Design of an Integrated Bell-State Analyzer on a Thin-Film Lithium Niobate Platform

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***Abstract*—Trapped ions are excellent candidates for quantum computing and quantum networks because of their long coherence times, ability to generate entangled photons as well as high fidelity single- and two-qubit gates. To scale up trapped ion quantum computing, we need a Bell-state analyzer on a reconfigurable platform that can herald high fidelity entanglement between ions. In this work, we design a photonic Bell-state analyzer on a reconfigurable thin-film lithium niobate platform for polarization-encoded qubits. We optimize the device to achieve high fidelity entanglement between two trapped ions and find $>99\%$ fidelity. Apart from that, the directional coupler used in our design can achieve any polarization-independent power splitting ratio which can have a rich variety of applications in the integrated photonic technology. The proposed device can scale up trapped ion quantum computing as well as other optically active spin qubits, such as color centers in diamond, quantum dots, and rare-earth ions.**

***Index Terms*—Bell-state analyzer, thin-film lithium niobate, scalable quantum computing, trapped ions, entanglement, polarization qubits, polarization-independent directional coupler.**

I. Introduction

TRAPPED ions are one of the most advanced platforms for quantum computing and quantum networks. They exhibit long coherence times [1]–[3], naturally emit photons entangled with their internal qubit memories [4]–[6], and support high-fidelity single- and two-qubit gates [7], [8]. Apart from that, they can be trapped in a compact surface electrode ion-trap with integrated waveguides and grating couplers for ionization, cooling, coherent operation and quantum state preparation, and detection [9]. But quantum computers and networks based on trapped ions also require photonic devices in order to interconnect different nodes of the network [10], [11]. The key optical component in these devices is the photonic Bell-state analyzer [12], which heralds the successful entanglement between distant qubits. Such entanglement provides a photonic interconnect between trapped ions, which can be used to scale up trapped ion quantum computers [2], [13] as well as enable long-distance quantum networks [10], [14]–[16]. But to realize these interconnects in a scalable way requires compact reconfigurable chip-integrated devices that can perform Bell-state analysis between trapped ions at different nodes [10], [14].

Thin-film lithium niobate is a promising material platform to implement photonic Bell analyzers on a compact chip. Lithium niobate has a broad transparency window over the visible spectrum [17], making it compatible with many ion species. It also possesses a high electro-optic coefficient, which enables reconfigurable photonic devices with ultra-fast switching speed [18], [19]. Moreover, it has excellent thermo-optic and piezoelectric properties for nanophotonic applications [20]. Recent progress in fabrication has enabled ultra-low loss thin-film lithium niobate waveguides in both the visible [17] and telecom range [21]. Apart from that, thin-film lithium niobate can be used for quantum frequency conversion which is beneficial for implementing quantum networks [16], [22]–[24].

But applying thin-film lithium niobate devices to photons generated by trapped ions is challenging because trapped ions naturally emit polarization-encoded photonic qubits [25], [26]. Thin-film lithium niobate waveguides possess small sidewall angles [27] and require partial etching to achieve low waveguide loss [17], [21]. These properties create a large polarization anisotropy, which makes it difficult to engineer a photonic Bell-state analyzer for polarization qubits. In particular, the Bell-state analyzer typically employs a non-polarizing beam splitter, which is hard to engineer with a highly anisotropic device structure. Previously, slot waveguides have been developed in the silicon technology [28]–[30] to achieve polarization-insensitive on-chip components that could be used for Bell-state analysis. Due to low index-contrast and reactive ion etching technique [17], it is hard to engineer slot waveguide structure in thin-film lithium niobate to achieve polarization-insensitive operation. Recently, polarization-insensitive modulators and switches have been achieved in a bulk lithium niobate [31] and hybrid silicon and lithium niobate platform [32] using polarization diversity where two orthogonal polarizations have been modulated separately. Very recently, Zhang *et al.* [33] designed a polarization-insensitive directional coupler with fully etched ridge waveguide structure which can suffer high waveguide loss [17], [21], [34]. Apart from that, two orthogonal polarizations can experience different sidewall surface roughness in a fully etched ridge waveguide structure

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