Deterministic Phase-Matching of Micro-Transfer-Printed Periodically-Poled Lithium Niobate Waveguides

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Abstract: State-of-the-art periodically-poled lithium niobate waveguides struggle with extreme fabrication sensitivity, resulting in unpredictable phase-matching wavelengths. We developed a micro-transfer-printed periodically-poled lithium niobate waveguide that enables deterministic phase-matching at a predefined wavelength through optical feedback.

Introduction

The uprise of thin-film lithium niobate (LN) waveguides has set new records in both modulation and frequency conversion efficiencies due to the sub-wavelength confinement made possible [1]. That same confinement enables strong dispersion engineering through the waveguide dimensions, but simultaneously comes with much larger fabrication sensitivity. This poses a challenge for the phase-matching in $\chi^{(2)}$ processes, as the mode indices are affected by fabrication variation. It is well-known this sensitivity reduces the conversion efficiency of long periodically-poled lithium niobate (PPLN) waveguides [2], but also makes the exact phase-matching wavelength unpredictable. Therefore, it becomes problematic to reliably co-integrate frequency converters with e.g. on-chip lasers. We have developed a new type of nonlinear waveguide, where PPLN is micro-transfer-printed (µTP) onto a silicon photonics (SiPh) chip at a back-end level [3]. Its hybrid geometry makes it possible to tweak the waveguide dimensions based on optical feedback, allowing us to place the phase-matching at the desired wavelength. Together with the strength of micro-transfer printing to densely co-integrate different materials, it becomes possible to phase-match frequency converters to integrated lasers or other resonant components on a single chip.

Fabrication sensitivity of PPLN waveguides

The nonlinear waveguide is fabricated through micro-transfer printing, where a suspended PPLN film is picked and printed on a silicon nitride (SiN) waveguide (Figure 1a). This introduces a strong $\chi^{(2)}$ nonlinearity onto the silicon photonics platform, allowing for efficient frequency conversion. We consider second harmonic generation (SHG) from 1550 nm to 775 nm, with the mode profiles depicted in Figure 1b. To examine the fabrication sensitivity of the waveguide, we look at the effect of LN thickness variations on the phase-matching wavelength in

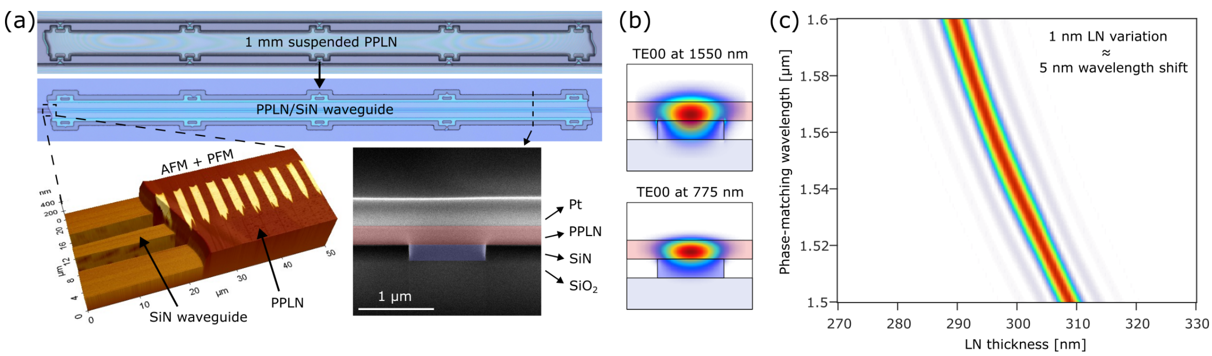

Fig. 1. (a) Fabrication of the nonlinear waveguide: suspended PPLN film is picked and printed on SiN waveguide (with AFM/PFM image and SEM cross section), (b) Waveguide mode profiles at 1550 and 775 nm, (c) Fabrication sensitivity of the phase-matching wavelength.

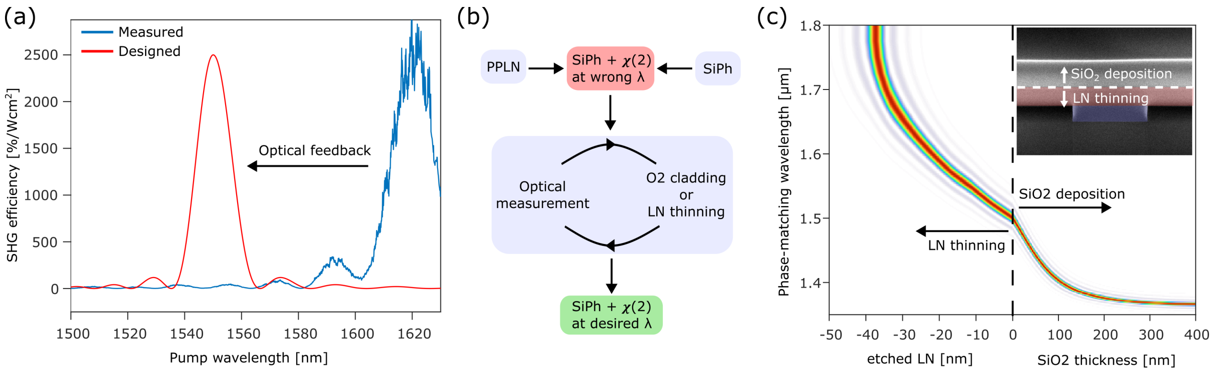

Fig. 2. (a) Measured SHG of a nonlinear waveguide, (b) Schematic of the deterministic phase-matching through optical feedback, (c) Effect of oxide cladding and LN thinning on the phase-matching wavelength.

Figure 1c. For every nanometer in LN thickness, there is a wavelength shift of five nanometers. As current fabrication processes are unable to have sub-nanometer control, the operating wavelength becomes unpredictable. Similarly, conventional lithium-niobate-on-insulator (LNOI) rib waveguides rely on a shallow etch which lacks sub-nanometer control. Hence, the same unpredictable phase-matching is observed.

Deterministic phase-matching in transfer-printed PPLN waveguides

We measure the fabricated nonlinear waveguide and observe phase-matching at 1620 nm instead of the designed 1550 nm, with a conversion efficiency of 2500 %/Wcm^2 (Figure 2a). As discussed, this discrepancy can be fully attributed to the fabrication sensitivity. Nevertheless, our hybrid waveguide geometry allows to compensate for this sensitivity. In contrast to conventional LNOI rib waveguides, we have access to the pristine top interface of the PPLN slab. By adjusting this interface based on optical feedback, the waveguide modes are pulled up or down, shifting the phase-matching to lower or higher wavelengths, respectively, with the workflow shown in Figure 2b. To lower the interface, we have developed a LN wet etch, similar to Zhuang et al. [4], which is compatible with the silicon photonics platform to thin down the transfer-printed PPLN. The etch has a measured RMS roughness of 0.33 nm and an etch rate that can be made low enough (order of 1 nm/min) for controlled thinning. Additionally, due to the slab geometry, the PPLN can be thinned without the poled domains appearing through the anisotropy of the wet etch. As a result, the waveguide modes are pushed down and the phase-matching wavelength increases, as shown in Figure 2c. Conversely, by adding a thin controlled oxide cladding, we can effectively thicken the PPLN slab and pull the modes up, shifting the phase-matching to lower wavelengths. Thus, based on optical feedback, the phase-matching point can be systematically shifted towards the designed wavelength. Furthermore, this is compatible with co-integration of other components such as integrated lasers or detectors, as these are readily protected from the LN wet etch by a thin oxide layer [4]. Lastly, any remaining fine tuning can be done with the thermo-optic effect through integrated heaters.

Conclusion

We have developed an efficient nonlinear waveguide on the silicon photonics platform through micro-transfer printing of periodically-poled lithium niobate. Its hybrid geometry enables deterministic placement of the phase-matching wavelength through optical feedback. We believe this is an important step towards integrating efficient nonlinear waveguides in photonic integrated circuits.

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