Focusing grating couplers for radio-frequency surface ion traps

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Abstract. We present a photonic integrated circuit design with multiple focusing grating couplers that can be used in a surface ion trap. This system allows transferring laser radiation from different laser sources to the ion trapped 240 μm above the surface for further manipulations.

1. Introduction
Grating couplers are widely used in photonic integrated circuits for coupling laser light between optic fibers and waveguides [1–3]. Here we demonstrate a novel grating coupler system that allows laser light transfer from a radio-frequency (RF) ion trap surface to the stored ion.

Typically, in RF surface ion traps, electrodes are located on one surface, while stored ion is held above this surface at some altitude [4]. Such ion traps can be used for different applications: from frequency standards to quantum computers [4,5]. Laser light is used for manipulations with the ion energy levels.

2. Methods
The grating coupler system was calculated using the Wave Optics module of COMSOL Multiphysics to be used with the $^{171}$Yb⁺ ion trap, where an ion is held 240 μm above the surface of electrodes. As can be clearly seen from figure 1, the grating couplers are located around the electrode and focus the laser light on the stored ion.

The laser light propagates through the optical waveguide to the grating couplers, where it goes out and focuses on the ion. Five lasers with different wavelengths (369, 399, 435, 745, and 935 nm) are used for manipulations with the $^{171}$Yb⁺ ion [6]. Silicon nitride (Si₃N₄) is used as a material for integrated optical waveguides and grating couplers due to its ability to propagate light in a wide optical range and low losses.
**Figure 1.** Schematic representation of the RF surface trap with grating couplers designed to transfer laser light from grating couplers to the ion (a), the grating region near the central electrode (b).

**Figure 2.** Schematic picture of a grating coupler (a) and its focusing configuration (b).

The main objective of calculating a focusing grating coupler for an ion trap is to create the smallest possible waists of the laser beams for all required wavelengths at an altitude of the stored ion. The focusing configuration of a grating coupler was obtained by changing an angle $\theta$ of emitted light along the grating coupler to focus it into one spot, as shown in figure 2. Bragg condition for an angle $\theta$ can be written as $n_{\text{eff}} = n_1 \cdot \sin(\theta) = \frac{\lambda}{\Lambda}$, where $n_{\text{eff}}$ is an effective refractive index of a grating, $n_1$ is a refractive index of the medium above the grating, $\lambda$ is a wavelength of the laser light and $\Lambda$ is a grating period. It also can be rewritten for the coordinate $x$ as $\Lambda(x) = \frac{\lambda}{n_{\text{eff}} - \frac{x}{\sqrt{x^2 + h^2}}}$, $x$ and $h$ are given in figure 2.

It also can be linearly approximated through $A_{n+1}$ and $A_n$: $A_{n+1} = k \cdot A_n + c$, where $A_n$ is the n-th period of the grating, $k$ and $c$ are coefficients of the linear approximation. Therefore, we need to find coefficients $k$ and $c$, which give us the smallest waists for the studied wavelengths.
3. Results and Discussion
Optimized values of \( k, c \), corresponding laser light and grating parameters are presented in table 1. We also calculated “coupling efficiency” for each grating coupler as a ratio of the power in the focusing spot to the initial power of the laser light in the waveguide before the grating coupler. Power is calculated by the standard COMSOL functions by integrating the Poynting vector over the area around the waveguide and focusing spot.

Typical wavefront and beam profile near the focus are presented in figure 3. The wavefront near the focus is flat and the beam profile is almost Gauss-shaped. It makes possible to conclude that we created a beam waist in the desired area. The waist of the beam is calculated on the power level \( 1/e^2 \).

| Wavelength (\( \lambda \)), nm | \( k \)     | \( c \), nm | First grating period (\( A_1 \)), nm | Waist of the beam (w), \( \mu \) m | Coupling efficiency |
|-------------------------------|------------|-------------|---------------------------------|---------------------------------|-------------------|
| 369                           | 0.99972    | 1.9e-4      | 230                             | 5                               | 0.25              |
| 399                           | 0.99941    | 1.63e-6     | 260                             | 6                               | 0.31              |
| 435                           | 0.99954    | 5.7e-5      | 278                             | 8                               | 0.28              |
| 760                           | 0.99966    | 2.1e-3      | 515                             | 10                              | 0.31              |
| 935                           | 0.99983    | 7e-6        | 614                             | 10                              | 0.3               |

Figure 3. An example of simulated grating coupler: wavefront near focus (a) and beam profile in the focus (b). The red line represents a cut plane of the diffracted beam on the focus. Presented figures are obtained from an optimized 935 nm grating coupler.

Transverse focusing (perpendicular to the plane in figure 2) could be performed by adding curvature to the grating stripes. Such a process is described in [7]. Calculations and optimizations in the third dimension require a lot of computing power or require new approaches since the focusing region is more than 200 \( \mu \)m above the surface. It will be done as the next step in our research.

4. Conclusion
In conclusion, we have designed and optimized a waveguide system with the focusing grating couplers for usage in the RF surface ion trap, where the ion is held 240 \( \mu \)m above the surface of electrodes. This system allows delivering laser light within a range of wavelengths from 369 nm to 935 nm, with the beams waists in focus in a range from 5 to 10 \( \mu \)m for every wavelength. Coupling efficiency for all grating couplers is higher than 25%.
References

[1] Marchetti R, Lacava C, Carroll L, Gradkowski K and Minzioni P 2019 Coupling strategies for silicon photonics integrated chips [Invited] Photonics Res. 7 201

[2] Vermeulen D and Poulton C V 2018 Optical Interfaces for Silicon Photonic Circuits Proc. IEEE Inst. Electr. Electron. Eng. 106 2270–80

[3] Cheng L, Mao S, Li Z, Han Y and Fu H Y 2020 Grating couplers on silicon photonics: Design principles, emerging trends and practical issues Micromachines (Basel) 11 666

[4] Niedermayr D 2015 Cryogenic surface ion traps (Innsbruck: University of Innsbruck)

[5] Brown K R, Kim J and Monroe C 2016 Co-designing a scalable quantum computer with trapped atomic ions Npj Quantum Inf. 2

[6] Huntemann N 2014 High-Accuracy Optical Clock Based on the Octupole transition in 171Yb+ (Hannover: University of Hannover)

[7] Mehta K K 2017 Integrated optical quantum manipulation and measurement of trapped ions (Cambridge: Massachusetts Institute of Technology)