quixquantum.com

For photonic integrated quantum applications

Silicon nitride building blocks

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Contents

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Introduction

This paper introduces the silicon nitride (Si3N4) integrated waveguide technology used by QuiX Quantum for integrated optics and describes its advantages with respect to other on-chip photonic platforms. Integrated optics is a technology that miniaturizes free-space optics onto a small chip.

Photonic integrated circuit: On-chip circuit of light which performs multiple photonic operations.

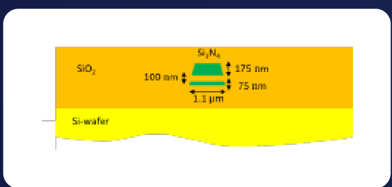
The first section of this paper explains the silicon nitride integrated waveguide technology and emphasizes the low loss of our platform, which allows a high functional density on a photonic chip. After introducing the technology, we discuss the fundamental photonic building blocks that can be produced in the silicon nitride platform. Using only a small number of fundamental building blocks enables a wide variety of on-chip functionality and complicated photonic integrated circuits, such as the QuiX Quantum photonic processor.

This paper is for readers who want to familiarize themselves with the silicon nitride platform and who want to learn how QuiX Quantum can offer solutions for your quantum applications by using photonic integrated circuits.

Integrated photonics using silicon nitride waveguides

A large variety of material platforms exists that can be used to realize integrated waveguides. In our chips, we use silicon nitride (Si¬3N4) waveguides constructed with the TriPleX technology. The Si3N4 waveguides are embedded in an LPCVD silicon dioxide (SiO2) cladding. The silicon nitride material has a wide transparency window ranging from 405 nm to 2350 nm and TriPleX waveguides have the lowest reported waveguide loss of 0.1 dB/cm down to 0.1 dB/m. Furthermore, thick, crack-free waveguides are possible with the TriPleX technology since the silicon nitride is deposited into trenches etched in the silicon oxide cladding instead of depositing the silicon nitride layers onto the substrate followed by waveguide definition through etching. This allows a wider range of dispersion engineering and reduces the sidewall roughness.

Waveguide: an on-chip channel which guides light. The photonic equivalent of an electrical wire.



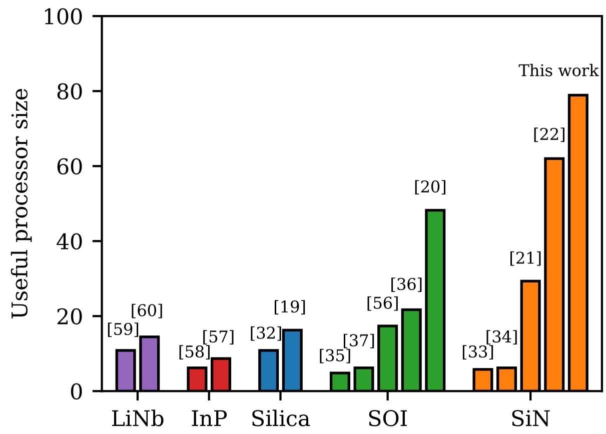
For the photonic processor, QuiX Quantum uses the asymmetric double stripe waveguide cross section shown here in the sketch with the specific dimensions for 1550 nm. The asymmetric cross section combines a thin lower Si¬3N4 layer with a thick upper Si¬3N4 layer. This allows the realization of both low contrast modes for optimal fiber coupling and high contrast modes for a tight bend radius of 100 µm.

Next to the asymmetric double stripe waveguide cross section, the well-developed silicon nitride TriPleX technology platform offers various other waveguide cross sections. These are specialized for specific, low-loss applications that allow a large on-chip complexity. More information about the TripPlex technology used by QuiX Quantum can be found in the paper: Roeloffzen, C. G. H. et al. Low-Loss Si3N4 TriPleX Optical Waveguides: Technology and Applications Overview. IEEE J. Select. Topics Quantum Electron. 24, 1–21 (2018).

Promise of silicon nitride waveguides

The silicon nitride waveguide technology is very promising for photonic integrated circuits since it offers the lowest reported on-chip waveguide loss ranging from 0.1 dB/cm down to 0.1 dB/m. The silica used for optical fibers theoretically has lower loss, however it is very challenging to grow low loss silica on-chip since silica has a lower refractive index with respect to silicon. Using specific claddings or dopings it is possible to slightly increase the refractive index of silica such to form a weak-guiding waveguide, but it still prevents tight bending radii making it is unsuited for densely integrated on-chip photonic technologies.

In order to compare the scalability of various material platforms, a measure called 'useful processor size' is used. This is the number of unit cells that can be sequentially concatenated before reducing the transmission to an arbitrary value. A unit cell is a tunable beamsplitter followed by a phase shifter. The useful processor size shows that silicon nitride is the most scalable platform allowing for the largest useful processor size.



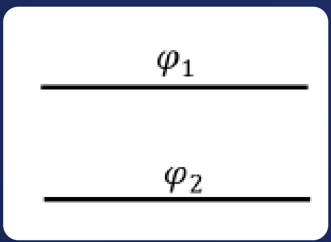
References to the cited papers can be found in the paper Taballione C. et al. arXiv:2203.01801 (2022)

Building blocks in silicon nitride

A photonic chip essentially consists of many building blocks stacked together. These are mostly confined to in-plane integration since the use of the third dimension is minimized due to the high fabricational complexity. A photonic integrated circuit comprises a large sequential stacking of building blocks. A large variety of functional operations can be realized using only a small set of fundamental building blocks. To understand the on-chip photonic technology it is important to know what the fundamental building blocks are and how they work. In this section, we will discuss these fundamental building blocks and mention the specs of the building blocks offered by QuiX Quantum.

Phase shifter

$$e^{i\varphi} = e^{i(\varphi 1-\varphi 2)} = e^{i2\pi(n1\,d1-n2d2)/\lambda}$$



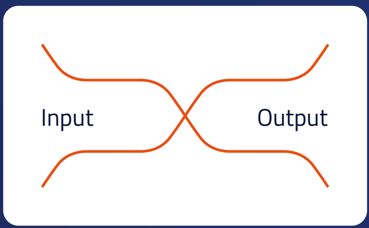
Where λ is the wavelength of the light, $n_{1,2}$ is the refractive index of waveguide 1,2, $d_{1,2}$ is the physical path length of waveguide 1,2, and φ is the phase difference between waveguide 1 and 2. This is visualized in the sketch on the left. The optical path length is defined as $n_1 d_1$. By changing the optical path length one can change the phase between waveguide 1 and 2, which is often realized by changing the refractive index of the material, since it is hard to tune the actual length of the waveguide once it has been fabricated.

Refractive index tunability can be achieved through thermal heating, stress and doping. We typically use thermal tuning for our phase shifters since it is a lossless and compact solution. An increase in temperature results in a linear change of the refractive index through the thermo-optic effect. The thermo-optic coefficient of silicon nitride is given as:

$$\frac{dn_{si2N4}}{dT} = (2{,}45 \pm 0{,}09) \times 10^{-5} = \frac{RIU}{°C}$$

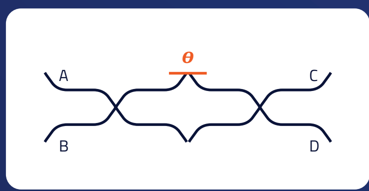
Using sufficiently long heaters placed on top of the waveguides, it is possible to achieve a full 2π phase shift. The heaters are made of platinum and typically have a width of 30 µm and height of 50 nm. Both placing the heaters on top of the waveguides and heating the waveguides do not affect the loss in any way.

Beamsplitter



A beamsplitter is a device that can split an incoming light beam into two outcoming beams by a given splitting ratio. To realize an on-chip beam splitter, two waveguides are brought close together, forming a so-called directional coupler, such that light from one waveguide can couple to the other waveguide. Depending on the waveguide cross section and the interaction length (the length along which the waveguides remain closely together) it is possible to transfer a specific fraction of the light to the other waveguide. By combining two 50/50 beamsplitters with a phase shifter in between, it becomes possible to make the beamsplitters tunable such that it divides the power over any desired ratio. This will be explained in the next part about the Mach-Zehnder interferometer. In general for 50/50 beamsplitters operating at 1550 nm the splitting ratio will not vary more than 10%.

Tunable beamsplitter



A tunable beamsplitter is a device that can tune the amount of light going to the output ports in any desired ratio. In integrated photonics this device is formed by combining two fixed 50/50 beamsplitters, i.e., directional couplers, and a phase shifter (in red). This means that a tunable beamsplitter is strictly not a fundamental building block. However, since it is used so often in both classical and quantum experiments, we treat it here as a fundamental building block. In the picture on the right a sketch of tunable beamsplitter is shown, which is also known as a Mach-Zehnder interferometer (MZI). Using the phase shifter one can change the phase of a light beam propagating in the upper waveguide with respect to the light beam in the lower waveguide. The two beams recombine at the second 50/50 beamsplitter, such that they interfere constructively or destructively. Using the interference, it is possible to steer the light coming from input A to output C or output D or any combination in between. The phase change is induced by thermal-optical tuning as described in the previous section. It is important that the other waveguide inside the MZI, that has no phase shifter, does not experience any heating and subsequent refractive index change, meaning that there is zero thermal cross talk between the two arms of the interferometer. The tunable beamsplitter is characterized in terms of its tuning range, visibility and extinction ratio. At 1550 nm we measured hundreds of tunable beamsplitters and obtained an average visibility of 99.9% with a standard deviation of 0.05%.

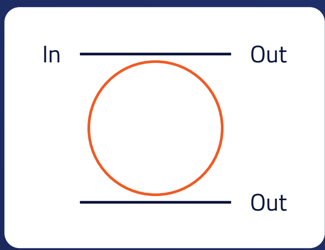
Delay line

Delay lines are simple building blocks that delay the light in a waveguide respect to another by increasing the optical path length of the waveguide. A delay line is preferred above a tunable phase shifter if a fixed-value delay needs to be implemented. For delays longer than the wavelength of light, spirals are used. The loss of the delay lines, both fixed and spiral delays, can be as low as to that of a straight waveguide. The delay lines on our TriPleX platform are lossless components apart from the intrinsic waveguide loss.

Spot-size converter

Spot-size converters (SSC) are very crucial building blocks enabling light coupling from a source (free space, fiber or a chip) to a waveguide on a photonic integrated circuit. In spot-size converters the thickness of the waveguide changes using a vertical taper. This leads to an adiabatically transitioning of the mode field diameter of the guided light to an external coupling component. The spot-size converter might look trivial, however high-level engineering is needed to guarantee that the mode field diameters of the connected components have a perfect optical overlap. Our spot-size converters have a single mode fiber-to-chip coupling loss of around 0.5 dB per facet.

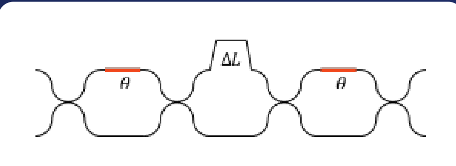
Ring resonator Filter



Optical filtering is an important functionality that can be achieved using microring resonators. A microring resonator is a circularly travelling cavity that supports light propagation along its perimeter. Light can couple from the bus waveguide into the cavity and whenever the light travelling inside the cavity experiences constructive interference, it continues to propagate inside the resonator. This only occurs at wavelengths resonant with the optical cavity length. The ring waveguide behaves thus as a wavelength selective optical cavity that stores, enhances and transmits only resonant light, while light at non-resonant wavelengths does not couple into the cavity. The Q-factor determines the optical filtering bandwidth, where a higher Q-factor correspond to a narrower filtering bandwidth. A high Q-factor requires low internal cavity loss. Currently, Q-factors of 10^6 can be obtained, which require a relatively large radius of 300 μm to 500 μm, thus providing a small free spectral range (FSR). By combining multiple ring resonators, it is possible to create more advanced types of filtering such as Vernier filters. A Vernier filter extends the free spectral range of the filter without sacrificing a narrow spectral bandwidth.

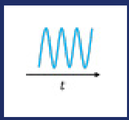
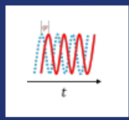
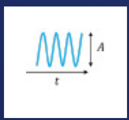
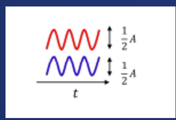
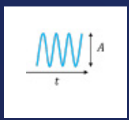
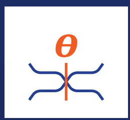
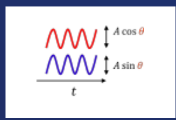
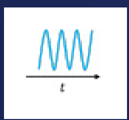
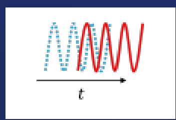
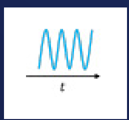
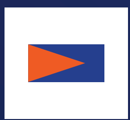
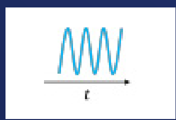
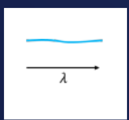
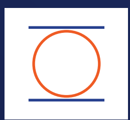
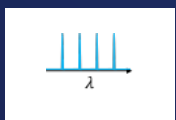
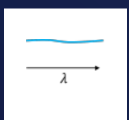
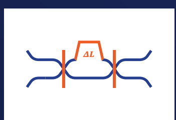
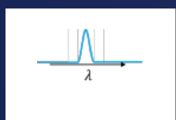
Mach-Zehnder Filter

Mach-Zehnder filters (MZFs) are another type of wavelength-dependent filters. The MZF consist of two tunable beam splitters connected to each other with a path length difference ΔL between the two connecting waveguides. Here the free spectral range of the filter scales inversely with the path length difference ΔL. Because the filter is not limited by bending loss, it is possible to achieve a larger free spectral range. This comes at the cost of much wider filter bandwidth, which typically has a sinusoidal spectral response. By combining multiple MZF one can realize versatile wavelength filters in both extinction ratio and FSR. This makes it possible to achieve higher order filters or filters with a flat-top response. They can for example be used to create switched delay lines. Combining ring resonator filters and Mach-Zehnder filters allows realizing most filter types.



Summary of the building blocks

The table below summarizes the operations of all the mentioned building blocks. Combining these building blocks leads to a large range of complex operations and on-chip photonic functionality.

Input	Building block	Output	Comment
			Tunable
			Tunable
			Here for 50/50 BS, but any fixed ratio can be designed
			Tunable
			For perfect coupling
			High Q, small FSR
			Broader filter bandwidth, broader FSR

What we offer

In the large photonics ecosystem, QuiX Quantum specializes in quantum applications and photonic processors by making use of reconfigurable photonic integrated circuits based on the low-loss Si¬3N4 platform. Integrated photonics is a rapidly growing field with a multitude of both scientific and commercial applications ranging from sensing, telecommunication, 5/6G wireless communications and machine learning. A field that would strongly benefit from integrated photonics is quantum information processing, for reasons such as phase stability, reconfigurability and high component density. Combining these with the low loss and versatility of the silicon nitride platform, QuiX Quantum strongly believes in its prospects for quantum applications.

The photonic processors developed at QuiX Quantum are used for processing many light modes with applications in large multimode interferometric experiments, matrix multiplication and quantum computing. More information can be found in our white paper The QuiX Quantum photonic processor.

We also have extensive knowledge of quantum applications using photonic integrated circuits such as quantum random number generators (QRNG) and quantum key distribution (QKD) on-chip. It is possible for our engineers to design and test photonic chips which can be used in QRNG, QKD and quantum sensing.

Interested in silicon nitride photonic chips?

If reading this paper sparked your interest in the silicon nitride platform for photonic chips or if you want to know if a specific problem is solvable using a photonic chip, do not hesitate to contact us! QuiX Quantum engineers are happy to discuss our photonic solutions for your problems and look for a solution suited to your needs. They can also give more details or perform an evaluation study for your specific application.

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