

Integrated Beam Steering Using a 2D Focusing Grating Coupler for Scalable Trapped Ion Quantum Computing

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Abstract: A scalable beam steering device is proposed for control of ion trap quantum computers. A combination of a waveguide array and a two-dimensional focusing grating coupler is used to generate $8 \times N$ beam spots at 729 nm wavelength in free space.

Keywords: Quantum computing, ion trap, integrated photonics

I. INTRODUCTION

The ion-trap quantum computer has attracted much attention because of its long coherence time and room temperature operation [1-5]. In this method, laser-addressed ions electrostatically trapped in free space are used as qubits. Using Coulomb forces, multiple ions are suspended in a chain with a pitch of several microns. State preparation and readout is performed by irradiating specific wavelengths corresponding to the ions' intrinsic energy levels. To increase scalability, monolithic integration with microfabricated surface electrode traps and photonic integrated circuits has been achieved. [6-9]. To increase the number of ions, and thus the computing power, photonic integrated circuits using grating couplers (GCs) have been reported [10, 11]. However, it is difficult to selectively focus light onto narrowly pitched ions due to diffraction limitations. We have reported a 729-nm wavelength GC array with one-dimensional focusing using $^{40}\text{Ca}^+$ qubits, achieving -36 dB crosstalk and 98% diffraction efficiency [12]. One way to obtain multiple well-focused beams is to share a large aperture GC with multiple waveguides [13]. In this paper, we report a scalable integrated beam steering device capable of individually addressing densely arranged ions using a combination of a waveguide array, planar lens, and a two-dimensional focusing GC. This design achieves a smaller spot size than the previously reported work.

II. CONCEPT AND DESIGN

In a focusing lens, the angle of incidence of a collimated beam is converted into the image location. Since a 2D focusing GC is analogous to a lens, the same behavior can be obtained by changing the angle of the input light [13]. Fig. 1 shows the proposed optical steering device using this property. Light is input from one of the waveguides corresponding to the location of ion, and the light is converted into a collimated beam using a planar lens. Then, the output collimated beam propagates into the 2D focusing GC and generates a tightly focused beam spot in free space. The angle of the collimated beam varies depending on the position of the waveguide. Therefore, by selecting the input waveguide, the position of the beam spot can be changed. In general, beam size of focused light is governed by the diffraction limit – a large GC is needed to generate a tightly focused beam. However, it is difficult to arrange multiple large GCs on the wafer considering densely arranged ions. The advantage of this configuration is that multiple tightly focused beams can be generated by switching the input waveguide, sharing a single large GC. In this study, we aimed to generate eight spots corresponding to 8 ions lined up at a pitch of 5 μm , located 50 μm away from the chip surface. The schematic image of the two-dimensional focusing GC is shown in Fig. 2.

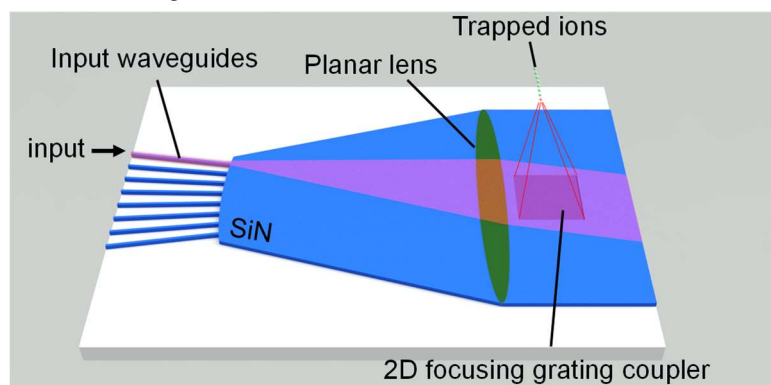


Fig. 1. Schematic of the proposed beam steering device.

The grating is designed such that the angle of the input collimated beam is 0° . The grating period is set to satisfy the following equation so that the light is focused on the target position,

$$\theta_i = \tan^{-1}\left(\frac{x_i - x_c}{H}\right) \quad (1)$$

where θ_i is the diffraction angle of i^{th} grating tooth, x_i is the position of i^{th} grating tooth, x_c is the position of target, and H is the height of the target position. To obtain the light focusing in the Y-axis direction, the curvature of the grating is set by finding Δx where the optical path length of input light to the target is equal. In this study, diffraction calculation using the angular spectrum method is used to the obtained wavefront on the GC surface to confirm the beam shape in free space [14].

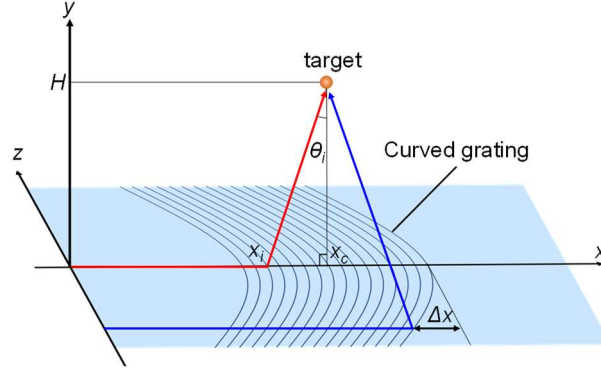


Fig. 2. Schematic image of the 2D focusing GC

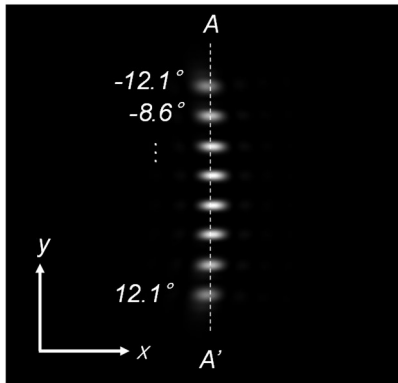
III. RESULTS AND DISCUSSION

In this section, the device design is discussed in detail assuming 8 ions. Then, the scalability of this device is also assessed for large-scale ion trap quantum computers.

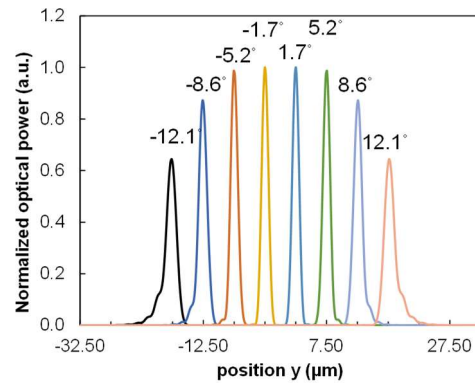
A. Device performance

The GC was designed for 729 nm with $^{40}\text{Ca}^+$ qubits, so a SiN device layer was used as it is transparent for this wavelength. The Y-direction GC aperture was $40\text{ }\mu\text{m}$, as a large width was needed to focus light tightly on the $5\text{ }\mu\text{m}$ pitch ion chain. The diameter of the collimated beam input to the GC was set to $25\text{ }\mu\text{m}$ so that the GC covers most of the light. Conversely, a tightly focused spot is not necessary in the X-direction; a slightly larger beam spot is desirable to allow misalignment of focused beam due to fabrication tolerances. Therefore, the X-axis dimension of the GC was set to $10\text{ }\mu\text{m}$, which is shorter than the Y-axis.

Fig. 3 (a) shows the optical intensity distribution at $z = 50\text{ }\mu\text{m}$. This is a superposition of all intensity spots generated by input beams at eight different angles. By changing the input beam angle in the range of $\pm 12.1^\circ$, we were able to achieve eight well-separated spots with a pitch of $5\text{ }\mu\text{m}$. A slight bowing of the beam position was obtained when the input angle was increased, which was due to the change in diffraction angle of the GC for angled input beams. Such a shift in the beam position causes insufficient light irradiation onto the ions located on the straight line. In the $\pm 12.1^\circ$ range, however, the peak intensity was as high as the maximum value as shown in the 1D plot in Fig. 3 (b). It was also confirmed that the light intensity at the neighboring peak positions, corresponding to the neighboring ions, was kept low.



(a) 2D profile of optical intensity



(b) 1D plot of optical intensity in the A-A' cross section

Fig. 3. Simulated beam shape at $z = 50\text{ }\mu\text{m}$ with various input beam angles

B. Scalability

Next, we will discuss the scalability of this device. The GC width in the Y-dimension was set to $40\ \mu\text{m}$ for an 8-ion array with $5\ \mu\text{m}$ pitch. By arranging N of this device in the Y-axis direction with a pitch of $40\ \mu\text{m}$, a beam steering device for $8 \times N$ ions can be realized. In Fig. 4 (a), a device configuration assuming 24 ions is shown. Here, a planar lens was assumed to be an ideal lens. With a distance from the lens to the waveguide of $80\ \mu\text{m}$, waveguides need to be placed about every $4.6\ \mu\text{m}$ as shown in Fig. 4 (b) to obtain the required angle range of $\pm 12.1^\circ$. To minimize crosstalk with the neighboring lens, the divergence angle of light from the waveguide must be reduced. Therefore, a wide waveguide width of $3.4\ \mu\text{m}$ was used to obtain a beam diameter of $25\ \mu\text{m}$ after the lens. The design of the GC itself is the same as the previous discussion. By switching the light between the 24 waveguides, we were able to obtain 24 spots with a period of $5\ \mu\text{m}$ as shown in Fig. 5. As there is no physical limitation on the scaling for this device, it is possible to realize many focused beam spots easily. We believe such an advantage is beneficial to realize a large-scale ion trap quantum computer.

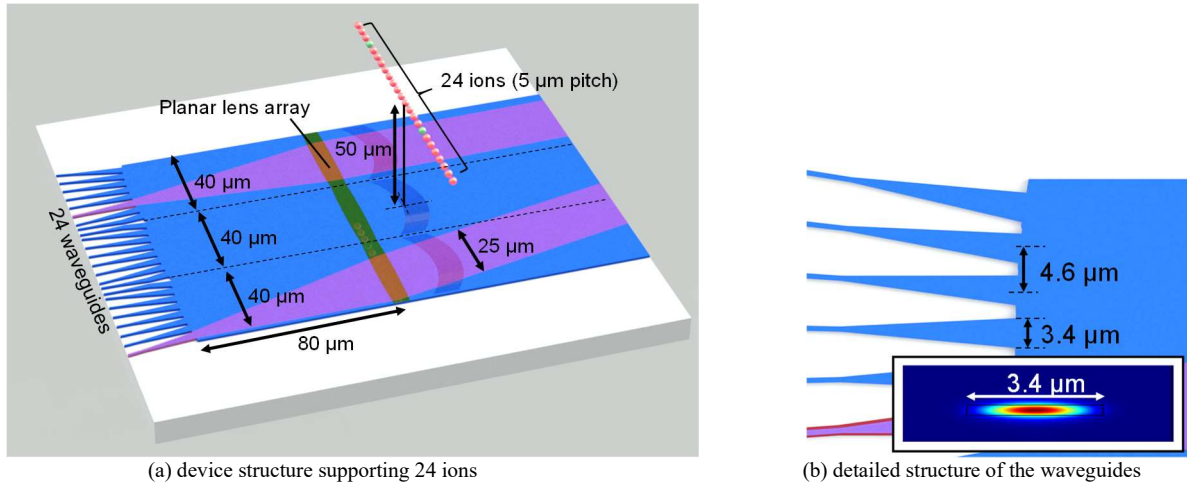


Fig. 4. Scaled beam steering device

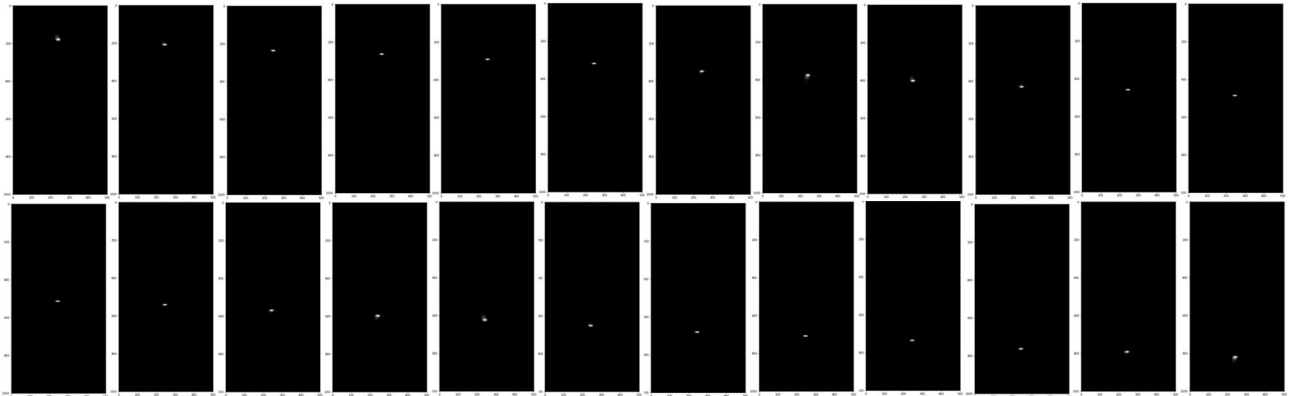


Fig. 5. Optical intensity at $z = 50\ \mu\text{m}$ for 24 ions

IV. CONCLUSION

A scalable beam steering device was proposed for control of ion trap quantum computers. The device was built on a SiN device layer transparent to $729\ \text{nm}$, using $^{40}\text{Ca}^+$ ions as a qubit. A large aperture 2D focusing GC was shared with multiple input waveguides and a planar lens to generate tightly focused beams in free space, corresponding to $5\ \mu\text{m}$ pitch trapped ions. Scalability for an $8 \times N$ ion array was also demonstrated by arranging the beam steering device in series with a $40\ \mu\text{m}$ pitch. As there is no physical limitation on the scaling for this device, it is possible to realize arbitrarily many beam spots. We believe such an advantage is beneficial to the large-scale ion trap quantum computers.

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