Integrated Photonic Technologies for Quantum Communications

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We present recent developments of integrated quantum photonic circuits for applications in quantum communications. A chip-to-chip quantum communication system is demonstrated, employing InP-based transmitter and SiON-based receiver devices. A quantum photonic interconnect is realised to enable the coherent distribution of qubit entangled states between two silicon-based devices.

Photonics has been fundamental in the development of quantum information and communication technologies, as well as providing insight into the fundamental mechanisms of nature. Quantum photonic experiments have had a central role in the advancement of quantum technologies, with single and multi-photon experiments being performed in bulk optical, fibre optic, and more recently integrated photonic platforms. Integrated photonics has provided the miniaturisation, manufacturability and reconfigurability required for demanding applications within classical telecommunication and photonic technologies. and has recently been adopted in many quantum technologies, including quantum computing and metrology. The inherent stability, miniaturisation and reconfigurability has led to many experiments, otherwise impractical, in a manufacturable and scalable manner. Recent demonstrations include; quantum sensing with integrated photonics [1], on chip generation and manipulation of photons for quantum information processing in silicon [2], integrated single photon detectors [3], quantum simulation in silica circuits [4], and numerous quantum computation tasks on a single reconfigurable photonic processor [5].

Quantum Key Distribution (QKD) has developed over the last few decades from proof-of-principle experiments to robust long range demonstrations in free-space and fibre optics, and even work towards satellite communications. Previously many demonstrations of quantum secured communication have utilised integrated components or processes for the benefits of miniaturisation, manufacturability, or complexity. Electro-optic modulators have provided multi-protocol operation [6], planar lightwave circuitry has been used for time-bin decoding asymmetric interferometers [7], and lithium niobate polarisation modulators have been used for miniaturised chip "clients" [8].

Recent work in Bristol has led to the development of integrated photonic transmitters and receivers for high speed, multi-protocol QKD, utilising commercial fabrication facilities (Figure 1). This has exploited indium phosphide for the monolithic integration of laser diodes, high-speed electro-optic phaser modulation, and monitoring photodiodes, to prepare multi-protocol weak coherent time-bin encoded states, for communication over optical fibre. The receiver circuitry is fabricated from silicon oxynitride with thermo-optical reconfigurability, and off-chip superconducting single photon detectors, providing high efficiency, low noise, and low jitter measurement. The results are comparable to state-of-the-art performance, with high clock rates of 1.7 GHz, low quantum bit error rates of 0.88%, and estimated secret key rates up to 568 kbs^{-1} for an emulated 20 km fibre link, demonstrating the feasibility of using integrated photonic circuitry for quantum communication applications, with a low cost, small footprint, and flexible circuitry [9].

The coherent distribution and manipulation of quantum information between quantum circuits would further facili-

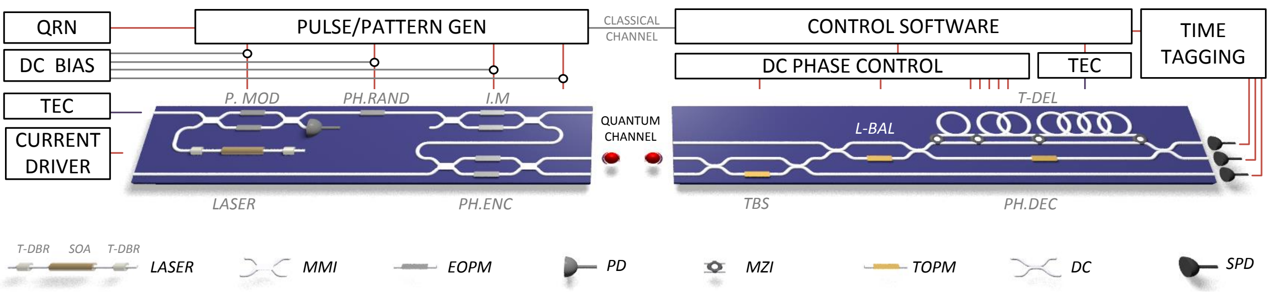

FIG. 1: **Integrated Photonic Devices for Quantum Key Distribution**. Schematic of the GHz clock rate, reconfigurable, multi-protocol, integrated indium phosphide transmitter device (left), which encodes quantum information with time-bin encoded, weak coherent light to be transmitted over optical fibre to a Silicon Oxynitride receiver circuit that passively decodes the quantum information with off-chip single photon detectors(right).

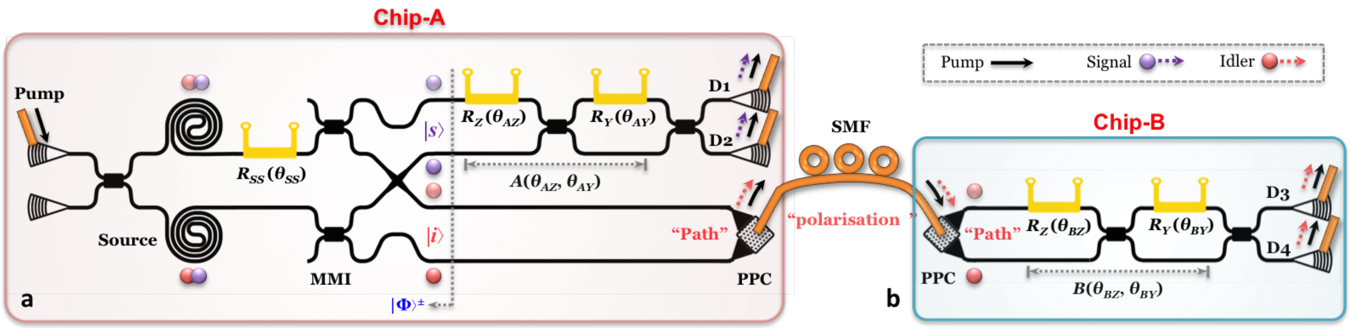

FIG. 2: **Quantum photonic interconnect and entanglement distribution between two integrated Si photonic chips.** **a**. Chip-A comprises path-entangled states generation, arbitrary projective measurement, and path-polarisation conversion (PPC). **b**. Chip-B includes a projective measurement and PPC. [10]

tate applications in quantum communications, computation and sensing. By using a silicon-based technology platform we have demonstrated a quantum photonic interconnect by converting the stable path encoded qubits favourable in integrated platforms, to polarisation encoded qubits, stable across free-space links. We demonstrated the distribution of entanglement generated on-chip, to violate Bell's inequality across separated integrated chips [10], paving the way to larger photonic resources to be interconnected (Figure 2).

Elsewhere, silicon micro-ring resonators and other integrated components have been used to demonstrate the generation of time-bin entangle photons [11], a crucial resources for long range fibre optic quantum communication and key distribution. These demonstrations show proof of principle results of high coincident counts, good state fidelity, with stable operation of interferometers. Continuous-variable quantum communication can also benefit from the developments led by classical telecommunications, with work with on-chip entanglement [12], and towards quantum random number generation and quantum key distribution with standard telecommunication integrated platforms.

Integrated photonics has developed to an extremely mature and robust platform in which to implement quantum technologies, by monolithically combining the integration of lasers, single photon sources, high complexity of passive and active circuits with high speed electro-optic modulation, for quantum communication, sensing, simulation and computation. Development continues to improve performance, with increasingly low propagation loss and high efficiency coupling between devices and fibre. Demonstrations of higher speeds, with more efficient sources and single photon detectors will improve performance and capabilities, allowing for the implementation of future quantum secured communications such as wavelength-division-multiplexed communication, and measurement-device-independent QKD, and even through to all optical quantum repeaters for long range future quantum networks.

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