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(Article begins on next page)

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Quantum imaging with photon-number correlations

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Abstract—**Non-classical correlations in optical beams offer the unprecedented opportunity of surpassing conventional limits of sensitivity and resolution in optical measurements and imaging, especially but not only, when a low photon flux down/single photons are measured. We review the principles quantum imaging and sensing techniques presenting some state-of-the-art achievements in the field. These quantum protocols have the potential to trigger major steps in many application ranging from radiometry to biophotonics.**

Index Terms—**Quanum correlations, quantum metrology, quantum optics, quantum imaging, super-resolution**

I. INTRODUCTION

The measurement of changes in intensity or in phase of an electromagnetic field, after interacting with matter, is the most simple way to extract relevant information on the properties of a system under investigation, whether a biological sample or a digital memory disc.

However, quantum mechanics establishes fundamental bounds to the sensitivity [1], [2], which is limited, in general, by the mean energy of the probe, or, equivalently, by its mean number of photons. This is in accordance to the intuitive idea that gaining the perfect knowledge on a system would require an infinite amount of physical resources. The lower bound to the uncertainty when restricted to the use of classical probe states is achieved by a coherent state, and it is usually referred as to "shot noise limit" (SNL) $U_{SNL} \sim \langle N_P \rangle^{-1/2}$, where $\langle N_P \rangle$ is the mean number of photons of the probe. Not by chance, the SNL coincides with the conventional statistical scaling after N independent repetitions of the same measurement. Indeed, this means that photons behave somehow independently each other, thus exhibiting Poissonian photon number statistics [3]. Anyway, quantum mechanics does not prevent to have light beams with fluctuation quieter than Poissonian, or more in general with a strong degree of cooperation among photons, namely where the probability of detecting a photon at a certain time t is correlated or anti-correlated to the detection of a photon at time t_0. Such states of light can be used to reduce the noise of measurements below the SNL. On the other side, the wave nature of light imposes a limitation in the spatial resolution achieved in conventional optical imaging system, the Rayleigh diffraction limit (RDL), that for a microscope is $0.61\lambda/NA$, NA being the numerical aperture and λ the wavelength. Instead, resorting to the corpuscular nature of light and the nowadays capability of counting photons one by one, allows devising strategies going beyond the RDL.

In the following we will consider some examples of the application of these principles in two significant cases: the sub-shot-noise quantum imaging (SSN-QI) of a weak absorbing object and the super-resolution fluorescence microscopy (SRFM)

II. SSN-QI OF WEAK ABSORBING OBJECT

The classical bound to the sensitivity in absorption (loss) measurement is given by $U_{SNL} \simeq [(1-\alpha)/\langle N_P \rangle]^{1/2}$, where $0 \leq \alpha \leq 1$ is the fractional loss of the sample. This can be the main source of uncertainty, for example when dealing with delicate system such as biological samples or photosensitive chemicals. It turns out that ordinary (classical) probe beams, namely with Poissonian photon number distribution, are fundamentally inadequate to measure small losses with the highest sensitivity. Instead, a perfect control or the knowledge of the number of photons probing a sample increases drastically the sensitivity in detecting small changes in the beam due to the interaction, and therefore in estimating the physical parameters related to it. Photon-number correlation are a natural way to realize this goal [3]. In the quantum process of spontaneous parametric down conversion (S-PDC) the photons are emitted in pairs nearly at the same time and position, generated from the decaying of a pump photon such that the energy and momentum are conserved. Even though the emission of a pair is a quantum random process, not different from photon emission by a thermal source, the presence of one photon with a certain direction and frequency is bound to the presence of a "twin" photon in a correlated spatial-frequency mode. The emission finally results in two beams, dubbed "Twin Beam" (TWB), which have perfectly correlated photon number distribution in space and time [3]. Thus, the random intensity noise in the probe beam addressed to the sample can be known by measuring the correlated (reference) beam and subtracted [4], obtaining sub-shot-noise (SSN) sensitivity $U_{SSN} \simeq \sqrt{\alpha} U_{SNL}$. It scales much more favorably than the classical bound for small absorption and represents also the ultimate quantum limit.

The spatially multi-mode nature of twin beam in traveling wave PDC process, allows to realize SSN-QI of structured object in one shot (wide field imaging): in 2017 we have realized the first SSN wide field microscope [7]. Fig. 1 shows the quantum enhanced sensitivity in images of a weak absorbing test object ($\alpha = 0.01\%$), representing the Greek letter "ϕ". The advantage in terms of noise reduction is roughly of 20% for $5\mu m$ of resolution and 10^4 pixel in the image, 70% for $30\mu m$ of spatial resolution.

Beside SSN sensitivity in absorption/transmission measurement [4], [5], [6], [7], TWB has been considered for quantum
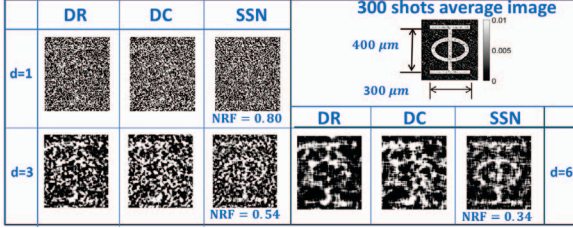
Fig. 1. Single-shot images in the direct classical (DC), differential classical (DC), and sud-shot-noise (SSN) case, compared in each panel for the same value of spatial resolution parameter d (the spatial resolution is $d*5\mu$m). The mean number of photons detected per pixel is $N \sim 1000$. The upper-right panel is the image of the object after the average over 300 shots. Courtesy from [3]

Fig. 2. (a) experimental scaling of the FWHM of the point spread function (y-acsis) in in function of the order of the coincidence K (x-acsis). The green dashed line is the theoretical RDL not corresponding with the measured one, which is the point for $K = 1$. (b) Direct mapping of the signal emitted by two NV centers, whose distance is below the RDL, by the confocal microscope. (c) Map of the $g^{(2)}$ function (two-fold temporal coincidence of photons). The presence of two dips reveal the existence of two distinct centers. (d) super-resolved reconstruction of the emitters using the combination of the intensity map and the $g^{(2)}$ function.

enhanced sensing [8], [9], [10], ghost imaging [11], plasmonic sensors [12], quantum reading of digital memories [13] and interferometry [14]. In radiometry, the quantum spatial correlation enable the absolute calibration of spatially resolving detector [15].

III. SRFM BY PHOTON ANTIBUNCHING

Quite recently, significant results in SRFM have been reached by techniques exploiting the non linear behavior of the fluorophores, as stimulated emission depletion (STED) and ground state depletion (GSD). Nevertheless, these schemes are characterized by rather specific experimental requirements (dual laser excitation system, availability of luminescence quenching mechanisms, nontrivial shaping of the quenching beam, high power); furthermore, they are not suited for applications where the fluorescence is not optically induced.

A possibility to overcome these limitations is offered by the correlation properties of quantum light. Fluorophores and markers used in biological microscopy can be chosen among single photon emitters such as quantum dots, dye molecules or NV centers in nano-diamond. A single photon emitter presents by definition a strong anti-correlation, because the presence of a photon at time t_0 excludes the presence of an other photon at the same time. This effect is known as anti-bunching and can be exploited in many applications, from quantum information and communication to metrology and super-resolution imaging. The idea is that measuring two-fold coincidences ($g^{(2)}$ Glauber correlation function) among the arrival of photons in each position of the image plane, allows one to build a spatial map representing the number of active emitters in each position. If two of them are closer than the RDL, thus indistinguishable from the standard fluorescence intensity map, still the presence of coincidences indicate that there are actually two different sources. This further information, beside the mere intensity distribution, allows to reconstruct a super-resolved map [16]. In general, for an arbitrary number of centers in the cluster, a scaling factor of $1/\sqrt{K}$ is achieved,for K-fold coincidence measurement ($g^{(K)}$). We have given an experimental demonstration of this
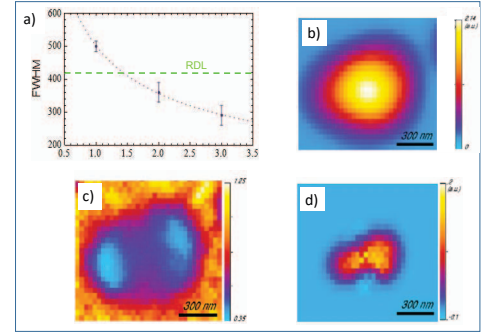
scheme in 2014 [17], exploiting NV-centers in a single photon confocal microscope, and Fig.2 presents our results.

Recently it has been proposed to combine this high order correlation function method with the use of structured excitation light [18]. It has been shown that in this case one could reach a resolution increase of $K + \sqrt{K}$ with respect to the RDL.

An other technique realized in 2017 [19], exploits anti-bunching together with the natural "photo-blinking" effect found in many types of fluorophores and a fiber bundle collecting light with certain spatial resolution. After the reconstruction, a final resolution of 20 nm has been reported.

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