QUANTUM IMAGING

Beating the classical camera

By utilizing the spatial quantum correlations of light, Italian researchers have now performed imaging at significantly higher signal-to-noise ratios than those possible through classical techniques.

Stefanie Barz and Philip Walther

Image sensors based on CCD arrays are an important part of daily life and are found at the heart of digital cameras, including those in cellular phones and other portable electronic devices. There is a strong and continual technological trend for manufacturers to reduce the size of CCD pixels, thereby allowing more pixels to be squeezed onto a sensor and thus in principle increasing the imaging resolution.

However, as the pixel size shrinks so does the amount of light illuminating each individual pixel. Ultimately, at low enough light levels the quantum nature of light becomes dominant, with single-photon fluctuations inherently limiting the quality of the detected image. This is typically defined as the shot-noise limit, and presents a fundamental challenge when working with low photon flux illuminations[1].

Now, writing in *Nature Photonics*, Giorgio Brida and co-workers report the successful realization of a quantum-enhanced set-up for imaging weakly absorbing objects at a performance beyond the shot-noise limit[2]. In their experiment, Brida *et al.* exploit a process called parametric down-conversion, in which a nonlinear crystal splits an incoming photon into a 'signal' photon and an 'idler' photon[3]. Owing to energy and momentum conservation, the signal and idler photons have a spatial quantum correlation, making it possible to perform quantum-enhanced imaging at a sub-shot-noise level[4]. Brida *et al.* report a signal-to-noise ratio improvement of up to 70% compared with differential classical imaging, and up to 30% compared with direct classical imaging. Remarkably, these results are obtained without any post-processing to subtract various types of background noise.

The quantum relation is manifested in perfect pair-wise correlations of the transverse momentum component with respect to the propagation direction of the incoming laser light; that is, the momentum of one photon unambiguously defines the momentum of the other. In the experiment of Brida *et al.*, these correlations are optically Fourier transformed to a plane in the far field that is perpendicular to the propagation direction of the photons. The transformation maps each photon's propagation direction to a corresponding point in this plane; in other words, the momentum correlations of the photons are transformed to photon-number correlations. The detection of N photons for the signal beam at a position x, given by $N(x)$, implies with certainty that N photons for the idler beam will be at the position $-x$, given by $N(-x)$, owing to the perfect correlations of the generated photon pairs. As a consequence, the spatial fluctuations of two selected symmetrical regions of the plane are correlated at the quantum level. These intensity correlations are the resource of the quantum enhancement, and must be present over large spatial areas of the beam for the scheme to be useful as an imaging technique.

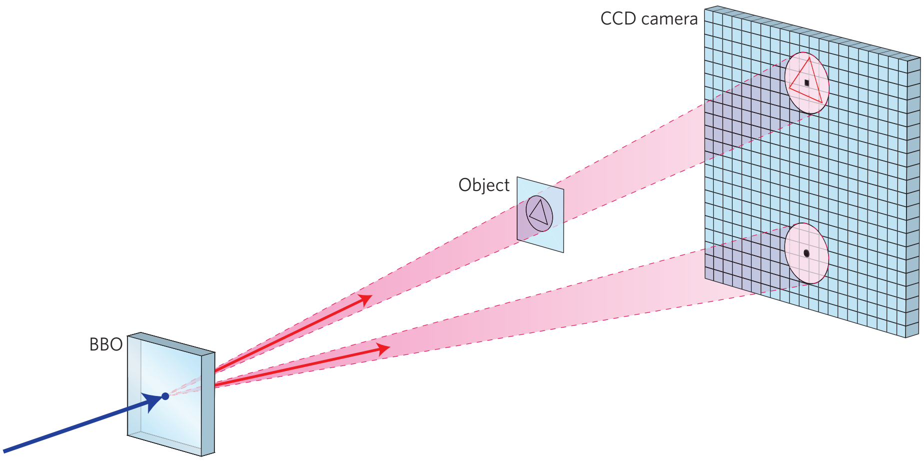

Figure 1 | The differential quantum imaging experiment of Brida and colleagues. The β-barium borate (BBO) crystal converts one laser photon into two photons that are quantum correlated in momentum and position. These non-classical correlations are used for the improved differential imaging of a weakly absorbing object.

Brida *et al.* use this quantum mechanical effect to improve differential imaging — a classical method for creating images of weakly absorbing objects. Differential imaging is a technique in which a probe beam is split into two branches: one contains the object and the other functions as a reference. The idea is to take the image formed behind the object and subtract the reference image.

In classical differential imaging methods using laser light, the shot-noise present in the two laser branches leads to significant deterioration of the imaging quality in the low-flux regime, which limits imaging sensitivity. In the case of quantum imaging, the noise in the two down-conversion branches is quantum-correlated, and thus subtraction leads to an improved image of the weakly absorbing object.

This capability results from a strong correlation in photon numbers, which in the ideal case reduces the variance in photon number difference between the two beams to zero. By taking the ratio of this variance to the shot noise, one obtains a basic parameter called the noise reduction factor — an absolute value that functions as a sensitive measure for the degree of quantum correlation. For coherent light this parameter is equal to one, and for the ideal case of quantum correlated twin beams it approaches zero. Optimal sensitivity, which can in principle be achieved by direct classical imaging techniques, can be surpassed as soon as the noise reduction factor is less than 0.5. This is typically quantified by the improvement of the signal-to-noise ratio. Brida *et al.* report a noise reduction factor (below the classical border) of about 0.45 (±0.005) for their imaging method when capturing the intensity pattern with a CCD camera and taking mean values over large spatial samples.

To achieve this quantum-enhanced noise reduction, several significant improvements over former experiments[5] were necessary. Correlated photon pairs were generated using a β-barium borate nonlinear crystal pumped with the third harmonic (355 nm) of a Q-switched Nd:YAG laser with a repetition rate of 10 Hz and a pulse width of 5 ns. The image of a weakly absorbing object — a π-shaped titanium deposition — was obtained by capturing the intensity pattern of the photons in the optical and reference channel with a CCD camera (Fig. 1). The noise reduction factor σ is directly dependent on the optical channel's transmittance η by the relation $\sigma = 1 - \eta$; the higher the absorption of the object (and thus the loss of photons), the smaller will be the improvement for the imaging. It is therefore experimentally challenging to balance the parameters for imaging in the quantum regime.

Furthermore, the pump beam's finite waist leads to momentum uncertainties in the created photons, which decrease the coherence area in the photon numbers. The last technical challenge is the ratio between the coherence area and the pixel dimensions. Because a quantum correlation in photon numbers can only be obtained while the detection area is larger than the coherence area, this value must be sufficiently large. The authors achieved this by properly designing the pump beam and by expanding the detection area to create 'superpixels' of combined pixels.

Although the experiment of Brida *et al.* has numerous potential applications for imaging with low photon fluxes, several limitations currently exist. First, the transmittance in the optical channel must be as high as possible to achieve a sufficient noise-reduction factor. This requires all objects and optical elements within a system to be weakly absorbing and of low photon loss. Second, preparation of the down-converted light is demanding: the inhomogeneities of the signal and idler beams must be eliminated and the spectral band must be chosen around the centre wavelength. Unfortunately, the optimization of the beams' preparation is in conflict with the best possible transmittance. Thus, all the parameters for the experiment cannot be optimized simultaneously, which limits this quantum-enhanced technique.

Furthermore, this technique has to be carried out without any background correction; the typical noise originating from diffuse light scattering or electronic background will always be present in the images and cannot be removed. However, other limitations such as the current challenge of increasing the ratio of the pixel size and the coherence area may be overcome in the near future. ❐

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CARBON NANOTUBES

Breaking Kasha's rule

The emission of visible light from a dye encapsulated within a carbon nanotube gives great hope and new opportunities for the design of nanoscale optoelectronic devices.

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In optically functional molecules such as dyes, fluorescence (or phosphorescence) generally occurs from the excited state with the lowest energy. This is known as "Kasha's rule" — first formulated in 1950[1] by Michael Kasha — and is a general principle with only a few rare exceptions (for example, compounds such as azulene and cyclazine[2]). Now, according to recent research[3] it seems that the dye α-sexithiophene, when encapsulated in a single-wall carbon nanotube (SWCNT), exhibits emission that also breaks this rule. The finding is significant because it suggests that organic-dye–nanotube hybrid light emitters can operate at higher photon energies than first thought, reaching to visible wavelengths. It also shows that nanotubes can help shield and protect sensitive light-emitting materials from the environment, improving their stability and offering new regimes of operation.

The physical principle of Kasha's rule is as follows. In terms of energy levels, the upper excited states are usually more closely spaced than the energy gap between the lowest excited state (a singlet or triplet) and the ground state. As a result of this close spacing, the rates of non-radiative decay between the upper states far exceed the rates of luminescence, thus impeding the emission of light. Only in the lowest excited state does radiative decay become comparable to non-radiative decay. This rule was also thought to apply to SWCNTs encapsulating dye molecules, because SWCNTs and dyes are strongly coupled through π–π interactions. However, recent research by Maria Loi and co-workers[3] demonstrates an exception to this principle.

Single-wall carbon nanotubes are cylindrical graphite tubes with diameters of approximately 1 nm that exhibit either metallic or semiconducting properties depending on how the graphite sheet is rolled. In semiconducting SWCNTs, photoluminescence and electroluminescence from the lowest excited state is observed, adhering to Kasha's rule and indicating the potential of SWCNTs for optoelectronic device applications[4]. However, as the lowest excited states of semiconducting SWCNTs are in the infrared region, the emission of visible light from SWCNTs should not be possible.

Various organic and inorganic materials can be encapsulated in the inner hollow space of a carbon nanotube to create hybrid designs with new optical properties.