Entanglement-enhanced Attosecond-scale Time-of-flight Measurements

Paul G. Kwiat, Colin P. Lualdi, Spencer Johnson

Department of Physics, Illinois Quantum Information Science and Technology Center,

University of Illinois Urbana-Champaign, Urbana, Illinois, US

Improved metrology is one of the promises of the quantum information age, and optical systems have already demonstrated impressive progress in the area. For example, the well-known Hong-Ou-Mandel (HOM) two-photon interference technique [1] enabled the first precise determination of the photon tunneling time [2], in part due to the intrinsic immunity to dispersion of the underlying phenomenon [3]. In this example, photons are directed to opposite sides of a 50-50 beamsplitter; assuming the two photons are indistinguishable from each other – spectrally as well as temporally – there is a destructive interference effect that causes the photons to 'bunch' at the beamsplitter output, so that the probability for the photons to take both output ports simultaneously vanishes, leading to a dip in coincidences. The width of the dip, which limits the relative time-of-flight resolution of the measurement, depends inversely on the bandwidth of the photons; for example, by engineering a source with ~300-nm bandwidth, dip widths as low as 7 fs were achieved [4]. Another advantage of the HOM effect is that it is immune to asymmetric loss before the beamsplitter, as well as resilient to background noise photons.

These benefits persist and are further enhanced by directing *energy-entangled* photons into the HOM beamsplitter. In this case, the coincidence dip is modulated by the beat note of the frequencies of the two photons [5], leading to potentially much sharper variations in the count rate versus relative arrival times. Here we report the realization of a highly non-degenerate frequency entangled source (starting from a non-degenerate polarization-entangled photon source [6]), and its use to achieve attosecond-scale time-of-flight measurements (~2-nm path length differences), at the Cramér-Rao bound, i.e., obtaining the maximum amount of Fisher information per photon; see Fig. 1. The resulting system holds great promise for applications in microscopy, imaging biological systems, and even remote sensing of objects, e.g., detecting small vibrations off distant objects reflecting one of the photons.

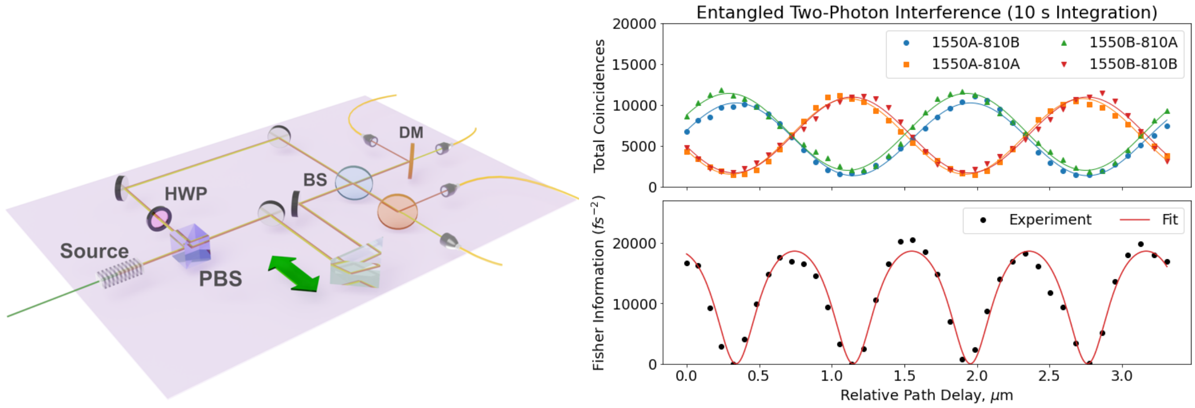

Fig. 1a Experimental setup to demonstrate high-resolution time-of-flight measurement, using energy-entangled photons. The source creates a pair of nondegenerate polarization-entangled photons, at 810 and 1550 nm; a polarizing beam splitter (PBS) and half wave plate (HWP) convert these into energy-entangled photons, which are then recombined on the final beamsplitter (BS) after experiencing a tunable relative delay. The output modes of the BS are measured after a dichroic mirror (DM) using single-photon counting SNSPDs. b. Measured high-visibility two-photon interference fringes showing the expected beat note between interfering energy-entangled photons as a function of relative path delay. c. Calculated Fisher information per photon, along with theoretical prediction.

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Semiconductor quantum dots as a resource for photonic quantum science and technologies

Andreas Pfenning[1]
[1]University of Würzburg, 97070 Würzburg,Germany

To be updated

Quantum Networks: Single Photons to Multipartite Entanglement

Rob Thew
University of Geneva, Switzerland

Quantum networks are built on photons. I will discuss some of our work on generating “good” photons and using them. How one defines “good” being highly dependent on what you plan on using them for. Whether they are actually “good” also requires some means to quantify or certify them. I will present some of our resent efforts to find meaningful ways to certify single photon sources [1], and demonstrate how these can then be used to efficiently generate multipartite entanglement. In particular, we have developed a scheme for 8-partite entanglement that heralds these multipartite entangled states at a rate of around 10^3 s^1. To certify this entanglement, we have developed a scheme that requires only a couple of measurement settings independent of the number of parties involved and where the computational requirements reduce to a simple matrix eigenvalue problem [2].

We will then put this in a network setting and present a DLCZ-inspired entanglement distribution using scheme these single photons [3] and discuss some of the challenges for realising quantum repeaters and some of the alternatives and possible solutions that we are working on [4].

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Enabling direct SI-traceable measurements of quantum dot single-photon sources

A. Gamouras[1], M. G. White[2,3], N. A. Tomlin[3], M. S. Stephens[3], J. H. Lehman[3], J. Jin[1], D. Dalacu[1] and R. L. Williams[1]

[1]*National Research Council Canada, Ottawa, Ontario, Canada*
[2]*University of Colorado, Boulder, Colorado, USA*
[3]*National Institute of Standards and Technology, Boulder, Colorado, USA*

Single-photon emitters and single-photon detectors are essential to quantum communication, sensing, and information processing technologies. Single-photon sources also have the potential to be implemented as standard radiometric sources to calibrate single-photon detectors [1]. Presently, attenuated laser sources and conventional photodetectors are widely used to calibrate the detection efficiency of single-photon detectors [2, 3]. With ongoing work towards the development of quantum integrated circuits and similar technologies that incorporate single-photon sources and detectors on a single chip [4, 5], it would be advantageous to utilize integrated components to verify system performance. One method of characterizing a single-photon source is to measure the optical power of the emitted photons. Performing this measurement on-chip would enable single-photon detector efficiency calibrations within the same quantum-integrated device. The objective of this work is to develop and implement an SI-traceable radiometer chip in the measurement of photons from a semiconductor nanowire quantum dot single-photon source.

Planar bolometric electrical substitution radiometers (PBRs) under development at the National Institute of Standards and Technology (NIST) incorporate a vertically-aligned carbon nanotube absorber, superconducting niobium transition edge sensors, and a tungsten heater fabricated on a silicon nitride membrane [6, 7]. A newly designed radiometer chip prototype aims to achieve sensitivity in the picowatt power range, enabling the direct measurement of optical power from a quantum dot single-photon source embedded within a semiconductor nanowire waveguide structure, designed and fabricated at the National Research Council of Canada (NRC) [8, 9]. This type of quantum emitter calibration is a first step in creating SI-traceable measurement standards for integrated quantum photonics technologies.

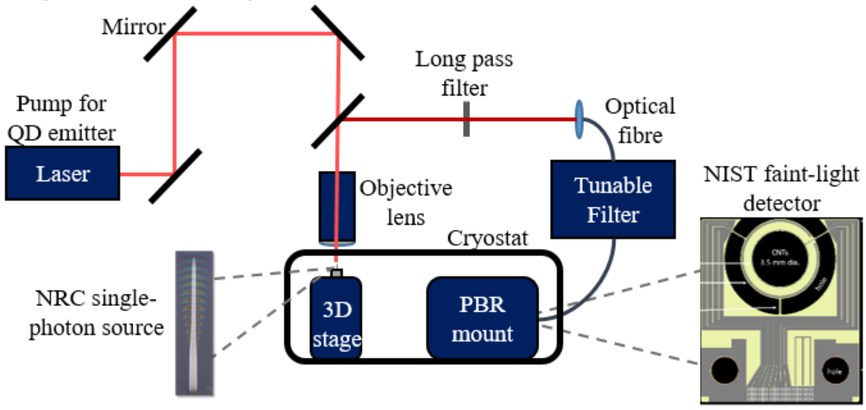

Fig. 1 Diagram of measurement apparatus with NIST PBR and NRC quantum dot emitter in the same cryostat.

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InGaAs/InP single photon avalanche diode with high photon detection efficiency and low dark count noise

Chan-Yong Park[1], Soo-Hyun Baek[1], Sun-Ho Kim[1], Jung-Hyun Kim[1], Chulwoo Park[2]

[1]*Wooriro Co,. Ltd: 102-22. Pyeongdongsandan 6beon-ro, Gwangsan-gu, Gwangju, 62453, Republic of Korea*

[2]*SK telecom, Innovation Business Development Team 1 : 65 Eulji-ro, jung-gu, Seoul, 04539, Republic of Korea*

The InGaAs/InP avalanche photodiode has been widely used as a detector for optical communication because of its high quantum efficiency and high-speed operation at 1550 nm wavelength, where the transmission loss in silica optical fibers is lowest. In addition, the dark count noise of InGaAs single photon avalanche diode(SPAD) is also very low thanks to significant improvements in InGaAs epitaxial technology. For this reason, InGaAs SPAD-related devices are used as key components in quantum key distribution (QKD) network. In this study, we report on the design, fabrication and characterization of a SPAD with a very low dark count rate at high photon detection efficiency (PDE).

The SPAD structure and fabrication techniques have been described in our previous reports [1]-[2]. A double Zn-diffusion technique was used for the fabrication of InGaAs SPADs. In general, since the dark count rate (DCR) is proportional to the volume of the InGaAs active region, the diameter of the InGaAs absorption region should be as small as possible and the thickness should be thin to reduce the DCR. However, small quantum efficiency or photon detection efficiency (PDE) are expected with thin InGaAs absorbing layers. To overcome this, a face-down(back illumination) structure was adopted with an integrated lens. A dual anode(DA) SPAD also was demonstrated for GHz operation [2]. The chip-on-carrier(CoC) was assembled by flip-chip bonding technique between the fabricated SPAD chip and a quartz carrier with Au-Sn solder bump. The CoC was mounted TO8 package for SPAD module or mini-flat package for DA-SPAD.

For device characterization, an attenuated laser pulse with a 190ps of FWHM and 1550nm wavelength was used as a single photon source. The gate frequency and gate width were 10 MHz and 2 ns, respectively. The photon incident frequency was 100 kHz. An average number of photons of 0.1 was used.

Fig. 1 shows DCP/gate versus PDE and Fig. 2 shows total afterpulse probability(APP) versus PDE for the fabricated SPAD(TO8 coaxial module) as functions of several temperatures. A DCP/gate less than 1×10^{-6} was measured at 37% of PDE and -40 °C, while DCP/gate of 1×10^{-6} was measured at 15.6% of PDE and +10 °C, respectively. The APP decreases as temperature increases as shown in Fig.2.

We also fabricated DA-SPAD for 1 GHz gate frequency application and measured the performance. For the test condition of 1 GHz gate frequency with 400ps gate width, 3.125MHz photon repetition rate, 0.1 photon number on average, and 15V of gate voltage, a DCP/gate less than 1×10^{-6} and APP of 3.9% were obtained at -15 °C.

InGaAs SPAD technology can be applied to the long-range 3D image sensor. We will report fabrication of InGaAs solid-state photomultiplier(SSPM) and some achievements for SSPM as a photon number resolver (PNR).

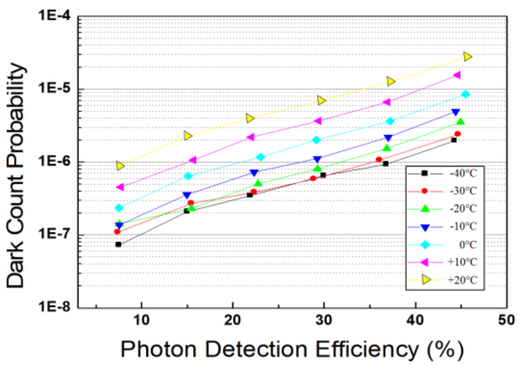

Fig. 1 DCP/gate vs PDE as functions of several temperatures. (2ns gate width and 10MHz gate frequency)

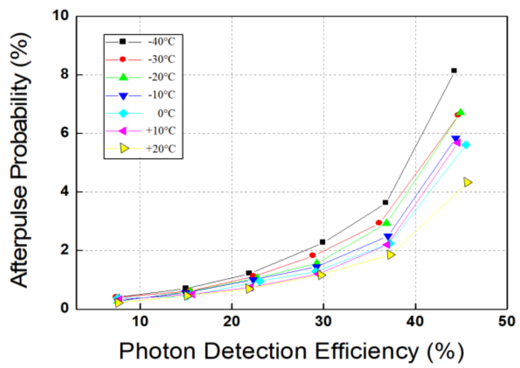

Fig. 2 Total afterpulse probability vs PDE as functions of several temperatures. (2ns gate width and 10MHz gate frequency)

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Developing Metrology at the photon counting regime for testing the implementation security of Quantum Communications

Marco Gramegna[1]

[1] *INRIM - Istituto Nazionale di Ricerca Metrologica, 10135 Torino, Italy*

In an increasingly global and connected society, the demand for enhancing the amounts of data being transmitted and stored online goes at the same pace with the need to strengthen the security of such data and communications. Nowadays, most of the cybersecurity infrastructures rely on the exchange and use of digital cryptographic keys. However, recent advances in the realisation of a quantum computer [1], able also to decrypt all the confidential information which was previously encrypted, have dramatically raised the threat to this infrastructure.
The research to develop "quantum safe" cryptographic techniques to protect against this threat, is the same way very active. These techniques include schemes based on the principles of physics, most notably Quantum Key Distribution (QKD) [2], that operating in the single-photon regime, distributes secret digital keys over optical links (both fiber based or open air). Uniquely, it provides protocols whose security can be proven by the laws of quantum mechanics, rather than by relying on unproven assumptions about the computational resources available to an adversary.

Although QKD protocols can be proven unconditionally secure in theory, in practice any deviations of the real system from the idealised model could introduce vulnerabilities [3]. For QKD technology to become a viable real-world solution, end-users need confidence in it, and this requires its metrological characterisation of physical parameters of the practical QKD system devices.

Quantum Optics methods are peculiar for developing effective measurement techniques suitable for the photon counting regime [4]. This talk will describe the on-going effort to establish a reliable metrology for quantum communication [5,6], providing an overview of recent developments of SI-traceable measurements, at the single-photon level, to characterise QKD technologies (single-photon sources, detectors, etc.) [7] and hardware vulnerabilities of practical QKD systems (assembled transmitter and receiver modules) for the main prominent cyber-attacks [8], and to provide measurement procedures for practical assessment of QKD implementation security and effective QKD protocols [9], in alignment with the actual standardisation development efforts [10].

Moreover, the expertise gained in developing the measurements for practical QKD implementation security can be used in the drafting of measurement specifications and standardisation documents (ETSI ISG-QKD) and of QT Standardisation roadmaps (FGQT, EMN-Q) [10,11].

Finally, a mention will be provided on the strategic role that NMIs and DIs [12] results to be fundamental for developing metrology for Quantum Technologies. To this purpose, it will be illustrated the effort for the establishment of a coordinated calibration services and measurement facility platform in the context of the European Metrology Network for Quantum Technologies [13, 14].

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Rise of the Machines: Making better photons by getting rid of experimentalists

Jihun Cha, Sebastian Malewicz, Fatemeh Mohit, Ming Su,
Marcelo Almeida, Till Weinhold, and Andrew White

Centre for Engineered Quantum Systems and the School of Mathematics and Physics,
University of Queensland, Brisbane QLD 4072 AUSTRALIA

There is now an enormous opportunity to interconnect quantum components together into complex, short- and long- range networks of sensing, communication, and computational elements. Photons are a natural choice for networking quantum technologies as their quantum nature survives at room temperature and long distance propagation is possible, either via optical fibre or through free space.

Here we explore using machine learning (ML) to optimise production, coupling, routing, and circuitry for single photons. Our single-photon source platform is resonant excitation of individual quantum dots coupled to a micropillar cavity [1]. Multiphoton suppression in the quantum dot emission—as well as single-photon indistinguishability and brightness—are directly influenced by the spatiotemporal characteristics of the optical excitation pulses. We use ML techniques to tailor the excitation laser pulse properties in real-time, significantly reducing the search time for optimal parameters. We also employ ML to control a deformable mirror, correcting for aberration on the single-photon wavefront field to maximise the coupling between the source output and a single-mode fibre [2]. This combination provides a toolbox for enhancing the performance of any solid-state single-photon source.

Photonic integrated circuits (PICS) will be essential for scalably realising photonic quantum technologies. Actively coupling photons into PICS requires high-fidelity integrated switches [3]. Current best practice—manual optimisation of electronic signals for each individual switch on a chip—is slow and unscalable. We use ML—simulated annealing—to optimise driving parameters for up to 4 switches on a single chip, achieving a significant speed up in tuning while retaining optimal performance. PICS often interface light in and out of the chip using edge coupling, which severely limits chip geometry as well as adding complication to fabrication. Using ML—inverse design [4]—we are developing efficient out-of-plane couplers and small-footprint waveguide crossings that are easier to manufacture and have higher circuit density. Our new architecture lowers entry costs for photonic integrated circuitry development, and we will ensure widespread adoption by disseminating to the community the full details of our designs and fabrication methodologies.

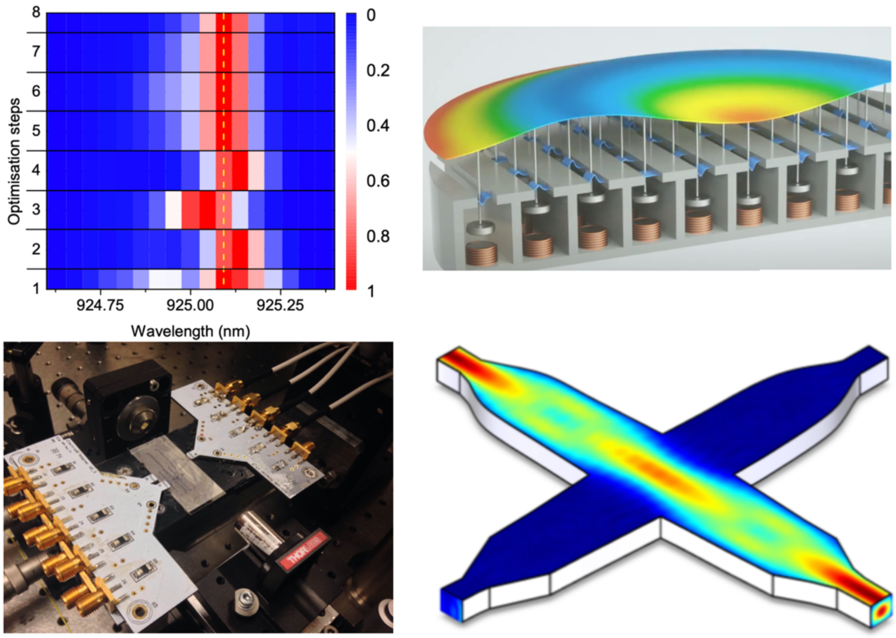

Fig. 1 *Top left*: Evolution of pump spectra driven by machine learning (ML) to optimise nonclassical visibility between photons from quantum-dot micropillar-cavity source. *Top right*: Deformable mirror shaped by ML to optimise coupling of single photons into fibre. *Bottom left*: Optical switch—indiffused waveguides in lithium niobate ($LiNbO_3$)—characterised by ML. *Bottom right*: Initial design of waveguide crossing before optimisation by ML.

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SPAD arrays advance spatial and temporal resolution

Cyril Saudan[1], Harald Homulle[1], Augusto Carimatto[1], Ivan Michel Antolović[1*]
[1]*Pi Imaging Technology, EPFL Innovation Park, 1015 Lausanne, Switzerland*
**michel.antolovic@piimaging.com*

Single-photon avalanche diodes (SPADs) detect single particles of light with picosecond time precision. Single-pixel SPADs are widely used due to three distinct strengths: high signal-to-noise ratio (SNR) at low light, high speed and fine timing precision. Consequently, SPAD found their use in confocal microscopy, flow cytometry, fluorescence lifetime measurements, particle sizing, quantum computing, quantum key distribution and single molecule analysis. Building SPADs in standard complementary metal-oxide-semiconductor (CMOS) technology enabled an increase in the number of SPAD pixels in a scalable way, paving the way for SPAD arrays and SPAD image sensors [1,2].

The former are of particular interest for time-resolved confocal microscopy, a powerful and versatile tool for research fields such as life and materials sciences: SPAD arrays improve both the spatial resolution and signal-to-noise ratio. In image scanning microscopy (ISM) [3,4], each pixel acts as a virtual small pinhole with good lateral and axial resolution, while multiple pixels collect the signal of a virtual large pinhole. Fig. 1 shows examples of different SPAD array uses in confocal microscopy.

More recently, tailored fabrication processes, design improvements, and the use of optimized micro-optics have enabled current SPAD arrays to reach sensitivities and noise levels comparable to single-pixel devices. We present different SPAD array architectures for point, line and image sensing (Fig. 2) with more than 50% peak sensitivity and less than 1 cps/µm^2 dark count rate.

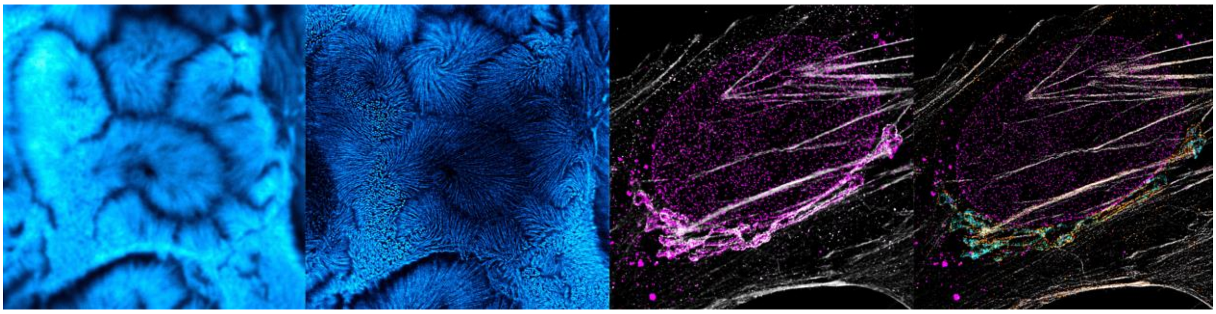

Fig. 1 Increased resolution and multicolor imaging with SPAD23 [5]. Confocal image (left) compared to image reconstructed by using a SPAD array with timing information (middle left). Stimulated emission depletion (STED) microscopy image (middle right) compared to a STED image with lifetime information (right), allowing for additional color contrast. Courtesy of Abberior Instruments.

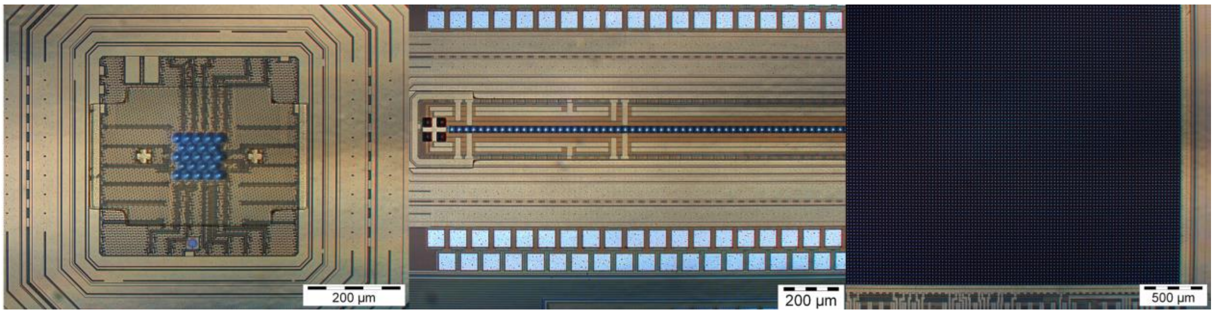

Fig. 2 Point (left), line (center) and image (right) sensor based on SPAD pixels.

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High-rate entanglement between a semiconductor spin and indistinguishable photons

N. Coste[1], D. Fioretto[1], N. Belabas[1], S. C. Wein[2,3], P. Hilaire[2,4], R. Frantzeskakis[5], M. Gundin[1], B. Goes[3], N. Somaschi[2], M. Morassi[1], A. Lemaître[1], I. Sagnes[1], A. Harouri[1], S. E. Economou[6], A. Auffeves[3], O. Krebs[1], L. Lanco[1,7], and P. Senellart[1]

1 Université Paris-Saclay, CNRS, Centre de Nanosciences et de Nanotechnologies, 91120, Palaiseau, France
2 Quandela SAS, 10 Boulevard Thomas Gobert, 91120, Palaiseau, France
3 Université Grenoble Alpes, CNRS, Grenoble INP, Institut Néel, 38000 Grenoble, France
4 Huygens-Kamerlingh Onnes Laboratory, Leiden University, P.O. Box 9504, 2300 RA Leiden, The Netherlands
5 Department of Physics, University of Crete, Heraklion, 71003, Greece
6 Department of Physics, Virginia Tech, Blacksburg, Virginia, 24061, USA
7 Université Paris Cité, CNRS, Centre de Nanosciences et de Nanotechnologies, 91120, Palaiseau, France

Over the last decade, semiconductor quantum dots have been proven to be an efficient technology for the generation of highly indistinguishable single photons [1]. In 2009, Lindner and Rudolph proposed to make use of the spin of a carrier in a quantum dot to generate chains of entangled photons in a linear cluster states [2]. To be useful for measurement-based quantum computing or quantum communications, such linear cluster states should be generated at high rate and the photons should be indistinguishable to create higher dimensionality graph states through linear gates.
In the present work, we report on the high-rate entanglement generation between a single electron spin and two indistinguishable photons. We study a single electron spin in a quantum dot deterministically positioned at the center of an electrically controlled micropillar cavity. The cavity allows for efficient photon collection owing to the Purcell effect and the electrical control allows for the introduction of the electron in the quantum dot as well as for the reduction of surrounding charge noise. The optical selection rules linking the electron spin state to the polarization of the emitted photon lead to spin-photon entanglement whenever optically exciting the system in a coherent spin superposition. After spin initialization, the excitation laser pulse sequence is synchronized to the spin precession induced by a small in-plane magnetic field (40 mT). Performing polarization-resolved three-photon correlations, we demonstrate genuine three-partite entanglement with a fidelity to the state above 63%. The photons are shown to be highly indistinguishable with mean wavepacket overlap of 88%. Owing to the high operation rate of the system (80 MHz) and the efficient collection of the photons, the spin-photon and spin-photon-photon entanglement generation rates are shown to be respectively 3 and 2 orders of magnitude higher than the previous state of the art [3].

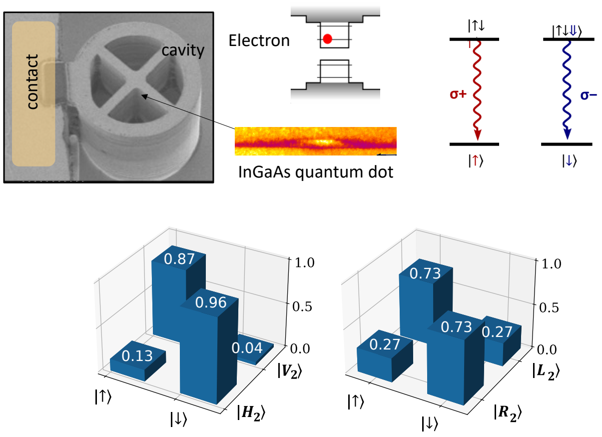

Figure : Top left: Scanning electron microscopy image of the device comprising a single InGaAs quantum dot (TEM image) centered in a connected micropillar cavity. Application of a bias allows charging the quantum dot with a single electron. Top right: optical selection rules linking the electron spin state and the polarization of light. Bottom: conditional probabilities of the spin and second photon states obtained using the third photon to measure the spin. These measurements allows demonstrating both spin-photon and spin-photon-photon genuine entanglement.

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On-chip Quantum Secure Communications

T.K. Paraiso, T. Roger, D.G. Marangon, I. de Marco, M. Sanzaro, R.I. Woodward, J.F. Dynes, Z. Yuan, A.J. Shields

Toshiba Europe Ltd, Cambridge Research Laboratory, Cambridge, U.K

Quantum communications is probably the closest quantum technology to practical deployment and large-scale commercialisation. In the wake of ever increasing quantum processors performance and the threats they represent against conventional public key cryptography algorithms methods, quantum key distribution (QKD) arose as means to establish symmetric encryption keys between distant parties, with information theoretic security. In the last 2 decades increasing efforts were deployed world-wide to develop quantum communication infrastructures. However for a viable integration in our conventional communication infrastructure, it is essential to overcome the challenges of cost, scalability and power consumption [1].

A promising candidate to tackle these challenge is to use miniaturization of the optical hardware onto photonics chips. While attractive this solution also presents its own challenges and while over the last few year, a number of core QKD functions were implemented on chip, a complete chip-based QKD system remained a long sought-after goal [2]. First, in order to guarantee the scalability and power efficiency, it is essential both to minimize the overall number of components integrated on chip and to reduce the use of power hungry components. Second, system integration requires co-designing photonic chips and driving electronics, ensuring real-time operation and quantum secure operation via the use of quantum random numbers.

In this tal,k we review our recent developments of versatile quantum communication light sources exploiting advanced laser modulation techniques and show we how these sources enabled the demonstration of the first standalone chip-based quantum cryptography system [3].

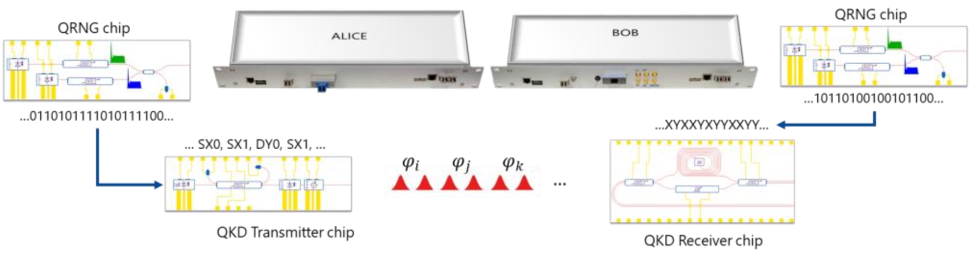

Fig. 1 A compact, standalone QKD system based on a set of compatible quantum photonic integrated chips. Each quantum unit fits in a 19” 1U rackmount enclosure. Quantum random numbers are generated on-chip continuously at 4 Gbit/s and converted in real-time into prepare and measure patterns to control the QTx and QRx chips.

The first part of the talk describes the realization of a set of individual photonic chips for the functions of QKD transmitter (QTx), QKD receiver (QRx) and quantum random number generation (QRNG), designed to be compatible with each other to operate in a high-bit rate time-bin BB84 protocol. The second part of the talk focuses on the system integration of these chips, including packaging, feedback control for autonomous operation and interface with commercial grade data encryption system. The system demonstrated continuous operation without user intervention over multiple days over all metropolitan distances. As a benchmark figure, quantum secure encryption key were exchanged at rates over 470 kbps over 10 km of fibre. While interfaced with an AES encryptor, we showed that the system was able to steadily generate sufficient quantum key material to serve over 1300 AES-256 key per second [3]. We conclude with a discussion on the perspectives of scaling up the QKD chip technology to promote their actual deployment in the field.

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New materials platforms for quantum memory

Elizabeth A. Goldschmidt
Physics Department, University of Illinois Urbana-Champaign, Urbana, IL USA

Optically active and highly coherent emitters in solids are a promising platform for a wide variety of quantum information applications, particularly quantum memory and other quantum networking tasks. Rare-earth atoms, in addition to having record long coherence times, have the added benefit that they can be hosted in a wide range of solid-state materials. We can thus target particular materials (and choose particular rare-earth species and isotopes) that enable certain application-specific functionalities. I will discuss several ongoing projects with rare-earth atoms in different host materials and configurations. This includes investigations of inhomogeneous broadening in rare-earth ensembles, which is highly host-dependent and plays an important role in which quantum memory protocols can be implemented in any given system. I will present results on our efforts to identify and grow new materials with rare-earth atoms at stoichiometric concentrations in order to reduce the disorder-induced inhomogeneous broadening. I will also discuss our work investigating photonic integration of rare-earth doped samples that aims to increase the light-atom interaction for practical quantum devices. I will show results from our work with rare-earth atom dopants in thin-film lithium niobate, which admits standard nanofabrication techniques, and show the suitability of this platform for quantum applications.

Noise-resistant quantum communications using hyper-entanglement

Jin-Hun Kim[1], Yosep Kim[1], Dong-Gil Im[1], Chung-Hyun Lee[1], Jin-Woo Chae[1], Giuliano Scarcelli[2], & Yoon-Ho Kim[1]

[1]*Department of Physics, Pohang University of Science and Technology (POSTECH), Pohang 37673, Republic of Korea*

[2]*Fischell Department of Bioengineering, University of Maryland, College Park, Maryland 20742, USA*

Quantum information protocols are being deployed in increasingly practical scenarios, via optical fibers or free space, alongside classical communication channels. For long-distance quantum communication protocols, the distribution of entanglement through noisy quantum channels remains a critical unsolved gap. Indeed, entanglement is very fragile to noise-induced degradation, so that even a perfectly-prepared entangled state quickly degrades to a partially mixed state, where quantum operation ceases to be possible; and, the presence of noise within the quantum transmission channels is nearly unavoidable as it can come from stray light, crosstalk or linear/nonlinear effects in the transmission medium. Recent years have witnessed tremendous efforts for noise suppression within transmission channels or proposals to switch to quantum protocols to high-dimension entangled states to attenuate this issue.

Here, instead, we show that hyper-entanglement, the property of quantum states that are simultaneously entangled in several degrees of freedom, can be effectively employed to protect entanglement distribution from noisy transmission channels [1]. Our strategy does not require changing the intrinsic quantum communication protocol under exam: instead, we take advantage of the fundamental property of hyperentanglement, i.e. the additional quantum correlation in a different space, to discriminate "signal" photons, i.e. the entangled photons endowed with such correlation, from "noise" photons coming from other sources.

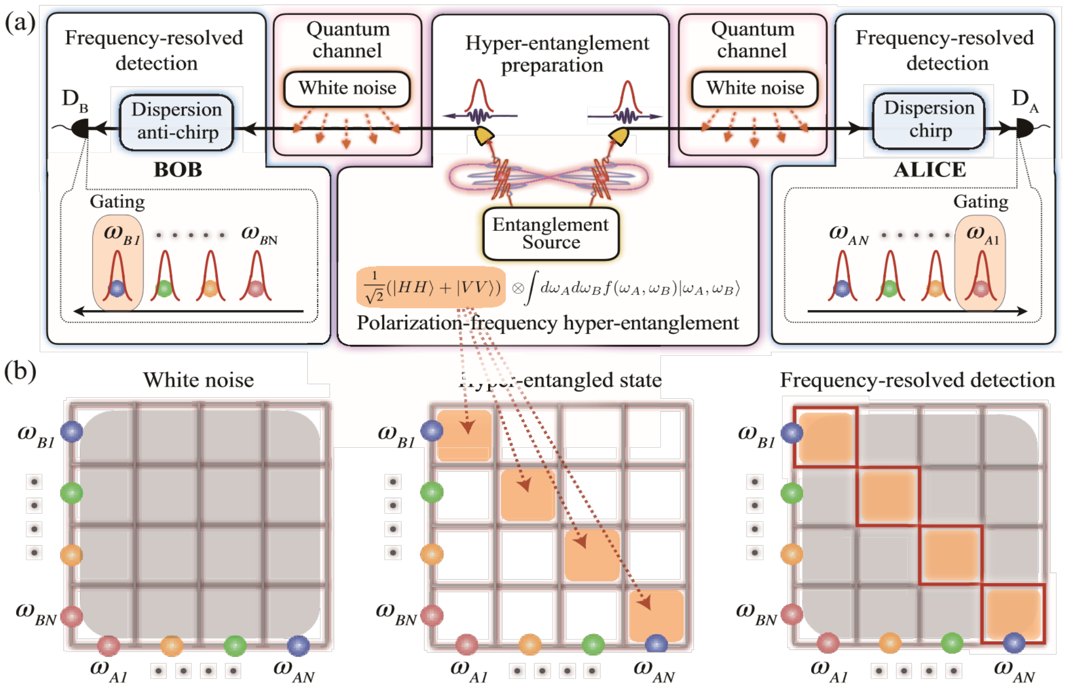

Fig. 1: (a) Conceptual schematic of noise-resistant quantum communication using polarization-frequency hyperentanglement. To distribute polarization entanglement to Alice and Bob through noisy quantum channels, frequency-time entanglement of the photons is utilized. The frequency-anticorrelation property of the photons makes possible the lossless conversion of the correlated frequency-bins to the correlated time-bins via dispersive media. Gated coincidence detection effectively performs measurement of correlated frequency-bins. (b) Due to the frequency-anticorrelation nature of the photon pairs, the correlated frequency bins are anti-diagonally distributed, while the white noise from the quantum channels is not. Each correlated frequency-bin represents a probability amplitude of a polarization-entangled photon pair. Frequency-resolved detection via gated coincidence measurement enables effective rejection of white noise, making possible noise-resistant quantum communication.

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Quantum advantage with photons

Chao-Yang Lu
University of Science and Technology of China, Hefei, P.R. China
Email: cylu@ustc.edu.cn

Quantum information sciences aim to provide advantages in certain tasks, such as communication security, measurement precision, and computational capability, compared to the classical means. In this talk, I will report our recent efforts in demonstrating quantum teleportational, metrological, and computational advantages using photons, and exploring possible applications in real world.

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Improving Superconducting Nanowire Single Photon Detectors: where is the limit?

V. Zwiller [1,2]

[1]Quantum Nano Photonics, Dept of Applied Physics, Royal Institute of Technology, Stockholm, Sweden
[2]Single Quantum BV, Delft, Rotterdamseweg 394, The Netherlands

Superconducting Nanowire Single Photon Detectors are now well established at the detectors with the highest performances in terms of time resolution, detection efficiency, spectral range, dark counts and saturations rates. A wide number of applications is enabled by these detectors including Lidar, microscopy, quantum communication and integrated photonics. We will discuss these applications along with the specific detector requirements for technologies based on single photon detection to have wide societal impact.
Further improvements in terms of time resolution, photon number resolution and extended detection ranges will also be discussed.