

Master thesis

Optical integration for surface ion traps

Michael RAFFETSEDER
12002056

Innsbruck
March, 2026

Advised by
Mag. Dr. Philipp Schindler and
Dr. Bassem Badawi
Institute of experimental physics.

A thesis submitted to the faculty of mathematics,
computer science and physics, of the University of
Innsbruck in partial fulfillment of the requirements for the
degree of Master of Science (MSc).

Abstract

Even though functional quantum computers based on trapped ions already exist, it is expected that the number of ions must be greatly increased to build a truly useful device. Ion traps designed for scalability are often realized as surface traps. In this architecture, the electrodes creating the electromagnetic fields required for trapping the ions are located in-plane, which allows benefiting from the semiconductor industry's advanced manufacturing technologies. Since the manipulation of ions relies predominantly on laser pulses, integrating optical components into the ion trap could allow control of more ions. This thesis characterizes a photonic chip intended to individually address single ions, located in a string of 10 particles, with a laser pulse. The chip is based on silicon nitride waveguides to route light from optical fibers to an out-coupling region, consisting of a total internal reflection mirror. Using an apparatus specifically built for this purpose, it is shown that the waveguides have low propagation losses of less than -0.5 dB/cm and the out-coupled beam is nearly diffraction-limited with an M^2 value of $1.21(5)$ perpendicular to the ion string and $1.17(7)$ in direction of the ions. These properties make this photonic circuit design suitable to advance future trapped ion experiments.

Zusammenfassung

Obwohl es bereits funktionierende Quantencomputer basierend auf gefangenen Ionen gibt, kann man davon ausgehen, dass die Anzahl der Ionen noch stark erhöht werden muss, um ein wirklich nützliches Gerät zu bauen. Um mit mehr Ionen arbeiten zu können werden Ionenfallen oft als Oberflächenfallen ausgeführt. In einer Oberflächenfalle sind die Elektroden, die das elektromagnetische Feld erzeugen, in einer Ebene platziert, wodurch die Fallen mittels etablierten Technologien aus der Halbleiterindustrie gefertigt werden können. Nachdem die Manipulation der Ionen vorwiegend über Laserpulse geschieht, können integrierte optische Komponenten dazu beitragen, die Anzahl der Ionen zu erhöhen. In dieser Arbeit wird ein integrierter Photonik-Chip charakterisiert, der einzelne Ionen in einer Kette von 10 Teilchen adressieren wird. Der Chip basiert auf Wellenleitern aus Siliziumnitrid, die Licht aus optischen Fasern zu einem Spiegel, basierend auf Totalreflexion, leiten. Der Spiegel koppelt den Laserstrahl aus dem Chip aus, und richtet ihn auf die Ionen. Auf einem speziell dafür gebauten Messapparat wird gezeigt, dass die Wellenleiter geringe optische Verluste von weniger als -0.5 dB/cm aufweisen, und dass ein nahezu beugungsbegrenzter Laserstrahl ausgekoppelt wird, mit einem M^2 Wert von $1.21(5)$ senkrecht zu der Ionenkette, und $1.17(7)$ in Richtung der Ionen. Mit diesen Eigenschaften kann der Photonik-Chip gewinnbringend für zukünftige Experimente mit gefangenen Ionen eingesetzt werden.

Acknowledgments

First and foremost I want to thank my advisors Bassem Badawi and Philipp Schindler to give me the opportunity to work on tomorrow's technology. Bassem, thank you for sharing your microfabrication expertise and providing guidance on the laboratory work, while at the same time giving me the freedom to realize my own ideas through trial and (often) error. Accompanying you on the trips to Zürich and Gross-Umstadt was both insightful and a lot of fun. Philipp, thank you introducing me to this interesting topic, for the valuable feedback on this thesis, and your patience when explaining fundamental concepts of ion traps.

I want to thank the whole AG Quantum Optics and spectroscopy and specifically Bassem Badawi, Philip Holz, Nicolas Jungwirth, Eric Kopp, Thomas Monz, Michael Pasquini, Philipp Schindler, Marco Schmauser, and Marco Valentini of the Cryo subgroup. Being part of your team and working together has been a great experience, and this work would have never been possible without your support. Thank you Wolfgang Kuen, Kilian Prokop, and Ronny Wehinger from the electronic workshop, for providing help on the numerous electronic devices needed for the laboratory setup, and for your ability to fix whatever I managed to break. Another important contribution for which I am grateful was made by Lukas Markt, Anton Schönherr, and Christoph Wegscheider from the mechanical workshop, who helped with the design and fabrication of several key components. A lot of parts were ordered for the lab setup, with our secretaries Renate Rupprechter and Verena Tanzer taking care of the heaps of paperwork; thank you for that!

Life in Innsbruck would not have been the same if not for my friends, with whom I shared many "adventures" over the last years. Another thank you goes out to my parents and family, especially my little nieces, who I always look forward to seeing.

This work is dedicated to my girlfriend Silvia, who is always there for me whenever I need her. Without you, I would have probably lost (the rest of) my mind during the excruciatingly slow process of writing this thesis.

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1 Introduction

Over the course of the last several decades, computing has undergone a tremendous evolution. Starting from mechanical relays and vacuum triodes, the invention of semiconductor based integrated circuits has enabled technology inconceivable to the founders of information processing. Semiconductor devices were enabled by understanding and exploiting the quantum mechanical laws which govern the dynamics of electrons in a crystal lattice. In contrast to transistors, which need many quantum particles (electrons) to function, recent technological advances allow controlling single quantum particles,¹ such as isolated trapped atoms. It was realized that having precise control over the quantum state of several particles allows performing logical operations which can potentially tackle problems inaccessible to classical information processing units. These logical operations, called quantum gates, form the basis of a quantum computer. In a regular computer, the fundamental unit of information is the bit, which is essentially one of two voltage levels. In contrast, a quantum computer operates on qubits (quantum bits), which are well-defined quantum states.

While classical processors have reached remarkable performance, present day quantum computers are on the brink of finding the solution to some highly specific problems faster than any known algorithm running on the world's fastest supercomputers [1]. Even though these problems are specifically tailored to be easy for quantum computers and hard for classical computers, this is an impressive achievement, especially when considering that the number of qubits on such a quantum processor is still very limited. Today's quantum computers contain only several tens of qubits, while state-of-the-art CPUs contain billions of transistors clocked at GHz speeds. Scaling up the number of (high quality) qubits promises the ability to execute more elaborate algorithms, potentially enabling applications ranging from chemistry and material science to optimization and machine learning.

Note that at this exciting point in time, it is very much unclear, how the qubits of a truly useful quantum computer will look like. There are many ideas including the use of superconducting resonant circuits, highly excited (Rydberg) atoms, or nitrogen vacancy centers in diamond. One promising technological platform utilizes the electronic states of individual atomic ions to encode information. The ions are trapped in a vacuum chamber by an electromagnetic field. The confinement is created by applying a combination of radio-frequency (RF) and quasi-static (DC) potentials to electrodes surrounding the particles. Laser cooling causes the individual ions to crystallize in a one dimensional string. The electrostatic repulsion separates the charged particles sufficiently, such that they can be resolved on a camera and individually addressed

¹"Quantum Particle" is a vague term, as it could describe anything that requires a quantum mechanical description; ranging from particles of light to oscillation states of a superconducting resonator.

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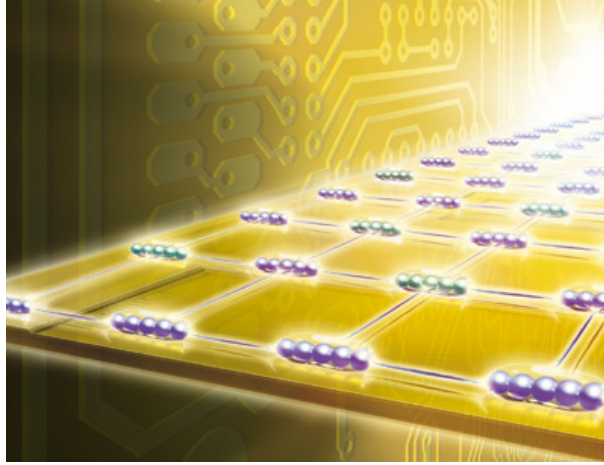


Figure 1.1: Artistic illustration of a surface ion trap, supporting an array of ion strings. Image Credit: Harald Ritsch

by laser beams. A quantum circuit is executed by applying a series of laser pulses to manipulate and read out the electronic state. Conditional logic operations between pairs of ions, such as the controlled-not (CNOT) gate, are achieved by exciting motional modes shared by all ions (coulomb bus). Even though this approach has enabled high-fidelity operations, it is believed that the number of ions in a single string with individual qubit control is limited to less than fifty.

Several approaches have been suggested to scale up the number of ions by separating them into smaller-sized registers, which requires a way of transferring quantum information between the ions. Remote entanglement using photonic interconnects offers the advantage of a potentially large distance between the individual modules, or even between separated vacuum chambers [2, 3]. Other approaches include utilizing the dipole interaction of nearby oscillating ion strings [4], or transporting individual ions from storage registers to dedicated interaction zones, where the exchange of quantum information is mediated by the coulomb force [5].

These capabilities are not readily achieved by traps with conventional macroscopic electrodes in a three-dimensional configuration. Among other reasons, this is why ion traps designed for scalability have shifted towards surface traps (figure 1.1). In this architecture, the electrodes creating the confining potential are placed in a single plane, with the ions levitating above the chip's surface. Drawing from established chip fabrication technologies allows creating almost arbitrary electrode geometries, resulting in a well-controlled shape of the confining electromagnetic potential. This allows to confine multiple smaller sized ion strings (ion registers) in separate potential wells on a single chip as visualized in figure 1.1.

Operation of an ion trap places high demands on the electrical and optical pulses applied to the trap. For example the ability to perform operations on individual ions requires tightly focused laser beams with precise timing and optical phase coherence [6]. In a conventional ion trap, light is delivered to the ions by coupling a free-space

beam through a view-port into the vacuum chamber, which poses a hindrance to scalability. In order to build a truly scalable ion trap system, it is crucial that the amount of required control hardware remains manageable. Surface ion traps offer an appealing way to directly integrate functionality into the trap chip. Such functionality can include electronic devices such as purpose-built digital-analog converters or on-chip filters [6]. Since the control of trapped ions largely depends on optical signals, integrated photonic circuits, which are the focus of this thesis, offer a way towards scalability.

Integrated photonics are mainly developed for their application as high-bandwidth, low-latency interconnects in communication hubs operating at infrared wavelengths. Optical components which can be integrated on-chip range from passive building blocks such as waveguides, splitters and wavelength filters to active elements including laser, modulators and detectors [7].

Photonic integration, especially in the visible range, promises to advance several technological challenges faced by surface ion traps. It is conceivable that the future trapped ion quantum processor incorporates a photonic chip which performs tasks ranging from light distribution and qubit manipulation to state read-out [8].

The thesis presented here starts by introducing some concepts of quantum computing 1.1, before providing background on the operation of an ion trap 2. The next chapter 3 focuses on optical integration by discussing some theoretical concepts necessary for the operation of optical waveguides, before introducing building blocks and material platforms for photonic integration. The chapter then concludes by introducing the photonic chip used for the experimental part of this thesis. The laboratory work conducted during this thesis is focused on a specific photonic circuit demonstrating one approach capable of individually addressing each ion in a string of $10\ ^{40}\text{Ca}^+$ ions trapped in a single potential well. Chapter 4 reviews how to characterize a tightly focused laser beam using a microscope, before chapter 5 discusses the measurement setup and properties of the out-coupled laser beam. Finally, chapter 6 summarizes the thesis and provides an overview of the next steps in this project in particular and the prospects of optical integration for ion traps in general.

1.1 Quantum information processing

This section is intended to introduce some general concepts of quantum computing, and their near-term applications. The promise of a large-scale quantum computer is currently generating significant interest not only from academic institutions, but also corporate entities are investing heavily into research and development in this area. A major motivation comes from the fact that there exist algorithms leveraging quantum mechanical laws which could potentially outperform today's fastest supercomputers.

The most prominent example is the prime factoring algorithm by Peter Shor [9], which promises an exponential speedup compared to any known classical algorithm, and could therefore corrupt the security of the common RSA asymmetric encryption protocol. Even though current quantum computers are nowhere near factoring a cryp-

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tographically relevant number², there are a number of applications such as optimization problems relevant for chemistry where current or near future quantum computers can be usefully applied [11].

The main difference between classical processors and their quantum counterpart is the nature of the fundamental units of information. While a classical bit can take two values, say 0 and 1, a quantum bit (*qubit*) can be in any superposition of the two states $|0\rangle$ and $|1\rangle$:

$$|\psi\rangle = a_0 |0\rangle + a_1 |1\rangle \quad \text{with} \quad a_i \in \mathbb{C} \quad (1.1)$$

Where the probability to find the qubit in state $|i\rangle$ is given by $|a_i|^2$.

It seems that two complex numbers are required to fully describe ψ . Requiring the qubit to be normalized ($|a_0|^2 + |a_1|^2 = 1$), and realizing that any global phase $e^{i\alpha} |\psi\rangle$ with $\alpha \in \mathbb{R}$ is physically irrelevant, two real numbers θ, φ are in fact sufficient to fully describe any pure two level quantum state [12]:

$$|\psi\rangle = \cos(\theta/2) |0\rangle + e^{i\varphi} \sin(\theta/2) |1\rangle \quad (1.2)$$

The similarity to spherical coordinates facilitates visualizing a state as a point on a sphere (Known as Bloch sphere). Any coherent manipulation of a single qubit can be seen as a rotation on this spherical surface. Note that a single measurement performed on a qubit is always projective, meaning that it can only determine whether the qubit is in state $|0\rangle$ or $|1\rangle$, and it gives no information about the coefficients a_i . Preparing a qubit repeatedly in the same state - and measure in different bases - allows to statistically infer the relative phase φ between the states, as well as the amplitudes $\cos(\theta/2)$ and $\sin(\theta/2)$ of either state [12].

Apart from the (coherent) superposition property described above, quantum particles can exhibit a second property called *entanglement*, a quantum phenomenon without a classical counterpart. A compound state is called entangled, when it can no longer be decomposed into a product of single qubit states [12]. Even though the precise mechanisms are still subject to intense research, entanglement is expected to be the resource from which quantum processors draw their computational power [12]. In the two qubit case the general pure state might be written as:

$$|\psi\rangle = a_{00} |00\rangle + a_{01} |01\rangle + a_{10} |10\rangle + a_{11} |11\rangle \quad (1.3)$$

Where e.g. $|01\rangle$ is shorthand for $|0\rangle \otimes |1\rangle$, which is the state where the first qubit is in state $|0\rangle$, and the second qubit is in state $|1\rangle$ and $a_{ij} \in \mathbb{C}$ are the (normalized) coefficients, analogous to equation (1.1). A striking property of some entangled states is the fact that measuring one of the qubits immediately fixes the state of the second particle.

²Even though factoring a 2048 bit number, as commonly used by RSA encryption protocols, will realistically be out of reach of quantum computers even in the near future, the prospect of large-scale quantum computers has already led to the development and deployment of post-quantum encryption protocols [10].

Since an n qubit state can be in a superposition of all possible combinations, the amount of classical information required for a complete description scales with 2^n , making it impossible to store in the memory of any classical computer even for moderate numbers of n . Note that this is only true for the most general case. In many relevant quantum systems, entanglement is more limited, and the n qubit state can be decomposed into so-called matrix product states, which do allow an efficient classical description.

The execution of a quantum algorithm typically starts by preparing the qubits in a well-defined initial state, which is then manipulated to yield the desired outcome. Just as a classical algorithm can be decomposed into logical binary operations, a quantum algorithm consists of a number of gates. It has been shown that any quantum algorithm can be arbitrarily well approximated by single qubit manipulations and a gate acting on two qubits [12]. An ideal quantum gate is represented by a unitary operator, which corresponds to a deterministic (coherent) evolution of the state. The time evolution operator being unitary implies that quantum information is preserved, and any quantum gate is reversible.

In order to extract information at the end of a quantum algorithm, the state of the qubits has to be read out (measured). A measurement is fundamentally different from a gate, since it irreversibly and probabilistically projects the quantum state to an eigenstate of the measurement operator, effectively "collapsing" the state. The state of the qubits is described by a number of continuous variables, but a single measurement can only yield one discrete outcome. Therefore, many quantum algorithms have to be run multiple times to reconstruct the quantum state at the end of the algorithm.

Quantum error correction (QEC)

While the framework sketched above might eventually enable devices capable of having a major impact on society, present day quantum computers are still rather limited. Shor's factoring algorithm is on the one hand largely responsible for generating a significant amount of interest in quantum computers, but on the other hand it is also a good example of an algorithm out of reach for current devices limited by the effects of noise and decoherence [13].

Since none of the operations needed to execute a quantum algorithm, such as state preparation, qubit manipulation, and state readout, are free of errors, it is not guaranteed that the measured output state of a quantum computer matches the result of the idealized quantum algorithm. In order to get reliable results from a noisy quantum processor running a sufficiently complex sequence, it is believed that quantum error correction is necessary. Quantum error correction works similar to classical error correction, which was developed when classical processors were not as reliable as they are today [14]. The general idea is to use redundancy to encode *logical qubits* on several physical qubits, and perform computations on the logical, fault-tolerant, level. Redundancy only improves the overall performance if the noise level is sufficiently small, since every logical operation requires the manipulation of multiple qubits. It has been shown [15] that error thresholds exist, below which quantum error correction can increase

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the reliability of a quantum circuit. Note that the overhead in the form of physical operations per logical operation increases dramatically as the error approaches this threshold, highlighting the need for high quality physical qubits.

One challenge for quantum error correction is to preserve the coherent evolution of the qubits, which means that the state of the qubit can not be read out during execution of the algorithm, since this would destroy any superposition. Note that since a single qubit is described by two real numbers, it can acquire errors in both phase and amplitude. An elegant approach is to project the error syndrome onto ancillary qubits, which can then give information about whether an error occurred. Using more than one ancillary qubit allows extracting information about which error occurred on which qubit, potentially enabling mid-circuit error correction.

One example of such an error-correcting code is the Steane code [16]. It uses 7 physical qubits to encode one logical qubit. The device presented in this thesis is planned to employ the Steane code at some point in the future, using registers of 10 qubits, with 3 being used as ancillaries.

Applications for near-term quantum computers

Even though the overhead required for error correction currently prohibits the construction of fault-tolerant quantum computers, recent devices have entered the realm of *Noisy Intermediate-Scale Quantum (NISQ)* [11] devices. These are devices consisting of 50 to several hundreds of qubits, which is insufficient for useful error correction codes. Therefore, NISQ devices are incapable of running arbitrarily long computations. Even though these devices can not yet be considered truly useful, recent advances have demonstrated a number of applications highlighting the potential of the technology.

As already envisioned by Feynman in his now legendary speech [17], using quantum computers to simulate quantum systems is still one of the most obvious tasks. A motivation comes from the difficulty of simulating highly entangled systems on a classical computer. The variational quantum eigensolver [18] is one example of an algorithm utilizing a hybrid approach with both classical and quantum resources. It employs the variational principle to estimate the ground state energy of a quantum system, and has already been applied to simple molecules [19, 20]. The quantum processor is used to find the energy of a given state, and a regular computer runs an optimization algorithm to find the configuration yielding the lowest energy.

While there are many more applications even for non-fault-tolerant quantum computers, the example above is chosen to highlight that while quantum computers will most certainly not replace their classical counterpart in the foreseeable future, a hybrid approach might prove fruitful already in the near term. Furthermore, running such algorithms on actual hardware provides an important validation for the noise models underlying the theoretical description of the quantum circuits.

2 Trapped ion quantum computing

After having touched on the principles of quantum computers, this section discusses one particular physical implementation of such a device. In the trapped ion quantum computing architecture, a qubit consists of a single charged particle trapped in ultra-high vacuum chamber by means of electromagnetic fields. An illustration of a trapped ion string is shown in figure 2.1. The discrete energy level structure of the atoms provides a natural way to encode quantum information, with lasers being the predominant way to manipulate the electronic states [21]. The vacuum with pressure in the order of $\lesssim 10^{-10}$ mbar is necessary to minimize collisions between the ions and atoms in the background gas, which could potentially cause chemical reactions or the loss of an ion.

For trapped ion experiments, mainly group 2 atoms are used. Once they are ionized, they have an alkali-like level structure due to their remaining single valence electron in the S shell. Such atoms are suitable for laser cooling by using the short-lived $S_{1/2} \leftrightarrow P_{1/2}$ dipole transition [6]. The simple level structure of alkali-like atoms implies that the $P_{1/2}$ state does not have a lot of decay channels, which makes re-pumping of atoms leaving the cooling cycle feasible [22].

Selecting the appropriate ion species is influenced by several considerations, including the choice of energy levels forming the logical states $|0\rangle$ and $|1\rangle$. One limitation is that each level has to be sufficiently long-lived in comparison to the execution time of quantum gates. The type of qubit is determined by which transition is utilized, with the most important candidates being the optical and the hyperfine qubit [6]. The optical qubit leverages a long-lived dipole-forbidden transition, for example the $4S_{1/2} \leftrightarrow 3D_{5/2}$ quadrupole transition in $^{40}\text{Ca}^+$, with an energy splitting corresponding to deep red 729 nm light. Note that the finite lifetime poses a fundamental limit to the coherence time of the qubit. In order to achieve high-fidelity gate operations, the laser driving the qubit transition must maintain phase-coherence throughout the execution of the quantum circuit, leading to stringent requirements on the laser's frequency stability with linewidths below approximately 1 Hz [6].

A hyperfine qubit on the other hand utilizes the hyperfine transitions found in atoms with non-zero nuclear spin, and has energy differences in the microwave range. Those transitions are typically not driven directly, but two lasers with a frequency difference corresponding to the hyperfine splitting, are used to drive an off-resonant Raman transition. In this case, phase coherence is required between the two lasers but not for each beam individually, which can be achieved by using the same laser source for either beam [23]. Advantages of the hyperfine qubit include the in principle unlimited lifetime as well as the existence of transitions which are in first order insensitive to magnetic field fluctuations, named clock transition for their use in atomic clocks [21].

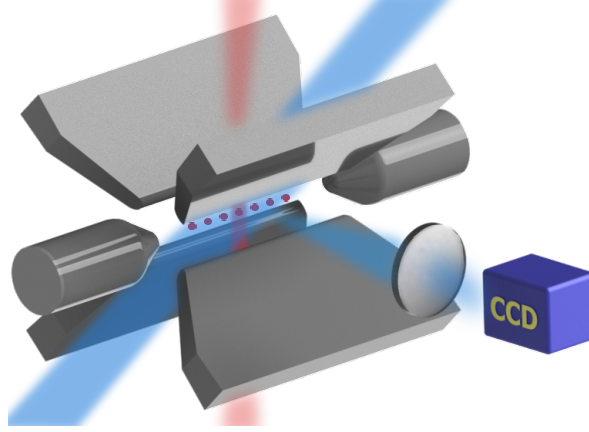


Figure 2.1: A schematic visualization of a string of ions suspended in a linear Paul trap. The characteristic blade shaped RF electrodes provide radial confinement with additional conical end-cap DC electrodes creating the axial confinement. The state of the qubits is controlled with lasers and read out via a CCD camera.

On the other hand, the Raman transition suffers from spontaneous emission from the excited level, an effect which can be compensated at the cost of higher laser intensity [24].

Another important consideration are the wavelengths of the required lasers, since high-quality sources and optical elements are not as readily available for wavelengths in the ultraviolet range. Particularly in the context of optical integration, short wavelengths increase the manufacturing complexity and limit the choices of suitable materials [8]. On the other hand, short wavelengths reduce the execution time of quantum gate operations [6], due to the enhanced coupling to motional modes.

The device discussed in this thesis is designed to use calcium ions which have been very successfully used in previous experiments. More specifically, $^{40}\text{Ca}^+$ without a nuclear spin can be used as an optical qubit, utilizing the metastable D state. The excited state has a lifetime greater than 1 s, which is not a limiting factor in current devices [25].

2.1 Ion crystal in a linear Paul-Trap

When loading multiple (sufficiently cold) ions into one potential well, the repulsion between the charged particles forces them to arrange in a crystalline way [21]. Mathematically, the arrangement of ions can be seen as a series of coupled harmonic oscillators. The joint motional modes of this coulomb crystal provide a means to transfer quantum information between the individual particles. This is achieved by exciting and de-exciting the center of mass mode by means of lasers blue- and red-detuned from the qubit transition [26].

Depending on the relative strength (more accurately: curvature) of the potential in either spatial dimension, as well as on the number of particles, the ions will arrange

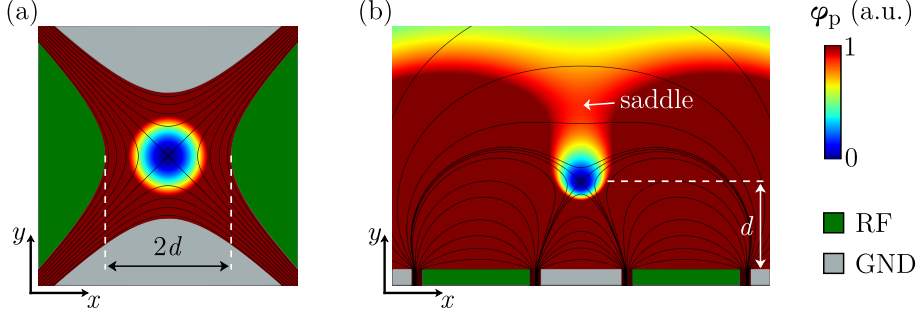


Figure 2.2: Potential cross-section created by applying RF voltages to the green electrodes for two different electrode configurations. The gray electrodes are held at ground potential. The solid black lines indicate the instantaneous equipotential lines, and the resulting pseudo-potential is encoded in color. d is minimal ion-electrode separation. (a) shows hyperbolic electrodes, providing ideal confinement and (b) shows a planar electrode configuration, which suffers from smaller trapping depths due to the presence of a saddle point above the potential minimum (indicated by the arrow). Image modified from [28].

differently, ranging from 1D to 3D shapes. For gate based quantum computing applications, the most often used configuration for quantum computation is that of a linear string, while a 2D crystal is most often used for quantum simulation [27]. Figure 2.1 shows an illustration of a typical trap containing a string of ions.

A force confining a charged particle in all directions can not be created using static electric fields, as stated by Earnshaw's theorem [29]. In a linear Paul trap, radio frequency (RF) voltage is applied to an electrode arrangement creating a rapidly alternating quadrupole potential in the x - y plane, which confines the ions to the z -Axis (RF-null). This field is superimposed with a DC potential, confining along the z direction, leading to a total electric potential given by: [21]

$$\varphi(t) = \frac{U_{RF}}{2d^2}(x^2 - y^2) \cos(\Omega_{RF}t) + \frac{U_{DC}}{2z_0^2}(2z^2 - x^2 - y^2) \quad (2.1)$$

where we assumed ideal hyperbolic electrode geometries as shown in figure 2.2 (a). d is the distance between the center of the trap and the electrodes, and z_0 is the distance from the axial potential minimum to the DC (end-cap) electrodes. For realistic electrode geometries, the electric potential is reduced by a constant factor, and the quadrupole potential given in equation (2.1) is only accurate to leading order at the trap center [21]. As shown in figure 2.2 (b), a quadrupole potential can also be created by in-plane electrodes, forming the basis for surface ion traps. Note that even though the RF potential is anti-confining in one direction at any given time t , the rapid switching in combination with the particle's inertia allows stable trapping for certain combinations of U_{RF} and Ω_{RF} . In order to get a perspective on the physical and electrical dimensions of an ion trap, we give some design parameters of a successful design used in Innsbruck [30] (this trap design is visualized in figure 2.1). It uses an ion-electrode distance d of 0.8 mm and the distance between the center of the trap (ion position) to the DC electrodes is 2.5 mm. Further it uses an RF signal of $U_{RF} = 100$ V

2 Trapped ion quantum computing

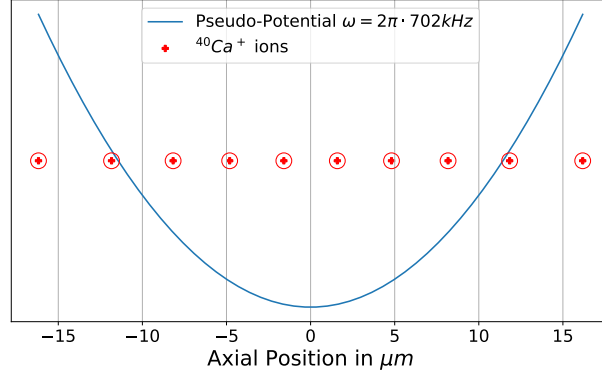


Figure 2.3: Non-equidistant ion positions numerically obtained for a linear string of 10 $^{40}\text{Ca}^+$ ions in a harmonic potential.

driven at $\Omega_{RF} = 2\pi \cdot 23.5 \text{ MHz}$, and the static voltage is held at $U_{DC} = 1 \text{ kV}$.

In the case of suitable trapping parameters (for details see e.g. ref. [21]), the ion motion is that of a harmonic oscillator with a frequency distinctively lower than the driving RF frequency Ω_{RF} . This *secular motion* is modulated by a (typically small) oscillation at Ω_{RF} , called micro-motion. In case the micro-motion is sufficiently small, it is validated to describe the ions as being trapped inside a harmonic pseudo-potential [21]:

$$\varphi_p = \frac{m}{2}(w_x^2 x^2 + w_y^2 y^2 + w_z^2 z^2) \quad (2.2)$$

Where we used the ion mass m . Further $w_x \approx w_y$ are the radial (secular) frequencies, and w_z is the axial frequency. Trapping singly charged $^{40}\text{Ca}^+$ ions with the trap parameters given above, yields a radial secular frequency of $\omega_r \approx 5 \text{ MHz}$, and an axial secular frequency of $\omega_z = 1.2 \text{ MHz}$ [30].

Typically, the voltages are chosen such that the confinement in the axial direction is weaker than in the radial direction. Multiple ions in the same potential well therefore arrange themselves in a linear configuration along the trap axis (Ion string). The equilibrium positions of the ions in the string can be found by minimizing their potential energy with respect to the ions position $\{z_i\}_{i=1\dots N}$. The relevant potential energy is the combination of a harmonic potential plus the Coulomb ion-ion interaction potential:

$$E_{pot}(\{z_i\}_{i=1\dots N}) = \sum_i \frac{1}{2} m \omega_z^2 z_i^2 + \sum_{i < j} \frac{q^2}{4\pi\epsilon_0} \frac{1}{|z_i - z_j|} \quad (2.3)$$

Where m is the mass and q is the charge of one ion, ω_z the axial trap frequency, and ϵ_0 is the vacuum permittivity. Typical values for the axial trap frequency ω_z in a surface ion trap are between $2\pi \cdot 500 \text{ kHz}$ and $2\pi \cdot 3 \text{ MHz}$, corresponding to an ion pitch between $8.9 \mu\text{m}$ and $2.7 \mu\text{m}$, in the case of two $^{40}\text{Ca}^+$ ions. Figure 2.3 shows the $N = 10$ case relevant for this work. The close spacing of the ions already hints at the difficulty of individually addressing each ion without affecting the neighboring ions, which is a motivation for the addressing unit discussed in this thesis.

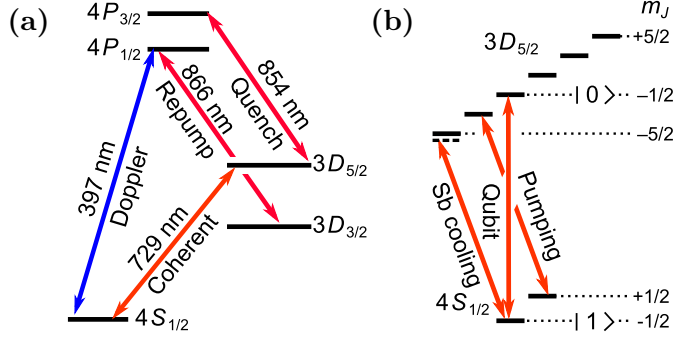


Figure 2.4: The transitions of the $^{40}\text{Ca}^+$ ion relevant for ion trapping. (a) A simplified level scheme of $^{40}\text{Ca}^+$, showing the relevant energy levels and their transition wavelengths. (b) A magnetic field lifts the Zeeman degeneracy, allowing a narrow-linewidth 729 nm laser to selectively address the individual sublevels including motional sideband (Sb) operations. The states used for quantum logic ($|0\rangle$ and $|1\rangle$) are the ones exhibiting the least sensitivity to magnetic field fluctuations. Image modified from [25].

2.2 Ion manipulation

The operation of an ion trap quantum computer requires lasers for a variety of tasks, ranging from ionization of a neutral precursor to coherent gate operations. One possibility to load ions into the trap uses an oven which provides a flux of hot neutral atoms. Choosing appropriate lasers for photo-ionization provides a means for isotope selective ionization, e.g. for ^{40}Ca a two-step process is applicable, using 423 nm for isotope selective excitation and 375 nm for ionization [25]. Once the atoms are ionized, the electric field of the Paul trap confines the ions.

In the next step the Ca^+ ions are Doppler cooled, with a red-detuned 397 nm laser acting on the short-lived $4S_{1/2} - 4P_{1/2}$ transition. In order to recycle ions lost to the metastable $3D_{3/2}$ state an additional re-pumping laser at 866 nm is used [25]. The relevant energy levels are shown in Figure 2.4. Since high-fidelity gate operations require the ions to be in, or near their motional ground state [23], additional laser cooling steps are required. Concluding the cooling procedure, several cycles of sideband cooling remove a single motional quantum in each cycle until the ions end up in their ground state [25]. Finally, the ions are optically pumped into the $|1\rangle = |4S_{1/2}, m_j = -1/2\rangle$ Zeeman sublevel, using a 729 nm excitation laser in combination with a 854 nm quenching laser [25] (see also figure 2.4(b))

Qubit manipulations rely on addressing single ions with phase-coherent 729 nm light. Interaction of the ion with a narrow-linewidth laser tuned resonant to the optical qubit transition, causes a periodic transition between the $|0\rangle$ and $|1\rangle$ states (Rabi flops). If we assume that the ion is initially prepared in the $|\psi(t=0)\rangle = |0\rangle$ state when the laser is turned on, the probability of finding it in the $|1\rangle$ state after a time t is given by [21]:

$$|\langle 1|\psi(t)\rangle|^2 = \sin^2 \Omega t \quad (2.4)$$

where we introduced the resonant carrier Rabi frequency Ω . The term carrier transition is used for ion-laser interactions, which leave the occupancy of the motional modes unchanged. While the carrier interaction forms the basis for single qubit rotations, two qubit gates require excitation of the joint motional modes of the ion crystal. De-tuning the laser by the frequency of the center-of-mass mode (=secular frequency), gives a way of entangling the addressed qubit's electronic state with the joint motional state [21]. One popular example of a two-qubit gate uses the scheme proposed by Sørensen and Mølmer [26], which works even when the atoms are not in their motional ground state.

Maximizing the Rabi frequency is beneficial, since it determines the speed at which quantum gates can be executed. The Rabi frequency is proportional to the amplitude of the electric field of the addressing laser, and consequently proportional to the square root of the intensity. For single ion addressing, a tightly focused laser beams is crucial for two main reasons: (i) The peak intensity increases for a smaller spot, enabling faster qubit operations for a given optical power and (ii) The optical cross-talk is reduced. Optical cross-talk refers to unwanted excitation of the neighboring ions. Optical cross-talk can be suppressed by choosing the laser beam spot significantly smaller than the ion pitch.

The outcome of a quantum circuit is determined by means of fluorescence measurements. By shining 397 nm light on the ion string, the ions either scatter the light if they are projected into the $|1\rangle = |4S_{1/2}, m_j = -1/2\rangle$ state or remain dark if they are in the $|0\rangle = |3D_{5/2}, m_j = -1/2\rangle$ state (see figure 2.4). The scattered light can be collected using an objective and measured with an electron multiplying CCD camera, which offers spatial discrimination between the ions in the string, even if a global read-out beam was applied. Ion traps capable of running quantum error correction algorithms will probably need to do mid-circuit measurements on a subset of ions (The ancillary qubits) [6], without affecting the quantum state of the rest. In that case photons of the read-out pulse scattered off the trap or off the ancillary qubits could provide a source of decoherence, if they interact with the computational ions [31].

2.3 Scaling the number of ions

Conventional ion trap designs (figure 2.1) store all ions in a single string. For quantum information processing, this approach restricts the number of ions, partly because the number of motional modes of the ion crystal increases with the number of ions, which makes resolved sideband operations more difficult [21]. This issue is addressed by a modular approach, where the ions are contained in smaller-sized (sub-)registers. Communication between the ion registers can be achieved by a successful design paradigm termed *quantum charge-coupled devices (QCCD)* [5].

In the QCCD architecture, the ion trap is segmented into several zones. The ions are stored in a memory region, and each ion can be selectively transported (shuttled) to an interaction zone. Inside the interaction zone, the aforementioned coulomb bus is used to create entanglement. Transport is achieved by an RF field confining the ions radially, and numerous quasi-DC control electrodes, creating the axial confinement,

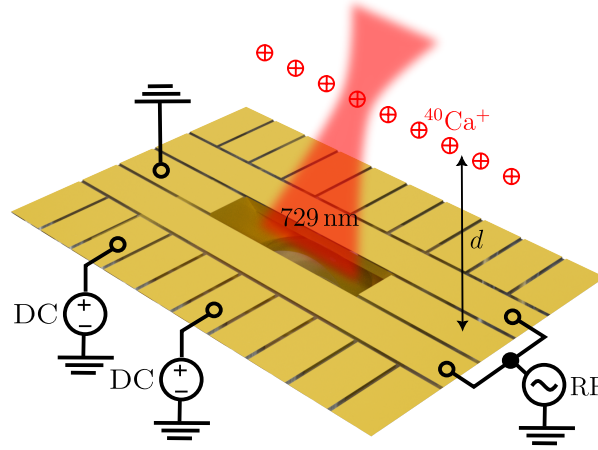


Figure 2.5: Schematic image of a surface ion trap, with all electrodes (gold) located in-plane. The RF rails provide axial confinement, while a number of DC electrodes provide axial confinement and can also be used for micro-motion compensation. Controlling the voltages on a number of DC electrodes simultaneously allows transporting the ions in the axial direction, as well as splitting and merging operations. The trap layout shown here features a slot in the center of the trap for optical access.

as visualized in figure 2.5. The large number of DC electrodes allows fine-grained control over the shape of the axially confining potential. This enables operations such as splitting and merging the ion string [5]. Another building block of the QCCD architecture are junctions. The junctions allow complex trap layouts, with multiple storage and interaction zones, potentially enabling highly parallel operation of the quantum information processor [5].

To achieve the complicated trap layouts required for modular ion traps, advanced fabrication methods are required. The most straightforward approach is to use in-plane electrode configurations [32], as shown in figure 2.5. Surface traps are particularly interesting for scalable architectures, since they can draw from established chip fabrication technologies. The semiconductor industries high level of process control allows creating feature sizes in the sub micro meter regime, with very high accuracy and repeatability. Apart from ability to create (almost) arbitrary electrode layouts, chip fabrication methods can be used to directly integrate electrical and optical components. Chapter 3 will elaborate on the prospects of integrated photonics for ion traps.

Since purely two-dimensional electrode configurations suffer from a shallow trapping potential depth, as visualized in figure 2.6, several approaches have used microfabrication technologies such as wafer-stacking, or MEMS (micro-electromechanical systems) technology to create three-dimensional structures [33].

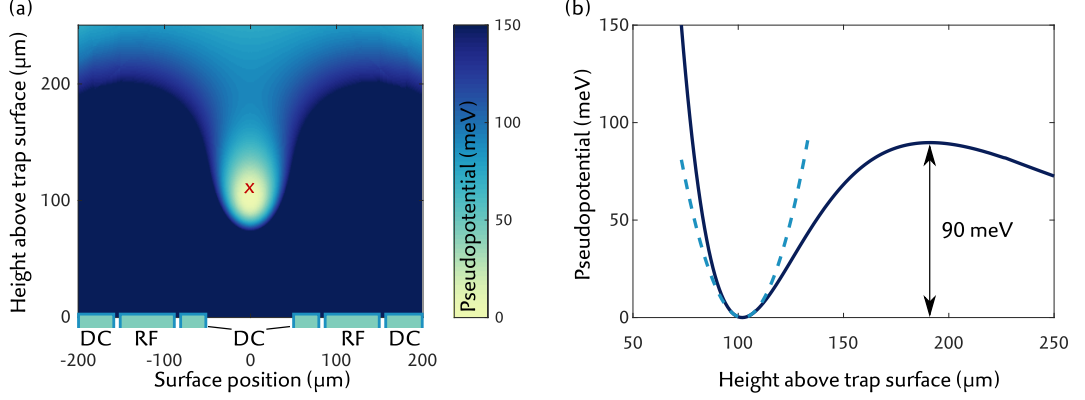


Figure 2.6: A simulation of the pseudo potential of a surface ion trap which offers optical access through a slot in the trap surface (left). The right figure shows the pseudo-potential as a function of ion height with a harmonic approximation. Note the shallow potential depth of 90 meV. Image modified from [34].

Motional heating

In principle, by reducing the ion-electrode spacing, one could achieve the same secular trap frequencies at lower voltages. Lower voltages allow to further decrease the electrodes and the required gaps in between, thus achieving scaling by miniaturization as is routinely demonstrated by semiconductor devices. One key limitation for decreasing the ion-electrode separation is the strong increase of motional decoherence [35], caused by random excitation of motional modes (heating).

Heating is primarily caused by electric field noise with spectral components close to the traps secular frequencies [35]. Since the magnitude of this effect is much higher than expected from considerations of Johnson-Nyquist noise or black-body radiation, this effect has been termed *anomalous heating* [36]. While the mechanism is still not entirely clear, it can be expected that the main causes are surface effects, which might be caused by impurities deposited on the chip's surface [35]. It has been shown that the heating rates Γ increase strongly for decreasing ion-surface separation d : $\Gamma = d^{-\beta}$, with exponents ranging from $\beta = 2.6$ [37] to $\beta = 4$ [38]. In order to maintain high-fidelity operations, the ion-surface distance is therefore limited to $d \gtrsim 30 \mu\text{m}$, with typical values in the order of $50 \mu\text{m} < d < 150 \mu\text{m}$ [39].

Operating a surface ion trap at cryogenic temperatures ($T \approx 4 \text{ K}$) has been shown to decrease motional heating by approximately two orders of magnitude [35]. Cryogenic operation suppresses out-gassing of in-vacuum components, making it easier to establish ultra-high vacuum. Further, collisions of ions with background gas particles are reduced. Therefore, the device discussed in subsequent chapters of this thesis (chapter 3.3) is designed to operate in a cryogenic environment.

3 Optical Integration

In the previous chapter it was discussed how the number of qubits in an ion trap can be scaled up by employing a micro-fabricated surface ion trap, and now we will go on to discuss how integrated optical components might open a route towards a truly scalable system. In order to take full advantage of the increased qubit count, optical control of individual ions is desired. Individual ion addressing requires tightly focused laser beams, with spot sizes significantly smaller than the ion-spacing. For example, an optical cross-talk of less than -40 dB for an ion pitch of $3.18\text{ }\mu\text{m}$ requires a beam diameter of less than $2.96\text{ }\mu\text{m}$, assuming a perfectly diffraction limited Gaussian beam¹. An unavoidable consequence of a tightly focused beam is its large divergence angle; the exemplary beam given above would have a divergence half angle θ of 8.9° (for a 729 nm laser). Therefore, free-space addressing units require one or more bulky objectives to create a high-quality focus, especially if the distance to the ions increases.

In the case of the traditional approach using addressing beams propagating parallel to the chip surface, clipping of the beam at the chip's edge limits the minimal laser beam size [40]. This issue has been addressed by laser beams perpendicular to the trap surface, for example in combination with micro-fabricated focusing mirrors integrated in the chip's surface [41]. Even though such system can be in principle expected to scale to a large number of addressing sites, free-space laser beams suffer from several issues, including the difficulty to align many tightly focused beams precisely to the ion positions. Further, creating many small focal spots is typically achieved with optical path lengths in the order of meters, which makes the laser susceptible to environmental fluctuations, such as temperature and air pressure variations. Such fluctuations can introduce instabilities in the direction of the laser beam (beam pointing instabilities), which translate to intensity noise at the ion position [8]. Further, environmental fluctuations can cause (relative) phase fluctuations. Both effects are detrimental to high-fidelity operations.

Integrating photonic components into the trap chip promises an appealing way to increase both qubit count and gate fidelity. The limitations on the number of qubit imposed by bulky free-space optics are avoided, and the much smaller and highly stable optical path of integrated devices makes them resistant to environmental fluctuations. Integrated photonics devices are typically interfaced with an optical fiber which may be glued to the chip's facet. Lithographically defined optical waveguides are used to route the laser to out-coupling structures, such as diffractive gratings. Integrated waveguide splitters and active switches can be used to distribute light from a single source, naturally enabling phase-coherence [8]. Apart from addressing, integrated

¹Properties of Gaussian beams are discussed in section 4.1.

3 Optical Integration

detectors could potentially enhance qubit read-out speed and fidelity [42, 43].

The first section (3.1) of this chapter discusses some theory relevant for operation of optical waveguides, before section 3.2 introduces technology and material platforms interesting for ion trapping applications. Finally, this chapter concludes by introducing the specific photonic integrated circuit used in this thesis (section 3.3).

3.1 Electromagnetic waves in a dielectric material

In this section some fundamental properties of optical waves inside a material are reviewed, before applying them to the operation of photonic waveguides, which are the basic building block of a photonic integrated circuit. Light in a waveguide is propagating in discrete modes, which are special solution to the electromagnetic wave equation.

We start by deriving the wave equation from Maxwell's equations, which describe electromagnetic phenomena at the fundamental level:

$$\begin{aligned}\nabla \cdot \mathbf{D} &= \rho_f & \nabla \times \mathbf{E} &= -\partial_t \mathbf{B} \\ \nabla \cdot \mathbf{B} &= 0 & \nabla \times \mathbf{H} &= \mathbf{J}_f + \partial_t \mathbf{D}\end{aligned}\tag{3.1}$$

Where $\mathbf{D}$ is the electrical displacement field given by $\mathbf{D} = \epsilon_0 \mathbf{E} + \mathbf{P}$, using the electric field $\mathbf{E}$, the polarization density $\mathbf{P}$, and the vacuum permittivity ϵ_0 . $\mathbf{B}$ is the magnetic field, related to the magnetizing field $\mathbf{H}$ via the magnetization $\mathbf{M}$: $\mathbf{B} = \mu_0(\mathbf{H} + \mathbf{M})$, where μ_0 is the vacuum permeability. Further ρ_f and $\mathbf{J}_f$ are the free charge and current density, respectively.

Subsequently, we shall restrict the discussion to non-magnetic, linear and isotropic dielectric materials, and neglect free charges or currents an approximation which is often valid in the field of optics [44]: $\mathbf{M} = 0, \mathbf{D} = \epsilon \mathbf{E}, \rho_f = 0, \mathbf{J}_f = 0$, where we introduced the material electric permittivity ϵ . In this case, Maxwell's equations reduce to:

$$\begin{aligned}\nabla \cdot \epsilon \mathbf{E} &= 0 & \nabla \times \mathbf{E} &= -\mu_0 \partial_t \mathbf{H} \\ \nabla \cdot \mathbf{H} &= 0 & \nabla \times \mathbf{H} &= \epsilon \partial_t \mathbf{E}\end{aligned}\tag{3.2}$$

Combining the two curl equations leads to:

$$\epsilon \mu_0 \partial_t^2 \mathbf{E} = -\nabla \times \nabla \times \mathbf{E}\tag{3.3}$$

$$= -\nabla(\nabla \cdot \mathbf{E}) + \nabla^2 \mathbf{E}\tag{3.4}$$

which, in the case of a homogeneous material ($\nabla \epsilon = 0$), gives the wave equation:

$$\partial_t^2 \mathbf{E} - v^2 \nabla^2 \mathbf{E} = 0\tag{3.5}$$

where the speed of light v inside a material is given by

$$v = \frac{1}{\sqrt{\epsilon \mu_0}} = \frac{1}{n \sqrt{\epsilon_0 \mu_0}} = \frac{c}{n}\tag{3.6}$$

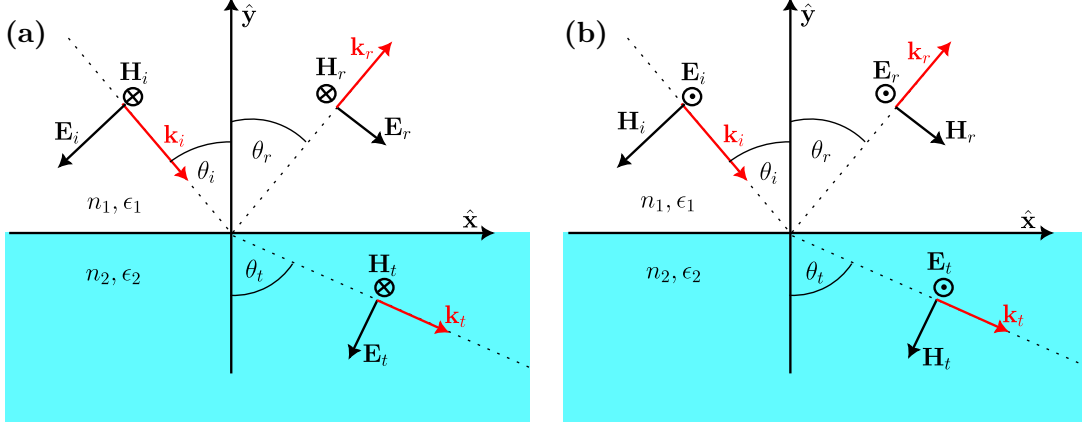


Figure 3.1: A plane wave incident on a boundary between two homogeneous dielectric materials. The wave is partly transmitted (refracted) and reflected. (a) shows a p-Polarized wave, while (b) shows the s-Polarized case. The subscripts indicate the incident, reflected and transmitted wave respectively.

using the index of refraction $n = \sqrt{\epsilon/\epsilon_0}$ and the speed of light in vacuum $c = 1/\sqrt{\epsilon_0\mu_0}$.

Solutions to the wave equation (3.5) are given by monochromatic plane waves:

$$\mathbf{E}(t, \mathbf{r}) = \mathbf{E}_0 e^{i(\mathbf{k} \cdot \mathbf{r} - \omega t)} \quad (3.7)$$

$$\mathbf{H}(t, \mathbf{r}) = \frac{1}{i\omega\mu_0} \nabla \times \mathbf{E}(t, \mathbf{r}) = \frac{1}{\omega\mu_0} \mathbf{k} \times \mathbf{E}(t, \mathbf{r}) \quad (3.8)$$

with wavevector $\mathbf{k}$, related to the light's frequency ω via $|\mathbf{k}| = n\omega/c$. The condition $\nabla \cdot \mathbf{E} = i\mathbf{k} \cdot \mathbf{E} = 0$ for homogeneous materials restricts the vectorial components of $\mathbf{E}$ to a purely transversal wave. Note that in general, $\mathbf{k}$ (as well as n, ϵ) can take complex values, in which case the energy contained in the wave is not conserved along the direction of propagation.

Refraction and reflection

The plane wave can be used to obtain an understanding of an electromagnetic field passing a homogeneous interface with surface normal $\hat{\mathbf{n}}$ from one material with index n_1, ϵ_1 into another material with index n_2, ϵ_2 (visualized in figure 3.1). As will become apparent, the boundary conditions implied by Maxwell's equations necessarily lead to transmission losses in the case of $n_1 \neq n_2$. Across the interface, Maxwell's equations dictate continuity of $\mathbf{E}, \mathbf{H}$ in the tangential direction, and continuity of $\epsilon\mathbf{E}, \mathbf{H}$ along the normal direction:

$$\begin{aligned} (\mathbf{E}_2 - \mathbf{E}_1) \times \hat{\mathbf{n}} &= 0 & (\epsilon_2 \mathbf{E}_2 - \epsilon_1 \mathbf{E}_1) \cdot \hat{\mathbf{n}} &= 0 \\ (\mathbf{H}_2 - \mathbf{H}_1) \times \hat{\mathbf{n}} &= 0 & (\mathbf{H}_2 - \mathbf{H}_1) \cdot \hat{\mathbf{n}} &= 0 \end{aligned} \quad (3.9)$$

As shown in figure 3.1, the plane of incidence spanned by $\hat{\mathbf{n}}$ and $\mathbf{k}_i$ shall be the $x - y$ plane. At the interface, the incident beam $\mathbf{E}_i$ is split in a reflected part $\mathbf{E}_r$ and

3 Optical Integration

a transmitted part $\mathbf{E}_t$, each assuming the form of a plane wave with wave-vectors $\mathbf{k}_i$, $\mathbf{k}_r$ and $\mathbf{k}_t$ respectively. Requiring the waves to have the same wavenumber along the interface, we obtain the condition:

$$\mathbf{k}_i \cdot \hat{\mathbf{x}} = \mathbf{k}_r \cdot \hat{\mathbf{x}} = \mathbf{k}_t \cdot \hat{\mathbf{x}} \quad (3.10)$$

or

$$k_i \sin(\theta_i) = k_r \sin(\theta_r) = k_t \sin(\theta_t) \quad (3.11)$$

with $k = |\mathbf{k}| = nc/\omega$ for the wave-vectors and angles θ relative to the surface normal as depicted in figure 3.1. Since we have $k_i = k_r$ and $k_i n_1 = k_t n_2$, we recover the law of reflection: $\theta_i = \theta_r$, and Snell's law of refraction:

$$n_1 \sin(\theta_i) = n_2 \sin(\theta_t) \quad (3.12)$$

Two independent modes of polarization are possible for the incident wave: (i) s-Polarized with $\mathbf{E}_i = E_i \hat{\mathbf{z}}$ or (ii) p-Polarized with $\mathbf{H}_i = H_i \hat{\mathbf{z}}$ as shown in figure 3.1. Applying the boundary conditions (3.9) allows finding expressions for the relations between E_i , E_r and E_t , which, in the case of an s-Polarized wave, read [44]:

$$t_s := \frac{E_t}{E_i} = \frac{2n_1 \cos(\theta_i)}{n_1 \cos(\theta_i) + n_2 \cos(\theta_t)} \quad (3.13)$$

$$r_s := \frac{E_r}{E_i} = \frac{n_1 \cos(\theta_i) - n_2 \cos(\theta_t)}{n_1 \cos(\theta_i) + n_2 \cos(\theta_t)} \quad (3.14)$$

The equations above are called Fresnel equations for the transmission and reflection coefficients, and they also give the correct phase relation between the plane waves. For a p-Polarized wave, the expression is similar, but omitted for brevity. The relative power reflected at the interface can be calculated via $R_s = |r_s|^2$. In contrast, the relative transmitted power is $T_s = 1 - R_s \neq |t_s|^2$, since the transmitted wave generally propagates in a different medium [44].

In the case $n_1 > n_2$, there exists a critical angle of incidence θ_c , above which Snell's law can not be fulfilled for any real θ_t : $\sin(\theta_c) = n_2/n_1$. Allowing $\sin(\theta_t) = \sin(\theta_i)n_1/n_2 > 1$ gives a way of applying the Fresnel equations even in the case $\theta_c < \theta_i \leq \pi/2$. In that case the transversal component of the transmitted wavevector $\mathbf{k}_t$ is purely imaginary:

$$\mathbf{k}_t \cdot \hat{\mathbf{y}} = n_2 k_0 \cos(\theta_t) \quad (3.15)$$

$$= n_2 k_0 \sqrt{1 - \sin^2(\theta_t)} \quad (3.16)$$

$$= i k_0 \sqrt{(n_1 \sin(\theta_i))^2 - n_2^2} \quad (3.17)$$

where the positive sign in the last equation was chosen since it leads to an exponential decline when inserted into the plane wave equation (3.7).

3.1 Electromagnetic waves in a dielectric material

In this case the Fresnel power coefficients for reflection become unity, which is why this effect is called total (internal) reflection. On the other hand, the Fresnel amplitude coefficient for reflection turns into a complex number, which corresponds to a nontrivial phase shift experienced by the totally reflected wave. Since the phase shift generally differs for s and p polarization, it can be used to change linearly polarized light to a circular polarization and vice versa [44].

The exponentially declining wave travelling *along* the interface is called an evanescent wave. Even though the evanescent wave is not transporting energy away from the interface in the case of total internal reflection, absorption of the wave can still cause losses [44]. Note the importance of the index contrast $n_1^2 - n_2^2$ in equation (3.17) which, for a given angle of incidence, determines the penetration depth into the optically thinner medium.

If total internal reflection occurs on a sufficiently thin film, the non-zero amplitude of the evanescent field on the opposite interface might still cause partial transmission [44]. This phenomenon, analogous to the quantum mechanical tunnel effect, is called frustrated total internal reflection and will be used later to investigate the evanescent coupling of two parallel waveguides.

Guiding optical waves

Generally speaking, a waveguide is a structure which constrains the direction of propagation of a (electromagnetic) wave. In the case of waves in the optical regime, a waveguide is most commonly formed by a longitudinally extruded refractive index profile. If a higher index material (waveguide core) is surrounded by a cladding which is optically thinner, light launched into the core at sufficiently flat angles is trapped by total internal reflection, as conceptually visualized in figure 3.2(a). The condition for total internal reflection allows defining a numerical aperture for the waveguide, which is connected to the half angle θ of the cone of light accepted by the waveguide:

$$NA = \sqrt{n_{wg}^2 - n_c^2} = n \sin(\theta) \quad (3.18)$$

where n_{wg} , n_c , n are the refractive indices of the waveguide core, cladding and surrounding medium, respectively. A more detailed mathematical treatment gives rise to discrete modes, as shown in figure 3.2(b). A waveguide mode is essentially a field distribution which solves Maxwell's equations and maintains its shape during propagation. Finding the modes supported by a particular waveguide geometry is fundamental for engineering integrated optical devices.

Since we are interested in monochromatic light fields, which do not change shape in direction of propagation, the longitudinal component and the time dependence of the electric field can be factored out:

$$\mathbf{E}_{wg}(t, \mathbf{r}) = \mathbf{E}(y, z) \cdot e^{i(\beta x - \omega t)} \quad (3.19)$$

where we assumed propagation in the $\hat{\mathbf{x}}$ direction. $\beta = k_x$ is the longitudinal wavenumber, related to the speed of propagation v via $v = \omega/\beta$. In this case, the wave equation

3 Optical Integration

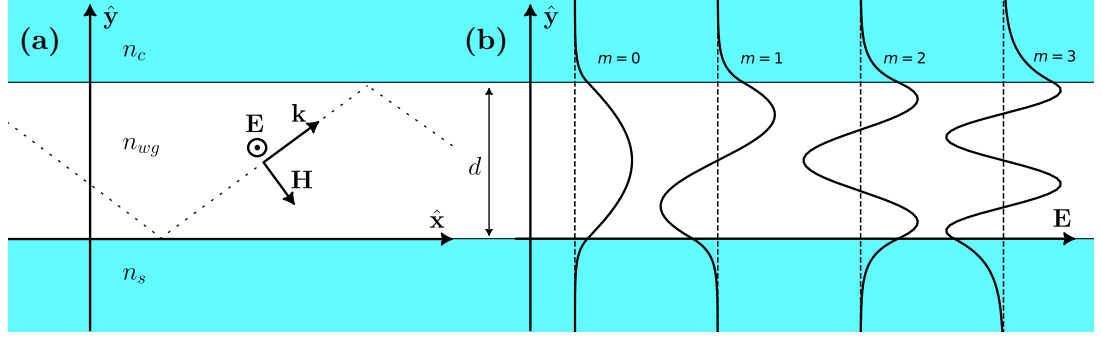


Figure 3.2: Schematic representations of a slab waveguide. **(a):** In the ray-optics picture the guidance of light can be imagined as a series of total internal reflection events. The direction of the electric field $\mathbf{E}$ indicates the transverse electric (TE) character. **(b):** This specific waveguide geometry supports four distinct TE modes. Note how higher order modes penetrate deeper into the cladding. Computation assumed a symmetric silica cladding ($n_c = n_s$), a silicon nitride waveguide core with $d = 1 \mu\text{m}$, and an optical wavelength of $\lambda = 729 \text{ nm}$.

(3.5) inside a homogeneous segment reduces to the 2D Helmholtz equation:

$$(\partial_y^2 + \partial_z^2)\mathbf{E} + (n^2 k_0^2 - \beta^2)\mathbf{E} = 0 \quad (3.20)$$

Considering a confined light field, only discrete values of β can solve the equation above, corresponding to the guided modes of the waveguide [45]. It is common to describe a particular waveguide mode using the effective index, which is defined as: $n_{eff} = \beta/k_0$, using the wavenumber in vacuum $k_0 = \omega/c = 2\pi/\lambda$.

Inserting equation (3.19) into Maxwell's curl equations and evaluating the result component-wise, we find that $\mathbf{E}(y,z)$ and $\mathbf{H}(y,z)$ are fully specified by the longitudinal components E_x and H_x . In particular, no solution can be found in the case of a fully transversal mode ($E_x, H_x = 0$), excluding the trivial case of a constant cross-section, where the equations are solved by a plane wave propagating in the $\hat{\mathbf{x}}$ direction. Further, a mode confined in both lateral directions can be neither transversal electric (TE; $E_x = 0$), nor transversal magnetic (TM; $H_x = 0$), with the notable exception of radially symmetric index profiles [46].

Maxwell's equations are in general not readily solved for arbitrary waveguide geometries. Practically relevant exceptions include radially symmetric waveguides, such as optical fibers, and two-dimensional planar (slab) waveguides [45]. Photonic integration often relies on thin films deposited on a substrate, which approximate a slab waveguide geometry. Since this layer offers confinement in only a single direction, it can not be used for on-chip routing. Patterning the thin film forms a rectangular cross-section, which guides the light in two direction, and can thus be used as a photonic wire. In contrast to the slab waveguide, analytic treatment of the rectangular waveguide geometry requires approximations. For example, in the effective index method, a rectangular waveguide is treated as a superposition of two perpendicular slabs [45]. The slab waveguide can further be considered as the limit of a rectangular waveguide with an aspect ratio approaching infinity.

3.1 Electromagnetic waves in a dielectric material

In the following section, the focus is on infinitely extended slab waveguides with piecewise homogeneous material (step-index waveguides, as opposed to graded-index waveguides), following the treatment found in ref. [45]. In such a waveguide we distinguish three different refractive index zones with $n_c \leq n_s < n_{wg}$ (see figure 3.2):

$$n(x, y, z) = \begin{cases} n_c & y > d & \dots \text{cladding} \\ n_{wg} & 0 \leq y \leq d & \dots \text{waveguide core} \\ n_s & y < 0 & \dots \text{substrate} \end{cases} \quad (3.21)$$

Considering propagation in the x direction, the lack of confinement along $\hat{\mathbf{z}}$ caused by the translational symmetry of the slab waveguide, leads to a constant field in the z direction [45]: $\partial_z \mathbf{E}, \partial_z \mathbf{H} = 0$. As a consequence, the polarization of the modes can be either transverse electric (TE) with $\mathbf{E} \cdot \hat{\mathbf{x}} = 0$, or transverse magnetic (TM) with $\mathbf{H} \cdot \hat{\mathbf{x}} = 0$. The following derivation considers only the TE mode, but the mathematical treatment of the TM mode is similar. Using the conditions above, it follows directly from Maxwell's curl equations that the electric field of the TE mode has only a single non-zero component: $\mathbf{E}(t, \mathbf{r}) = E_z(y) e^{i(\beta x - \omega t)} \hat{\mathbf{z}}$.

Since we are interested in modes confined in the y direction, we choose an Ansatz which is exponentially decaying outside the core region and oscillatory within the core:

$$E_z(y) = \begin{cases} A e^{-\delta(y-d)} & y > d \\ B \sin(\kappa y) + C \cos(\kappa y) & 0 \leq y \leq d \\ D e^{\gamma y} & y < 0 \end{cases} \quad (3.22)$$

Where δ, κ and γ are determined by the Helmholtz equation, using the longitudinal wavenumber β :

$$\delta^2 = \beta^2 - k_0^2 n_c^2 \quad (3.23)$$

$$\gamma^2 = \beta^2 - k_0^2 n_s^2 \quad (3.24)$$

$$\kappa^2 = k_0^2 n_{wg}^2 - \beta^2 \quad (3.25)$$

The boundary conditions for Maxwell's equations (3.9) require continuity of both E_z and $\partial_y E_z$. Applying the boundary conditions to the Ansatz function (3.22) leads to the *dispersion relation* of TE slab waveguides [45]:

$$\tan(\kappa d) = \frac{\kappa(\gamma + \delta)}{\kappa^2 - \gamma\delta} \quad (3.26)$$

The discrete nature of the solutions more apparent when rewriting the dispersion relation using the mode number $m = 0, 1, \dots$:

$$\kappa d = (m + 1)\pi - \tan^{-1} \frac{\kappa}{\gamma} - \tan^{-1} \frac{\kappa}{\delta} \quad (3.27)$$

The equation above can be solved numerically, from which we obtain both the propagation constant β and the field distribution of the mode. The slab waveguide shown in figure 3.2(b) is an example of a waveguide supporting 4 discrete modes.

3 Optical Integration

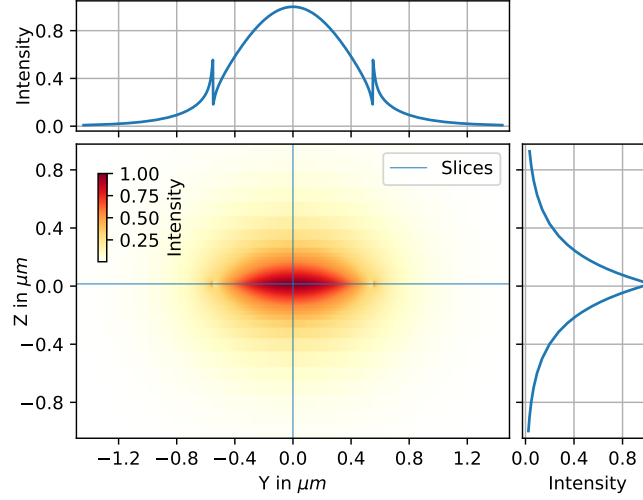


Figure 3.3: The intensity profile of a rectangular silicon nitride waveguide (width: $1.1\,\mu\text{m}$, height: $30\,\text{nm}$) embedded in a silicon oxide cladding. The right and top plots are sections through the profile. The mode shown here corresponds to (quasi-) TE polarization. The discontinuities visible in the upper plot are a direct consequence of the boundary conditions imposed by Maxwell's equations (3.9).

For a given laser wavelength, there exists a maximum mode number m_{max} , above which the dispersion relation does not yield a solution. The number of modes supported by a waveguide depends on both the thickness of the core d and the refractive index contrast. For an asymmetric waveguide ($n_c \neq n_s$) there exists a thickness d below which the waveguide does not support a single mode. On the contrary, a symmetric waveguide ($n_c = n_s$) supports the fundamental mode $m = 0$ even for an arbitrarily small thickness [45].

For practical reasons it is often desirable to have only a single mode propagates. For practical reasons it is often desirable to have only a single mode propagating inside the waveguide. If multiple modes are propagating simultaneously, the difference in propagation constant causes beating between the modes and the shape of the field is no longer constant (modal dispersion). As is apparent from figure 3.2(b), higher order waveguide modes are generally less tightly confined inside the core material and have a higher electric field amplitude at the boundaries of the waveguide core which increases both sidewall scattering, and the losses caused by bends in the waveguide [45]. Single mode operation is further critical for on-chip couplers, which depend on the overlap of modes in adjacent waveguides, and are therefore very sensitive to the confinement of the light inside each waveguide.

Three-dimensional waveguides can in general not be analytically solved with a closed form solution. A common approach to numerical simulation is to use Eigenmode solvers, which translate a discretized version of Maxwell's equations into an Eigenvalue problem, with the square of the propagation constant β^2 being the Eigenvalue [47].

3.1 Electromagnetic waves in a dielectric material

Figure 3.3 shows the fundamental mode of a rectangular waveguide found by a numerical eigenmode solver. One useful approximate method of obtaining the mode profiles and the propagation constants β for a rectangular cross-section is the effective index method, which treats a rectangular waveguide as a superposition of two perpendicular slab waveguides. For a rectangular cross-section this method allows finding an analytic approximation of the modes, but the method is also advantageous for numerical analysis since it can reduce the computational complexity. In the case of thin films, which are particularly relevant to optical integration, the effective index method allows reducing the dimensionality of the problem, enabling the simulation of larger and more complex devices or components.

Note that for guided modes it is required that $n_s k_0 < \beta < n_{wg} k_0$, which satisfies the condition of total internal reflection. If $\beta < n_s k_0$, γ (and potentially δ) is an imaginary number, in which case the field amplitude in the substrate does not decline away from the waveguide core. Solutions with $\beta < n_s k_0$ are called radiation modes, and can be described by plane waves. Taken together, the discrete set of guided modes and the continuous set of radiation modes form a basis set, into which any initial electric field configuration can be decomposed [45].

We shall mention at this point that the modes $(\mathbf{E}_m, \mathbf{H}_m)e^{i(\beta_m x - \omega t)}$ found by exactly solving the Helmholtz equation for any waveguide cross-section are mutually orthogonal under the inner product defined by integration of the x component of the Poynting vector $\mathbf{S} = \text{Re}(\mathbf{E} \times \mathbf{H})$:

$$\langle (\mathbf{E}_m, \mathbf{H}_m), (\mathbf{E}_l, \mathbf{H}_l) \rangle := \frac{1}{4} \iint_{\mathbb{R}^2} dy dz (\mathbf{E}_l^* \times \mathbf{H}_m + \mathbf{E}_m \times \mathbf{H}_l^*) \cdot \hat{\mathbf{x}} \quad (3.28)$$

$$\langle (\mathbf{E}_m, \mathbf{H}_m), (\mathbf{E}_l, \mathbf{H}_l) \rangle = 0 \quad \text{for } l \neq m \quad (3.29)$$

Since the Poynting vector represents the density of the local energy flux, this condition is also called power orthogonal.

Directional waveguide couplers

If two waveguides are routed close to each other, overlapping modes can cause power transfer from one waveguide to the other. On one hand, this property is desired when designing on-chip couplers for light distribution, on the other hand it can limit dense integration. For ion trapping in particular, parasitic leakage from one waveguide to the next causes optical cross-talk which is a source of infidelity. Central to the discussion of waveguide coupling are the so-called supermodes, which are the modes of the compound structure, and the isolated modes, which are the modes of either waveguide in isolation. Figure 3.4 shows how the supermodes are delocalized over both waveguides. The supermodes form an orthogonal basis for guided modes, similar to the modes of a single waveguide. Since an initial field distribution can be decomposed into a superposition of supermodes, the finite splitting of the propagation constant leads to beating, with a fraction of the optical power oscillating between the waveguides.

In this section we shall focus on the relation between the supermodes and the isolated modes of two parallel and lossless waveguides which are weakly coupled. Weak coupling

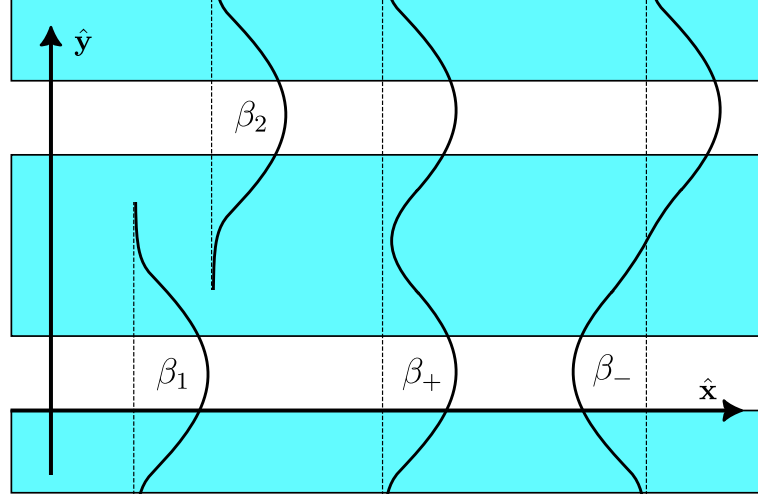


Figure 3.4: The lowest order eigenmodes of a compound structure ($\beta_{\pm}$) can be approximated by an in-phase and out-of-phase superposition of the lowest order modes of two isolated waveguides ($\beta_{1,2}$).

implies that significant power is exchanged only after a propagation distance which is much longer than the wavelength. The geometry and separation of the waveguides shall remain constant in direction of propagation. Further, only two isolated modes (one per waveguide) shall contribute to coupling as visualized in figure 3.4. This assumption is justified when only two modes have similar propagation constant and polarization [45]. In this case, the field distribution as a function of propagation length x might be written as:

$$(\mathbf{E}, \mathbf{H})(x) = b_1(x)(\mathbf{E}_1, \mathbf{H}_1) + b_2(x)(\mathbf{E}_2, \mathbf{H}_2) \quad (3.30)$$

where $(\mathbf{E}_i, \mathbf{H}_i)$ is the power-normalized field in mode i , and b_i are the complex field amplitudes. The spatial evolution of the field amplitudes is described by two coupled differential equations [45]:

$$\partial_x \begin{pmatrix} b_1 \\ b_2 \end{pmatrix} = i \begin{pmatrix} \beta'_1 & \kappa_{12} \\ \kappa_{21} & \beta'_2 \end{pmatrix} \begin{pmatrix} b_1 \\ b_2 \end{pmatrix} \quad (3.31)$$

Where the off-diagonal elements $\kappa_{12,21}$ are the coupling constants. The diagonal elements of the coupling matrix can be approximated by the isolated propagation constants ($\beta'_{1,2} = \beta_{1,2}$) if the waveguides are sufficiently far apart [45], an assumption we shall henceforth make. The eigenvalues of the coupling matrix correspond to the propagation constants $\beta_{\pm}$ of the supermodes and can be written as: $\beta_{\pm} = \bar{\beta} \pm \sigma$, using the symbols: $\sigma := \sqrt{\delta^2 + \kappa_{21}\kappa_{12}}$, $\bar{\beta} := (\beta_1 + \beta_2)/2$ and $\delta := (\beta_1 - \beta_2)/2$. A full solution to equation (3.31) can be written as:

$$\begin{pmatrix} b_1 \\ b_2 \end{pmatrix} (x) = e^{i\bar{\beta}x} \begin{pmatrix} \cos(\sigma x) + i\frac{\delta}{\sigma} \sin(\sigma x) & i\frac{\kappa_{21}}{\sigma} \sin(\sigma x) \\ i\frac{\kappa_{12}}{\sigma} \sin(\sigma x) & \cos(\sigma x) - i\frac{\delta}{\sigma} \sin(\sigma x) \end{pmatrix} \cdot \begin{pmatrix} b_1(0) \\ b_2(0) \end{pmatrix} \quad (3.32)$$

3.1 Electromagnetic waves in a dielectric material

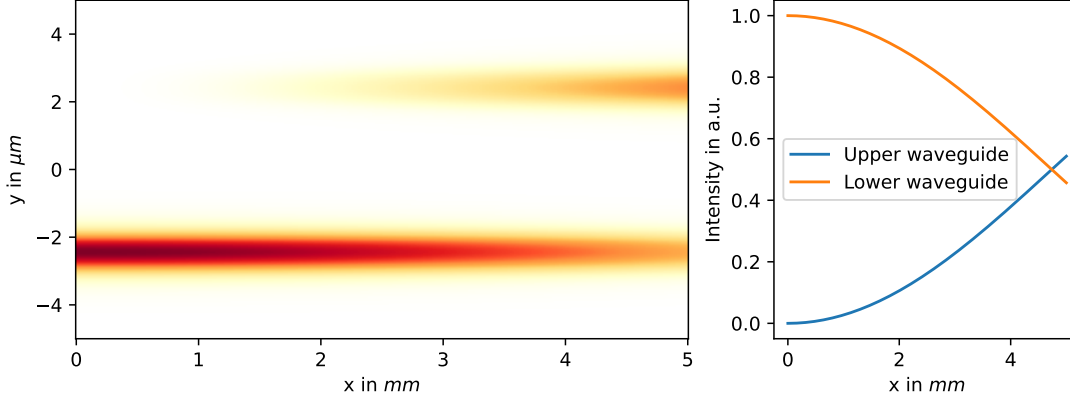


Figure 3.5: A simulation of a synchronous ($\beta_1 = \beta_2$) directional coupler. The mode exclusively launched into the lower waveguide slowly leaks into the upper waveguide during propagation from left to right. Image credit: Nicolas Jungwirth

If we assume that initially all the light is contained in the first waveguide ($P_2(0) = 0$), we can find an expression for the optical power in the first waveguide:

$$P_1(x) = P_1(0) \left(1 - \frac{\kappa_{21}\kappa_{12}}{\sigma^2} \sin^2(\sigma x) \right) \quad (3.33)$$

The maximum fraction of out-coupled power might be written as:

$$\frac{\kappa_{21}\kappa_{12}}{\sigma^2} = 1 - \frac{(\beta_1 - \beta_2)^2}{(\beta_+ - \beta_-)^2} \quad (3.34)$$

And the characteristic length L_c after which the maximum power is transferred is:

$$\sigma L_c = \frac{\pi}{2} \Rightarrow L_c = \frac{\pi}{\beta_+ - \beta_-} \quad (3.35)$$

From the equations above we can see that if the waveguides are synchronous ($\beta_1 = \beta_2$), any finite coupling causes a splitting of the supermodes $\frac{1}{2}(\beta_+ - \beta_-) = \sqrt{\kappa_{21}\kappa_{12}}$, leading to complete exchange of power eventually. Figure 3.5 shows a numerical simulation of two synchronous waveguides, where the mode slowly leaks from one waveguide to the other. Synchronous waveguides can be used to implement optical splitters with an arbitrary splitting ratio, by choosing well-defined fractions of the characteristic length L_c . Since the coupling constants (or equivalently the splitting of the supermodes) depends on the overlap of one waveguide's mode field with the core of the other waveguide, they show an exponential dependence on the waveguide separation [45]. Therefore, the coupling ratio is strongly influenced by manufacturing inaccuracies. In order to be less sensitive to these inaccuracies, integrated splitters often use non-constant cross-sections [48]. Note that synchronous operation does not necessarily imply that the waveguides have the same geometry. Different geometry waveguides have different dispersion relations, therefore synchronous operation might be accidentally achieved at some wavelengths [45].

3 Optical Integration

On the other hand, for asynchronous waveguides and sufficiently small coupling, the supermodes approach the modes of the isolated waveguides, and negligible power is transferred. This behavior can be exploited to minimize parasitic coupling for closely spaced waveguides. By choosing waveguides with an alternating cross-section, the mismatch in propagation constant $\beta_1 - \beta_2$ limits the maximum power transferred [49]. The photonic device discussed in this thesis uses this principle to reduce optical cross-talk in the single ion addressing unit.

3.2 Photonic integration technologies

In this section, some practical considerations to photonic integration are discussed with a focus on their application to ion trapping. We start by discussing some materials commonly used for photonic integration, before going on to introduce several devices, which are potentially interesting for large scale ion traps, such as modulators used for active signal routing and integrated detectors. The section concludes by discussing how to couple light into the photonic circuit.

Materials for integrated photonics

For optical telecom applications, integrated photonics operating at near- to mid-infrared wavelengths are already very much established, enabling high-bandwidth and low-latency communication in data-centers and communication hubs. An example of a widely used optical wavelength is the telecom C-band at 1550 nm, where optical fibers have exceptionally small attenuation of less than 0.2 dB/km [50], making them well suited for long-distance communication.

Since silicon is optically transparent at telecom wavelengths and has a high refractive index, it is readily usable for passive optical elements, such as waveguides or splitters [51]. The advance of silicon-based integrated photonics is closely related to innovations in CMOS foundries, in which the vast majority of semiconductor devices are built. Due to the semiconductor industry's larger research and development budget, integrated photonic devices generally try to make use of the same technology [7]. Consequently, the number of components on a photonic integrated circuit follows a trend reminiscent of Moore's law [7]. Note that the capabilities of cutting edge CMOS foundries in terms of minimal feature sizes ($\mathcal{O}(7\text{ nm})$ fin width of finFET transistors [52]) vastly exceed the requirements of integrated photonics. On the other hand, silicon is not ideal for advanced integrated devices. It exhibits inversion symmetry, and therefore a vanishing Pockels coefficient, making silicon unusable for electro-optical modulation [51]. Further, the indirect band-gap of silicon prohibits its use as an efficient light source [51].

Materials which are highly suited for laser applications are III-V semiconductors. III-Vs are compounds of a group III element such as Al, Ga, In and a group V element such as N, P, As, Sb. III-Vs typically have a direct band-gap and their permittivity (the square of the refractive index) is a non-linear function of electric field strength,

enabling their use as active components and modulators. A hindrance to the use of III-V materials in silicon photonics is that they are a contaminant in CMOS foundries [7]. To combine the advantages of III-Vs with those of silicon is an important area of research in silicon photonics, requiring the use of monolithic integration, such as epitaxial growth, or novel bonding methods. Integrating III-Vs will require the photonics industry to eventually emancipate from CMOS technology [7].

Ion trapping as an application for integrated photonics has very specific requirements. Most notably, as described in previous chapters, ion trapping requires wavelengths ranging from the near-ultraviolet (UV) to the infrared (IR). Short wavelengths are not the primary interest of integrated photonics. Consequently, ion trap designers can draw less from established functional blocks, but have to start component design from scratch [53]. In general, short wavelengths limit the material selection greatly [54]. Especially silicon is not suited for shorter wavelengths, due to its band-gap at $1.1\,\mu\text{m}$ [55]. Even if a material is transparent at the wavelength of interest, other loss mechanisms than bulk absorption exist. Scattering at the sidewall roughness of the waveguide, which increases unfavorably for shorter wavelengths [56], is often the dominant loss contribution. Sidewall scattering depends non-trivially on the waveguide geometry. It is influenced by the field amplitude at the waveguide core boundary and by the area of the sidewall [57]. The field amplitude can be minimized by choosing a weakly confining waveguide, where the mode is distributed over a larger area [57]. Downsides of the decreased confinement include the requirement for larger bending radii and increased parasitic coupling between waveguides [58]. Note that this is a general trade-off between high-confinement waveguides required for high-density integration and low-confinement waveguides offering low propagation losses.

Two materials which are suitable for visible wavelengths are silicon nitride (Si_3N_4) and aluminum oxide (alumina, Al_2O_3). Both of these materials are already established in some CMOS processes [7]. The most widely used cladding material is silicon oxide (silica, SiO_2) in its amorphous (glassy) form. Silica offers exceptionally low transmission losses, as evident from its usage in optical fibers. The large band-gap of silica enables its use for wavelengths $\lambda \gtrsim 157\,\text{nm}$ [59]. Depending on the method of deposition, the shortest wavelengths for which silicon nitride is transparent are in the ultraviolet between $275\,\text{nm}$ and $320\,\text{nm}$ [60]. Since the wide transparency window of SiN covers all visible wavelengths and ranges far into the infrared, it is potentially suited for routing all lasers required for Ca ion trapping. A potential hindrance could be the high-intensity $397\,\text{nm}$ light required for laser cooling and state detection, since the scattering losses strongly increase for wavelengths $\lambda \leq 400\,\text{nm}$ [58]. Especially for such wavelengths, alumina provides decreased scattering losses [58]. Since alumina has a smaller refractive index than silicon nitride, the mode is less confined to the waveguide, making it less suitable for dense integration [61]. An interesting alternative are composite structures consisting of alumina and hafnia (HfO_2), which have an increased index compared to alumina, while staying transparent even in the near-UV and are compatible with CMOS [62].

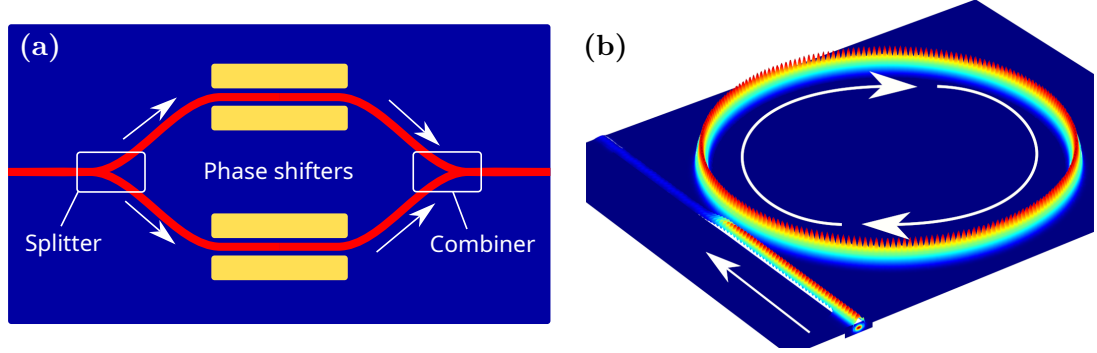


Figure 3.6: Illustrations of two integrated devices used for modulation. (a): A Mach-Zehnder interferometer. The red lines indicate the waveguides. Phase-shifters (gold pads) allow controlling the optical power in the output port. (b): Simulation of a micro-ring resonator evanescently coupled to a single waveguide driven at resonance. The light's instantaneous intensity is shown in color. Figure (b) was modified from ref. [63].

Intensity modulators

For optical telecom, active modulation of the laser's intensity is a crucial requirement. For ion trapping, a chip based modulator is also very attractive, since it would allow having a single optical feed-line from which the light is distributed on-chip to address individual ions. The highly stable optical paths offered by integrated photonic circuits provide natural phase-coherence between the addressing laser beams.

Intensity modulation can be achieved by having a phase-shifter integrated into a Mach-Zehnder interferometer, as visualized in figure 3.6(a). In a Mach-Zehnder interferometer, the initial beam is split by 50:50 beam splitter. Subsequently, the two beams propagate while acquiring a difference in phase, after which the beams are combined in a second beam splitter. The accumulated phase-difference determines the fraction of light exiting the output port of second-beam splitter. The integrated version of a Mach-Zehnder interferometer is readily formed by using either directional couplers or Y-junctions (figure 3.6(a)) as beam splitters. Modulation is achieved by controlling the difference in optical path length between the two arms of the resonator.

A second form of intensity modulation is achieved by micro-ring resonators (figure 3.6(b)), which are the integrated analogs of an optical cavity. A ring resonator is formed by one or more closed loop waveguides, which are coupled to one or two straight waveguides. The resonance criterion is met if the optical path length is an integer multiple of the wavelength. If a ring resonator is driven at resonance, the transmitted power is strongly attenuated, as visualized in figure 3.6(b). Micro-ring resonators might be used to form devices such as integrated mirrors, wavelength filters, or amplitude modulators. Modulation can be achieved by shifting the resonance frequency through manipulation of the optical path length. A fundamental difference between the two devices is the response to modulation. While the transmitted intensity of the Mach-Zehnder interferometer is a sinusoidal function of the accumulated phase difference (i.e. linear for small phase differences), the ring-resonator shows a highly

non-linear Lorentzian response [64]. Since the ring resonator is very sensitive to shifts in its resonance frequency, modulation requires smaller changes in optical path length, which leads to a smaller footprint compared to Mach-Zehnder interferometers [64].

There are several ways to modulate the optical path length, including the use of heater-elements (thermo-optical modulation), non-linear materials (electro-optical modulation), or piezo elements (strain-optical modulation). Integrated photonics for telecom applications are pushing towards modulation bandwidths of > 100 GHz [7], which is most readily achieved by electro-optical modulation. Since none of the waveguide materials previously discussed (silicon, alumina, silicon nitride) show a non-linearity, electro-optical modulation requires materials such as III-V semiconductors. Due to the unavailability of III-Vs operating at visible and near-UV photonics, modulation technologies in this range have focused on heated ring-resonators. Piggybacking on the innovations of silicon photonics, it can be expected that short-wavelength electro-optical modulators eventually become available [65].

For ion trapping, the modulation frequency is not the limiting factor, making thermo-optical modulators suitable, even though heat dissipation could be an issue for larger scale cryogenic setups with numerous heater elements. Other than modulation frequency, light distribution systems for integrated individual ion addressing should have excellent modulation depth. Achieving a high extinction ratio might require several modulators in series, but should pose no fundamental issue [66]. As an alternative, a high extinction ratio integrate optical switch might be achieved by mechanically moving the waveguide using the coulomb force or piezo elements, with structures fabricated using MEMS (micro electromechanical systems) technologies [67].

Integrated detectors

Probably the most challenging optical component to directly integrate into an ion trap are detectors for ion state readout. Readout is typically performed by illuminating the ion at a wavelength which corresponds to a short-lived dipole-allowed transition. If the ion is in state $|1\rangle$, the resonant laser can excite this transition, causing the ion to scatter many photons in all direction (bright state). If the ion is found in state $|0\rangle$, the laser is nowhere near resonance, and the ion remains dark. In order to achieve fast readout, it is desirable to collect a large fraction of the scattered photons, which can be achieved by detectors with an active area covering a large solid angle, or the use of optical elements for light collection. In conventional optical setups the photons are collected with a high-NA objective and guided on the active region of a CCD camera [25]. The resolution of the camera enables distinguishing between the individual ions. Low photon count rates can be detected by an electron multiplying CCD camera with a high quantum efficiency.

Since any detector has finite dark-count rates - both intrinsically and due to background-scattered light - high fidelity state discrimination requires setting a threshold on the photon number to distinguish between bright and dark states. Note that this results in a trade-off between readout speed and fidelity. Integrated approaches with potentially low dark counts and a high quantum efficiency are single-photon detectors, such as

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single photon avalanche detectors (SPAD) or superconducting nanowire single photon detectors (SNSPD).

Avalanche photodiodes operate by applying a high reverse bias to a p-n junction, such that charges created by an incident photon trigger an avalanche of charges, which can be easily converted to a digital pulse. Avalanche photodiodes have the advantage of being relatively easy to integrate in established CMOS processes. Especially when operated above their breakdown voltage (Geiger mode), the dark counts create a significant amount of field noise, which can cause loss of ions and prohibits coherent operations in the presence of an avalanche photodiode [68]. Shielding layers covering the active region of the photodiode have been used to achieve ion state detection [43]. Note that when designing single-photon detecting photodiodes special care should be taken to avoid background-scattered light entering the detector since that could easily saturate the device, rendering it unusable [69].

In contrast to single photon avalanche detectors, superconducting nanowires can not be operated at room temperature, but require cryogenic operation at temperatures below 10 K. A photon incident on the nanowire can create a local disturbance to the superconducting current, which can propagate and briefly cause the wire to lose its superconductivity. The finite resistance then creates a small, but measurable, voltage spike. SNSPDs allow faster operation compared to avalanche detectors, with a pulse decay constant much lower than the lifetime of the ions scattering transition [70], which makes them less susceptible to saturation. Further advantages include high quantum efficiency and extremely low dark counts under ideal conditions. The application of nanowires in Paul traps might be hindered by the strong RF fields, which can strongly increase dark counts, and therefore degrade the performance of the detector [42].

Both devices face similar challenges regarding the geometry. To achieve fast readout a large solid angle and therefore a large active area is required. On the other hand, the detectors should be able to distinguish between closely spaced ions, and therefore only photons from a single ion should reach the active area. Approaches to address this issue include increased ion separation, or bringing the ions close to the substrate for detection [8]. Alternatively, the ions could be read out sequentially, using tightly focused laser beams to excite only selected ions, or shuttling operations to transport ions to the detection zone.

Coupling

Since on-chip light generation is not a near-term goal of ion trap chips, efficient coupling of light into the chip remains an issue. Subsequently, the light must be coupled out of the chip to interact with the ions. For either purpose a diffraction grating structure might be used. An integrated grating consists of alternating low-index (cladding) and high-index (waveguide) material. The precision of microfabrication technologies allows controlling both the grating period and the fill-factor (the percentage of the grating period filled by high-index material). Designing a grating with locally varying period and duty-cycle allows tailoring the free-space beam shape [53]. With this ability, a grating can be used to focus the beam onto the targeted ion position, and also

3.3 Optical integration in the Millenion project

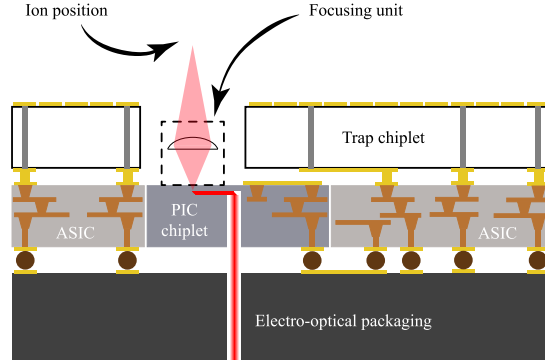


Figure 3.7: This conceptual illustration shows the System-in-Package approach followed in the Millenion project. Using separate chiplets, each with a specific functionality, allows to benefit from multiple technological platforms. The trap chiplet, hosting the electrodes needed for ion trapping, could be bonded to an application specific integrated circuit (ASIC), as well as a photonic integrated circuit (PIC), both mounted on a common interposer. Image credit: Bassem Badawi [72]

to create almost arbitrary intensity profiles, which can be used to minimize optical cross-talk [71].

Apart from grating-based in-coupling, directly gluing an optical fiber to the chip's facet is another approach. Facet coupling completely avoids a free-space laser beam and the associated beam pointing instabilities. Low-loss facet coupling is possible when the shape of the fiber mode is similar to the mode supported by the waveguide. Mode-matching can be achieved by using tapered waveguide structures at the chip's edge which adiabatically change the shape of the mode from the fiber mode to the desired waveguide mode. Alignment of the fibers can be simplified by placing them in V-shaped grooves either directly on-chip or in separate building blocks called V-groove arrays, which allow gluing of multiple fibers simultaneously. The chip layout introduced in the next section is designed to use facet coupling assisted by a pre-assembled V-groove fiber array.

3.3 Optical integration in the Millenion project

While previous approaches to the integration of photonic components into micro-fabricated ion traps have focused on monolithic integration, the Millenion project [73] uses separated chiplets with distinct functionality, bonded to one common interposer, as shown in figure 3.7. Building blocks might include both integrated electrical and integrated photonics components. The photonics chiplet might be used for all the tasks discussed in the previous chapters, including laser cooling, state manipulation and readout, without requiring optical access from outside the vacuum chamber.

The goal of the first project phase is to create an ion trap capable of individually addressing each qubit in a string of 10 ions sharing a single potential well. While integrated photonics can potentially be used for a variety of applications required

3 Optical Integration

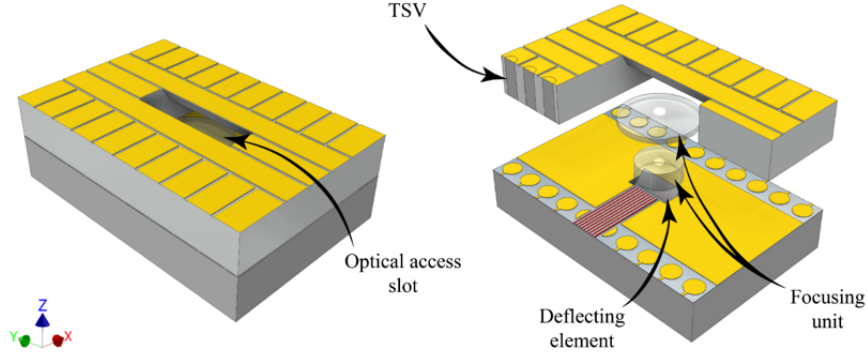


Figure 3.8: Heterogeneous integration combines the strengths of a dedicated trap chiplet made out of borosilicate glass (top), with a photonic integrated circuit utilizing the silicon nitride platform. The trap chip includes a slot through which the laser is focused on the individual ions in the 10 qubit string. Through-substrate vias (TSVs) allow using the lower side of the trap chip and the upper side of the PIC chip as a signal routing layer. Image credit: Bassem Badawi [72]

for operating a trapped ion quantum processor, individual ion addressing is one of the more technologically challenging tasks, due to the need for tightly focused laser beams with minimal alignment tolerances. If the design works satisfactory, a large scale system can be realized consisting of multiple potential wells with registers of 10 ions each. In the ongoing phase, an ion trap is manufactured, with one building block being a trap chiplet made out of borosilicate glass. The second building block, which is the focus of this thesis, is a silicon nitride photonic integrated circuit bonded to the trap chiplet as shown in figure 3.8.

Having the functionality separated allows for more design flexibility and shorter development cycles, but requires the use of bonding technologies which might have sub- μm alignment tolerances. Joining the chiplets will be achieved by thermo-compression bonding of gold pillars. The gold bond additionally creates electric connections between the chiplets, such that either chip can be used for signal routing. By using relatively thick gold pillars as bonding structures, the elasticity of the gold compensates the mismatch in temperature expansion when being cooled to cryogenic temperatures.

Trap chip

The main function of the trap chip is to provide electrodes with a precise shape creating well-defined DC and RF fields required for trapping the charged particles. Having a larger number of DC-electrodes allows to shuttle the ion by controlling the location of the axial potential minimum, and compensate for stray electric fields.

The heterogeneous integration approach described here allows utilizing the strength of different materials for their distinct function. Especially for cryogenic operation it is desirable to have a material with low RF absorption losses, since these losses can heat the trap. The material used in this project is borosilicate glass, with beneficial

RF properties. The trap chiplet features through-substrate vias, which are electrically connected to the lower chiplets. This makes it possible to use the lower side of the trap chip, and the upper side of the chiplets underneath, for signal routing.

An optical access slot enables individual ion addressing through the trap chip. The geometry of the slot must be chosen carefully to maintain high secular frequencies and a deep trapping potential (See also figure 2.6 in the theory section), while also providing a sufficiently large numerical aperture (NA) for the addressing laser beam. As visualized in figure 3.8, the ion addressing unit uses dielectric lenses to focus the laser to the ions. Even though the dielectric properties of the polymer in a cryogenic environment are still subject to further investigation, it can be expected that dielectric exposure contributes significantly to ion heating rates [74]. Choosing the slot as small as possible has the additional benefit of minimizing the area of exposed dielectric.

Photonic integrated circuit layout

The close spacing of the ions makes individually addressing all of them using focusing grating couplers difficult. Since every ion would require its own grating coupler, and the optical access offered by the slot in the trap chiplet is limited, the individual grating couplers would need to be very small, which limits their numerical aperture (NA) and a smaller NA leads to a larger minimal beam size.

The photonic chip design discussed here aims to demonstrate the feasibility of using a single total internal reflection mirror in combination with a 3D printed micro-optical lens stack to individually address each qubit in a string of 10 ions. The layout of the fabricated chip is depicted in figure 3.9. It was manufactured by the company LioniX using a silicon nitride platform, which is well suited for the 729 nm wavelength required for driving optical qubit transitions in $^{40}\text{Ca}^+$. Figure 3.10(a) visualizes the layer stack. The photonic wafers are made out of silicon, with an 8 μm silica layer on top. A 30 nm patterned silicon nitride layer forms the waveguides. Finally, an additional 3 μm silica layer provides the cladding. The photonic circuit features several waveguides, which are to be edge-coupled to optical fibers. In order to achieve maximum coupling efficiency, the mode field diameter of the waveguide at the chip's in-coupling facet is designed to match the optical fiber mode at 4.5 μm , ensuring low coupling losses of ≤ 0.5 dB. Starting from an initial width of 0.5 μm the waveguide widens over a length of 422 μm to a final width of 1.1 μm , which reduces the 4.5 μm fiber mode to the intended mode field diameter of 1.92 μm .

Facet coupling a total of 14 waveguides (10 for ion addressing and 4 as alignment helpers) to optical fibers will be achieved by means of a pre-assembled V-groove array. This is a glass block with precisely manufactured V-grooves in which the individual fibers are placed. Since the relative position of the fibers is fixed, it suffices to align and glue the glass block to the photonics chip, alleviating the need for individual fiber alignment.

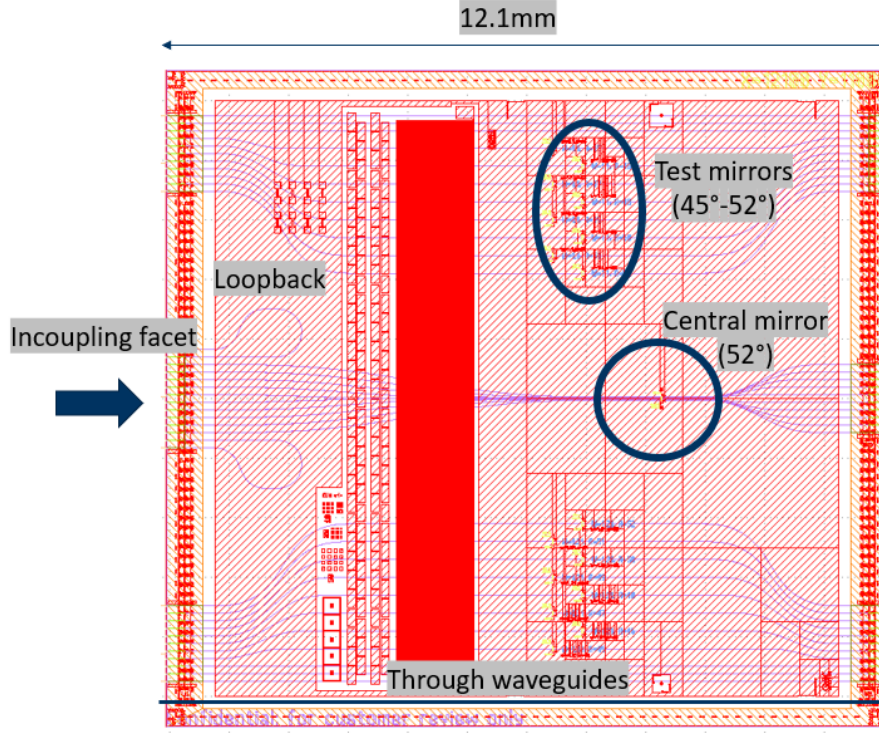


Figure 3.9: This figure shows the schematics of the photonic chip. The patterned gold surface is shown in red; the structures are used to test manufacturing capabilities and to create alignment markers needed for bonding. The chip features several SiN waveguides, which are shown as violet lines. The upper and lower three waveguides are routed straight through the chip. The next 8 waveguides on either side run to a different total internal reflection mirror each, which are cut at angles relative to the chip's surface ranging from 45° to 52° . The central part of the chip is intended for single ion addressing. The 10 central waveguides are out-coupled by means of a single larger mirror, cut at 52° . The purpose of the loops is to ease alignment of a V-groove fiber array.

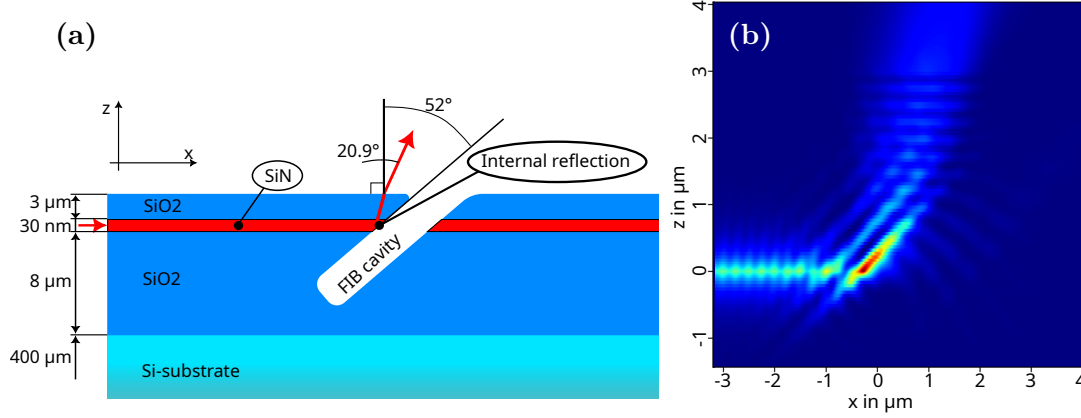


Figure 3.10: The laser is out-coupled by means of total internal reflection, created by a cavity cut into the chip. (a): A schematic cross-section of the photonics chip including the cavity milled using a focused ion beam (FIB). The red layer indicates the silicon nitride waveguides, with the laser propagating from left to right. Note that the out-coupled beam is not perpendicular to the chips surface, partly due to refraction at the chip's surface. (b): A snapshot of a finite-differences time domain (FDTD) simulation of the internal reflection mirror. The color indicates the light intensity. Clearly visible is the evanescent field penetrating into the gap. Image credit: Nicolas Jungwirth

Total internal reflection mirror

Out-coupling the light contained in the waveguide is achieved by a total internal reflection mirror. Total internal reflection occurs on an angled waveguide-air interface² formed by focused-ion-beam milling, as visualized in figure 3.10. A scanning electron microscope image of the cavity is shown in figure 3.11.

Using the effective index of the 1.1 μm wide waveguide as obtained by numerical simulations ($n_{eff} = 1.462$), the critical angle for total internal reflection is found at 43.2°. In order to reach a safe margin, the larger central mirror is milled at 52°. For testing purposes, the chip also features 16 smaller mirrors ranging from 45° to 52° in 1° increments, as detailed in figure 3.9. Note that the out-coupled laser beam is in general not perpendicular to the chip's surface. Using Snell's law of refraction (3.12) the out-coupling angle predicted by the ray-optics model for the 52° mirror is found at 20.9° (See figure 3.10).

Focusing unit

After exiting the total internal reflection mirror, the light is highly divergent. The half-angle of the exiting cone of light was measured at about 15°, which requires additional optical elements to focus the light coming out of one specific waveguide on the respective ion, while minimizing the intensity at the other ions. This project uses a sequence of several micro-sized lenses, subsequently called lens stack, as shown in

²When the device is in operation, it will be a waveguide-vacuum interface.

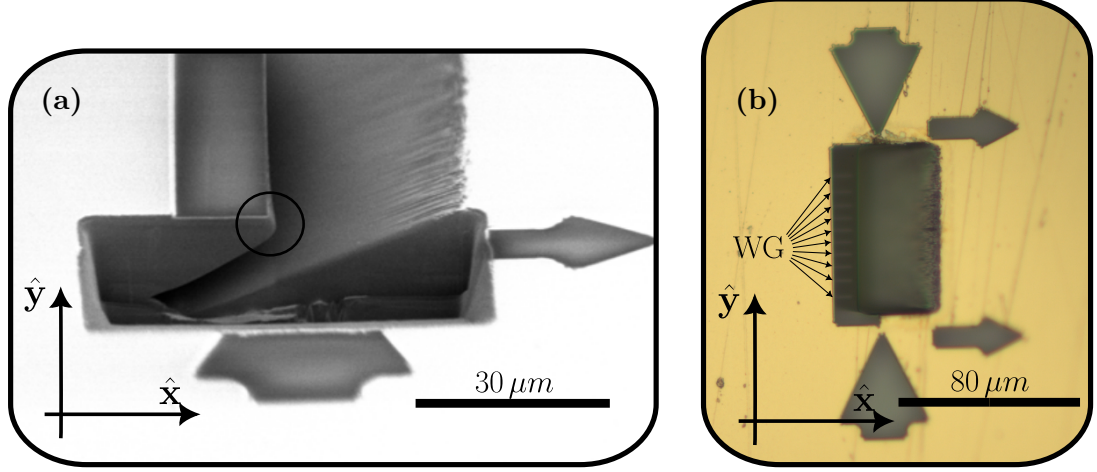


Figure 3.11: Images of the out-coupling element. (a) Scanning electron microscope image of a cavity milled by a focused ion beam, forming a total internal reflection mirror. The light areas are covered in gold, and the waveguides run from left to right, located $3\ \mu\text{m}$ beneath the chip's surface. The shape of the out-coupled beam might be influenced by the rounded edge of the cavity (marked by the black circle). The angle between the reflecting interface and the chip's surface normal is 52° . Image credit: LioniX (b) Top-view microscope image of the same cavity. Faintly visible are the 10 central waveguides (WG). The scratches originate from the polishing procedure.

figure 3.12. The purpose of the lens stack is to create the desired beam shape and position of the focal spot. The light exiting all 10 central waveguides is focused by the same lens stack.

The lenses are manufactured by the company printoptix, using a liquid resin (Ip-Dip 2), which is polymerized in a two-photon-absorption process. The simultaneous absorption of two photons requires a high photon density, typically achieved by focusing a femtosecond laser beam with a high-NA objective into the liquid resin. Since the two photon absorption rate is proportional to the square of the intensity of the laser beam, the volume in which polymerization occurs (voxel) is very small, allowing the fabrication of sub diffraction-limited structures [75]. This process, very much similar to 3D printing, allows creating almost arbitrary shapes. Using a highly aspherical design creates an intentionally elliptic beam spot at the ion position. The smaller axis of the ellipse is aligned with the axis of the ion string, minimizing optical cross-talk, while the larger axis relaxes the required alignment accuracy. The properties of the polymer in a cryogenic environment are still partly unknown. Of particular interest for ion trapping are the dielectric properties, which could contribute to motional heating of the ion string. Additionally, the shrinkage of the polymer when being cooled to cryogenic temperatures is important, since it influences the focal length of the lenses.

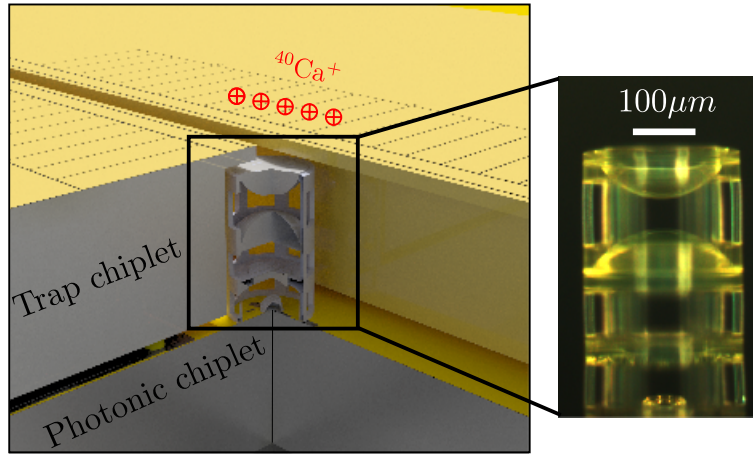


Figure 3.12: Visualization of the bonded trap, consisting of the trap chiplet and the photonics chiplet. The lens stack is printed on top of the photonics chiplet, and sits in a cavity inside the trap chiplet. The purpose of the lenses is to focus the highly divergent out-coupled light onto the ions. Each of the ions in a 10 ion string is individually addressed with light exiting one specific waveguide. All ions in the string share the same lens-stack. The right inset shows a dark-field micrograph of the fabricated lens stack.

4 Properties of the out-coupled laser beam

Minimizing the focal spot at the ion position is crucial for individual ion addressing, since it enables fast qubit operations at low optical power and simultaneously minimizes unwanted excitation of the neighboring ions (optical cross-talk). The smallest beam spot can be achieved if the laser beam matches a Gaussian intensity distribution, in which case the beam is termed diffraction limited [76].

In the first part of this chapter, fundamental properties of a Gaussian laser beam are reviewed. The chapter continues by discussing methods to quantify how well the out-coupled laser beam matches the targeted Gaussian mode. Since a microscope is used to obtain images of the out-coupled laser beam, the chapter concludes by discussing the influence of the microscope's lenses on the beam shape. This is relevant because microscope images tend to be blurred due to the finite resolution of the objective, and small objects can therefore appear artificially enlarged.

4.1 The ideal Gaussian laser beam

The field distribution of the Gaussian laser beam is the fundamental solution to the Helmholtz equation ($\nabla^2 \mathbf{E} + k^2 \mathbf{E} = 0$) under the paraxial approximation, which implies that the propagation angle between the beam and the optical axis (defined as z) is small. A visualization of the electric field of such a Gaussian mode is shown in figure 4.1. The intensity distribution of the Gaussian beam is given by:

$$I(x, y, z) = I_0 \frac{w_{x,0}}{w_x(z)} \frac{w_{y,0}}{w_y(z)} \exp\left(-\frac{2(x-x_0)^2}{w_x(z)^2}\right) \exp\left(-\frac{2(y-y_0)^2}{w_y(z)^2}\right) \quad (4.1)$$

where we introduced the beam waist radius $w_{i,0}$, the beam radius as function of propagation distance $w_i(z)$, and the position of the beam waist i_0 , for $i \in \{x, y\}$. Further, I_0 is a constant related to the maximal field amplitude. In case of an elliptic beam, the equation above assumes that the principle axes of the ellipse are aligned with the x and y axes. As visualized in figure 4.1, the beam radius is given by

$$w_i(z) = w_{i,0} \sqrt{1 + \left(\frac{z - z_{i,0}}{z_{i,R}}\right)^2} \quad \text{for } i \in \{x, y\} \quad (4.2)$$

with $z_{i,0}$ being the position of the smallest beam radius and $z_{i,R}$ is the Rayleigh length. In the case of the Gaussian beam, the Raleigh length is determined by the beam waist

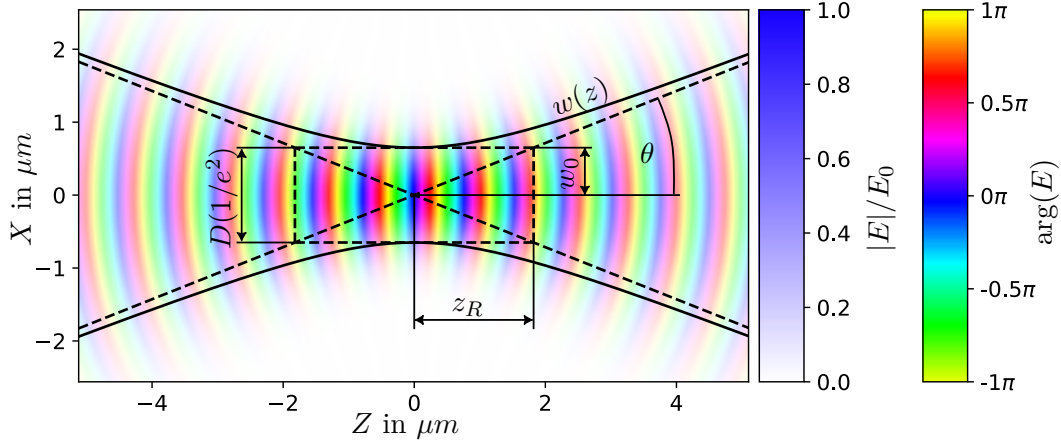


Figure 4.1: Visualizing the (complex) field of an ideal Gaussian beam. The hyperbolic solid black lines indicate the beam radius $\pm w(z)$, w_0 is the beam waist radius, $D(1/e^2) = 2w_0$ is the beam waist diameter, z_R is the Rayleigh length, and θ is the half angle of the far-field divergence cone. The scale is exemplary for $w_0 = 0.65 \mu\text{m}$ and $\lambda = 729 \text{ nm}$, and the maximal field amplitude is normalized to one.

radius $w_{i,0}$:

$$z_{i,R} = n \frac{\pi w_{i,0}^2}{\lambda} = \frac{1}{2} k w_{i,0}^2 \quad \text{for } i \in \{x, y\} \quad (4.3)$$

In the case of a stigmatic beam ($z_{x,0} = z_{y,0}$) with a circular cross-section ($w_{x,0} = w_{y,0}$), the Rayleigh length is the distance from the smallest beam diameter where the area of the beam doubles. The strong dependence of the Rayleigh length on the beam waist radius implies that a tightly focused Gaussian beam with 729nm wavelength and a waist radius of $0.65 \mu\text{m}$ has a Rayleigh length of $1.82 \mu\text{m}$ while the same beam with a larger waist radius of 1 mm has a Rayleigh length of 4.31 m , which is larger than typical laboratory scale free-space propagation distances. In case the beam size does not change significantly during propagation a beam is often called collimated.

Quantifying the size of a laser beam

Since the laser beam does not have a well-defined edge, several conventions exist for specifying the beam diameter. One of the most commonly used conventions for a Gaussian beam is twice the beam waist radius $D(1/e^2)(z) := 2w(z)$. The notation indicates that this diameter is the full width of the beam, where the intensity drops to $1/e^2$ of the maximum intensity at a given position z . The fraction of power contained within the $D(1/e^2)$ beam diameter is approximately 86.47%, independent of z .

Obtaining the Gaussian beam size from beam profiler images is done by employing the following procedure. First the positions x_0, y_0 are approximated by the position of the maximum pixel value and one-dimensional slices are extracted. The data in each

4 Properties of the out-coupled laser beam

slice is fitted with the following equation:

$$I(x) = I_{max} \cdot \exp\left(-\frac{(x - x_0)^2}{2\sigma^2}\right) + c_0 \quad (4.4)$$

where $I(x) = I(x, y = y_0)$ is the slice through the intensity distribution and I_{max}, x_0, σ and c_0 are independent fit parameters. The y direction is treated analogously using the slice $I(y) = I(x = x_0, y)$. The beam diameter is then given by $D_x(1/e^2) = 4\sigma$, and x_0 gives an estimation of the beam center position with sub-pixel accuracy. The offset c_0 was introduced to account for background noise. Comparing the diameter in x and y direction can give a measure for the ellipticity, if the principle axis of the ellipse coincide with the coordinate axes. A more general method would need to estimate the orientation of the ellipse, before extracting the one dimensional profiles along the principle axis, but was not applied.

It is important to note that this method for measuring the beam size is only meaningful if the beam is well-described by a Gaussian. Especially if the beam contains side lobes caused by aberrations or clipping of the beam, the fitting method can underestimate the beam size drastically by only fitting the most prominent peak. A measure applicable to any beam shape is the $D4\sigma$ diameter. The σ indicates that this method uses the second moment width of the intensity distribution $I(x, y)$:

$$D_x 4\sigma = 4 \sqrt{\frac{\iint I(x, y) (x - \bar{x})^2 dx dy}{\iint I(x, y) dx dy}} \quad (4.5)$$

Where $\bar{x}$ is the centroid position:

$$\bar{x} = \frac{\iint I(x, y) x dx dy}{\iint I(x, y) dx dy} \quad (4.6)$$

The y direction is again treated analogously. Since the centroid position of any laser beam follows a straight line (assuming propagation inside a homogenous material) [77], the centroid position as a function of propagation distance can be used to extract the direction of propagation. Note that for an ideal Gaussian beam, the $D(1/e^2)$ and $D4\sigma$ diameter are equivalent.

The generality of the $D4\sigma$ beam diameter is reflected by its use as definition of the laser beam size in the ISO 11146 norm [78]. The main difficulty in evaluating the integrals for the $D4\sigma$ method is the sensitivity to non-zero pixel values far away from the beam center; i.e. background noise. This is especially prominent when the laser beam is small compared to the sensor area of the detector. For that reason, the ISO norm specifies an approach which iteratively narrows the region of interest over which the integrals are evaluated and includes sophisticated background subtraction. Data evaluation in this project employed a $D4\sigma$ method which is not ISO compatible, and relied on the background correction applied by the software included with the beam profiler. In order to remove stray pixel values, a 3x3 median smoothing kernel was applied to the images, which makes the $D4\sigma$ method more reliable. In hindsight, instead of manually implementing the $D4\sigma$ method, existing software packages such as the python package `laserbeamsize` [79] should have been used.

Beam divergence and M^2

As shown in figure 4.1, the far-field divergence angle of the ideal Gaussian beam is given by:

$$\tan \theta = \frac{w_0}{z_R} = \frac{2}{kw_0} = \frac{\lambda}{n\pi w_0} \quad (4.7)$$

One defining property of a Gaussian beam is that it diverges less than any other beam shape for a given beam waist diameter, or equivalently, it can be focused to a smaller spot for a given divergence angle. This property can be exploited to quantify how well a "real" laser beam matches the fundamental Gaussian beam, by measuring its divergence and comparing it to the divergence of a Gaussian beam with the same beam waist. This is especially important because a laser beam can be similar in shape to a Gaussian profile, but in reality consists exclusively of higher order modes, which becomes apparent only through its large divergence [77].

Estimating the divergence of a laser beam can be achieved by measuring the beam diameter at different axial positions and then fitting the obtained values to the beam waist equation:

$$w(z) = w_0 \sqrt{1 + \left(\frac{z - z_0}{z_R} \right)^2} \quad (4.8)$$

using the beam waist w_0 , Rayleigh length z_R and position of the waist z_0 as independent fit parameters. Recall that the Rayleigh length z_R of a Gaussian beam is already determined by the beam waist, but this does not hold for arbitrary beam shapes. Interestingly, as long as the second moment width is used to describe the beam diameter, the spatial evolution of the beam diameter as described by equation (4.8) holds true for any beam shape [77].

The fit parameters can be compared to the ideal Gaussian by defining the M^2 parameter:

$$M^2 := \frac{\pi w_0^2 n}{\lambda} / z_R \geq 1 \quad (4.9)$$

The beam propagation factor M^2 describes how much more the beam diverges when compared to a Gaussian with the same beam waist radius: $\tan \theta^{Real} = M^2 \tan \theta^{Gauss}$. Alternatively, it can be used to calculate how much larger the waist radius is compared to an ideal beam with the same divergence: $w_0^{Real} = M^2 w_0^{Gauss}$.

In order to achieve accurate values for M^2 , it is crucial to measure at multiple positions both close to the waist and at multiple positions at least a Rayleigh length away from the waist, with the recommended procedure specified in the ISO 11146 norm [78].

4.2 Imaging a tightly focused laser beam

Before the out-coupled laser beam arrives at the detector, it goes through the optical path of a microscope, which consists of an objective and a tube lens. Since the resolution of a microscope is fundamentally limited by diffraction, it might be expected that

4 Properties of the out-coupled laser beam

the image of the laser beam formed on the detector is artificially enlarged by blurring. In this section, we will review some fundamental concepts of microscopy, and discuss their implications on imaging a small laser beam spot. Even a perfect objective, free of aberrations and other image distortions, introduces some blurring due to its finite numerical aperture (NA). The NA is related to the cone of light accepted by the microscope objective via $NA = n \sin \theta$, where n is the refractive index of the medium surrounding the objective (Air in many cases), and θ is the half-angle of the acceptance cone.

Note that the magnification M of a microscope does not influence the resolution, and it is determined by the ratio of the focal length of the tube lens f_{tube} to the focal length of the objective f_{obj} : $M = f_{tube}/f_{obj}$. As a consequence the magnification of a microscope might differ from the objective's nominal magnification, if the objective is combined with a different tube length with improper focal length. The magnification can be chosen such that the size of the PSF matches the detector's pixel size, thus maximizing the field of view without losing resolution.

A microscope essentially transfers light from an object (object plane) to the camera (image plane). Since the shape of the object in the image plane is invariant to displacement in the object plane, and the size of the image scales linearly with the size of the object, the action of a microscope can be described as a linear space-invariant system [44]. Such a system is fully described by the impulse response function h , i.e. the field distribution in the image plane (F_{im}) is given by a convolution of the field in the object plane (F_{obj}) with the impulse response h : $F_{im} = F_{obj} * h$.

In the context of microscopy, the impulse response is given by the image produced on the camera by an object with no spatial extent. The response of such a point-like object has finite width, and is called a point spread function (PSF). In advanced microscopy setups, such as the ones used in biological imaging, precise knowledge of the PSF is crucial, since it allows for de-blurring of the image by means of digital post-processing (de-convolution algorithms). An accurate model can be found experimentally by imaging a point-like object, such as a single fluorescing molecule. Alternatively, under the assumption of a well-corrected objective with a circular aperture (pupil), the PSF is already fully described by the numerical aperture.

Especially when considering the influence of a microscope on a laser beam, it is important to distinguish between coherent and incoherent illumination. Illumination is called coherent, when the relative optical phase between two points in the object space remains fixed, which requires both spatial and temporal coherence of the illuminating light source. Both conditions are clearly fulfilled by our case of a monochromatic laser beam. The fundamental difference between the two cases is that incoherent light is additive in intensity, while coherent light is additive in field amplitude. The consequence for microscopy is that the field in the image plane E_{im} formed using coherent illumination is described by a convolution of the electric field in the object plane E_{obj} with the coherent point spread function h_{coh} : $E_{im} = E_{obj} * h_{coh}$. In contrast, incoherent illumination leads to the intensity in the image plane I_{im} being given by a convolution of the intensity in the object plane I_{obj} with the incoherent PSF h_{inc} : $I_{im} = I_{obj} * h_{inc}$. Note that either expression neglects the vectorial character of the

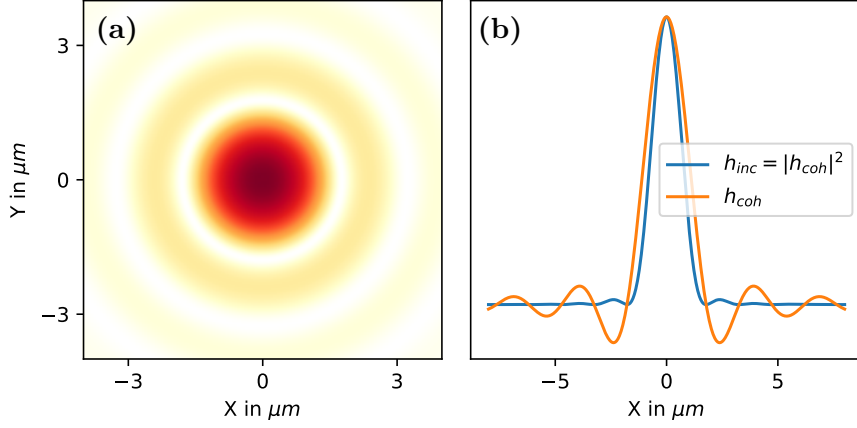


Figure 4.2: (a) Schematic image of an incoherent point spread function (Called Airy pattern), where the color has been exaggerated of better visibility of the fringes. (b) Cross-section of the incoherent and coherent point-spread functions, normalized to the peak value. The Scale is exemplary for $\lambda = 729 \text{ nm}$ and $NA = 0.25$.

electric field, which is valid for sufficiently low NA.¹

Next we will discuss how to obtain the PSF for an objective with a given numerical aperture. We shall distinguish between the front focal plane (the object plane), and the rear focal plane. Focal plane is the term for a plane parallel to the lens going through the focal spot. Be reminded that the field in the rear focal plane of an (infinitely large) lens can be described by a Fourier transform of the field in the front focal plane [76]:

$$\tilde{E}(k_x, k_y) = \frac{1}{2\pi} \iint E(x, y) \exp(-i(k_x x + k_y y)) \quad (4.10)$$

$$= \mathcal{F}[E](k_x, k_y) \quad (4.11)$$

where we defined z as the optical axis and $k_{x,y}$ are the transversal wave-numbers. The effect of a finite sized aperture is that it excludes high spatial frequencies from being transmitted. Consequently, a microscope objective can be seen as a low-pass filter acting on the spatial frequencies [76]. The (normalized) amplitude transmission function of a circular pupil is given by:

$$\tilde{h}_{coh}(k_x, k_y) = \frac{1}{\pi k_{max}^2} \begin{cases} 1 & k_x^2 + k_y^2 \leq k_{max}^2 \\ 0 & \text{else} \end{cases} \quad (4.12)$$

The maximum value for the radial spatial frequency k_{max} is determined by the acceptance cone of the objective: $k_{max} = k_0 n \sin \theta = k_0 NA$ with $k_0 = 2\pi/\lambda$ being the wave-number in vacuum. The chosen notation indicates that the amplitude transmission function is the Fourier transform of the coherent PSF, which can be intuitively understood by seeing the action of the tube lens as a second Fourier transform:

$$h_{coh} = \mathcal{F}^{-1}[\tilde{h}_{coh}] \quad (4.13)$$

¹Especially for high-NA setups, full vectorial models of the PSF are used.

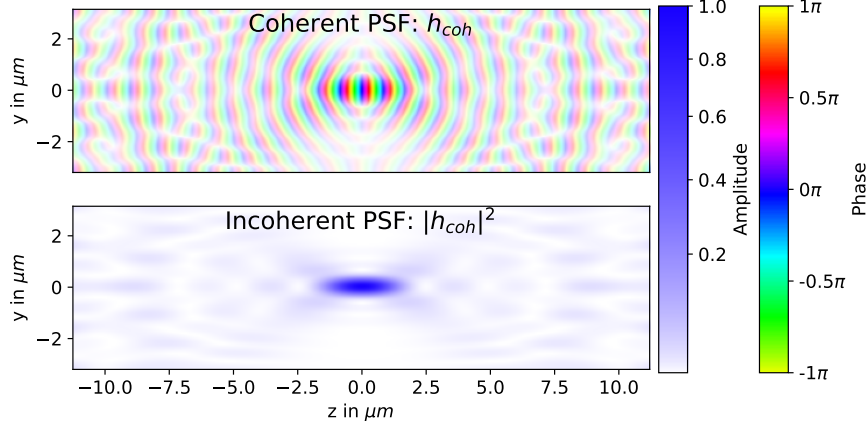


Figure 4.3: Sections through the 3D point-spread-function for coherent (top) and incoherent (bottom) illumination. The scale is exemplary for $NA = 0.7$ and $\lambda = 729$ nm. The axial (z) size of the PSF determines the depth of focus. Both amplitude and phase are encoded in color: Hue indicates phase, while amplitude is encoded in saturation.

which can be evaluated to:

$$h_{coh}(x,y) = \frac{J_1(r')}{\pi r'} \quad \text{with} \quad r' = k_0 NA \sqrt{x^2 + y^2} \quad (4.14)$$

using the first Bessel function of first kind J_1 . Note that by choosing the same units in the image plane as in the object plane, we intrinsically assumed unity system magnification.

Considering incoherent illumination, it can be shown that the optical (intensity) transfer function is given by the auto-correlation function of the coherent amplitude transfer function [44]. It follows directly from applying the convolution theorem that the incoherent point spread function is then simply the absolute square of the coherent PSF: $h_{inc} = |h_{coh}|^2$. Both functions are shown in figure 4.2. We find that the coherent PSF has a wider central lobe and more pronounced fringes. For most cases relevant to microscopy this implies that coherent illumination results in worse resolution, although this is not generally true. The phase of the coherent PSF can interfere with the field in the object plane which can result in artificial sharpening of the image and therefore even *increase* the resolution compared to incoherent illumination in some cases [76]. In particular, if the object field contains no spatial frequencies which are being cut off by the pupil, it remains entirely unaffected, while the incoherent model would lead to blurring, as will be shown in figure 4.4.

Depth of focus and the three-dimensional point-spread-function

So far we have discussed the transfer of a light distribution from the object plane to the image plane. Additionally, objects slightly out-of-focus are visible on the image. The range in which objects are visible is called depth of focus. Similar to the lateral resolution, the focal depth is also determined by the NA of the objective. The

longitudinal resolution can be understood by considering the three-dimensional light distribution around the image plane created by a point-like object in the object plane. Mathematically, this effect is described by a three-dimensional point-spread-function. The 3D-PSF can again be derived by a Fourier transform of the transfer function. As dictated by the Helmholtz equation ($\nabla^2 \mathbf{E} + k^2 \mathbf{E} = 0$), the components of a wave-vector in free space must satisfy:

$$-(k_x^2 + k_y^2 + k_z^2) + k^2 = 0 \quad (4.15)$$

where k is the wave-number inside the propagation medium $k = nk_0$. Therefore, in the case of coherent illumination, the amplitude transfer function is given by a generalized pupil function [80], which restricts the transmitted values of the longitudinal wave-number k_z :

$$\tilde{h}_{coh}^{(3D)}(k_x, k_y, k_z) = \delta(k_z - \sqrt{k^2 - k_x^2 - k_y^2}) \tilde{h}_{coh}(k_x, k_y) \quad (4.16)$$

In the equation above, we used the 2D amplitude transfer function $\tilde{h}_{coh}$ as previously defined in equation (4.12) and, δ is the well-known Dirac distribution.

Figure 4.3 shows numerical computations of the resulting three-dimensional point-spread-functions $h_{coh}^{3D} = \mathcal{F}^{-1}[\tilde{h}_{coh}^{3D}]$ and $h_{inc}^{3D} = |h_{coh}^{3D}|^2$. Similar as before, in most applications, incoherent illumination results in a better image quality due to the smaller focal depth than coherent illumination. In contrast, a laser beam naturally fulfills the Helmholtz equation and is therefore not at all influenced by the longitudinal resolution.

This conclusion is numerically validated by computing the three-dimensional electric field distribution of an ideal Gaussian laser beam, and performing a convolution operation with the 3D point-spread-function, as shown in figure 4.4. Indeed, convolution with the coherent PSF does not have a strong effect on the beam shape. As a comparison, the not physically relevant case of incoherent illumination of the same beam is shown, which significantly broadens and elongates the beam. It is interesting to see how the phase structure of the larger coherent convolution kernel interferes with the phase of the laser beam leaving the image unaffected. The implication is that as long as a laser beam is not being clipped by the objective, the numerical aperture does not lead to blurring of the image.

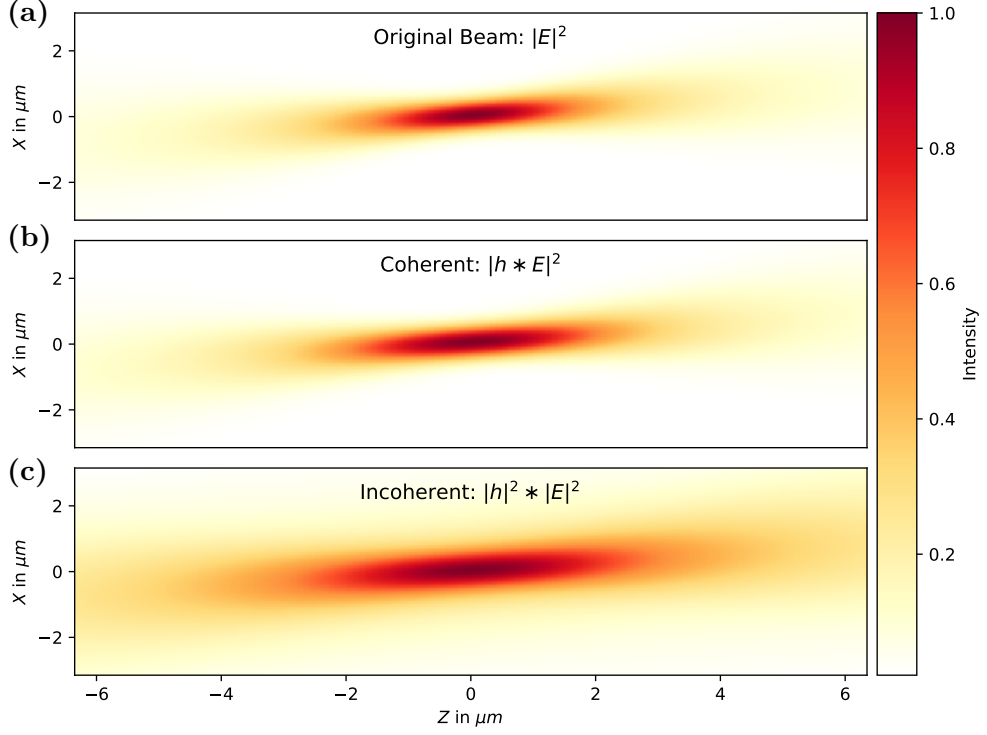


Figure 4.4: This figure shows the influence of a coherent and incoherent convolution of a three-dimensional point-spread-function h corresponding to a $NA = 0.7$ objective, with an ideal Gaussian laser beam. **(a)** Cross-section through the intensity profile of the beam. The laser beam waist diameter ($1.3\mu\text{m}$) and the angle to the z -Axis (20.9°) are chosen similar to the beam out-coupled by a total internal reflection mirror of the photonic circuit. **(b)** Numerical simulation of the microscope image of the same beam, found by convolution with the 3D coherent point-spread-function. The coherent convolution preserves the shape of the laser beam. **(c)** Numerical simulation of how an object with the same size and amplitude as the laser beam would look like when illuminated with incoherent light. In all cases, the image plane would be parallel to the $x - y$ plane.

5 Characterization of the photonic chip

The laboratory work conducted during this thesis consisted of designing and setting up a measurement apparatus. The setup was then used to conduct measurements on the optical properties of the photonic integrated circuit introduced in section 3.3. The performance of the fabricated photonic circuit was characterized by quantifying the optical losses and investigating the size and divergence of the laser beam out-coupled by the total internal reflection mirror. The properties of the out-coupled light fields were analyzed both with and without the micro-optical lens stack. This chapter aims to present relevant results and practical experiences obtained with the optics chip, and their implications for future ion trap experiments. After introducing the measurement setup, it discussed the losses and coupling efficiency of the photonic elements present on the chip before moving on the diameter, shape and divergence of the out-coupled laser beam. The next topic is the influence of the focusing unit on the beam shape. Finally, the unwanted excitation of adjacent waveguides is quantified and compared to simulations. The photonic structures were exclusively excited with a laser wavelength of 729 nm, corresponding to the optical qubit transition in $^{40}\text{Ca}^+$.

5.1 Measurement Setup

The photonic chip was characterized using macroscopic optics to edge-couple a laser into the chip and a microscope to image the out-coupled laser beam. The waveguides are excited with a free-space laser beam which is focused to the facet of the chip, instead of placing a bare fiber close to the chip. A computer aided design (CAD) model of the complete apparatus is shown in figure 5.1 and figure 5.2 provides a schematic overview of the optical elements. The axis definitions used throughout the project are shown in figure 5.3(b).

In order to achieve adequate in-coupling efficiency, precise alignment of the waveguide to the exciting laser beam is required. This is achieved by placing the chip on a six axis nano-positioning stage (Thorlabs NanoMax MAX683/M), which forms the heart of the setup. Each axis can be moved by a stepper motor and by a piezo actuator. The stepper motors provide alignment over a travel range of 4 mm (6° for the angular axis), with an accuracy of roughly one micro meter, while the piezo actuator offers movement in the single nano meter range, but only over 30 μm travel range. The NanoMax features a common point of rotation for all angular axes.

The photonic chip is placed on a custom-made aluminum mount, such that the in-coupling end of the central waveguides coincides with the pivot point of the stage. The chip is placed against an edge, for some degree of reproducibility when swapping chips. The chip-mount also allows inserting a mirror behind the chip as shown in

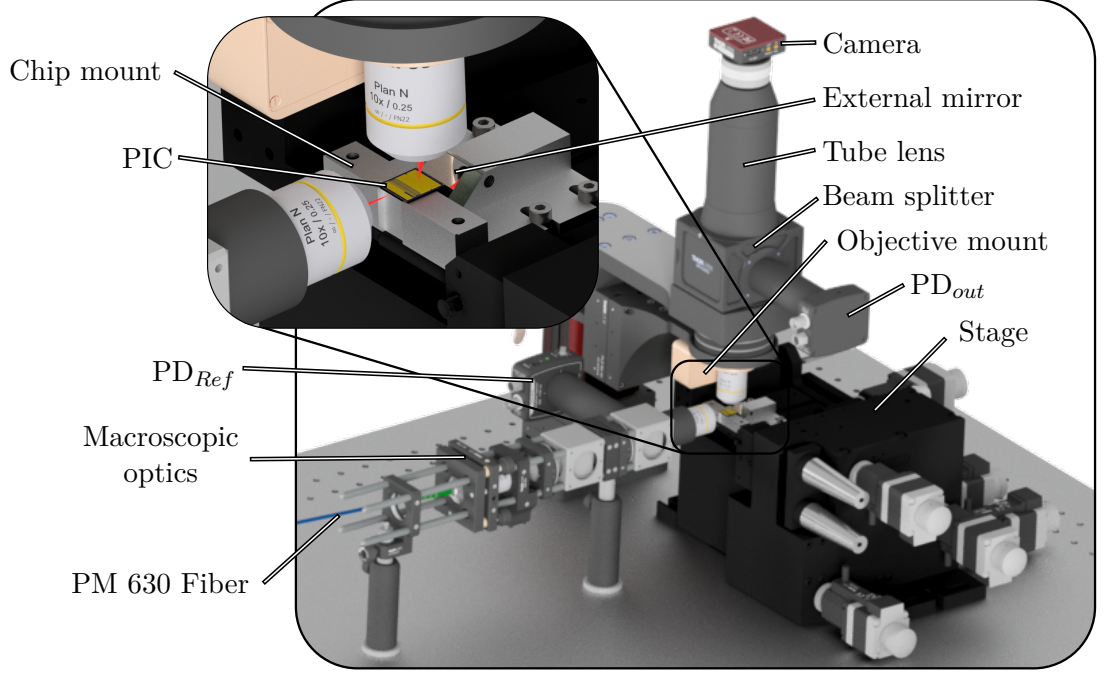


Figure 5.1: Computer aided design (CAD) renderings of the experimental setup. The six axis nanopositioning stage onto which the chip is mounted is shown in black (The protruding elements are the stepper motors). The upper half of the image shows the microscope. The cube located above the microscope objective incorporates a 50:50 beam splitting plate. The transmitted light goes through the tube lens and is detected on a camera (top), while the reflected light is directed on a photodiode (PD_{out}) allowing to measure the optical power in the out-coupled laser beam. The microscope is mounted on a two axis (x - y) translation stage, with a second stage moving the objective in the vertical (z) direction. An additional Piezo mount (shown in pink) provides enhanced positioning accuracy of the objective's z -Position. The inset shows a close-up of the photonic integrated circuit (PIC) mounted on the custom-made chip mount, with the red cones indicating the in-coupled and out-coupled laser beams. An external mirror included in the chip mount allows examining the laser out-coupled horizontally at the rear chip facet. Schematics of the macroscopic optics and the optical elements of the microscope are shown in figure 5.2.

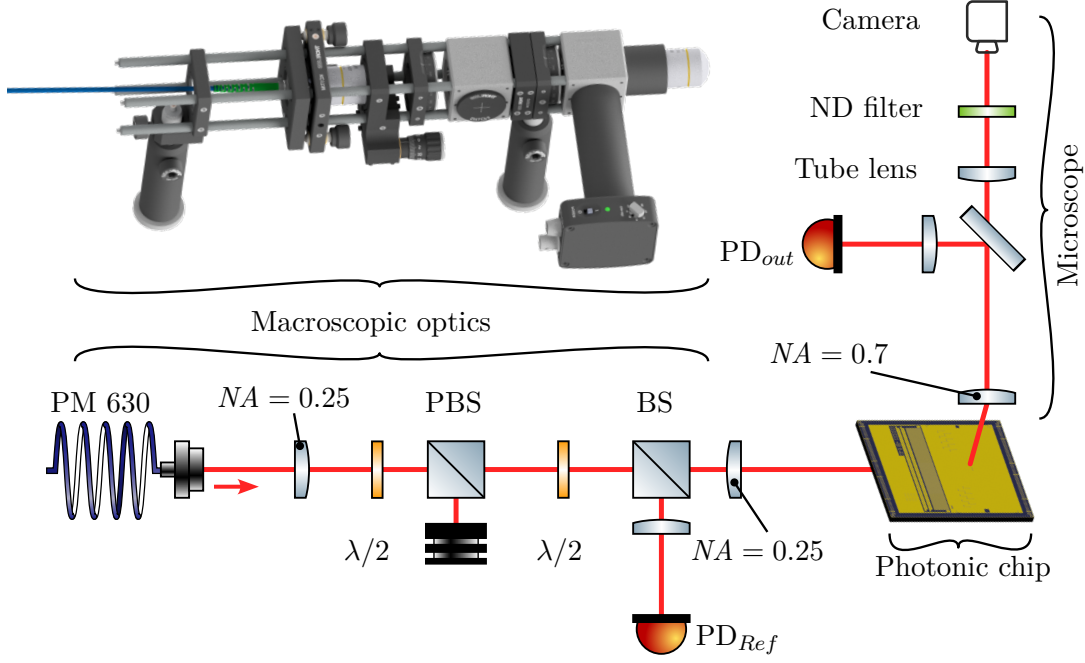


Figure 5.2: Schematics of the optical setup. The polarization maintaining fiber (PM 630) output (left) is collimated by means of a microscope objective ($NA = 0.25$), and is later focused using the same objective, effectively projecting a 1:1 image of the fiber facet on the chip's incoupling facet. The inset shows a CAD rendering of the cage system containing the macroscopic optics. In the collimated beam path, the first $\lambda/2$ wave-plate is used to regulate the power transmitted through the polarizing beam splitter (PBS) and the second $\lambda/2$ controls the polarization of the laser beam. A non-polarizing beam splitter (BS) is used to divert some light onto a photodiode (PD_{Ref}), giving a power reference. The right side shows the microscope used to detect the light out-coupled by the total internal reflection mirror located on the photonic chip. A beam-splitting plate placed in the collimated beam path of the microscope allows to simultaneously create a camera image and measure the out-coupled power (PD_{out}). The focusing lenses in front of the photodiodes are used to ensure that all the light is incident on the active area of the detectors.

5 Characterization of the photonic chip

the inset in figure 5.1. This external mirror is used for re-directing the light coupled out horizontally at the rear facet into the vertical direction. This is necessary for the waveguides routed through the chip without integrated out-coupling structures, which is used for measuring the mode field diameter at the chip's edge.

The waveguides are excited by a free-space laser beam, guided by regular (macroscopic) optical elements mounted in a cage system. An illustration and description of the optical setup can be found in figure 5.2. The light source used for this project is a 729 nm seed laser of a tapered amplifier (Toptica TA100). Using regular optics offers several advantages over positioning a fiber close to the chip's facet:

- It eliminates the risk of mechanical contact between the fiber and the chip, which could displace the chip. Therefore, the chip can be placed on the mount without requiring any fixation.
- Additional optical elements, such as polarization-controlling elements can be inserted directly into the beam path.
- A beam splitter can be easily inserted into the beam path, which allows diverting some light onto a detector, giving a live power reference.

The out-coupled laser beam is observed under a microscope (Thorlabs Cerna Mini SFM2). As described in section 3.3, the laser out-coupled by the total internal reflection mirror is generally not perpendicular to the chip's surface. Therefore, there is an angle between the optical axis of the microscope and the out-coupled laser beam. To ensure that all the power contained in the beam is collected by the microscope objective an objective with a sufficiently large acceptance cone, i.e. a large numerical aperture, must be chosen, as was painfully found out...

Measuring properties of the laser beam such as its far field divergence or the out-coupling angle requires taking images of the beam both close to the waist, and at least a Rayleigh length away from the waist. Taking images at different positions was done by controlling the vertical position of the microscope objective. The small Rayleigh length (In the order of $4\text{ }\mu\text{m}$) of the tiny out-coupled laser beam requires sub- μm positioning accuracy of the objective. This is achieved by a Piezo actuated objective mount (Thorlabs PFM450E). The slices can then be used to extract the full three-dimensional intensity profile of the laser beam.

Acquiring images of the laser beam was mainly done with a beam profiler (Femto Easy Beam Beam Pro 6.3+) which offers a small pixel size, but has the disadvantage that the structures on the chip's surface are not visible. The microscope can alternatively be equipped with a regular RGB camera (Thorlabs CS165CU1/M), which allows taking images of the chip's surface. This is especially useful during in-coupling since the camera image shows whether the laser beam is close to the intended waveguide. Figure 5.3(a) shows an image of the facet during in-coupling, and figure 5.3(c) shows the out-coupled laser beam.

The measurement setup includes photodiodes (Thorlabs PDA36A2) to simultaneously measure the power of both the excitation beam and the out-coupled laser. This

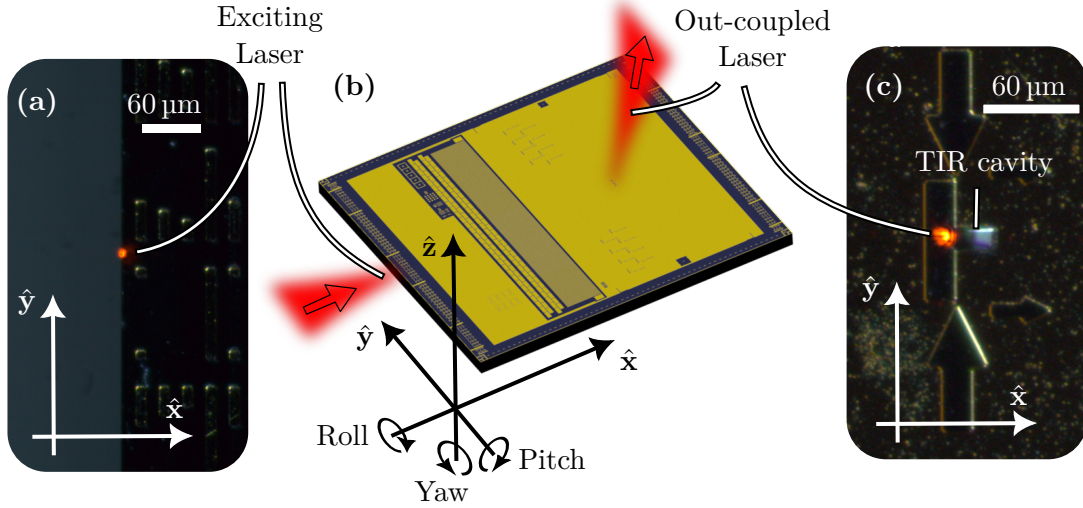


Figure 5.3: This image visualizes how a free-space laser beam is coupled in and out of the photonic chip. (a): Typical image of the front facet during in-coupling. The patterned gold can be used as a way mark when aligning the targeted waveguide to the focal point of the laser source. (b): An illustration of the photonic chip, including the in- and out-coupled laser beam, to indicate the axis definitions used throughout this project. The ion string would be oriented parallel to the $\hat{y}$ -Axis. (c): An exemplary image of a test mirror out-coupling a laser beam. The light blue area is the cavity forming the total internal reflection (TIR) mirror. The arrows in the patterned gold will be used as alignment markers when bonding the photonic chip to the trap chip. (a) and (c) were acquired with the RGB camera, using an objective with 10x magnification.

is done by installing beam splitters in the collimated beam path of the microscope and of the cage system. The light reflected by the beam-splitters is then focused on the active area of the photodiodes as shown in figure 5.2. Careful calibration of the photodiodes is required to get an accurate measure of the optical power in either beam. The photodiode giving the power reference (PD_{Ref}) was calibrated by measuring the optical power in front of the chip with a power-meter (Thorlabs PM400) as a function of photodiode voltage. The photodiode for measuring the power in the out-coupled beam (PD_{out}) was then calibrated by re-directing the beam exiting the cage system with a mirror into the vertical direction and collecting the light using the microscope. Measuring the voltage of PD_{out} as a function of the voltage of PD_{Ref} then gives the desired calibration value. Note that the splitting ratio of the non-polarizing beam splitter is influenced by the polarization of the laser beam, which means that the calibration values are only valid for one particular polarization.

All mechanical stages, as well as the camera and beam profiler can be controlled with their respective vendor-supplied application running on a PC. The analog output voltages of the photodiodes are digitalized by using a (National Instruments USB-6001) analog-digital converter, which has its own software provided by National Instruments. Each of the vendor-supplied applications provides some form of an application programming interface (API), which allowed to create a common python interface to communicate with the devices [81]. The python package uses a central configuration file where the default position of the stages as well as the calibration of the photodiodes and other default settings are specified. Creating programmatic control was mainly motivated by the difficulty of manually finding the optimal chip position in each of the six axis simultaneously. The optimal chip position is the one which maximizes the total efficiency, i.e. the fraction of out-coupled laser power to the optical power in the excitation beam. The python interface opened up the possibility to employ algorithms, capable of automatically finding the optimal position (See also section 5.3 for details on the optimization algorithm used). The software also proved useful for automated acquisition of many beam-profiler images as a function of objective position. An important part of the software is the creation of log files, which allow linking the acquired images (and measured optical powers) to the respective stage positions, which greatly improves data interoperability.

5.2 Chip polishing

After fabrication, individual chips are cut out of a wafer in a process called dicing. The photonic chips discussed in this thesis are diced with a saw, which does not produce a clean facet. The ragged facet is not suitable for reliably coupling the focused laser beam into the waveguide, and therefore requires polishing. An example of a die (individual chip) after sawing, compared to a chip after polishing, is shown in figure 5.4. In some cases a fraction of the light could be coupled into the non-polished chips, as apparent from the light exiting the total internal reflection mirrors, which amounted to between 0.1 % and 11 % of the power in the exciting laser beam. In about a third of the cases,

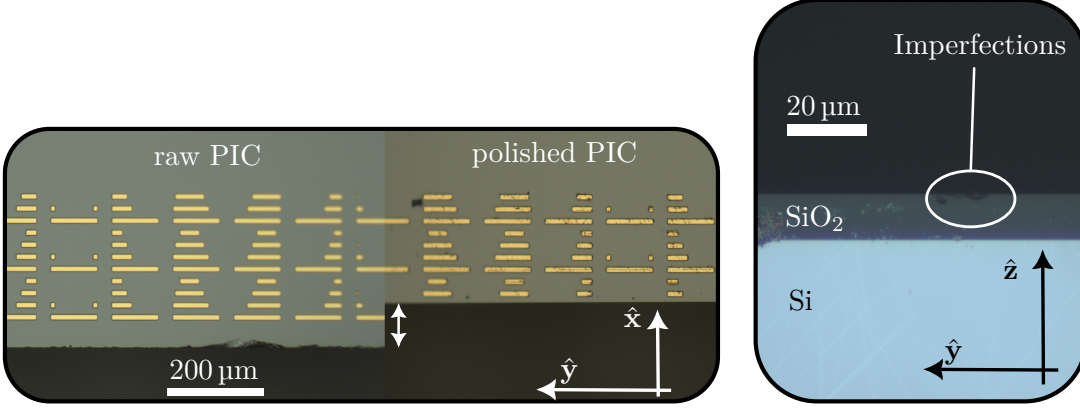


Figure 5.4: (Left): Comparison of a photonic chip before and after polishing. The arrow indicates the amount of material removed. (Right): The in-coupling facet of the polished chip. Some imperfections remain even after polishing, potentially reducing the yield.

no out-coupled light could be observed at all. On the contrary, on the polished chips, some out-coupled light could be observed on every single waveguide.

As demonstrated by a group at the ETH Zürich [82], it is possible to polish photonic chips by hand and achieve a high in-coupling efficiency. We made several attempts at polishing the photonic circuits by hand. While manual polishing reduced the roughness by orders of magnitude (Compare the raw chip in figure 5.4 to the polished chips in figure 5.5), we did not get satisfactory results, as the amount of out-coupled light varied strongly between different waveguides on the same chip. This was judged from the intensity of the out-coupled laser beam on the camera images (No quantitative result is available). The main difficulty when polishing lies in preventing small parts of the chip's edge from chipping off, as visible in figure 5.5. The waveguides are located only $3\text{ }\mu\text{m}$ below the chip's edge, which makes them especially susceptible to this kind of damage. Manual polishing was attempted by using another custom-made chip-holder. The holder features a rubber sealing ring around the out-coupling mirrors, which is intended to prevent residues from entering the cavity forming the total internal reflection mirror. Regular Thorlabs fiber polishing paper placed on a rubber mat was used, starting with a grit size of $6\text{ }\mu\text{m}$ ($30\text{ }\mu\text{m}$ is too coarse) and gradually reducing the grit size to $1\text{ }\mu\text{m}$. The finishing paper ($0.01\text{ }\mu\text{m}$ grit) was not applied, since even the $1\text{ }\mu\text{m}$ grit paper introduced chipping to the front facet which we could not get rid of, as apparent from figure 5.5. As a lubricant, both deionized water and isopropanol were used with similar results. To prevent the chipping, we tried to put wax on the edge, intended to provide a support matrix, but this did not help. The ETH group uses a sacrificial piece of silicon glued with wax on top of the chip to provide the required support for the chip's edge when polishing by hand. We did not follow this approach for fear that the wax would fill up the out-coupling cavity.

Finally, the polishing was done by an external company (Helia photonics), employing a specialized polishing machine (made by the company Krelltech). Figure 5.4 shows

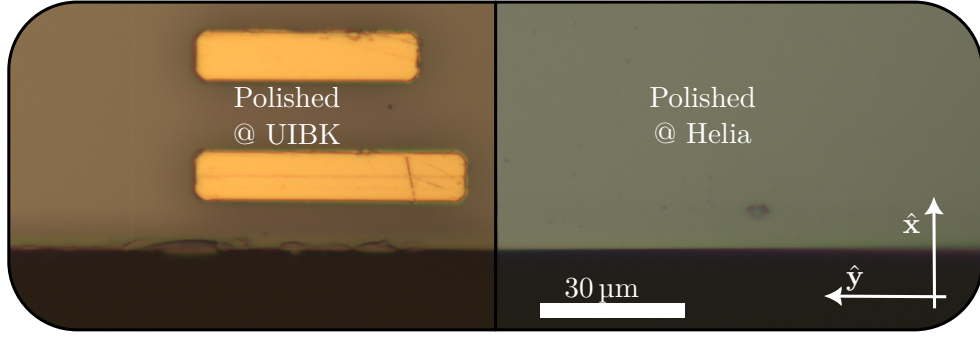


Figure 5.5: Close-up of the in-coupling facet, to compare the best result from polishing by hand (left) with a chip polished by Helia Photonics (right).

a comparison between a raw chip with no polishing, and a chip polished by Helia and figure 5.5 compares our own best effort polishing to the chip received from Helia. The few remaining imperfections are only relevant when they happen to lie exactly at the location of a waveguide. We are certain that this was the case for one out of approximately 50 waveguides tested (see figure 5.6(a)), but it could have also influenced the in-coupling efficiency of the other waveguides. It was found that polishing introduces scratches in the patterned gold intended for signal routing, as shown in figure 5.6(b). To protect the gold coating in the next polishing run, the surface of the chips was spin-coated with 1 ml of a protective resin (AZ P4K-AP). The resin is intended to be easily removable with a solvent after polishing.

5.3 Optical losses

An important characteristic of the addressing unit is the percentage of light delivered to the targeted position. Optimizing the efficiency is important to achieve fast qubit gate operations at low optical input power. The intensity at the ion position is limited by the power threshold of the photonic structures. Especially in the case of high optical losses, damage due to power dissipation can therefore limit the achievable speed of qubit gates.

There are several loss mechanisms present on the photonic circuit. On the chip design discussed here, we can identify in-coupling losses at the front facet, propagation losses of the waveguide, transmission and imperfect out-coupling at the total internal reflection mirror and finally absorption and scattering caused by micro-optical focusing unit. While we were not able to quantify each contribution independently, the apparatus allows measuring the total efficiency. We define the total efficiency as the optical power collected by the microscope objective divided by the power of the exciting laser beam. Comparing the losses of the waveguides with a total internal reflection mirror to the waveguides routed through the chip without a mirror provides a means for estimating the efficiency of the integrated out-coupling element. Note that the polarization of the exciting beam was held constant during these measurements, but

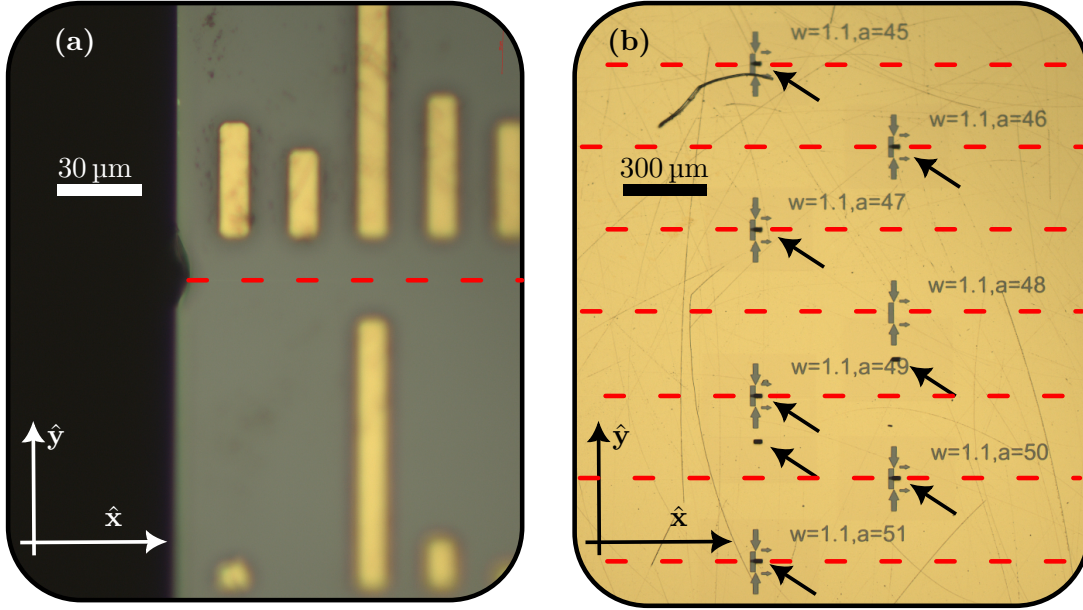


Figure 5.6: Microscope images of chip7, which was polished by Helia. (a): Chipping which occurred at the in-coupling end of the waveguide leading to a 50° test mirror (red dashed line). (b): The gold surface shows scratches after polishing. Shown here is the region of the chip which contains the test mirrors, with each of them out-coupling a single waveguide. The black spots, marked by the arrows, are the cavities cut into chip. Some cavities are unintentionally offset to the waveguides (red dashed lines). The letters are written into the patterned gold and indicate the angle at which the cavity is cut.

the orientation of the (predominantly linear) polarization was not determined. Polarization can be expected to have an influence on both the propagation losses inside the waveguides and the efficiency of the total reflection mirror.

The total efficiency of the waveguides routed through the chip without any mirror was measured at $P_{out}/P_{in} = 72.6(17) \%$, which corresponds to a loss of 1.39(10) dB. The given quantity is the mean of 6 different waveguides and the uncertainty is standard deviation. For these waveguides, the losses consist of in-coupling losses at the front facet, waveguide propagation losses and out-coupling losses at the rear facet. The in-coupling losses can be further divided into losses due to mode-mismatch and Fresnel reflection losses at the air-waveguide interface, while at the out-coupling facet mode-mismatch does not play a role, and only the Fresnel losses have an influence. See also section 3.1 for details on the Fresnel losses. Using the simulated effective index of the waveguide ($n_{eff} = 1.462$), the interface reflection is expected to account for 0.15 dB at both the in-coupling and out-coupling facet. Numerical simulations done by the manufacturer indicate that for a perfectly Gaussian beam with a $4.5 \mu\text{m}$ waist diameter, the mode-mismatch should account for less than 0.5 dB. In-house simulations of the same waveguide geometry result in slightly higher losses of 0.72 dB. Note that the actual shape of the in-coupling beam deviates from the ideal circular Gaussian. Computing the expected overlap of the actual input light field with the waveguide mode could make the simulations more accurate.

The considerations above lead to expected coupling losses between 0.8 dB and 1.02 dB, depending on which simulation result we trust more. Since the waveguides propagate over a length of 1.21 cm, we can attribute the unaccounted losses to a propagation loss between 0.30 dB/cm and 0.49 dB/cm. The magnitude of the propagation loss is comparable to similar platforms; for example Ref. [58] estimated the propagation loss of a silicon nitride waveguide at 633 nm to be 0.3 dB/cm. They used a waveguide cross-section of $0.5 \mu\text{m} \times 100 \text{ nm}$, while our design uses $1.1 \mu\text{m} \times 30 \text{ nm}$.

Measuring the amount of light out-coupled by the total internal reflection mirrors, we find that the total efficiency decreases significantly; Figure 5.7(a) shows a scatter plot of the values obtained for the two chips with a polished in-coupling facet. The outlier in figure 5.7(a) can be attributed directly to chipping at the in-coupling facet, as shown in figure 5.6(a). These measurements were conducted on chips without any focusing elements. Each chip has a number of test mirrors at different angles out-coupling a single waveguide mode, and one larger central mirror at 52° out-coupling ten separate waveguides. While the limited number of test mirrors does not allow for meaningful statistics, a total of 21 waveguides out-coupled by the central mirror were measured, leading to a mean efficiency of 23(4) %. Comparing the result with the through-waveguides, we conclude that a loss of about 5.0(8) dB can be attributed to the central mirror.

Numerical simulations of the total internal reflection mirror are shown in figure 5.7(b). The simulation result does not fit well to the measurements. For one, it does not explain the high measured losses, and secondly the simulation shows a dependence on the mirror angle which is not present in the data. According to the simulations not all the light is reflected by the cavity inside the chip, but some light is transmitted

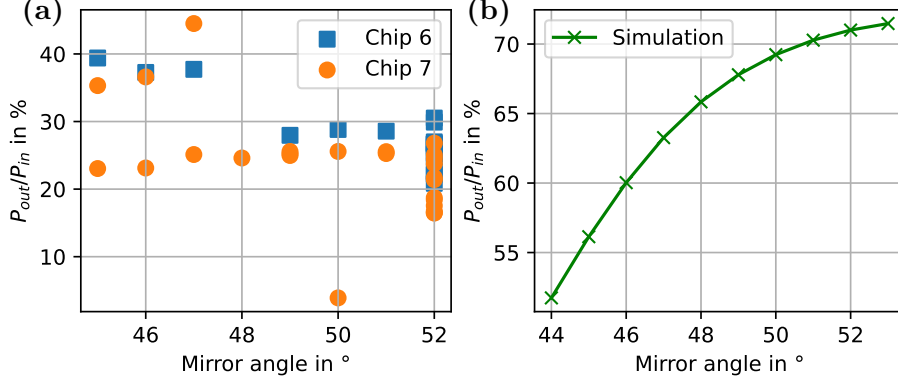


Figure 5.7: Comparing the measured total efficiency of the photonic circuit without focusing elements to simulations. **(a)** Experimentally obtained values for the total efficiency. Each chip has a total of 10 waveguides out-coupled by the central 52° mirror and one or two test mirrors for each integer angle from 45° to 52° . The outlier at 50° corresponds to imperfections (chipping) at the in-coupling facet, as shown in figure 5.6(a). **(b)** The total efficiency as expected from numerical simulations. Included losses are the coupling losses of 0.72 dB, interface reflection losses of 0.15 dB at the facet and 0.19 dB at the chip’s surface, and the simulated transmission loss of the total internal reflection mirror.

through the internal reflection mirror. Simulations indicated that transmission is the highest loss contribution. This transmission loss increases for mirrors closer to the total reflection boundary of 43.2° , but this trend is not reproduced by the experimental values, which even hint at an increase in efficiency for smaller angles.

At the time of this writing, the discrepancy between simulation and measurement has not been resolved. Scattering on imperfections in the waveguide air interface forming the total reflection mirror could potentially explain the high measured losses. On the other hand, if significant scattering occurred, it could be expected that this distorts the shape of the out-coupled beam, but the beam profiles (One example is shown below in figure 5.11), show no significant aberrations. Some light might get out-coupled in direction of the air interface. The numerical simulations are set up such that this light is not counted as lost, but even if the simulations accounted for tangential out-coupling, the magnitude of the correction is expected to be insufficient to explain the high losses. One possible source for measurement errors could be the use of different microscope objectives for collecting the out-coupled light. While the photodiodes used for measuring the optical power were calibrated with a $NA = 0.25$ objective, the efficiency of the internal mirrors was measured with a $NA = 0.7$ objective. While this is not expected to influence the results significantly, it should nevertheless be ruled out.

Further investigation should focus on measuring whether the efficiency of the 45° mirrors is indeed higher than for the 52° mirror, which is currently used as the central mirror. A 45° mirror would be convenient, because the out-coupled beam is then perpendicular to the chip’s surface and no angle-correcting elements are needed. Additionally, looking into the influence of polarization both experimentally and numerically

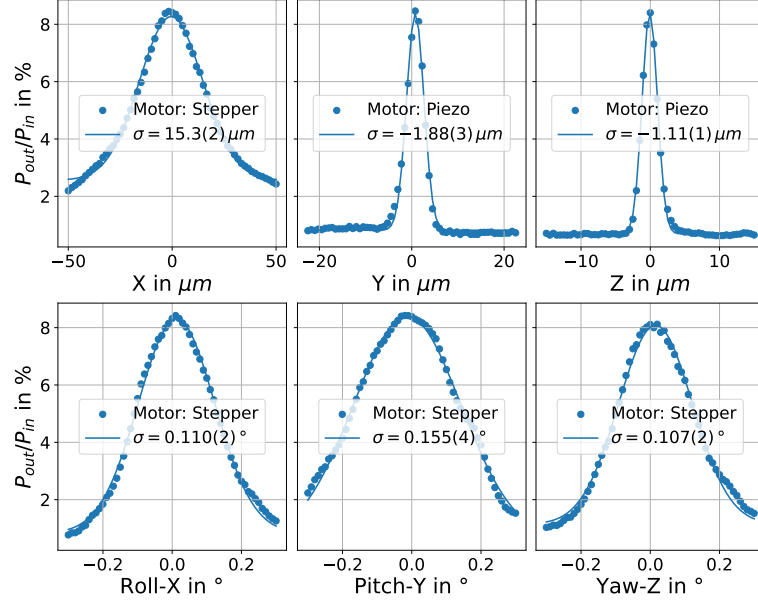


Figure 5.8: The sensitivity of the total efficiency P_{out}/P_{in} to chip displacement. The values were obtained by incrementing each of the six degrees of freedom while keeping the others constant. The standard deviation σ of Gaussian fits is used as a measure for the width of the peaks. The more sensitive axis (Y and Z) are moved by a high-precision Piezo actuator. This data was taken on a chip without high-quality facet polishing, which explains the low maximum values.

could increase the understanding of the out-coupling losses.

In-coupling sensitivity

Of practical interest is not only the maximum achievable efficiency, but also the sensitivity to misalignment of the chip, since that determines the required accuracy when attaching optical fibers to the chip.

Figure 5.8 shows the efficiency as a function of chip displacement in all six degrees of freedom. The x axis is the propagation direction of the waveguide, and z is the chip's surface normal, as shown previously in figure 5.3. As expected, the coupling efficiency is most sensitive to misalignment in the z and y direction, which are the axes perpendicular to the waveguide. In contrast, sensitivity to x displacement is determined by the Rayleigh length and divergence of the excitation laser beam. It is important to note that figure 5.8 greatly over-estimates the sensitivity to angular displacement. The decline in efficiency when moving stage's angular axes comes from imperfect decoupling of the axes, i.e. moving the pitch axis also displaces the in-coupling point vertically (and similarly for the yaw and roll axis). Imperfect in-coupling is probably caused by the in-coupling end of the waveguide not coinciding with the common pivot point of the stage. This effect is most prominent when considering rotation along the laser beam axis (roll), which can be expected to have negligible effect during the lim-

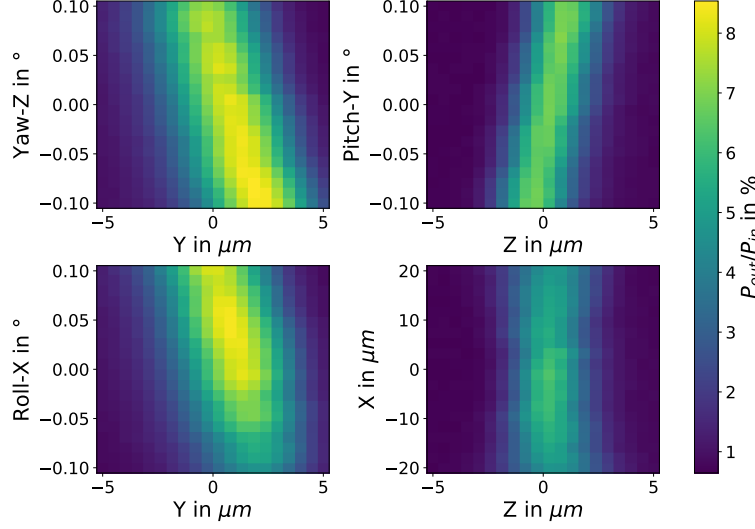


Figure 5.9: The total efficiency P_{out}/P_{in} measured on each point of a rectangular grid spanned by those pairs of axes which are expected to show the highest correlation. The skewed shapes clearly indicate the imperfect de-coupling. This data was taken on a chip without high-quality facet polishing, which explains the low maximum values.

ited travel range of the stage ($\pm 3^\circ$). The correlation of some selected pairs of axes is explored in figure 5.9, which clearly shows that moving the Pitch and Yaw axes of the alignment stage also displaces the chip laterally. Note that contrary to optical fibers which typically have a small difference in refractive index between core and cladding, the coupling efficiency of the photonic chip is not limited by the numerical aperture of the high-index-contrast waveguides: ($NA = \sqrt{n_{SiN}^2 - n_{SiO}^2} \approx 1.41$). In conclusion, it is still not clear how sensitive the in-coupling efficiency is to angular displacement, but, giving an educated guess, angular displacement is probably not the limiting factor if an accuracy of 1° or better can be achieved.

Algorithmic optimization of the coupling efficiency

Since it was unclear which percentage of the incident light can be out-coupled by the total internal reflection mirrors, considerable effort was put into finding the chip position which achieves the highest efficiency. Manually optimizing all five relevant degrees of freedom (Excluding the roll axis), is difficult due to the imperfect decoupling. A python interface [81] for the stage was created specifically to allow automated optimization.

After implementing basic procedures such as steepest ascent or pattern search without satisfactory results, a particularly interesting stochastic evolutionary algorithm was employed, namely the *covariance matrix adaptation - evolution strategy* (CMA-ES) [83]. Evolutionary algorithms are heuristic strategies suited to find the optimum of a function (in this context often called fitness function) in a large search space,

where exhaustive grid-search is infeasible due to the computational cost of the function evaluations. While a more common subclass of evolutionary strategies, the genetic algorithms, search for the optimum of a function by evolving the candidates (points in the search space) through mechanisms such as selection, cross-over and mutation, CMA-ES tries to find the optimum by evolving the probability distribution from which the next candidates are drawn. It starts with a multivariate Gaussian distribution, where the covariance matrix is the identity, centered around an initial guess. A (small) set of candidates is drawn from the distribution, and their fitness is evaluated. Depending on the location and spread of the best performing subset of the candidate points, the covariance matrix underlying the distribution from which the next candidates are drawn is updated. For example, if most of the best candidates lie close together in one direction but are spread out in another direction, the width of the distribution is reduced in one direction, but enlarged in the other direction. While a detailed explanation is beyond the scope of this thesis, the key points making the covariance matrix approach well-suited for many practical optimization problems are:

- CMA-ES is a stochastic method and does not rely on gradients, which makes it resistant to noise. This is especially crucial for experimental data.
- It can be applied without any information on the optimization target (black-box functions).
- While faster algorithms exist when the structure of the optimization target is known, CMA-ES is fast on very general objective functions. Applied to this specific problem, the optimum was reliably found after $\lesssim 150$ function evaluations.
- CMA-ES is quasi free of hyper-parameters which would need manual tuning. While it internally uses a number of free parameters (such as the number of candidates in each step), the scheme includes heuristics for finding default parameters which generally work well.

Apart from the advantages listed above, the algorithm also enables a way of learning about the optimization target. When it converges to an optimum of a function, the covariance matrix simultaneously converges towards the inverse Hessian at this point. This is particularly interesting for the use-case discussed here, because the eigenvectors of the Hessian give the direction of principal curvature and the eigenvalues correspond to the curvature of the optimization function. The direction of principal curvature can be expected to be the decoupled degrees of freedom, i.e. moving the chip along the direction with the least curvature (=sensitivity) probably corresponds to a pure pitch or yaw movement around the in-coupling point, even though the in-coupling point might not coincide with the pivot point of the stage. Measuring the correlation between the principal axis of the covariance matrix similar to figure 5.9 and checking if the axes are indeed decoupled, is still an interesting task left undone.

CMA-ES works best when each independent variable has a similar influence on the function value. This was achieved by re-scaling each axis by the width of the peaks shown in figure 5.8, which was found by Gaussian fits.

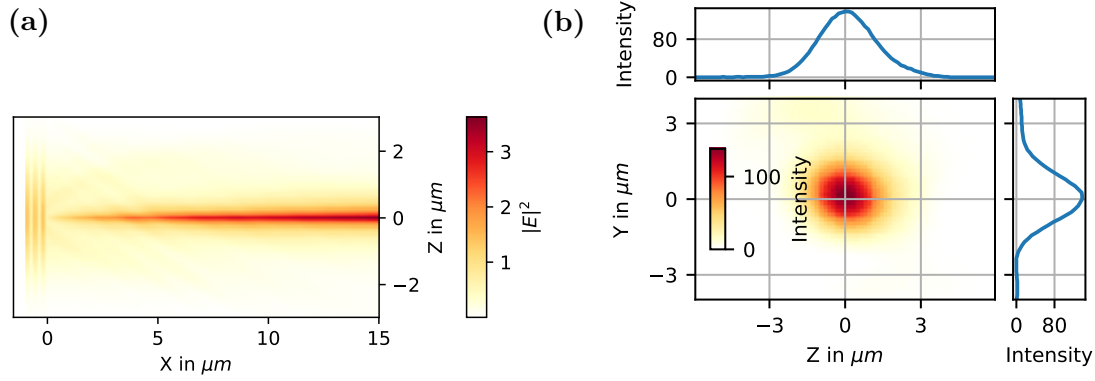


Figure 5.10: (a) Numerical simulation showing how the free-space input mode (left) is accepted by the waveguide. The tapered waveguide then transforms the mode over a length of $422\mu\text{m}$ to the intended mode-field diameter (Outside the simulated domain). Image credit: Nicolas Jungwirth. (b) Intensity profile of the laser coming out of a waveguide without an integrated mirror at the chip's rear facet. The plots to the side are slices through the intensity profile at the maximum pixel value. The image was taken using a 10×0.25 NA objective.

The algorithm was validated by running it 100 times for the same initial position. It was found that the resulting covariance matrix indeed converges towards a similar structure. The strong coupling between pairs of axes is apparent from the condition number of the covariance matrix (The magnitude of the largest eigenvalue divided by the magnitude of the smallest eigenvalue), which consistently reached values > 30 , even after re-scaling.

The algorithm was first employed on the chips without high-quality polishing applied to the in-coupling facet. It was hoped that the inconsistent values of the coupling efficiency could be mitigated by precise chip alignment, but it turned out that they are mainly caused by the varying degree of chipping. On the polished chips consistent values for the coupling efficiency were found by only optimizing the x , y and z position. Further optimizing pitch and yaw (using the CMA-ES algorithm) was found to improve the efficiency only marginally.

5.4 Shape of the waveguide mode at the rear facet

The best coupling efficiency is achieved when the mode profile at the chip facet matches the input beam. Figure 5.10(a) shows a snapshot of a numerical simulation of a Gaussian free-space beam being in-coupled into a waveguide. The waveguides routed through the chip without a total internal reflection mirror provide a means to measure the optimal input mode profile. The waveguide taper, which adiabatically shrinks the input mode to the final guided mode, is reversed at the end, thus enlarging the waveguide mode towards the rear out-coupling facet. Therefore, it can be assumed that exciting the waveguide mode with a free-space beam having the same shape as

the out-coupled intensity profile gives the best possible mode-matching. Since the beam exits along the x -Axis, an external mirror included in the chip mount re-directs the laser beam into the vertical direction (z -Axis), where it is readily observed on the microscope. Due to the restricted access caused by this mirror, only microscope objectives with a sufficiently large working distance and consequently a low numerical aperture (NA) could be used.

One exemplary intensity profile of the out-coupled laser beam at the rear facet is shown in figure 5.10(b). Due to imperfect background subtraction, the more accurate $D4\sigma$ method for measuring the beam diameter could not be meaningfully applied. Since the beam shape is well described by a Gaussian profile, inferring the beam diameter from a Gaussian fit is appropriate, yielding a diameter of $3.72(7) \mu\text{m}$ in z and $3.6(4) \mu\text{m}$ in y . The result is given as the mean of 6 different waveguides and the uncertainty is the standard deviation. These results agree well with simulations conducted by LioniX, which give an expected mode field diameter at the chip facet of $3.37 \mu\text{m}$ in z and $3.65 \mu\text{m}$ in y . The slightly higher measured diameter in the z direction can probably be attributed to curvature of the chip facet induced by polishing, which could act similar to a lens. It is possible that a portion of the laser beam was clipped by the objective with a numerical aperture of 0.25, which could result in an artificially enlarged beam size on the camera. Numerically quantifying this effect is still outstanding at the time of this writing.

The intensity profile at the facet can be used to obtain a lower limit on the coupling losses due to mode-mismatch. A scalar approximation for the maximal possible overlap of the measured intensity profile I_m with the ideal Gaussian beam I_{Gauss} can be found by:

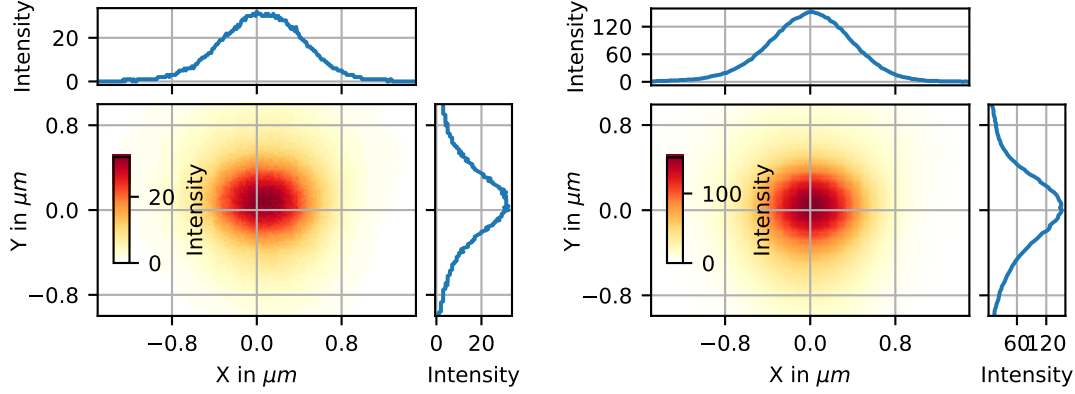
$$\mathcal{O} \leq \frac{\iint \sqrt{I_m(y,z) \cdot I_{Gauss}(y,z)} dy dz}{\iint I_m(y,z) dy dz \cdot \iint I_{Gauss}(y,z) dy dz} \quad (5.1)$$

Note that this expression can only give an upper bound on the overlap, since it discards both the phase information of the field and the (vectorial) polarization. Evaluating the integrals for the mode profile shown in figure 5.10(b) and an ideal Gaussian input beam with a diameter of $4.5 \mu\text{m}$, gives an overlap of 95 % (0.22 dB minimal loss). This value is significantly better than the 0.5 dB/0.72 dB expected from simulations, but it can only be considered a lower bound on the coupling losses.

5.5 Shape of the out-coupled laser beam

Now we turn our attention to the shape, diameter and divergence of the beam out-coupled by a total internal reflection mirror without the focusing unit. Since this laser beam gives the initial field distribution for the subsequent lens stack, a good understanding is the foundation for future design optimizations of the focusing unit.

On the central mirror, a total of 21 waveguides were inspected using the 50x 0.7 NA objective, resulting in a mean beam diameter of $D4\sigma(X) = 1.94(5) \mu\text{m}$ and $D4\sigma(Y) = 2.1(3) \mu\text{m}$. Only 16 data points were used for the y -diameter because of some light



(a) Imaging the output of the central mirror with a 100x $NA = 0.8$ objective.

(b) Imaging the output of the central mirror with a 50x $NA = 0.7$ objective.

Figure 5.11: Images of the laser beam out-coupled by a total internal reflection mirror without micro-optics. The plots to the side are slices through the intensity profile at the maximum pixel value.

coming out of the wrong waveguides, as discussed in section 5.7, which greatly enlarges the second moment width. The given quantity is the diameter of the beam waist, and the height of the waist above the chip's surface is consistent with zero. Numerical simulations conducted by LioniX indicate that the waveguide supports an elliptical mode with a mode-field diameter (MFD) of $1.63\,\mu\text{m}$ in the z direction and $1.94\,\mu\text{m}$ in the y direction. The axis notation is chosen to highlight that the beam profiler acquires images of the out-coupled beam, while the simulation describes the mode inside the waveguide. Be reminded that the x axis is defined as the waveguide propagation direction, and the mirror re-directs the beam into the vertical (z) direction. The measured diameter of the beam in x is higher than the simulated z diameter, while the measured size in y is consistent with the simulation. This could be explained by the internal mirror having a larger effect on the beam size along the plane of incidence ($x - z$ plane), than on the beam size in y direction. Looking back at the scanning electron microscope image shown in figure 3.11, this could probably be explained by the rounded edge of the reflecting interface. The reliability of the measured diameter could be improved by adhering to the $D4\sigma$ method as specified by ISO 11164 [78], since the uncertainty is mostly due to background noise, which is aggravated by the small beam size relative to the detector area.

In order to validate the method of measuring the beam size, the out-coupled beam on one specific waveguide was imaged using several microscope objectives. Two representative intensity profiles obtained with two objectives are shown in figure 5.11, and the results are summarized in table 5.1: Due to the aforementioned limitations of the implemented $D4\sigma$ method, the diameter in table 5.1 is obtained using the Gaussian fit method. We see that there is indeed a clear trend visible in the data: A higher

Table 5.1: The beam diameter obtained by fitting a Gaussian to the beam profile for a number of different objectives. For $NA \neq 0.7$ only a single data point is available, and no reliable estimation of the uncertainty can be given.

Objective:	10x 0.25 NA	20x 0.4 NA	50x 0.7 NA	100x 0.8 NA
$D(1/e^2)(X)$	2.71 μm	2.02 μm	1.72(7) μm	1.52 μm
$D(1/e^2)(Y)$	2.73 μm	1.90 μm	1.70(8) μm	1.57 μm

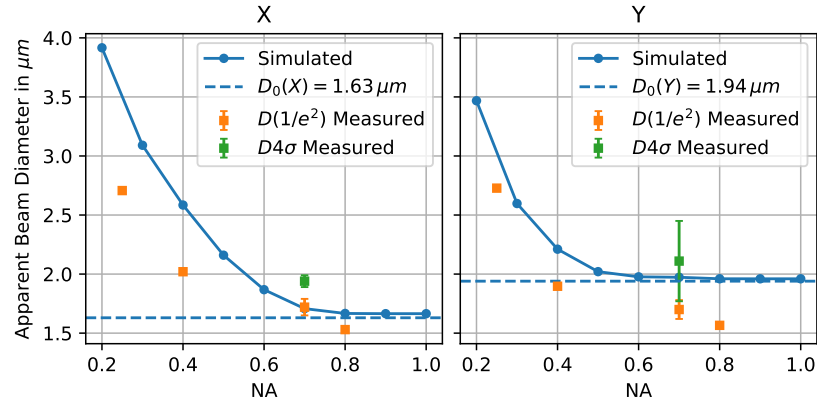


Figure 5.12: Estimating the influence of the microscope objective on the apparent beam diameter in x and y . The apparent beam diameter was computed by performing a convolution operation of an ideal Gaussian laser beam with a numerical model of the objective's coherent point-spread-function (PSF) (as detailed in section 4.2), for a number of objectives with a different numerical aperture (NA). The size of the laser beam (D_0 ; dashed line) was chosen to match the simulated waveguide mode, and the out-coupling angle is 19.2° . The measured data as given in table 5.1 is visualized as comparison.

numerical aperture yields a smaller apparent beam diameter. Numerical investigations were conducted to determine whether this trend can be consistently explained by clipping of the laser beam at the objectives' pupil. As discussed in section 4.2 the objective acts as a low-pass filter on the spatial frequencies of the object (The laser beam). I.e. if the beam does not have spatial frequencies higher than the objective's cut-off frequency ($k_{max} = k_0 NA$), the spot size on the detector is not at all influenced by the objective, even though the size of the objective's point-spread-function (PSF) might be similar to, or even larger, than the laser beam. By computing the coherent three-dimensional PSF for a number of different numerical apertures and performing a convolution operation with the electric field of an ideal Gaussian laser beam, the size of the image on the detector can be estimated. The laser beam was chosen to match the simulated waveguide mode propagating at an angle of 19.2° to the optical axis of the microscope. The result of this analysis is shown in figure 5.12. We find qualitative agreement with the measurement in the sense that a smaller numerical aperture indeed results in a larger apparent beam size. On the other hand the simulation does not fit quantitatively to the measurements. It yields a larger apparent beam diameter and a stronger decrease of the apparent beam size with increasing NA, than what was observed. Further, the measured beam size in y direction is significantly smaller than the simulated waveguide mode. The discrepancy can probably be explained by the Gaussian fit under-estimating the beam size, and therefore predicting a larger divergence angle. Alternatively, the model of an objective which cuts-off all light outside the acceptance cone defined by the NA might be too pessimistic, and the objective probably accepts more light than specified.

Divergence and propagation angle of the out-coupled beam

Measuring the far-field divergence angle of the out-coupled beam is important to estimate how well the beam can be focused by the subsequent lens stack. In order to estimate the divergence of a laser beam, multiple intensity profiles along the direction of propagation are required, which allows reconstructing the three-dimensional intensity distribution of the beam, as visualized in figure 5.13. Multiple slices through the laser beam were acquired by moving the objective along the vertical (z) direction. Since the gold structures on the chip's surface are not visible on the beam profiler, the z position of the surface is not known. Therefore, the position yielding the highest intensity was defined as $z = 0$. The chip's surface is visible when using the RGB camera. Judging from the images of the out-coupled laser beam acquired with the RGB camera, the position of the highest intensity is consistent with it being on the chip's surface, with an approximate uncertainty of $3\mu\text{m}$. Slices through the intensity profile were acquired by moving the objective from $z = -10\mu\text{m}$ to $z = 10\mu\text{m}$ and taking images every $0.4\mu\text{m}$. Since the Rayleigh length of an ideal beam with a waist of $1.94(5)\mu\text{m}$ would be $4.1(2)\mu\text{m}$ (and that for non-ideal beams with the same waist smaller), this range of objective positions is adequate for estimating the beam's far-field divergence.

For objective positions $z < 0$, it can be expected that the focal plane of the objective

5 Characterization of the photonic chip

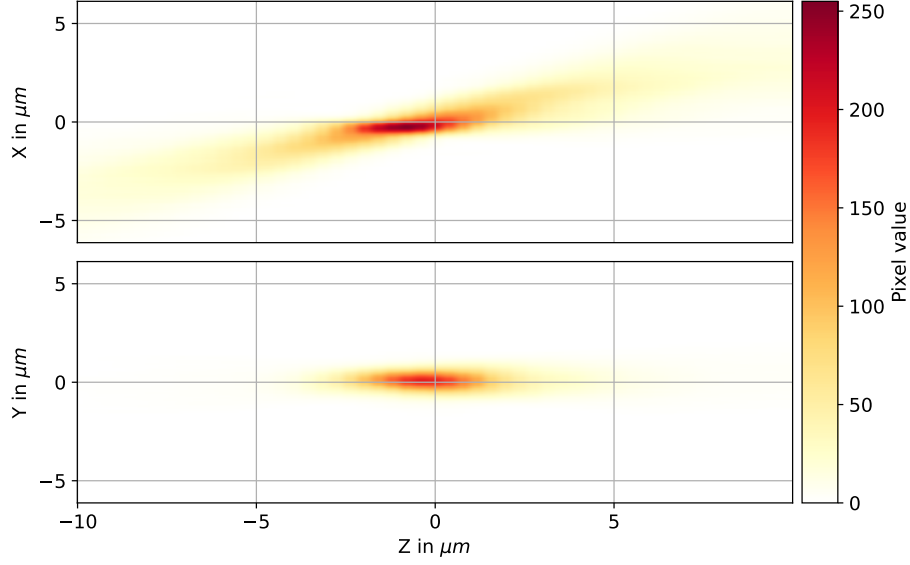


Figure 5.13: Slices through the 3D intensity profile along the vertical (z) direction showing the propagation angle and beam divergence (Color indicates intensity). The laser beam is coupled out of a waveguide by the central total internal reflection mirror without beam shaping elements. The 3D structure was acquired by stacking images taken at different heights of the microscope objective.

lies beneath the chip's surface. Intuitively it might be expected that this distorts the image in some way, but this intuition comes from experience with regular microscopy which typically uses incoherent illumination. If we consider a laser beam propagating through the optical path of a microscope, the objective first collimates the laser beam and the tube lens then focuses the laser, thus creating a secondary beam waist close to, or at, the detector plane. If the out-coupled beam waist lies exactly in the focal plane, the secondary beam waist will be found precisely in the detector plane. On the other hand, if the out-coupled waist is located before or after the focal plane, the secondary beam waist will be found before or after the detector plane. In that case, the detected image appears enlarged due to the divergence of the laser beam. Since the divergence is symmetric about the beam waist position, the apparent beam size is also symmetric about beam waist position, whether the focal plane lies inside the chip or not. This conclusion is also reflected in the data, as visualized in figures 5.13 and 5.14.

The far-field divergence angle can be estimated by evaluating the beam size and position for each image, and fitting a hyperbolic waist (equation (4.8)) to the beam size as function of objective height. The result of this procedure applied to one exemplary out-coupled laser beam is shown in figure 5.14. Repeating the measurement for a number of waveguides allows obtaining reliable results. The results as a function of the angle of the total internal reflection mirror are shown in figure 5.15. The divergence angle θ of the laser beam was found at $16.0(6)^\circ$ in x direction and $14.0(17)^\circ$ in y

5.5 Shape of the out-coupled laser beam

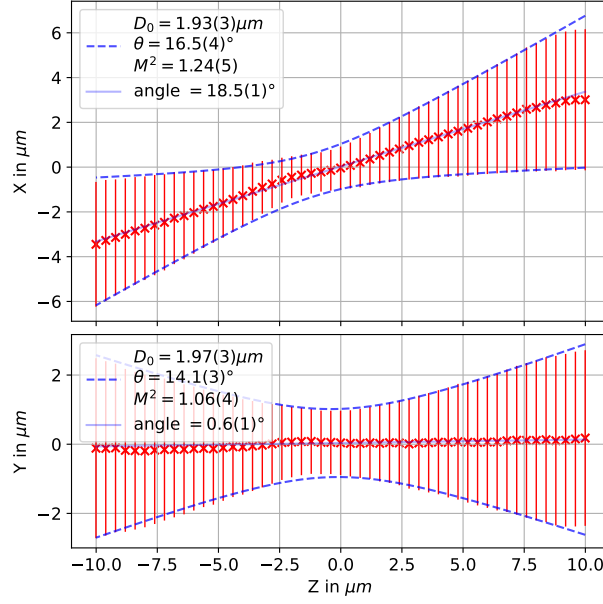


Figure 5.14: The waist of a laser beam out-coupled by the central mirror without beam shaping elements. Each vertical line corresponds to one image taken at an objective height z . The crosses indicate the center position of the beam, while the length of the vertical bars shows the beam size ($D4\sigma$). The propagation angle is found by a linear fit. Fitting the beam waist (dashed lines) allows extracting the half angle θ of the divergence cone as well as the beam waist diameter D_0 . The beam divergence parameter M^2 was inferred from the fit parameters. This procedure is done for both the x -Axis as shown in the upper plot and the y -Axis (lower plot).

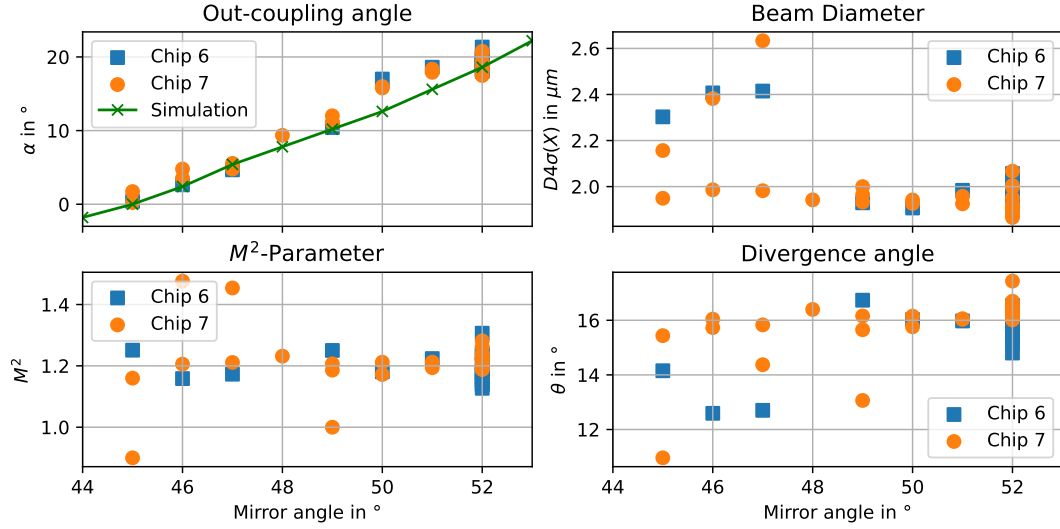


Figure 5.15: Properties of the laser beam out-coupled by a total reflection mirror, without the focusing unit. Each data point is extracted from a fit as shown in figure 5.14. Both chips have a total of 10 waveguides out-coupled by the central 52 $^\circ$ mirror and one or two test mirrors for each integer angle from 45 $^\circ$ to 52 $^\circ$.

direction. The divergence can be compared to the ideal Gaussian beam, by computing the M^2 beam divergence parameter. Using the Rayleigh length found by fitting, results in $M^2(X) = 1.21(5)$ and $M^2(Y) = 1.17(7)$, which can be considered almost diffraction limited.

Another figure of interest which can be extracted from the stack of images is the angle at which the beam is out-coupled, relative to the surface normal. As shown in figure 5.14, a linear fit on the beam position as function of the objective height is a suitable method for finding this out-coupling angle α . In the case of the 52 $^\circ$ mirror, α was measured to be 19.2(9) $^\circ$. Figure 5.15 shows excellent agreement of the measured angle with numerical simulations. Alternatively, applying Snell's law already describes the results well. For the 45 $^\circ$ mirror, the angle was found at 0.8(8) $^\circ$, consistent with the expected value of 0 $^\circ$. Similarly to the beam size, the apparent out-coupling angle is also influence by light clipped at the entrance pupil of the objective. Figure 5.16 shows a simulation of the measured and simulated out-coupling angle and the fraction of light entering the objective as a function of numerical aperture (NA).

5.6 Intensity distribution at the ion position

As discussed in the previous section, the laser beam exiting the total reflection mirror is highly divergent, which would result in an intensity distribution which is much larger than the ion pitch, making the beam unsuitable for individual addressing. In order to create a focused beam spot at the targeted ion position, a stack of lenses is 3D printed on top of the chip.

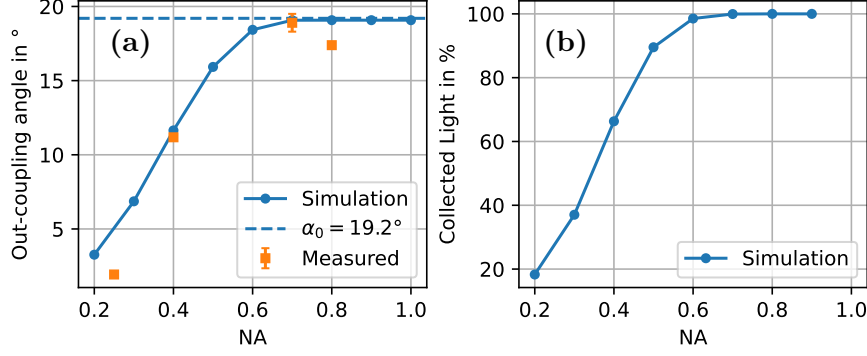


Figure 5.16: Simulating the influence of the microscope objective on the apparent out-coupling angle. (a) The apparent out-coupling angle of an ideal Gaussian beam as function of the objective’s numerical aperture (NA). The simulated data was produced in the same way as the one shown in figure 5.12. For $NA \neq 0.7$ the lack of measured data prohibits an estimation of the uncertainty. (b) The optical power of the same laser beam collected by an objective, as function of the numerical aperture.

Due to time constraints, the manufactured chips with micro optics did not have a polished facet, and therefore the optical losses of the lens stack could not be meaningfully analyzed. On two out of three chips no out-coupled light could be detected at all and on the third chip, the total efficiency ranges from 0.4 % to 11.5 %. These variations can be attributed to the amount of chipping at the front facet.

Illustrations of the laser beam waist created by the focusing unit are shown in figure 5.17. The focusing effect of the lenses can be clearly observed, but the quality of the beam at the focus is far from ideal. The lens stack was designed such that the beam is focused more tightly in the direction of the ion string (y) than in the x direction, reducing the optical cross-talk and at the same time relaxing the required alignment accuracy compared to a circular beam. Unfortunately, the $D4\sigma$ method does not yield a meaningful result for the beam size and the Gaussian fit method is not applicable to the highly aberrant beam.

The measurement apparatus used only allows coupling light into one waveguide at a time, which makes it difficult to accurately measure the relative positions of the individual focal spots from multiple waveguides. Attaching an array of fibers to the front facet will allow for more accurate measurements of the relative position of the beam spot, because different waveguides can be excited without having to move the chip or the microscope. Nevertheless, the gold alignment markers on the chip’s surface can be used to as a reference to align images of the laser coupled out of different waveguides at different stage positions. The gold markers were made visible using bright illumination and long exposure times. Figure 5.18 shows an overlay of the focal spots created by a single lens stack for different waveguides, where the intended linear arrangement of the focal spots is visible.

Measuring the height of the lenses’ focal spot can be done by using the gold markers on the surface as a reference. Since the beam waist position is not well-defined due to

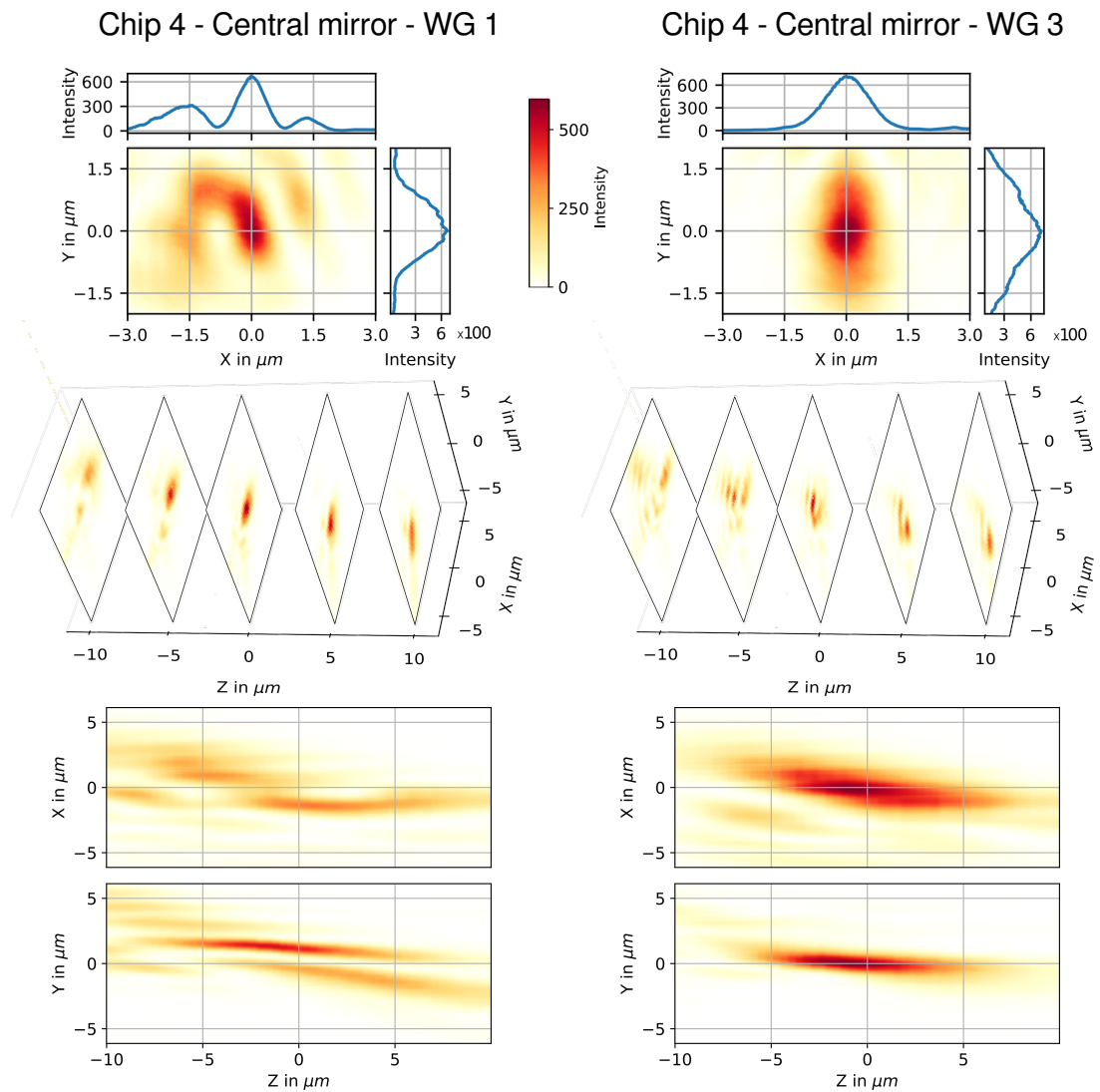


Figure 5.17: The focal spot created by the micro-optical lens stack, shown for two different waveguides on the same mirror and same lens-stack. The top plots show the beam profiler image at $z = 0$, including 1D slices through the intensity profile along the blue lines. In middle plots an isometric view on some acquired images is shown, and the lower plot shows 2D slices along the vertical (z) direction through the image stack.

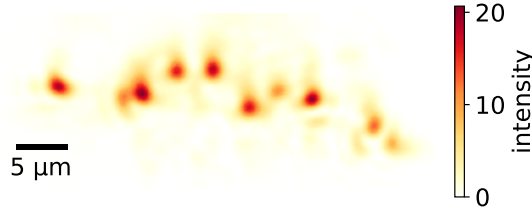


Figure 5.18: Overlays of the focal spots above the lens stack. The chip position (and microscope stage position) was changed during acquisition of the different beam spots, therefore image alignment is necessary. The relative position of the beam spots is found by a second image for each spot taken at the same position of the microscope and photonic chip, without the laser beam, such that the patterned gold is visible, giving a reference for alignment. These images are programmatically overlaid to find out how much the images of the focal spots need to be shifted. The intended linear arrangement is somewhat visible from the data, but note that this method of image alignment is highly inaccurate.

the high amount of aberrations, the values obtained have considerable uncertainties. The mean height of the focal spot above the chip surface was found at $606(8) \mu\text{m}$, which is consistent with the targeted ion position of $600 \mu\text{m}$ above the photonics chip.

It is expected that the main reason for the disappointing optical performance of the lens stack is a design error. Figure 5.19 shows the elements relevant for beam-shaping. The first optical element in the lens stack is a prism intended to re-direct the out-coupled beam into the z direction. Since the first attempt of measuring the out-coupling angle without the lens stack used a microscope objective with a NA of 0.25, the out-coupling angle was originally estimated at 7° , while it is now confirmed to be $19.2(9)^\circ$ (See also figure 5.16). Therefore, the prism was designed to correct only 7° of the out-coupling angle, which leads to some light being clipped at the outer edges of the lenses, leading to aberrations in the focal plane. This behavior is confirmed by a ray-optics simulation, as shown in figure 5.19.

The next iteration of the focusing unit will use the same chip layout, but with a central mirror milled at 45° , altogether eliminating the need for angle-correcting optics. Design changes of the 3D printed lenses can be easily made without large additional costs due to the flexibility of the manufacturing process. This ability highlights the practicality of the chiplet approach followed in this project.

5.7 Parasitic waveguide coupling

High-fidelity gate operations require that addressing one ion does not have a large influence on the other ions. Therefore, the laser intensity at the other ions should be as small as possible. In the chip layout discussed here, the waveguide geometry and separation is designed such that the leakage from one waveguide to the next is below -30 dB . As apparent from the beam profiler images (Figure 5.20), the light exiting the waveguide next to the intended waveguide is clearly much higher than the design specifications.

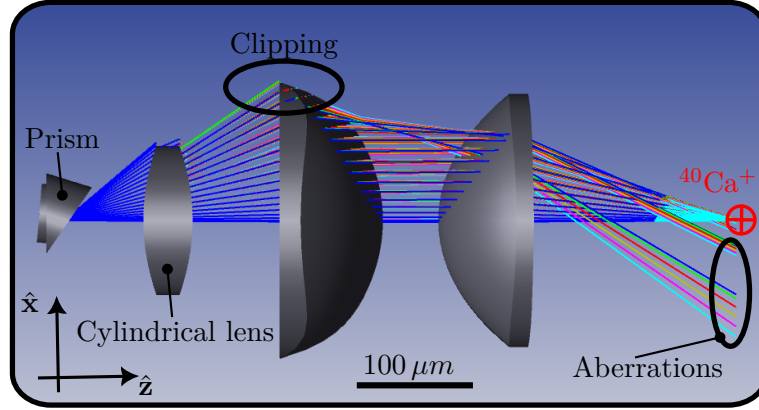


Figure 5.19: Ray-Optics simulation of the lens stack using the software Zemax OpticStudio. Different colors indicate different waveguides / ion positions. The prism on the left does not fully correct the non-perpendicular out-coupling, which leads to clipping at the edge of the lenses, degrading the focus at the ion positions. Image credit: Bassem Badawi.

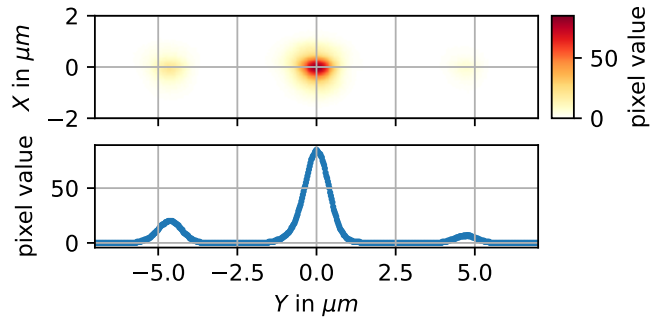


Figure 5.20: Light coupled out of the central mirror when exciting one of the middle waveguides (Color indicates intensity). Clearly visible is the light coming out of the neighboring waveguides. This image was acquired on a chip without the lens stack. The plot on the bottom shows the intensity profile along the green line, indicating the relative height of the side-peaks.

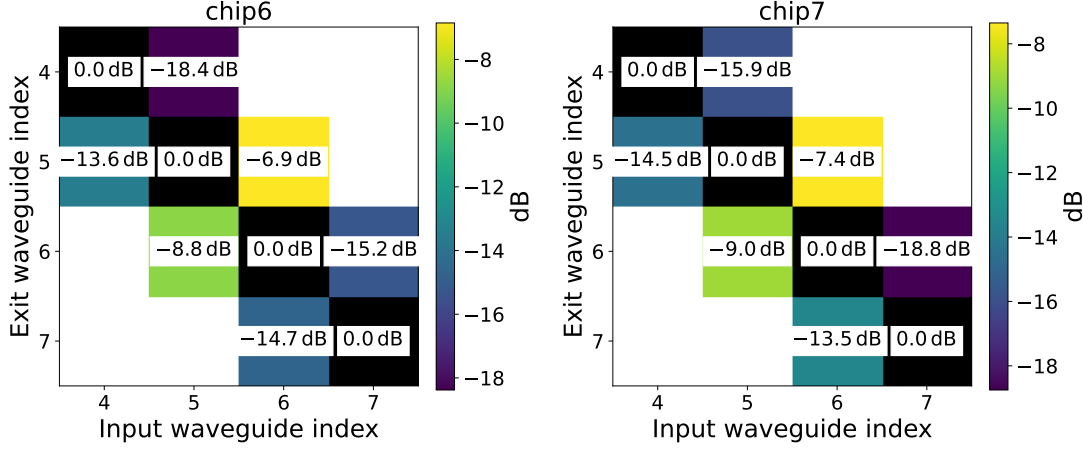


Figure 5.21: Estimating the leakage from the central waveguides to their left and right neighbors. Each value was extracted from a single image as shown in figure 5.20. Of the 10 waveguides joining on the central mirror, only the middle ones with the highest leakage values could be analyzed with this method.

The fraction of light coming out of the neighboring waveguides can be found by integrating the intensity profile of the side-peaks and normalizing it to the integral over the main (middle) peak. A quantitative result was found by partitioning the image into equally sized squares centered around each peak, and summing the pixel values, which gives a measure for the optical power contained in each peak. The results of this analysis are visualized in figure 5.21. Since the optical power in the peaks is normalized to the power in the middle peak, the amount of light coming out of the middle peak is unity (or 0 dB).

For both of the two polished chips it is consistently found that the leakage is the highest when coupling in to one of the middle waveguides (Waveguides No.4 to No.7 of the ten waveguides routed to the central mirror). Considering only the middle waveguides (No.5 and No.6), the relative optical power in the side-peaks is estimated at $-8.0(9)$ dB. On the outer waveguides (Index 1,2,3 and 8,9,10), the side-peaks are not visible on the beam profiles. This can be explained by the non-equidistant spacing of the waveguides. Especially the middle ones are routed very closely. Additionally, the tight spacing of the middle waveguides is preserved over a long propagation distance of 4.2 mm, which could lead to a larger amount of light leaking from one mode to the next. The trend towards higher leakage for more closely spaced waveguides indicates that the observed optical cross-talk is indeed caused by parasitic evanescent coupling of the waveguides, and not by other effects such as stray light coupled into the wrong waveguide.

The parasitic coupling and the resulting optical cross-talk limits how tightly the waveguides can be routed. Simulations conducted by LioniX indicate that the waveg-

5 Characterization of the photonic chip

guides must be separated at least $4.84\mu\text{m}$ to achieve less than -30 dB leakage. Apart from the separation, this low level of cross-talk is achieved by choosing waveguides with two alternating widths. In this case the mismatch in the propagation constant limits the maximum amount of optical power which can be transferred from one waveguide to the next, as was discussed in section 3.1. Our simulations of the fabricated waveguide layout estimate the maximum fraction of power coupled out of a waveguide to be -31.65 dB , thus confirming the design specifications. As discussed in section 3.1, the optical power oscillates between two coupled waveguides in direction of propagation, which means there exists a characteristic propagation length L_c after which the maximum amount of light is coupled into the next waveguide. Our simulation indicate that this length is $L_c = 0.33\text{ mm}$.

The ion trap layout discussed here will use a 10 ion string at an axial secular trap frequency of 702 MHz , which leads to a separation of $3.18\mu\text{m}$ between the middle ions. Be reminded that the propagation axes of the laser beams out-coupled of all waveguides are parallel. Therefore, the waveguide spacing must be chosen to match the ion spacing, up to a constant factor determined by the magnification of the lens stack. The lens stack was designed with an effective magnification of -0.657 , to have the waveguides separated by a larger distance than the ions, which reduces waveguide coupling.

The reason for the large difference between simulation and experiment is not yet resolved. One potential explanation could be the polarization of the waveguide mode. It could prove conclusive to measure how the polarization of the excitation laser influences the cross-talk. The simulations assumed a (quasi) transversal electric waveguide mode, but the polarization of the input light was not determined. Since the light inside a transversal magnetic waveguide mode is less confined, higher coupling can be expected, but it is unclear if this effect can account for the large discrepancy. Another possibility is that the simulations underestimate the parasitic coupling, because imperfections in the waveguide are not accounted for. Scattering on defects such as roughness on the waveguide sidewall could lead to enhanced leakage through in- and out-coupling of cladding radiation modes, which transport energy away from the waveguide into the cladding.

In order to put the magnitude of the optical cross-talk in perspective, The influence of the optical cross-talk on coherent qubit operations can be considered by recalling that the time it takes to perform a qubit operation is determined by the Rabi frequency. Since the Rabi frequency is proportional to the square root of the light's intensity, a cross-talk of $-8.0(9)\text{ dB}$ implies that a coherent rotation on one ion by an angle causes the neighboring ion to rotate by $39(4)\%$ of that angle. In order to build a functioning trapped ion quantum computer this amount of crosstalk constitutes a serious limitation.

Going ahead, further investigation should focus on determining whether the high level of cross-talk is persistent when the laser is coupled into the chip using a fiber array, and also the polarization dependence should be analyzed. Future designs could reduce the crosstalk by choosing a larger waveguide separation until close to the out-coupling region. Further measures could include a higher asymmetry between the

neighboring waveguide geometry, although it is not yet clear how this influences the presumed coupling of cladding radiation modes.

5.8 Data and software availability

The beam profiler images acquired during the course of this thesis and the according log files, as well as the numerical simulations conducted by Nicolas Jungwirth, can be found in a Zenodo repository [84]. Included in the repository are text files, which contain notes taken during data acquisition. The control software created for automatic control of the devices and evaluation of the raw data can be found under [81]. The source code of this thesis as well as further data evaluation and visualization scripts are located at the GitLab instance hosted by the University of Innsbruck¹.

¹https://git.uibk.ac.at/csaz1107/optical_integration_msc.git

6 Summary and Outlook

This thesis aimed at characterizing the optical properties of the individual ion addressing unit used in the Millenion project. The (to my knowledge) unique approach followed in the Millenion project separates the trap chip providing the electrodes required for ion confinement from the photonic chip comprising the ion addressing unit. The integrated photonic chip alleviates the need for addressing single ions in the vacuum chamber through transparent view-ports using a high-NA objective. Instead, optical fibers glued to the chip's facet allow to couple a laser into waveguides forming the photonic circuit. A patterned silicon nitride thin film, clad in silicon oxide comprises the waveguides, which route the 729 nm laser beam required for optical qubit operations in $^{40}\text{Ca}^+$ to the out-coupling region. Instead of using the more common approach to out-couple the laser with a diffraction grating integrated in the patterned silicon nitride layer, the photonic chip discussed in this thesis uses a total internal reflection mirror milled into the chip's surface to re-direct the beam into the vertical direction. After the beam exists the total reflection mirror, a sequence of lenses 3D-printed on top of the chip focuses the laser to the intended ion position.

The laboratory work conducted during this thesis consisted of designing and setting up a measurement apparatus to characterize the optical performance of the photonic circuit. The optical chip was placed on a six-axis stage, and the laser was coupled into the chip by focusing a free-space laser beam (excitation laser beam) on the in-coupling end of the waveguides. The out-coupled light was then observed with a microscope. Photodiodes included in the setup allow measuring the optical power collected by the microscope objective.

It was found that the amount of light exiting the waveguides at the rear facet without total internal reflection mirrors is 72.6(17) % of the optical power in the excitation beam. With this result, the propagation loss was estimated to be less than 0.5 dB/cm. Using the total reflection mirror to out-couple the laser beam, the amount of out-coupled light decreases drastically, to only 23(4) %. As this result does not agree with what is predicted by numerical simulations of the out-coupling element, the causes for the high measured optical loss at the total internal reflection mirror are not yet clear.

The beam exiting the chip without the stack of lenses was found to be almost diffraction limited, with an M^2 divergence parameter of 1.21(5) perpendicular to the ion string and 1.17(7) parallel to the ion string. The location of the waist of the out-coupled beam is consistent with it being on the surface of the chip, and the waist diameter was found to be 1.94(5) μm perpendicular to the ion string and 2.1(3) μm in direction of the ion string. The measured size fits well to the simulated mode profile supported by the waveguide. Further, the out-coupled beam propagates at an angle of 19.2(9) $^\circ$ to the surface normal, which is consistent with the simulations. The nearly

diffraction-limited beam is suited to be focused to a small spot by the subsequent lens stack, which will result in fast qubit operations and low optical cross-talk, when the photonic chip is finally used to address trapped ions.

The lens stack intended to focus the laser onto the targeted ion position was found to introduce a large amount of aberrations, which prohibited measuring the size of the final focal spot. It is expected, that the geometry of the optical elements included a design mistake, as it assumed the wrong out-coupling angle of the laser beam exiting the total reflection mirror. We are confident that the next iteration of the focusing unit will preserve the high quality of the laser beam exiting the total internal reflection mirror.

Currently unresolved is the issue of high leakage between two parallel adjacent waveguides, which was measured to be $-8.0(9)$ dB between the middle two waveguides, thus being much higher than the design specifications of less than -30 dB. We expect that the next fabrication run can improve the parasitic coupling by increasing the distance between parallel waveguides.

Summing up, the focusing unit discussed in this thesis offers some potential advantages over grating based out-coupling, such as the smaller footprint and the high quality beams exiting the total reflection mirrors. If the issues of high optical losses at the out-coupling mirror, high parasitic coupling between adjacent waveguides, and the poor optical performance of the lens stack can be resolved, this design could prove advantageous for large-scale trapped ion quantum processors. Further, the modular chiplet based approach of the Millenion project is highly suited to combine the best suited materials for each chiplet, while additionally allowing faster design iterations. In order to further characterize the photonic circuit, the most important task will be to determine how polarization influences the measured properties, such as optical losses, parasitic coupling or the shape of the out-coupled beam. Since the chip is intended to be used in a cryogenic environment, another important step will be measuring the thermal shrinkage of the polymer comprising the lens stack, since changes in the geometry of the lenses influence the focal length of lenses. Other chip layouts, which were not yet available for this thesis, will include different test structures, to allow measuring the losses caused by bends in the waveguide, as well as more detailed investigations into the coupling of two parallel waveguides.

Looking ahead, the next steps required to successfully employ the photonic chip to ion traps include bonding the photonic chiplet to the trap chiplet, with initial tests on wafer level bonding yielding promising results. Further, gluing an array of optical fibers to the chip's in-coupling facet will be necessary to couple the laser into the waveguides once the trap is located in the vacuum chamber. In the longer run, the silicon nitride platform is suited to perform additional tasks, with on-chip light distribution and switching being an appealing goal to keep the amount of external control hardware manageable while scaling up the number of high-fidelity qubits required for a truly useful quantum processor.

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