TOWARDS REAL-TIME QUANTUM IMAGING WITH SINGLE PHOTON AVALANCHE DIODE CAMERAS

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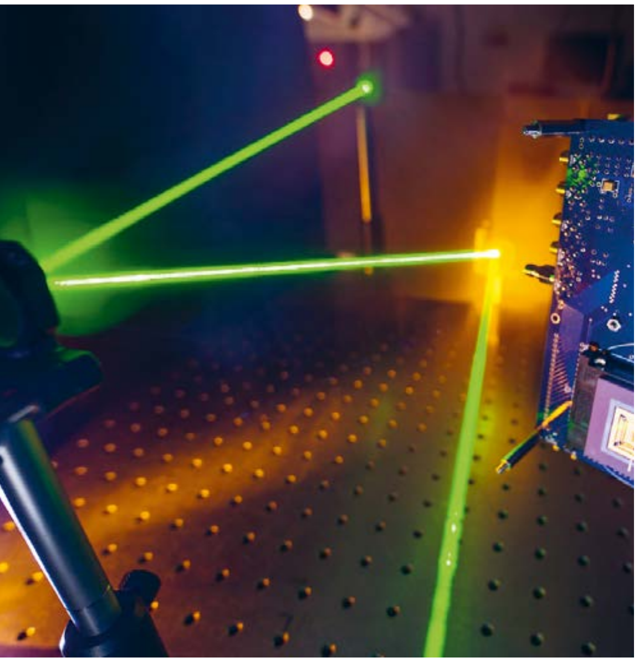

By harnessing the properties of photonic quantum states and their interaction with the environment, quantum imaging promises to go beyond the limits of classical imaging. However, the inherent weakness of detected signals and the fragility of quantum states make their properties difficult to measure in practice. In recent years, the emergence of single-photon sensitive cameras enabled the field to take a step closer to practical applications. In this respect, single-photon avalanche diode (SPAD) cameras are one the most promising technologies as they can detect single photons across many pixels with unparalleled speed, temporal resolution, and very low noise.

https://doi.org/10.1051/photon/202110736

Quantum imaging harnesses quantum properties of light to break the fundamental limitations of imaging. In a typical quantum imaging system, a non-classical state of light illuminates an object from which an image is formed onto a set of photodetectors. The specific measurement performed by the detectors (e.g. single or coincidence detections) combined with the state properties (e.g. single-photon, entangled photon pairs or squeezed states) enables to improve the image quality. Proof-of-principle demonstrations range from super-resolution to contrast-enhanced and sub-shot-noise imaging, leading to the development of unique imaging modalities such as imaging with undetected photons, quantum illumination and non-local imaging [1]. However, despite recent significant advancements in this field, the practical potential of quantum imaging can be questioned. The doubts about applicability arise from a combination of limiting factors including the inherently weak intensity of quantum sources, the fragility of quantum states and the difficulty to measure their properties. While source brightness is likely to keep improving constantly because it is an essential aspect also for other fields such as quantum communications, the efficiency of imagers for quantum light has stalled for several years and impedes the advances in quantum imaging. To highlight how critical this is, it is worth noting that most quantum imaging experiments performed to date used raster-scanning single-pixel techniques to capture images, which is obviously a very photon-inefficient, time-consuming, and non-scalable process.

In recent years, the development of single-photon sensitive cameras such as electron multiplied charge coupled device (EMCCD), intensified Complementary Metal Oxide Semiconductor (iCMOS) and iCCD, enabled the detection of extremely weak optical signals — down to the single photon level — over a large number of spatial positions in parallel. However, single-photon sensitivity is generally not sufficient in quantum imaging experiments because most protocols also require measuring the N^th^-order optical correlation function ($G^{(N)}$). But it turns out that performing high-order correlation measurements is much more delicate than forming an image by photon accumulation. For example, schemes based on entangled photon pairs reconstruct images by measuring the second-order spatial correlation function. In practice, this is achieved by identifying photons detected in coincidence between different pixels of the sensor in each frame, and then accumulating these measurements. Such a procedure is, however, extremely challenging. Indeed, the presence of spurious detection events due to dark and electronic noise, background light, and the presence of multiple pairs in a single frame strongly hinder the process by producing 'accidental' coincidences *i.e.* coincidences that do not originate from the simultaneous detection of two photons from an entangled pair. This process is also very sensitive to losses because the probability of detecting two photons is the square of that of

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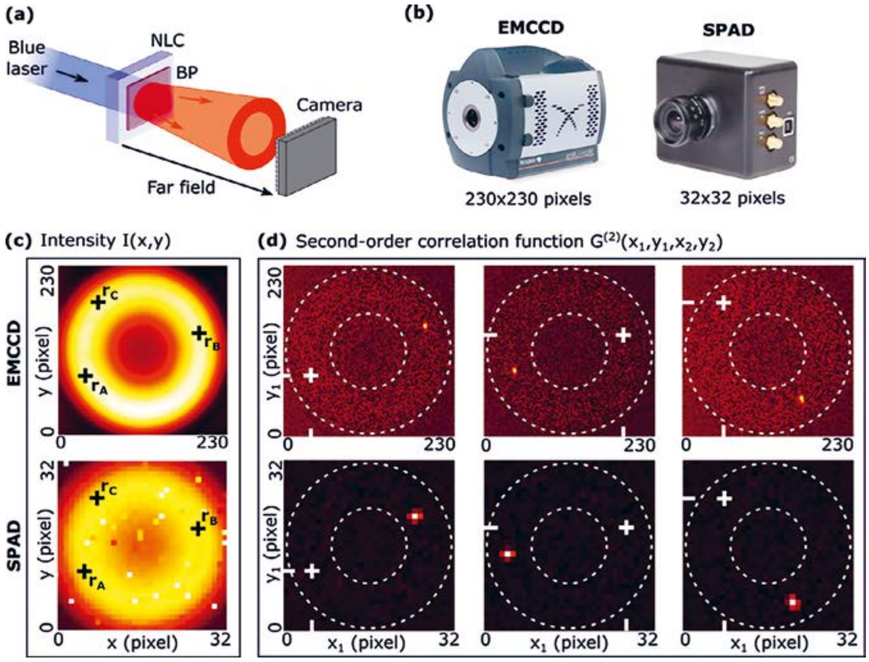

Figure 1. Measuring a spatially resolved second-order correlation function ($G^{(2)}$) under entangled photon pairs illumination. (a) Simplified experimental setup for imaging spatially entangled photon pairs in the far field. Photon pairs are produced by type-I spontaneous parametric down conversion in a 0.5 mm-thick non-linear crystal of β – Barium Borate. (b) Images of the two types of single photon sensitive cameras used in the experiment: EMCCD and SPAD array. (c) Intensity images measured by each camera showing the typical ring shape of photon pairs sources. (d) Spatially resolved second-order correlation functions $G^{(2)}(x_1, y_1, x_2, y_2)$measured by each camera. To visualize this, three projections of $G^{(2)}$ relative to three different references pixels $r_2 = \{ r_A, r_B, r_C \}$ of the sensors are shown: $G^{(2)}(x_1, y_1, x_A, y_A)$ (left), $G^{(2)}(x_1, y_1, x_B, y_B)$ (center) and $G^{(2)}(x_1, y_1, x_C, y_C)$ (right). In each projections, a peak of correlations is visible and centred around the symmetric pixel $r_1 = -r_2$. These symmetric peaks are clear signatures of anti-correlations between photon pairs due to momentum conservation in the pair generation process. $G^{(2)}$ was acquired in 17 hours with the EMCCD and in 140 seconds with the SPAD camera. More details can be found in [2,9]. BP: Bandpass filter; NLC: Non-linear crystal.

the overall detection efficiency of the system. In addition, such a task is even more difficult if one seeks to identify N-fold coincidences to retrieve Nth-order spatial correlation functions in the case of quantum states composed of more than two photons. Today, there is no camera that can take a picture of high-order optical correlations in real time.

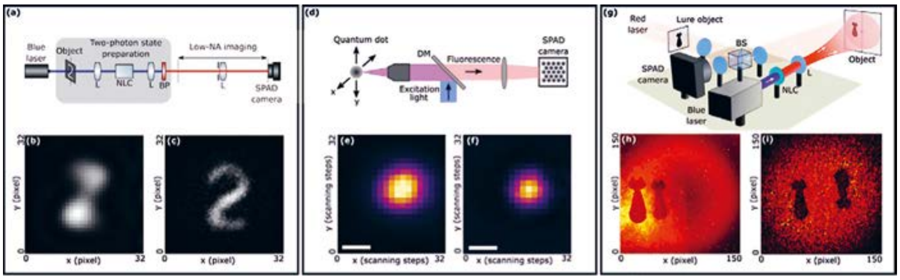

Figure 2. Three experimental demonstrations of quantum imaging with SPAD cameras. (a) Experimental setup used by A. Stefanov's group to achieve super-resolution imaging by measuring a spatially resolved $G^{(2)}$ with a SPAD camera (32×32 pixels) [6]. By measuring second order correlations between photon pairs, an image of the object '2' is retrieved with better resolution (c) than that obtained under classical coherent illumination (b). (d) Experimental setup used by D. Oron's group to perform quantum imaging scanning microscopy using a SPAD array (23 pixels) [10]. By measuring second order photon anti-bunching in single photons produced by a quantum dot, the width of the point spread function (f) is narrower than that obtained by conventional imaging scanning microscopy (e), which enables super-resolution imaging. (Scale bar: 0.25 μm). (g) Experimental setup used by D. Faccio's group to achieve full-field quantum illumination imaging with a SPAD camera (512×512 pixels) [9]. Images of two cat-shaped objects illuminated by a classical source (red laser) and photon pairs beam are superimposed on the sensor (h). By measuring second order correlations between photon pairs, an image showing only the object illuminated by photon pairs can be retrieved (i). L: lens; NLC: Non-linear crystal; NA: Numerical aperture; BS: beam splitter.

In recent years, some solutions have been developed to reconstruct spatially resolved second-order correlation function in photon-pairs-based imaging schemes ($G^{(2)}$). One popular approach uses post-processing algorithms with EMCCD cameras to suppress accidental coincidences and retrieve a spatially resolved ($G^{(2)}$) across thousands of pixels [2]. However, this approach requires millions of frames, which in practice corresponds to many hours of acquisition even using the fastest EMCCD cameras on the market (frame rate ~100Hz and ~1ms exposure time). Another method that was developed combines an intensifier and a low-noise scientific CMOS camera to achieve similar results, but is currently limited to few hundreds of pixels and also requires several hours of acquisition [3]. These prohibitive acquisition times result from the fact that currently single-photon sensitive camera technologies, including EMCCD, iCCD, iCMOS, do not have good enough noise properties, temporal resolution and/or acquisition speed to quickly and precisely identify photon coincidences. Even if these devices can still be used in laboratory proof-of-principle experiments and will further improve in the coming years, it is clear that a major step forward is required to go from measurements times of hours to seconds, a major step that SPAD cameras seem capable of achieving.

SPAD CAMERA FOR QUANTUM IMAGING

Single-pixel SPADs have long been the detectors of choice in many quantum optics experiments. Their recent implementation in CMOS technology enabled the development of the so-called SPAD cameras, a technology that is currently booming [4]. Like intensified and EM cameras, SPAD cameras offer single photon level sensitivity, but with unparalleled speed, temporal resolution and very low noise. Thus far, these imaging devices have demonstrated their capabilities in many classical optics applications including fluorescence lifetime imaging, light detection and ranging (LiDAR), non-line-of-sight imaging and imaging through scattering media. In the last decade, they also started to be used in quantum optics experiments. In 2016, the group of A. Stefanov at the University of Bern used a 8×16 pixel SPAD camera to perform multi-pixel coincidence measurement under photon-pair illumination [5]. Thanks to the capability to set a very small coincidence window (265ps) and operate at a very high frame rate (250kHz), the SPAD camera was able to detect the presence of spatial correlations between photon pairs in less than 3 minutes by averaging coincidence detections over the pixels. However, it was not efficient enough to retrieve the full spatially resolved second-order correlation function that is key to perform quantum imaging. Furthermore, a post-processing technique had to be used to significantly reduce the accidental background. This ineffectiveness was mainly due to the extremely low photon detection efficiency (PDE= quantum efficiency × fill factor) of 0.57 % of the device and the presence of a significant crosstalk between adjacent pixels. Nevertheless, this study was the first to highlight the potential of SPAD cameras for imaging quantum properties of light.

In the following years, significant technological advances were achieved that improved the spatial resolution, PDE and the pixel crosstalk in SPAD cameras. In this respect, some established companies such as Horiba and Hamamatsu, as well as a handful of start-ups such as *MicroPhotonDevice* (MPD) and *PhotonForce*, even started to release first commercial versions of SPAD cameras. Using a larger chip made of 32×32 pixels, A. Stefanov's group later achieved super-resolution imaging and entanglement characterisation [6,7] by measuring the spatially resolved $G^{(2)}$ under photon pair illumination, but these experiments still required tens of hours of acquisition. In 2020, the group of Prof. D. Faccio at the University of Glasgow made an important step forward in terms of speed by achieving high-dimensional entanglement certification in less than 140 seconds by measuring the full spatially resolved $G^{(2)}$ of spatially entangled photons using a commercial 32×64 pixels SPAD camera from MPD [8] (Fig. 1). In collaboration with the group of Prof. E. Charbon at École Polytechnique Fédérale de Lausanne, they later pushed the limit of resolution by performing photon pair imaging using a prototype of SPAD camera composed of 512×512 pixels [9], but at the cost of many hours of acquisition because the camera speed was not fully optimised. In addition, SPAD cameras have also been envisaged for multi-pixel coincidence counting using different types of illumination than photon pairs. For example, the group of Prof. D. Oron at the Weizmann Institute recently used a SPAD camera to characterise the lack of high order spatial correlation in optical signals produced by single-photon emitters (quantum dots) for super-resolution imaging [10]. All these early proof-of-principle demonstrations have triggered many other research teams to explore SPAD camera for quantum imaging, most of them located in Europe (Fig. 2).

CONCLUSION

SPAD cameras are a rapidly growing technology with enormous potential for quantum imaging. Their single photon sensitivity, very high frame rate (up to 800 kHz) and unmatched temporal resolutions (hundreds of picoseconds) make them very promising for measuring spatially resolved high-order optical correlation functions that are at the basis of many quantum imaging schemes. The drawbacks of current models — including a relatively low fill factor, limited spatial resolution in the 2D pixel arrangement, low quantum efficiency and crosstalk — are being resolved very quickly thanks to the growing interest of these devices to be used in large consumer markets (*e.g.* cell phone cameras). Today, there are already some prototypes made of hundreds of thousands of pixels, with fill factor around 80 % and quantum efficiencies as high as 40 %. In addition, rapid progress in improving their temporal resolution suggest SPAD cameras will enable the measurement of entanglement in time between photons, paving the way towards the development of time-gated quantum imaging applications such as quantum LiDAR and quantum non-light-of-sight imaging. One may thus envisage soon a quantum video camera of the size of a cell phone camera for implementing quantum imaging in real-world applications such as biological imaging, microscopy, radar and sensing. ●

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