International Conference on Integrated Quantum Photonics

Final Conference of PICQUE and QUCHIP projects

Rome, 26-29 September 2017

ABSTRACT BOOK

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POSTER PRESENTATIONS

Invited talks

BosonSampling

Scott Aaronson[1]

[1]*University of Texas at Austin*

I'll give a theoretical introduction to BosonSampling, a 2011 proposal by me and Alex Arkhipov for demonstrating a clear quantum computational advantage using a relatively simple linear-optical setup.

Topics will include:
The connection between quantum optics and the matrix permanent
The computational complexity of the permanent, and its relationship to the complexity of BosonSampling
The hardness of approximate BosonSampling, and the conjectures on which it depends
The problem of verification of BosonSampling devices
Scaling with imperfect photon sources; Scattershot BosonSampling
BosonSampling with lost photons and dark counts

Engineering parametric down-conversion in multimode nonlinear waveguides

***M. Jachura*[1], *M. Karpiński*[1], *C. Radzewicz*[1], *D. Bharadwaj*[2], *J. Lugani*[2],**
***K. Thyagarajan*[2], *K. Banaszek*[1,3]**

[1]*Faculty of Physics, University of Warsaw, Pasteura 5, 02-093 Warszawa, Poland*
[2]*Department of Physics, IIT Delhi, New Delhi 110016, India*
[3]*Centre of New Technologies, University of Warsaw, Banacha 2c, 02-097 Warszawa, Poland*

Parametric down-conversion in nonlinear waveguides is a promising source of nonclassical light for quantum communication protocols, quantum metrology, and other quantum-enhanced applications. In many cases, available waveguides support multiple transverse spatial modes at the desired wavelengths, as shown in Fig. 1(a). In a series of papers [1-6] we have demonstrated that intermodal dispersion provides a powerful tool to control the characteristics of radiation generated via parametric down-conversion. In multimode waveguides the efficiency of the three-wave mixing process for given frequencies depends strongly on the specific combination of the spatial modes for the signal, the idler, and the pump fields. This effect has been confirmed experimentally [1] by realizing mode-selective sum frequency generation which provides two-dimensional maps of the effective phase matching, such as the one presented in Fig. 1(b). Such characterisation allows one to identify the operating regime for type-II parametric down-conversion capable of producing orthogonally polarized photon pairs in fundamental spatial modes of the waveguide. The spatial purity of the generated photons has been verified by measuring the beam quality factors [2,3] and subsequently by two-photon Hong-Ou-Mandel interference, depicted in Fig. 1(c), and generation of polarization-entangled photon pairs in the Shih-Alley configuration [4], both yielding visibilities consistently above 90%. Spectral degeneracy of photon pairs generated in higher transverse spatial modes allows one to generate entangled states of spatial qubits, realized as superpositions of a photon in two orthogonal transverse modes of the waveguide. Deterministic single-qubit gates to manipulate such systems can be implemented as integrated dynamic mode converters based on the electro-optic effect in nonlinear channel waveguides [5]. Alternatively, the generated entanglement can be tested with the help of inverting interferometers that detect the spatial parity of the input beam [6].

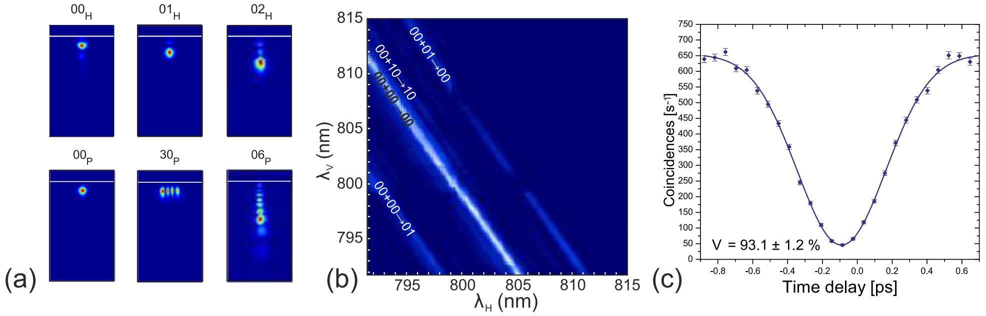

Figure 1: (a) Exemplary transverse modes for the fundamental (H) and sum-frequency (P) fields [3]. (b) A two-dimensional phase matching map as a function of the fundamental wavelengths λ_H, λ_V [1]. (c) Hong-Ou-Mandel dip for photon pairs generated in a multimode waveguide without spatial filtering [4].

References

[1] M. Karpiński, C. Radzewicz, and K. Banaszek, Appl. Phys. Lett. **94**, 181105 (2009).

[2] M. Karpiński, C. Radzewicz, and K. Banaszek, Opt. Lett. **37**, 878 (2012).

[3] M. Karpiński, C. Radzewicz, and K. Banaszek, in *Proc. SPIE* 8518, Quantum Communications and Quantum Imaging X, 85180J (2012).

[4] M. Jachura, M. Karpiński, C. Radzewicz, and K. Banaszek, Opt. Express **22**, 8624 (2014).

[5] D. Bharadwaj, K. Thyagarajan, M. Jachura, M. Karpiński, and K. Banaszek, Opt. Express **23**, 33087 (2015).

[6] M. Jachura, M. Karpiński, K. Banaszek, D. Bharadwaj, J. Lugani, and K. Thyagarajan, Phys. Rev. A **95**, 032322 (2017).

Single-copy entanglement detection

Borivoje Dakić[1]

[1]*Institute of Quantum Optics and Quantum Information, Austrian Academy of Sciences, Boltzmanngasse 3, A-1090 Vienna, Austria*

A main focus of current practical quantum information research is on the generation of large-scale quantum entanglement involving many particles with the goal of achieving real applications of quantum technologies. An important instance of this challenge is the verification problem, i.e. how to reliably certify the presence of quantum resources, in particular quantum entanglement. The plausibility of standard verification schemes (e.g. based on entanglement witnesses) is questionable, since they require repeated measurement on large ensemble of identically prepared copies, which is highly demanding to achieve in practice when dealing with large-scale entangled quantum systems. In this talk, I will present our recent work [1] where we develop a novel method by formulating verification as a decision procedure, i.e. entanglement is seen as the ability of quantum system to answer certain "yes-no questions". We show that for a variety of large quantum states even a single copy suffices to detect entanglement with a high probability by using local measurements. For example, a single copy of a 24-qubit linear cluster state suffices to verify entanglement with more than 95% confidence. Our method is applicable to many important classes of states, such as cluster states or ground states of local Hamiltonians in general.

References

[1] A. Dimić, and B. Dakić, "Single-copy entanglement detection", arXiv:1705.06719 (2017).

AlGaAs photonic devices for quantum information

J. Belhassen[1]*, G. Maltese*[1]*, S. Francesconi*[1]*, G. Sinnl*[1]*, A. Lemaître*[2]*, M. Amanti*[1]*, F. Baboux*[1] *and*

S. Ducci[1]

[1] *Laboratoire Matériaux et Phénomènes Quantiques, Sorbonne Paris Cité, Université Paris Diderot - CNRS UMR 7162*
Paris, France

[2] *Centre de Nanosciences et de Nanotechnologies, CNRS/Université Paris Sud, UMR 9001, 91460 Marcoussis, France*

Nonclassical states of light are key components in quantum information science; in this domain, the maturity of semiconductor technology offers a huge potential in terms of ultra-compact devices including the generation, manipulation and detection of many quantum bits [1]. Among the different resources under development, on-chip entangled photon sources play a central role for applications spanning quantum communications, computing and metrology. In this talk I will present our last achievements on AlGaAs photonic devices emitting non-classical states of light at room temperature via spontaneous parametric down conversion; the choice of this platform combines the advantages of a mature fabrication technology, photon pair emission in the C-telecom band, a direct band-gap and a high electro-optic effect. The characterization of the quantum states emitted by such devices demonstrates their ability to produce highly indistinguishable and entangled photons [2].

Different device designs can be adopted depending on the target application; I will show that collinear phase matching geometries are particularly attractive to produce broadband strongly anticorrelated frequency states which can be used for instance in multiusers quantum key distribution protocols [3] or to produce high dimensional qudits. On the other hand, devices emitting counterpropagating photons using a transverse pump configuration allow engineering and control a large variety of frequency states, an easy monolithic integration of sources and photonic circuits [4] and the production of Schrödinger cats and compass states.

The compliance of our sources with electrical pumping, together with the possibility to fabricate versatile and massively parallel devices make our approach a promising candidate for real-world quantum information.

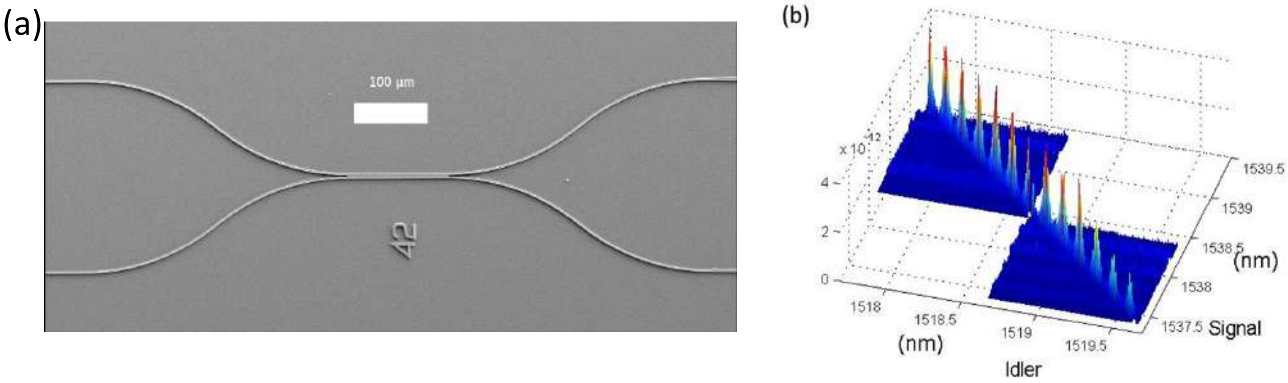

Figure 1: . (a) monolithic integration of a photon pair source and a beam-splitter; (b) measure of comb-like frequency correlations leading to photonic qudits.

References

[1] A. Orieux et al. ‘Semiconductors devices for entangled photons generation: a review’, Rep. Prog. Phys. 80 076001 (2017).

[2] C. Autebert et al ‘Integrated AlGaAs source of highly indistinguishable and energy-time entangled photons’, Optica 3, 143 (2016).

[3] C Autebert et al. ‘Multi-user quantum key distribution with entangled photons from an AlGaAs chip’, Quantum Sci. Technol. 1, 01LT02 (2016).

[4] J. Belhassen et al. ‘On-chip monolithic integration of heralded single photons sources and beam splitters’, QIM Conference Paris, April 2017.

Shaping the photon: Tailoring spontaneous emission in advanced single-photon sources

A. Fiore[1]*, S. Birindelli*[1]*, M. Cotrufo*[1]*, C.Y. Jin*[1]*, F.M. Pagliano*[1]*, D. Pellegrino*[1]*, M. Petruzzella*[1]*,*
F.W.M. van Otten[1]*, Ž. Zobenica*[1]*, L.H. Li*[2] *and E.H. Linfield*[2]

[1]*Dep. Applied Physics, Eindhoven University of Technology, The Netherlands*
[2] *School of Electronic and Electrical Engineering, University of Leeds, United Kingdom*

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Deterministic single-photon sources based on semiconductor quantum dots (QDs) are gaining increasing acceptance due to the recent progress in efficiency and indistinguishability and to their potential application within large-scale quantum photonic integrated circuits (QPICs). Nevertheless, major challenges must be solved in order to make them really scalable to large arrays and to unlock the full potential of light-matter interaction in solid-state systems. In this talk I will focus on the control of single-photon generation from QDs embedded in nanophotonic cavities. The simultaneous static control of the QD exciton energy and of the cavity frequency [1] will be shown to enable fully-tuneable, Purcell-enhanced, integrated single-photon sources. Additionally, the dynamic control of the exciton energy [2] or the cavity field [3] (on timescales shorter than the natural emission lifetime) allows the real-time control of the emission process, and thereby enables tailoring the photon temporal profile, opening new opportunities for the application of integrated matter-photon interfaces.

References

[1] M. Petruzzella, T. Xia, F. Pagliano, S. Birindelli, L. Midolo, Z. Zobenica, L.H. Li, E.H. Linfield and A. Fiore, *"Fully tuneable, Purcell-enhanced solid-state quantum emitters"*, Appl. Phys. Lett. 107, 141109 (2015)
[2] F.M. Pagliano, Y.J. Cho, T. Xia, F. van Otten, R. Johne and A. Fiore, *"Dynamically controlling the emission of single excitons in photonic crystal cavities"*, Nature Communications, 5, 5786 (2014)
[3] C.-Y. Jin, R. Johne, M.Y. Swinkels, T.B. Hoang, L. Midolo, P.J. van Veldhoven and A. Fiore, *"Ultrafast non-local control of spontaneous emission"*, Nature Nanotechnology, 9, 886 (2014)

Title:

Single and Multi photon counting using an array of SNSPDs

Authors:

A. Gaggero, R. Leoni

Abstract:

Single photons can be used as quantum bits for the optical implementations of quantum information processing (QIP) protocols. A lot of effort has been devoted to scale such implementations up to few tens of photons, which can only be achieved by integrating the key quantum optical functionalities of single-photon generation, linear processing and detection, on the same chip. Semiconductor photonic integrated circuits (PICs) operating at the single-photon level offer this perspective, but single-photon detection in waveguides is still challenging. Indeed, integrated quantum photonics has so far been limited to passive implementations, due to the difficulty of integrating the detectors on the same substrate with sources and waveguide circuits. SNSPDs are the unique detectors that showed an integration compatibility with standard semiconductor PICs, by the way a full integration of all the key component (sources, reconfigurable PICs and detectors) is still lacking and far to be achieved. In this presentation we present the state of the art of SNSPDs performances with a particular focus on the optimization of the System Detection Efficiency, discussing the role of the optical coupling, of the absorbance of the film and of the internal quantum efficiency of SNSPDs particularly focusing on the activities carried out in Rome at IFN-CNR.

Verification of Quantum Technology

The Qtech has an acute verification and validation problem: On one hand since classical computations cannot scale up to the computational power of quantum mechanics, verifying the correctness of a quantum-mediated computation is challenging, on the other hand the underlying quantum structure resists classical certification analysis. The central objective of this tutorial is to present recent advances in this field.

Title: A frequency-multiplexed source of heralded single photons

Steven Kolthammer, Imperial College London (UK)

Abstract:

The intrinsic limitations of a heralded single-photon source can, in theory, be overcome by multiplexing many independent sources. In practice, the challenge in doing so is to efficiently combine the outputs of identical sources conditioned on their heralding outcomes. A promising approach is to multiplex sources in the frequency domain [1-3], leveraging photon-pair spectral correlations readily generated by parametric fluorescence along with recent tools for measuring and manipulating the frequency of single photons. In this talk, I'll report our experimental demonstration of this concept and discuss its potential for improving upon current single-photon sources.

[1] T. Hiemstra et al., CLEO/Europe-EQEC, EB7.2 (2017); [2] C. Joshi et al., CLEO, FTh1C.2 (2016); C. Joshi et al., arXiv:1707.00048 (2017); [3] M. Grimau Puigibert et al., arXiv:1703.02068 (2017).

Generation of entangled quantum states with on-chip optical frequency combs

Christian Reimer,[1] Michael Kues,[1,2] Piotr Roztocki,[1] Benjamin Wetzel,[1,3] Yaron Bromberg,[4]
*Brent E. Little,[5] Sai T. Chu,[6] David J. Moss,[7] Lucia Caspani,[8] and **Roberto Morandotti**[1,9,10]*

[1]INRS-EMT, 1650 Boulevard Lionel-Boulet, Varennes, Québec J3X 1S2, Canada
[2]School of Engineering, University of Glasgow, Rankine Building, Oakfield Avenue, Glasgow G12 8LT, Scotland
[3]Department of Physics and Astronomy, University of Sussex, Falmer, Brighton BN1 9RH, England
[4]Racah Institute of Physics, The Hebrew University of Jerusalem, Jerusalem 91904, Israel
[5]Xi'an Institute of Optics and Precision Mechanics of CAS, Xi'an, China
[6]Department of Physics and Material Science, City University of Hong Kong, Tat Chee Avenue, Hong Kong, China
[7]Centre for Micro Photonics, Swinburne University of Technology, Hawthorn, VIC, 3122 Australia.
[8]Institute of Photonics, Department of Physics, University of Strathclyde, Glasgow G4 0NW, Scotland.
[9]Institute of Fundamental and Frontier Sciences, University of Electronic Science and Technology of China, Chengdu 610054, China
[10]National Research University of Information Technologies, Mechanics and Optics, St. Petersburg, Russia

Pure single photons, as well as entangled photon pairs form crucial building blocks for applications in optical quantum information processing, quantum communications, as well as imaging and sensing with resolutions exceeding the classical limit. The generation of optical quantum states has mainly been dominated by source based on spontaneous parametric down-conversion (SPDC) in diverse second-order nonlinear media, as these sources offer high nonlinearities and several different phase-matching conditions. In recent years, significant progress has been made to generate optical quantum states also by means of spontaneous four wave-mixing (SFWM) within third-order nonlinear media, which usually suffer from lower nonlinearities, but offer the possibility to achieve very compact and nano/micro engineered devices. Making use of standard semiconductor fabrication techniques, integrated photonics has established itself as a compelling platform for quantum applications. In particular, on-chip solutions have been studied and developed, including integrated quantum circuits, sources, and detectors [1]. Indeed, most integrated quantum devices have been based on path-encoded schemes, where phase shifters, interferometers and beam splitters are used in perfect analogy to their free-space counter parts. In contrast, several classical integrated devices make use of integrated microring resonators, which have been widely used to achieve classical frequency combs [2], mode-locked lasers [3], signal processing [4], and more. While microring resonators have also been used for quantum state generation, they have mainly been used to exploit field enhancement, while the frequency multimode nature of frequency combs has not yet been fully investigated for optical quantum state generation.

Here we investigate quantum state generation using integrated optical frequency comb sources, based on these resonant devices, particularly focusing on the impact of their frequency multi-mode nature. We demonstrate the generation of multiplexed heralded single photons [5], which exhibit perfect purity within the measurement uncertainty. Making use of polarization mode dispersion, we realized first direct generation of cross-polarized photon pairs on a photonic chip [6], and using a pulsed excitation of the micro cavity we realized the simultaneous generation of multiple two-photon entangled states [7], as well as the first on-chip generation of multi-photon entangled quantum states [7].

References

[1] D. Bonneau et al., "Silicon quantum photonics," in Silicon Photonics III, Springer, pp. 41-82
[2] T. J. Kippenberg et al., "Microresonator-based optical frequency combs," Science 332, 555 (2011)
[3] M. Kues et al., "Passively mode-locked laser with an ultra-narrow spectral width," Nature Photon. 11, 159-162 (2017)
[4] M. Ferrera et al., "On-chip CMOS –compatible all-optical integrator," Nature Commun. 1, 29 (2010)
[5] C. Reimer et al., "Integrated frequency comb source of heralded single photons," Opt. Express 22, 1023 (2014)
[6] C. Reimer et al., "Cross-polarized photon-pair generation and bi-chromatically pumped optical parametric oscillation on a chip," Nature Commun. 6, 8236 (2015)
[7] C. Reimer et al., "Generation of multiphoton entangled quantum states by means of integrated frequency combs," Science 351, 1176 (2016)

Femtosecond laser writing for integrated quantum photonics

Roberto Osellame[1,2]

[1]*Istituto di Fotonica e Nanotecnologie – Consiglio Nazionale delle Ricerche, Piazza L. da Vinci 32, 20133 Milano - Italy*
[2]*Dipartimento di Fisica – Politecnico di Milano, Piazza l. da Vinci 32, 20133 Milano - Italy*

The use of integrated photonics in quantum optics experiments has introduced dramatic improvements in terms of stability and scalability of the set-up. In particular, femtosecond laser direct writing (FLDW) of photonic circuits [1] enabled the manipulation of polarization encoded single photons and their use for advances quantum simulations in glass chips [2,4]. As a further significant advantage, FLDW enabled the realization of 3D photonic circuits, introducing an additional dimension with respect to standard planar circuits. The unique 3D capabilities of this technology enabled the implementation of unprecedented layout for the quantum processing of information [5,6].

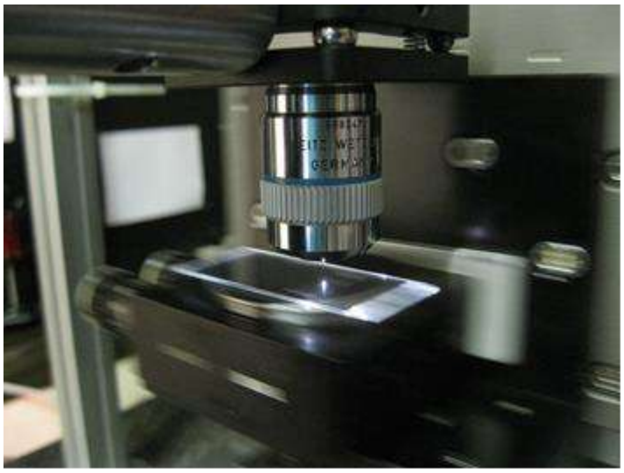

Figure 1: Picture of the femtosecond laser writing process. Ultrashort pulses are focused inside a transparent substrate. A nonlinear absorption process allows the creation of a positive index change confined to the focal volume. Translation of the sample with respect to the laser beam is exploited to directly draw complex and three-dimensional photonic circuits.

A few relevant examples will be discussed in this presentation with particular focus on the key enabling capabilities of this technology with applications to quantum computing, simulation and communication.

References

[1] *Femtosecond laser micromachining: photonic and microfluidic devices in transparent materials*, R. Osellame, G. Cerullo, and R. Ramponi, eds., Vol. 123 (Springer Science & Business Media, 2012).
[2] L. Sansoni, F. Sciarrino, G. Vallone, P. Mataloni, A. Crespi, R. Ramponi, and R. Osellame, "Two-Particle Bosonic-Fermionic Quantum Walk via Integrated Photonics," *Phys. Rev. Lett.* **108**, 010502 (2012).
[3] A. Crespi, R. Osellame, R. Ramponi, V. Giovannetti, R. Fazio, L. Sansoni, F. De Nicola, F. Sciarrino, and P. Mataloni, "Anderson localization of entangled photons in an integrated quantum walk," *Nature Photonics* **7**, 322–328 (2013).
[4] G. Corrielli, A. Crespi, R. Geremia, R. Ramponi, L. Sansoni, A. Santinelli, P. Mataloni, F. Sciarrino, and R. Osellame, "Rotated waveplates in integrated waveguide optics," *Nature Communications* **5**, 4249 (2014).
[5] A. Crespi, R. Osellame, R. Ramponi, M. Bentivegna, F. Flamini, N. Spagnolo, N. Viggianiello, L. Innocenti, P. Mataloni, and F. Sciarrino, "Suppression law of quantum states in a 3D photonic fast Fourier transform chip," *Nature Communications* **7**, 10469 (2016).
[6] F. Caruso, A. Crespi, A.G. Ciriolo, F. Sciarrino, and R. Osellame, "Fast escape of a quantum walker from an integrated photonic maze," *Nature Communications* **7**, 11682 (2016).

Silicon-based materials for optical quantum technologies

Francesco Martini[1], *Robert Cernansky*[1], *Ioannis Chatzopoulos*[1], *Alberto Politi*[1]

[1]*Department of Physics and Astronomy, University of Southampton, Southampton, SO17 1BJ, United Kingdom*

The advance of optical quantum technologies relies on the development of new materials to integrate various photonic components on the same device. The list of requirements – including low linear and non-linear losses, availability of fast switching techniques and possibility to integrate detectors, all in a scalable fabrication material – is extremely challenging. Here we focus on silicon-based materials, which provide superior scalability thanks to well-developed fabrication processes in the field of electronics.

Single photon sources are crucial components for any future quantum photonic technology [1]. In recent years, there has been a strong effort to develop technologies compatible with existing telecommunication infrastructures. Superconducting nanowire single photon detectors (SNSPD) are the preferred technology for detecting photons in the telecom wavelength range, due to their superior characteristics and lack of competitive semiconductor-based detectors. This, however, introduces limitations in the development of scalable technologies, since SNSPDs require operation at cryogenic temperatures. A further limitation is given by the impossibility of using the thermo-optical effect to control the phase of quantum states, as the thermo-optic coefficients decrease when lowering the temperature [2]. We solve this problem by developing a CMOS compatible single photon source at near-visible wavelengths, where single photon avalanche detectors are available in silicon with high efficiency. We demonstrate photon pair generation at 785nm using spontaneous four wave mixing (SFWM) in a silicon nitride device. The strong confinement and high quality factor of our ring resonators provides MHz generation rates with mW-level pump powers. We observe absence of two-photon absorption, thanks to the wide bandgap of SiN. Finally, the narrow bandwidth of the resonators can match the transition of atoms usually employed in quantum memories [3].

Silicon carbide offers unparalleled properties suitable especially for quantum and integrated non-linear optics. Its non-centrosymmetric crystal structure grants both third-order and second-order non-linear effects, with a significant $\chi^{(2)}$ susceptibility of 34 pm/V. The high refractive index of 2.6, indispensable for deep integration of photonic components and small modal volume in resonators, together with the wide electronic bandgap of 2.3 eV, could allow efficient non-linear optics processes without incurring in multiple photon absorption. Furthermore, the high electro-optic coefficient could be used for the fabrication of fast, low-loss electro-optic modulators. 3C-SiC thin layers can be grown directly on top of a silicon substrate thanks to a CVD process, providing an optimal starting point for fabrication of optical devices. The presence of point defects in the crystal [4] provides the possibility to engineer spin qubits with long coherence times. This talk will review the advances in the fabrication of SiC photonic components [5] for quantum technologies using photons and spins [6].

References

[1] J. L. O'Brien, A. Furusawa, and J. Vučković, Nat. Photonics **3**, 687 (2009).

[2] A. W. Elshaari, I. E. Zadeh, K. D. Jons, and V. Zwiller, IEEE Photonics J. **8**, 1 (2016).

[3] K. F. Reim, J. Nunn, V. O. Lorenz, B. J. Sussman, K. C. Lee, N. K. Langford, D. Jaksch, and I. A. Walmsley, Nat. Photonics **4**, 218 (2010).

[4] A. L. Falk, B. B. Buckley, G. Calusine, W. F. Koehl, V. V Dobrovitski, A. Politi, C. a Zorman, P. X.-L. Feng, and D. D. Awschalom, Nat. Commun. **4**, 1819 (2013).

[5] F. Martini and A. Politi, Opt. Express **25**, 10735 (2017).

[6] G. Calusine, A. Politi, and D. D. Awschalom, Phys. Rev. Appl. **6**, 14019 (2016).

A Universal Device for Quantum Communications

George Roberts, Marco Lucamarini, James Dynes, Bernd Frohlich, Zhiliang Yuan and Andrew Shields
Toshiba Research Europe Ltd, Cambridge, UK

Phase encoding is one of the most robust methods for transmitting qubits over long distances. Typically it involves sending weak coherent pulses from an attenuated laser diode through an unbalanced Mach Zehnder interferometer that uses a phase modulator in one arm to encode a phase difference between the two output pulses. The qubit state can be read-out by measuring the interference after a matched interferometer at the receiver.

Here we demonstrate an alternative method, employing direct phase modulation of the source. It involves using a second quasi-continuous laser diode, to manipulate the coherence and phase of the output pulsed laser diode. Applying small modulations to the drive voltage of the master laser allows different qubit states to be encoded as a phase difference between pulse pairs from the slave. We show this method allows record low half-wave voltages, $V_{\square\square}$= 0.35V, compatible with CMOS drive voltages. Furthermore driving the master below the lasing threshold breaks the coherence between successive pulse pairs, as required for the security of many quantum key distribution protocols.

We demonstrate that this technique can be used to realize a flexible, universal transmitter for quantum key distribution that can be electrically programmed for different protocols, including *BB84*, *Distributed Phase Shift* and *Coherent One Way*. We characterize the performance of each and discuss the prospects for realizing greatly simplified and improved devices for quantum communications.

Quantum enhancement of accuracy and precision in optical interferometry for optical property measurements

***F. Kaiser*[1], *P. Vergyris*[1], *D. Aktas*[1], *C. Babin*[1,2], *L. Labonté*[1], *and S. Tanzilli*[1]**

[1] *Université Côte dAzur, Institut de Physique de Nice (INPHYNI), CNRS UMR 7010, Parc Valrose, 06108 Nice Cedex 2, France*

[2] *Ecole Normale Supérieure de Lyon, 46 Allée dItalie, 69364 Lyon Cedex 07, France*

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White-light interferometry is one of today's most precise tools for determining optical material properties. Achievable precision and accuracy are typically limited by systematic errors due to a high number of interdependent data fitting parameters. Here, we introduce spectrally-resolved quantum white-light interferometry as a novel tool for optical property measurements, notably chromatic dispersion in optical fibres. By exploiting both spectral and photon-number correlations of energy-time entangled photon pairs, the number of fitting parameters is significantly reduced which eliminates systematic errors and leads to an absolute determination of the material parameter. By comparing the quantum method to state-of-the-art approaches, we show quantum supremacy through 2.4 times better measurement precision, despite involving 62 times less photons. The improved results are due to conceptual advantages enabled by quantum optics, which are likely to define new standards in experimental methods for optical materials characterization.

Title:

Photonic quantum computing exploiting the superposition of gates and other features

Abstract:

The advantages of the photons makes optical quantum system ideally suited for fundamental quantum physics experiments and a variety of applications in quantum information processing. Here I will review results for the realization of secure quantum cloud computing, where quantum information is securely communicated and computed. As for photons ideally suited quantum computational architectures I will present experiments that are based on the superposition of the order of quantum gates as well as multi-photon processing using integrated waveguide structures.

The last part of my talk will be dedicated to the measurement of experimental benchmark values for hyper-complex extensions of quantum mechanics that relay on quaternions (instead of complex numbers). As outlook I will briefly discuss the scale-up of photonic quantum computing by using high-efficient detectors and solid-state single-photon sources.

Experimental Quantum Hamiltonian Learning

[1]*Quantum Engineering Technology Labs, H. H. Wills Physics Laboratory and Department of Electrical and Electronic Engineering, University of Bristol, BS8 1FD, UK.*
[2]*Quantum Architectures and Computation Group, Microsoft Research, Redmond, Washington 98052, USA.*
[3]*Department of Applied Physics, Eindhoven University of Technology, P.O. Box 513, NL-5600MB Eindhoven, The Netherlands*

Efficiently characterising quantum systems, verifying operations of quantum devices and validating underpinning physical models, are central challenges for the development of quantum technologies and for our continued understanding of foundational physics. Machine-learning enhanced by quantum simulators has been proposed as a route to improve the computational cost of performing these studies. Here we interface two different quantum systems through a classical channel — a silicon-photonics quantum simulator and an electron spin in a diamond nitrogen-vacancy centre — and use the former to learn the latter's Hamiltonian via Bayesian inference. We learn the salient Hamiltonian parameter with an uncertainty of approximately 10^{-5}. Furthermore, an observed saturation in the learning algorithm suggests deficiencies in the underlying Hamiltonian model, which we exploit to further improve the model itself. We go on to implement an interactive version of the protocol and experimentally show its ability to characterise the operation of the quantum photonic device. This work demonstrates powerful new quantum-enhanced techniques for investigating foundational physical models and characterising quantum technologies.

Contributed talks

Scaling up Entanglement in Integrated Silicon Quantum Photonics

Jeremy C. Adcock, Caterina Vigliar, Raffaele Santagati, Joshua W. Silverstone, Mark G. Thompson

Quantum Engineering Technology Labs, H. H. Wills Physics Laboratory and Department of Electrical & Electronic Engineering, University of Bristol, UK

Graph states are a ubiquitous in quantum information theory and quantum information protocols [3]. Here, we use a silicon photonic chip to generate all six fully entangled four qubit graph states with four-photons.

We use a pulsed laser to to coherently pump four SFWM spiral waveguide sources, which, after spectral demultiplexing, produce two Bell pairs in the path-qubit basis [2]. We then send the signal photons from each pair to an on-chip, reconfigurable entangling gate, which, combined this with local unitaries on each qubit, allows us to produce all six graph states of four qubits [3] (see Figure 1d). The photons are then detected off chip.

Our two Bell sources have fidelities $85.1 \pm 0.9\%$ and $91.0 \pm 0.7\%$ respectively, both of which beat the previous record for fully integrated sources and manipulation [1]. Furthermore, by varying phase shifters on two spatially separated qubits in turn, two-photon reverse Hong-Ou-Mandel (HOM) fringes with visibility $97.7 \pm 0.5\%$ and $99.4 \pm 0.4\%$ are readily produced (shown in Figure 1b). Also, a preliminary four-photon triggered HOM fringe of visibility $68.4 \pm 8\%$ has been demonstrated (Figure 1e).

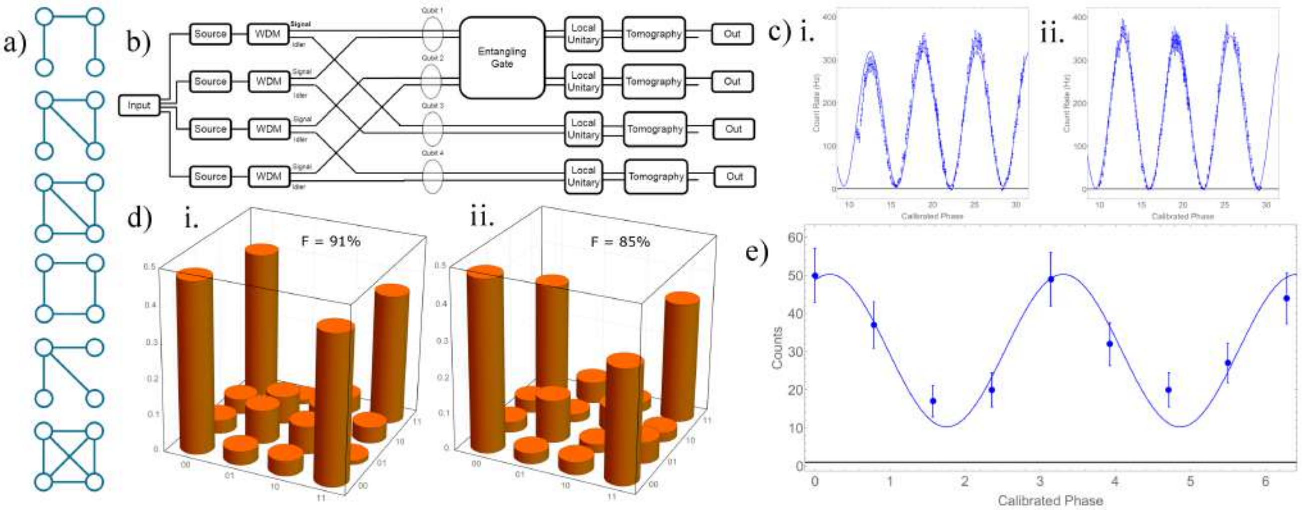


Figure 1: a) A schematic of the chip used to generate the four-photon graph states. b) A bright light fringe using one of the interferometers on the device. c) Reverse Hong-Ou-Mandel fringe produced on chip from source i. one (visibility $97.7 \pm 0.5\%$) and ii. two (visibility $99.4 \pm 0.4\%$). d) Complete tomographic measurements of the two photon states produced on chip with the entangling gate switched off, showing fidelities of i) $91.0 \pm 0.7\%$ and ii) $85.0 \pm 0.9\%$. e) Preliminary triggered HOM fringe of visibility $68.4 \pm 8\%$.

This device is universal in measurement-based protocols on these states, and as such makes an ideal test-bed for protocols such as such as secret sharing and quantum computation. The chip demonstrates a milestone for quantum photonic chip scale and functionality in silicon, and paves the way for exciting multi-photon and measurement-based experiments in the future.

References

[1] J. Silverstone, et al. “Qubit entanglement between ring-resonator photon-pair sources on a silicon chip” Nature communications **6** (2015).

[2] J. Silverstone, et al. ”silicon quantum photonics.” IEEE Journal of Selected Topics in Quantum Electronics **22**.6 (2016): 390-402. APA

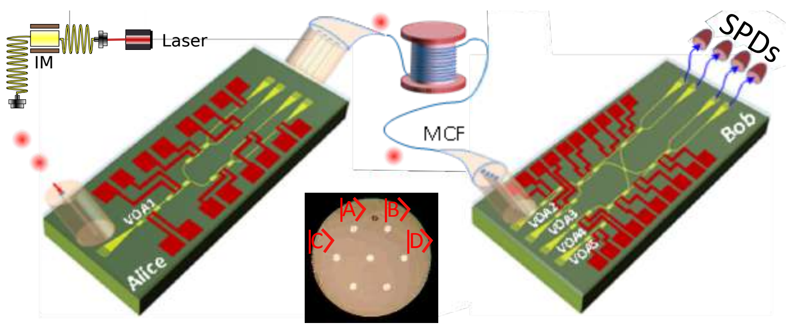
[3] Hein, Marc, Jens Eisert, and Hans J. Briegel. “Multiparty entanglement in graph states.” Physical Review A **69**.6 (2004): 062311.

Quantum key distribution using space division multiplexing.

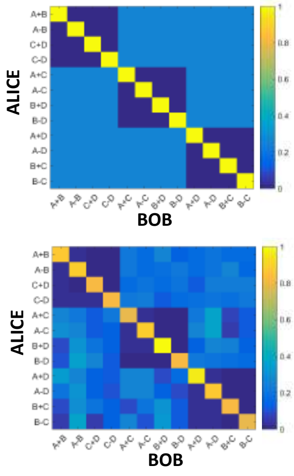
Yunhong Ding†*, Davide Bacco*, Kjeld Dalgaard, Karsten Rottwitt, and Leif Katsuo Oxenløwe*

Department of Photonics Engineering, Technical University of Denmark, 2800 Kgs. Lyngby, Denmark.
† *yudin@fotonik.dtu.dk, * dabac@fotonik.dtu.dk*

Quantum key distribution (QKD), a technique based on quantum physics laws, provides unconditional secure quantum keys shared between two or more clients (Alice and Bob)[1]. Most of QKD systems are implemented in a point-to-point link using bulky and expensive devices. Consequently, a large scale deployment of this technology has not been already achieved. A solution may be represented by integrated photonic circuits, which provide excellent performances (compacts, good optical phase stability, access to new degrees of freedom), and are particularly suitable for the manipulation of quantum states. Recent experiments have already demonstrated conventional binary QKD systems, using polarization and phase reference degrees of freedom [2,3]. Moreover, by using integrated solution new high-dimensional (HD) quantum states can be generated and propagated. HD quantum states are suitable for longer transmission distance and higher secret key rate transmission, being more robust to noise level and allowing an higher channel capacity [4]. In this paper, we show the first silicon chip-to-chip HD decoy-state quantum key distribution protocol based on spatial degrees of freedom (the cores of a multi-core fiber -MCF-). By tuning cascaded Mach-Zehnder interferometers (MZIs), it is possible to prepare HD quantum states in different mutually unbiased basis (MUBs) (Fig. 1 (b)). A train of weak coherent pulses are injected into the Alice chip, where multiple variable optical attenuators (VOAs) are used to decrease the number of photons per pulse ($\mu < 1$) [5]. Furthermore, through a combination of MZIs and VOAs, a decoy state-technique is implemented in order to avoid particular eavesdropping intrusion, like photon-number-splitting (PNS) attack. During the key generation process, Alice, by using an FPGA board (Fig. 1(a)), randomly chooses one of the bases and one of the four states to transmit to Bob. The ququart are matched to four cores of a multi-core fiber, through a highly efficient MCF grating coupler. After the transmission link, the quantum states are coupled into Bob's chip (Fig. 1(a)) through the MCF coupler, and randomly measured in one of the bases. In the subsequent distillation process, counts measured in the wrong bases are discarded. Acquired experimental data show stable and good results for more than 11 minutes of measurement with a quantum bit error rate below the threshold of individual and coherent attacks.



(a) Experimental setup



(b) MUBs

Figure 1: The setup used in the HD-QKD proof of concept experiment in (a). In (b) are reported MUBs tomographies (theoretical and experimental). By using the (classical) definition of fidelity ($F(x,y) = \sum_i \sqrt{p_i q_i}$, we obtain 0.977 ± 0.01

References

[1] C. H. Bennett, G. Brassard, "Quantum Cryptography: public key distribution and coin tossing," in Proceeding of IEEE International Conference on Computer, Systems & Signal Processing 175 – 179 (1984).

[2] P. Sibson, et al., "Chip-based Quantum Key Distribution," *Nat. Commun.* **8**:13984 (2017)

[3] C. Ma, et al., "Silicon photonic transmitter for polarization-encoded quantum key distribution," *Optica* **3** (2016)

[4] N. J. Cerf , et al. Security of Quantum Key Distribution Using d-level system. *Phys. Rev. Lett.* **88** (2002)

[5] Y. Ding, et al., "High-Dimensional Quantum Key Distribution based on Multicore Fiber using Silicon Photonic Integrated Circuits," arXiv:1610.01812 (2016)

Electro-mechanical control of an on-chip beam splitter with an embedded single photon source

Z.K. Bishop, A.P. Foster, B. Royall, C. Bentham, M.S. Skolnick, and L.R. Wilson

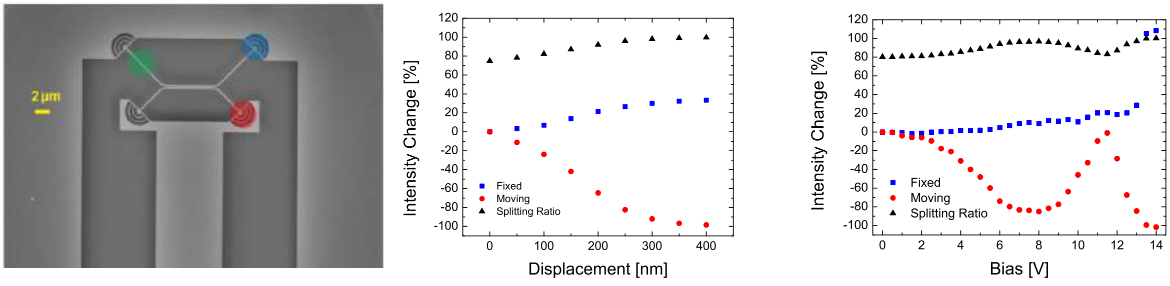
Department of Physics and Astronomy, University of Sheffield, S3 7RH, United Kingdom

The tuning of photonic elements is an important step in realizing on-chip quantum optical circuits. Here, we demonstrate tuning of an on-chip beam splitter by electro-mechanical control of a directional coupler (DC). Single photons evanescently couple from one suspended nanobeam waveguide to the other with a different probability depending on the controllable vertical separation between the two.

The device (shown in Fig. 1a) is fabricated from a *p-i-p-i-n* diode. The DC and the cantilever are defined within the 160 nm thick *p-i-p* GaAs membrane containing InGaAs self-assembled quantum dots (QDs) within the intrinsic region, and are isolated from the *n*-GaAs substrate by a 2 μm thick intrinsic sacrificial AlGaAs layer. Each arm of the DC is terminated with a Bragg outcoupler (OC) to enable efficient collection of the transmitted photons. Electrical contacts are made to the top *p* and the bottom *n* layers so that charge can build up between the two under bias. Due to the electrostatic force the cantilever then displaces towards the substrate and thus changes the vertical separation between the waveguides. This in turn varies the splitting ratio of the DC. The displacement of the cantilever is expected to increase quadratically with bias until it is pulled-in onto the substrate after it has displaced by $1/3$ of the initial distance between the two (here 2 μm).

The device was operated under reverse bias and was studied using micro-photoluminescence spectroscopy with spatially resolved collection at a temperature of 4 K. A single QD emitting at 910 nm positioned in the fixed waveguide was excited using a single-mode laser, and its emission was recorded from both the fixed and the moving OCs past the coupling region of the DC (marked in green, blue and red respectively in Fig. 1a). The expected theoretical change in the splitting ratio (defined as the percentage of light transmitted through the fixed arm to that coupled over to the moving arm) at this wavelength as a function of vertical displacement between the waveguides is shown in Fig. 1b. Measured changes to the collected single-photon emission versus bias are presented in Fig. 1c. The measured splitting ratio of the DC varies from $80/20\%$ at 0 V to $100/0\%$ at the pull-in voltage of 13.5 V. This is in good agreement with theory, according to which the splitting ratio changes from $75/25\%$ when waveguides are at the same level to $100/0\%$ when displaced by 400 nm. The unexpected peak in the signal from the moving side at around 11.5 V is caused by interference effects due to the cantilever-substrate distance variation, as well as collection efficiency changes, during the measurement. The single-photon nature of the collected emission was verified with $g^{(2)}(\tau)$ measurement using the DC as the on-chip beam splitter.

This proof of concept provides a basis for the electro-mechanical control of on-chip photonic devices using simple and easy-to-fabricate structures for use in III-V semiconductor quantum optical circuits.



(a)

(b)

(c)

Figure 1: (a) SEM image of the device with the embedded QD's position marked in green, and fixed and moving OCs from which signal was collected marked in blue and red respectively, (b) FDTD simulation results of the splitting ratio versus vertical displacement for a DC made from 280 nm wide and 160 nm thick waveguides with a horizontal separation of 100 nm, (c) Experimental results of changes to the splitting ratio of the DC versus bias.

Multiphoton interference in time with a fiber-integrated interferometer

Joelle Boutari[1]*, Andreas Eckstein*[1]*, Steven W. Kolthammer*[1]*, Ian A. Walmsley*[1]

[1]*University of Oxford, Clarendon Laboratories, Parks Road, OX1 3PU, United Kingdom*

Multiphoton interference lies at the core of several quantum information processing tasks. For this purpose, complex on-chip interferometers have been developed to manipulate the spatial mode structure of single photons. We develop an alternative guided-wave approach using time-bin modes pulses that differ only by a temporal delay [1,2], and fiber optics, which provides a route to large-scale devices requiring few physical components.

In our work, heralded single photons are generated at standard telecommunications wavelengths by a spontaneous parametric wave-mixing. The photons randomly populate a sequence of several temporal modes which access a fiber network [3] through an optical switch. The optical network is composed of multiple cavities with path length differences matching the delay separating time bins. The cavities are connected by evanescent coupling. For two cavities, interference between any set of input modes is achieved after a number of round trips in the network equal to the number of input modes. The temporal modes are then released through an optical switch and measured by photon counting. We present progress towards multiphoton interference, verify its non-classical features, and discuss technical requirements and prospects for large-scale operation.

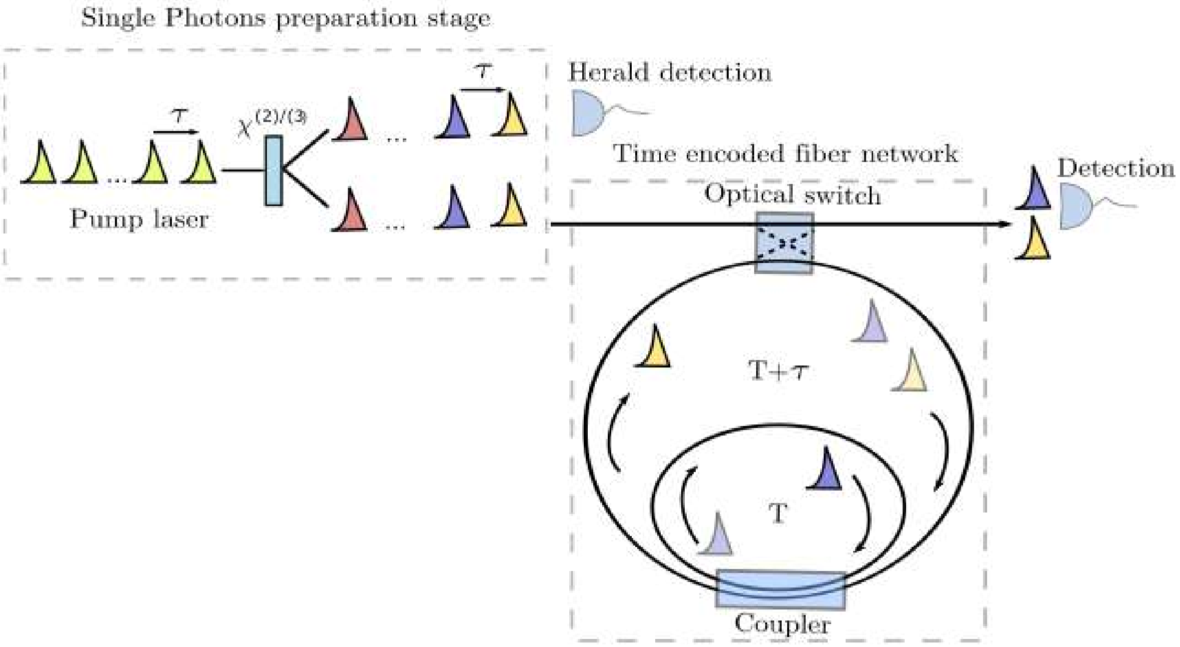


Figure 1: Schematic of the time-bin fiber interferometer interfaced with a heralded single photon source.

References

[1] P. C. Humphreys, B. J. Metcalf, J. B. Spring et al,”Linear Optical Quantum Computing in a Single Spatial Mode”, Phys. Rev. Lett. **111**, 150501 (2013).

[2] A. Regensburger, C. Bersch, B. Hinrichs et al, “Photon propagation in a discrete fiber network: an interplay of coherence and losses”, Phys. Rev. Lett. **107,** 233902 (2011).

[3] J. Boutari, A. Feizpour, S. Barz, et al, “Large scale quantum walks by means of optical fiber cavities” J. Opt **18**, 094007 (2016).

Boson sampling with Gaussian measurements

Levon Chakhmakhchyan

Centre for Quantum Information and Communication, Ecole polytechnique de Bruxelles, CP 165, Université libre de Bruxelles, 1050 Brussels, Belgium

We develop an alternative boson sampling model, which operates on single-photon input states followed by linear interferometry and Gaussian measurements [1]. The hardness proof for simulating such continuous-outcome measurements is established in two main steps, making use of the symmetry of quantum evolution under time reversal. Namely, we first construct a time-symmetric version of scattershot boson sampling, in which, as opposed to the original proposal [2], both halves of a collection of two-mode squeezed vacuum states undergo a linear-optical transformation. This time-symmetric scattershot model yields, as a corollary, an instance of boson sampling from Gaussian states where photon counting is hard to simulate. Then, a time-reversed setup is used to develop a boson sampling model in which the simulation of Gaussian measurements – namely the outcome of unbalanced heterodyne detection – is proven to be computationally hard. Our work thus explores minimal extensions of Gaussian computational models [3] that are able to provide a quantum advantage: previous approaches made use of either non-Gaussian evolution, or Gaussian input state and evolution but non-Gaussian measurements [2, 4-6]. In contrast, our model operates on non-Gaussian input, (passive, i.e. linear-optical) Gaussian evolution and Gaussian measurements, thus completing the set of models with minimal non-Gaussian components that give rise to quantum superiority [1]. Furthermore, these results illustrate how time symmetry may serve as a tool for analyzing the computational complexity of novel physically-motivated computational problems.

References

[1] L. Chakhmakhchyan, N. Cerf, “Boson sampling with Gaussian measurements”, Preprint at arXiv:1705.05299 (2017).

[2] A. P. Lund, A. Laing, S. Rahimi-Keshari, T. Rudolph, J. L. OBrien, T. C. Ralph, “Boson Sampling from a Gaussian State”, Phys. Rev. Lett. **113**, 100502 (2014).

[3] C. S. D. Bartlett, B. C. Sanders, S. L. Braunstein, K. Nemoto, “Efficient Classical Simulation of Continuous Variable Quantum Information Processes”, Phys. Rev. Lett. **88**, 097904 (2002).

[4] S. Rahimi-Keshari, A. P. Lund, T. C. Ralph, “What Can Quantum Optics Say about Computational Complexity Theory?”, Phys. Rev. Lett. **114**, 060501 (2015).

[5] T. Douce, D. Markham, E. Kashefi, E. Diamanti, T. Coudreau, P. Milman, P. van Loock, G. Ferrini, “Continuous-Variable Instantaneous Quantum Computing is Hard to Sample”, Phys. Rev. Lett. **118**, 070503 (2017).

[6] C. S. Hamilton, R. Kruse, L. Sansoni, S. Barkhofen, C. Silberhorn, I. Jex, “Gaussian Boson Sampling”, Preprint at arXiv:1612.01199 (2016).

On chip analysis of path-polarization hyperentangled cluster photon states

M. A. Ciampini[1], A. Orieux[1,2], S. Paesani[1,3] , C. Vigliar[1] , V. Cimini[1] , G. Corrielli[4,5] , A. Crespi[4,5] , R. Ramponi[4,5], R. Osellame[4,5], M. Paternostro[6], M. Barbieri[7], P. Mataloni[1]*

[1] Dipartimento di Fisica, Sapienza Università di Roma, P.le Aldo Moro 5, 00185, Rome, Italy;
[2] Telecom ParisTech, CNRS-LTCI, 46 rue Barrault, F-75634 Paris CEDEX 13, France;
[3] Centre for Quantum Photonics H H Wills Physics Laboratory and Department of Electrical and Electronic Engineering, University of Bristol, Merchant Ventures Building, Woodland Road, Bristol BS8 1UB, UK;
[4] Istituto di Fotonica e Nanotecnologie - Consiglio Nazionale delle Ricerche (IFN-CNR), I-20133 Milano, Italy;
[5] Dipartimento di Fisica - Politecnico di Milano, I-20133 Milano, Italy;
[6] Centre for Theoretical Atomic, Molecular and Optical Physics,
School of Mathematics and Physics, Queen's University Belfast, Belfast BT7 1NN, United Kingdom;
[7] Dipartimento di Scienze, Università degli Studi Roma Tre, Via della Vasca Navale 84, 00146, Rome, Italy;

Encoding many qubits in different degrees of freedom (DOFs) of single photons is one of the routes towards enlarging the Hilbert space spanned by a photonic quantum state. Hyperentangled photon states (i.e. states showing entanglement in multiple DOFs) have demonstrated significant implications for both fundamental physics tests and quantum communication and computation. Increasing the number of qubits of photonic experiments requires miniaturization and integration of the basic elements and functions to guarantee the setup stability. This motivates the development of technologies allowing the control of different photonic DOFs on a chip. Femtosecond laser writing on a glass makes possible to use both path and polarization of photon states enabling precise control of both degrees of freedom [1].

In this work, we demonstrate the contextual use of path and polarization qubits [2] propagating within a laser written integrated quantum circuit and use them to engineer a four qubit hyperentangled cluster state [3]. We also characterize the cluster state by identifying the strength of the qubits correlation by means of multipartite non-locality tests. We present a recipe that can be applied to any cluster state subset and only requires the knowledge of its adjacency matrix. We apply our scheme to a four-qubit linear cluster state, such that shown in Figure 1. Our results show good agreement with what we expected from the experimental realization of the state and pave the way toward the diagnostic of larger quantum networks. Furthermore, we tested the quality of our cluster state by performing Grover's search algorithm following the one-way quantum computation model. Our results show a probability of tagging the correct item of >95% [3].

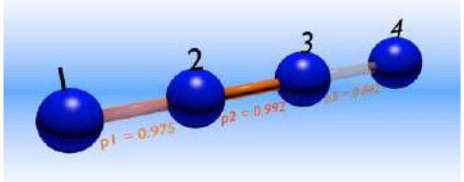


Figure 1: Four qubit linear cluster state. The values p1,p2,p3 represent the strength of the links between adiacent qubits. p=0 means no correlation, p=1 means perfect correlation.

References

[1] Della Valle, G., Osellame, R., Laporta, P., "Micromachining of photonic devices by femtosecond laser pulses," Journal of Optics A: Pure and Applied Optics 11.1, 013001, (2009).

[2] Barbieri, M., Cinelli C., Mataloni, P., De Martini F., "Polarization-momentum hyperentangled states: Realization and characterization," Physical Review A **72**, 052110 (2005).

[3] Ciampini, M. A., Orieux, A., Paesani, S., Sciarrino, F., Corrielli, G., Crespi, A., Ramponi, R., Osellame, R., and Mataloni, P., "Path-polarization hyperentangled and cluster states of photons on a chip," Light: Science & Applications **5**, e16064, (2016).

All-optical generation of tensor-network states

I. Dhand*[1]*, M. Engelkemeier*[2]*, R. Kruse*[2]*, L. Sansoni*[2]*, S. Barkhofen*[2]*, C. Silberhorn*[2] *and
***M. B. Plenio*[1]**

[1]*Institut für Theoretische Physik, Albert-Einstein-Allee 11, Universität Ulm, 89069 Ulm, Germany.*
[2]*Department of Physics and CeOPP, University of Paderborn, Warburger Strasse 100, D-33098 Paderborn, Germany.*

We propose an all-optical setup to generate entangled multi-qubit states encoded in temporal modes of light. The setup employs a nonlinear waveguide in a fiber loop to generate one- and higher-dimensional tensor-network states of light. We illustrate the generation of two different classes of entangled tensor-network states, namely the W and the GHZ states, which are important resources for quantum communication and computation. Furthermore, we report on a variational algorithm to simulate the ground-state physics of many-body systems, and we show the efficacy of existing fiber-loop devices to simulate the spin-$1/2$ Heisenberg model. Finally, the setup is demonstrated to be robust to realistic losses, mode mismatch and dark counts.

Integration of single-photon sources and detectors on GaAs platform

G.E.Digeronimo[1], *M.Petruzzella*[1], *S.Birindelli*[1], *R.Gaudio*[1], *S.Fattah Poor*[1], *F.W.M. von Otten*[1] *and A.Fiore*[1]

[1]*Eindhoven University of Technology,*
P.O. Box 513, 5600MB Eindhoven, The Netherlands

Quantum photonic integrated circuits (QPICs) on a GaAs platform allow the generation, manipulation, routing, and detection of non-classical states of light, which could pave the way for quantum information processing based on photons.

Here we present the prototype of a multi-functional QPIC together with our achievements in terms integration of each component of the circuit [1]. Photons are generated by excited InAs quantum dots (QDs) and routed through ridge waveguides towards photonic crystal cavities acting as filters. The filters, featuring a transmission of 20% and a free spectral range ≥66 nm, are able to select a single excitonic line out of the complex emission spectra of the QDs. The QD emission can be detected by the on-chip superconducting single photon detectors (SSPDs).

SSPDs made of niobium nitride (NbN) nanowires are patterned on top of suspended nanobeams (SNBs), instead of a more conventional ridge waveguide, and show a device quantum efficiency up to 28% establishing a new record on the GaAs platform. Moreover, two electrically independent SSPDs on top of the same SNB form a very compact autocorrelator system for on-chip $g^{(2)}(\tau)$ measurements. This, together with a jitter (127ps) much shorter than the QD lifetime (0.94ns), shows that the proposed integrated circuit is suitable for the on-chip measurement of single-photon emission.

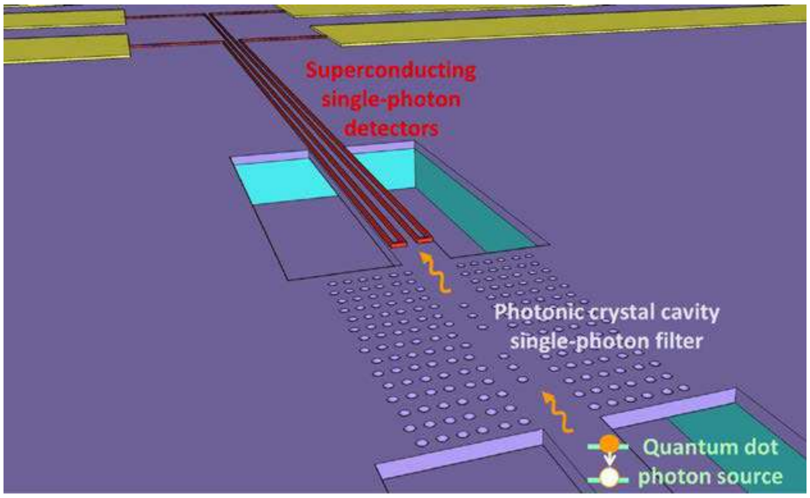


Figure 1: Sketch of the proposed QPIC

References

[1] G.E. Digeronimo, M. Petruzzella, S. Birindelli, R. Gaudio, S. Fattah Poor, F.W.M. van Otten and A.Fiore, “Integration of single-photon sources and detectors on GaAs”, Photonics, 3, 55 (2016).

On-chip, tunable all-electrical single photon sources

***C. Dangel*[1,3,4]**, *J.P. Lee*[1,2], *E. Murray*[1,3], *A. J. Bennett*[1], *D. J. P. Ellis*[1], *I. Farrer*[3], *P. Spencer*[3], *D. A. Ritchie*[3], *and A. J. Shields*[1]

[1]*Toshiba Research Europe Limited, Cambridge Research Laboratory, 208 Science Park, Milton Road, Cambridge, CB4 0GZ, United Kingdom*

[2]*Engineering Department, Cambridge University, 9 J. J. Thomson Avenue, Cambridge, CB3 0 FA, United Kingdom*

[3]*Cavendish Laboratory, Cambridge University, J. J. Thomson Avenue, Cambridge, CB3 0HE, United Kingdom*

[4]*Physik Department, Technische Universität München, 85748 Garching, Germany*

Quantum technologies, such as linear optical quantum computing, need indistinguishable single photons. If generated by different self assembled semiconductor quantum dots, transitions need to be tuned to the same energy. For large scale integration, all-electrical excitation and tuning is advantageous, as many single photon sources can be integrated with high-density on-chip or within a photonic circuit using standard photo-lithographic techniques.

Our scheme employs two neighbouring quantum LEDs (see figure 1). One LED is driven electrically so that the InAs quantum well around the dots known as the wetting layer emits light that excites quantum dot transitions in Diode 2. The emission energy of the quantum dot transitions in Diode 2 can be electrically tuned via quantum confined Stark effect. We observe tuning of the transition over 5nm. Moreover, we show tuning of the fine structure splitting which may be useful in future devices that emit entangled photon pairs. We show antibunched dot emission with a second-order correlation function of $g^{(2)}(0) = 0.06$.

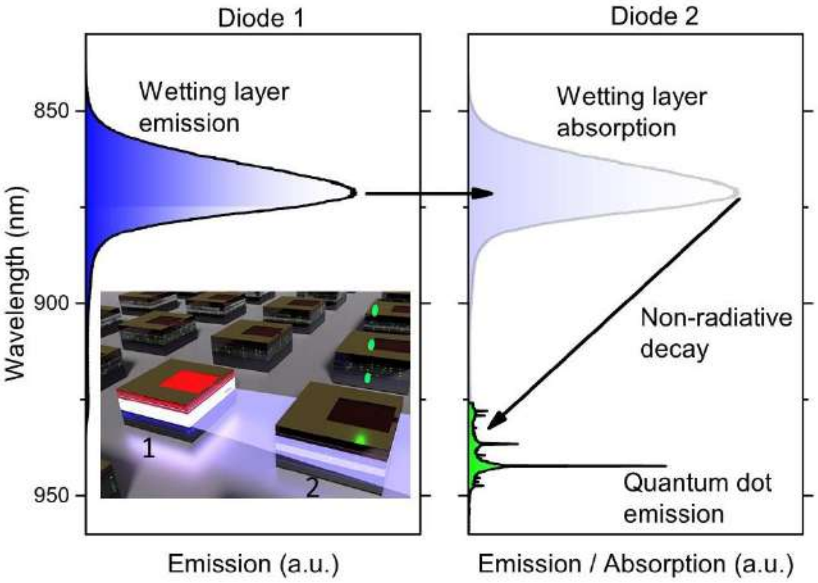


Figure 1: Principle of operation: (left) wetting layer emission of Diode 1 is absorbed by Diode 2 and (right) excites quantum dot transitions. Inset shows visualisation of the operation principle.

References

[1] J. P. Lee et al, “Electrically driven and electrically tunable quantum light sources”, Appl. Phys. Lett. **110**, 071102 (2017).

Hybrid Quantum Circuits

Ali W. Elshaari[1,||]*, Iman Esmaeil Zadeh*[2]*, Andreas Fognini*[2]*, Michael E. Reimer*[3]*, Dan Dalacu*[4]*, Philip J. Poole*[4]*,*
Val Zwiller[1]*, Klaus D. Jöns*[1]
[1]*Quantum Nano Photonics Group, Department of Applied Physics and Center for Quantum Materials, Royal Institute of Technology (KTH), Stockholm 106 91, Sweden*
[2]*Kavli Institute of Nanoscience Delft, Delft University of Technology, Delft 2628 CJ, The Netherlands*
[3]*Institute for Quantum Computing and Department of Electrical & Computer Engineering, University of Waterloo, Waterloo, ON N2L 3G1, Canada*
[4]*National Research Council of Canada, Ottawa, ON K1A 0R6, Canada*
[||] *e-mail address: elshaari@kth.se*

Quantum optical applications require a scalable approach combining bright on-demand quantum emitters and complex integrated photonic circuits. Currently, one of the most promising quantum sources are based on III/V semiconductor quantum dots (QD)[1]. However, demonstrating complex photonic circuitry based on III-V semiconductors faces tremendous technological challenges in circuit fabrication and deterministic integration of single photon sources[2]. On the other hand, silicon and silicon nitride based photonic circuits are CMOS compatible and well-developed for large scale and complex integration. We take the best of both worlds by developing a new hybrid on-chip nanofabrication approach[3, 4]. We demonstrate on-chip generation, spectral filtering, and routing of single-photons from selected single and multiple III/V semiconductor nanowire quantum emitters all deterministically integrated in a CMOS compatible silicon nitride (SiN) photonic circuit. Our new approach eliminates the need for off-chip components, opening up new possibilities for integrated quantum photonic systems with on-chip single- and entangled-photon sources.

A major problem with integrated quantum photonics is the suppression of excitation lasers and elimination of unwanted emission lines. This proved to be a considerably difficult task, which hindered the demonstration of on-chip single-photons without the use of external bulky filters. Here, we have overcome this hurdle and realize single-photons generation and filtering on-chip. The emission from a nanowire embedded in a SiN waveguide is filtered on-chip without the aid of off-chip components. Wavelength and polarization filtering is performed using an electrically-controlled integrated ring resonator filter[5]. Taking advantage of our new on-chip single-photon filtering and routing, we are able to perform wavelength division multiplexing/demultiplexing of on-demand quantum emitters. We realize a multi-frequency quantum channel comprising two independently selected and deterministically integrated nanowire-QDs2. Finally, we implement a scalable in-plane pumping scheme which decouples the excitation laser from the QD emission. The broadband nature of the pump suppression and the absence of resonant photonic structures makes it attractive for large scale integration and performing resonant excitation of QDs on-chip.

References

[1] N. Somaschi, V. Giesz , L. De Santis, J. C. Loredo, M. P. Almeida, G. Hornecker, et al., "Near-optimal single-photon sources in the solid state," Nat Photon, vol. 10, pp. 340-345, 05//print 2016.

[2] M. Davanco, J. Liu, L. Sapienza, C.-Z. Zhang, J. V. D. M. Cardoso, V. Verma, et al. (2016, November 1, 2016). A heterogeneous III-V/silicon integration platform for on-chip quantum photonic circuits with single quantum dot devices. ArXiv e-prints 1611. Available: http://adsabs.harvard.edu/abs/2016arXiv161107654D

[3] I. Esmaeilzadeh, A. W. Elshaari, K. D. Jöns, A. Fognini, D. Dalacu, P. J. Poole, et al., "Deterministic integration of single photon sources in silicon based photonic circuits," Nano Letters, 2016.

[4] A. W. Elshaari, I. Esmaeil Zadeh, A. Fognini, M. E. Reimer, D. Dalacu, P. J. Poole, et al. (2016, November 1, 2016). On-Chip Single-Photon Sifter. ArXiv e-prints 1611. Available: http://adsabs.harvard.edu/abs/2016arXiv161103245E

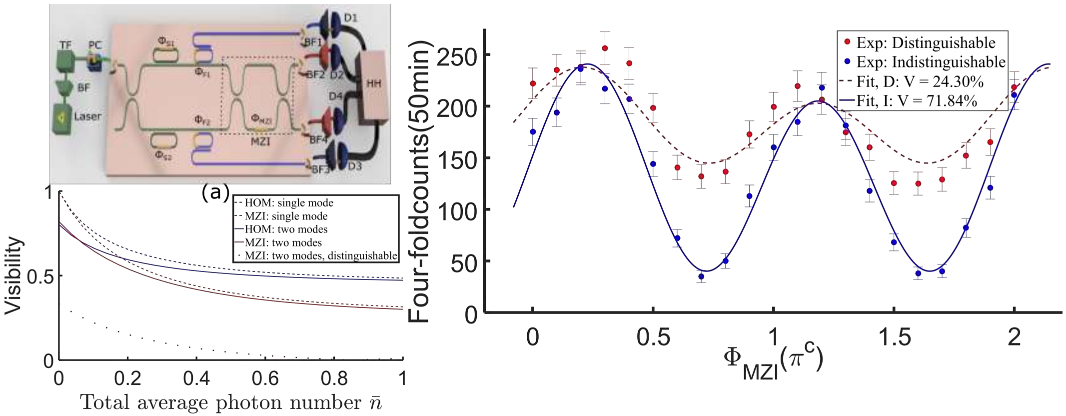
[5] A. W. Elshaari, I. E. Zadeh, J. K. D, Jons, and V. Zwiller, "Thermo-Optic Characterization of Silicon Nitride Resonators for Cryogenic Photonic Circuits," IEEE Photonics Journal, vol. 8, pp. 1-9, 2016.

On-chip quantum interference of micro-ring resonator heralded sources in Si-photonics

Imad Faruque, Damien Bonneau, Gary F. Sinclair, John G. Rarity, Mark G. Thompson

Quantum Engineering Technology Labs, H. H. Wills Physics Laboratory & Department of Electrical and Electronic Engineering, University of Bristol, Merchant Venturers Building, Woodland Road, Bristol BS8 1UB, United Kingdom.

Comprehensive works on photon pair generation have been done in silicon photonics [1], but very little has been done on interfering heralded photons from different sources—a crucial step towards implementing complex circuits—and has been limited to straight waveguides [2]. We report a 4-photon measurement in silicon-on-isolator, demonstrating on-chip Mach-Zehnder Interference (MZI) visibility of $71.84 \pm 3.11\%$ among heralded photons generated from two separate micro-resonators. This value of visibility matches with the estimated average photon number ~ 0.09 as in figure 1(b). The heralded single-photon purities from each source are estimated as $86.20 \pm 3.89\%$ and $78.69 \pm 2.44\%$ by examining the second order correlation $g_{xx}^{(2)}(0)$ [3]. This, in turn, provides an estimate of the maximum overlap (indistinguishability) between these sources as $82.36 \pm 2.25\%$ by using Cauchy-Schwarz inequality.



(b)

(c)

Figure 1: (a) The experimental setup contains a laser light passing through a broadband filter (BF), a tunable bandwidth filter (TF) and a polarisaion controller (PC) and coupled to the photonics circuit. It consists of a directional coupler (DC), micro-ring resonator sources (Φ_{S1}, Φ_{S2}), micro-ring filters (Φ_{F1}, Φ_{F2}) and MZI. Photon-pair generated by the sources are interfered and coupled off-chip and filtered (BF1 to BF4) and collected by single photon detectors (D1 to D4) connected to coincidence logic unit (HH). (b) Numerically estimated visibility of HOMI and MZI with respect to average photon number generated per pulse upto 10 multi-pair emission. (c) The solid blue line fits temporally indistinguishable raw four-fold data (blue events) and estimates visibility of $71.84 \pm 3.11\%$ with 95% confidence interval. The red events are temporally distinguishable.

Our current result is a step towards building more complicated quantum photonics devices. However further investigation on the purity and indistinguishability—especially understanding the impact of the resonator temporal dynamics—is necessary for designing better sources.

References

[1] J. W. Silverstone, D. Bonneau, J. L. OBrien and M. G. Thompson, "Silicon Quantum Photonics," in IEEE J. Sel. Topics Quantum Electron. **22** (2016).

[2] K. Harada, H. Takesue, H. Fukuda, T. Tsuchizawa, T. Watanabe, K. Yamada, Y. Tokura and S. Itabashi, "Indistinguishable photon pair generation using two independent silicon wire waveguides," New J. Physics **13(6)**, (2011).

[3] A. Christ, K. Laiho, A. Eckstein, K. Cassemiro and C. Silberhorn, "Probing multimode squeezing with correlation functions," New J. Physics **13**, (2011).

Telecom single photon sources for multi-qubit experiments

Chiara Greganti[1], *Peter Schiansky*[1], *Philip Walther*[,2]

[1]*Vienna Center for Quantum Science and Technology, Faculty of Physics, University of Vienna, 1090 Vienna, Austria.*
Institute for Quantum Optics and Quantum Information, Austrian Academy of Sciences, Boltzmanngasse 3, A-1090 Vienna, Austria.

Multi-photon states generation is currently of great interest for near-future quantum simulation and quantum computation experiments. Up-to-date spontaneous parametric down conversion is an eligible process to produce as many as 10 entangled photons [1]. Here we experimentally investigate the properties of two single-photon sources, based on PPKTP crystals in the telecom wavelength regime, and underline the main characteristics for quantum interference between independent photons (see Fig. 1).

A single-photon grating spectrometer is also described as important tool for the preparation of high quality single photons.

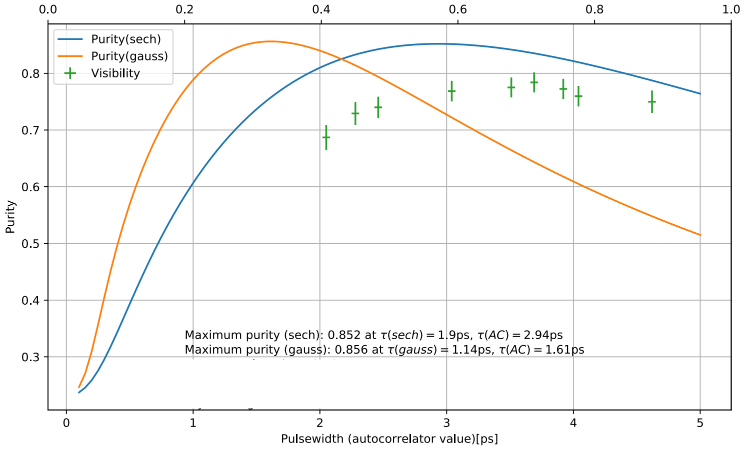


Figure 1: Simulation and experimental data of the purity of independent single photons: the simulation are extracted from the numerically calculted joint spectral amplitude whereas the experimental data correspond to visibilities of quantum interference.

References

[1] X.-L. Wang, et al. , “Experimental ten-photon entanglement,” Phys. Rev. Lett. 117, 210502 (2016).

Endurance of quantum coherence in Born-Markov open quantum systems

***A. Perez-Leija*[1,2], *D. Guzman-Silva*[3,5], *R. de J. Leon-Montiel*[4], *M. Gräfe*[3], *M. Heinrich*[3,5], *H. Moya-Cessa*[5], *K. Bursch*[1,2], *and A. Szameit*[3,5]**

[1]*Max-Born-Institut, Berlin, Germany*
[2]*Humboldt-Universität zu Berlin, Institut für Physik, AG Theoretische Optik Photonik, Berlin, Germany*
[3]*Institute of Applied Physics, Friedrich-Schiller-University Jena, Jena, Germany*
[4]*Instituto de Ciencias Nucleares, Universidad Nacional Autónoma de México, Cd.Mx, México*
[5]*Institut für Physik, Universität Rostock, Rostock, Germany*

Conventionally, quantum systems interacting with the environment are termed 'open quantum systems' (OQS), and as such they constitute the most common structures encountered in nature. Along these lines, the standard phenomenological approach for describing the evolution of OQS is the so-called Born-Markov master equation [1]. In its simplest configuration, OQS subject to Born-Markov premises can be investigated in quantum networks in which environmental effects are manifested as pure dephasing [2,3]. Mathematically, such networks are described by the stochastic equation

$$-\frac{d\psi_n}{dt} = \varepsilon_n(t)\psi_n + \sum_{m\neq n}^{N} \kappa_{m,n}\psi_m \quad .$$

Here, $\hbar = 1$, ψ_n represents the wave function at site n, and $\kappa_{m,n}$ are the hopping rates between the (m,n) sites. Moreover, $\varepsilon(t)$ denotes the fluctuating site energies having properties of Gauss-Markov processes satisfying the conditions $\langle \varepsilon_n(t) \rangle = 0$ and $\langle \varepsilon_n(t)\varepsilon_m(t') \rangle = \gamma_n \delta_{m,n} \delta(t-t')$ with $\langle \cdots \rangle$ denoting stochastic average and γ_n being the dephasing rates [3].

This model fundamentally describes the behavior of single-particle OQS, it does not show any divergence from wave mechanics [4]. Indeed, the richness and complexity of genuine quantum processes are only appreciable when a manifold of indistinguishable particles are jointly considered [5]. We studied theoretical and experimentally a Born-Markov OQS within the single- and two-excitation manifolds. In our experiments, OQS are implemented in waveguide networks inscribed in fused silica glass by means of the femtosecond laser writing technique [6]. In the context of photonic waveguides, the individual propagation constants, here denoted as $\beta_n(t)$ for the n-th site, play the role of site energies and the hopping rates result from the evanescent overlap between normal modes supported by adjacent sites. To produce dephasing-like effects in the waveguides we induce longitudinal random fluctuations in their refractive indices. This is readily accomplished by varying the inscription velocity of the waveguides. Correspondingly, to inspect the evolution of indistinguishable bosons we use two-photon light from a SPDC source. Results show that even when individual particles do not preserve any quantum coherence in the presence of noise, surprisingly two-particle states preserve, on average, quantum coherence despite the impact of dephasing.

References

[1] H.J Carmichael, "Statistical methods in quantum optics", (Springer, 1998)
[2] M.B Plenio and S.F. Huelga, "Dephasing-assited transport: quantum networks and biomelecules", New J. Phys. **10**, 113019 (2008).
[3] A. Eisfeld and J.S. Briggs, "Classical master equation for excitonic transport under the influence of an environment", Phys. Rev. E **85**, 046118 (2012).
[4] T. Yu and J.H. Eberly, "Sudden death of entanglement", Science **323**, 598 (2009)
[5] J.C.F. Matthews and M.G. Thompson, "Quantum optics: An entangled walk of photons", Nature **484**, 47 (2012)
[6] K. Itoh et al.,"Ultrafast processes for bulk modification of transparent materials", MRS Bull. **31**, 620 (2006)

Gaussian Boson Sampling

***Craig S. Hamilton*[1], *Regina Kruse*[2], *Linda Sansoni*[2] *Sonja Barkhofen*[2], *Christine Silberhorn*[2], *Igor Jex*[1]**

[1]*FNSPE, Czech Technical University, Prague, Czech Republic*
[2]*Integrated Quantum Optics, University of Paderborn, Paderborn, Germany*

Boson Sampling [1] has recently emerged as a tool to explore the power of quantum computation over classical computation and provide evidence against the extended Church-Turing thesis. The protocol involves sending single photon Fock states through a linear interferometer, where the output distribution of photons is difficult to predict. This is because the probability of a photon pattern at the output depends upon the permanent of a matrix, which is known to be a computationally difficult (#P hard) problem. However, as single photons are currently generated probabilistically it makes the scaling to the necessary high photon numbers experimentally challenging.

It is therefore interesting from an experimental, as well as a theoretical, perspective to investigate other photonic states that may be used in Boson sampling problems. Here, we present Gaussian Boson Sampling [2], a classically hard-to-solve problem that uses squeezed states instead of single photons. By using such states we circumvent the problem of generating single photons. We first derive a new formula for the probability to measure a specific photon patterns from a general Gaussian state, which is related to a matrix function called the *hafnian*. Based on this result, we design Gaussian Boson Sampling, a #P hard problem, using squeezed states. This approach leads to a more efficient photonic boson sampler with significant experimental advantages over existing protocols.

References

[1] S.Aaronson and A. Arkhipov, “The Computational Complexity of Linear Optics”, Theory of Computing, **9**, 143 (2013).

[2] C. S. Hamilton, R. Kruse, L. Sansoni, S. Barkhofen, C. Silberhorn and I. Jex “Gaussian Boson Sampling”, Preprint at arXiv:1612.01199 (2016).

Photon-number-resolving detector free of systematic errors for strongly nonclassical light characterization and single emitter counting

***J. Hloušek*[1], *I. Straka*[1], *L. Lachman*[1], *M. Dudka*[1], *M. Miková*[1], *M. Mičuda*[1], *R. Filip*[1], *M. Ježek*[1]**

[1]*Department of Optics, Palacký University, 17. listopadu 1192/12, 771 46 Olomouc, Czech Republic*

Single-photon detectors capable of measuring ultra-weak optical signals represent a crucial tool for quantum technology, optical communication, and biomedical imaging. The key requirement for exploring statistical properties of light is the ability to distinguish individual photons. As an ideal unlimited photon-number resolution is virtually impossible, the photon statistics has to be estimated from raw coincidence distribution of a practical photon-number-resolving detector (PNRD). Furthermore, interesting quantum features of the detected light can be assessed directly from the coincidence statistics on optical multiplexing networks [1-2].

We present a fully reconfigurable PNRD consisting of tunable free-space multiport network and single-photon avalanche diodes. The detector features precise balancing with no crosstalk between detection ports. Data processing is based on real-time recording of all types of coincidence events. To estimate the photon statistics of detected light, a novel expectation-maximization-entropy algorithm is devised using entropy regularization of the popular maximum-likelihood expectation-maximization technique [3-4]. Furthermore, we present an experimental method of recognizing quantum non-Gaussian (QNG) multiphoton states employing the reconfigurable PNRD. QNG is a native quantum property of Fock states, that exhibits higher resilience to losses than the negativity of Wigner function. It was recently proven to be an efficient tool for evaluation of single-photon sources and a sufficient test for discrete-variable quantum key distribution.

We demonstrate high-fidelity photon statistics measurement of various sources of light, including simulated emission from a cluster of 1-9 single-photon emitters. We prove QNG despite detection efficiency of 50%. Additional loss tolerance is evaluated in the form of QNG depth, defined as the maximum attenuation, for which the quantum state is still QNG. We discuss emitters counting based only on their collective emission [5-6].

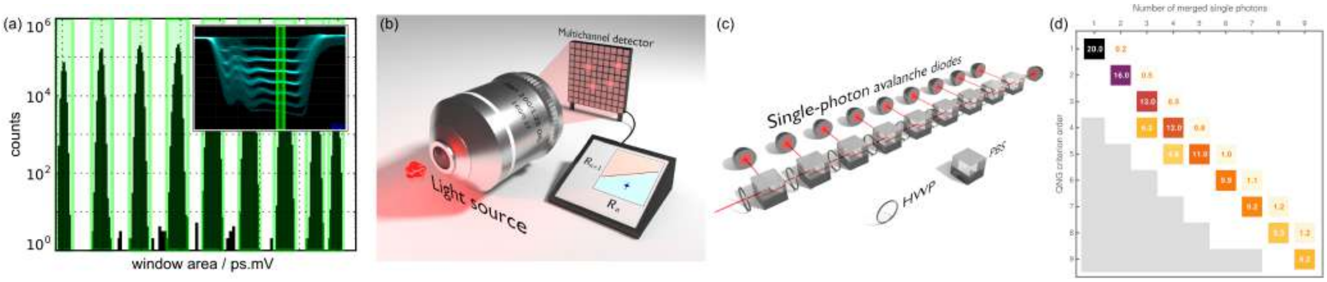


Figure 1: **(a)** Example of typical coincidence histogram of our PNRD with raw voltage output shown in the inset. The detector development is supported by Czech Science Foundation: GAČR 17-26143S. **(b)** Experimental QNG witness [1] – multiphoton light is collected and brought to a balanced multichannel detector, where the highest coincidences are compared to the QNG threshold. **(c)** The detector used consists of 10 single-photon avalanche diodes and a balanced fully-reconfigurable optical multiport network. **(d)** Table of observed QNG depths (in dB).

References

[1] I. Straka et al., Quantum non-Gaussian multiphoton light, Preprint at arXiv:1611.02504 (2016).

[2] J. Sperling et al., Detector-independent verification of quantum light, Preprint at arXiv:1701.07640 (2017).

[3] J. Řeháček et al., Multiple-photon resolving fiber-loop detector, Phys. Rev. A 67, 061801(R) (2003).

[4] F. Marsili et al., Physics and application of photon number resolving detectors based on superconducting parallel nanowires, New J. Physics 11, 045022 (2009).

[5] A. Kurz et al., Counting fluorescent dye molecules on DNA origami by means of photon statistics, Small 9, 4061 (2013).

[6] H. Ta et al., Mapping molecules in scanning far-field fluorescence nanoscopy, Nat. Commun. 6, 7977 (2015).

Active Demultiplexing of Single Photons from a Solid State Source

***Francesco Lenzini*[1], *Ben Haylock*[1], *Juan C. Loredo*[2], *Raphael A. Abraho*[2], *Nor A. Zakaria*[2], *Sachin Kasture*[1], *Isabelle Sagnes*[3], *Aristide Lemaitre*[3], *Hoang-Phuong Phan*[4], *Dzung Viet Dao*[4,5], *Pascale Senellart*[3,6], *Marcelo P. Almeida*[2], *Andrew G. White*[2], *Mirko Lobino*[1,4]**

[1] *Centre for Quantum Dynamics, Griffith University, Queensland, Australia*
[2] *Centre for Engineered Quantum Systems, Centre for Quantum Computer and Communication Technology, School of Maths and Physics, University of Queensland, Queensland, Australia*
[3] *CNRS-LPN Laboratoire de Photonique et de Nanostructures, Universite Paris-Saclay, Marcoussis, France*
[4] *Queensland Micro and Nanotechnology Centre, Griffith University, Queensland, Australia*
[5] *School of Engineering, Griffith University, Queensland, Australia*
[6] *Departement de Physique, Ecole Polytechnique, Universite Paris-Saclay, Palaiseau, France*

We demonstrate the active temporal-to-spatial demultiplexing of a stream of single photons using an integrated photonic switch with 80MHz repetition rate to create multi-photon sources with small resource overhead. This photonic switch is suitable for use with high brightness solid state GaAs/InGaAs quantum dots deterministically coupled to micro-pillar cavities, operating at 932 nm. These sources demonstrate high indistinguishability between photons emitted from the same device over large timescales [1, 2]. The combination of these sources with a fast photonic switch and suitable delay lines as shown in Figure 1(a) allows for the creation of a multi-photon source in a manner that the multi-fold rate scales polynomially with photon number.

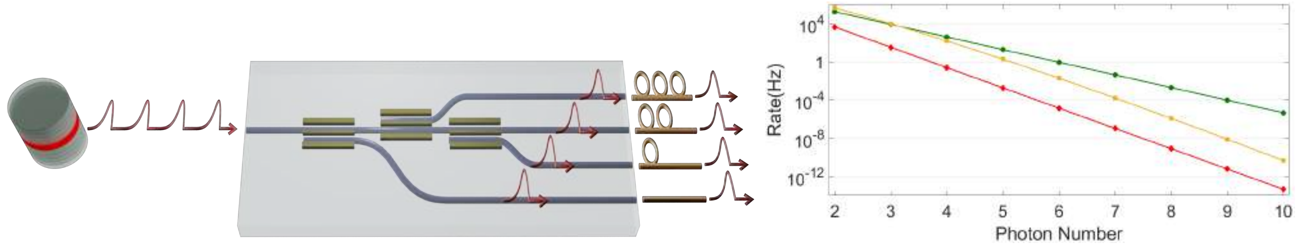


Figure 1: (a) A temporal stream of single photons emitted from a micro-pillar QD are injected into a photonic switch, and routed to the suitable length delay line to overlap all photons in time. (b) Multi-photon rate for state of the art platforms: red for spontaneous parametric down-conversion sources, yellow for passively multiplexed QD single emitters, and green for the performance of the demonstrated photonic switch.

A 1:4 photonic switch is fabricated on an X-cut lithium niobate substrate via the creation of annealed proton exchange waveguides [3]. These waveguides form a network of electro-optically reconfigurable directional couplers, controlled by electrodes which synchronously switch so the first photon is sent to output one, the second to output two, and so forth.

Figure 1b compares the measured performance of the demultiplexing device, with calculated multi-photon count rates when coupled to a state of the art micro-pillar quantum dot to other possible multi-photon sources. Active demultiplexing can enable a 6-photon rate 0.01 Hz, three orders of magnitude larger than what could be obtained with unmultiplexed SPDC sources [4], and scales equivalently to a multiplexed heralded SPDC source with single photon probability enhancement of $> 600\%$. With improvements in source brightness and photonic switch transmission this scheme provides a pathway to intermediate size multi-photon sources.

References

[1] J. C. Loredo, et al., Scalable performance in solid-state single-photon sources, Optica 3, 433 (2016).

[2] H. Wang, et al., Near-transform-limited single photons from an efficient solid-state quantum emitter, Phys. Rev. Lett. 116, 213601 (2016).

[3] P. G. Suchoski, T. K. Findakly, and F. J. Leonberger, Stable low-loss proton-exchanged $LiNbO_3$ waveguide devices with no electro-optic degradation, Optics Letters 13, 11 (1988)

[4] N. Somaschi, et al., Near optimal single photon sources in the solid state, Nat. Photon. 10, 340 (2016).

Photostable Molecules on Chip: Integrated Single Photon Sources for Quantum Technologies

P. Lombardi[1,4]***, A. P. Ovvyan***[2,3]***, S. Pazzagli***[2,4]***, G. Mazzamuto***[1,2]***, G. Kewes***[5]***, O. Neitzke***[5]***, N. Gruhler***[3]***, O. Benson***[5]***, W. H. P. Pernice***[3]***, F. S. Cataliotti***[2,4]***, and C. Toninelli***[1,2]

[1]*National Institute of Optics (CNR-INO), Florence, Italy*
[2]*European Laboratory for Nonlinear Spectroscopy (LENS), Via Carrara 1, 50019 Sesto F.no, Italy*
[3]*Institute of Physics, University of Muenster, Muenster, Germany*
[4]*Dipartimento di Fisica ed Astronomia, Universita degli Studi di Firenze, Sesto Fiorentino, Italy*
[5]*AG Nano-Optik, Institut fur Physik, Humboldt-Universitat zu Berlin, Berlin, Germany*

Efficient quantum light sources and non-linear optical elements at the few photon level are the basic ingredients for most applications in nano and quantum technologies. On the other hand, on-chip integration is necessary to envision a scalable platform for quantum information and communication.

In this work we demonstrate the potential of a novel hybrid technology which combines single organic molecules as quantum emitters and dielectric chips, consisting of ridge waveguides and grating far-field couplers [1]. Dibenzoterrylene molecules in anthracene crystals are particularly suitable quantum systems for this task, due to outstanding photophysical properties [2,3] in samples as thin as few tens of nanometers. Here the emitters are integrated by spin-coating onto the photonic chip. We demonstrate at room temperature the emission of single photons from DBT molecules into ridge waveguides with a branching ratio up to 40%, corresponding to an estimated in-guide brightness around $50MHz$ for cw pumping at saturation intensity. These results are competitive with state-of-the-art single photon emission into propagating guided modes from solid state systems [4,5], while offering a novel platform with unprecedented versatility. Single waveguided photons can be readily processed on-chip or extracted into a quasi-gaussian mode in free space with overall efficiency around 16%. We also discuss options to further improve the collection efficiency and applications to quantum optics [6] and to study manybody-induced quantum correlation effects [7].

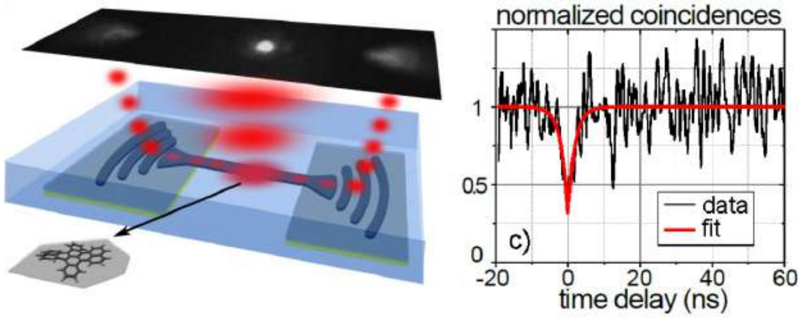


Figure 1: Cartoon and fluorescence image collected with an EMCCD camera showing signal from both the confocal excitation spot and the outcouplers; antibunching dip measured in correspondence of all output ports revels single-photon nature of the signal.

References

[1] P. Lombardi et al., Preprint at arXiv:1701.00459v1 (2017).
[2] C. Toninelli et al., Opt. Express **18**, 6577 (2010).
[3] J. B. Trebbia et al., Opt. Express **17**, 23986 (2009).
[4] R. S. Daveau et al., Optica **4.2**, 178 (2017).
[5] R. S. Davanco et al., Preprint at arXiv:1611.07654 (2016).
[6] J. Hwang and E. A. Hinds, New J. Phys. **13**, 085009 (2011).
[7] A. Goban et al., Phys. Rev. Lett. **115**, 063601 (2015).

Frequency-entangled qudits in AlGaAs waveguides

***G. Maltese*[1]*, A. Minneci*[1]*, C. Autebert*[1]*, A. Lemaitre*[2]*, F. Baboux*[1]*, M. Amanti*[1]*, T. Coudreau*[1]*, P. Milman* [1] *, S. Ducci*[1]**

[1]*Laboratoire Matriaux et Phnomnes Quantiques, Universitè Paris Diderot, Sorbonne Paris Citè, CNRS-UMR 7162, 75205 Paris Cedex 13, France*

[2]*Centre de Nanosciences et de Nanotechnologies, CNRS/Universitò Paris Sud, UMR 9001, 91460 Marcoussis, France*

The generation, manipulation and detection of non-classical states of light on a miniaturized chip is a major issue for future quantum information technologies. Among the different material platforms explored in these last years AlGaAs attracts a particular interest due to its compliance with electrical injection [1] and electro-optic effect. Here we demonstrate AlGaAs waveguides with high rate of biphoton generation ($2.37MHz$) and signal-to-noise ratio (SNR) up to $5x10^4$. This potentially brings us in the condition of achieving a 0.99 fidelity for the generation of entangled states. Our devices, based on a modal phase-matching scheme, include two Bragg mirrors providing both a photonic band gap confinement for a TE Bragg pump mode around $780nm$ and total internal reflection claddings for the twin photons TE and TM modes centered at $1560nm$. Furthermore, the dispersion properties of our devices, together with the modal reflectivity on the waveguide facets, allow engineering the joint spectrum of the emitted biphoton state to get comb-like spectral correlations, corresponding to frequency-entangled qudits. Indeed the facets create a Fabry-Perot cavity for both output modes, inducing regular time-delays between photons directly transmitted through the waveguide facet and photons having experienced one or more round trips [2]. Taking this into account, the expression of the joint spectral density $|\Phi(\omega_s,\omega_i)|^2$ of the emitted biphoton state is: $|\Phi(\omega_s,\omega_i)|^2 = N^{-1}|\alpha_p(\omega_s,\omega_i)|^2|A(\omega_s,\omega_i)|^2 f_{TE}(\omega_s,\omega_i) f_{TM}(\omega_s,\omega_i)$. Here $\alpha_p(\omega_s+\omega_i)$ is the spectral amplitude of the pump beam, $A(\omega_s,\omega_i)$ is the three-wave-mixing phasematching function, f_{TE} and f_{TM} describe the effect of the reflection on the waveguide facets for the generated TE and TM polarized photons, respectively and N is a normalization constant. Figure 1 reports the measurement of a portion of the JSD for the biphoton state emitted by our device under CW pumping, as well as a Hong-Ou-Mandel measurement. The amplitude of the biphoton wavefunction is distributed along $\omega_s+\omega_i=\omega_p$ and oscillates with peaks at $\omega_s-\omega_i$. This suggests that the generated state is an entangled qudit structure $\Phi=\sum_i^n \alpha_i|\omega_i,\omega_{n-i}>$ as pointed out also in [3]. Contrary to recent experiments that required spectral filters and/or modulators, or external cavities to engineer the target state, our devices represent a miniaturized source, working at room temperature and telecom wavelength.

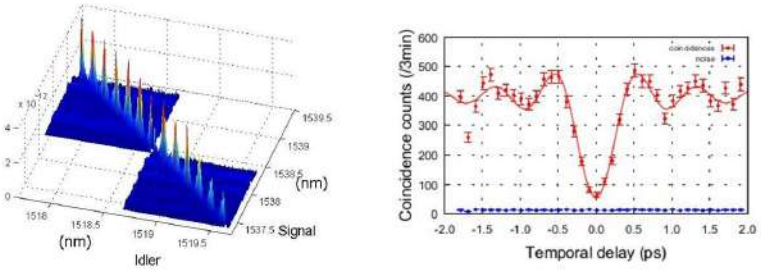


Figure 1: Left:Measurement of the joint spectral density. Right: HOM dip measured by pumping the sample with a CW Ti:Sa laser; the generated photons are filtered on a 10.8 nm bandwidth.

References

[1] F. Boitier et al., Electrically Injected Photon-pair Source at Room Temperature, Phys. Rev. Lett 112, 183901 (2014).

[2] A. Eckstein et al., High-resolution spectral characterization of two photon states via classical measurements, Laser Photon. Rev., 8, 76 (2014).

[3] R-B Jin et. al., Simple method of generating and distributing frequency-entangled qudits, Quantum Sci. Technol. 1, 015004 (2016).

An integrated Pulse-Position Resolving Detector based on spatially multiplexed superconducting nanowires

F. Mattioli, A. Gaggero, F. Chiarello, M. Graziosi, G. Torrioli and R. Leoni*
Istituto di Fotonica e Nanotecnologie
IFN – CNR,
Rome, Italy
**francesco.mattioli@ifn.cnr.it*

The growing complexity of the integrated experiments for quantum photonics applications is requiring architectures that are more complicated and the on-chip manipulation of an increasing number of optical modes. This implies also the integration of an increasing number of detectors, requiring sophisticated electronic for their simultaneous readout. SNSPDs are the best candidates as single photon detectors for their leading performances in terms of quantum efficiency, time jitter and count rate, and because of the capability of being integrated with optical circuits on different platforms. Recently, it has been shown a scalable electrical readout scheme for single-photon pulse-position SNSPD arrays [1]. Our approach consists of a modified spatially-multiplexed PNRD (photon number resolving detector) [2] made of a series of N superconducting NbN nanowires with, in parallel, an opportunely selected set of AuPd resistors fabricated on-chip. This approach, providing the coupling to a cryogenic high impedance amplifier to preserve the linearity of the voltage outputof the pulse-position resolving detector (PPNR), enables the simultaneous read out of about ten elements with a single coaxial rf cable.

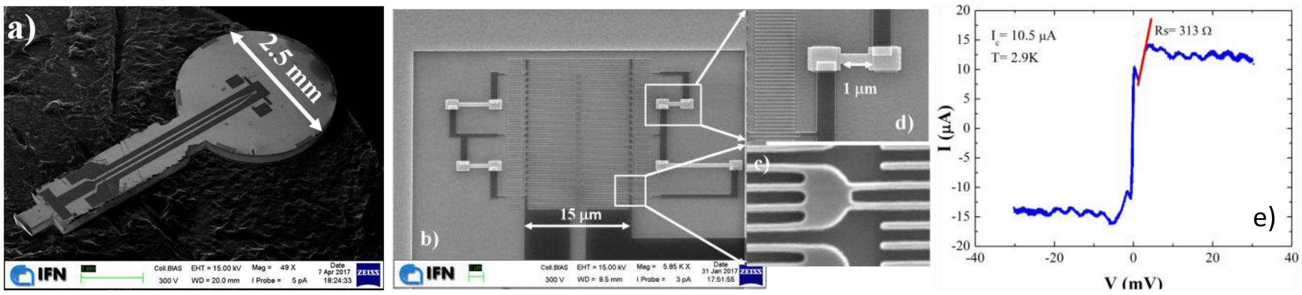


Figure 1: a)-d) Scanning electron micrographs of: a) Silicon substrate shaped as a lollipop used to achieve self-alignment of the PPRD with a SM fiber. The PPRD is fabricated on 262 nm thick SiO2 λ/4 cavity on top of the silicon substrate, 200µm thick. b) Each one of the 4 pixels of the PPRD have an on chip resistance in parallel (20, 50, 80 and 160 Ω). c) Enlarged view of the 80 nm wide NbN meandered nanowires (filling factor of 50%). d) Enlarged view of an on chip 20Ω AuPd resistance. e) IV characteristics of a PPRD measured at 2.9K; the linear fit of the ohmic branch (red line in the figure) is used to infer the sum value of the series resistances Rs ≈ 313 Ω (in agreement with the nominal value of 310 Ω).

A 4-pixel PPRD with 4 different on chip parallel resistances of nominal values R_i = 20 Ω, 50 Ω, 80 Ω, 160 Ω has been fabricated as a proof of concept detector. We used a two parallel nanowire approach [3, 4], to improve the signal to noise ratio (SNR) of the PPRD in order to discriminate the 4 different output levels. The device is operated in a single photon regime and read out with a standard 50 Ω input room temperature rf electronic. The optical characterization shows clearly distinguishable pulses of different amplitude, even if, due to the 50 Ωrf readout, the output of the detector is not linear because of a non ideal voltage reading.

References

[1] V.B. Verma et al., Appl. Phys. Lett. **104**, 051115 (2014).
[2] Mattioli et al., Supercond. Sci. Technol. **28,** 104001(2015).
[3] M. Ejrnaes, R. Cristiano, O. Quaranta et al.,Appl. Phys. Lett. **91**, 262509 (2007).
[4] F. Marsili, et al., Nano Lett., **11**, 2048 (2011)

An efficient plug-and-play single photon source, and limits on spectral purity and heralding efficiency for photon pairs

Evan Meyer-Scott, Nicola Montaut, Johannes Tiedau, Linda Sansoni, Harald Herrmann, Raimund Ricken, Viktor Quiring, Tim J. Bartley, and Christine Silberhorn

Integrated Quantum Optics, Dept. of Physics, University of Paderborn, Warburger Straße 100, 33098 Paderborn, Germany

We report on a fully fiber-coupled heralded single photon source with 46 % raw heralding efficiency [1]. The source (Fig. 1a) is based on type-II parametric down-conversion in a periodically-poled lithium niobate waveguide, producing degenerate photon pairs at 1558 nm. Many previous attempts at packaging single photon sources have resulted in sharply reduced performance [2], but by filtering just the heralding arm the heralding efficiency is limited only by optical losses, which we keep low by careful selection and coupling of components. However, when both photons are tightly filtered, for example to increase the spectral purity for multiphoton interference, this high efficiency is no longer possible for both photons [3]. We use our source to probe this tradeoff, finding that as filters (Fig. 1b) are narrowed, the signal and idler heralding efficiencies necessarily decrease (Fig. 1c) [4]. We also find fundamental limits to these quantities and discuss the source engineering needed to avoid this problem. Our heralded single-photon source is well-suited for applications in quantum communication, networking, and information processing where hands-off operation is desired without sacrificing laboratory-scale performance. For applications requiring multiphoton interference, however, our work highlights the need to properly tailor the photon generation process to the application rather than rely on filtering after photon generation.

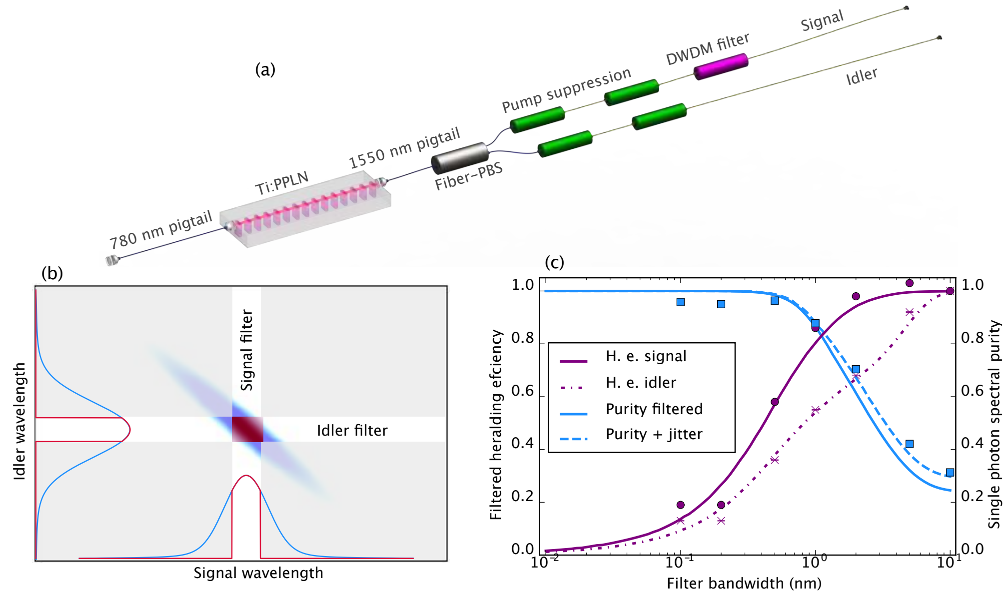


Figure 1: (a) Fiber-coupled single photon source with high heralding efficiency. Arbitrary spectral filters are then added in place of the DWDM filter to probe the tradeoff between heralding efficiency and spectral purity. (b) Spectral filtering of correlated two-photon joint spectrum. (c) Theoretical (curves) and experimental (points) tradeoff between heralding efficiency and spectral purity of the reduced heralded single-photon state.

References

[1] N. Montaut, et al. “High efficiency ‘plug & play’ source of heralded single photons”, arXiv:1701.04229 (2017).

[2] L. Oesterling, et al. “Development of photon pair sources using periodically poled lithium niobate waveguide technology and fiber optic components”, J. Mod. Opt. **62**, 1722 (2015).

[3] P. J. Mosley, et al. “Heralded generation of ultrafast single photons in pure quantum states”, Phys. Rev. Lett. **100**, 133601 (2008).

[4] E. Meyer-Scott, et al. “Filtering is not enough for pure, efficient photon pairs”, arXiv:1702.05501 (2017).

Engineering of orbital angular momentum supermodes in coupled optical waveguides

A. Turpin[1], **G. Pelegrí**[1], **J. Polo**[1], **J. Mompart**[1] **and V. Ahufinger**[1]

[1]*Departament de Física, Universitat Autònoma de Barcelona, E–08193 Bellaterra, Spain*

During the last decade there has been a significant interest in the use of multimode optical fibers, which allow complex structured light modes such as light modes carrying orbital angular momentum (OAM), to increase the channel capacity in optical communications. At variance with polarization -only allowing for the transmission of, at most, two orthogonally polarized signals without crosstalk at a single wavelength-, OAM modes have the advantage that the dimensionality of the Hilbert space formed by OAM modes can be arbitrarily increased as one increases the number of light modes with different azimuthal indices that propagate within the same waveguide. Thus, the use of light beams carrying OAM adds more degrees of freedom to the control of light beams in integrated optical devices. Since most applications of integrated optical devices take profit of the evanescent field of optical waveguides to couple two or more of these using photon tunneling, the additional degrees of freedom offered by OAM optical modes provide an alternative tool to control photon tunneling in coupled waveguides.

In this work [1], we investigate the propagation of OAM modes in a system of three cylindrical waveguides arranged in a triangular configuration. In particular, we show that photon tunneling amplitudes between OAM modes of adjacent waveguides that have opposite topological charge are, in general, complex. For the particular case of the in-line and the right triangle configurations, we demonstrate the existence of bright and dark supermodes in the system, which are characterized by their coupling and decoupling from the central waveguide, respectively. Thus, we discuss that any of these two configurations can be used to implement an OAM cloner and an OAM inverter by simply adding dissipation in the central waveguide while taking advantage of the projection of the input state into the dark supermode when it propagates through the system.

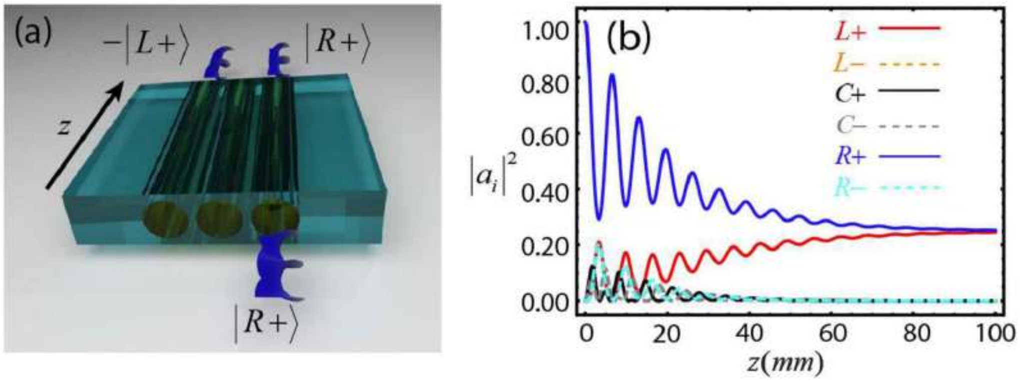


Figure 1: (a) Illustration of an OAM cloner of the $|R+\rangle$ mode (with one positive unit of OAM at the right waveguide) to the waveguide L, and (b) the corresponding intensity evolution along the z direction of $|L+\rangle$ (red-solid curve), $|L-\rangle$ (orange-dashed curve), $|C+\rangle$ (black-solid curve), $|C-\rangle$ (gray-dashed curve), $|R+\rangle$ (blue-solid curve), and $|R-\rangle$ (turquoise-dashed curve) OAM modes. For details and parameter values see [1].

References

[1] A. Turpin, G. Pelegrí, J. Polo, J. Mompart and V. Ahufinger, "Engineering of orbital angular momentum supermodes in coupled optical waveguides", Scientific Reports, in press (2017); arXiv:1610.01359v3.

Quantum metrology enhanced by entanglement from boson sampling

Daniel Nagaj[1]

[1]*Institute of Physics, Slovak Academy of Sciences*

Quantum enhanced metrology. There are many ways that quantum mechanics can be used to improve the sensitivity in quantum metrology beyond shot noise, i.e. $1/\sqrt{\#\text{ of tries}}$. The goal is reaching the Heisenberg limit. This has been achieved for example by NOON states. However, these states are notoriously hard to generate, and sensitive to noise. We thus choose to look for other avenues to quantum improvement.

Our goal is to determine an unknown phase, that is applicable in varying amounts to photons in various modes (not only to one particular mode). For example, imagine a photon in a particular mode running through some length of a medium where the phase applies.

Boson sampling generates useful entanglement. In [1], Motes et al. presented a way to utilize spontaneously generated entanglement from a multimode interferometer to beat the shot-noise limit in quantum metrology. Theirs is a boson sampling approach, using a multimode interferometer built from a unitary transformation, an application of an unknown phase, and a reverse of the unitary transformation: $B = U^\dagger V_\varphi U$. With no phase applied, $B = \mathbb{I}$. The authors now choose U to be a Fourier transform, and apply the phase in a gradient way (as black boxes),

$$V_\varphi = \sum_x e^{ix\varphi} |x\rangle\langle x|. \tag{1}$$

Putting in 1 photon per mode, and counting how often they detect 1 photon in each of the output modes allows them to determine the unknown phase φ with precision

$$\Delta\varphi = \Theta\left(N^{-\frac{3}{2}}\right) = \Theta\left((\#\text{uses})^{-\frac{3}{4}}\right), \tag{2}$$

recalling that the application of the phase as in (1) is equivalent to $N(N-1)/2$ applications of the phase φ. This is better than shot noise $(\#\text{uses})^{-\frac{1}{2}}$, but worse than the Heisenberg limit $(\#\text{uses})^{-1}$.

Our results: towards the Heisenberg limit using Boson Sampling. We answer several open questions from [1], and add some of our own. First, we show that applying an unknown phase to just one (or several) of the modes can not give one a metrological improvement over shot noise in the scenario $B = U^\dagger V_\varphi U$. Second, we prove some of the numerical results in [1]. Third, we show that when one applies the phase in a nonlinear fashion, using

$$V_\varphi = \sum_x e^{if_x\varphi} |x\rangle\langle x| \tag{3}$$

with f_x a polynomial in x with degree a, the resulting phase precision scales like

$$\Delta\varphi = \Theta\left((\#\text{ uses})^{-1+\frac{1}{2(a+1)}}\right), \tag{4}$$

i.e. arbitrarily close to the Heisenberg limit (with growing a). Fourth, we show conditions on the “mixing” unitary U behind an interferometer highly sensitive to phase – it is enough to “mix” the modes up, so that the probabilities of single photons going from mode any x to any mode y are roughly equal. This is of course satisfied by the Fourier transform in [1], but other options are viable too.

References

[1] Keith R. Motes, Jonathan P. Olson, Evan J. Rabeaux, Jonathan P. Dowling, S. Jay Olson, and Peter P. Rohde, Linear optical quantum metrology with single photons: Exploiting spontaneously generated entanglement to beat the shot-noise limit. Phys. Rev. Lett. 114, 170802 (2015)

Bound states and entanglement generation in waveguide QED

P. Facchi[1,2]*, M. S. Kim*[3]*, S. Pascazio*[1,2,4]*, F. V. Pepe*[2,5]*, D. Pomarico*[1,2]*, T. Tufarelli*[6]

[1]*Dipartimento di Fisica, Università di Bari, I-70126 Bari, Italy*
[2]*INFN, Sezione di Bari, I-70126 Bari, Italy*
[3]*QOLS, Blackett Laboratory, Imperial College London, London SW7 2AZ, United Kingdom*
[4]*Istituto Nazionale di Ottica (INO-CNR), I-50125 Firenze, Italy*
[5]*Museo Storico della Fisica e Centro Studi e Ricerche "Enrico Fermi", I-00184 Roma, Italy*
[6]*School of Mathematical Sciences, University of Nottingham, Nottingham NG7 2RD, United Kingdom*

We investigate the behavior of a pair of two-level quantum emitters ("atoms"), embedded in a quasi-one-dimensional waveguide [1]. Integrated photonic circuits and superconducting qubits provide one of the most interesting experimental platforms for realizating dimensional reduction and engineering the atom-field coupling [2,3].

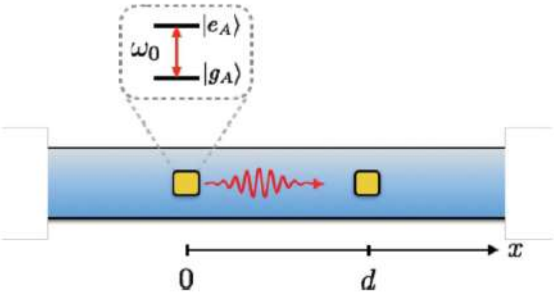


Figure 1: Two identical two-level atoms are fixed at relative distance *d* in a one-dimensional waveguide, with propagation directionalong the x axis. Both atoms are coupled to the same guided mode of the field.

While an isolated atom would unavoidably decay to its ground state, in the considered configuation the atom cannot decay if its excitation energy is smaller than the threshold for photon propagation. Moreover, when two atoms are coupled to the same waveguide mode, nontrivial bound states can exist even above the propagation threshold, due to interference effects. We explore the one-excitation sector of the rotating-wave Hamiltonian and find the existence of a single entangled bound state above threshold, occurring for discrete values of the interatomic distance. Hence, under proper conditions on the distance and the excitation energy, a generic initial state can spontaneously relax towards an asymptotic entangled state, in which the two atoms share an excitation. We study the properties of such states in terms of the interatomic entanglement, and determine the typical timescale of relaxation from the analytical properties of the resolvent of the Hamiltonian. We also find that both bound states and the entanglement-by-relaxation protocol are robust against small parameter variations. We finally comment on the interplay with possible detrimental effects, and generalize to multilevel atoms and sectors with a larger number of excitations.

References

[1] P. Facchi, M. S. Kim, S. Pascazio, F. V. Pepe, D. Pomarico, and T. Tufarelli, "Bound states and entanglement generation in waveguide quantum electrodynamics", Physical Review A 94, 043839 (2016).
[2] A. Wallraff, D. I. Schuster, A. Blais, L. Frunzio, R.-S. Huang, J. Majer, S. Kumar, S. M. Girvin, and R. J. Schoelkopf, "Strong coupling of a single photon to a superconducting qubit using circuit quantum electrodynamics", Nature 431, 162 (2004).
[3] I.-C. Hoi, A. F. Kockum, L. Tornberg, A. Pourkabirian, G. Johansson, P. Delsing, and C. M. Wilson, "Probing the quantum vacuum with an artificial atom in front of a mirror", Nature Physics 11, 1045 (2015).

A general quantum photonic model for cavity-emitter systems evanescently coupled to a waveguide

***Frédéric Peyskens*[1]*, Darrick Chang*[2]*, Dirk Englund*[1]**

[1]*Quantum Photonics Group, RLE, Massachusetts Institute of Technology, Cambridge, Massachusetts 02139, USA*
[2]*ICFO-Institut de Ciencies Fotoniques, Mediterranean Technology Park, 08860 Castelldefels, Barcelona, Spain*

Efficient quantum interfaces converting quantum states from one physical system to another are important components for realizing a plethora of quantum computing applications. One way of achieving such quantum connectivity is through the optical interactions of single photons with quantum emitters. [1] Since single photons can be routed on photonic integrated circuits (PICs) and interfaced with on-chip quantum emitters, one can integrate many functionalities on a single chip, eventually paving the way towards scalable quantum devices. [2] In order to improve the interaction efficiency between photons and quantum emitters, a variety of approaches using dielectric waveguides and cavities ([3,4]) as well as plasmonic waveguides ([5]) have been suggested. However, to the best of our knowledge, a general study of such integrated quantum photonic platforms, including all relevant interactions and loss channels, is still missing. As a result, the requirements to optimize certain quantum functionalities (e.g. a single photon source) within an integrated quantum photonics platform still remain elusive.

We will introduce a general quantum photonic model of a quantum emitter coupled to an integrated photonic cavity, which in itself evanescently interacts with a nearby waveguide. Using a density matrix analysis we investigate the effect of the different coupling strengths and loss channels on the system's transmission $\mathscr{T}$ and reflection $\mathscr{R}$ as well as on the single photon purity (characterized by the second order correlation function $g^{(2)}(0)$) of the transmitted and reflected light. For weak coherent input fields we show that $\mathscr{T}$ and $\mathscr{R}$ can be analytically obtained by the stationary solutions of the Heisenberg equations:

$$\mathscr{R} = \left| 1 + \frac{\Gamma_c}{\Gamma_{1D}} + \frac{2i\Delta_c}{\Gamma_{1D}} + \frac{4\Omega^2}{\Gamma_{1D}\Gamma_e\left(1+\frac{2i\Delta_e}{\Gamma_e}\right)} \right|^{-2}, \qquad \mathscr{T} = \left| \frac{\left(1+\frac{2i\Delta_e}{\Gamma_e}\right)\left(\frac{\Gamma_c}{\Gamma_{1D}}+\frac{2i\Delta_c}{\Gamma_{1D}}\right)+\frac{4\Omega^2}{\Gamma_{1D}\Gamma_e}}{\left(1+\frac{2i\Delta_e}{\Gamma_e}\right)\left(1+\frac{\Gamma_c}{\Gamma_{1D}}+\frac{2i\Delta_c}{\Gamma_{1D}}\right)+\frac{4\Omega^2}{\Gamma_{1D}\Gamma_e}} \right|^2 \tag{1}$$

where Γ_e and Γ_c are the decay rate of the emitter and cavity respectively, Ω the coupling strength between the emitter and the cavity, Γ_{1D} the decay rate into the waveguide and Δ_e and Δ_c the detuning of the emitter and cavity frequency from the driving frequency. Our numerical density matrix analysis perfectly corresponds with this analytically expected trend. Moreover, our model predicts the expected Jaynes-Cummings normal mode splitting for strong emitter-cavity coupling. These sanity checks are used to corroborate the validity of the suggested model.

Subsequently, we will present a comparative analysis between the weak and strong coupling regime of integrated quantum photonic platforms and demonstrate how their performance can be optimized using careful tuning of all coupling rates involved. Finally, we will discuss our experimental efforts on the realization of high efficiency and high purity integrated single photon sources using the above model. Since our model can be applied to any kind of cavity-emitter system (ranging from low-Q integrated nanoplasmonic antennas to high-Q dielectric ring resonators) coupled to a 1D continuum of waveguide modes, it is broadly applicable in the design and optimization of integrated quantum photonic systems (such as e.g. on-chip single photon sources).

References

[1] H. Kimble, "The quantum internet", Nature **453**, 1023–1030 (2008).

[2] J. O'Brien, A. Furusawa, and J. Vučkovič, "Photonic quantum technologies", Nature Photon. **3** 687–695 (2009).

[3] D. Englund, et al., "Controlling cavity reflectivity with a single quantum dot", Nature **450** 857–861 (2007).

[4] S.L. Mouradian, et al., "Scalable Integration of Long-Lived Quantum Memories into a Photonic Circuit", Phys. Rev. X **5** 031009 (2015).

[5] D. Chang, et al., "A single-photon transistor using nanoscale surface plasmons", Nature Physics **3** 807–812 (2007).

Single-photon Quantum Contextuality on a chip

Andrea Crespi[1,2], Marco Bentivegna[3], Ioannis Pitsios[2,1], Davide Rusca[2], Davide Poderini[3], Gonzalo Carvacho[3], Vincenzo D'Ambrosio[4], Adan Cabello[5], Fabio Sciarrino[3], and Roberto Osellame[2,1]

1. Dipartimento di Fisica - Politecnico di Milano, p.za Leonardo da Vinci 32, 20133 Milano, Italy
2. Istituto di Fotonica e Nanotecnologie - Consiglio Nazionale delle Ricerche (IFN-CNR), p.za Leonardo da Vinci 32, 20133 Milano, Italy
3. Dipartimento di Fisica - Sapienza Universita di Roma, p.le Aldo Moro 5, 00185 Roma, Italy
4. ICFO - Institut de Ciencies Fotoniques, The Barcelona Institute of Science and Technology, 08860 Castelldefels (Barcelona), Spain
5. Departamento de Fısica Aplicada II, Universidad de Sevilla, 41012 Sevilla, Spain

In classical physics, the various properties of the objects exist independently of the context, i.e. whether and how measurements are performed. In Quantum physics this assumption appears to be wrong and Nature is indeed "contextual" [1,2]. Contextuality has been observed in many different physical systems, such as single photons [3], neutrons [4] and ions [5], and it is considered to play a fundamental role in the quantum computation advantage [6]. Here, we demonstrate for the first-time quantum contextuality in an integrated photonic chip. The chip implements different combinations of measurements on a single photon delocalized on four distinct spatial modes. Contextually is confirmed by violations of a CHSH-like non-contextuality inequality. This pave the way to compact, portable devices for contextuality-based quantum protocols [7].

References

[1] Bell, J. S. On the problem of hidden variables in quantum mechanics. Rev. Mod. Phys. 38, 447-452 (1966)
[2] Kochen, S. & Specker, E. P. The problem of hidden vari- ables in quantum mechanics. J. Math. Mech. 17, 5987 (1967)
[3] Lapkiewicz, R. et al. Experimental non-classicality of an indivisible quantum system. Nature 474, 490-493 (2011)
[4] Hasegawa, Y., Loidl, R., Badurek, G., Baron, M. & Rauch, H. Violation of a Bell-like inequality in single-neutron interferometry. Nature 425, 45-48 (2003)
[5] Kirchmair, G. et al. State-independent experimental test of quantum contextuality. Nature 460, 494-497 (2009)
[6] Howard, M., Wallman, J., Veitch, V., & Emerson, J. Con- textuality supplies the 'magic' for quantum computation. Nature 510, 351-355 (2014)
[7] Cabello, A., D'Ambrosio, V., Nagali, E. & Sciarrino, F. Hybrid ququart-encoded quantum cryptography pro- tected by Kochen-Specker contextuality. Phys. Rev. A 84, 030302(R) (2011)

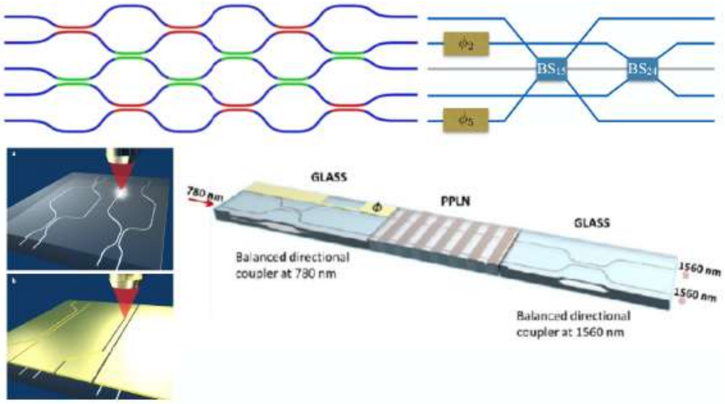
Reconfigurable Femtosecond Laser Written Integrated Photonic Devices for Quantum Information

***A.S. Rab*[1], *F. Flamini*[1], *I. Pitsios*[2,3], *S. Atzeni*[2,3], *L. Magrini*[1], *L. Banchi*[4], *G. Corrielli*[2,3], *V. D'Ambrosio*[1], *M. Bentivegna*[1], *E. Polino*[1], *T. Zandrini*[2,3], *D. Caprara*[1], *M. Valeri*[1], *A. Crespi*[2,3], *N. Spagnolo*[1], *R. Ramponi*[2,3], *P. Mataloni*[2,3], *S. Bose*[4], *R. Osellame*[2,3], *F. Sciarrino*[1]**

[1]*Dipartimento di Fisica - Sapienza Universitá di Roma, P.le Aldo Moro 5, I-00185 Roma, Italy*
[2]*Istituto di Fotonica e Nanotecnologie . Consiglio Nazionale delle Ricerche (IFN - CNR), P.za Leonardo da Vinci, 32, I-20133 Milano, Italy*
[3]*Dipartimento di Fisica - Politecnico di Milano, P.za Leonardo da Vinci, 32, I-20133 Milano, Italy*
[4] *Department of Physics and Astronomy, University College London, Gower Street, WC1E 6BT London, United Kingdom*

Integrated photonics is the frontline concept in the technological advancement of optical devices for information processing. Femtosecond Laser Writing is a technique which allows to write waveguides directly into transparent materials, without the use of masks, speeding massively the engineering process of the photonic devices, with relatively low costs and the possibility of writing polarization independent waveguides, allowing the encoding of information in polarization entangled photons.

Here we present three major works in the use of novel femtosecond laser written photonic devices in quantum information experiments. First we will present the first femtosecond laser written reconfigurable chip operating at telecom wavelength, demonstrating optimal performance of the device in the quantum regime, by measuring single and two photon interference with viabilities close to 99% [1]. Then we will discuss about the use of a reconfigurable photonic device in the investigation of entanglement generation due the evolution of the spin chain, by mapping the Hamiltonian into a discrete quantum walk of single photons, achieved by combining two femtosecond laser written devices in series, one simulating the quantum state transport, the second characterizing the entanglement [2]. Finally we present the first integrated single photon source at telecom wavelength by femtosecond laser writing, achieved by creating a system of three photonic devices: a thermally reconfigurable chip, PPLN crystal with inscribed waveguides and a directional coupler, allowing the control over the state of the generation between $|11\rangle$ and $|20\rangle$.



References

[1] F. Flamini, L. Magrini, A.S. Rab, N. Spagnolo, V. D'Ambrosio, P. Mataloni, F. Sciarrino, T. Zandrini, A. Crespi, R. Ramponi & R. Osellame, Thermally reconfigurable quantum photonic circuits at telecom wavelength by femtosecond laser micromachining, Light: Science & Application **4**, e354 (2015).

[2] I. Pitsios, L. Banchi, A.S. Rab, M. Bentivegna, D. Caprara, A. Crespi, N. Spagnolo, S. Bose, P. Mataloni, R. Osellame & F. Sciarrino, Photonic Simulation of Entanglement Growth After a Spin Chain Quench, Preprint arXiv:1603.02669 (2016).

On-chip conversion of quantum entanglement between different degrees of freedom

Xifeng Ren

Key Laboratory of Quantum Information, University of Science and Technology of China, CAS, Hefei, 230026, People's Republic of China

In the quantum world, a single particle can have various degrees of freedom to encode the quantum information. Controlling multiple degrees of freedom simultaneously is necessary to describe a particle fully and, therefore, to use it more efficiently. Here, we introduce the transverse waveguide mode degree of freedom to quantum photonic integrated circuits, and demonstrate the coherent conversion of photonic quantum state between path, polarization and transverse waveguide mode degree of freedom on a single chip for the first time. The preservation of quantum coherence in these conversion processes is proven by single photon and two photon quantum interference using a fiber beam-splitter or on-chip beam-splitters. These results provide us with the ability to control and convert multiple degrees of freedom of photons for the quantum photonic integrated circuit-based quantum information process.

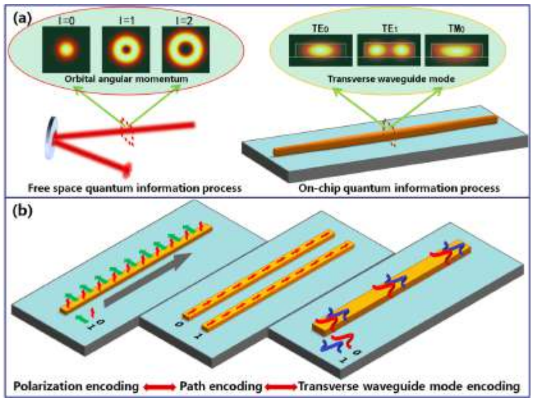


Figure 1: (a) Transverse waveguide mode as a new on-chip quantum information encoder. In free space high dimensional quantum information processes, orbital angular momentums of photons are usually used to encode information. Correspondingly, transverse waveguide mode can be used as a new degree of freedom for on-chip high dimensional quantum information process. Inset on upright corner shows the energy distributions of the fundamental mode (TE_0, TM_0) and the first higher-order mode (TE_1) in a multi-mode waveguide. The silicon-on-insulator (SOI) strip waveguide has a cross section of $\sim 750nm \times 220nm$. (b) On-chip coherent conversion of quantum states between different degrees of freedom, such as paths, polarization, and the transverse waveguide mode, is essential for using different degrees of freedom simultaneously.

References

[1] Feng, L. T. *et al.* On-chip coherent conversion of photonic quantum entanglement between different degrees of freedom. *Nature Commun.* **7**, 11985 (2016).

Driven quantum dynamics

***L. Sansoni**[1,*], **S. Barkhofen**[1], **T.J. Bartley**[1], **R. Kruse**[1], **C.S. Hamilton**[2], **I. Jex**[2], **C. Silberhorn**[1]*

[1] *Integrated Quantum Optics, Universität Paderborn, Warburger Strasse 100, 33098 Paderborn, Germany*
[2] *FNSPE, Czech Technical University in Prague, Brêhová 7, 119 15, Praha 1, Czech Republic*
[*] *linda.sansoni@uni-paderborn.de*

Quantum dynamics of many-particle systems is attracting more and more attention. In this regard the main issue, from the experimental point of view, is the generation of many walkers. For example photonic implementations suffer from losses and low signals, which make it a hard task. A way to tackle this challenge is to generate particles directly inside the network instead of preparing the input state outside. This is what we call a *driven system*.

Here we present driven dynamics based on the generation of particles within the network. This approach can be explored in the framework of quantum walks [1] and search algorithms [2]. The introduction of the generation inside the network strongly affects the evolution of the walkers giving rise to new effective linear evolutions that depend on the generation parameters. A driven dynamics can also be exploited for boson sampling protocols [3]. When using heralded single-photon sources based on parametric down-conversion, this approach offers enhancement in the input state generation rate over scattershot boson sampling [4], reaching the scaling limit for such sources [5]. More significantly, this approach offers a dramatic increase in the signal-to-noise ratio with respect to higher-order photon generation from such probabilistic sources, which removes the need for photon number resolution during the heralding process as the size of the system increases.

References

[1] C. S. Hamilton *et al.*, “Driven Quantum Walks”, Physical Review Letters **113**, 083602 (2014).
[2] C. S. Hamilton *et al.*, “Driven Discrete Time Quantum Walks”,New Journal of Physics **18**, 073008 (2016).
[3] S. Aaronson, A. Arkhipov, “The Computational Complexity of Linear Optics”, Theory of Computing **9**, 143 (2013)
[4] A. Lund *et al.*, “Boson Sampling from a Gaussian State”, Physical Review Letters **113**, 100502 (2014)
[5] S. Barkhofen *et al.*, “Driven Boson Sampling”, Physical Review Letters **118** 020502 (2017)

Quantum storage of heralded single photons in a laser written waveguide

***A. Seri*[1], *G. Corrielli*[2], *D. Lago*[1], *A. Lenhard*[1], *M. Mazzera*[1], *R. Osellame*[2], *Hugues de Riedmatten*[1,3]**

[1]*ICFO - Institut de Ciencies Fotoniques, The Barcelona Institute of Technology, Castelldefels, Spain*
[2]*IFN - Istituto di Fotonica e Nanotecnologie, CNR and Dipartimento di Fisica, Politecnico di Milano, Milano, Italia*
[3]*ICREA - Institució Catalana de Recerca i Estudis Avançats, Barcelona, Spain*

The efficient and reversible mapping of quantum states of light into collective excitations of atomic ensembles represents one of the most promising routes towards the realization of quantum memories. Rare earth doped crystals, in particular, offer long lived spin states and are naturally suitable for miniaturization and integration, e.g. in form of waveguides, of several quantum memories onto a single substrate. The latter would greatly facilitate the scalability and, thanks to the tight confinement of light, would lead to a strong enhancement of the light matter interaction. Pr^{3+}:Y_2SiO_5 is currently one of the best systems for quantum memory applications, in fact it is the only solid-state system in which externally generated heralded single photons have been stored with on-demand retrieval [1]. Moreover, very efficient storage of weak coherent states [2] as well as the longest storage time ever demonstrated in any system (in the regime of 1 minute for classical images) [3] have been shown with this crystal. Despite this, only two approaches for integration have been reported so far in this material [4,5]. The first one is based on evanescent coupling with TeO2 waveguides deposited on a bulk crystal [4]. The second one is based on femtosecond laser micromachining [6]: a fs-pulsed laser is highly focused in the crystal to create pairs of parallel damage tracks. As a consequence of a positive change of refractive index between the two tracks, the light is guided (type II waveguide). In this approach, the interaction between the light confined in the waveguide and the active ions was shown to be higher and storage with on-demand retrieval was performed with bright light pulses using the atomic frequency comb (AFC) protocol, demonstrating the first implementation of an integrated on-demand spin wave optical memory [5].

We propose a new platform for integrated optical memory based on the same technique: we fabricate a single mode *type I* waveguide in Pr^{3+}:Y_2SiO_5 , performing just one long damage track along the crystal in which, due to different fabrication parameters, the positive change of refractive index coincides with the track itself. Contrary to the *type II* waveguides studied in [5], *type I* waveguides provide higher confinement without increasing the losses, thus further increasing the light-ions interaction. Moreover they can be easily addressed with fibers and standard glass chips (differently from *type II* waveguides). We demonstrate that the coherence properties of the material are in the same order of magnitude as for the bulk (a factor 3 lower), despite the invasive fabrication process. We perform storage of ultranarrowband single photons generated by spontaneous parametric down conversion (SPDC) and with telecom heralding, using the AFC protocol for storage times in the order of μs, thus proving that laser written memories can operate in the quantum regime. This device opens new perspectives for the implementation of miniaturized and integrated quantum memories.

References

[1] A. Seri, A. Lenhard, D. Rielander, M. Gundogan, P. M. Ledingham, M. Mazzera, and H. de Riedmatten, ”Quantum correlations between single telecom photons and a multimode on-demand solid state quantum memory”, Preprint at arXiv:1701.09004v1 (accepted in Phys. Rev. X)

[2] M. P. Hedges, J. J. Longdell, Y. Li and M. J. Sellars, ”Efficient quantum memory for light”, Nature **465** 1052 (2010)

[3] G. Heinze, C. Hubrich and T. Halfmann, ”Stopped Light and Image Storage by Electromagnetically Induced Transparency up to the Regime of One Minute”, Phys. Rev. Lett. **111** 033601 (2013)

[4] S. Marzban, J. G. Bartholomew, S. Madden, K. Vu, and M. J. Sellars, ”Observation of Photon Echoes From Evanescently Coupled Rare-Earth Ions in a Planar Waveguide”, Phys. Rev. Lett. **115** 013601 (2015)

[5] G. Corrielli, A. Seri, M. Mazzera, R. Osellame, and H. de Riedmatten, ”Integrated Optical Memory Based on Laser-Written Waveguides”, Phys. Rev. Applied **5**, 054013 (2016)

[6] F. Chen and J. R. Vazquez de Aldana, ”Optical waveguides in crystalline dielectric materials produced by femtosecond-laser micromachining”, Laser Photonics Rev. **8**, 251 (2014)

Silicon quantum photonics in the short-wave infrared

Joshua W. Silverstone, Lawrence Rosenfeld,
Benjamin Slater, Döndü Sahin, Mark G. Thompson

Centre for Quantum Photonics,
H. H. Wills Physics Laboratory and Merchant Venturers School of Engineering,
University of Bristol, Bristol BS8 1TL

Integrated quantum photonics places much hope on silicon photonics—and the mature fabrication it brings—to provide the very large scale that quantum technologies requires [1]. Silicon-on-insulator waveguides, with their tight confinement and strong nonlinearity, have been an important test bed for nonlinear optics [2] including photon-pair generation via spontaneous four-wave mixing (SFWM) [3]. However, doubts in silicon's viability for both quantum and nonlinear optics have been raised, due to its strong two-photon absorption (TPA) around 1.55 µm. TPA limits nonlinear optical processes, and the generated carriers add loss, heat, and unwanted dynamics [2]. Cross-TPA reduces heralding efficiency, fundamentally limiting photon-pair source performance [4]. Only two approaches exist: find a material system with a larger bandgap; or use photons with less energy. We choose the latter route, and explore silicon quantum photonics (SiQP) in the short-wave infrared (SWIR) band, around 2.1 µm.

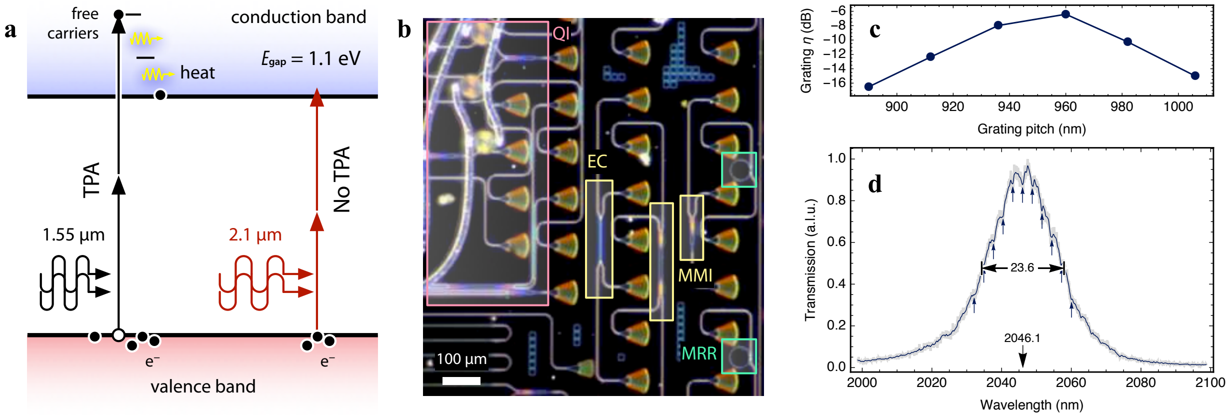


Figure 1: **a** Simplified band diagram and nonlinear effects in silicon. **b** Micrograph of fabricated SWIR SiQP devices. Measured grating transmission and ring resonator spectrum (**c**, **d**).

The SWIR presents a number of opportunities, in addition to the suppression of TPA. We will discuss these, as well as the challenges, and outline our progress to date in exploiting this new band for SiQP. We will discuss the design and technical challenges of devices; show results on new passive structures, including waveguide couplers and delay lines; report on our progress towards generating and collecting photon pairs in the mid-IR; and finally outline our development of integrated SWIR-optimised single-photon detectors.

The SWIR route avoids the known barriers of SiQP in the telecom band, and presents exciting opportunities and challenges for large-scale quantum optics.

References

[1] J. W. Silverstone, *et al.* "Silicon Quantum Photonics", IEEE J. Sel. Top. Quantum Electron., 22, **6**, 390 (2016).
[2] B. Jalali, "Silicon photonics: Nonlinear optics in the mid-infrared", Nat. Photon. **4**, 506 (2010).
[3] J. E. Sharping, "Generation of correlated photons in nanoscale silicon waveguides", Op. Ex. **14**, 12388 (2006).
[4] C. A. Husko, *et al.* "Multi-photon absorption limits to heralded single photon sources", Sci. Rep. **3**, 3087 (2013).

Noise features dictating the ultimate precision of frequency estimation

A. Smirne[1], **J. Haase**[1], **J. Kołodyński**[2], **R. Demkowicz-Dobrzański**[3], **S.F. Huelga**[1]

[1] *Institute of Theoretical Physics, Universität Ulm, Albert-Einstein-Allee 11D-89069 Ulm, Germany*
[2] *ICFO-Institut de Ciències Fotòniques, The Barcelona Institute of Science and Technology, 08860 Castelldefels, Spain*
[3] *Faculty of Physics, University of Warsaw, 02-093 Warszawa, Poland*

Quantum metrology protocols allow in principle to surpass the precision limits typical to classical statistics, leading from the standard quantum limit (SQL) to the Heisenberg limit (HL) [1], see also the Figure. However, such a quantum advantage is jeopardized by the interaction of the probes with their surrounding environment, which typically constrains it to a constant factor, thus bounding the error to the SQL [2-4]. Recently [5], it was shown that the quantum enhancement in the scaling of precision with the number of probes can be restored partially, but significantly also in the presence of noise, by exploiting some key features of the probes' dynamics. For any phase-covariant dynamics, where the action of the noise commutes with the unitary encoding, one can achieve an asymptotic precision which is intermediate between the SQL and the HL if and only if the short-time evolution departs from a time-homogeneous (semigroup) dynamics. After briefly recalling this general result, I will further illustrate the specific role played by the (non-)phase covariance of the dynamics, as well as its possible deviations from time-homogeneity, by taking into account a physically relevant example. The microscopic derivation of the open-system dynamics in the spin boson model will allow us to clarify the effects of the different kinds of noise on the estimation precision achievable via measurements on the probes [6].

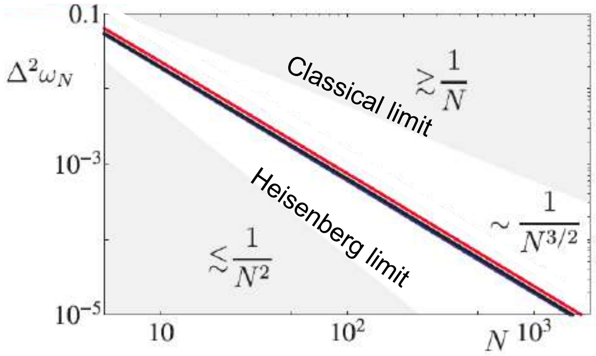


Figure 1: The interaction with an environment with a finite correlation time allows for noisy metrological limits that surpass the standard quantum limit imposed by the central limit theorem. We demonstrate the existence of a fundamental (Zeno) limit (in black) to the best attainable precision in noisy frequency estimation and its attainability (in red) using quantum probes initially prepared in an entangled state [5]. While the asymptotic Zeno-resolved precision is above the Heisenberg unitary limit, no further improvements are feasible by exploiting non Markovian effects and therefore this bound provides a fundamental limit to the resolution for a broad class of system-environment interactions.

References

[1] V. Giovannetti, S. Lloyd, and L. Maccone, Science **306**, 1330 (2004).
[2] S. F. Huelga, C. Macchiavello, T. Pellizzari, A. K. Ekert, M. B. Plenio, and J. I. Cirac, Phys. Rev. Lett. **79**, 3865 (1997).
[3] B. M. Escher, R. L. de Matos Filho, and L. Davidovich, Nat. Phys. **7**, 406 (2011).
[4] R. Demkowicz-Dobrzański, J. Kołodyński, and M. Guţă, Nat. Commun. **3**, 1063 (2012).
[5] A. Smirne, J. Kołodyński, S. F. Huelga, and R. Demkowicz-Dobrzański, Phys. Rev. Lett. **116**, 120801 (2016).
[6] J. Haase, A. Smirne, J. Kołodyński, R. Demkowicz-Dobrzański and S. F. Huelga, in preparation.

Optical phase measurements with single-photons and two-photon phase sensitivity

P. Vergyris[1], *F. Kaiser*[1], *N. Montaut*[2], *O. Alibart*[1], *H. Herrmann*[2], *C. Silberhorn*[2], *S. Tanzilli*[1]

[1]*Université Côte d'Azur, CNRS, Institut de Physique de Nice, France*
[2]*Integrated Quantum Optics, Universität Paderborn, Warburger Strasse 100, 33098 Paderborn, Germany*

Quantum metrology holds the great promise of overcoming the shot-noise limit in phase-sensing measurements compared to classical strategies, by exploiting multi-photon states [1]. However, such photonic schemes are hard to be implemented experimentally [2], since the simultaneous detection of all the involved photons is required. Therefore those protocols are hardly competitive with classical approaches. In this work, we propose and demonstrate a new strategy allowing phase sensing with two-photon phase sensitivity while relying on the detection of single photons only. Strikingly, two-photon phase shifts can be retrieved thanks to classical intensity measurements with a standard photodiode. Our idea is inspired by the concept of induced coherence without induced emission [3].

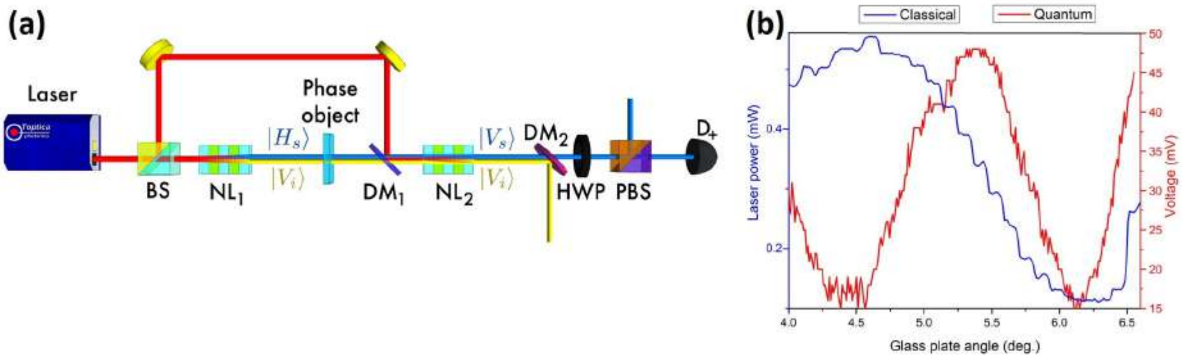


Figure 1: a) Experimental setup. b) Results for phase-sensing using classical (blue) and quantum (red) strategies.

The basic principle of the experimental setup is depicted in Figure 1(a). Two nonlinear crystals (NL$_1$ and NL$_2$) are coherently illuminated by a continuous-wave 780 nm pump laser (red lines). In the first crystal (NL$_1$), cross-polarised non-degenerated signal and idler paired photons $|H_s\rangle|V_i\rangle$ are generated through type-II spontaneous parametric downconversion (SPDC) (blue and yellow lines). Subsequently, they are transmitted through a phase object, where the individual photons accumulate a phase shift of ϕ_s and ϕ_i, respectively. After being transmitted through a dichroic mirror (DM$_1$), this quantum state is coherently superposed with the one generated in NL$_2$ through type-0 SPDC, *i.e.* $|V_s\rangle|V_i\rangle$. Therefore, the quantum state reads: $|\psi\rangle = \left(e^{i(\phi_s+\phi_i)}|H_s\rangle + |V_s\rangle\right) \otimes |V_i\rangle/\sqrt{2}$.

The signal photon is subsequently projected in the phase-sensitive diagonal basis. Interference fringes originating from phase shifts accumulated by both signal and idler photons appear now exclusively in the signal photon intensity. Notably, no coincidence detection is necessary. The experimental results are shown in Figure 1(b). The results clearly demonstrate a two-photon enhanced phase sensitivity associated with the quantum approach.

Besides a significant reduction in the measurement apparatus resources, our technique has a great potential for future applications. Our experiment demonstrates that the advantages of quantum-enhanced phase-sensing can be fully exploited even by classical intensity measurements, paving the way towards resource-efficient and practical quantum metrology.

References

[1] M. W. Mitchell, J. S. Lundeen, and A. M. Steinberg, "Super-resolving phase measurements with a multiphoton entangled state", Nature **429**, 161–164 (2004).

[2] P. Vergyris, T. Meany, T. Lunghi, G. Sauder, J. Downes, M. J. Steel, M. J. Withford, O. Alibart and S. Tanzilli, "On-chip generation of heralded photon-number states", Scientific Reports. **6**, 35975 (2016).

[3] X. Y. Zou, L. J. Wang, and L. Mandel, "Induced coherence and indistinguishability in optical interference", Phys. Rev. Lett. **67**, 318–321 (1991).

Poster Presentations

Experimental benchmark of Boson Sampling with pattern recognition techniques

***Iris Agresti*[1]*, Niko Viggianiello*[1]*, Fulvio Flamini*[1]*, Nicolò Spagnolo*[1]*, Andrea Crespi*[2]*, Roberto Osellame*[2]*, Nathan Wiebe*[3]*, Fabio Sciarrino*[1]**

[1] *Dipartimento di Fisica, Sapienza Università di Roma, Piazzale Aldo Moro 5, I-00185 Roma, Italy*
[2] *Istituto di Fotonica e Nanotecnologie, Consiglio Nazionale delle Ricerche (IFN-CNR), Piazza Leonardo da Vinci, 32, I-20133 Milano, Italy*
[3] *Station Q Quantum Architectures and Computation Group, Microsoft Research, Redmond, WA, United States*

The difficulty of validating large-scale quantum devices, such as Boson Samplers (Fig. 1), poses a major challenge for any research program that seeks to show quantum advantages over classical hardware. Boson Sampling is a computational problem formally defined by Aaronson and Arkhipov [1] in 2011 that has been shown to be classically intractable (even approximately) under mild complexity theoretic assumptions. Thus, demonstrating that a quantum device can efficiently perform Boson Sampling is powerful evidence that quantum computing can bring exponential advantages over its classical counterpart. However, despite the fact that Boson Sampling is within our reach [2], its measurement statistics are intrinsically exponentially hard to predict, so that the validation of a Boson Sampler is not a straightforward task for large quantum systems.

To address this problem, we propose a novel data-driven approach wherein models are trained to identify common pathologies using unsupervised machine learning algorithms. The aim is to find an inner structure in an unknown data set through clustering, grouping data in different classes according to collective properties recognized by the algorithm. We illustrate this idea by training a classifier that uses K-means clustering [3] to distinguish between Boson Samplers that use indistinguishable photons from those that do not. We train the model on numerical simulations of small-scale Boson Samplers and then validate the pattern recognition technique on larger numerical simulations as well as on integrated photonic platforms in both traditional Boson Sampling experiments and scattershot experiments [4]. This approach performs substantially better on the test data than previous methods and underscores the ability to further generalize its operation beyond the scope of the examples it was trained on.

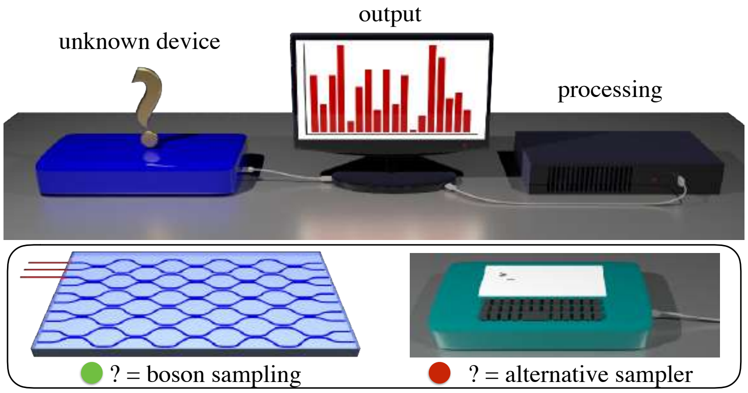


Figure 1: **Validation of Boson Sampling experiments.** An agent has to discriminate whether a finite sample obtained from an unknown device has been generated by a quantum device implementing the Boson Sampling problem or by an alternative sampler.

References

[1], S. Aaronson, A. Arkhipov,“The computational complexity of linear optics”, in *Proceedings of the Forty-third Annual ACM Symposium on Theory of Computing, STOC’11*, 333-342 (ACM, 2011).

[2] A. Crespi *et al.*, “Integrated multimode interferometers with arbitrary designs for photonic boson sampling”, Nature Photonics **7**, 545549 (2013).

[3], J. MacQueen,“Some methods for classification and analysis of multivariate observations”, in *Proceedings of the Fifth Berkeley Symp. on Math. Statist. and Prob*, 281-297 (1967).

[4] M. Bentivegna *et al.*, “Experimental scattershot boson sampling”, Science Advances **1**, 3, (2015).

Deterministic positioning of quantum emitters in photonic devices

Chenglong Zhao[1], *Joshua Hendrickson*[2], *Piyush J. Shah*[2], *Luke J. Bissell*[2]

[1]*Department of Physics, Department of Electro-Optics and Photonics, University of Dayton, 300 College Park, Dayton, Ohio 45469-2314, USA*

[2]*Air Force Research Laboratory, WPAFB, Ohio 45431, USA*

The promise of quantum technologies for secure communication and information processing relies on coupling single-photon sources (SPS) to optical microcavities (OMCs) [1]. The light–matter interaction in these systems is sensitive to the SPS position and orientation with respect to the OMC. Current SPS-to-OMC coupling technologies limit quantum-photonic device manufacturability by either requiring high-cost and non-scalable nanofabrication techniques such as e-beam lithography, or lacking the ability to select optimal SPSs and control their orientations. At the same time, nanoscale light emitters are being realized as ideal biosensors due to their ability to be conjugated with biomarkers. In particular, nanodiamonds with color centers stand out from other quantum emitters due to their brightness, photostability, nontoxicity, and ability to act as nanoscale temperature and magnetic sensors [2,3]. The coupling of quantum emitters to OMCs enhances the signal from the biosensor, but the path forward from laboratory demonstrations of this effect to a commercially scalable technology has not been demonstrated.

Our work solves this materials-processing challenge by borrowing from additive manufacturing. We will deterministically print nanodiamonds containing nitrogen-vacancy color centers (NVNDs) from a transparent substrate on to an OMC by using opto-thermal expansion under laser heating. Figs. 1a-b schematically show the working principle of the proposed method as follows: (1) NVNDs are dispersed on a transparent substrate. (2) A search algorithm locates nanodiamonds that only have one nitrogen–vacancy color center, using single-photon correlation measurements. (3) A laser beam is focused on the substrate right beneath the NVND, which causes a sudden thermal expansion of the substrate due to the opto-thermal effect. This rapid thermal expansion kicks the NVND off the surface (Fig. 1a, side view). (4) The NVND flies to the top surface where the OMC is located. The OMC we will use is a 1D photonic crystal cavity, designed with an electric field gating the target location (Fig. 1b, top view). Electric field gating around the NVND target location will: i) trap the NVND, ii) align the color center's optically excited dipole with the electric field, and iii) could serve to electrically excite the quantum emitter. Importantly, our method allows for the simultaneous manipulation of both the SPS position and orientation with respect to the quantum-photonic device, and can be conducted at ambient conditions. This method can be generalized to emitters without excited state dipoles, such as the Ge- and Si-vacancy color centers: the orientation of the color center can be determined optically, and the induced electric dipole of the nanodiamond may be oriented by an external electric field.

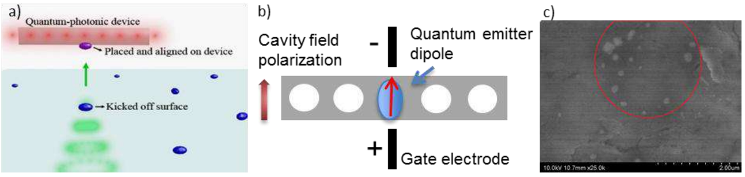


Fig. 1. Schematic illustration of placing and aligning emitters with a photonic device. a) side view. b) top view. c) Gold nanoparticles placed on a metallic tip using the proposed method.

As a proof-of-principle demonstration, Fig. 1c shows an SEM image of 200 nm gold nanoparticles which were kicked on to a metallic tip. We will present our characterization of the positioning accuracy of this method using both nanodiamonds and gold nanoparticles, elucidate the influence of nanoparticle shape on the trapping and positioning efficiency, and the coupling of these nanoparticles to optoelectronic circuits.

References

[1] I. Aharonovich, D. Englund, and M. Toth, “Solid-state single-photon emitters,” Nat. Photonics **10**, 631–641 (2016).
[2] I. Aharonovich and E. Neu, “Diamond nanophotonics,” Adv. Opt. Mater. **2**, 911–928 (2014).
[3] Y. Wu, F. Jelezko, M. B. Plenio, and T. Weil, “Diamond quantum devices in biology,” Angew. Chem. Int. Ed. **55**, 6586–6598 (2016).

Experimental violation of local causality in a quantum network.

Gonzalo Carvacho[1], Francesco Andreoli[1], Luca Santodonato[1], Marco Bentivegna[1], Rafael Chaves [2] & Fabio Sciarrino[1].

1 Dipartimento di Fisica - Sapienza Università di Roma, P.le Aldo Moro 5, I-00185 Roma, Italy.

2 International Institute of Physics, Federal University of Rio Grande do Norte, 59070-405 Natal, Brazil

Bell's theorem plays a crucial role in quantum information processing and thus several experimental investigations of Bell inequalities violations have been carried out over the years. Despite their fundamental relevance, however, previous experiments did not consider an ingredient of relevance for quantum networks: the fact that correlations between distant parties are mediated by several, typically independent sources. Here, using a photonic setup, we investigate a quantum network consisting of three spatially separated nodes whose correlations are mediated by two distinct sources (Figure 1). This scenario allows for the emergence of the so-called non-bilocal correlations, incompatible with any local model involving two independent hidden variables. We experimentally witness the emergence of this kind of quantum correlations by violating a Bell-like inequality under the fair-sampling assumption. Our results provide a proof-of-principle experiment of generalizations of Bell's theorem for networks [1], which could represent a potential resource for quantum communication protocols.

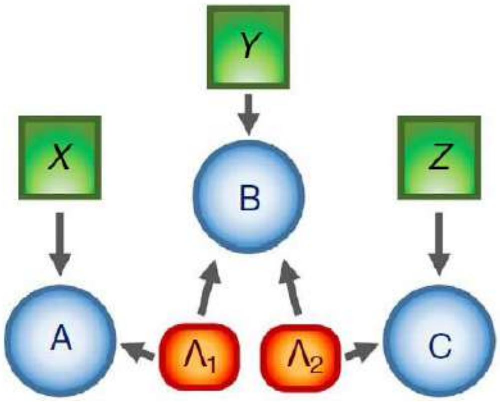


Figure 1: Directed Acyclic Graphs (DAG) can represent different causal structures, for instance the nodes in the graph represent the relevant random variables with arrows accounting for their causal relations for a tripartite scenario with two independent local hidden variable, that is, bilocal hidden variable (BLHV) model.

References

[1] G. Carvacho, F. Andreoli, L. Santodonato, M. Bentivegna, R. Chaves and F. Sciarrino, "Experimental violation of local causality in a quantum network", Nature Communications 8, 14775 (2017).

Experimental signature of Quantum Darwinism in photonic cluster

M. A. Ciampini[1], *G. Pinna*[1], *P. Mataloni*[1], *M. Paternostro*[2]

[1] *Dipartimento di Fisica, Sapienza Università di Roma, P.le Aldo Moro 5, 00185, Rome, Italy;*
[2] *Centre for Theoretical Atomic, Molecular and Optical Physics,*
School of Mathematics and Physics, Queen's University Belfast, Belfast BT7 1NN, United Kingdom;

Quantum Darwinism is a theory proposed by Zurek in 2009 [1], in which the process of proliferation of information from a quantum system to an environment is discussed. The theory explores the borders between the quantum and the classical world: information about a quantum state can be accessed by multiple observers interrogating the environment which is connected to the system itself (Figure 1a). If the observers agree about the results of their measurements, then "objectivity", which is a fundamental feature of the classical world, is born. This is a shift in perspective from an approach in which the environment in a quantum structure is only considered as an agent introducing decoherence on the system.

In this work, we give the first experimental verification of the predictions of Quantum Darwinism, extending Zurek's framework by considering either interacting and non-interacting environmental qubits. We use cluster states as the main platform of investigation, identifying one of the nodes as the system (A in Figure 1b-c) and the others with the environment. In a cluster state qubit correlation can be activated by performing C-Phase operations between adjacent qubits.

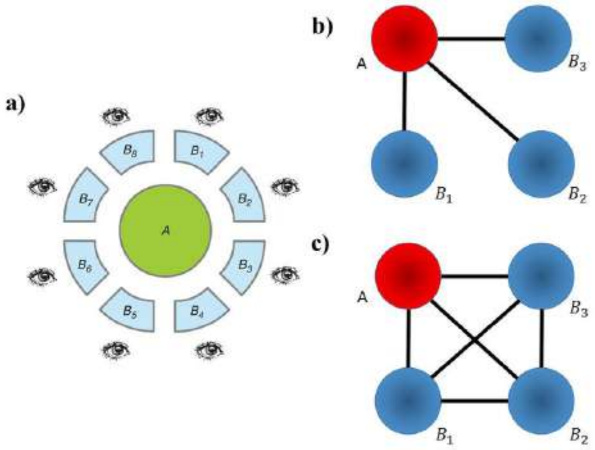


Figure 1: a) Scheme in which multiple observers interact with independent fragments of an environment to extract information about the system. b) Four qubits "Star" cluster state, in which the system is correlated to the other qubits of the environment. c) Four qubits "Web" cluster state, which introduces correlations between environment qubits.

We show a definite experimental signature of quantum Darwinism using a four-qubit cluster state, generated by a path-polarization hyperentangled source [2]. In Figure 1b we introduce direct connection between the system and the environment. This state, which we dub "Star Cluster" follows Zurek's model, and shows the presence of Darwinism. Introducing interaction between qubits (Figure 1c), however, disrupts Darwinism demonstrating that even the amount of correlations in the environment is fundamental for assessing the characteristics of the system.

References

[1] Zurek, W. H., Nature Physics **5**, 181 - 188 (2009)

[2] Barbieri, M., Cinelli C., Mataloni, P., De Martini F., "Polarization-momentum hyperentangled states: Realization and characterization," Physical Review A **72**, 052110 (2005).

Development of an integrated photon pair source at telecom wavelength fully realized by femtosecond laser micromachining

Simone Atzeni[1,2], Adil Syed Rab[3], Giacomo Corrielli[1,2], Emanuele Polino[3], Mauro Valeri[3], Nicolò Spagnolo[3], Andrea Crespi[1,2], Fabio Sciarrino[3], Roberto Osellame[1,2]

1 Dipartimento di Fisica - Politecnico di Milano, P.za Leonardo da Vinci, 32, 20133 Milano, Italy
2 Istituto di Fotonica e Nanotecnologie - Consiglio Nazionale delle Ricerche (IFN-CNR), P.za Leonardo da Vinci, 32, 20133 Milano, Italy
3 Dipartimento di Fisica - Sapienza Università di Roma, P. le Aldo Moro, 5, 00185 Roma, Italy

The efficient generation of high quality quantum states of light is one of the main challenges in the field of experimental quantum optics, and plays a central role in the development of photonic quantum technologies. Several methods have been sifted to increase the capabilities of single photon sources, and the integrated optics approach represents a promising strategy, offering unique features of compactness and stability [1]. Here we report the development and the characterization of all the components required for building an integrated source of single photon pairs at telecom wavelength, based on spontaneous parametric down conversion (SPDC) in non-linear waveguide. A schematic of the source is reported in figure 1.

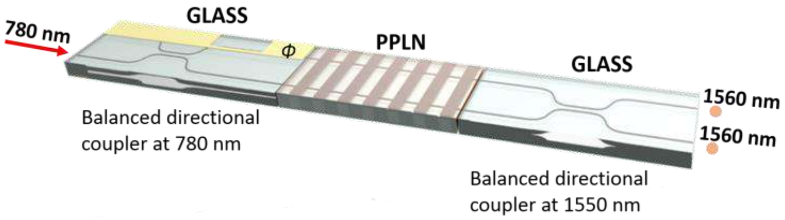


Figure 1: The pump light, impinging on an input port of a balanced directional coupler is equally split and directly coupled to an array of two waveguides in periodically-poled lithium niobate. A pair of photons at telecom wavelength is thus generated in one of the two nonlinear waveguides through SPDC. An additional directional coupler recombines the two separated spatial modes to produce the output state.

Remarkably, all the components have been realized by femtosecond laser writing, proving that this relatively novel fabrication technique is extremely flexible, and allows to process glass as well as crystalline materials [2]. The first chip consists in a balanced directional coupler at 780 nm wavelength realized in aluminum-borosilicate glass (EAGLE2000, Corning). A thermo-optical phase adjuster fabricated on the top of one of the output arm can control the relative phase between the two outputs of the directional coupler. A complete tunability of the device over the 0-2π range can be achieved with low power consumption. The waveguides in MgO:PPLN have been inscribed by adopting a multi-scan approach and they show single-mode behavior at both fundamental and down-converted wavelength. The preservation of the non-linear properties of the material, as well as the spectral features of the generated light were studied in the classical regime through second harmonic generation experiments. This characterization showed that a very high degree of spectral indistinguishability can be reached between the photons generated in the two waveguides. A third glass chip containing a directional coupler (balanced within a 10 nm bandwidth centered at the generated wavelength) produces interference between the two optical modes and, depending from the value of the phase ϕ, permits to produce either a pair of indistinguishable photons or an entangled NOON state and the device output. Additionally, we developed and characterized another glass chip, containing a pair of integrated half waveplates with rotated axes followed by a balanced and polarization insensitive directional coupler. The use of such device in replacement of the third stage of figure 1 transforms our device in a source of entangled photons in the polarization Bell Φ^+ state. The results obtained are very encouraging toward the realization of a reconfigurable and very versatile integrated photon pair source, with multiple applications in quantum technologies.

References

[1] S. Tanzilli et al., “Highly efficient photon-pair source using periodically poled lithium niobate waveguide”, Electronics Letters 37, 1 (2001).

[2] G. Della Valle et al, “Micromachining of photonic devices by femtosecond laser pulses”, Journal of Optics A 11, 049801 (2008).

Laser written integrated programmable multiport interferometer

***I.V. Dyakonov*[1], *A.A. Kalinkin*[1], *M.Yu. Saygin*[1], *I.V. Radchenko*[1], *I.B. Bobrov*[1], *I.A. Pogorelov*[1], *S.A. Evlashin*[2], *P.V. Dyakonov*[2], *S.M. Zyryanov*[1,2], *S.S. Straupe*[1] and *S.P. Kulik*[1]**

[1]*Faculty of Physics, Lomonosov Moscow State University, Russia*
[2]*Skobeltsyn Institute of Nuclear Physics, Lomonosov Moscow State University, Russia*

Current challenges in experimental quantum optics become utterly demanding to optical hardware performance. Traditional bulk optical setups no longer fulfil the photonic processing requirements for tasks like linear optical quantum computing [1], boson sampling [2], quantum walks [3], etc., which should be implemented on an essentially scalable, flexible and low loss optical platform. Semiconductor industry disposes cutting-edge technology for programmable integrated photonic device fabrication and packaging providing all the necessary tools for boosting experimental research in the areas listed above. However, this technology is hardly available for average quantum optical laboratory.

In our work we demonstrate the power of femtosecond laser micromachining for active integrated photonic device prototyping. Femtosecond laser writing is an established tool for rapid prototyping of sophisticated optical waveguide structures [4]. Laser writing of thermooptically controlled devices has recently been demonstrated on individual tunable element scale [5]. We further develop the technique and fabricate 4×4 integrated interferometer thermooptically adjustable applying voltage to 12 chrome heaters patterned using femtosecond laser writing facility on a metallic film deposited on the chip surface. We demonstrate 5 ms switching time and design adaptive algorithms for precise calibration of the device to perform desired unitary transformation. Furthermore, we extend reconfigurability principle to polarization degree of freedom of quantum states of light. employing induced anisotropy feature of written waveguide structures tunable integrated waveplate device is designed and fabricated. We believe our results may stimulate research in integrated quantum photonics field endowing researchers with an affordable programmable integrated device fabrication approach.

References

[1] J. Carolan et al., “Universal linear optics”, Science **349(6249)** (2015).

[2] S. Aaronson and A. Arkhipov, “The computational complexity of linear optics”, Preprint at arXiv:1011.3245v1 (2010).

[3] H. B. Perets et al,“Realization of quantum walks with negligible decoherence in waveguide lattices” Phys. Rev. Lett., **100:170506** (2017)

[4] A. Crespi et al. “Integrated multimode interferometers with arbitrary designs for photonic boson sampling”, Nature Photonics **7** (2013)

[5] F. Flamini et al. “Thermally reconfigurable quantum photonic circuits at telecom wavelength by femtosecond laser micromachining”, Light: Science and Application **4:e354** (2015)

An On-chip Homodyne Detector for Measuring Quantum States

Giacomo Ferranti[1], *Francesco Raffaelli*[1], *Dylan H. Mahler*[1], *Philip Sibson*[1], *Jake E. Kennard*[1], *Alberto Santamato*[1], *Gary Sinclair*[1], *Damien Bonneau*[1], *Mark G. Thompson*[1], *Jonathan C. F. Matthews*[1],

[1]*Quantum Engineering Technology Labs, H. H. Wills Physics Laboratory and Department of Electrical & Electronic Engineering, University of Bristol, BS8 1FD, UK*

Balanced homodyne detection is a well-developed technique allowing to perform measurements of quadratures on a quantum electromagnetic field. Due to its high versatility, it has found a large number of applications ranging from characterisation of quantum states [1] and processes [2] to continuous variables quantum computing and quantum key distibution [3].

A homodyne detector consists of an optical beamsplitter and a pair of photodiodes. The signal field of interest interferes on the beamsplitter with a powerful coherent beam named Local Oscillator (LO) and the two output fields are measured by the two photodiodes. The generated currents are then processed by an electronic circuit that takes their difference and amplifies it. The resulting electronic signal is proportional to the quadrature $Q(\theta)$ of the signal field, where θ is the optical phase difference between signal and LO. For a sufficient number of different local oscillator phases, it is possible to use measurements of this type to reconstruct the full state of the quantum optical signal field using a reconstruction technique named homodyne tomography[4].

Use of homodyne detectors on more than a small number of optical modes has so far been limited by the interferometric stability of quantum optical experiments. Integrated quantum photonics, in which optical sources, circuits and detectors are monolithically integrated on a semi-conductor chip, has the potential to solve this issue due to its inherent interferometric stability, but homodyne characterisation of quantum states on integrated optical devices has never been demonstrated until now. The recent integration of cryogenically cooled superconductive nanowire single photon detectors [5] has enabled detection of single photons on-chip, but to date more general quantum states of light still need to be coupled off-chip to be characterised.

Here we present the first, to our knowledge, integrated homodyne detector capable of performing measurements of quantum states of light on a silicon-on-insulator optical chip. The device relies on two on-chip germanium photodiodes operating at room temperature and at a wavelength of 1550nm and shows high speed and low noise, with a 3dB bandwidth of 150MHz and a shot-noise clearance of 11dB. These specifications allowed us to perform homodyne tomography of coherent states of different amplitudes with fidelities above 99%.

The integrated homodyne detector was also used to generate random numbers by sampling quadratures of the vacuum state. The numbers were generated at a rate of 1.2Gbps and pass all of the statistical tests provided by the NIST test suite.

References

[1] K. Vogel and H. Risken, ”Determination of quasiprobability distributions in terms of probability distributions for the rotated quadrature phase”, Phys. Rev. A, vol. 40, pp. 2847-2849, Sep 1989.

[2] S. Rahimi-Keshari, A. Scherer, A. Mann, A. T. Rezakhani, A. I. Lvovsky, and B. C. Sanders, ”Quantum process tomography with coherent states”, New Journal of Physics, vol. 13, no. 1, p. 013006, 2011.

[3] S. L. Braunstein and P. van Loock, ”Quantum information with continuous variables”, Rev. Mod. Phys., vol. 77, pp. 513-577, Jun 2005.

[4] A. I. Lvovsky, ”Iterative maximum-likelihood reconstruction in quantum homodyne tomography,” Journal of Optics B: Quantum and Semiclassical Optics, vol. 6, p. S556, 2004.

[5] S. Khasminskaya, F. Pyatkov, K. S lowik, S. Ferrari, O. Kahl, V. Kovalyuk, P. Rath, A. Vetter, F. Hennrich, M. M. Kappes, Gol’tsmanG., KorneevA., C. Rockstuhl, R. Krupke, and W. H. P. Pernice, ”Fully integrated quantum photonic circuit with an electrically driven light source”, Nat Photon, vol. 10, pp. 727-732, nov 2016.

Observation of Majorization Principle for quantum algorithms via 3-D integrated photonic circuits

Fulvio Flamini[1], *Niko Viggianiello*[1], *Taira Giordani*[1], *Marco Bentivegna*[1], *Nicolò Spagnolo*[1], *Andrea Crespi*[2,3], *Giacomo Corielli*[2], *Roberto Osellame*[2,3], *Miguel Angel Martin-Delgado*[4] and *Fabio Sciarrino*[1]

[1]*Dipartimento di Fisica, Sapienza Università di Roma, Piazzale Aldo Moro 5, I-00185 Roma, Italy*
[2]*Istituto di Fotonica e Nanotecnologie, Consiglio Nazionale delle Ricerche (IFN-CNR), Piazza Leonardo da Vinci, 32, I-20133 Milano, Italy*
[3] *Dipartimento di Fisica, Politecnico di Milano, Piazza Leonardo da Vinci, 32, I-20133 Milano, Italy*
[4]*Departamento de Física Teórica I, Universidad Complutense, Parque de las Ciencias 1, 28040 Madrid, Spain*

The Majorization Principle is a fundamental statement ruling the dynamics of information processing in optimal and efficient quantum algorithms. They are conjectured to obey a quantum arrow of time governed by the Majorization Principle: the probability distribution associated to the outcomes gets ordered stepby- step until achieving the result of the computation [1]. We have observed experimentally the Majorization Principle in two quantum algorithms, namely the quantum fast Fourier transform (qFFT) and a recently introduced validation protocol for the certification of genuine many-boson interference [2]. The demonstration has been performed through integrated 3-D photonic circuits fabricated via femtosecond laser writing technique [3], which allows to monitor unambiguously the effects of majorization along the execution of the algorithms. The measured observables provide a strong indication that the Majorization Principle holds true for this wide class of quantum algorithms, thus paving the way for a general tool to design new optimal algorithms with a quantum speedup.

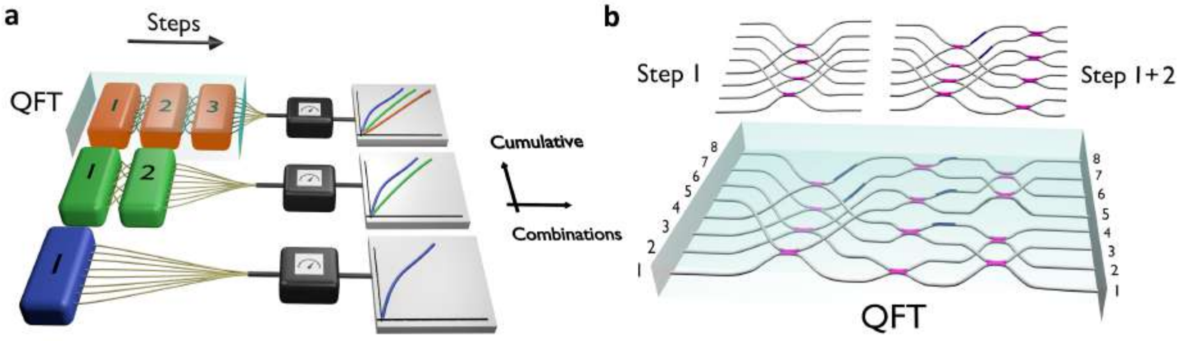


Figure 1: **The Majorization Principle in quantum algorithms.** a) The experimental observation of the Majorization Principle is performed comparing the cumulative probabilities of the quantum register after different numbers of steps in the algorithm (blue: 1; green: 2; orange 3). b) By exploiting the 3-D capability of the femtosecond laser writing we can effciently decompose the evolution in a logarithmic number of steps, corresponding to the partial instance of the qFFT, between which a step-by-step majorization is observed.

References

[1] J. I. Latorre and M. A. Martin-Delgado, Majorization arrow in quantum-algorithm design. Phys. Rev. A **66**, 022305

[2] M. C. Tichy, K. Mayer, A. Buchleitner, and K. Mlmer, Stringent and efficient assessment of Boson-Sampling devices. Phys. Rev. Lett. **113**, 020502

[3] R. Osellame, S. Taccheo, M. Marangoni, R. Ramponi, P. Laporta, D. Polli, S. De Silvestri, and G. Cerullo, Femtosecond writing of active optical waveguides with astigmatically shaped beams. J. Opt. Soc. Am. B **20**, 1559.

Pure downconversion photons through sub-coherence length domain engineering

***Francesco Graffitti*[1]*, Dmytro Kundys*[1]*, Derryck T. Reid*[1]*, Agata Brańczyk*[2]*, Alessandro Fedrizzi*[1]**

[1]*Scottish Universities Physics Alliance (SUPA), Institute of Photonics and Quantum Sciences,*
School of Engineering and Physical Sciences, Heriot-Watt University, Riccarton, Edinburgh EH14 4AS, UK
[2]*Perimeter Institute for Theoretical Physics, Waterloo, Ontario, N2L 2Y5, Canada*

Photonic quantum technology relies on efficient sources of coherent single photons, the ideal carriers of quantum information. Heralded single photons from parametric downconversion (PDC) can approximate on-demand single photons to a desired degree, but in a typical heralded PDC source the signal photon emerges in a spectrally mixed state due to strong (anti)correlation in the joint spectrum of PDC photon pairs. One method for reducing spectral correlations is spectral filtering, but this compromises the heralding efficiency and brightness of the source and introduces mixture in other degrees of freedom: further source engineering is therefore required to enhance the signal photon purity. To this end, several studies have introduced domain-engineering techniques for controlling the spectral response of a poled nonlinear crystal by shaping its phase matching function (PMF).

In our recent work [1], we propose crystal nonlinearity engineering techniques with sub-coherence-length domains. We first introduce a combination of two existing methods: a deterministic approach with coherence-length domains [2] and probabilistic domain-width annealing [3]. We then show how the deterministic domain-flip approach can be implemented with sub-coherence length domains, allowing a sensibly higher flexibility in tailoring the PMF with respect to other engineering methods. Our new techniques are fast, can readily be implemented commercially, and create high purity photons outperforming previous algorithms in particular for short nonlinear crystals matched to femtosecond pump lasers (see fig.1). We experimentally characterise our method through a high-precision measurement of multi-photon interference between two heralded photons generated by two independent sources. We also show that by considering sub-coherence-length domains it is possible to generalise the algorithm in [2] to the case of complex target field amplitude, allowing us to approximate more exotic cases such as complex-chirped nonlinearity profiles or antisymmetric PDC joint spectra.

We expect that the versatility of our new domain engineering techniques can offer a range of interesting applications both in single photon generation through four-wave mixing in integrated photonics as well as in 'classical' nonlinear optics for which domain engineering was originally designed.

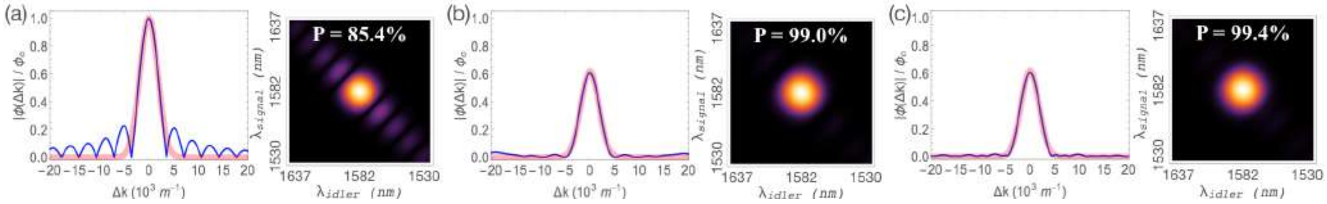


Figure 1: Phase matching function and corresponding joint spectral amplitudes and purities for a short (2 mm) KTP crystal. (a) Standard ppKTP crystal having a sinc-shaped PMF. (b,c) Crystal engineered with our new methods: annealing (b) and sub-coherence length domains (c). Our new algorithms provides an improvement in the heralded photon's purity of about 2% with respect to the algorithm proposed in [2].

References

[1] F. Graffitti, D. Kundys, D.T. Reid, A.M. Brańczyk and A. Fedrizzi, "Pure down-conversion photons through sub-coherence length domain engineering", Preprint at arXiv:1704.03683 (2017).

[2] J. Tambasco, A. Boes, L. Helt, M. Steel, and A. Mitchell, "Domain engineering algorithm for practical and effective photon sources", Optics express **24**, 961619626 (2016).

[3] D. Reid, "Engineered quasi-phase-matching for second- harmonic generation", Journal of Optics A : Pure and Applied Optics **5**, S97 (2003).

Quantum state engineering using the one dimensional discrete time quantum walk

Luca Innocenti[1], *Helena Majury,*[1,2] *Alessandro Ferraro*[1], *Mauro Paternostro,*[1] *Nicolò Spagnolo*[3], *Fabio Sciarrino*[3]

[1]*Centre for Theoretical Atomic, Molecular and Optical Physics,*
School of Mathematics and Physics, Queen's University, Belfast BT7 1NN, United Kingdom
[2] *Centre for Secure Information Technologies (CSIT), Queens University, Belfast BT7 1NN, United Kingdom,*
[3] *Dipartimento di Fisica, Sapienza Universita` di Roma, Piazzale Aldo Moro 5, I-00185 Roma, Italy,*

The ability to generate arbitrary quantum states is far reaching both from a fundamental and from an applied point of view, and at the core of many recent quantum technologies. Engineering entangled states in high-dimensional Hilbert spaces is however a generally hard task for state of the art technologies. We show how a coined discrete-time quantum walk on a line [1, 2, 3], using a coin operator changing at every step, can be used to generate arbitrary quantum states in the Hilbert space of a single high-dimensional qudit.

The system under consideration is that of a *quantum walker*, having a position degree of freedom, and a 2-dimensional *coin* degree of freedom. The position is initially fixed at some initial site. The walker is evolved for a number *n* of discrete steps. At every step 1) a unitary *coin operator* changes the state of the coin, without affecting the position degree of freedom of the walker, and 2) a *shift operator* changes the position of the walker conditionally to its coin state. The coin operator is usually chosen to be fixed at all steps, but with this restriction there is very little freedom in the quantum states resulting after a fixed number of steps.

Allowing the coin to vary at every step, we show that an appropriate choice of coin operators allows the walker to result in any target superposition of position states, after projection on a suitable coin state at the end of the walk. For this purpose we develop a set of necessary and sufficient conditions for a state in the position + coin space to be a possible output for a quantum walk evolution. From this conditions we derive a constructive way to compute all the coin operators that must be used to generate a specific final target state. We also present a numerical way to compute these coin operators using global optimization techniques.

Finally, we present a novel experimental proposal for the implementation of the above protocol with linear optics, using the orbital angular momentum and the polarization of a photon as position and coin degrees of freedom.

References

[1] Y. Aharonov, L. Davidovich, and N. Zagury, "Quantum random walks", Phys. Rev. A 48, 1687–1690 (1993).
[2] A. Ambainis, E. Bach, A. Nayak, A. Vishwanath, and J. Watrous, "One-dimensional quantum walks", Proc. 33th STOC, pages 60–69, New York, NY, (2001).
[3] S. E. Venegas-Andraca, "Quantum walks: a comprehensive review", Quantum Inf Process, 11:1015–1106 (2012).

Quantum non-Gaussianity of multi-photon light

Lukáš Lachman, Ivo Straka, Josef Hloušek, Martina Miková, Michal Mičuda, Miroslav Ježek, Radim Filip

Department of Optics, Faculty of Science, Palacký University,
17. listopadu 1192/12, 771 46 Olomouc,
Czech Republic

Quantum attributes of light has been so far related to in-compability with mixtures of coherent states. The progress in quantum optics indicates that this feature do not suffice to witness exotic behavior of light anymore. On the other hand, quantum non-Gaussianity is starting to appear as a promising property reflecting interesting states of light suitable for quantum protocols [1]. We introduce hierarchy of criteria of quantum non-Gaussianity and predict this attribute can be observed on states of light with high mean number of photons even when the light is attenuated above fifty percent [2]. These criteria test click statistics gained on an array of beam splitters and avalanche photo-diodes and therefore they are suitable for many experimental platforms.

References

[1] M. Lasota, R. Filip, V. C. Usenko, ”Sufficiency of quantum non-gaussianity for discrete-variable quantum key distribution”, arXiv:1603.06620 (2016).
[2] I. Straka, L. Lachman, J. Hloušek, M. Miková, M. Mičuda, M. Ježek, Radim Filip, ”Quantum Non-Gaussian Multiphoton Light”, arXiv:1611.02504 (2016).

Programmable quantum state engineering in multimode fibers

***Saroch Leedumrongwatthanakun*[1], *Luca Innocenti*[2], *Hugo Defienne*[1,3],*Thomas Juffmann*[1,4],**
***Alessandro Ferraro*[2], *Mauro Paternostro*[2], *Sylvain Gigan*[1]**

[1]*Laboratoire Kastler Brossel, UMR8552 Université Pierre et Marie Curie, Ecole Normale Supérieure, Collège de France, CNRS, 24 rue Lhomond, 75005 Paris, France*
[2]*Centre for Theoretical Atomic, Molecular and Optical Physics, School of Mathematics and Physics, Queens University Belfast, Belfast BT7 1NN, UK*
[3]*Department of Electrical Engineering, Princeton University, Princeton, NJ, 08544, USA*
[4]*Physics Department, Stanford University, 382 Via Pueblo Mall, Stanford, California 94305, USA*
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Programmable two-photon quantum walks through a multimode fiber, acting as a linear coherent 100s-mode optical platform, can be implemented by using the knowledge of its transmission matrix in combination with spatial wavefront modulation of two photons. We demonstrate that the two-photon quantum interference between two modes distributed among different spatial-polarization modes can be programmed from Hong-Ou-Mandel bunching effect to photon antibunching.

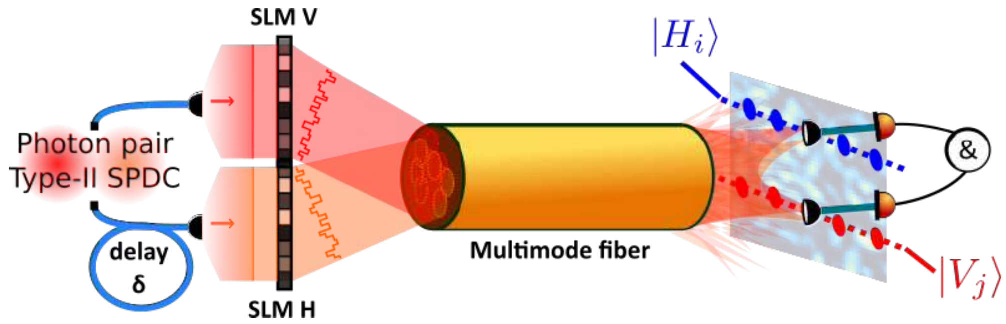

Figure 1: Programmable two-photon quantum walks through a multimode fiber: The transverse wavefronts of two-photon generated from a type-II colinear SPDC are independently modulated by the spatial light modulators (SLM V and SLM H). The high-dimensional entangled states can be engineered on desired output modes.

Propagation of indistinguishable photons in a complex manner allows designing useful high-dimensional states. The ability to address the dimensionality and a class of the states is promising. We will describe our theoretical and experimental efforts towards generating high-dimensional one- and two-photon multipartite entangled states, namely W states and Dicke states. This work paves the way for controllable photonic state-engineering strategies based on random media and wavefront shaping.

Perfect probabilistic storing and retrieving of unitary channels

***Michal Sedlák*[1], *Alessandro Bisio*[2], *Mário Ziman*[1]**

[1] *RCQI, Institute of Physics, Slovak Academy of Sciences, Dúbravská cesta 9, 84511 Bratislava, Slovakia*
[2] *QUIT group, Dipartimento di Fisica, INFN Sezione di Pavia, via Bassi 6, 27100 Pavia, Italy*

Soon after the first quantum algorithms emerged also the questions of universal quantum devices were investigated. One can imagine having universal cloner, processor or a multimeter. In such a device one part of quantum system would serve as the data register and the other as a program register, which determines an operation to be performed on the data. Although such devices would be very useful, they are not allowed by quantum mechanics in their ideal form. For cloners we have no cloning theorem, linearity restricts also multimeters and for quantum processors Nielsen and Chuang proved that error free implementation of k distinct unitaries requires k dimensional program register, which is effectively a No-programming theorem. These restrictions can be treated in two ways. Either we ask for approximate devices, which always produce an output, or we require the device to be probabilistic, but if it is successful it always produces a perfect (precise) output. Study of optimal cloners proved to be useful and this motivates also the study of other universal devices. Recently, cloning was considered for quantum operations [1]. This unveiled unexpected feature called super-replication [2] in which one can deterministically generate with an exponentially small error up to N^2 copies of a single-qubit unitary operation U starting only from N copies. While studying cloning of unitary transformations it was realized there is a closely related task, which only differs in the causal order of available resources. While in cloning the cloned transformation is available after we have the input states for the clones, one can consider also a task where the order is reversed.

Consider a set of unitary channels on the d dimensional Hilbert space. Suppose one of these channels, further denoted as $\mathscr{U}$, is chosen randomly and we have access only to N uses of it today. Our aim is to propose a strategy that contains channel $\mathscr{U}$ N-times and stores it in a state of a quantum memory. This phase of the task is called storing. Later, after we lost access to $\mathscr{U}$, we are requested to apply $\mathscr{U}$ on an unknown state ξ. Our goal is to choose storing and retrieving strategy in such a way that we would be able to retrieve channel $\mathscr{U}$. This task was first considered in the approximative way by Bisio et.al. [3]. Our goal is to study the perfect probabilistic version of the problem, and we call the task *perfect probabilistic storing and retrieving of a unitary channel*. The main difference is that we want to retrieve the quantum channel from the quantum memory only without error and with highest possible probability P_S, which we require to be the same for all unitary transformations $U \in SU(d)$.

We derived the following results with the use of the formalism of quantum combs. We found the optimal probability of success of perfect probabilistic storing and retrieving of a qubit unitary channel from its N uses and it reads $P_S = N/(N+3)$. We investigated also the qudit version of the problem (d arbitrary) and until now we were able to solve $N = 1$ up to $N = 5$ setting. All the results we have found can be described by the formula $P_S = N/(N-1+d^2)$, which suggests a conjecture that the previous formula holds for N and d arbitrary. Very recently, we managed to reduce the general problem to a linear program for optimization of probability distributions and we believe that soon we will either verify or reject the above conjecture. Our current results have surprising features. Let us start by comparison with the approximate version of the problem (termed quantum learning). Optimal solution of the approximate version turns out to be an estimate and prepare strategy, thus quantum memory is not essentially needed. In contrast for our problem quantum memory can not be avoided. Our results have implication also for covariant probabilistic universal quantum processors. One of the main questions for them is the relation between the dimension of the program register and the probability of success. This question although very important is still unsolved even for this specific class of processors, where the relation of the program state to the implemented unitary transformation is specified by some representation $W(U)$ of the special unitary group $SU(d)$ and the success probability is the same for all unitaries. Our results imply a lower and an upper bound on the dimension of the program register for a given probability of success P_S.

References

[1] G. Chiribella, G.M. DAriano, and P. Perinotti, Phys. Rev. Lett. 101, 180504 (2008)
[2] G. Chiribella, Y. Yang, and C. Huang, Phys. Rev. Lett. 114, 120504 (2015).
[3] A. Bisio, G. Chiribella, G. M. D'Ariano, S. Facchini, P. Perinotti, Phys. Rev. A 81, 032324 (2010)

On-chip monolithic integration of heralded single photons sources and beam splitters

***J. Belhassen*[1], *Y. Haoulia*[1], *Q. Yao*[1], *G. Boucher*[1], *A. Lemaître*[2], *M. Amanti*[1], *F. Baboux*[1], *S. Kolthammer*[3], *I. Walmsley*[3], *S. Ducci*[1]**

[1]*Laboratoire Matériaux et Phénomènes Quantiques, Université Paris Diderot, Sorbonne Paris Cité, CNRS-UMR 7162, 75205 Paris Cedex 13, France*
[2]*Centre de Nanosciences et de Nanotechnologies, CNRS/Université Paris Sud, UMR 9001, 91460 Marcoussis, France*
[3]*Clarendon Laboratory, Oxford University, Parks Road, Oxford OX1 3PU, United Kingdom*

Nonclassical light sources and linear optical components are essential tools for quantum information; the integration of these elements in a single chip is a key issue for future quantum processors. Among the different platforms for quantum photonics AlGaAs is particularly attractive, since it combines high second order nonlinearity, direct bandgap and electro-optics effect. These properties have already led to the demonstration of electrically driven two-photon sources based on spontaneous parametric down-conversion [1], to the generation of biphoton states with high level of entanglement [2,3] and to photonic circuits manipulating quantum states [4].

In this work, we report the design, fabrication and characterization of the monolithic integration of a source of heralded photons with a 50/50 beam splitter. The sample is grown by molecular beam epitaxy using a (100)-oriented GaAs substrate, and processed by reactive ion etching to design a beamsplitter having straight waveguides as input and output ports. This beamsplitter is a multimode interferometer, which has been characterized in terms of optical losses, splitting ratio and sensitivity to polarization. Photon pairs are generated through type II spontaneous parametric down conversion. Among the two photons generated, one of them is used as herald (the one directly outgoing from the straight waveguide), while its twin enters the beamsplitter (Figure 1). This configuration allows to realize an integrated Hanbury-Brown and Twiss experiment, by measuring the coincidences between the two outputs of the beamsplitter. The extracted autocorrelation function $g^{(2)}(\tau)$, which characterizes the statistical properties of the emitted light [5], serves as a benchmark for the integrated source and beamsplitter.

Results show a $g^{(2)}(0)$ value of 0.10, demonstrating the non-classical nature of the generated photons. Due to their robustness, adjustable splitting ratio, and their easy implementation, waveguide beamsplitters with internal generation of photon pairs provide a promising step towards fully integrated quantum circuits.

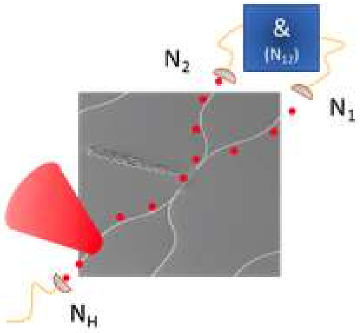

Figure 1: Principle of the on-chip heralded Hanbury-Brown and Twiss measurement.

References

[1] F. Boititer *et al.*, Phys. Rev. Lett. **112**, 183901 (2014).
[2] A. Orieux *et al.*, Phys. Rev. Lett. **110**, 160502 (2013).
[3] C. Autebert *et al.*, Optica **3**, 143-146 (2016).
[4] J. Wang *et al.*, Opt. Comm. **327**, 49-55 (2014).
[5] A. B. Uren *et al.*, Phys. Rev. A **72**, 021802 (R) (2005).

Direct characterisation of a nonlinear photonic circuit's wave function with laser light

***Francesco Lenzini*[1]*, Alexander N. Poddubny*[2,3,4]*, James Titchener*[4]*, Paul Fisher*[1]*, Andreas Boes*[5]*, Sachin Kasture*[1]*, Ben Haylock*[1]*, Matteo Villa*[1]*, Arnan Mitchell*[5]*, Alexander S. Solntsev*[4]*, Andrey A. Sukhorukov*[4]*, and Mirko Lobino*[1,6,*]**

[1]*Centre For Quantum Dynamics, Griffth University, Brisbane QLD 4111, Australia*
[2]*ITMO University, Saint Petersburg 197101, Russia*
[3]*Ioffe Institute, Saint Petersburg 194021, Russia*
[4]*Nonlinear Physics Centre, Research School of Physics and Engineering, Australian National University, Canberra ACT 2601, Australia*
[5]*School of Engineering, RMIT University, Melbourne VIC 3000, Australia*
[6]*Queensland Micro- and Nanotechnology Centre, Griffth University, Brisbane QLD 4111, Australia*
[*]*m.lobino@griffith.edu.au*

As integrated photonic circuits for quantum technologies grow in complexity, efficient methods for their characterisation become essential. A previous solution, Stimulated Emission Tomography [1], uses only laser light and standard optical power meters to reconstruct the two-photon state produced by a nonlinear optical circuit. However, the technique has been shown to be intolerant to any losses of light [2] and difficult to scale, requiring full knowledge of the circuit's linear optical properties [3]. In our work, we propose and demonstrate a fast, reliable method based on sum frequency generation which works regardless of propagation losses and can be applied to any arbitrary nonlinear optical circuit [4].

We applied this protocol to a multi-channel nonlinear waveguide network which we designed using the technique of quantum state engineering with specialised poling patterns [2], and fabricated in lithium niobate using reverse proton exchange [5]. Using both our protocol and single photon coincidence counting, we measured a $99.28 \pm 0.31\%$ fidelity between quantum and classical characterisation.

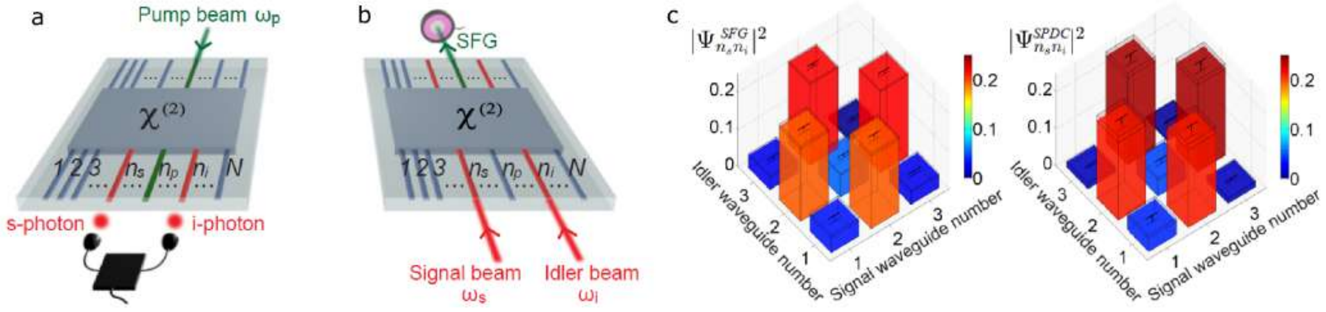

Figure 1: **a.** Generation of photon pairs by SPDC with a particular output state from the device. **b.** Reconstruction of the two photon state by SFG measurements. **c.** Comparison between relative squared amplitudes of the wavefunction elements predicted by SFG and measured by coincidence counting.

References

[1] M. Liscidini, and J. E. Sipe, "Stimulated emission tomography", Phys. Rev. Lett. **111**, 193602 (2013).
[2] J. G. Titchener, A. S. Solntsev, and A. A. Sukhorukov, "Generation of photons with all-optically-reconfigurable entanglement in integrated nonlinear waveguides", Phys. Rev. A **92**, 033819 (2015).
[3] L. G. Helt, and M. J. Steel, "Effect of scattering loss on connections between classical and quantum processes in second-order nonlinear waveguides", Opt. Lett. **40**, 1460 (2015).
[4] F. Lenzini, et al., "Direct characterization of a nonlinear photonic circuit's wave function with laser light", Preprint at arXiv:1703.01007 (2017).
[5] F. Lenzini, S. Kasture, B. Haylock, and M. Lobino, "Anisotropic model for the fabrication of annealed and reverse proton exchanged waveguides in congruent lithium niobate", Opt. Express **23**, 1748 (2015).

Experimental implementation of three- and four-qubit linear-optical quantum logic circuits

R. Stárek, M. Mičuda, M. Miková, I. Straka, M. Dušek, P. Marek, M. Ježek, R. Filip, J. Fiurášek

Department of Optics, Palacký University, 17. listopadu 1192/12, 77146 Olomouc, Czech Republic

Proof of principle experiments realized with bulk linear optics are the testing ground for the design of integrated optical circuits. Here, we present an experimental demonstration of a three- and four-qubit linear-optical quantum logic circuits. Our robust and versatile schemes exploit encoding of two qubits into polarization and path degrees of freedom of single photons, and involve several inherently stable interferometers. This approach allows us to design complex quantum logic circuits that combine several single- and multi-qubit gates and can realize genuine three-qubit quantum Fredkin and four-qubit quantum Toffoli gates [1]. Although every quantum circuit can be realized using single and two-qubit gates, the Fredkin gate as well as the Toffoli gate are essential since they can simplify the structure of quantum circuits dramatically. The Fredkin gate (known as controlled-SWAP) swaps two target qubits if and only if the control qubit is in the logical state $|1\rangle$. The four-qubit Toffoli gate (known as controlled-controlled-controlled-NOT) flips the logical state of a target qubit if and only if three control qubits are in state $|1\rangle$. Even though both circuits allow deterministic implementation of single and two-qubit gates, the overall schemes are probabilistic due to the nature of the used three and four-qubit controlled-Z gate which is realized by two-photon interference on an unbalanced beam splitter [2].

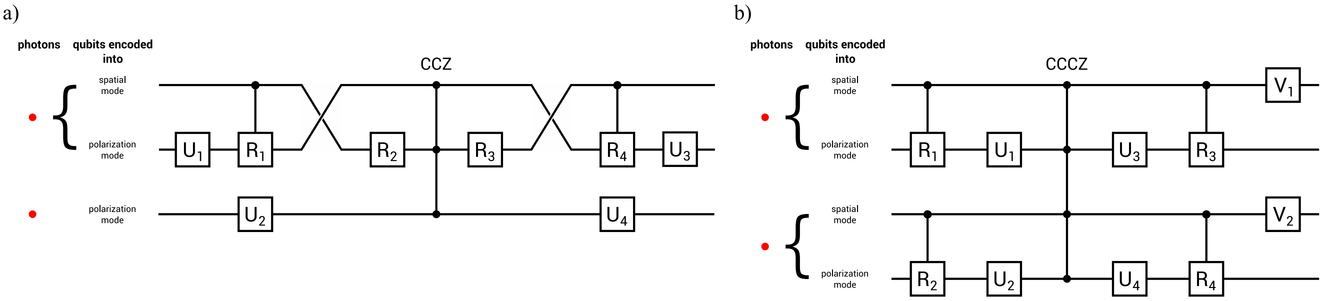

Figure 1: Schemes of the implemented a) three-qubit, b) four-qubit logic circuit.

Both linear-optical quantum logic circuits are shown in Fig. 1. Single-qubit unitary gates $\mathrm{R_j}$ and $\mathrm{U_j}$ are implemented in polarization modes by rotable half-wave plates, and sequences of a rotable half-wave plates and quarter-wave plates, respectively. The two-qubit controlled rotation gates $\mathrm{CR_j}$ are realized by a rotating half-wave plate which is inserted only in one arm of a Mach-Zehnder interferometer supporting the spatial qubit. Single-qubit phase gates $\mathrm{V_j}$ are achieved by changing optical phase in Mach-Zehnder interferometer.

We have performed a process reconstruction of the implemented Fredkin and four-qubit Toffoli gate using full quantum process tomography and Monte Carlo sampling procedure, respectively. The achieved gate fidelity for Fredkin gate yielded F=0.901(1) and for Toffoli gate F_{MC}=0.912(42) with uncertainty of F_{MC} estimated to 0.011.

References

[1] R. Stárek, M. Mičuda, M. Miková, I. Straka, M. Dušek, M. Ježek, and J. Fiurášek, “Experimental investigation of a four-qubit linear-optical quantum logic circuit,” Sci. Rep. **6**, 33475 (2016).

[2] M. Mičuda, M. Sedlák, I. Straka, M. Miková, M. Dušek, M. Ježek, and J. Fiurášek, “Efficient experimental estimation of fidelity of linear optical quantum Toffoli gate,” Phys. Rev. Lett. **111**, 160407 (2013).

Probing the measurement process in Discrete-Time Quantum Walks via recurrence

***Thomas Nitsche*[1], *Regina Kruse*[1], *Linda Sansoni*[1], *Martin Štefaňák*[2], *Aurél Gábris*[2,3] *Tamás Kiss*[4], *Igor Jex*[2], *Sonja Barkhofen*[1], *Christine Silberhorn*[1]**

[1]*Applied Physics, University of Paderborn, Warburger Str. 100, 33098 Paderborn, Germany*
[2]*Department of Physics, Czech Technical University in Prague, Břehová 7, 11519 Prague, Czech Republic*
[3]*Department of Theoretical Physics, University of Szeged, Tisza Lajos körút 84, H-6720 Szeged, Hungary*
[4]*Wigner Research Centre for Physics, Hungarian Academy of Sciences, P.O. Box 49, H-1525 Budapest, Hungary*

The measurement process plays a crucial role in quantum mechanics as it interrupts the unitary evolution of a state. The consequences are apparent when investigating the return probability (Polya-number) of a particle in a Hadamard walk on the line [1,2]: Depending on whether the evolution is influenced by a measurement, either a transient or a recurrent evolution can be observed. We investigate both cases experimentally in a time-multiplexed architecture [3] and monitor the evolution of the walker over 39 steps, revealing the fundamental differences of the two cases as predicted by theory: In the measurement-free-regime, the Polya-number will gradually approach 1. In contrast, the measurement-induced-regime yields an asymptotic value of $2/\pi$.

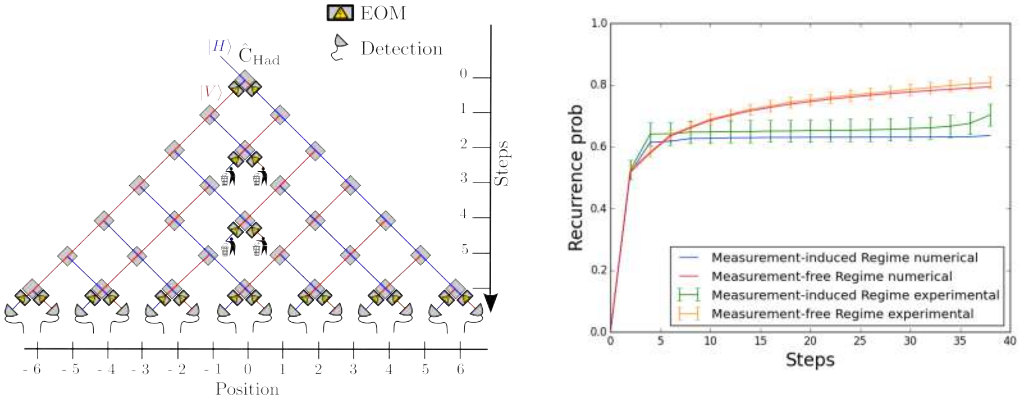

Figure 1: left: Illustration of the implementation of a sink at position 0. right: The experimental and numerical return probabilities for the measurement-free- and the measurement-induced-regime.

We enhance the established architecture of a time-multiplexing quantum walk setup [3] by adding the possibility of dynamic and deterministic outcoupling, which is crucial for probing measurement-induced effects.

In order to probe the two different regimes of recurrence, it is necessary to determine the probability that the walker returns to the origin for the first time. When just measuring a photon at the origin, the information how many times before the photon has crossed this distinguished position is not available per se. However, deterministically coupling out all light at the origin (position 0) before examining a certain step ensures that what is eventually detected at position 0 has reached it for the first time (see Fig. 1). We refer to the outcoupling at position 0 as a sink, as light is directed out of the loop not for the detection, but simply to drain the state of all components that do not belong to the state we project onto.

The evolution of the walker is monitored from step 2 to step 39 for both the measurement-free-regime (no sinks) and the measurement-induced-regime (sinks) (see Fig. 1). The experiment exhibits a good overlap with the numerical data and clearly shows the difference between the two regimes.

References

[1] M. Štefaňák, I. Jex, and T. Kiss, PhysRevLett **100**, 020501 (2008)

[2] F. A. Grünbaum, L. Velázquez, A. H. Werner, and R. F. Werner, Commun. Math. Phys. **320**, 543 (2013)

[3] A. Schreiber, A. Gábris, P.P. Rohde, K. Laiho, M. Štefaňák, V. Potoček, C. Hamilton, I. Jex, C. Silberhorn, Science **336**, 6077 (2012)

Integrated DBT molecules on chip as single photon emitters

A. P. Ovvyan [1,2,3,Ω], P. E. Lombardi [2,4,Ω], S. Pazzagli [3,4], G. Mazzamuto [2,4], G. Kewes [5],
O. Neitzke [5], N. Gruhler [1], O. Benson [5], W. H. P. Pernice [1],
F. S. Cataliotti [2,3] and C. Toninelli [2,4]
[1] *Institute of Physics, University of Münster, Münster, Germany*
[2] *LENS, Via Carrara 1, 50019 Sesto F.no, Firenze, Italy*
[3] *Università di Firenze, Via Sansone 1, I-50019 Sesto F.no, Firenze, Italy*
[4] *CNR-INO, Instituto Nazionale di Ottica, Via Carrara 1, 50019 Sesto F.no, Firenze, Italy*
[5] *Nano-Optik, Institut für Physik, Humboldt-Universität zu Berlin, Berlin, Germany*
[Ω] *Contributed equally to this work*

We report coupling of single photons emitted from organic Dibenzoterrylene (DBT) molecules embedded in thin anthracene crystals into ridge Si_3N_4 waveguides at room temperature.
Single DBT molecules show photostable emission at room and cryogenic temperature. Because of good structural matching between the anthracene matrix and the molecules, the zero-phonon lines are very stable against bleaching, thus making DBT a promising single photon source for chip-based quantum applications [1].

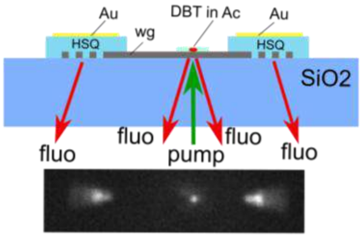

Fig.1. Model of nanophotonic device with integrated DBT molecule with resulting fluorescence signal on EMCCD camera

To characterize the emission properties, we use a nanophotonic device consisting of two grating couplers (input and output ports) connected by a nanophotonic waveguide (fig.1). The grating couplers are covered with a Hydrogen silsesquioxane (HSQ) buffer layer with gold mirror on top to increase the coupling efficiency. The photonic components are prepared from silicon nitride-on-insulator wafers consisting of 175 nm stoichiometric Si_3N_4 on top of 500um glass substrate. The devices are realized with three steps of electron-beam lithography followed by reactive ion etching [2]. Subsequently DBT molecules embedded in anthracene crystals are deposited onto the photonic chip by spin-coating.

We achieve isolated excitation of a single DBT molecule by scanning the sample with a laser beam and detecting the fluorescence signal (λ=780nm) collected from the confocal point of illumination and from the grating couplers. When the molecule is optically pumped (λ=767nm), the fluorescence evanescent field couples into the waveguide and is detected at the grating couplers and the confocal point. Using a Hanbury Brown and Twiss (HBT) setup to measure the second order autocorrelation function we find *antibunching* with $g^{(2)}(0)$=0.50±0.05 from grating couplers and $g^{(2)}(0)$=0.35±0.07 from illumination point.

Our device provides nanoscale foot-print, scalability and dense integration on chip at low cost. Such nanophotonic circuits with efficiently coupled/integrated quantum light sources are promising solutions for on-chip quantum photonics.

References

[1] C. Toninelli, K. Early, J. Bremi, A. Renn, S. Götzinger, V. Sandoghdar, “Near-infrared single-photons from aligned molecules in ultrathin crystalline films at room temperature”, Opt. Express **18**, 6577–6582 (2010)
[2] A.P. Ovvyan; N. Gruhler; S. Ferrari.; W.H.P. Pernice, “Cascaded Mach-Zehnder interferometer tunable filters“, Journal of Optics **18**, 064011 (2016)

Experimental quantum Hamiltonian learning: integrated quantum photonics to learn quantum spin dynamics and models

***S. Paesani*[1], *J. Wang*[1], *R. Santagati*[1], *S. Knauer*[1], *A. A. Gentile*[1], *N. Wiebe*[2], *M. Petruzzella*[3], *J.L. O'Brien*[1], *J.G. Rarity*[1], *A. Laing*[1] and *M.G. Thompson*[1]**

[1] *Quantum Engineering Technology Labs, H. H. Wills Physics Laboratory and Departrtment of Electrical and Electronic Engineering, University of Bristol, BS8 1FD, UK*
[2]*Quantum Architectures and Computation Group, Microsoft Research, Redmond, Washington 98052, USA*
[3]*Department of Applied Physics, Eindhoven University of Technology, P.O. Box 513, Eindhoven, The Netherlands*

The efficient characterization and validation of the underlying model of a quantum physical system is a central challenge in the development of quantum technologies. However, the impossibility to efficiently predict the behaviour of complex quantum models on classical machines makes this challenge to be intractable to classical approaches. The combination of machine learning techniques and quantum information processing has been proposed as an efficient solution [1]. We here present experimental quantum Hamiltonian learning (QHL), where the behaviour of a quantum Hamiltonian model is efficiently predicted by a quantum simulator, and the predictions are contrasted with the data obtained from the quantum system to infer the system Hamiltonian via Bayesian methods [2]. In our experiment the quantum simulation is performed via a silicon quantum photonic chip, classically interfaced with an electron spin in a diamond nitrogen-vacancy center to learn its Hamiltonian via QHL (Fig.1).

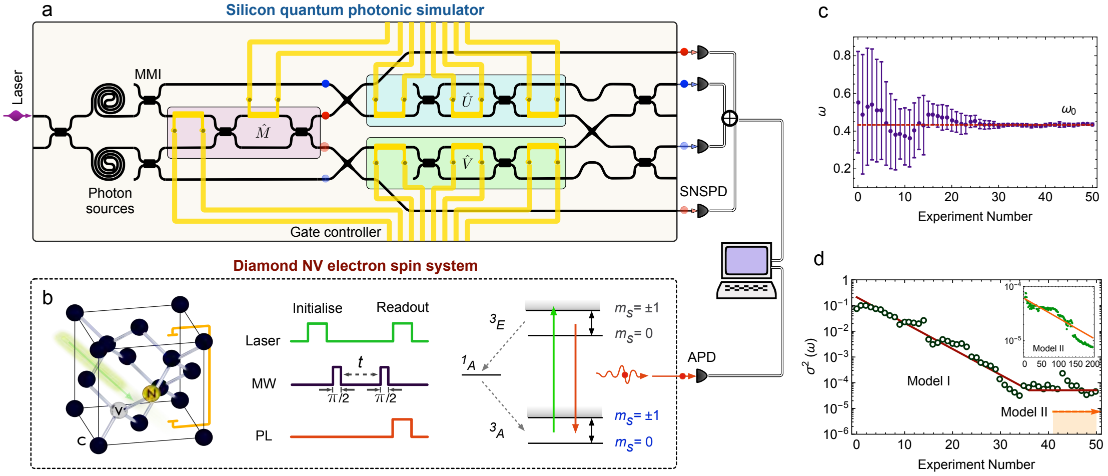

Figure 1: The Silicon photonics quantum simulator in a) is used to learn the Hamiltonian quantum dynamics of the diamond NV electron spin in b). The two different systems are interfaced classically, allowing the implementation of the quantum Hamiltonian learning protocol using classical machine learning techniques. c) Experimental results for the QHL protocol, showing the probability distribution over a normalized frequency $\omega = \nu/\Delta\nu$ converging to the correct value ω_0 of the electron spins Hamiltonian. d) Evolution of the covariance of the distribution during the protocol. The limitations of the Rabi model (Model I) to describe the dynamics are manifested by a saturation of the covariance norm, which indicates a limit in our ability to learn within that model. Using a chirped Rabi model (Model II) we are able to improve the limit, giving evidence that Model II provides a better representation of the real quantum system.

Modelling the spin's Hamiltonian with a Rabi model $\hat{H}(\nu) = \nu\hat{\sigma}_x/2$, we are able to learn the parameter $\nu = 6.93 \pm 0.09$ MHz, which is consistent with the Rabi frequency of the NV spin $\nu_0 = 6.90$ MHz (Fig.1c). Furthermore, in Fig.2d we show how QHL is able to detect limitations of the model to represent the real system, manifested by a saturation of the covariance, and allows us to improve the model itself via an additional chirping parameter (Fig.2d inset). This shows a powerful new application: quantum simulators can learn automatically how to best simulate a quantum system, giving potential key insights on the underpinning quantum physics.

References

[1] N. Wiebe et al., Hamiltonian learning and certification using quantum resources, PRL **112**, 190501 (2014).
[2] J. Wang et al., Experimental quantum Hamiltonian learning, Nature Phys. (2017) doi:10.1038/nphys4074

Transmission of photonic path entanglement through multi-core optical fibers

***Hee Su Park*[1] *and Hee Jung Lee*[1]**

[1]*Korea Research Institute of Standards and Science, Daejeon 34113, South Korea*

Photonic spatial modes are useful information carriers for quantum photonics thanks to their intrinsic infinite dimensionality and relative ease of implementing single-photon unitary operations [1]. This work presents a method to transport high-dimensional spatial quantum states through optical fibers that can ideally realize quantum communication or quantum interface without space restriction. Multiple paths of single photons are respectively coupled to different cores within a common cladding of a multi-core fiber (MCF) shown in Fig. 1. An ideal MCF can preserve the relative phases between the different core-mode components according to propagation. The influence of ambient vibration and temperature change is also suppressed because all the modes share the same medium.

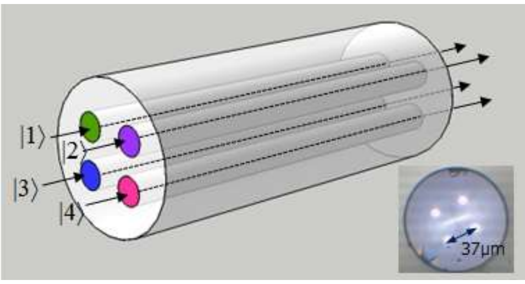

Figure 1: Transmission of single-photon path qudits through a multi-core fiber. Inset: the cross section of the four-core fiber.

To demonstrate the quantum state transmission, we generate spatially entangled photon pairs between two MCFs by spontaneous parametric down-conversion (SPDC). The end faces of the two fibers are imaged on a periodically poled lithium niobate (PPLN) crystal surface with a non-collinear geometry [2]. The two images overlap inside the crystal, therefore when one down-converted photon is coupled to core i ($i = 1, 2, ...$) of the first MCF (MCF1), the other twin photon is coupled to core i of the second MCF (MCF2) [1]. The probability amplitude and phase of each photon pair generation are determined by the field distribution of the pump laser around the core images that can be controlled, for example, by a spatial light modulator (SLM). We use a narrow-band cw diode laser (wavelength 775 nm) as a pump, and commercially-available four-core fibers (Fibercore SM4C1500) to guide the telecom-band (wavelength around 1550 nm) photons. The entangled photon-pair state has a general form:

$$|\Psi\rangle = a|1\rangle_1|1\rangle_2 + b|2\rangle_1|2\rangle_2 + c|3\rangle_1|3\rangle_2 + d|4\rangle_1|4\rangle_2 \ , \tag{1}$$

where $|i\rangle_j$ denotes the single-photon state in core i of MCFj, and a, b, c and d are complex constants.

For measurement of the generated states, photons exiting the MCFs are collimated and reflected by SLMs, respectively, before being coupled into single-mode fibers connected to single-photon counters. The phase pattern on each SLM chooses a core mode or a multi-core superposition state to be projection measured [2]. Quantum state tomography reconstructs the quantum state and verifies the entanglement through entanglement measures. Methods for state engineering and long-distance transmission will further be discussed.

References

[1] S. P. Walborn, D. S. Lemelle, M. P. Almeida, and P. H. S. Ribeiro, "Quantum key distribution with higher-order alphabets using spatially encoded qudits", Phys. Rev. Lett. **96**, 090501 (2006).

[2] H. J. Lee, S.-K. Choi, and H. S. Park, "Experimental demonstration of high-dimensional photonic spatial entanglement between multi-core optical fibers", Preprint at arXiv:1610.04359 (2016).

Entanglement of photons in their dual wave-particle nature

***Adil S. Rab*[1], *Emanuele Polino*[1], *Zhong-Xiao Man*[2], *Nguyen Ba An*[3], *Yun-Jie Xia*[2], *Nicolò Spagnolo*[1], *Rosario Lo Franco*[4,5], *Fabio Sciarrino*[2]**

[1]*Dipartimento di Fisica, Sapienza Università di Roma, Piazzale Aldo Moro, 5, I-00185 Roma, Italy*
[2]*Shandong Provincial Key Laboratory of Laser Polarization and Information Technology, Department of Physics, Qufu Normal University, Qufu 273165, China*
[3] *Shandong Provincial Key Laboratory of Laser Polarization and Information Technology, Department of Physics, Qufu Normal University, Qufu 273165, China*
[4] *Dipartimento di Energia, Ingegneria dell'Informazione e Modelli Matematici, Università di Palermo, Viale delle Scienze, Edificio 9, 90128 Palermo, Italy*
[5]*Dipartimento di Fisica e Chimica, Università di Palermo, via Archirafi 36, 90123 Palermo, Italy*

Wave-particle duality is the most fundamental description of the nature of a quantum object which behaves like a classical particle or wave depending on the measurement apparatus. On the other hand, entanglement represents nonclassical correlations of composite quantum systems, being also a key resource in quantum information. Despite the very recent observations of wave-particle superposition [1-3] and entanglement [4-6], whether these two fundamental traits of quantum mechanics can emerge simultaneously remains an open issue. In this work [7] we introduce and experimentally realize a scheme that deterministically generates wave-particle entanglement of two photons, A and B, in the state: $|\Phi\rangle_{AB} = \frac{1}{\sqrt{2}}(|\text{wave}\rangle_A |\text{wave}\rangle_B + |\text{particle}\rangle_A |\text{particle}\rangle_B)$, where the single-photon states $|\text{wave}\rangle$, $|\text{particle}\rangle$ are defined so that represent respectively the capacity and the incapacity of the photon to produce interference. The elementary tool allowing this achievement is a scalable all-optical single-photon setup which exploits the polarization and the path degrees of freedom of the photon (fig.1). It can be in principle extended to generate multiphoton wave-particle entanglement. Our study reveals that photons can be entangled in their dual wave-particle nature and opens the way to potential applications in quantum information protocols exploiting the wave-particle degrees of freedom to encode qubits.

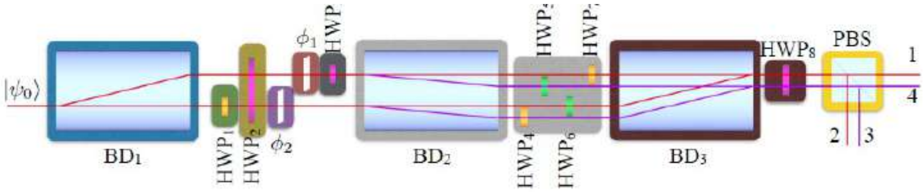

Figure 1: Layout of the experimental implementation of the wave-particle toolbox. Angles of the optical axis orientations for the half-wave plates are: $\text{HWP}_1(45°)$, $\text{HWP}_2(22.5°)$, $\text{HWP}_3(22.5°)$, $\text{HWP}_4(45°)$, $\text{HWP}_5(0°)$, $\text{HWP}_6(0°)$, $\text{HWP}_7(45°)$.

References

[1] Peruzzo, *et al.*, J.L, "A quantum delayed choice experiment", Science, **338**, 634–637 (2012).

[2] Kaiser, *et al.*,"Entanglement-enabled delayed choice experiment", Science, **338**,637–640 (2012).

[3]Tang, J. S., *et al.*,"Realization of quantum Wheeler's delayed choice experiment",Nat. Photon., **6**, 600–604 (2012).

[4] Hensen, B. *et al.*,"Loophole-free Bell inequality violation using electron spins separated by 1.3 kilometres", Nature, **526**, 682–686 (2015).

[5]Giustina, M. *et al.*,"Significant-loophole-free test of bell's theorem with entangled photons", Phys. Rev. Lett., **115**,250401 (2015).

[6] Shalm, L. K. *et al.* ,"Strong loophole-free test of local realism", Phys. Rev. Lett., **115**,250401 (2015).

[7] Rab A.S., *et al.* ,"Entanglement of photons in their dual wave-particle nature", Preprint at arXiv:1702.04146 [quantph].

Joint Spectral Density measurement of energy correlations of photon pairs in an integrated micro-ring resonator

M. Previde Massara[1], D. Grassani[1], A. Simbula[1], M. Galli[1], S. Pirotta[1], T. Baehr-Jones[2], M. Hochberg[2], N. C. Harris[3], C. Galland[4], M. Liscidini[1], and D. Bajoni[1]

1. Universita degli Studi di di Pavia, Italy

2. Coriant Advanced Technology Group, USA

3. Department of Electrical Engineering and Computer Science, Massachusetts Institute of Technology, USA

4École polytechnique fédérale de Lausanne, Switzerland

Compact silicon integrated devices, such as micro-ring resonators, have recently been demonstrated as efficient sources of quantum correlated photon pairs [1,2]. The possibility of mass production of integrated devices requires the implementation of fast and reliable techniques to monitor the device performances. In the case of time-energy correlations, this is particularly challenging, as it requires the reconstruction of the biphoton wavefunction (BPW). This is even more demanding for micro-ring resonators, as the bandwidth of the generated photons is typically tens or hundreds of pm [3,4]. Here we show the reconstruction [5,6] of the Joint Spectral Density (JSD) of photons pairs generated by SFWM in a ring resonator by studying stimulated four wave mixing. We also show that this result can be used to discriminate between the generation of nearly-uncorrelated and highly-correlated photon pairs.

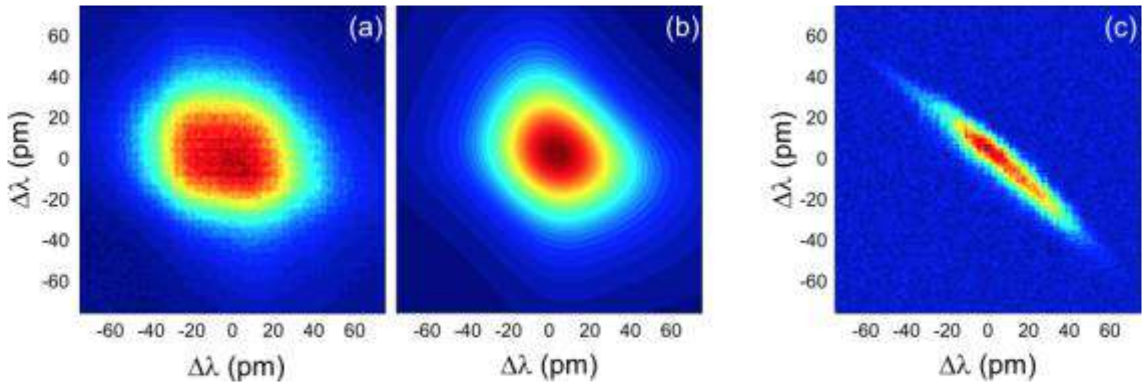

Figure 1: (a) Measured JSD for a 21 ps laser pump pulse and (b) corresponding calculated JSD. (c) Measured JSD in the case of continuous wave pump.

The sample is a ring resonator with Q~40000. In a first experiment we excite the resonator with pulses filtered to a linewidth of 90 pm and use a CW for the signal resonance. In this configuration the generated photons are nearly uncorrelated [7]. The calculated Schmidt number is indeed K=1.09. In Fig. 1(a) and 1(b) we show the corresponding measured JSD and the calculated one, respectively. From the measured JSD, one can calculate a lower bound for the Schmidt number K_{bound}=1.03, which does not take into account the eventual phase correlations. We then use a CW pump to study the generation of pairs of highly-correlated photons. In Fig. 1(c) we show the corresponding measured JSD. This last measurement indicatess that, in contrast to the case of pulsed pumping, the photon pairs are now time-energy correlated.

References

[1] D. Grassani et al., Optica 2.
[2] N.C.Harris et al., PRX 4, 041047 (2014).
[3] S. Azzini et al., Opt. Lett. 37, 3807 (2012).
[4] M. Avenhaus, Opt. Lett. 34, 2873 (2009).
[5] M. Liscidini et al., PRL 111, 193602 (2013).
[6] A. Eckstein et al. Laser Photon. Rev. 8, L76 (2014).
[7] L. G. Helt et al., Opt. Lett. 35, 3006 (2010).

Spatial mode filtering using adiabatic passage and supersymmetric waveguides

***G. Queraltó*[1], *V. Ahufinger*[1], *J. Mompart*[1]**

[1]*Departament de Física, Universitat Autònoma de Barcelona, E–08193 Bellaterra, Spain*

Integrated optical devices exhibiting both high fidelity and high speed transmission are expected to foster novel communication platforms paving the way for scalable photonic quantum technologies. In particular, Space-Division Multiplexing devices [1] have attracted a lot of attention due to the increasing demand of high-capacity optical transmissions being Supersymmetric (SUSY) optical devices [2] one of the most promising alternatives to standard spatial multiplexing devices offering global phase-matching and efficient mode conversion in an integrated and scalable way. SUSY can be applied to Helmholtz optics due to the analogies between the time-independent Schrödinger and Helmholtz equations and offer new ways to control the modal content of light beams in optical waveguides. On the other hand, Spatial Adiabatic Passage (SAP) techniques [3] have been proposed and experimentally reported as a high-efficient and robust method to transfer a light beam between the outermost waveguides in a system of three identical evanescently-coupled waveguides.

We propose to combine SUSY and SAP techniques to design an efficient and robust spatial mode filtering device, which can be used to manipulate and study the modal content of an input field distribution, to filter signals and remove non-desired modes or to mode division multiplexing/demultiplexing applications. It consists of a system of three coupled waveguides, with two identical step-index external waveguides and a supersymmetric central one with the separation between waveguides engineered to optimize spatial adiabatic passage for the first excited spatial mode. We demonstrate that by injecting a superposition of the two lowest transverse electric spatial modes into the left waveguide, the fundamental mode remains in the left waveguide while the first excited mode is fully transmitted into the right waveguide obtaining each spatial mode at a different output. The implementation of SAP techniques in combination with SUSY structures is proposed for the first time giving a great improvement in terms of robustness and efficiency obtaining output fidelities $\mathscr{F} > 0.90$ for a broad range of geometrical parameter values and light's wavelengths, reaching $\mathscr{F} = 0.99$ for optimized values.

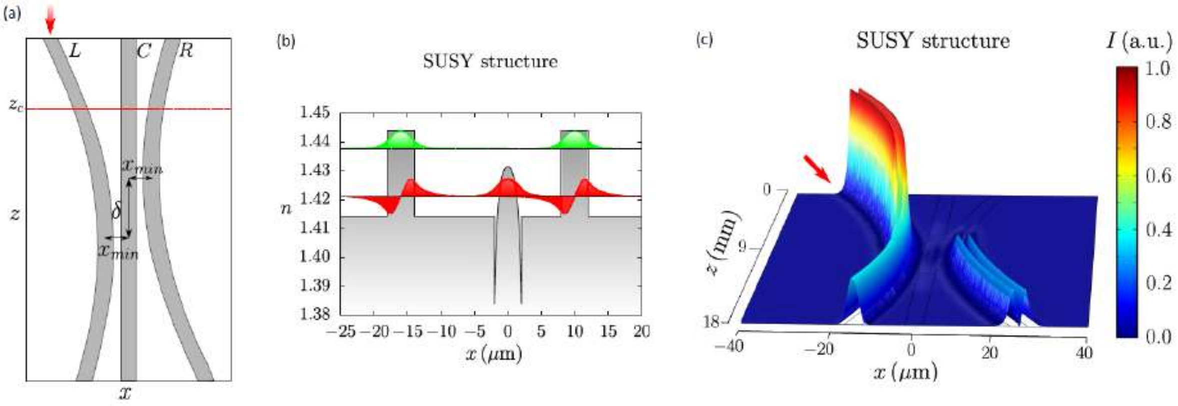

Figure 1: (a) Schematic representation of the proposed mode filtering device viewed from above. (b) Refractive index distribution and transverse mode profiles of each waveguide at z_c (c) Numerical simulations using Finite Difference Methods of light intensity propagation. Parameter values: $\lambda = 1.55\,\mu$m, $\delta = 4$ mm and $x_{min} = 7\,\mu$m.

References

[1] D.J. Richardson, "New optical fibres for high-capacity optical communications", Phil. Trans. R. Soc. A **374**, 20140441 (2016).

[2] M. Heinrich, M.A. Miri, S. Sttzer, R. El-Ganainy, S. Nolte, A. Szameit and N. Christodoulides, "Supersymmetric mode converters", Nat. Commun. **5**, 3698 (2014).

[3] R. Menchon-Enrich, A. Benseny, V. Ahufinger, A.D. Greentree, Th. Busch and J. Mompart, "Spatial adiabatic passage: a review of recent progress" Rep. Prog. Phys. **79**, 074401 (2016).

Generalized Hadamard transformations for validation of multi-particle interference

***Niko Viggianiello*[1], *Andrea Crespi*[2,3], *Fulvio Flamini*[1], *Marco Bentivegna*[1], *Nicolò Spagnolo* [1], *Luca Innocenti*[4], *Daniele Cozzolino*[5], *Daniel J. Brod*[6,7], *Ernesto F. Galvão*[6,7], *Roberto Osellame*[2,3] and *Fabio Sciarrino* [1]**

[1]*Dipartimento di Fisica, Sapienza Università di Roma, Piazzale Aldo Moro 5, I-00185 Roma, Italy*
[2]*Istituto di Fotonica e Nanotecnologie, Consiglio Nazionale delle Ricerche (IFN-CNR), Piazza Leonardo da Vinci, 32, I-20133 Milano, Italy*
[3] *Dipartimento di Fisica, Politecnico di Milano, Piazza Leonardo da Vinci, 32, I-20133 Milano, Italy*
[4]*Centre for Theoretical Atomic, Molecular and Optical Physics, School of Mathematics and Physics, Queens University, Belfast BT7 1NN, United Kingdom*
[5]*Department of Photonics Engineering, Technical University of Denmark, 2800 Kgs. Lyngby, Denmark*
[6] *Perimeter Institute for Theoretical Physics, 31 Caroline Street North, Waterloo, ON N2L 2Y5, Canada*
[7]*Instituto de Fsica, Universidade Federal Fluminense, Av. Gal. Milton Tavares de Souza s/n, Niteroi, RJ, 24210-340, Brazil*

Recently, interference of multi-particle states has raised a strong interest in the scientific community, since it is believed to be at the very heart of post-classical computation. In this context, Boson Sampling [1] devices exploit multi-photon interference effects to provide evidence of a superior quantum computational power with current state-of-the-art technology. Thus, the capability to correctly certify the presence of multi-particle interference and find optimal platforms, becomes a crucial task because is expected to find numerous applications in photonic quantum information as a diagnostic tool for quantum optical devices.

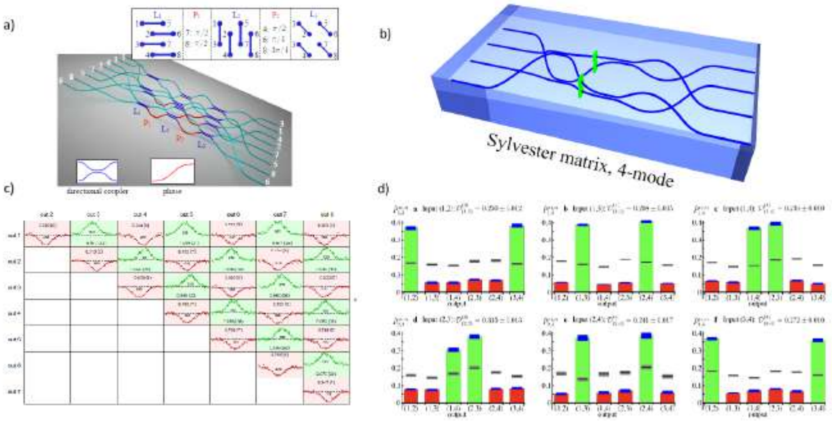

Figure 1: a) Internal structure of 8-mode integrated interferometers implementing the symmetric matrix over the optical modes. The mode arrangement has been chosen in a way to minimize bending losses. b) internal structure of a 4-mode Sylvester matrix. c) Complete set of 28 measured 2- fold coincidence patterns (raw experimental data) for all output combinations in the 8-mode chip. d) Complete set of 2-indistinguishable photon input-output counts in a scattershot configuration for a 4-mode Sylvester. Grey bars: distinguishable case.

We investigate different scenarios, namely, when the consider only a fixed set of input modes, but also for the situation where all input sets can be used. We find that, in certain cases, the best choice for this task consist of Hadamard [2-4] interferometers which we implemented with a novel architecture enabled by the 3D capabilities of femtosecond laser writing. We derive and experimentally demonstrate a novel zero-transmission law based on symmetric interferometers (Fig. 1) and we verifyied the optimality of these platforms by performing further Bayesian analysis and by maximizing the total variation distance between the probability distributions corresponding to indistinguishable and distinguishable particles. The results suggest an immediate application for scattershot Boson Sampling experiments [5], where an exponential advantage in terms of generation rate is obtained with respect to the fixed-input problem. The main advantage of this technique consists in the large fraction of input-output suppressed combinations when these trasformations are injected with indistinguishable photons. In summary, this work represents a further step for quantum interference analysis and it is worth noting that Hadamard matrices naturally appear as the optimal designs for identifying genuine photonic indistinguishability in multimode interferometers and a powerful tool to validate Boson Sampling experiments.

We aknowledge QUCHIP and 3D-Quest for funding this work.

References

[1] S. Aaronson and A. Arkhipov, The computational complexity of linear optics. *In ACM Press, editor, Proceedings of the 43rd annual ACM symposium on Theory of Computing*, pages 333342, (2011).

[2] A. Crespi, Suppression laws for multiparticle interference in sylvester interferometers. Phys. Rev. A **91**, 013811 (2015).

[3] A. Crespi, R. Osellame, R. Ramponi, M. Bentivegna, F. Flamini, N. Spagnolo, N. Viggianiello, L. Innocenti, P. Mataloni, and F. Sciarrino, Suppression law of quantum states in a 3d photonic fast fourier transform chip. Nature Commun. **7**, 10469 (2016).

[4] N. Viggianiello, F. Flamini, L. Innocenti, D. Cozzolino, M. Bentivegna, N. Spagnolo, A. Crespi, D.J. Brod, E. F. Galvao, R. Osellame and F. Sciarrino. Experimental generalized quantum suppression law in Sylvester interferometers, *Preprint at arXiv:1705.08650*, (2017).

[5] M. Bentivegna, N. Spagnolo, C. Vitelli, F. Flamini, N. Viggianiello, L. Latmiral, P. Mataloni, D. J. Brod, E. F. Galvao, A. Crespi, R. Ramponi, R. Osellame, and F. Sciarrino. Experimental scattershot boson sampling. Science Advances, **1**, e1400255, (2015).

Error Modelling in Complex Silicon Quantum Photonics Devices

Caterina Vigliar, Jeremy C. Adcock, Raffaele Santagati, Joshua W. Silverstone, Mark G. Thompson

Quantum Engineering Technology Labs, H. H. Wills Physics Laboratory and Department of Electrical
& Electronic Engineering, University of Bristol, UK

Silicon quantum photonics represents one of the most promising approaches in the development of large-scale photonic quantum technologies. The high miniaturisation capability, already matured in this platform, allows to integrate complex photonic circuits in small-scale chips, offering great stability and reconfigurability. The operation of quantum applications of increasing complexity on such devices requires a careful understanding of the practical experimental issues and precise error models [1]. However, as the typical sources of noise in this highly miniaturised environments are substantially different from the ones present in other platforms, a satisfactory error model for Silicon quantum photonics has yet to be completely established [2].

Here we try to develop a systematic study of error models able to describe the main sources of noise in Silicon quantum photonics: cavity-induced, thermo-optic, and electric cross-talks and source engineering. The accuracy of this model is tested on a Silicon chip embedding four on-chip photon-pair sources, on-chip filters, a reconfigurable two-qubit gate and local operations, aimed to build all six of the non-isomorphic complete graph states of four qubits [3], as shown in Fig.1. Preliminary calibration and tomographic results are reported in Fig.1 a-d, showing the operating regime of the device.

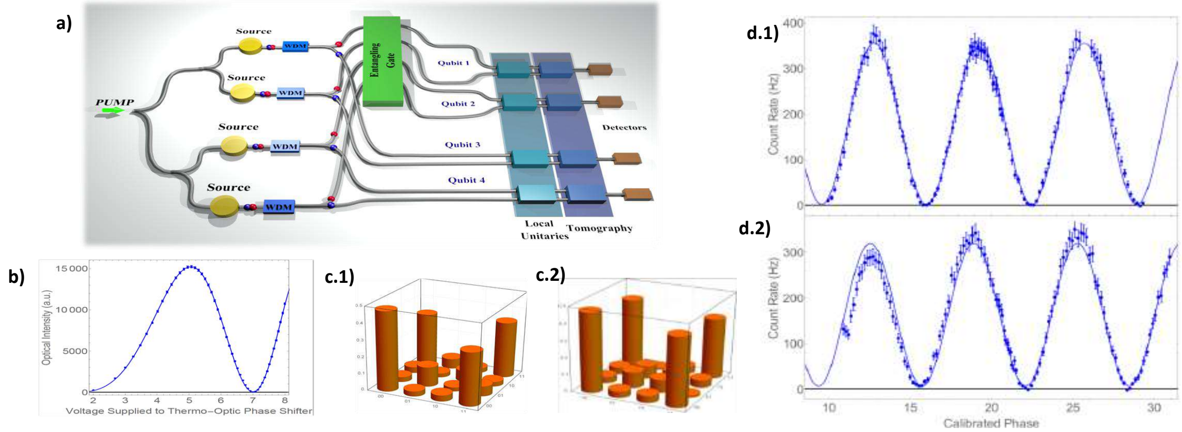

Figure 1: **a)** Schematic of the chip used to generate arbitrary four-photon graph states. **b)** A bright light calibration curve using one of the interferometers on the device. **c)** Sources $1-3$ and $2-4$ can produce $|\phi^+\rangle$ Bell states with fidelities 86.0 ± 0.9 and $91.0\pm0.7\%$ respectively. **d)** We observe high-visibility reverse Hong-Ou-Mandel interference fringes of $97.3\pm0.5\%$ and $98.6\pm0.4\%$, produced by simultaneously varying phase shifters on two spatially separated qubits.

Further developments will include experimental and theoretical studies on noise effects in the implementation of quantum protocols, such as measurement based quantum computation. By comparing theoretical and experimental results, these tests will provide a benchmark for the error model description of Silicon quantum photonics experiments.

References

[1] F. Flamini, et al. “Thermally reconfigurable quantum photonic circuits at telecom wavelength by femtosecond laser micromachining”, Light: Science & Applications **4**, e354 (2015).

[2] J. Silverstone, et al. ”Silicon quantum photonics”, IEEE Journal of Selected Topics in Quantum Electronics **22**, 390-402 (2016).

[3] Hein, Marc, Jens Eisert, and Hans J. Briegel. “Multiparty entanglement in graph states.” PRA **69**, 062311 (2004).

Polarization Encoded Quantum Computation on a Chip

***Jonas Zeuner*[1], *Aditya Sharma*[1], *Max Tillmann*[1], *René Heilmann*[2], *Alexander Szameit*[2] *and Philip Walther*[1]**

[1]*Faculty of Physics, University of Vienna, Boltzmanngasse 5, A-1090 Vienna, Austria,*
[2]*Institute of Applied Physics, Abbe Center of Photonics, Friedrich-Schiller Universität Jena, Max-Wien-Platz 1, D-07743 Jena, Germany*

Integrated photonics are emerging as a strong platform for quantum simulation and computation. The small size and intrinsic interferometric stability of waveguides makes them ideal candidates for the complex networks of linear-optic components needed for quantum computation. In this work, we use a femtosecond-laser-written waveguide to perform a nondestructive CNOT operation on two photons' polarization. Two additional maximally entangled photons are required as ancillas. The successful operation of this gate is heralded by detection of the two ancillary photons: the control and target photons do not have to be detected and can be used for subsequent logic operations [1]. In our experiment we show the first implementation of polarizing beam splitters in a femtosecond-laser-written waveguide and show the use of thermally expanded core fibers to increase our coupling performance to the chip.

References

[1] TB Pittman, BC Jacobs, and JD Franson, "Probabilistic quantum logic operations using polarizing beam splitters", Physical Review A, 64(6):062311, 2001

Integration of Photonic Crystal Devices

Chii-Chang Chen[1], W. Y. Chiu[2], Y. H. Wu[2], Y. J. Chan[2], Chia-Hung Hou[1], Hung-Ta Chien[1]

[1] *Department of Optics and Photonics, National Central University, Jhongli 320, Taiwan*
[2] *Department of Electrical Engineering, National Central University, Jhongli 320, Taiwan*

The photonic bandgap effect of photonic crystals (PCs) provides the highly confined mode needed to be control the propagation of the light. Due to their nanometer feature size, the device packing density can be increased. Several PC devices have been developed such as directional couplers[1], ring resonators[2], hollow waveguides[3], laser[4], lenses[5], etc. To integrate these devices, the fabrication process including the conventional pthotolithography and the e-beam lithography should be utilized. In this study, we realize the integrated nano-optics system consisting of a PC demultiplexer, a PC taper coupler, PC waveguide as well as two photodiodes for the detection of the light.

InGaAsP-based materials are chosen for the fabrication of the device. For the photodiodes, the partially p-doped photo-absorption layer is adopted to accelerate the diffusion of the electron form absorption layer to the depletion layer [6]. The PC demultiplexer is formed by periodically arranged air-holes in hexagonal lattice. The radius is chosen to be 0.33a. The normalized frequency of the complete photonic bandgap is between 0.2 and 0.3. The normalized frequency of 0.24 is chosen for the wavelength at 1.55μm. The corresponding lattice constant and radius of the air-holes are 0.375μm and 0.125μm, respectively. The sample is grown by metal-organic-chemical-vapor-deposition (MOCVD) on a semi-insulating InP substrate. The conventional waveguide and the photodiodes are fabricated by the conventional photolithography processes. The pattern of the PC region is defined onto the photoresist by electron-beam lithography and the inductively coupled plasma etcher. PC taper couplers are used between the conventional waveguides and the PC waveguides to reduce the coupling loss. Fig. 1(a) shows the layout of the system including the conventional waveguide and the SEM image after the fabrication (inset).

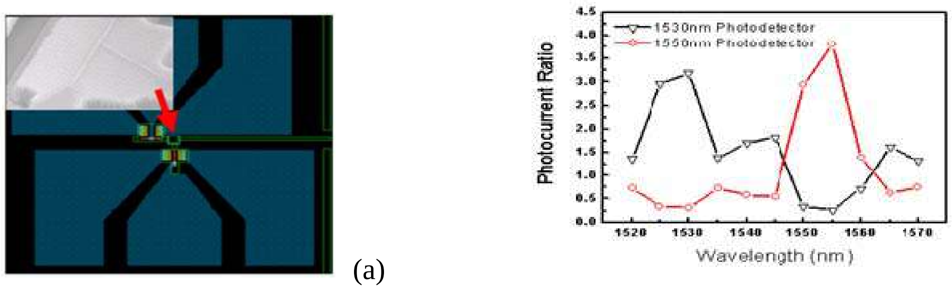

Fig.1 (a) Layout of integrated nano-optics system. The inset is the PC demultiplexer (b) Spectra of output current ratio of the photodetectors

A tunable semiconductor laser with its power of 0dBm is used as the light source. The wavelength of the input light is scanned from 1.52μm to 1.57μm. Fig. 1(b) shows the measured photocurrent ratios between two photodiodes. From the measured result, we can observe that the PC demultiplexer can successfully separate the different wavelengths. The photocurrent ratio is 3.2 (5dB) and 3.8 (5.8dB) for the photodiodes of 1530nm and 1550nm, respectively.

[1] C.-C. Chen, C.-Y. Chen, W.-K. Wang, F.-H. Huang, C.-K. Lin, W.-Y. Chiu, Y.-J. Chan, "Photonic crystal directional couplers formed by InAlGaAs nano-rods," Opt. Express 13, 38 (2005).

[2]W.-Y. Chiu, T.-W. Huang, Y.-H. Wu, Y.-J. Chan, C.-H. Hou, H.-T. Chien, C.-C. Chen, “A photonic crystal ring resonator formed by SOI nano-rods,” Opt. Express 15, 15500 (2007).

[3]H.-K. Chiu, F.-L. Hsiao, C.-H. Chan, C.-C.Chen, “Compact and low-loss bent hollow waveguides with distributed Bragg reflector,” Opt. Express, 16, 15069 (2008).

[4]L.-M. Chang, C.-H. Hou, Y.-C. Ting, C.-C. Chen, C.-L. Hsu, J.-Y. Chang, C.-C. Lee, G.-T. Chen, J.-I. Chyi, "Laser emission from GaN photonic crystals," Appl. Phys. Lett. 89, 071116 (2006).

[5]H.-T. Chien, C.-C. Chen, “Focusing of electromagnetic waves by periodic arrays of air holes with gradually varying radii,” Opt. Express 14, 10759 (2006).

[6]W.-Y. Chiu, J.-W. Shi, W.-K. Wang, Y.-S. Wu, Y.-J. Chan, Y.-L. Huang, and R. Xuan “Leaky-Wave photodiodes with a partially p-doped absorption layer and a Distributed-Bragg-Reflector for high-power and high-bBandwidth responsivity product performance” IEEE Photon. Technol. Lett. 18, 1267 (2006).

Single organic molecule coupling to a hybrid plasmonic waveguide

**S. Grandi[1], M. A. Nielsen[2], J. Cambiasso[2], S. Boissier[1], K. D. Major[1], C. Reardon[3],
T. F. Krauss[3], R. F. Oulton[2], E. A. Hinds[1], A. S. Clark[*1]**
1. Centre for Cold Matter, Blackett Laboratory, Imperial College London, South Kensington, SW7 2AZ, UK
2. Experimental Solid State Physics Group, Blackett Laboratory, Imperial College London, South Kensington, SW7 2AZ, UK
3. Department of Physics, University of York, York, YO10 5DD, UK

Efficient photon sources will enable many quantum technologies. Single dibenzoterrylene (DBT) molecules are promising photon sources, but often emit in an unknown direction making photon collection challenging. Dielectric structures redirect emission into single optical modes [1], but are relatively large due to the diffraction limit of light. Plasmonic devices, such as antennae, can concentrate the electromagnetic field at the site of an emitter on a surface in volumes below the diffraction limit and redirect emission into well-controlled directions, but often suffer from losses. Recently, planar dielectric antennae have shown promise for redirecting emission [2], however often they do not provide single mode operation or compatibility with integrated photonics.

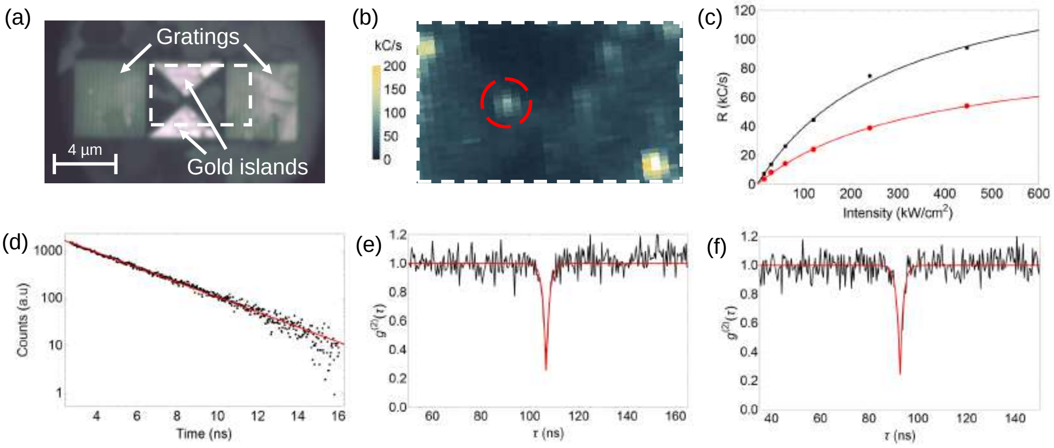

Fig. 1: (a) White-light image of a HPW showing input/output grating couplers and anthracene crystals on the surface. (b) Molecule fluorescence from the dashed box in (a). (c) Saturation curves for the molecule indicated with a red dashed circle in (b), showing count rates collected from the confocal microscope (black squares) and from a grating coupler (red circles). (d) Pulsed laser measurement of the molecule excited state lifetime. (e) $g^{(2)}(\tau)$ measured from the microscope only and (f) $g^{(2)}(\tau)$ measured from the grating and microscope.

Here we present a hybrid dielectric–metal approach in coupling a single molecule to an optical mode in an integrated planar device. We designed and fabricated a hybrid plasmonic waveguide (HPW) consisting of a dielectric slab with a nanoscale gap patterned in gold on the surface, as shown in Fig. 1(a). Replacing the silicon layer used in our previous work [3] with titanium dioxide (TiO_2) allows operation at $\sim$ 785 nm, the emission wavelength of DBT. Light propagating in the TiO_2 layer passes through the gap between the islands of gold. The width of the gap controls mode confinement: when the gap is $<$100 nm the propagating mode is mainly in the gap providing strong confinement; but when the gap is wider the mode decouples from the gold and propagates mainly in the TiO_2 with low loss. We deposited DBT-doped anthracene crystals on the surface (Fig. 1(a)) using a supersaturated vapour growth technique [4]. Using confocal fluorescence microscopy we found a DBT molecule positioned near the gap (Fig. 1(b)). We then measured the saturation intensity of the molecule (Fig. 1(c)) to be $I_{sat} = 325(27)$ kW/cm^2. Illuminating the molecule with a pulsed laser (Fig. 1(d)) we measured the lifetime of the molecule to be 2.74(2) ns. Under CW excitation we measured the second-order correlation function $g^{(2)}(\tau)$ of the light emitted directly into the microscope. This shows clear anti-bunching (Fig. 1(e)) with $g^{(2)}(0) = 0.25(6)$ proving this to be a single molecule. By detecting photons simultaneously from the microscope and from the grating coupler we measured $g^{(2)}(0) = 0.24(6)$ (Fig. 1(f)), demonstrating that this single molecule was emitting into the waveguide mode. By measuring the optical losses in our setup we calculated the coupling efficiency from the molecule to the HPW to be $\sim 22\%$. This method provides a route to building waveguide sources of photons in planar integrated quantum photonic circuits for applications in quantum technology.

References

[1] S. Faez *et al.*, Phys. Rev. Lett. **113**, 213601 (2014).
[2] X. L. Chu *et al.*, Optica **5**, 203–208 (2014).
[3] M. A. Nielsen *et al.*, Nano. Lett. **16**, 1410–1414 (2016).
[4] C. Polisenni *et al.*, Opt. Express **24**, 5615–5627 (2016).

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[*] Corresponding author: alex.clark@imperial.ac.uk