Expanding the Quantum Photonic Toolbox with Low-Loss AlGaAs-on-Insulator

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Abstract: We present the building blocks for a programmable quantum processor with AlGaAs-on-insulator integrated photonics, including low-loss waveguide crossers and > 30 dB extinction tunable interferometers, which we benchmark via photonic qubit demultiplexing with high extinction.

Silicon-on-insulator (SOI) has been the workhorse photonic integrated circuit (PIC) platform for over a decade due to its manufacturability and years of extensive component development, including tunable filters, Mach-Zehnder interferometers (MZIs), optical modulators, and nonlinear photon sources [1,2]. Despite this remarkable progress, silicon has several limitations for quantum PICs (QPICs), including a weak third-order nonlinearity, two photon absorption at telecommunication wavelengths, and relatively high propagation losses, which all impact the speed and efficiency of chip-scale SOI QPIC technologoes. Recently, we demonstrated a significant performance advantage by switching from silicon to AlGaAs, which exhibits the largest third-order nonlinearity of any PIC material, an index of refraction comparable to silicon, negligible two photon absorption, < 0.2 dB/cm propagation loss, and a factor of two larger thermo-optic coefficient, making it an attractive platform for QPICs [3,4]. Utilizing an AlGaAs-on-insulator (AlGaAsOI) microring resonator with a quality factor $Q > 1$ million, a 1,000-fold improvement in entangled-photon pair generation over SOI was achieved [5]. Here, we expand the AlGaAsOI QPIC toolbox to include low-loss waveguide crossers and tunable MZIs with up to 30 dB extinction. To benchmark the components, we demonstrate photonic path-encoded qubit demultiplexing using entangled-photon pairs generated from an AlGaAsOI microring chip with < 1 V switching voltage with performance to or exceeding SOI.

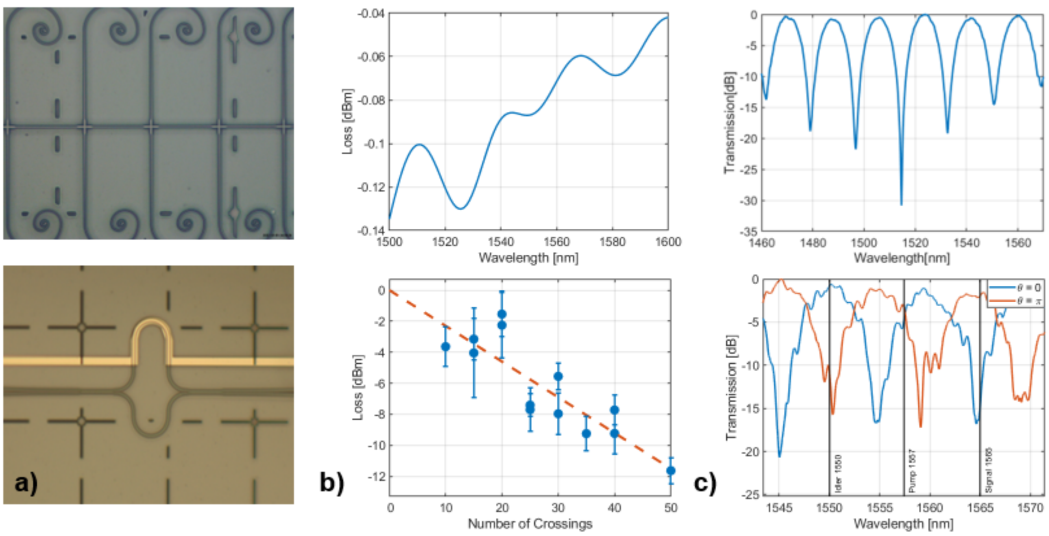

Fig. 1: **a)** Microscope image of AlGaAsOI waveguide crossers (top) and tunable interferometers (bottom). **b)** Simulated (top) and measured (bottom) waveguide crosser transmission demonstrating < 0.2 dB/crosser. **c)** Transmission spectra of interferometers with directional couplers (top) and MMIs (bottom) with > 30 dB extinction.

The waveguide crossers and an MZI are shown in the top and bottom panels of Fig. 1a), respectively. The fabrication process is similar to that described in Ref. [5], which utilizes 400-nm-high AlGaAs waveguides cladded by silica. These components are the basic building blocks for programmable quantum photonic processors and photonic qubit manipulation: crossers, for example, enable path-encoded Bell-state generation and demultiplexing of signal and idler photons on chip, while tunable interferometers are utilized for path-encoded single-qubit unitary operations, two-qubit entangling gates, and multi-qubit fusion gates. Our crossers are designed utilizing a swarm optimization protocol to maximize the transmission by allowing the width to vary at 13 locations. This design was optimized for a 100-nm bandwidth to ensure low-loss transmission for pump, signal, and idler photons from our entangled-photon pair sources. We simulate a propagation loss < 0.1 dB/crosser (Fig. 1b) top panel); however, the measured loss is closer to 0.2 dB/crosser (Fig. 1b) bottom panel), likely due to small variations in the fabrication. Nonetheless, these results are comparable to those typically achieved with SOI (~ 0.1 dB/crosser).

We fabricated two types of thermo-optically tunable MZIs utilizing either 3 dB directional couplers (DC) (Fig. 1c) top panel) or 3 dB multimode interferometers (MMIs) (Fig. 1c) bottom panel). The MMIs are designed such that they symmetrically taper from the 0.4 μm waveguide width to the 0.9 μm at the MMI core region separated by a 0.3 μm gap. The MMI core has a width of 2.1 μm and a length of 17.2 μm. The DCs are designed with two 0.4 μm waveguides separated by a 0.3 μm gap and a 17 μm coupling length. For the MZI with DCs (MMIs), a 29.5 μm (60 μm) path imbalance is used to achieve a free spectral range (FSR) of 9.8 nm (19.6 nm) as shown in the transmission spectra in Fig. 1c). For the MMI interferometer, the two traces are acquired at a relative phase of zero (1 V) and π (1.8 V). The transmission spectra demonstrate that > 30 dB (> 20 dB) of extinction is achieved with the two MZI designs. For the MMI interferometer, the lower extinction rate compared to the DC version is due to a deviation of the splitting ratios from 3 dB that can easily be corrected in future versions.

To benchmark the MZI performance, we utilized the version with MMIs to demultiplex signal/idler photon pairs injected into the top input channel of the MZI from a 13.91 μm AlGaAsOI microring resonator [5] whose wavelengths are indicated in the bottom panel of Fig. 1c). As shown in Fig. 2, an AlGaAsOI microring resonator is pumped at 1557 nm to generate signal-idler entangled-photon pairs at 1550 nm and 1565 nm, respectively, via spontaneous four-wave mixing. The photon pairs are sent via fiber to the MZI chip that demultiplexes them into their respective channels, followed by low-loss narrow-band filters and superconducting nanowire single-photon detectors (SNSPDs). Normalized counts on the two SNSPDs are shown in the right panel in Fig. 2 as a function of the applied MZI voltage, demonstrating > 14 dB extinction at ~ 1.6 V. This value is lower than the expected 20 dB due to the fact that the MZI FSR does not precisely match that of the microring resonator source. Ideally, for demultiplexing the pairs from the microring used in this experiment, the interferometer should have an FSR of 30 nm–a factor of four larger than the FSR of the source. The current 9.8 nm FSR introduces the asymmetry of the peaks and troughs of the signal and idler counts in Fig. 2.

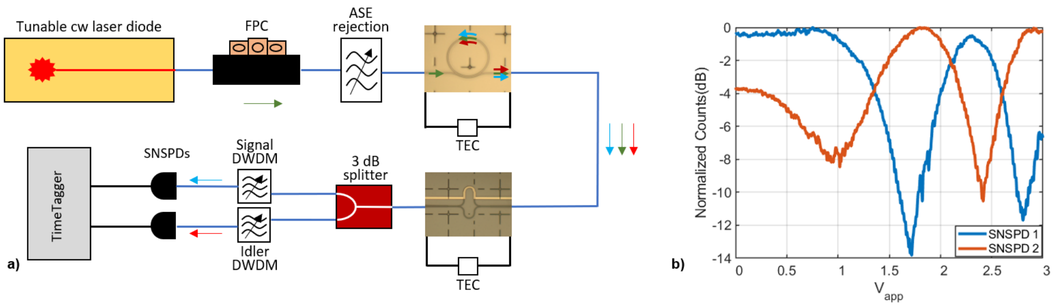

Fig. 2: **a)** Experimental schematic of photonic qubit demultiplexing using AlGaAsOI entangled-pair source and interferometer chips. **b)** Normalized counts on SNSPDs after demultiplexing.

In summary, we demonstrate advances in AlGaAsOI photonics with low-loss waveguide crossers and high-extinction tunable interferometers that pave the way for multi-functional and programmable QPICs in a highly nonlinear platform with ultrabright entangled-pair sources [5]. The key advantages here–less than 0.2 dB/cm propagation loss, > 1,000-fold improvement in pair generation over SOI, large index contrast, wide bandgap, and > 30 dB extinction tunable components, point to exciting prospects for monolithically integrated chips for high-speed quantum photonic processing and communications.

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