Lithium Niobate Nanophotonic Resonators for Quantum Simulations

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Primary CNF Tools Used: JEOL 9500, AJA Ion Mill, SC4500 Evaporator

Abstract:

Integrated photonic devices have enabled momentous progress in development of scalable quantum computing and information processing technologies. These devices are designed to control quantum states of light confined within nanophotonic structures to implement computing protocols. To that end, we demonstrate a frequency domain analog quantum simulator that can simulate a two-dimensional lattice of atoms on the thin-film lithium niobate platform. The device is fabricated at the Cornell NanoScale Facility (CNF).

Summary of Research:

Quantum simulation is one of the primary computational tasks that a quantum computer can perform much more efficiently than a classical computer. Over the past two decades, significant efforts have been made for efficient simulation of condensed matter systems [1]. Integrated photonic devices are well-suited for these applications due to their inherent scalability that can help build large-scale simulation and perform computational tasks [2]. One of the most promising techniques for quantum simulation with light involves photons in distinct frequency modes. Here, we demonstrate frequency domain simulation of the tight-binding model. This model describes a chain of atoms that have nearest neighbor coupling. We implement this by coupling adjacent frequency modes of an optical resonator with electro-optic modulation done using on-chip electrodes. With this system, we demonstrate simulation of a two-dimensional quantum random walk and simulation Bloch oscillations of an electron in the presence of an eternal electric field.

The device used for these simulations is a nanophotonic racetrack resonator fabricated on 600-nm X-cut lithium niobate on insulator (LNOI) wafer. The ring has a width of 1.5 µm and an etch depth of 300 nm. The device is patterned on the wafer using electron-beam-lithography on the JEOL 9500 machine using ZEP520A as the resist mask. After development, the device is etched using argon ion milling on the AJA ion mill achieving a 50% (300 nm) etching depth. The resist is then stripped using standard resist remover chemistry and the chip is prepared for a second electron-beam exposure. This is to pattern electrodes on both sides of the resonator as previously stated. The material is coated with PMMA resist and exposed again to pattern the electrodes. After development, the chip is deposited with a 400 nm layer of gold using an evaporator (SC4500). The electrode pattern is subsequently created by a resist liftoff process in acetone. Figure 1 shows an optical microscope image of a fabricated device at different magnifications.

The simulations are run on the temporal evolution of entangled photon pairs inside the resonator. These photons are also generated within the resonator using spontaneous parametric down conversion (SPDC), a process in which a laser photon annihilates to generate a photon pair [3]. Figure 2 shows evolution of a quantum random walk of the photon pairs. Each pixel in the images represent a resonator mode pair. Photons in one mode of the resonator can scatter to its two adjacent modes using the on-chip electro-optic modulator driven at a microwave frequency matching the resonators mode spacing. This implements a coin toss experiment

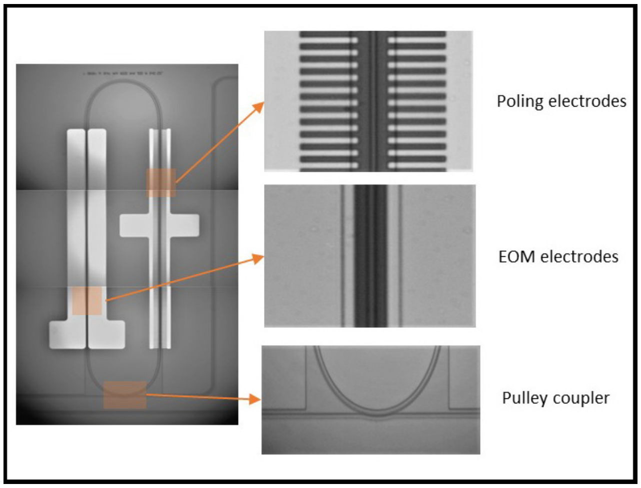

Figure 1: Microscope image of a fabricated device showing different sections of the device. These are: a ring resonator, an evanescently coupled waveguide to couple light into and out of the resonator, and electrodes patterned around the resonator.

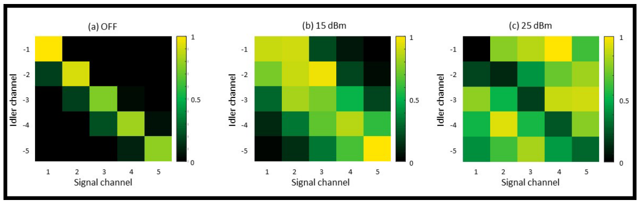

Figure 2: Quantum random walk of the frequency correlation of the photon pairs with (a) no modulation signal, (b) Microwave signal amplitude at 15 dBm and (c) at 25 dBm. The axes indicate the mode number of the resonator and the colormap shows the strength of the correlation at each mode pair. The spread of the correlation with increasing modulation amplitude is a signature of a random walk.

at each mode implementing the random walk. The spread of the random walk increases by increasing the mode coupling using a stronger microwave signal as shown in Figure 2. Another simulation we perform is motion of an electron under an influence of a constant electric field inside a crystal lattice. The electric field is simulated by detuning the microwave signal away from the resonator's mode spacing. This imparts a Bloch-like phase on the coupling [4]. Figure 3 shows the temporal correlation of the photon pairs. We see the correlation turns oscillatory when the microwave signal detuning is introduced with a frequency matching the detuning. These are Bloch oscillations simulated on the temporal correlation of the photon pairs.

Conclusions:

To conclude, we have designed and fabricated an optical quantum simulator based on thin-film lithium niobate. We have demonstrated simulation of quantum random walk and Bloch oscillations. Although these are simple simulations, they demonstrate the ability of this platform for frequency domain computational and simulation tasks. Furthermore, we envision that this demonstration will motivate experiments in quantum simulation on chip-scale architectures.

References:

[1] Reviews of Modern Physics 86.1 (2014): 153.

[2] Science 360.6386 (2018): 285-291.

[3] Reports on Progress in Physics 66.6 (2003): 1009.

[4] Optica 3.9 (2016): 1014-1018.

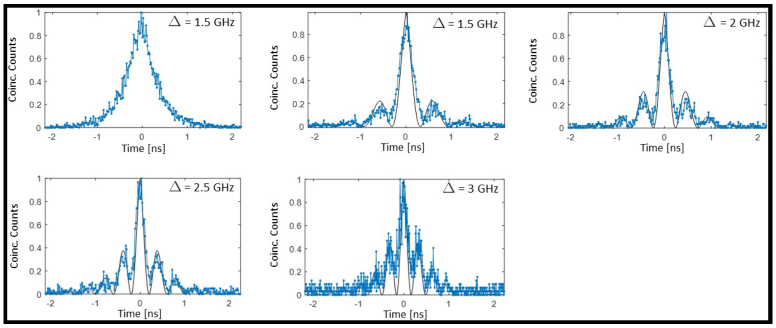

Figure 3: Temporal correlation of the photon pairs at different modulation detunings D. The oscillations occurring at non-zero detuning values are an analog of Bloch oscillations of an electron in the presence of a constant electric field.