guaranteeing strong advantages to the quantum protocol, then we realise quantum target detection both with twin beams and thermal light pointing out unequivocally the experimental advantage of the quantum illumination protocol in mesoscopic regime, with respect to its classical counterpart. This achievement, beyond paving the way of future practical application of quantum illumination, also provides a significant example of ancilla assisted quantum protocol besides the few previous realisations [15].

In the first configuration of our set up, type II Parametric Down Conversion light (with correlated photon pairs of orthogonal polarisations) is generated by means of a BBO non-linear crystal pumped with the third harmonic (355 nm) of a Q-switched Nd-Yag laser, with a repetition rate of 10 Hz and 5 ns of pulse width, after a spatial filtering. The correlated emissions are then addressed to a high quantum efficiency (about 80% at 710 nm) CCD camera. The exposure time of CCD and the synchronization with the pump are chosen such that each acquired frame corresponds to the emission generated by a single laser shot. Thus, the number of temporal modes collected is of some thousands, estimating the coherence time of PDC process around one picosecond. On one of the two paths it is posed a beam splitter that represents the target object and combines the PDC light with a thermal background produced by addressing a laser beam to an Arecchi's rotating ground glass.

In a second configuration the twin beam is substituted by beam split thermal light: this configuration allows the comparison with classical case.

The evident advantage of the quantum configuration is demonstrated in Figure 6.

3. Ghost Imaging towards medical diagnostic

Ghost Imaging [1,17] represents the first techniques where quantum correlations were exploited for imaging.

In this technique a light beam crosses (or it is reflected) by an object, that one wants to image.

However, the beam that crossed the object is detected by a detector without any spatial resolution (bucket detector). The image of the object is retrieved when the bucket detector signal is correlated with the signal of a spatial resolving detector measuring a light beam whose spatial noise is correlated to the previous beam. The first demonstration of this technique was achieved with quantum optical states of light, known as twin beams, produced by Parametric Down Conversion (PDC). Then it was shown, both theoretically and experimentally, that this result can be achieved also with beam-split thermal light [18,19,20,21,22,23], even if with a smaller visibility. Nevertheless, non-classicality of these states can be quantified by discord showing its relation with visibility [24].

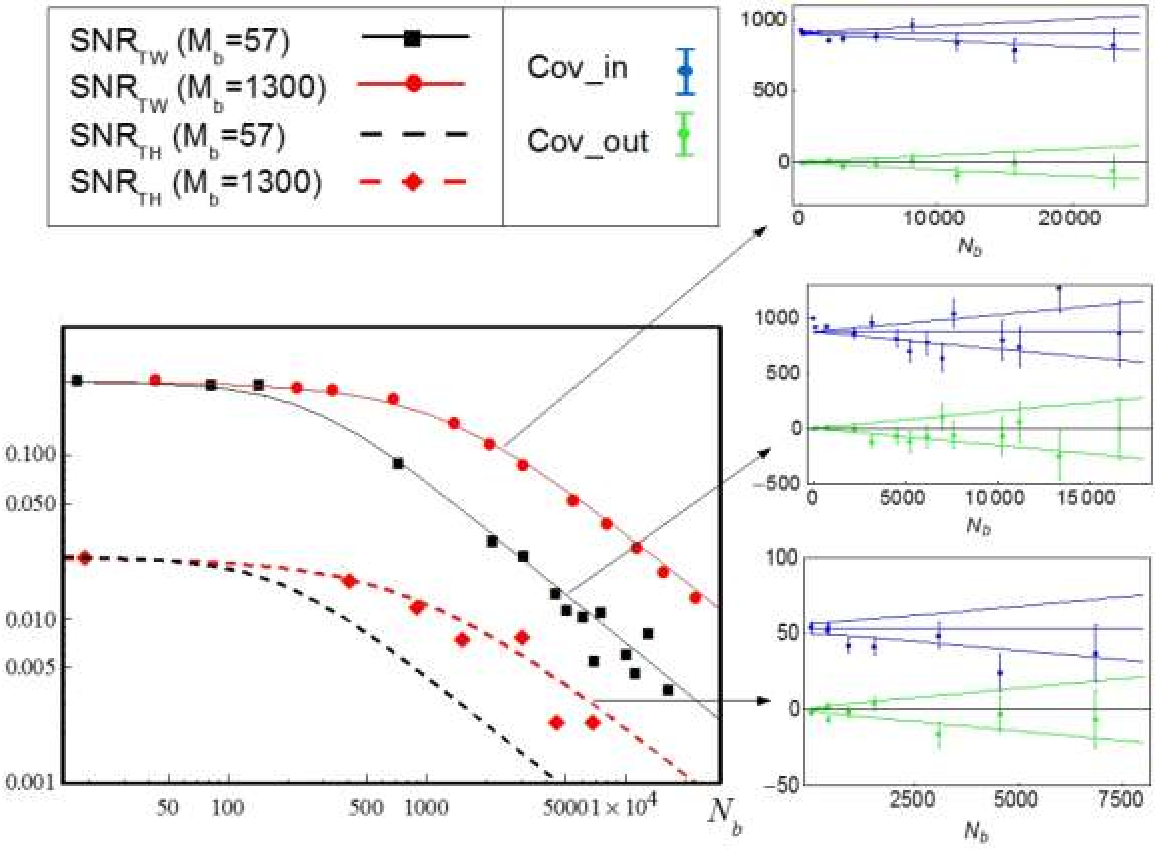

Figure 6. Signal to noise ratio (SNR) versus the total number of photons of the thermal bath normalized by the number of repetitions. The red (black) markers are the data for 1300 and 57 modes o thermal bath respectively,. The solid (dashed) theoretical curve corresponds to quantum (classical) illuminating beams. The lower curve of the classical protocol has not been compared with the experimental data because the SNR is so low that a very large number of images (out of the possibility of the actual setup) is required to have reliable points. The inset small graphs represent the value of the covariance for each measurement in presence and absence of the Target.

The interesting point now is realising configuration suited for practical applications. An idea is to retrieve the image of an object in a scattering media for medical diagnosis application, in particular for the diagnosis of breast cancer. In fact, multiple scattering influences the quality of such images, with degradation in resolution and contrast. Moreover, the most widespread method for medical and clinical diagnosis is X ray radiation imaging, with the drawback of ionizing and unsafe radiation. Hence, the use of optical photons is becoming an interesting method even if an accurate image deteriorated by multiple scattering of the blood and tissues can be retrieved only using second order correlation techniques such as Ghost Imaging.

In our work, we are investigating the use of a compact thermal light ghost imaging set-up for realistic application in breast cancer detection.

In our setup, a thermal beam is produced by addressing 1 ns laser pulses at 532 nm on an Arecchi disk. The thermal beam is divided by a 50-50 beam splitter; one part is sent through the object (a test bar of 1 mm x 5 m) in the scattering media. Both beams are imaged by means of a lens of focal length of 15 cm on two portions of a CCD array, synchronized with the laser; the portion with the direct image of the object is summed to obtain the bucket detector.

Ghost image is reconstructed by means of second order correlation coefficient. Preliminary results show that the image of the object can be retrieved, with a visibility:

$$V = \frac{\left|c^{(2)}_{in} - c^{(2)}_{out}\right|}{c^{(2)}_{in} + c^{(2)}_{out}},$$

of 50% where the indexes $c^{(2)}_{in}$ and $c^{(2)}_{out}$ indicates the mean second order correlation coefficients calculated respectively in a region with the object and outside it.

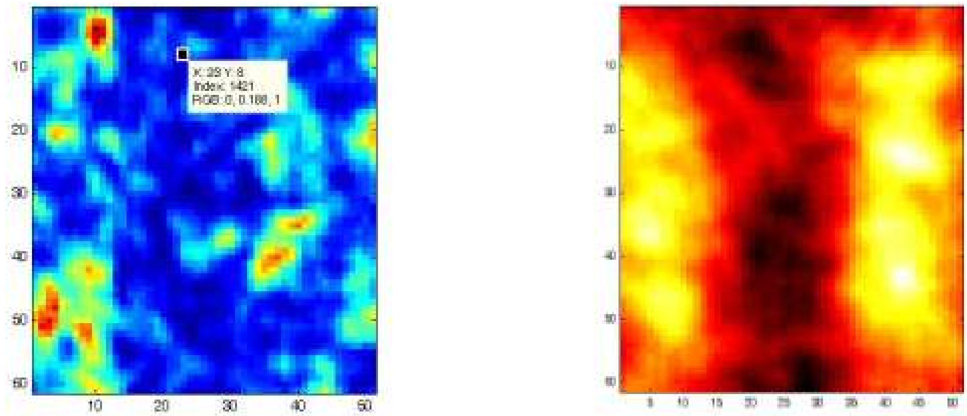

Figure 7. The left part shows the image of the object, deteriorated by the scattering of the light in the medium. In the right part we observe the reconstructed ghost image by means of second order correlation coefficient. The object is recognizable even if the limit of this reconstructed image is the current resolution of the imaging system. In fact, resolution is limited by the size of the speackles of the thermal beam that are of 200 μm of diameter. These are preliminary results and we are now working to reduce the size of the speackles.

4. Conclusion

We have reported the experiments performed in INRIM to overcome the limits imposed by classical physics by exploiting quantum properties of light. In particular, we described three approaches that exploit quantum correlation to improve imaging technique and the detection of weak objects.

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