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EDITORIAL
Single-Photon Devices and Applications

This special issue accompanies the 5th International Conference on Single-Photon Technologies held at the Physikalisch-Technische Bundesanstalt (PTB), Germany, in June 2011. This community has met every two years at national metrology institutes, starting with the initial meeting in 2003 at the National Institute of Standards and Technology (NIST, Gaithersburg), followed by the meetings at the National Physical Laboratory (NPL) in 2005, at the Istituto Nazionale di Ricerca Metrologica (INRiM) in 2007 and at the National Institute of Standards and Technology (NIST, Boulder) in 2009.

The aim of these workshops is to bring together a broad range of people with interests in single-photon technology and applications to help disseminate progress in the field.

At the 2011 workshop 67 talks (14 invited) and 16 posters were presented in 15 sessions. 109 participants from 15 countries participated, 71 from Europe (with 22 from Germany, 17 from Italy, and 11 from UK have been the major groups), 30 from North America (27 from USA), 6 from Asia and 2 from Australia.

A collection of selected papers on the scientific fields of single-photon science and technology has been published following each workshop so far, each dealing with specific topics. The first of these special issues followed the 2003 workshop and dealt mainly with single-photon detection using semiconductor devices, largely due to the fact that this was the most developed technology at that time [1]. The second special issue was more focused on single-photon sources, reflecting the large number of contributions at the 2005 workshop [2]. Superconducting detectors came into focus in the third issue following the 2007 workshop, which was held in conjunction with the EU 7th framework project Sinphonia [3]. In 2009, there were several fields of single-photon technology, which appeared in the special issue, such as photonic entanglement technology and applications, measures of nonclassicality; correlated, entangled, and factorable state source designs as fundamental physics tests [4].

The 5th workshop on single-photon devices and applications dealt specifically with the current state of the art and latest developments of single-photon detectors and sources with a focus on existing limitations, deficiencies and opportunities for improvement. These developments are driven by the emergence of many applications, which require such devices. These applications, such as quantum cryptography, quantum computation, correlated photon metrology, quantum imaging, quantum interferometry, entanglement, etc., comprise a new area of endeavor known as Quantum Information Technologies (QIT). For each application, different properties of the devices are required. Furthermore, there was a special session reporting on the results of a European Commission funded 7th framework project (www.quantumcandela.org), dealing specifically with the efforts towards realizing photon-based standards. Therefore, this workshop was an opportunity for researchers from universities, industrialists and metrologists to report on current and future developments in the above mentioned areas as well as from other areas of photon-detection research such as astrophysics, nuclear physics, biology, etc. In conclusion, for the community the intended outcome of this workshop was to continue working together and informing each other of developments and needs in this area and identify other applications that operate in low photon counting regimes.

The following topics were announced in the call for papers for this workshop and were discussed in detail also through invited speakers.

In the sessions on *detectors*, the definition of detector-related terms and characterization parameters in general, the efficient handling of multichannel data using field-programmable-gate arrays (FPGAs) and different detector types ranging from superconducting detectors to Si- and InGaAs-single photon avalanche detectors were discussed. Invited talks were held on new silicon SPAD technology (Angelo Gulinatti, Politecnico di Milano: "New Silicon SPAD technology for enhanced red-sensitivity, high-resolution timing and system integration"), photon detection with superconducting devices (Sae Woo Nam, NIST: "Optical and near-infrared photon detection with superconducting devices") and photon number resolution (Andrew Shields/Oliver Thomas, Toshiba: "Resolving the photon number with fast-gated silicon avalanche photodiodes").

The sessions on *sources* dealt with topics like emission and collection efficiency, photon statistics, purity of single-photon states of single-photon sources as well as entanglement generation. Invited talks were held on quantum dots (Joel Bleuse, CEA, Grenoble: "Quantum dots in tapered photonic wires: towards

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unit-efficiency single-photon sources''), high collection efficiency (Stephan Goetzinger, ETH Zürich: ''Planar dielectric antennas for collecting photons from a single emitter with near unity efficiency''), heralded and true single-photon sources (John Rarity, University of Bristol: ''Progress in single-photon sources, heralded versus true single photons'') and diamond defects (Jörg Wrachtrup, University of Stuttgart: ''Interfacing diamond defects'').

Applications of single-photon technology had invited talks from William H. Farr, JPL CalTech, on ''Single-photon detectors for capacity achieving optical communication'', from Don Figer, Rochester Imaging Detector Laboratory, on ''Single-photon detectors for inner and outer space'' and from Hugo Zbinden, University of Geneva, with the provocative title ''What are single photons good for?'', which is also the tutorial paper in this special issue.

In *metrology*, the metrological characterization of detectors, sources, components and systems were in the foreground as well as a special session on the realization of photon-based standards. Invited talk were held on quantum-enhanced metrology (Brian Smith, Clarendon Laboratory, University of Oxford: ''Quantum-enhanced metrology in the real world: Losses, decoherence, and noise make life on the quantum edge challenging'' and on photon-based standards: Alan Migdall, NIST, ''Single-photon tools, techniques, and prospects for metrology'' and Maria-Lusia Rastello, INRiM, ''Metrology towards quantum-based photon standards''.

Quantum cryptography, quantum key distribution and quantum computation continue to be main driving forces for the development of single-photon sources and detectors. Two sessions explicitly dealt with these topics with an invited talk from Paul Kwiat, University of Illinois, on ''Optimized (non)entanglement: designer sources for next-generation quantum information''.

For this special issue, nine papers were selected, including one tutorial. In the tutorial, Nicolas Sangouard and Hugo Zbinden discuss under the provocative title ''What are single photons good for?'' the possible future application fields of single-photon sources. They claim that ''*efficient sources, producing narrowband, pure and indistinguishable photons at appropriate wavelengths*'' are necessary to start what they call ''*a revolution in the framework of quantum communication*''.

Concerning detectors, the investigation of the performance of InGaAs single-photon avalanche detectors (SPAD) is a focus of this special issue. Alessandro Restelli, Joshua C. Bienfang and Alan L. Migdall discuss time-domain measurements of afterpulsing in a periodically-gated InGaAs SPAD. They experimentally investigate the performance of InGaAs single-photon avalanche detectors and achieve results with sub-nanosecond non-periodic gates that are comparable to systems operated in the regime of gigahertz periodic gating. Furthermore, they provide a quantitative connection between afterpulse probability and total avalanche charge.

Afterpulsing of InGaAs/InP SPADs is discussed in the paper by Mark A. Itzler, Xudong Jiang, and Mark Entwistle. They report on the afterpulsing behaviour of these detectors for gating frequencies between 10 MHz and 50 MHz. For obtaining the afterpulse probability, FPGA-assisted data acquisition was used. As a result, they find a simple power law dependence of the afterpulse probability from the hold-off time. Possible physical backgrounds for this simple dependency are discussed.

In a third paper on the afterpulsing of InGaAs APDs, Tommaso Lunghi and coworkers discuss the free running single-photon detection behaviour of negative feedback InGaAs/InP APDs. Here, the avalanche is effectively quenched and the afterpulsing significantly reduced by an integrated feedback resistor. Additionally, an active hold-off circuit is implemented, which leads to a further reduction of afterpulsing and to an improvement of the general detector characteristics. Free-running operation at 600 Hz dark count rate at detection efficiency of 10% is demonstrated. Also here, an FPGA algorithm is exploited.

Gulinatti and coworkers present their work on silicon SPADs aiming towards enhanced sensitivity for the red spectral range in combination with high-resolution timing and improved system integration. To achieve this, a new planar technology was introduced leading to a detection efficiency of 40% at 800 nm whilst leaving the temporal resolution still high at 90 ps compared to typical values of ~300 ps.

FPGAs are being used more and more in single-photon technologies and a session on this research was held during the workshop. In this special issue, Raphael Pooser and coworkers report on ''FPGA-based gating and logic for multichannel single-photon counting''. FPGA-based logic is used for both diode gating and coincidence counting utilizing multichannel InGaAs single-photon detectors aiming also towards use in QKD test beds.

Sebastiano Antonioli and coworkers report on ''Time-correlated single-photon counting system based on a monolithic time-to-amplitude converter''. These systems consist basically of a single-photon detection module, a time-correlated single-photon-counting acquisition board and a power management unit. In this paper, the design of a compact system with high temporal resolution, low differential nonlinearity, high counting rate and low power is reported. Together with multichannel time-to-amplitude converters, these systems may allow large scale multi-channel acquisition chains aiming towards the realization of architectures for multidimensional TCSPC measurements.

The heralded generation of single photons through nonlinear optical processes is one of the most efficient ways to obtain close-to-pure quantum states. Zhang and coworkers exploit group-velocity matching to demonstrate purity of up to 0.84. Experimental realization for spontaneous parametric down-conversion and spontaneous four-wave mixing is studied in detail in their paper on "Heralded generation of single photons in pure quantum states".

The interesting effect of unwanted entanglement and its reduction or elimination is discussed by Warren P. Grice and coworkers in their paper on "Auxiliary entanglement in photon pairs for multi-photon entanglement". For many applications the elimination or at least reduction of unwanted spatial and spectral entanglement is necessary and this paper points to a solution.

The next Single-Photon Workshop will be organized by and take place at the Oak Ridge National Laboratory in Oak Ridge, USA, in autumn 2013. We expect that in addition to single-photon source and detector development and characterization and their surrounding technology becoming more and more part of the "bright future for single photons", applications, topics like quantum information and communication, quantum metrology and quantum-enabled measurements will also join this bright future.

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