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On-chip integrated metasurfaces for circular light polarization for trapped-ion quantum applications

Anastasiia Sorokina[1,2,*], *Pascal* Gehrmann[1,2], *Steffen* Sauer[1,2], *Carl-Frederik* Grimpe[3], *Guochun* Du[3], *Elena* Jordan[3], *Tanja* Mehlstäubler[3,4,5], and *Stefanie* Kroker[1,2,3]

[1]Technische Universität Braunschweig, Institute of Semiconductor Technology, Hans-Sommer-Str. 66, Braunschweig, 38106, Germany
[2]Laboratory for Emerging Nanometrology (LENA), Langer Kamp 6a/b, Braunschweig, 38106, Germany
[3]Physikalisch-Technische Bundesanstalt, Bundesallee 100, Braunschweig, 38116, Germany
[4]Leibniz Universität Hannover, Institut für Quantenoptik, Welfengarten 1, Hannover, 30167, Germany
[5]Leibniz Universität Hannover, Laboratorium für Nano- und Quantenengineering, Welfengarten 1, Hannover, 30167, Germany

Abstract. In order to accomplish more functional and efficient light routing on a chip, photonic integration is necessary. Particularly in quantum technologies, which require a high precision of operation, avoiding bulky optical arrangements is in high demand. Scalable and robust photonic components open up a plethora of possibilities. The light guiding systems have to be able to cover a wide range of operational wavelengths and different light polarization states. In this work, we present the first numerical results for our approach of a PIC producing NIR circularly polarized light based on a Si_3N_4 material platform. This concept includes waveguides and metasurfaces that are easily integrable on the chip surface of many trapped-ion quantum computer architectures.

1 Introduction

Photonic integrated circuits (PICs), meeting a wide range of quantum applications, promise an enormous expansion of industrial and research capabilities. The necessary accuracy of operations and the performance and robustness of systems can be accomplished by reducing the size of light-guiding and focusing elements. PICs have an increasing impact in areas like, for example, trapped-ion quantum computers (QCs) [1,2,3], quantum sensing with neutral atoms [4,5], and quantum communication [6].

In order to eliminate well-established but bulky optical arrangements, accurate numerical and experimental investigations of the integrated on-chip systems are mandatory. Especially for QCs with ions as qubits, addressing multiple ion transitions with linearly and circularly polarized light in a wide range of wavelengths, from ultraviolet (UV) to near-infrared (NIR), requires higher precision and flexibility of on-chip routing. This can be accomplished via integrated waveguides (WGs), grating couplers (GCs) [7], and metasurfaces (MSs) based on a Si_3N_4 material platform. Together, these open up new possibilities for scalable optical systems which can be integrated with trap electrodes.

In Fig.1, we illustrate a schematic representation of the integrated PICs utilized to guide and focus light with linear and circular polarization. The structures are positioned below the electrodes required to trap the ions. In this configuration, RF and DC potentials create a pseudo-potential minimum above the surface in the free space. Followed by the ionization step, ions are addressed with the light to control the transitions between the states.

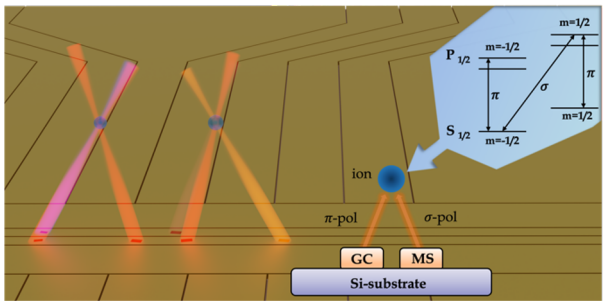

Fig. 1. Schematic representation of the integrated on-chip photonic structures focusing linearly (π) and circularly (σ) polarized light onto ions (shown in blue) above the chip surface. Here, GC is a grating coupler, MS is a metasurface, and the simplified diagram of the transitions between states with required π and σ polarized light is depicted in the insert.

2 Results and discussion

2.1 Design of the metasurface for circular polarization

For the operation in the visible (VIS) and NIR wavelength range, we take advantage of the wide transmission window of Si_3N_4 [8] enabling a low-loss light operation. Fig. 2 (left) depicts a designed structure that includes WGs, tapers, and a MS. Inspired by [9], where a circularly polarised light for the telecom wavelengths on Si has been investigated, we extended the concept to the wavelengths required for ion addressing. Based on the numerically determined effective refractive index from WG

* Corresponding author: a.sorokina@tu-braunschweig.de

simulations and Bragg conditions, we calculated the necessary period of the etched sections and their periodicity, which are 494 nm and 222 nm, respectively.

2.2 Numerically characterized light behavior controlled via the waveguide and metasurface

In order to ensure a single-mode WG with a predominantly confined quasi-TE fundamental mode, a numerical investigation of WG geometries has been carried out by the finite element method in COMSOL Multiphysics simulation software. Fig. 2 (right) shows the total electric field profile for the defined geometry of 520 x 200 nm^2 at the wavelength of 760 nm with the maximum intensity along the propagation direction. Together with a proper taper design, it allows maintaining equal and defined light characteristics from all four inputs of the WGs towards the MS.

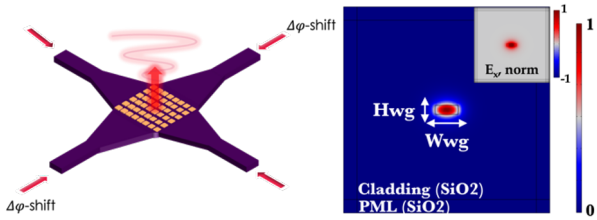

Fig. 2. Left) Schematic illustration of the photonic system with four WGs followed by tapers and a MS at the center to produce a circularly polarized light; right) Normalized total electric field and E_x component for the defined height (H_{wg}) and width (W_{wg}) of the WGs.

To control the state of the polarization above the structure, we investigated the phase difference between the E_x- and E_y-components of the total electric field. Characterization of the near and far-field behavior of the light has been evaluated by the finite-difference time-domain solver (FDTD) of Lumerical FDTD. Fig. 3 A) shows the calculated phase difference with an identical input into all WGs. The phase difference between E_y and E_x yields a 0°- phase shift at the center of the field distribution above the structure; therefore, linear polarization is maintained. In contrast, applying a 90°-phase shift on the two WG inputs produces a clear phase difference of 90°, leading to a circularly polarized light field above the MS (compare Fig. 2 B). Due to the symmetry of the structure, E_x- and E_y-components of the total electrical field show equal intensities and have a similar profile, as clearly shown in Fig.3 C), whilst E_z is almost negligible.

3 Outlook

Based on the described studies for the structures controlling the polarization states, we are expanding our possibilities with more fine-tuning of the shape of the etched elements on the MS. This enables a wide variety of focusing distances, beam sizes, and emission angles. For more advanced designs, gradient-based (adjoint) optimization methods and genetic algorithms are utilized.

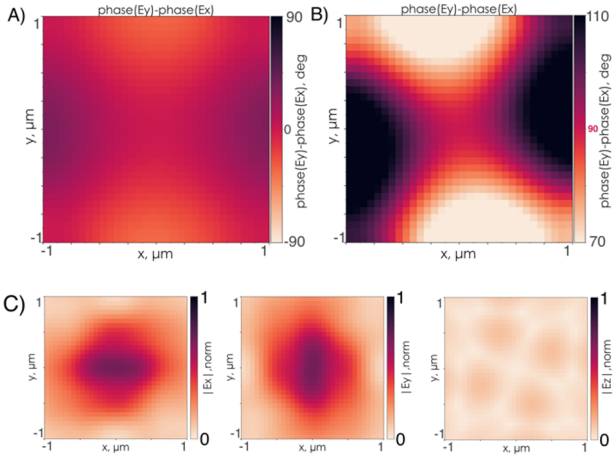

Fig. 3. A) and B) phase difference between E_y- and E_x-components of electric field above the structure without phase shift on all WG inputs and with a phase shift of 90° on two of the WG inputs, C) normalized $|E_x|$, $|E_y|$ and $|E_z|$ components of the electric field above the MS with the 90°-phase shift.

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