The impact of lateral leakage on the nonlinear optical waveguide design in lithium niobate on insulator (LNOI)

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ABSTRACT

In this contribution we show that lateral leakage at the second harmonic wavelength can cause a reduced nonlinear optical conversion efficiency in lithium niobate on insulator ridge/rib waveguides. By designing the waveguide parameters carefully, we avoided this effect, which enabled us to demonstrate a nonlinear optical conversion efficiency of ~780% $W^{-1}cm^{-2}$ in these waveguides.

Keywords: Nonlinear Optics, Lithium Niobate, Lateral Leakage, Quasi-Phase Matching.

1. INTRODUCTION

In recent years, lithium niobate on insulator (LNOI) has attracted significant interest in the integrated optics research community [1]. This interest can be attributed to the attractive material properties of lithium niobate, including strong electro optic, nonlinear optic and piezo electric effects. Furthermore, optical waveguides with strong optical field confinement can be achieved in this platform by optically loading the lithium niobate thin film with a strip of material that has a high refractive index (such as silicon nitride - SiN), or by etching the lithium niobate directly [1]. The strong optical mode confinement enables small waveguide bending radii and increased efficiency of the nonlinear optic and the electro-optic interaction. These properties enabled record breaking demonstration, such as a second-harmonic generation (SHG) efficiency of 2600% $W^{-1}cm^{-2}$ when using periodically poled waveguides [2] and a voltage length product of 2.8 Vcm when applying a voltage to co-planar electrodes [3].

The SHG efficiency of 2600% $W^{-1}cm^{-2}$ [2] was achieved by etching the lithium niobate directly, which is effective but requires dedicated fabrication approaches. Furthermore, the quasi-phase matching wavelength is strongly depended on the exact waveguide dimensions, which makes it prone to fabrication tolerances. A way to overcome these challenges is to dielectric loading the lithium niobate thin-film with a strip of SiN, as it allows one to harness the existing foundry fabrication infrastructure as only the nitride needs to be deposited and etched. However, the recently demonstrated conversion efficiency using silicon nitride loading on LNOI (160% $W^{-1}cm^{-2}$) was an order of magnitude lower compared to the theoretically predicted one (1600% $W^{-1}cm^{-2}$) [4]. The difference between the experimental and theoretical conversion efficiency has so far not been completely understood.

In this contribution, we investigate the impact of lateral leakage on SHG efficiency in strip loaded LNOI and find that the generated SH can leak into the slab modes due to TE to TM conversion [5], reducing the overall conversion efficiency of the device. We show how to design optical waveguides to avoid this effect. Applying these design considerations enabled us to demonstrate periodically poled SiN loaded LNOI waveguides with a conversion efficiency of ~780% $W^{-1}cm^{-2}$.

2. DESIGN AND SIMULATION

Lateral leakage in a photonic waveguide was first observed in silicon on insulator ridge/rib waveguides, where the TM optical waveguide mode couples to a TE slab mode, which has a higher effective refractive index [5]. The angle Θ under which the TM optical waveguide mode couples to the TE slab modes depends thereby on the phase matching ($n_{\mathrm{TE}} \sin\Theta = n_{\mathrm{TM}}$). This effect can be seen as a contribution to waveguide loss, which is unwanted in most cases.

Ridge waveguides in LNOI, such as the illustrated one in the inset of Figure 1, are prone to a similar effect. Periodically poled waveguides are usually fabricated on X-cut lithium niobate, which means that the TE polarization is used for pumping the nonlinear optical process and to employ the high nonlinear optical coefficient d_{33} along the crystallography Z-direction. However, as lithium niobate is birefringent, the effective index of the TM slab mode that surrounds the ridge waveguide, can be higher than that of the TE waveguide mode (as the ordinary refractive n_{o} index is higher than the extraordinary refractive n_{e} index in lithium niobate), resulting in coupling from TE guided mode to TM slab mode. Figure 1 shows the difference between the effective index of the TE waveguide mode and the TM slab mode ($\Delta n_{\mathrm{eff}} = n_{\mathrm{eff,TE\ waveguide}} - n_{\mathrm{eff,TM\ slab}}$) as a function of wavelength and lithium niobate thickness, using the following parameters: the silicon nitride (SiN) thickness was

400 nm, the etch depth (h_{etch}) was 350 nm and the waveguide width (w) was 2 µm. The black line in the graph indicates a refractive index difference between the modes of zero ($\Delta n_{\mathrm{eff}} = 0$), which means that waveguides that are above the black line can suffer from lateral leakage, such as the device design of Ref. [4]. One can see that the lithium niobate thin-film thickness needs to be thinner for waveguides that are designed for shorter wavelengths. For our design we chose a lithium niobate thin-film thickness of 300 nm, in order to avoid lateral leakage at the SH wavelength, when pumping the waveguide at C-band wavelengths.

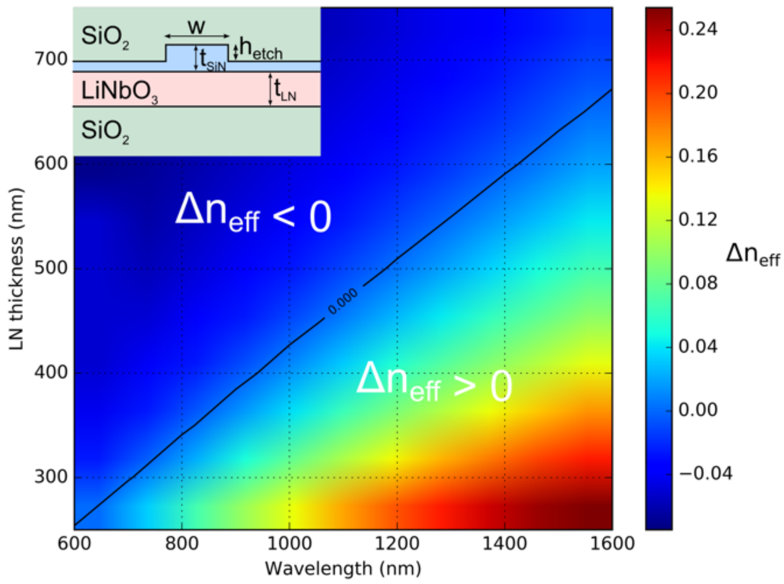

Figure 1. Effective index difference between the TE waveguide mode and the TM slab mode. Waveguide with $\Delta n_{eff} < 0$ can suffer from lateral leakage.

3. EXPERIMENTAL RESULTS

For the waveguide fabrication, we followed the fabrication steps described in Ref. [4]. First we patterned comb shaped electrodes on the surface of the lithium niobate thin-film, to which we applied three HV pulses to achieve domain inversion. The thinner lithium niobate thickness requires us to adapt the poling period of the quasi-phase matching structure to 4.98 µm. The length of the periodically poled waveguide was 4.8 mm. Afterwards, the comb electrodes for the poling process were removed by wet etching. A SiN layer with a thickness of 400 nm was deposited by reactive sputtering. The patterning of the SiN was achieved by standard lithography and a dry etching process. The waveguides were finally cladded with a SiO_2 cover layer with a thickness of 1 µm by means of PECVD.

The setup for characterizing the nonlinear waveguides is illustrated in Figure 2. Light from a tunable laser source is coupled in and out of the waveguide using lensed fibers. At the output the fundamental and SH wavelengths are separated using a wavelength division multiplexer (WDM) and detected by corresponding photodetectors.

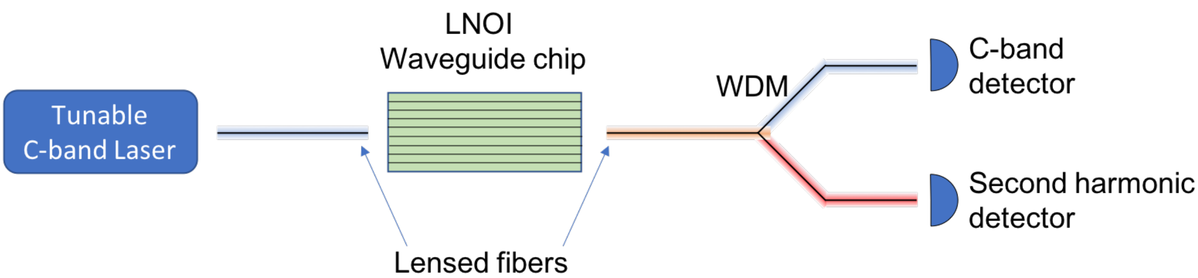

Figure 2. Illustration of the characterization setup for the SH generation in the periodically poled waveguides.

Figure 3(a) shows the fundamental and SHG power on the chip as a function of the pump wavelength. It can be seen that the SHG power is highest around a wavelength of 1.575 µm. The periodic oscillations in the fundamental and SH power can be explained by the Fabry-Perot effect from the end facets of the waveguide. Figure 3(b) shows the SHG efficiency as a function of the pump wavelength, where the green curve is a fitted sinc^2

function. It can be seen that a conversion efficiency of 780% $W^{-1}cm^{-2}$ is feasible in these waveguides, when the lateral leakage effect is avoided at the second harmonic wavelength.

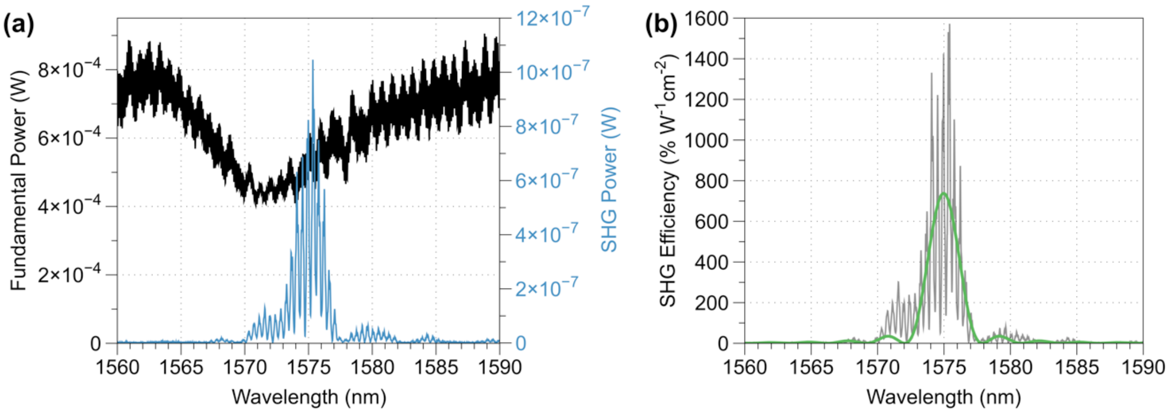

Figure 3. (a) Fundamental and SH power as a function of the pump wavelength; (b) SHG efficiency and fitted curve.

4. CONCLUSIONS

We have shown that engineering the lateral leakage of the SH in LNOI waveguides can enhance the conversion efficiency of the nonlinear optical process. This is achieved by reducing the thickness of the lithium niobate thin-film, so that the effective index of the TM slab mode is lower than the TE waveguide mode at the SH wavelength. This enabled us to demonstrate a SHG efficiency of ~780% $W^{-1}cm^{-2}$.

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