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On-chip analysis of time-bin encoded photons

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ABSTRACT

Two main challenges for quantum networks are state preservation and scaling current infrastructure. Photonic polarization qubits are susceptible to effective decoherence via polarization mode dispersion in optical fibers. This can be circumvented by encoding qubits in the photon's arrival time, i.e., time-bin encoding. Here, we present measurements on a thin-film lithium niobate integrated-optic device, designed to analyze telecom-wavelength photonic time-bin qubits. By thermo-optically tuning the phase and amplitudes of interfering processes traversing the photonic circuit on the device, we are able to obtain $\sim 83\%$ interference visibility, marking significant progress towards efficient time-bin encoding and analysis with integrated photonics.

Keywords: time-bin, integrated-optic, photonics, telecom

1. INTRODUCTION

Photons are ideal "flying" qubits in quantum network architectures, as they are easily transmitted over optical fiber and offer several degrees of freedom to encode quantum information. As the polarization of a photon can be measured and manipulated with readily available optical elements, polarization qubits have been the "workhorse of quantum photonics".[1] However, polarization qubits suffer from Polarization Mode Dispersion (PMD) due to birefringence in optical fibers. This leads to effective decoherence of the quantum state, which is accentuated for long-distance quantum communication, particularly with short photon wavepackets.

Time-bin qubits, where quantum information is encoded in the arrival time of the photon, are insensitive to polarization fluctuations in optical fiber.[2] This makes time-bin qubits ideal candidates for scaling quantum network infrastructure, as the fidelity of the quantum state can be maintained over the length of the channel (assuming insufficient dispersion to cause pulse overlap). The first experiment for generating and analyzing time-bin qubits was conducted in 1999 and it was claimed that the design could be fully integrated onto an optical chip in the future.[3] Here, we present measurements on a thin-film lithium niobate (TFLN) integrated-optic device, designed to analyze telecom (C-band) time-bin qubits.

2. THEORY

Shown in Fig. 1 is a schematic for a device capable of generating and analyzing time-bin photonic qubits.[3] It consists of a 2x2 interferometer, equipped with a phase shifter in the long arm, a variable coupler at the left splitter, and an optional fast optical switch at the right splitter.

Consider a single-photon pulse entering the interferometer from the left. Assuming that the difference between the long and short paths is much larger than the pulse duration, we obtain a photon at the output in a superposition state of having traversed the long and short paths of the interferometer. We can define eigenstates by the photon's arrival time, based on which path the photon had taken, i.e., $|\text{short}\rangle$ for the early arrival or $|\text{long}\rangle$ for the late arrival. Then, the state at the output is $\alpha\,|\text{short}\rangle + \beta\,|\text{long}\rangle$, where the phase and norm of α, β depend on ϕ, the imparted differential phase, and η, the coupler ratio at the left splitter, respectively. Therefore, any arbitrary time-bin qubit can be generated by varying η and ϕ. The fast optical switch at the right splitter

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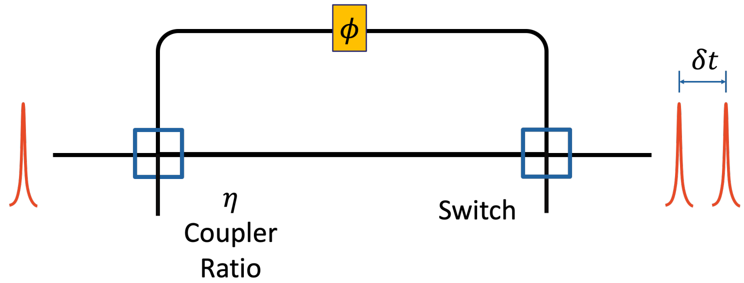


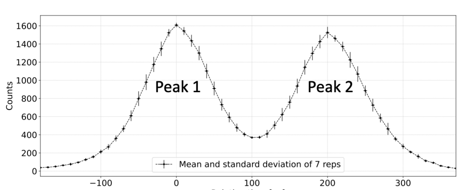
Figure 1. Schematic of device for generating (left-right) and analyzing (right-left) time-bin photonic qubits.

recombines the pulses traveling through either path–transmitting the early photon amplitude and reflecting the later one–so as to route them to the same output. In our experiment, this switch was replaced with a passive 50:50 splitter, at the cost of 50% of the photons being lost to the other output.

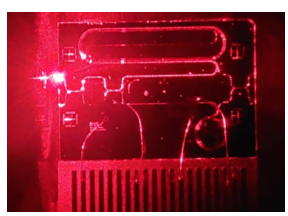
To analyze time-bin qubits, we use the same schematic, but the photon propagates from right to left. Consider two pulses temporally separated by δt entering the interferometer from the right. The switch is now set to route the early (late) pulse through the long (short) path. At the left splitter, the two processes, "early pulse took the long path" and "late pulse took the short path", interfere. By tuning η and ϕ, this interference can be made partially or completely destructive or constructive, meaning that we can project onto any arbitrary state of the 2-D Hilbert space. Note that since our device did not have a fast optical switch, we instead obtain three time-bins at the output (Fig. 2 (c)): both pulses take either the long or short paths, i.e., "late-long" or "early-short", respectively, and a "middle" time-bin comprising the interfering "early-long" and "late-short" processes. We can analyze the time-bin qubit by probing interference in this post-selected "middle" time-bin.

3. METHODS

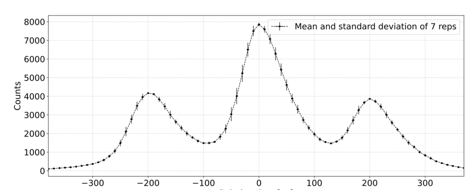
The time-bin analysis chip (shown in Fig. 2(b)) is a thin-film lithium niobate (TFLN) integrated-optic device. It comprises an unbalanced Mach-Zehnder interferometer that creates two time-bins separated by $\delta t \sim 200$ ps, as shown in Fig. 2(a). This interferometer is equipped with a thermo-optic phase shifter that tunes the phase difference between the long and short paths. The first "beam splitter" of this device is itself another balanced-path length Mach-Zehnder interferometer. The reflectivity/transmittivity of this can be tuned via another thermo-optic phase shifter, as shown in Fig. 3.



(a)



(b)



(c)

Figure 2. (a) A single pulse sent through the chip produces two pulses separated by $\delta t \sim 200$ ps . (b) TFLN chip's waveguides illuminated by an edge-coupled red laser beam. The actual measurements were done using 1560-nm light. (c) Three time-bins measured at the output of the chip. The "middle" time-bin counts are post-selected to probe interference.

The two time-bins are generated by sending <5-ps long, 1560-nm pulses into a free-space unbalanced Michelson interferometer. The path-length imbalance of this interferometer is set to match δt, i.e., $\Delta l = (c \times \delta t)/2 \sim$ 3 cm. The two time-bin pulses are edge-coupled into the chip using high-NA microscope objectives. We observed a net transmission of 0.01%.

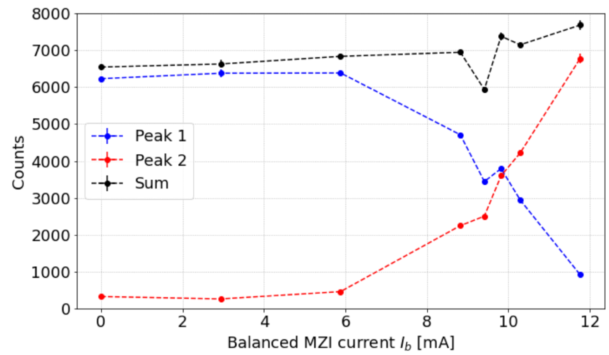
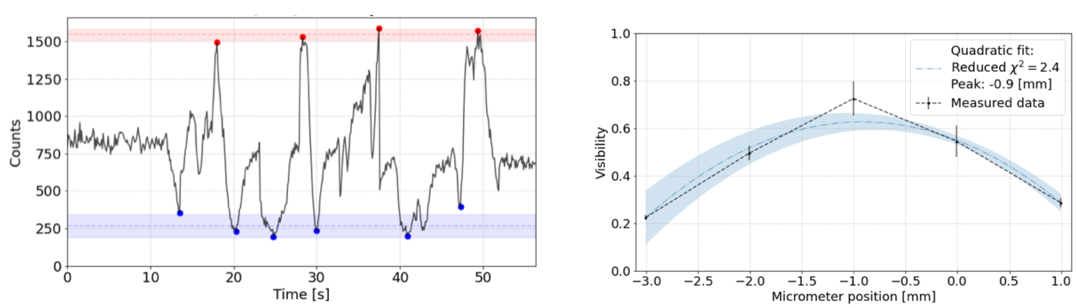


Figure 3. Varying the coupler ratio η of the chip's first "beam splitter" by applying a changing electrical current on the thermo-optic phase shifter. The peaks refer to those shown in Fig. 2(a). At ~ 10 mA current, $\eta \sim 1/2$, implying that the amplitudes of the early-long and late-short processes have been equalized.

Finer adjustments are made using the thermo-optic phase shifter on the chip's unbalanced interferometer to optimally match δt. The chip's balanced interferometer's phase shifter is used to equalize the amplitudes (intersection of Peak 1 and Peak 2 curves in Fig. 3) of the interfering early-long and late-short processes. This leads to high-contrast variation in the post-selected "middle" time-bin counts (Fig. 4, 5), measured using highly efficient ($\sim 90\%$) superconducting nanowire single photon detectors (SNSPDs).

4. RESULTS

For a given input δt to the chip, we varied the electric current applied to the thermo-optic phase shifter on the chip's unbalanced interferometer and observed counts in the "middle" time-bin (while keeping the early-long and late-short processes equalized) as shown in Fig. 4 (a). We repeated the process for different values of input δt by translating one of the mirrors of our free-space interferometer to vary Δl and obtained a maximum visibility of $\sim 71\%$ as shown in Fig. 4(b). Keeping this optimum input δt fixed, we inserted a polarizing beam splitter at the output and routed the transmitted photons to the SNSPDs. We observed $\sim 83\%$ fringe visibility, as shown in Fig. 5. This suggests that unwanted polarization transformations are occurring in the chip, leading to distinguishability between the early-long and late-short processes.



(a) (b)

Figure 4. (a) Variation in "middle" time-bin counts as the electric current applied to the chip's unbalanced interferometer's thermo-optic phase shifter is varied cyclically over time after an initial waiting period of ~ 10 s. (b) Measurement of fringe visibility at several micrometer positions specifying the relative position of one arm of the free-space Michelson interferometer near the equal path difference location. We fit the trend to a parabola to determine the micrometer position corresponding to optimal fringe visibility.

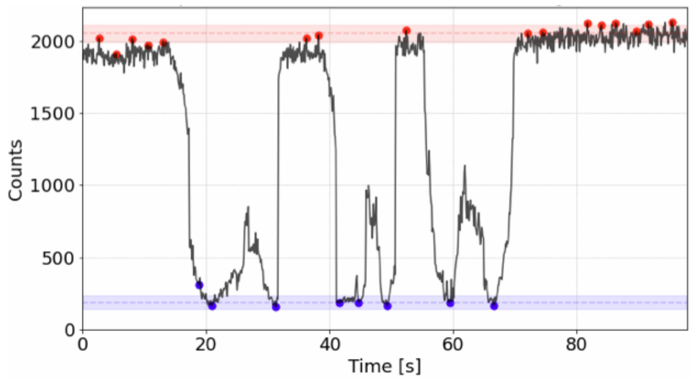


Figure 5. Higher contrast fringes in measured counts (than in Fig. 4(a)) obtained upon inserting a polarizing beam splitter at the output of the chip. A visibility of 83% was measured, implying that the light is undergoing unwanted polarization transformations in the chip, leading to distinguishability between interfering processes.

5. CONCLUSIONS AND OUTLOOK

Our results present significant progress towards realizing time-bin encoding in an integrated-optics platform. Active stabilization of the on-chip interferometer using a narrow-linewidth laser will reduce susceptibility to system-drift during the measurement process. Next-generation chips equipped with electro-optic modulators will facilitate faster tunability and prevent photon loss when post-selecting the "middle" time-bin by always routing the early(late) photon through the long(short) path. Polarization transformations in the chip and methods to mitigate unwanted transformations are currently under investigation.

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