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EDITORIAL

Single-photon technologies

This special issue accompanies the fourth international conference on single-photon technologies held at the National Institute of Standards and Technology (NIST) Boulder campus in November 2009. This community has met every two years at national metrology institutes following the initial meeting in 2003 at the NIST Gaithersburg campus. The aim of these workshops is to share progress in single-photon technologies, which has been rapid, and has led to continual evolution in the issues that are most important to the community. The *Journal of Modern Optics* has brought together a collection of related papers in support of every workshop thus far. The first special issue of the journal, covering the first workshop of 2003, was largely dominated by single-photon detection with semiconductor detectors, as this was the most mature of the technologies. The second workshop, two years later, saw many more contributions on single-photon sources. At the third workshop in 2007, properties of superconducting single-photon detectors were a focus through a special symposium in conjunction with EU Framework 7 project Sinphonia. Stefan Scheel presented the topical review on the single-photon sources and their key applications.

The single-photon workshop of 2009, which this special issue of the *Journal of Modern Optics* covers, held a focused symposium on photonic entanglement technology and applications looking at production and preservation of high-purity photonic entanglement from generation to delivery and detection and the principles behind the technology. Of equal importance in this focused symposium were measures of nonclassicality; correlated, entangled, and factorable state source designs for applications such as sensing and communication; as well as fundamental physics tests, given realistic source and detector backgrounds. The topics in this issue can be broadly grouped and defined as follows (authors of relevant papers appearing within this issue are indicated in brackets):

(a) Single-photon sources (or, more precisely, approximations thereof): sources which emit one photon at a time as required. These are typically implemented by an isolated quantum system that can emit only a single photon each time it is excited or through a nonlinear optics process whereby photons are created two at a time so that one photon heralds the presence of the other photon (Rangarajan, Aljunid). Also discussed are associated technologies to achieve high efficiency (Bogdanski).

(b) Single-photon detection, including photon-number-resolved detection: the ability to detect one, or few photons (Itzler, Hu, Gulinatti).

(c) Single-photon and optical entanglement applications: examples requiring both single-photon sources and detectors include quantum key distribution (Guha), quantum information processing (Rangarajan, Takeoka, Aljunid), linear optics quantum computing (Jennewein), quantum teleportation (Humble), three-dimensional (3D)-imaging (Krichel), bio-imaging (Rech), and astronomy (Harris).

(d) Single-photon metrology: measurement techniques required to characterise single-photon sources, detectors, and applications (Marino, Rangarajan).

To provide a broad picture, this issue of the Journal features a topical review on semiconductor-based single-photon detectors from world-leading researchers including Mark Itzler (Princeton Lightwave Inc.) and Sergio Cova (Politecnico di Milano).

Here we discuss the state-of-the-art of single-photon technologies and report on the workshop discussions of issues facing the field today. The reader is encouraged to read the topical reviews accompanying previous editions for more detailed information [1–3].

Single-photon sources and detectors are the two key technologies in the field that have reached a certain degree of maturity with devices finding their way into many commercial components. It is understood that sources and detectors cannot be characterised just by one parameter, and, similarly, improvements in just one of the parameters at the expense of the others are often of little value. Indeed, it is possible to find nearly ideal devices when only one parameter is considered, but performance of other parameters is often compromised. An example of such a trade-off for heralded sources is achieving a low second-order correlation value $g^{(2)}(t=0)$ at the expense of deterministic photon emission. For detectors, a clear trade-off is the

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detection efficiency versus detection speed (seen for example, in the transition-edge sensor). Much of the current work in this field involves identifying, studying, and addressing such trade-offs. Such trade-offs make it clear that an appropriate framework is needed to compare devices fairly with similar purposes, but different core technologies. The first step toward such a framework would be to standardise the parameter set used to characterise the performance of single-photon sources and detectors, along with their definitions. Of course it is also important to include relevant contextual information on the application of these devices when their performance is reported. The lack of standardisation was highlighted in 2005 at the fourth international conference on new developments in photodetection, where it was noted that one particular type of detector, let us call it the single-photon multiplier, had 12 other names, let alone a variety of physical properties, which are often unreported or reported inconsistently. Given that different applications have different requirements, this disarray makes it difficult for the end user to identify the best device for a particular application.

It is necessary to understand which are the important parameters and their definitions and how those parameters have been measured (i.e. at what wavelength, under what conditions, etc.). We understand that just deciding which parameters are important is a challenge and as such, that list can be expected to evolve as sources, detectors, and their applications advance. Wary as we are of the difficulty of this process, we begin here with a first draft of a list of parameters and definitions. We do encourage continued discussion of this topic and suggest that a session devoted specifically to it be included in the next single-photon workshop.

As just one example of a characteristic that is not straightforward to define is ''photon-number resolving'' (PNR) detection, as the name itself is something of a misnomer. Its name implies that its output indicates the number of incident photons, while characteristics including but not limited to nonunit detection efficiency, dark counts, and afterpulsing all conspire to widen the gap between the output results and its name. As to how detectors should be categorised with respect to PNR, contrary to intuition, we argue that two levels of capability (yes or no) do not provide an adequate description. Thus, we propose a definition involving three levels of capability, which we acknowledge is somewhat arbitrary, but captures some essence of the fundamental operation of the device:

(a) No PNR capability: for devices that are typically operated as a one-or-more-photon or no-photon device.

(b) Some PNR capability: for devices that are made from multiple detectors that individually have no PNR capability and thus are limited in the photon number that can be resolved to the number of individual detectors; in this case, characteristics of the device change with the number of photons detected as some of the individual elements with no PNR capability become unresponsive after firing, produce afterpulses, etc.

(c) Full PNR capability: devices whose output is inherently proportional to the number of photons, excluding usual saturation limits to which all detectors are subject to.

While we emphasise that system performance is of high interest, it is also very useful to distinguish the performance of system components, such as detectors and sources. In doing so, one must be mindful of which sub-components are inherent to the operation of the device and which are application-specific. For example, additional fibre optics and coaxial cables can introduce their own latency or losses to the system, but they are generally application-specific and should not be considered as a part of the detection system. However, if an electrical/optical element is inherently required to make a system functional (for example, a pump rejection filter for some parametric down conversion, four-wave mixing, and other sources), then its losses should be counted as a part of the source. In this vein, there is currently a European initiative on developing standards for the particular application of Quantum key distribution (QKD), which should address some of the issue of lack of standards [4].

Towards this goal, we propose the following definitions of key device parameters and suggest that, whenever appropriate, they should be defined as such and of course those parameters should be quantified as new results are published. In addition, we note that application specific figures of merit, that are *combinations* of more general parameters, are often used. While these can be very useful in narrow contexts and are worthy of reporting, we feel strongly that all the underlying universal parameters should be included as well, so that device performance can be estimated in any application. With respect to detectors, there have been recent efforts in the form of ''detector tomography'' that treats a detector as a quantum measurement device and provides a most general characterisation that can be independent of prior knowledge of the detector operation [5]. The basic method measures the detector response to a range of known input quantum states. Such schemes are certainly of much interest and offer significant potential, although at the current time it is not likely to be implemented widely by detector developers. As this field develops, we may see such techniques become more common and we look forward to continuing those discussions at the next workshop to be held at PTB Braunschweig, 27 June to 1 July, 2011.

The papers presented at these workshops and in these special editions show that significant advances are being made to address some of the issues that were highlighted in the first workshop back in 2003. The number of participants and industrial supporters has been increasing with each workshop. QKD has

Source parameter	Definition
Spectral, temporal, and spatial properties	The output of a single-photon source should be a coherent wavepacket, with $\mathrm{Tr}(\rho^2) = 1$ where ρ is density matrix of the state. For $\mathrm{Tr}(\rho^2) < 1$, the spectral, temporal, and spatial information, such as bandwidth, coherence time, or spatial profile should be given when available. For photon pair-based sources, this should include joint spectral distributions and number of Schmidt modes [6], which quantifies the level of spectral correlation between the frequencies of the photons of a pair.
Indistinguishability	While it is preferable completely to measure the spectral, temporal, and spatial properties of a source output, it is often difficult to implement and so other measures are often used. Indistinguishability of photons emitted from subsequent pulses or heralds is an acceptable measure useful for many applications and is indicated by the visibility of Hong-Ou-Mandel interference with single photons subsequently emitted from the same source. As visibility can be reduced by many mechanisms, all visibility measurements should be accompanied with statement quantifying any background or other mechanisms responsible for reducing that visibility from unity.
$P(n)$	Probability of n-photon emission per pulse, or per unit time for continuous wave (CW) source, for a given set-up. For a CW source it is helpful to include the coherence time and/or the bandwidth of the emitted light. This probability is the product of generation efficiency and extraction efficiency (listed below) and as such, is a most useful parameter for the end user of a source.
Generation efficiency (or probability)	Probability of single photons created within the source per pulse or per unit time for a CW source. If identified, generation efficiency dependence on collection spectral bandwidth, pump power, and other critical parameters such as the physical interaction volume defined by the collection should be given. For a heralded source, only one photon of a pair is counted in determining generation efficiency.
Extraction efficiency (or probability)	All optical losses in extracting the photons from where they are generated to where they are useful for an application. This will include losses owing to spectral filtering for defining the emission bandwidth and the rejection of any pump light, spatial filtering often into a single mode, geometric alignment, and beam-shaping optics. Usually characterised through transmittance measurements and mode overlap.
$g^{(2)}(r_1, t_1; r_2, t_2)$	Quantifying multi-photon emission through a second-order correlation function [7,8], $g^{(2)}(r_1, t_1; r_2, t_2)$ is most generally defined for two positions r_1 and r_2 and two times t_1 and t_2 as $$g^{(2)}(r_1, t_1; r_2, t_2) = \frac{\langle E^{(+)}(r_1, t_1)E^{(+)}(r_2, t_2)E^{(-)}(r_2, t_2)E^{(-)}(r_1, t_1)\rangle}{\langle E^{(+)}(r_1, t_1)E^{(-)}(r_1, t_1)\rangle\langle E^{(+)}(r_2, t_2)E^{(-)}(r_2, t_2)\rangle},$$ where $E^{(+)}$ and $E^{(-)}$ are the positive and negative frequency components of the electric field at time t. In single-photon source applications $r_1 = r_2$ when measured using a number-resolving detector although more typically r_1 and r_2 are located at the two output ports of a beamsplitter in a Hanbury-Brown Twiss interferometer arrangement so the r-dependence is often dropped in the notation. Expressing this in emission probabilities of the source we obtain, $$g^{(2)}(\tau = 0) = \frac{2P(2) + 6P(3) + \cdots}{(P(1) + 2P(2) + \cdots)^2},$$ with $\tau = (t_2 - t_1) - \frac{r_2 - r_1}{c}$. For a low-efficiency source with $P(n) \ll P(1)$ for $n > 1$, this simplifies to $$g^{(2)}(0) \approx \frac{2P(2)}{P(1)^2}.$$

(*continued*)

Continued.

Source parameter	Definition
Emission noise factor	For sources based on pair production, the coincidence-to-accidental ratio can conveniently quantify the level of unwanted background photons in the output mode. This emission mode should be clearly defined in terms of spatial, spectral, and temporal profiles which may be limited by optics such as apertures, fibre modes, spectral filters, temporal switches, etc. While not as convenient to quantify for deterministic sources, the parameter of interest is the ratio of photons in the desired output mode (spatial, spectral, and temporal) to photons collected, but in unwanted modes not rejected by the source output filters.
Maximum generation rate	Any limitations in the maximum operation rate of the source, whether pulsed or CW. This should include the minimum time between pulse attempts in a probabilistic source and any effects of an increased operation rate on other characteristics such as $P(1)$ and $g^{(2)}(r_1, t_1; r_2, t_2)$.
Detector parameter	
Detection efficiency (DE) and spectral responsivity	Probability of registering a single incident photon at a given wavelength. This should include all components and optics, such as spectral filters, or optical fibres that are required for use of the detector. If the DE depends on an incident photon rate, as a result of dead time, afterpulsing, or other mechanisms that may be rate dependent, the value should be extrapolated to an incident photon rate of 0. Other operating parameters should be included if the DE is dependent on those parameters. This is distinct from ''quantum efficiency'', which is typically only the probability of conversion of an incident photon into a charge carrier.
Dark count rate	The count rate registered by a detector in the absence of incoming photons.
Afterpulse probability	The probability for the detector to fire a second time right after a preceding detection event without being set off by a second photon. The afterpulse probability should be stated either for a specific time after the previous pulse or as a function of that time.
Dead time	The smallest time duration after which the detection efficiency is independent of previous photon detection history. Thus the dead time includes any efficiency transition times. Additionally it can be useful to quantify any effects associated with efficiency transients.
Timing latency	The time between a photon's arrival at the detector and the final readout from the electronics.
Timing jitter	The uncertainty in the timing latency owing to the detector and any electronics required for its operation.
PNR capability	No-, Some- or Full-PNR capability, see text.

benefited from advances in detection technology. Developments in single-photon source technology show great promise for future cryptography systems. QKD systems are now available commercially and were even used in conjunction with the 2010 World Cup Finals. From this, new areas of quantum technologies are being explored such as quantum repeaters, quantum memories, and quantum enabled measurements. Meanwhile, there are research groups using single-photon technologies to explore nature, from the minutiae of nanoparticles to the Brobdingnagian scale of the universe.

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