Integrated devices for quantum information with polarization encoded qubits

Ph.D. thesis project
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Framework of the project Quantum optics represents an experimental test bench for various novel concepts introduced within the framework of Quantum Information (QI) theory. Photons are natural candidates for QI transmission since they are practically immune from decoherence and can be distributed over long distances, both in free-space and in low-loss optical fibres. Photons are also important for future quantum networks and are an obvious choice for optical sensing and metrology. Finally, they are a promising candidate for computing.

However, the current technology does not allow the transition to technological applications for different practical limitations. Indeed, the development of increasingly complex quantum optical schemes, realized in bulk optics suffers from severe limitations as far as stability, operation precision and physical size are concerned.

Aim of this project is to take advantage of the resource represented by the integrated waveguide technology in order to realize new complex quantum optical devices that would otherwise be unfeasible using large-scale bulk optics alone.

In the last years different experiments were performed on integrated devices, but all of them are based only on path-encoded qubits with a given polarization state of the photons [1, 2, 3]. Nevertheless, many QI processes and sources of entangled photon states are based on the polarization degree of freedom. One important example is given by states built on many photons [4] and/or many qubits, and by several schemes of one-way optical quantum computing [5]. Hence it is of interest to include the use of photon polarization in quantum circuits by fabricating integrated polarization independent devices, i.e., ones that are able to efficiently guide and manipulate photons in any polarization state.

In this project I will investigate how to guide and manipulate photons in any polarization state by adopting a recently introduced technique, based on the use of ultrashort laser pulses, for direct writing of photonic structures in a bulk glass [6, 7].

First and second year project Direct fabrication of buried waveguides in glass is obtained by femtosecond laser micromachining. Femtosecond infrared pulses, focused into the substrate using a microscope objective, induce nonlinear absorption phenomena based on multiphoton and avalanche ionization. These processes lead to plasma formation and energy absorption in a small region confined around the focus, causing a permanent and localized modification of the bulk material. Adjusting the processing parameters, a smooth refractive index increase can be obtained, and light-guiding structures are produced by translating the substrate with respect to the laser beam. The ultrafast laser writing (ULW) technique allowed us to realize integrated
optical circuits. The maintenance of polarization entanglement and Bell-state analysis has been demonstrated in these integrated quantum devices [8], opening the way for the use of polarization entanglement in integrated circuits for QI processes, as enlightened on *Physics highlights of Physical Review* journals and on *News and Views* by *Nature* [9]. The first tested device was an ultrafast laser written beam splitters (ULWBS) fabricated with the directional coupler (DC) geometry, as shown in Fig. 1. As a first step I demonstrated the ability of the chip to preserve any incoming polarization state by injecting polarized light into the device and measuring the polarization degree of the outcoming photons (G), obtaining $G \geq 99.8\%$. Furthermore, the suitability of the ULWBS to handle polarization-encoded qubits was demonstrated by manipulating polarization-entangled states. We observed transmitted pairs of polarization entangled photons without altering their superposition state and utilized the device as an entanglement filter.

These experimental results demonstrate the suitability of this method to manipulate qubits encoded in the polarization of photon states and open the possibility to the manipulation of polarization encoded photonic qubits in chip-sized optical circuits. Moreover this technology is sufficiently mature to go beyond proof of principle demonstrations and can be used for the realization of innovative photonic devices for quantum information. In order to implement any all optical scalable quantum information process, one- and two-qubit gates, i.e. quantum operations acting on one qubit or simultaneously on two qubits, are necessary [10]. The foundamental two-qubit gate is the Controlled-NOT (CNOT) gate. The unitary transformation associated to this gate is:

$$U_{CNOT} = \begin{pmatrix} 1 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 \\ 0 & 0 & 0 & 1 \\ 0 & 0 & 1 & 0 \end{pmatrix}.$$

Such a transformation acts on two qubits: the state of the target is flipped if the control is in the logical state $|1\rangle$, otherwise it remains unchanged. Polarization encoded CNOTs were recently realized by using bulk optical setups [11]. The building blocks for the optical implementation of a CNOT gate for polarization encoded qubits are the partial polarizing beam splitters (PPBS), i.e. beam splitters with different splitting ratios for horizontal and vertical polarizations. One of the
Figure 2: Partially polarizing directional couplers. (a) Schematic of a waveguide directional coupler. (b) Horizontal (squares) and vertical (triangles) polarizations transmission of directional couplers with different interaction lengths, based on slightly birefringent waveguides. First, the $0 - 2\ mm$ interaction length range was investigated to evaluate the beating length difference between the two polarizations; the interval of interest to obtain the required PPBSs was estimated to be in the $5.6 - 8.2\ mm$ range, which was consequently explored. Error bars indicate fabrication reproducibility.

The tasks of the project has been the realization of an integrated polarization encoded CNOT device. The PPBS has been realized exploiting the residual birefringence of a glass substrate: simply varying the length of the interaction region the ULW technique allows to realize polarization dependent directional couplers (Fig. 2).

The scheme of the integrated CNOT realized with the laser written PPBS is reported in Fig. 3 (a). The truth table (i.e the action of $\mathcal{U}_{\text{CNOT}}$ on the computational basis) has been reconstructed (Fig. 3 (b)) and the device has been exploited as an entangling and dis-entangling gate. Furthermore a quantum process tomography (QPT) has been carried out in order to

Figure 3: (a) scheme of the integrated CNOT for polarization encoded qubits; (b) experimental truth table; (c-d) ideal and experimental real part of the process matrix associated with the CNOT gate, the imaginary part is negligible. $X, Y, Z$ refer to Pauli operators.
completely characterize the gate (Fig. 3 (c-d)): this technique allows to describe any generic operation acting on two qubits through a $16 \times 16$ matrix by measuring how 16 input states are transformed by the gate under consideration [12]. In particular we developed and exploited a new approach for the QPT reconstruction, a strategy for general non-trace-preserving maps, which can be used to take into account experimental imperfections which make the process under investigation to be non trace-preserving even if it is theoretically trace-preserving [13]. In order to quantify the overlap between the reconstructed map and the expected one we calculate the process fidelity which was found to be $F = 94.0\%$. Thanks to the experiments described so far it has been demonstrated that the ULW technique is suitable for the realization of polarization dependent or independent devices according to the geometry of the written waveguides and that polarization encoded qubits can be manipulated in integrated optics.

As a further step we exploited the ULW technique for quantum simulation on integrated optics. In this context quantum walk (QW) represents one of the most promising resources for the simulation of physical quantum systems [15], and has also emerged as an alternative to the standard circuit model for quantum computing [16]. Quantum walk is an extension of the classical random walk: a walker on a lattice “jumping” between different sites with a given probability. The features of the quantum walker are interference and superposition which lead to a non-classical dynamic evolution (Fig. 4).

Figure 4: (a) Unidimensional quantum walk: depending on the result of the coin toss the walker moves upward (U) or downward (D). (b) Scheme of an array of beam splitters (BSs) for a four-steps quantum walk. Vertical dashed lines indicate the steps $T$ of the quantum walk and the horizontal strips represent the position $|j\rangle$ of the walker. In an array with an even (odd) number of steps the output ports $J$ are grouped into the even (odd) final position $|j\rangle$ of the walker. (c) different behaviours of bosons and fermions on a BS.

Up to now the experimental implementations have been restricted to single particle quantum walk [17, 18], while very recently the quantum walks of two identical photons have been reported [19]. A possible scheme for simulating discrete quantum walks is an array of polarization insensitive beam splitters. The ULW technique allowed us to realize such device in a simple way by using an array of directional couplers (Fig. 5 (a)). We realized an array for a 4-step quantum walk. In order to obtain symmetric ($R=0.5$) directional couplers with the same splitting ratio for horizontal and vertical polarization, we adopted a 3-dimensional scheme for the waveguide array (Fig. 5 (b) -for more details see [20]). With an array of polarization independent BSs we simulated both single- and two-particle quantum walks, simply injecting one or two photons inside the chip. Furthermore the polarization entanglement has been exploited to simulate the bunching-antibunching feature of non interacting bosons and fermions: injecting polarization entangled photons into this kind of integrated QW either fermionic or bosonic statistics of a
Figure 5: (a) waveguide scheme of the integrated BS array for quantum walk simulation; (b) 3-dimensional structure of the BS array; (c-d) two particle quantum walk: ideal (top) and measured (bottom) distributions for bosonic (c) and fermionic (d) quantum walks.

two particle system could be simulated depending on the symmetry of the two-photon entangled state wavefunction. The ideal and measured distributions for bosonic and fermionic QW are reported in Fig. 5 (c-d). The similarities, i.e. the overlaps between expected and experimental distributions, have been measured obtaining values $S \sim 98.0\%$.

**Third year project** The above results obtained with QW are very promising, however they must be considered preliminary. The laser writing technique and the 3D scheme realized in [20] will be adopted to increase to six, eight or even more the number of steps of the QW device. Furthermore the insensitivity to photon polarization, high-accuracy in the phase control and intrinsic scalability of the integrated multi-DC network presented in [20], pave the way to further advanced investigations on complexity physics phenomena. For instance, by introducing suitable static and dynamic disorder in the walk it would be possible to simulate the interruption of diffusion in a periodic lattice. In these conditions, the Anderson localization could be observed [21]. In addition 3-dimensional geometries could be exploited in order to simulate not only nearest-neighbor interactions but also next-nearest-neighbor ones.

The integrated devices described so far have a good efficiency, however by increasing the length of the circuit the overall efficiency decreases because of the propagation and bending losses inside the ULW waveguides. This means that the measurements could require very long time. Very bright sources could simplify the measurement stage, hence an additional research of this project will be the development and the adoption of highly bright photon sources [22].

In the last years quantum information experiments are moving towards integration: up to now, regarding polarization encoded qubits, integrated sources and two-qubit gates are available, while active one-qubit gates and integrated photon detectors are still missing. A further possible
objective of my thesis work could be the realization of integrated one-qubit gates for polarization encoding, i.e. integrated waveplates realized by the ULW technique: a further building block for a “lab-on-chip”.

As mentioned for the CNOT gate, every quantum transformation can be fully described by the quantum process tomography. Such a reconstruction requires a large number of measurements (if \( d \) is the dimension of the Hilbert space associated to a map, a QPT requires \( d^4 \) measurements -for a two-qubit gate \( 4^4 = 256 \)). A new approach has been recently developed by Maciel and Vianna [23] which allows to decrease the number of measurements depending on the rank of the process under investigation. We would implement this method to characterize our integrated devices.

Publications


Preprints


References


Conferences

1. 453. WE-Heraeus Seminar, Quantum Communication Based on Integrated Optics, Bad Honnef (Germany) 22-25 March 2010, with a poster presentation: “Optical quantum integrated circuits for quantum information”;


3. SPIE Optics+Optoelectronics, Prague (Czech Republic) 18-21 April 2011, with an oral presentation: “Polarization entangled states measurement on a chip”;

4. CLEO2011 Lasers for photonic applications, Baltimore (Maryland USA) 1-6 May 2011, with an oral presentation: “Polarization entangled states measurement on a chip”.

Schools

1. QNLO 2010 Quantum and Non Linear Optics School, Sandbjerg (Denmark) 21-28 August 2010, with a poster presentation: “Optical quantum integrated circuits for quantum information”;

2. SUSSP67: Quantum information and coherence, Glasgow (Scotland) 28 July-10 August 2011, with a poster presentation: “Integrated photonic quantum gates for polarization qubits”. This poster won the poster prize competition.