Integrated Quantum Photonics

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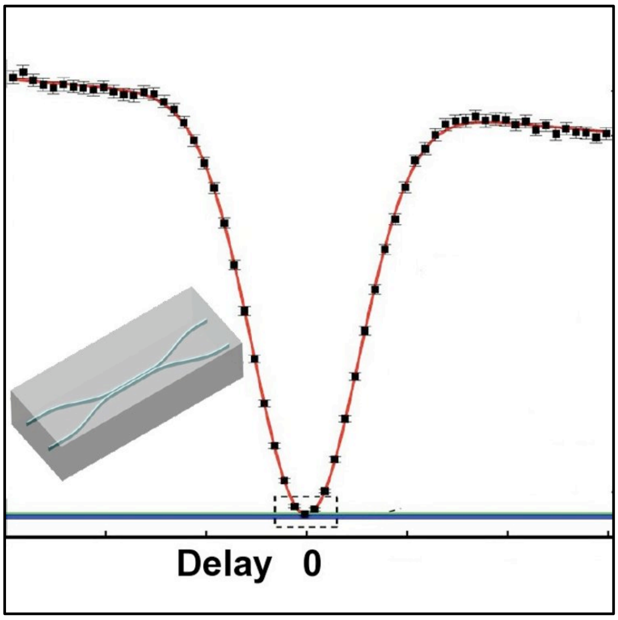
Quantum information science (QIS) is widely regarded as one of the most promising pathways towards disruptive information and communication technologies; it aims to harness quantum mechanical effects to develop quantum systems that will deliver significant improvements in information processing and security. QIS has also provided insights into the fundamental physical workings of Nature, asking for example fundamental questions about the control of coupled quantum systems.



A directional coupler. The rate (symbols) at which the photons are detected at each output of a directional coupler is a function of the delay between the arrivals of the photons at the coupler. The inset represents a schematic of a directional coupler in silica.

Photonics is destined to hold a central role amongst the physical approaches to explore the fundamentals of QIS and to implement devices that will technologically exploit QIS. Single photons are, indeed, ideal models for two-level quantum systems (qubits): they have a very low intrinsic noise, they can be sent at a very high speed, and they are relatively easy to manipulate. For these reasons, for example, photons have become the central information carrier in the first commercial quantum technology: quantum key distribution (QKD) systems that provide enhanced security based on the laws of quantum physics. Proofs of principle for quantum computation have also been demonstrated with photons [1].

Until recently, quantum photonic architecture comprised of large-scale optical elements, such as lenses, prisms and mirrors. This leads to severe limitations in miniaturization, scalability and stability, mainly due to the fact that the system is composed of discrete, bulky parts. The development of the first integrated quantum optical circuitry removes this bottleneck, allowing the realization of much more complex schemes, which are crucial to the progress of experimental QIS and the development of practical quantum technologies.

In quantum optics, information is encoded onto single photons propagating in superposition along multiple optical paths or “modes” [2]. The heart of quantum processing is therefore a linear optical network based on classical and quantum interference [3] between photons to split and combine optical modes. To realize operations between waveguide modes, as in free space beam splitters, it is possible to fabricate directional couplers: when two waveguides approach each other the evanescent fields of the two structures overlap and coupling is obtained. The key requirement to demonstrate that silica technology is an excellent candidate to implement quantum circuits is the achievement of high quality quantum interference between single photons. The rate of coincidental detection of two photons at the output waveguides of a directional coupler as arrival time between the photons is changed. The expected dip near zero delay in photon arrival time indicates quantum behaviour and demonstrates perfect interference within error-bars in integrated optics [4-5]. The same interference effect between single photons is also at the basis of optical two-qubit gates (as the controlled-NOT). An integrated optical network formed by directional couplers of different reflectivity was demonstrated, showing high fidelity operation.

Two-qubit operations are not enough for Quantum Information, also single qubit manipulation are needed for both the development and characterization of integrated photonic quantum devices. Mach-Zehnder interferometers (implementing preparation of any superposition state) were realized in silica chip. A metallic layer deposited on the top of the silica chip provides resistive heaters; metallic connections and contacts to physically control the phase inside the interferometer via thermo-optical effect [6].

The above components open up different perspectives to implement Quantum Technologies. For example, integrated networks were used from quantum metrology experiments that beat the standard quantum limit [6] and to realize a compiled version of Shor’s quantum algorithm to factorize the number 15 on an integrated waveguide chip [7].

The advent of integrated quantum photonics is necessary for the progression of quantum information science. These results provide fundamental building blocks from which future quantum devices will be constructed.

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