Chip integrated photonics for ion based quantum computing

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Abstract. Ion traps are a promising platform for the realisation of high-performance quantum computers. To enable the future scalability of these systems, integrated photonic solutions for guiding and manipulating the laser light at chip level are a major step. Such passive optical components offer the great advantage of providing beam radii in the µm range at the location of the ions without increasing the number of bulk optics. Different wavelengths, from UV to NIR, as well as laser beam properties, such as angle or polarisation, are required for different cooling and readout processes of ions. We present simulation results for different optical photonic components, such as grating outcouplers or waveguide splitters and their applications on ion trap chips. Furthermore, we will introduce the experimental setup for the optical characterisation of the fabricated structures.

1 Introduction

Today's demand for powerful computers is increasing in order to solve complex future problems. One promising approach is the quantum computer based on trapped ions on a surface chip with nanostructured components [1]. The qubits are realised by the internal states of individual trapped ions and will be controlled and transported between the loading, storage and interaction zones on future chips (see figure 1). The advantages of trapped ions as qubits are their very long coherence times, which are limited by the dephasing of technical sources, like vacuum pressure. Furthermore, the very high reliability and the existing knowledge about the preparation of the states and the readout of ions.
For the new generation of computers, growing scalability is of paramount importance: the more qubits, in our case ions, a quantum computer has, the more computing power it will provide. A big game-changer for scalability of ion-based quantum computers are the integrated passive optical components. Their integrability on chips and their small size allows for a variety of implementations compared to bulk optics. In this vein, the number of qubits can be drastically increased while complying with the DiVincenzo criteria for building a scalable, fault-tolerant quantum computing [2].

2 Optical componentes

Building an ion trap chip with integrated optics requires different components. The laser light has to get into the chip, it has to be distributed via waveguide splitters and extracted from the surface with grating couplers (see figure 2) so that the light can interact with the ions.

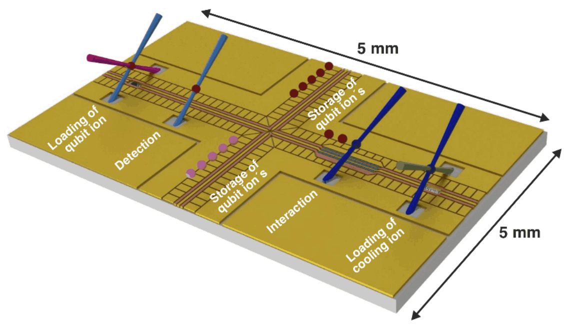

Figure 1. Possible ion trap chip design with different application zones. The ions act as qubits of the quantum computer. To cool or to detect ions, laser beams are sent via grating couplers. In the interaction zone, the qubits are used for calculations.

2.1 Properties and challenges

In general, you do not need a high light output power for the control of ions, in addition, there is the µm beam radius, which also has a positive effect on the required intensity. That´s why, the losses within the components are not the most significant challenge; rather, the coverage of all required wavelengths from UV to NIR should be accessi-

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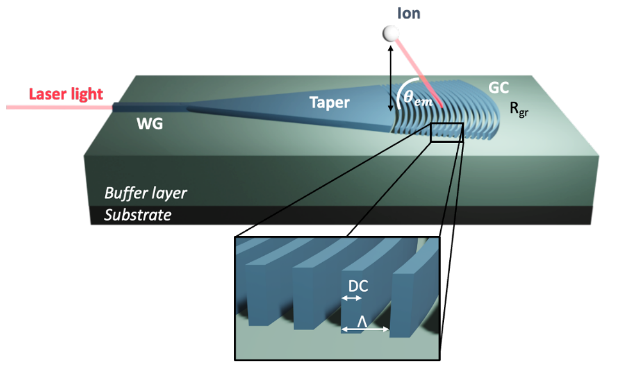

Figure 2. Sketch of a backward grating coupler. Laser light (red) is guided to the grating coupler (GC) via a waveguide (WG). A GC usually consists of a taper and a grating structure. The laser beam leaves the chip with the emission angle (θ_{em}) via the grating to interact with the ions. The properties of the emitted laser beam are defined by the period (Λ), the duty cycle (DC) and the radius of curvature R_{gr} of the grating.

ble (see figure 3). Therefore, *different materials* must be used to cover all wavelenghts of interest (see table 1). Nevertheless, it is worth bearing in mind that the outcoupled laser beams should not affect other ions. Furthermore, in addition to the state-of-the-art linear polarization for integrated grating couplers [3–5], *circular polarization* is important for cooling ions, for example.

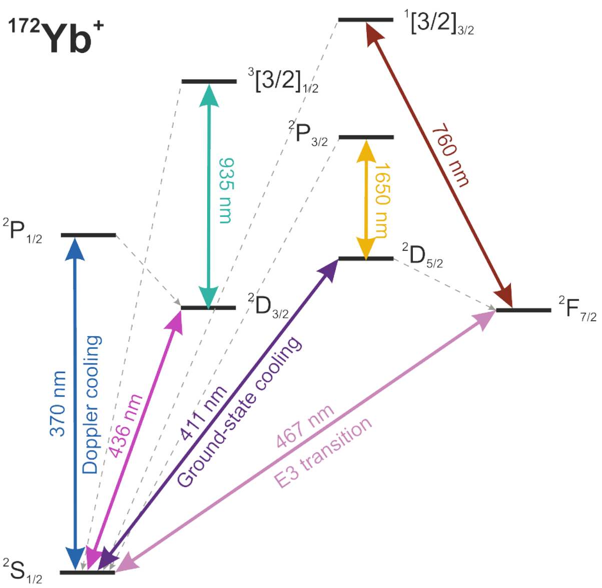

Figure 3. Level scheme of $^{172}Yb^{+}$ ions with all relevant transition wavelengths for our integrated optics. We use ^{172}Yb as a testbed for other future ion elements.

2.2 Simulations

Our numerical simulations consist of a combination of 2D and 3D calculations of waveguides (WG) and grating couplers (GC), calculated with COMSOL Multiphysics FEM and Lumerical FDTD solvers. We optimize the WG geometry to ensure a single-mode regime, at the same time with a high confinement of the fundamental quasi-TE mode. The design of the GCs involves optimizing the grating periods, duty cycles and curvature of the grating to ensure Gaussian beam and µm-focusing at the ion.

Table 1. Material platforms of waveguides for varying wavelengths.

Core material	Wavelength range [nm]
AlN/Al_2O_3	UV: 370 - 500
Si_3N_4	VIS-NIR: >500

Moreover, we verify the laser beam properties with Near to Far-Field Transformation, so that conclusions can be drawn about the laser beam at a typical ion height of 100 µm. We also calculate the effect of the GC and possible use of an ITO coating on top of the GC to minimize the influence of the micromotion on the ion.

3 Optical characterization

We are in the process of building optical setups to check the laser beam properties of our chips. To this end, we use microscopes with different optical components, CCD cameras and set up seven different laser systems for wavelengths between 370 and 1650 nm.

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