Descrizione del Progetto di Ricerca per l'attivazione di una borsa di studio di dottorato ai sensi di quanto disposto dal D.M. n. 1061 del 10/08/2021.

Quantum Computing with photonics. Design, Simulation, Optimization and Test of Silicon Photonics Integrated Circuits

Introduction

Research and innovation can boost a circular and competitive European manufacturing industry through digital technologies, for instance. Data interoperability and quality, as well as their structure, authenticity and integrity are keys for the exploitation of the data value, especially in the context of AI deployment. Quantum computing, i.e. the use of quantum-mechanical phenomena to perform computation, is a field that can make a radical change for people and businesses. One of the first proposals of using quantum mechanics to make computation was made by R. P. Feynman [1]. The most popular model of quantum computing is quantum circuit, which is based on quantum bit, or qubit.

Photonic Integrated Circuits (PICs), also known as optical chips, integrate multiple (at least two) photonic functions for information signals imposed on optical wavelengths. There are two main advantages of choosing photonics to approach quantum computing. The first is that the stochastic noise level is believed to be reduced several orders of magnitude below even the minimum noise for matter-based approach. Secondly, PICs are being strenuously pursued for classical computing purposes, and the core components necessary for the quantum architecture are already under research. Moreover, PICs have been proven to not only be CMOS compatible but also they can be built with nothing changed in CMOS fabrication techniques and standards [2,3].

Among all, Silicon Photonics [4] has high potential for an easy integration of complex optical system thanks to its low spectral dispersion and high refractive index. Silicon PICs for quantum computation can be achieved by linear optics quantum circuits and single photons.

- Linear optics quantum circuits use linear coincident basis gate that performs all the operations of a universal two qubits Controlled-NOT (C-NOT) gate and require only single photon at the input.
- Single photon sources (SPSs) based on color centers in semiconductors [5] offer a scalable fabrication process upon ion implantation, which can open devices manufacturing through the deterministic placement of emitters registered to optical circuits.
- Single photon detectors (SPDs) are widely developed, from group III-V heterostructure devices for near infrared (IR) detection, to 2-dimensional (2D) material for wide-band photodetection (graphene, transition metal dichalcogenides (TMDs), topological insulators (TIs) deposited on doped Si [6]).
- Nanowire-based devices are also considered as ideal platforms for single-photon emission and detection and spin manipulation [7-10].

All these aspects are being investigated in the INFN CSN5 Call project QUANTEP (Quantum Technologies Experimental Platform) funded for the three-year period 2021-2023 and involving eight INFN Structures and National Laboratories. The project is currently in progress and preliminary results have been presented [11,12] or are going to be presented [13] at national and international conferences.

Methods and goal of the project

The implementation of a deterministic controlled-NOT gate would require photon–photon nonlinearities. The missing photon-photon interaction can be implemented by means of linear optics [14]. However, linear optics quantum computation is inherently non-deterministic. To overcome this difficulty, a conditional C-NOT gate is introduced by using linear optical elements.
The most popular technology used for silicon photonics integrated circuits is Silicon On Insulator (SOI). First, a thick oxide layer is deposited on a silicon handling wafer. Then, silicon optical components are built over on the top. This SOI technology allows all the standard optical components to be realized in a single integrated chip: Bragg grating couplers, waveguides, splitters, filters, interferometers, resonators.
Different configurations and optimizations of all the structures (i.e. different layouts of waveguide, different beam splitting ratio of beam splitters, ...) should be tested to find out the best version for single photon sources, single photon detectors and polarization control devices implementation.

PhD student's contribution

- Simulation, optimization and design of standard silicon photonics structures for Linear Optics Quantum Computing. Simulation and optimization of these structures will be carried out with finite elements electromagnetic field solver (Lumerical/Ansys), layouts with dedicated CAD software (Luceda and TexEDA).
- Definition of the technological procedure for the fabrication of the PIC. A competitive high speed system to integrate the linear optics quantum circuit will be studied in the R&D stage for the definition of the technological procedure for the realization of silicon photonics structures for Linear Optics Quantum Computing at FBK - Fondazione Bruno Kessler for six months, presumably during the second year of the doctorate.
- Test and characterization of integrated Linear Optics Quantum Circuits. An on–chip conditional C-NOT gate according to the scheme making use of linear, coincidence basis gate which performs all the operations of a controlled-NOT gate and requires only a two-photon input [15] will be tested. The on–chip C-NOT gate will be characterized by revealing the two-photon interference visibility (quantum interference), the fidelity of the C-NOT gate (quantum process tomography), and the fidelity of the path-entangled state of two photons achieved by transforming with the C-NOT gate a factorizable input state (quantum state tomography).

Most of the research activity will be performed exploiting the instrumentation (single photon source, single photon detector, polarization control, finite elements electromagnetic field solver software) of the Quantum Technologies laboratory of INFN Roma Tor Vergata and University of Rome Tor Vergata Physics Department (task 1 and 3). A key role will of course be played by FBK to define the technological procedure for the realization of PICs for Linear Optics Quantum Computing.

Expected result from the PhD project

The PhD project will contribute to the advancement of the knowledge in the field of the Linear Optics Quantum computing by PICs. These results will define the benchmark for design and realize the next generation of quantum circuits for implementing linear quantum computation [16] as well as graph-

state quantum computation [17], particularly the implementation of all on-chip boson-sampling platform [18] by means of a single photon source which is demultiplexed by polarization control devices and polarized beam splitters.
The ultimate goal is to contribute to the valorization of human capital as key factor for the development of research and industry in Italy. The scientific profile of the formed figure is of very high level in the research and production context in a field at the frontiers of innovation.

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