

# Integrated quantum photonic technologies for applications communications and computation

(Invited paper)

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## Abstract

Quantum photonics has emerged as a promising approach to realizing large-scale and complex quantum technologies for applications in quantum communications and quantum information processing. Here we overview recent developments presenting circuits comprising hundreds of photonic components integrated into single coherent quantum systems.

**Keywords:** Quantum photonics, integrated optics, quantum information processing, quantum communications.

## 1. Introduction

Photonics is a promising approach to realizing quantum information technologies, where entangled states of light are generated and manipulated to implement fundamentally new modes of computation, simulation and communication, as well as enhanced measurements and sensing. Historically bulk optical elements on large optical tables have been the means by which to realize proof-of-principle demonstrators in quantum physics. Integrated quantum photonics has enabled a step change in this technology by controlling and manipulating single photons within miniature waveguide circuits. This technology approach is now being used to pioneered breakthroughs in quantum communications, quantum sensing and quantum information processing. Here we present recent developments in chip-to-chip quantum communications and on-chip quantum information processing.

## 2. Chip-based quantum communications

Quantum Key Distribution (QKD) provides a provably secure approach to share secret keys used to encrypt information by transmitting single photons through a quantum channel. It is one of the first commercially available quantum technologies and a leading candidate for securing communications against attacks from future quantum computers. Integrated photonics provides a stable, compact, miniaturized and robust platform to implement quantum communications systems. The inherent phase stability of integrated photonics makes it particularly suitable for manipulating quantum information encoded in different time-bins, an encoding extensively used in fiber-based QKD systems.

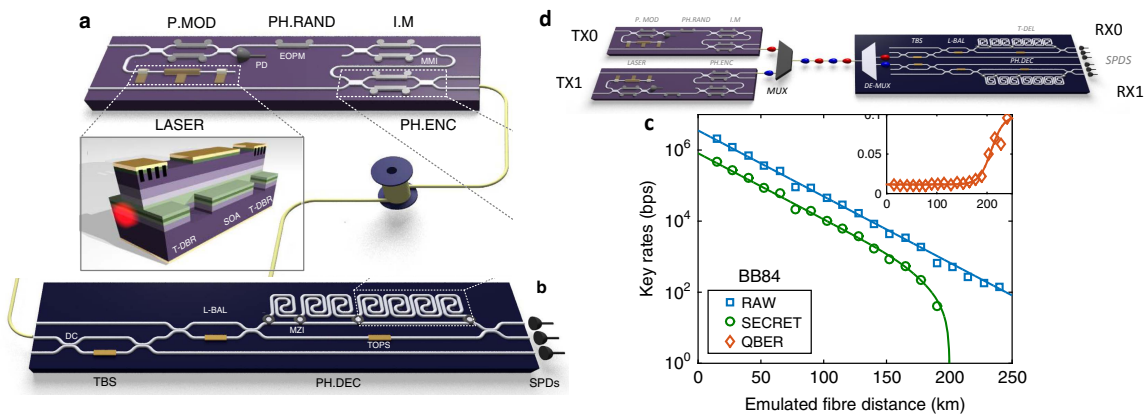


Figure 1: Chip-to-chip quantum communication system (a) InP transmitter chip (b) SiON receiver chip (c) Key rate for emulated fiber distance (d) WDM QKD link [1]

Chip-based QKD transmitters have been implemented in both the InP[1] and Silicon [2], [3] material platforms, with the first demonstration of a fully integrated chip-to-chip QKD system implemented with an InP transmitter chip and a Silicon Oxynitride receiver chip (Figure 1) [1]. These chips provide a complete chip-to-chip quantum photonic solution, and through programmable quantum circuitry can implement multiple QKD protocols, including Coherent One Way (COW) operating, Differential Phase Shift (DPS) and BB84 (see Figure 1c for an example). The data rate of these systems can be increased through wavelength division multiplexing (WDM), where multiple secret keys are distributed within a single optical fiber on different wavelengths. Figure 1c show one such approach where a WDM-QKD system was implemented using two GHz clocked InP QKD transmitters

and a single Silicon Oxynitride receiver with integrated de-multiplexing. The InP chips are fully integrated, incorporating all the necessary components including a tunable laser source and high-speed phase modulators. Using on-chip asymmetric MZI filters for wavelength de-multiplexing, the receiver splits the two channels into independent copies of the reconfigurable decoding circuitry. The combined WDM channels increase the secure key rate by a factor of two, to 1.11 Mbit/s over a 20 km emulated fiber. The increase in rates, and ability to scale up these circuits opens the way to new and advanced integrated quantum communication technologies and larger adoption of quantum-secured communications.

### 3. Chip-based quantum information processing

Quantum information processing, and particularly quantum computing, has generated much interest for its potential ability to outperform classical computing for many important tasks. Photons are considered as a promising candidate for implementing quantum information processing owing to their properties of long coherence time, ease of manipulation and light-speed transmission. The silicon-based quantum technology platform, where quantum states of light can be generated and manipulated using entirely silicon-based waveguide circuits [4], offers a range of benefits for quantum information processing, including high nonlinearities for efficient on-chip generation of quantum states of light, and high component densities for complex circuits. Using this silicon quantum photonic technology platform a wide range of quantum information processing demonstrators have been realized. Here we focus specifically on the more recent large-scale implementations.

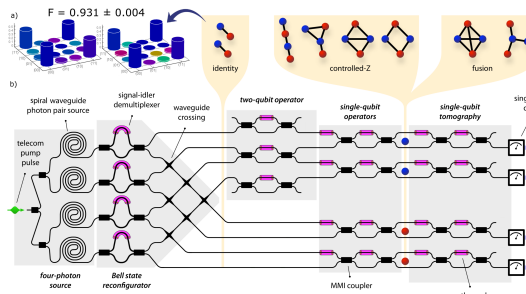


Figure 2: Graph state generator: (a) Reconstructed density matrices of on-chip Bell pairs, (b) Schematic of device [6]

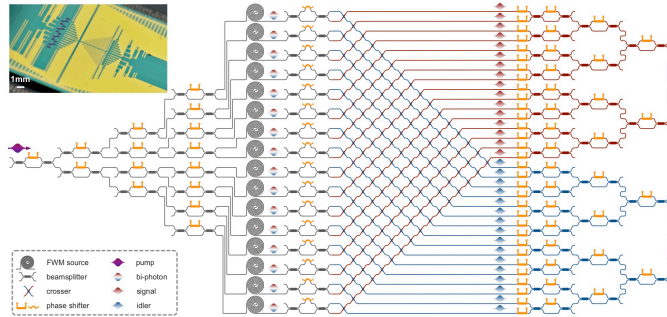


Figure 3: Highly reconfigurable quantum circuit for the generation, control and analysis of multi-dimensional quantum entanglement [5]

#### *Programmable four-photon graph states on a silicon chip*

Modern approaches to quantum information processing demands the generation of large entangled quantum states, typically graph states. To investigate such states of light, integrated quantum circuits are required that can generate and manipulate indistinguishable multi-photon states. Figure 2 show the first integrated quantum circuit capable of the on-chip generation and manipulation of four-qubit, four-photon graph states. The device generates two pairs of photons on-chip, then applies a switchable entangling gate (performing either a fusion or a controlled-Z operation) in order to entangle the qubit states and access all 6 of the 4-qubit graph states - creating genuine four-qubit entanglement. Whether the entangling gate is set to perform a fusion or a CZ operation determines the type of entanglement in the produced four-qubit state. The fusion operation yields Greenberger–Horne–Zeilinger type entanglement, whereas the CZ operation yields entanglement of the cluster state type. These comprise the only two classes of graph-state entanglement in four qubits, which are locally equivalent to the entire set of four-qubit graph states. The device produces Bell pairs with state-of-the-art fidelity, and the star-type graph state (inset of Figure 5) are verified by measuring that state's stabilizers.

#### *Large-scale multi-dimensional quantum photonics*

Multi-dimensional quantum systems exhibit distinct quantum properties and offer improvements in key applications such as increasing capacity in quantum communication, strengthening quantum correlations, and enriching quantum simulation and computing schemes. Photons represent a promising platform able to naturally encode and process these 'qudits' in various degrees of freedom, e.g., orbital angular momentum, temporal bin and frequency. However, these approaches present limitations in terms of controllability, precision, universality and a full integration of elements, which represent bottlenecks for further developments of multidimensional quantum photonic technologies.

By utilizing large-scale silicon quantum photonics, a chip was realized that could create, control and multidimensional entanglement up to dimensions  $15 \times 15$  [5]. The chip (Figure 3) comprised 16 photon sources that use spontaneous four-wave mixing to generate photon pairs in a superposition across 16 optical modes; 93 thermo-optic phase shifters; 122 multimode interference beamsplitters; 256 waveguide crossers and 64 grating

couplers. Greater than 500 photonic components monolithically integrated on a single chip. This chip enables the generation of multidimensional entangled states with an arbitrary degree of entanglement and arbitrary multidimensional measurements with very high fidelity, verified by quantum state tomography and Bell violations.

#### 4. Conclusion

Integrated quantum photonics is a versatile technology platform that is proving invaluable in the development of future quantum information technology applications, particularly in quantum communications and quantum computation. Large-scale quantum photonic circuits enable the on-chip generation and precise manipulation of complex photon states of light, whilst these stable, compact, miniaturized and robust platforms are also delivering the next generation of quantum communications devices.

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