DOCTORATE THESIS PROJECT:
QUANTUM WALK IN INTEGRATED PHOTONICS

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Introduction

The research path I will follow in my doctoral program is within the Marie Curie Training Network in Photonic Integrated Compound Quantum Encoding (PICQUE). The PICQUE project is a consortium of several universities and research institutes aimed to base an European collaborative foundation towards the development of quantum information and communication technologies based on photonic platforms.

Quantum information science aims to understand the quantum nature of information itself and elaborate it with physical systems which work within the laws of quantum mechanics, allowing the computation of high complexity systems [1]. In this framework, my research activity is focused on the study of quantum simulation and integrated photonics platforms, with the objective is to investigate the foundation of quantum mechanics and research on optical systems integration into small photonic chips. In particular, in close collaboration with Institute of Photonics and Nanotechnology (IFN - CNR), Rome's and Milan's branches, members of the PICQUE project consortium, the aim is to develop novel optical platforms for quantum simulation and quantum sensing. On one side the ongoing work is on improving the performance and operation of femtosecond laser written photonic chips, on the other side research of on superconducting single photon detector, which then will be combined to perform cutting edge experiments of quantum information and simulation.

1 Femtosecond Laser Writting

Integrated photonic chips are the founding technology for the transfer of large bulk optical experiments to a small table-top, few centimeters long devices, allowing the scaling of complexity of quantum optical experiments.

Among the various techniques of construction of these compact photonic devices, femtosecond micromachining is a novel technique which exploits the non-linear interaction of a tightly focused laser beam on a transparent material, locally modifing the material's properties at a micrometer scale [2]. From a photonic prospective such technique allows the micromachining of integrated photonic chips by moving the glass material along a controlled path it allows to write optical waveguides able to efficiently direct classical and quantum light [3].

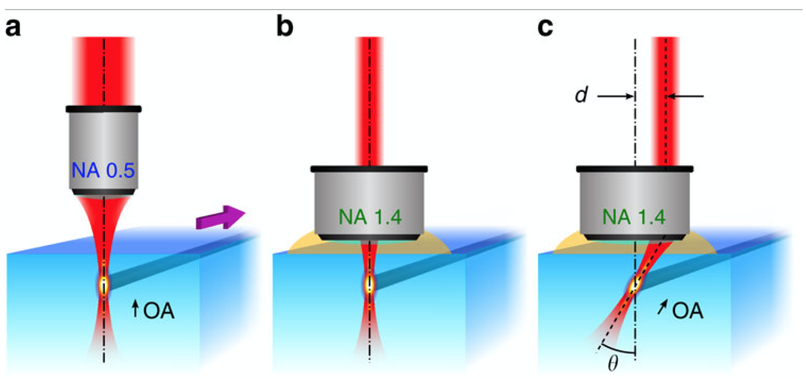

Figure 1: a) Traditional writing scheme adopting a focusing objective with moderate NA; (b) Equivalent waveguides can be created by underfilling a high-NA oil-immersion objective. (c) Offsetting the writing beam before the objective results in waveguide writing with an inclined laser beam; the resulting waveguide has an optical axis tilted by an angle that depends on the amount of offset d of the writing beam with respect to the objective axis [8].

In a quantum science prospective, these femtosecond laser written optical devices have been extensively used to couple and manipulate single photons for quantum information experiments [4, 5, 6]. The manipulation of the photons is done by properly designing series of directional couplers, the integrated corresponding of a beam splitters, and phase shifters, achieved by controlling the bending and the curvature of the waveguides, so to simulate the Hamiltonian required for the system under study. This is possible due the fact that any quantum computation process can be effectively performed by in linear optics by a series of beam splitter and phase shifters [7]. Among the various fabrication techniques for photonic chips currently available, femtosecond writing has an edge due several factors: the technique is massless and material efficient, which allows fast prototyping in a cost effective manner; it produces high quality birefringent waveguides, necessary for the polarization encoding of the photons; the devices can be coupled to single mode fibers with low insertion losses, due similar waveguide core size and refractive index, and propagation losses close to 0.01dB/cm; it allows the construction of three dimensional waveguide pattern in the chip, tapping in possibility of constructing extremely complex structures.

Based on such technology for the micromachining of integrated photonic devices, my research activity will follow on further development of these devices on two main aspects: aiming for structures with higher order of waveguides operating at different wavelengths and dynamical control over the phase of the photons, all aimed in performing experiments in quantum information to investigate both the technological applications and the foundations of quantum mechanics.

Past Projects

2 Reconfigurable Quantum Photonic Circuit for Telecom Wavelength

As previously mentioned, femtosecond laser written devices has been extensively used with single photons experiments at 785nm wavelength range. My first research project was to experimentally demonstrate the feasibility of a thermally reconfigurable photonic circuit operating at wavelength of 1550nm. The major interest in femtosecond written devices for telecom wavelength can be found in the massive industry for optical components at such wavelength, the global fiber communication network and the possibility to interface with these networks, due low insertion and propagation losses, for both laboratory quantum experiments and application at large scale [9].

The single photon source at 1550 wavelength was achieved by Spontaneous Parametric Down Conversion (SPDC) of a coherent laser beam at 785nm in a non-linear medium type I bismuth borate (BiBO) biaxial crystal [10]. Detection rates from the single photon source were approximately 16KHz for singles and 0.5KHz for coincidence counts in pulsed mode and 17KHz for single and 2KHz for coincidence in CW mode. The indistinguishability of the down-converted photons was done by synchronizing the paths of the photons interacting in a beam splitter, and performing a Hong Ou Mandel (HOM) interference dip [11], resulting in a classical to quantum visibilities of 0.986 ± 0.002 for CW mode and 0.994 ± 0.006 for pulsed mode.

For this proof-of-principle experiment a Mach-Zehnder interferometer was fabricated. The reconfigurability of the integrated waveguides required a local change in the refractive index over the desired waveguide, which was done by heat dissipated from applied resistive heaters. These resistive heaters are built still using femtosecond laser writing technology from a gold layer deposited over the borosilicate glass, following the length the inscribed waveguide of the device, as seen in Fig.[**?**], which is then connected to an external power supply and allows a full 2π phase rotation for coherent laser light with a dissipated power of approximately 0.5W.

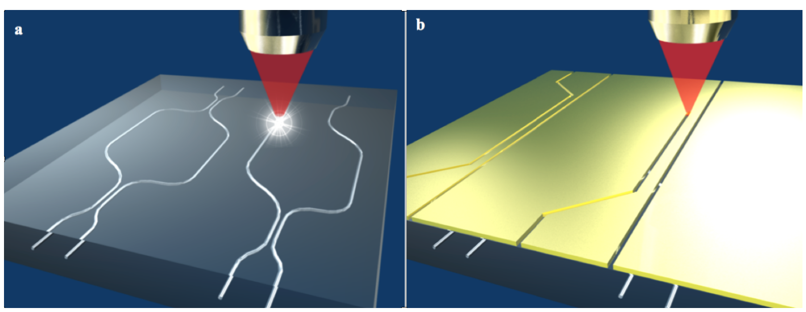

Figure 2: Femtosecond laser microfabrication process. (a) Direct writing of Mach-Zehnder interferometers in the bulk of a borosilicate slide. (b) After gold coating the sample top surface, the resistors are patterned by ablation using the same femtosecond laser. Accurate alignment (0,1 mm) between the resistors and the Mach-Zehnder arms is achieved by using the reference markers inscribed on the glass surface together with the interferometers.

The device state-of-the-art operation at 1550nm wavelength was demonstrated with coherent light, and single-photon and two- photon interference measurements. The light and the photons were coupled to the device with single mode fiber arrays for input and output, aligned mechanically with a 6-axis roto-translational stage each. The detection of the single photon was done by a pair of SPADs detectors operating in series, with one detector triggering the detection of the second detector, so to extrapolate the coincidence count for two photon interference.

By varying the applied phase shift, we measured the interference fringes for coherent light and single photon by detecting on a single output of the Mach-Zehnder interferometer, and interference fringes for two fold coincidence could on both outputs of the interferometer. To validate the purely quantum behavior of the two photon interference, we measured the bunching contribution by connecting a symmetric 50:50 in-fiber beam splitter at on the outputs, and measure the coincidence count at the two outputs of the beam splitter itself.

The measured fringe visibility for single photon was 0.981 ± 0.007, compatible with the classical light. For the two photon interference the measure fringe visibilities were 0.913 ± 0.006 for $|1,1\rangle$ states and 0.949 ± 0.007 for $|2,0\rangle$ states. In particular we can see two specific features of the fringes in Fig3: the half periodicity of the two photon interference fringes compared to coherent light and single-photon fringe, and that the $|2,0\rangle$ fringes are in counter-phase compared to the $|1,1\rangle$ fringes. These two results shows that the device is perfectly operation in the quantum regime [12].

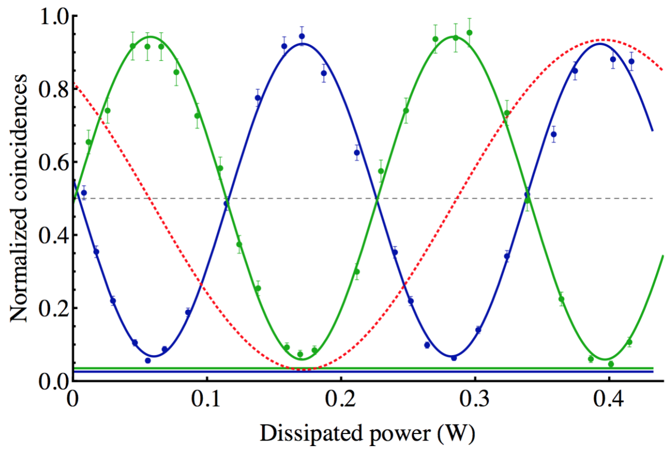

Figure 3: Experimental fringes for the Mach- Zehnder interferometer at 1550nm telecom wavelength. Red dashed line: single photon fringe. Blue dots: two photon coincidences of the output (1,1). Green dot: two photon coincidence of output (0,2). The two photon fringes show a double periodicity of the single photon fringe.

3 Entanglement Growth in Photonic Spin Chain Simulation

The possibility of using photonic networks to investigate various physical phenomena, by implementing arbitrary unitary transformations, allows us to simulate many processes which are extremely difficult to investigate directly in they natural occurrence. An example of such complex physical process is the quantum state transport in a spin chain [13] and the formation of "rainbow states", which is the generation of entanglement between sites symmetric to the center [14], an effect of entanglement growth in many-body systems due a sudden change in the Hamiltonian of system, known quantum quench.

In this experiment two photonic chips were engineered to simulate first the quantum state transport, namely the quantum transport chip, and secondly to certify the creation of these entangled rainbow states, namely entanglement characterization chip. The quantum transport chip was constructed to simulate an Hamiltonian of the dynamics of a 5 sites 1D spin chain evolving for 6 discrete time steps, which was experimentally possible thanks to three factors: first it is possible to map the spin nearest neighbor excitations wave into non-interacting fermions hopping though the sites of a lattice due Jordan-Wigner transformation [15]; second the continuous time quantum walk of multiple fermions can be simulated by a discrete quantum walk [16], providing a more accurate control over the Hamiltonian due the introduction of the coin operator [17]; third it is possible to simulate fermionic statistics in photonic platforms using photons entangled in an anti-symmetric states [18].

For the simulation of the spin excitation transport on the photonic platform, polarization- entangled pairs of photons were generated by SPDC process in a type-II BBO crystal at 785nm wavelength. The entangled state generated from the photon source was of the form $|\Psi^{\chi}_{2\mathrm{p}}\rangle = \frac{|HV\rangle + e^{i\chi}|VH\rangle}{\sqrt{2}}$, where χ is a relative phase factor between the two photons. By applying a liquid crystal retarder on one of the photons, it was possible to generated the two entangled photon states required to simulate bosonic and fermionic statistics, $|\Psi^{+}_{2\mathrm{p}}\rangle$ and $|\Psi^{-}_{2\mathrm{p}}\rangle$, which are respectively symmetric and anti-symmetric under particle exchange.

The simulated Hamiltonian from the first device was of the form of system represented a network of N fermions in a XY spin chain quench model [19, 20]

$$H = \sum_{i=1}^{N-1} \frac{1}{2} J_i (X_i X_{i+1} + Y_i Y_{i+1}) \tag{1}$$

where X_i, Y_i represent the Pauli matrices for the spin in the site i and N is the length of the chain. In particular the J_i is the neighbor site coupling parameter, from which is possible to determine the transmissivity of the directional couplers as $T_i = \sin^2(\epsilon J_i)$ with $\epsilon = \frac{N+1}{M} = \frac{2t^*}{M}$, where M are the layers of beam splitters for which a perfect quantum state transport after time $2t^*$ is obtained. In particular, if the initial state is in the form of a Néel state, the evolution of such state transitions from a separable state into an entangle state at t^*, and back to a separable state at $2t^*$. In our case we were interested in observing the generation of entanglement between the sites/waveguides symmetric to the centre at time t^*, corresponding to the "volume law" of multi-body entanglement generation, therefore the M=6 device's directional couplers were modeled as to obtain a complete state transport for $M = 12$.

The probability distributions for two-fold coincidences for all combinations of outputs were measured for both bosonic and fermionic quantum walks, and the respective correlation functions were derived. As it can be seen in Fig.4, we can observe two distinct aspects from the bosonic and fermionic distributions: where in the first case we have a strong bunching contribution, typical behavior of bosonic particles, as seen by the strong correlation function on the diagonal of the matrix, the second show clear signs of anti-bunching of the photons, as expected the Pauli exclusion principles for fermionic particles. The calculated similarities between the experimental ($\tilde{\Gamma}^{\mathrm{B/F}}_{ij}$) and theoretical ($\Gamma^{\mathrm{B/F}}_{ij}$) results were $\mathcal{S}^{\mathrm{B}} = 0.942 \pm 0.005$ and $\mathcal{S}^{\mathrm{F}} = 0.836 \pm 0.004$.

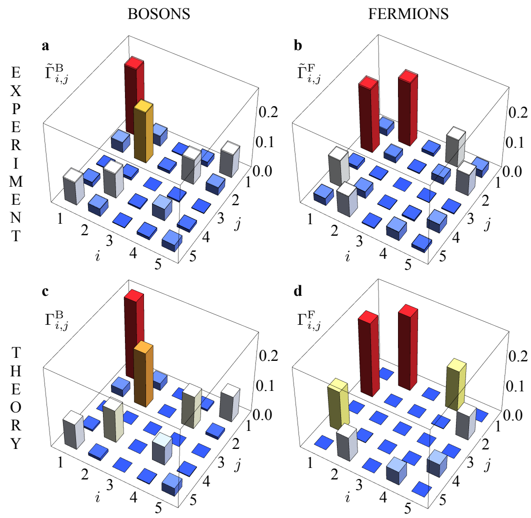

Figure 4: (a-b) Experimental results of the correlation function, $\tilde{\Gamma}_{ij}$, for bosonic and fermionic transport. (c-d) Theoretical prediction for the correlation function, for bosonic and fermionic transport obtained from the unitary matrix U of the transport device.

For the case study of the Néel state evolution, the $|\Psi^{-}_{2\mathrm{p}}\rangle$ entangled state, simulating fermionic quantum walk, was injected as initial state in the device. The expected output state was $|\psi_{\mathrm{out}}\rangle = (\alpha\,|10\rangle_{15} + \beta\,|01\rangle_{15})(\gamma\,|10\rangle_{24} + \delta\,|01\rangle_{24})\,|0\rangle_3$, where the parameters α, β, γ and δ, seen in Fig4, originate from the approximation of a perfect state transfer to a finite number of discrete step. To certify the generation of the path-entanglement state pairs symmetric to the central waveguide, the entanglement certification chip was coupled in series to the quantum transport chip, which applied a phase shift and a beam splitter operation between the pairs of waveguides (2,4) and (1,5) as seen in Fig.5-a. Two phase shifters were built on this second device, operating independently from each other on waveguides 2 and 5 as seen in Fig.5-c. The resistive heaters constructed for this device were contructed using the same femtosecond laser written technique described in the work of the reconfigurable Mach-Zehnder interferometer at telecom wavelength [12].

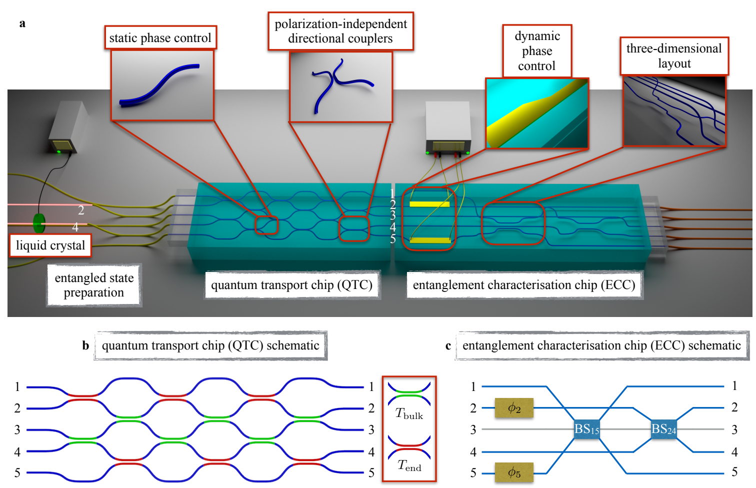

Figure 5: a. Representation of the experimental apparatus comprised of the first quantum transport chip and the second entanglement characterization chip. The insets highlight the specific elements and the three dimensional geometry of the photonic devices. b. Schematization of the quantum transport device of the first chip showing in green the directional couplers of the bulk (Tbulk = 0.36) and in red those at the edge (Tend = 0.25) of the device. c. Schematic representation of the entanglement characterization device of the second chip, showing the dynamic phase controls ϕ_2 and ϕ_5 acting on the 2nd and 5th waveguides and the 50/50 beam splitters between the (24) and (15) pairs of modes. The 3rd waveguide (in grey) is not involved in any interference processes

Initially the coherence between the waveguides was measured and the two-photon interference fringes were obtained by varying the phases ϕ_2 and ϕ_5.

The results are represented in Fig.7a-b with the quantity $S_1 = P'_{12} + P'_{14}$, where P'_{ij} is the two-photon probability at the outputs i and j of the second device for mode 1, following analogous quantities defined for modes 2, 4 and 5 ($S_2 = P'_{21} + P'_{25}$, $S_4 = P'_{41} + P'_{45}$ and $S_5 = P'_{52} + P'_{54}$), as function of the dissipated heat. Further characterization the degree of entanglement was done by evaluating the *entanglement fraction* of systems 1-5 and 2-4 with respect to the ideal one-photon Bell state $|\psi^+_{1\mathrm{p}}\rangle$: $\mathcal{E}_{ij} = {}_{ij}\langle\psi^+_{1\mathrm{p}}|\,\rho_{ij}\,|\psi^+_{1\mathrm{p}}\rangle_{ij}$, where ρ_{ij} is the reduced density matrix for two qubits in positions i and j [21]. This quantity can be measured by single (N') and two (P') photon probability distributions by defining the measurable quantities $\mathcal{E}_{15} = N'_5 - P'_{15}$ and $\mathcal{E}_{24} = N'_2 - P'_{24} - P'_{23} + P'_{34}$. By evaluating the entanglement fractions from the two-photon probabilities shown in Fig 7c we obtain $\mathcal{E}_{15} = 0.66 \pm 0.03$ and $\mathcal{E}_{24} = 0.74 \pm 0.03$. This amounts to an approximate verification of the output state from the first device and thereby the growth of entanglement to a volume law.

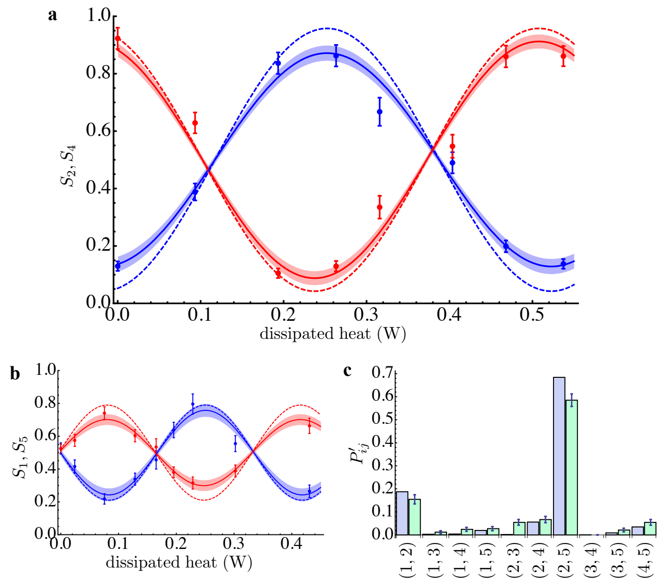

Figure 6: Interference fringes for S_2 (blue points) and S_4 (red points) as a function of the dissipated heat on mode 2 (proportional to ϕ_2). **b.** Interference fringes for S_1 (blue points) and S_5 (red points) as a function of the dissipated heat on mode 5 (proportional to ϕ_5). In both sub-panels **a** and **b**, solid lines and shaded areas represent respectively the best fit curves and fit curve error, while the dashed lines corresponds to theoretical predictions. **c.** Green bars: two-photon probability distribution obtained at the output of the second chip, when the polarization-entangled anti-symmetric state is injected into input 2 and 4 of the first chip. The distribution is obtained for values of the two phases which maximize P'_{25}; blue bars: theoretical predictions. All theoretical models are obtained taking into account the reconstructed matrices of the first chip ($\tilde{U}_H$ and $\tilde{U}_V$) and the coupling efficiencies at the interface between the two devices

Future Projects

4 Anderson Localization

The absence of diffusion in certain random lattices is a phenomena widely studied in solid state physics, optics and acoustic wave dynamics, and is called Anderson Localization [22]. Due to the failure of propagation of a wave in a disordered media it is expected that particle and energy transport through a disordered medium should be strongly suppressed and localized over time. This has been widely studied in various field of optics, both in classical and quantum regime [23, 4]. From a quantum photonic prospective, it is possible to simulate the Anderson localization by constructing a photonic device with a network of Mach-Zehnder interferometers with different phase shifts, which implements a discrete quantum walk in a lattice with static disorder, as demonstrate by Crespi *et al* [4], for single photon and two photon localization simulating bosonic and fermionic quantum walks.

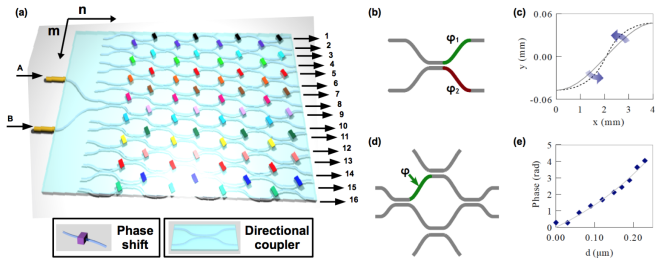

Figure 7: (a) Scheme of the network of directional couplers implementing a 8-step quantum walk with static disorder. Different colors stand for different phase shifts. (b) Controlled deformation of either of the two S-bent waveguides at the output of each directional coupler extends the optical path and is equivalent to the application of a phase shifter. (c) The deformation is given by a non-linear coordinate transformation, which is function of a deformation coefficient d (see Supplementary Information). The graph shows the undeformed S-bend (solid line), together with a deformed one (dashed). (d) Schematic of the Mach-Zehnder structure, representing the unit cell of the directional couplers network, fabricated for calibrating the phase shift induced by the deformation. (e) Phase shift induced by the deformation: theoretical curve calculated from the nominal geometric deformation (solid line), and experimental measurements (diamonds).

For a quantum simulation on integrated devices of the true Anderson localization in a random disordered lattice requires a number of step $N \to \infty$, or at least a large number of steps, exceeding the currect technological capability for integrated photonic devices. However, according to the Ergodic theory, instead of evolving the system for a large number of steps, we can simulate with a series of random noises to a setup with fewer steps and then averaging all the results, therefore opening the possibility of oberserving Anderson localization at a quantum level.

Following such path, a photonic device has been made with femtosecond laser writing technique, with a similar design concepts of the work done by Crespi *et. al*, but with 50 waveguides forming a series of 8 layers cascaded 50:50 directional couplers. Each waveguide applies a different phase transformation, so that for a quantum walker moving in a waveguide will experience a different static disorder given by it's nearest neighbors, allowing to study a different disordered system just by injecting the initial state shifter by one waveguide, so that by measuring the localization effects for different inputs, it is possible to extrapolate due to the Ergodic theory, a true Anderson localization over a larger time.

The objective of the experiment is to simulate Anderson localization for bosonic and fermionic two particle statistic, by studying the effect on the localization for various initial conditions for the photons input state.

5 Wave-Particle state entangled state

One of the most curious and hard to understand aspects of quantum mechanics, due to none classical equivalent, is the so called "Wave-Particle Duality", which arises from the property of quantum particles of behaving both as particles and as waves, in a wave-particle superposition state. Photons are the quantum particle of choice for studying this wave-particle feature of the quantum world, due their low decoherence and easy manipulation. In fact there have several experiments on the quantum delayed choice using photons [24, 25, 26]. These experiments originate from several thought experiments from John Archibald Weeler and they allow to actively "decide" if the photon will behave like a particle or a wave, allowing to investigate such behavior intrinsic to quantum mechanics.

We propose a scheme for deterministic generation of single photon wave-particle superposition state, which economizes the quantum resources required, it can be fully implement in a linear optical setup, and that is without delayed choice. Moreover we intend to create for the first time a multi-photon wave-particle entangle state, which have been unexplored so far in both aspects of theory and experiment. This is possible by exploiting both polarization and path degrees of freedom of photons, using polarization degree of freedom for quantum control and path degree of freedom for testing wave-particle properties.

$$|\Phi^+\rangle_{12} = |Particle\rangle_1 \, |Particle\rangle_2 + |Wave\rangle_1 \, |Wave\rangle_2 \tag{2}$$

6 On-chip long distance quantum teleportation

Quantum teleportation is the process of the transferring of quantum information exploiting the properties of entanglement. The first practical scheme for a feasible quantum teleportation was proposed by Bennet *et. al.* in 1993 [27], in which an entangled pair is generate and each particle sent to different locations, then on one of the entangled particle is carried a combined Bell state measurement with the qubit needed to be teleported, then by sending through a classical channel the information of the Bell state measurement, it is possible to reconstruct the teleported qubit on the second entangled particle in a far distant location.

Several experiments have been carried since then, succeeding in performing the teleportation of a generic quantum state, based on different schemes for encoding the teleported qubit and perform the Bell measurements required[28, 29]. Since then quantum teleportation has found it's ground in application in quantum technology as quantum relays [30], quantum repeaters [31] and linear optics quantum computing [32]. Moreover teleportation experiments have been largely studied permitting free-space long distancs teleportation without decoherence [33] and teleportation on silica based photonic chips [34].

Based on the novel development of femtosecond laser written devices for reconfigurability and exploiting the fact that such photonic devices are polarization independent, we propose a long distance quantum teleportation experiment with the use of an integrated photonic device at telecom wavelength based on Rome's teleportation scheme [29].

7 Superconducting Nanowire Single Photon Detector

In the field of quantum sensing my research will strictly follow a collaboration with the Institute of Photonics and Nanotechnology in Rome in the clean room development of state of the art Superconducting Nanowire Single Photon Detectors (SNSPDs), which, due their high count rate, low dark count and high detection efficiency, allow higher level of experiments in quantum information and simulation [35, 36]. These superconducting detectors are based on Silicon compounds, operating at temperatures of 4K, and offer a detection efficiency higher than 55-60%, exploiting the local break in superconductivity of the detector, therefore sensing a change in the resistance of the material when a photon is detected. These detectors are currently under development for single photon detection at wavelength of 1550nm, for application in quantum information experiments in the telecom wavelength.

Conferences, Training Schools and Secondment

8 Conferences

During my doctoral training I have participated to various scientific conferences:

- January 2015, Workshop in Integrated Quantum Photonics in Oxford
- June 2015, CLEO/Europe - EQEC 2015 in Munich
- July 2015, PICQUE Rome Scientific School (contributed poster)
- September 2015, Quantum Information and Processing Conference 2015 in Leeds (contributed poster)
- September 2015, 101 National Congress of SIF in Rome
- October 2015, Frontiers in Optics/Laser Science 2015 in San José
- April 2016, Bristol Young Scientist Conference in Bristol (contributed talk)
- April 2016, Bristol Quantum Information Technology Conference in Bristol

More conference participation are expected in the course of my doctoral period.

9 Training Schools

During my doctoral training I have participated to various career development training schools:

- October 2014, Training school in entrepreneurial training in Rome
- February 2015, First training school in science communication in Trieste

- February 2016, Second training school in science communication in Trieste

More career development training schools are expected in the course of my doctoral period.

10 QuTools GmhB

As part of the Doctoral program, I will carry a research secondment in the company QuTools GmhB in Munich, Germany. QuTools is an Associate Partner of the PICQUE project and it operates in developing, manufacturing and distributing quantum information products, including entangled photon sources, quantum random number generators, quantum cryptography systems and quantum optics components.

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