Towards Semiconductor-Superconductor-Crystal Hybrid Integration for Quantum Photonics

Maximilian Protte[1], Lena Ebers[2], Manfred Hammer[2], Jan Philipp Höpker[1], Maximilian Albert[1], Viktor Quiring[1], Cedrik Meier[1], Jens Förstner[2], Christine Silberhorn[1], Tim J. Bartley[1]

[1]Department Physics, University of Paderborn, Warburgerstraße 100, 33098 Paderborn, Germany

[2]Department of Electrical Engineering and Information Technology, University of Paderborn, Warburgerstraße 100, 33098 Paderborn, Germany

Author e-mail address: maximilian.protte@upb.de

Abstract: We fabricate silicon tapers to increase the mode overlap of superconducting detectors on Ti:$LiNbO_3$ waveguides. Mode images show a reduction in mode size from 6 µm to 2 µm FWHM, agreeing with beam propagation simulations.

1. Introduction

As a platform for integrated quantum photonics, titanium in-diffused waveguides in bulk lithium niobate (Ti:$LiNbO_3$) has proven very versatile in recent years [1,2]. Many functional devices have been demonstrated due to its low loss guiding (<0.1 dB/cm) and its standout electrooptical and nonlinear properties at 1550 nm, such as quantum light sources based on SPDC, passive routing and active modulation [2,3].

The low-loss propagation and high mode overlap with optical fiber (93%) originates from the weak guiding of the electro magnetic field. This makes Ti:$LiNbO_3$ ideal for building modular, fiber connected devices. However, the low confinement means coupling to small structures is challenging. This is particularly noticeable when coupling the evanescent field to superconducting detectors deposited on top of the waveguide, which we have recently demonstrated [4,5].

In this work, we take the first steps towards addressing the weak confinement of Ti:$LiNbO_3$ waveguides with additional semiconductor structures to build a hybrid semiconductor-on-crystal integration platform [3]. We have fabricated titanium in-diffused waveguides with silicon tapers, which draw the mode into Si waveguides with significantly stronger confinement. We analyze the effect of the taper length both theoretically and experimentally, and have imaged the resulting modes.

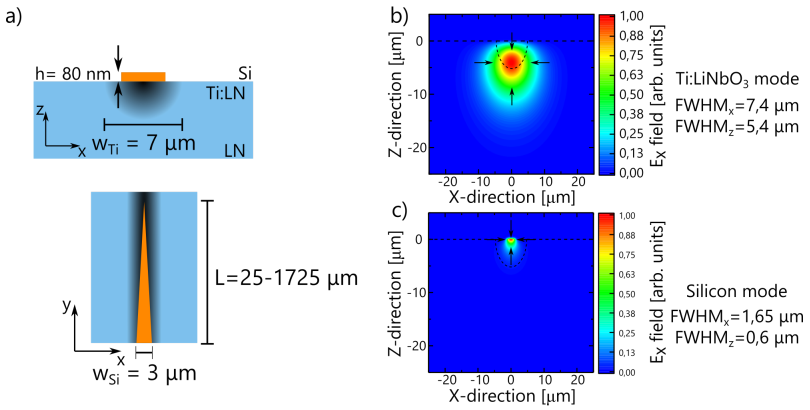

Fig. 1. a) pictures schematic of the fabricated silicon taper on top of a Ti:$LiNbO_3$ waveguide. b) and c) show the mode of the Ti:$LiNbO_3$ waveguide and the silicon waveguide on top.

2. Simulations

A schematic of the tapers is shown in Fig. 1 a). With the high refractive index of silicon, we seek to manipulate the guided TE mode of the Ti:$LiNbO_3$ waveguide (see Fig. 1 b)) such that a higher electric field concentration is achieved close to the surface. The effect of the tapers has been analyzed with the help of finite element method (FEM) and beam propagation (BPM) simulations. The TE mode of the unperturbed waveguide is shown in Fig. 1 b). The mode size is comparable to the mode of a single mode glass fiber at 1550 nm. At the end of the taper the calculated TE mode results in the distribution shown in Fig. 1 c). A linear taper with the parameters shown in Fig.

1 a) is designed to adiabatically change the mode from the input mode (Fig. 1 b)) to the output mode (Fig. 1 c)). Calculating the FWHM of the Intensity gives the values included in Fig. 1. By including the tapers, the mode size could be reduced to 22% and 11% of the initial size for x- and z- direction.

3. Fabrication

To achieve single mode guiding at a wavelength of 1550 nm a titanium layer of 86 nm is deposited on the lithium niobate. A photoresist is structured with a laser lithography resulting in a 7 µm wide stripe protecting the titanium. After a wet etching step, the remaining titanium is in-diffused at 1060 °C for several hours. The diffusion of the titanium results into the refractive index profile needed for waveguiding.

The silicon is deposited with a PECVD. With a gas mixture of silane and argon (2%/98%) a silicon film of 80 nm thickness is fabricated. A laser lithography system is used to pattern the tapers. A highly anisotropic etching is achieved with a dry etching process based on C_4F_8/SF_6 in an ICP-RIE. The tapers are covered with a protective layer of silicon dioxide. In order to image the field distribution on the end facet the sample needs to be polished to the position of the silicon tapers. Tapers with the parameters shown in Fig. 1 a) were fabricated.

4. Results and Outlook

For the analysis of the tapers, mode images at the end of the tapers are taken. By fitting the measured distribution to Hermite-Gaussian spatial modes, the FWHM can be calculated. The results are shown in Fig. 2 a). A decrease of the mode size can clearly be identified for sufficiently long tapers. A minimum of $FWHM_x$ = 2,3 µm and $FWHM_z$ = 1,9 µm could be achieved, resulting into 33% and 36% of the initial mode size. A clear manipulation of the mode size can be seen from the results and the inserts in Fig. 2 a).

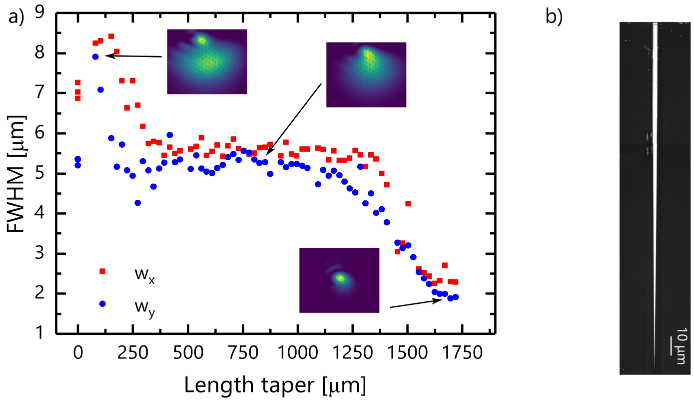

Fig. 2. a) shows the measured FWHM after the silicon taper. In b) a picture of the fabricated taper is displayed.

The mode images in Fig. 2 a) are highly promising. Not only is the mode made significantly smaller than for the standard waveguide structures, the main position of the power of the mode is drawn to the interface between the silicon and the lithium niobate. This is expected to provide a large overlap of the field with a detector placed at this interface, significantly increasing on-chip detection efficiency. However, more experiments need to be undertaken to determine other figures of merit for this system, particularly losses.

3. References

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