Fabrication Tolerant Inverse Design Grating Couplers for Scalable Trapped Ion Quantum Computing

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Abstract: A fabrication tolerant Si grating coupler for 1.762 μm operation is optimized with inverse design, allowing for −30 dB crosstalk between a pair of $^{133}Ba^{+}$ trapped ion qubits within expected fabrication variation.

1. Introduction

Quantum computing promises exponential processing speedup compared to classical computers for certain tasks. Trapped ions have been identified as a favorable medium; trapped ion quantum computers perform operations on single atoms through laser pulses carefully calibrated to energy state transitions. Photonic integrated circuits (PICs) are an encouraging platform for increasing scalability, as these systems are phase-stable, modular, and lithographically defined. On a small scale, monolithically integrated surface electrode traps with grating coupler optical antennas have been demonstrated for 1 and 2 qubit systems [1,2]. However, the grating coupler emission angle and beam profile are highly sensitive to fabrication variations like etch depth, etch width, and refractive index, which will intrinsically limit scaling to more qubits. To combat this, we propose a fabrication tolerant design for control of $^{133}Ba^{+}$ ion pairs using full etch gratings on a silicon-on-insulator (SOI) platform, eliminating the etch depth inconsistency and limiting the device layer Si variation. Furthermore, we show that −30 dB crosstalk is mostly achievable within etch width variability due to lithography, enabling robust single ion addressing of qubit pairs – a capability which has not yet been reported.

2. Grating Design

Table 1. Grating coupler design constraints

Ion pitch	Ion height	Beam waist	Wavelength	Si thickness	BOX	Etch
5.0 μm	72 μm	2.2 μm	1.762 μm	0.22 μm	2.0 μm	0.22 μm

To design the grating, the adjoint method of inverse design implemented in EMopt was used with strict constraints, outlined in table 1. A 5th order Fourier series expansion was used for pitch and duty factor, as this parameterization has been shown to be an effective method in designing focusing gratings [3,4]. An angled gaussian mode match at 72 μm was used for the figure of merit to emulate a gaussian beam irradiating the qubit. The etch depth was fixed at a full 0.22 μm, as this eliminates fabrication error due to Si over-etch or under-etch.

The optimal diffraction angle of a grating varies significantly due to the bottom oxide (BOX) thickness – an optimal angle destructively interferes with the back reflection and maximizes directionality upward to free space. Therefore, the first step in the inverse design process was to optimize the diffraction angle in a 2D FDFD simulation. This was achieved by finely sweeping the mode match angle over a small simulation window. Once the most efficient angle was found, the grating was optimized over the full simulation domain. Finally, the 2D grating was extruded to 3D using a 4 μm wide waveguide. A long, thin grating was selected for the elliptical output optical profile. This architecture eliminates any transverse misalignment, as the intensity varies minimally over several microns in this direction. Additionally, with thoughtful placement of the two gratings, −30 dB crosstalk can be achieved while still preserving 5 μm ion pitch. An example schematic can be seen in figure 1.

3. Simulation Results

The upward radiated power was simulated to be 61%, with the other 37% and 2% reflected down or back respectively. Figure 1 shows a 2D slice of the beam profile (middle) and a 3D top view (right), both on the ion plane. Using the higher order grating lobes, a best-case crosstalk of −30.5 dB can be achieved with careful alignment of the ion pair. Fine alignment tuning is possible – by modulating the DC biases in a surface electrode trap, the ions can be shuttled continuously over the trapping region. The ion pitch can also be changed with tuning of the RF electrode bias. Therefore, this design can be achieved experimentally.

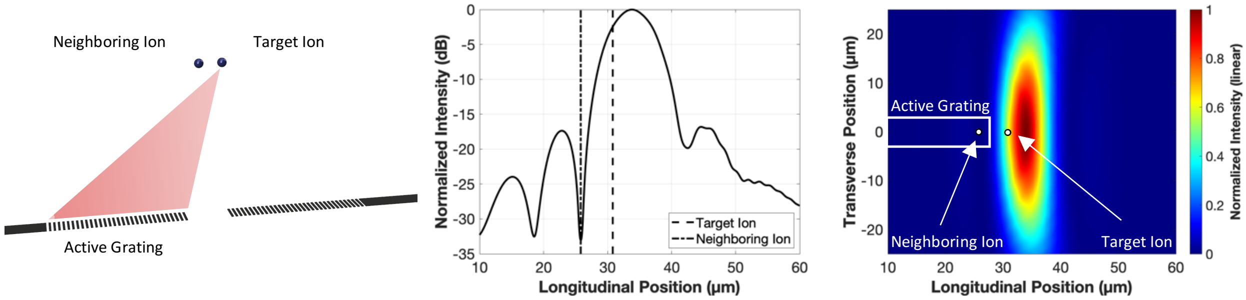

Figure 1. Side rendering of gratings (left), 2D longitudinal beam profile (middle) and 3D top view intensity profile (right)

4. Fabrication Tolerance

Fabrication tolerance was tested by changing the grating etch width. An exposure bound of ± 10 nm was assumed and 3D FDTD simulations were run to examine the effect of this fabrication inconsistency. As seen in figure 2, this resulted in only the emission angle changing with a relatively constant beam profile. Given the ability to continuously shuttle ions laterally within the trap, it is possible to achieve close to −30 dB crosstalk with ± 10 nm etch width broadening, with only two instances of crosstalk worse than −30 dB.

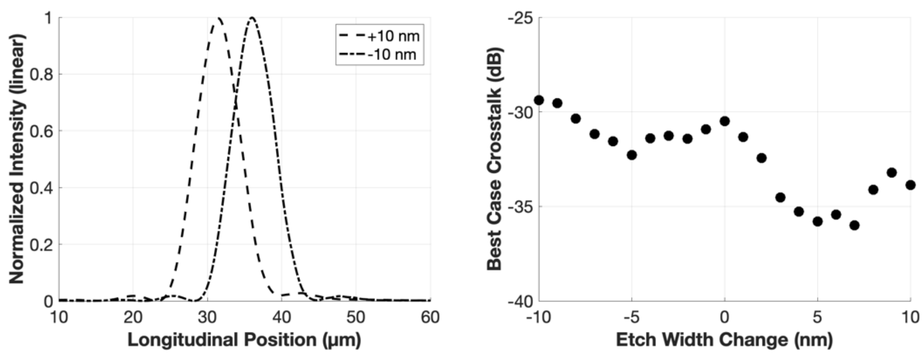

Figure 2. 2D linear scale beam profiles for ± 10 nm etch width (left) and best-case crosstalk vs etch width change (right)

5. Conclusion

A fabrication tolerant grating coupler optical antenna was simulated using inverse design optimization. Due to the full etch SOI design and the ability to move ions in the surface trap, it was shown that this design can achieve close to −30 dB crosstalk for ± 10 nm etch width lithography variation. These designs will be fabricated in conjunction with surface trap electrodes and tested on live $^{133}Ba^{+}$ ions. This architecture will then be used in demonstrating selective addressing of trapped ion qubit pairs, pushing towards high fidelity, highly scalable trapped ion PICs.

6. References

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