Improved second harmonic performance in periodically poled LNOI waveguides through engineering of lateral leakage

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Abstract: In this contribution we investigate the impact of lateral leakage for linear and nonlinear optical waveguides in lithium niobate on insulator (LNOI). Silicon nitride (SiN) loaded and direct patterned lithium niobate cross-sections are investigated. We show that lateral leakage can take place for the TE mode in LNOI ridge waveguides (X-cut lithium niobate), due to the birefringence of the material. This work gives guidelines for designing waveguides in LNOI that do not suffer from the lateral leakage effect. By applying these design considerations, we avoided the lateral leakage effect at the second harmonic wavelength of a nonlinear optical waveguide in LNOI and demonstrate a peak second harmonic generation conversion efficiency of \(-1160\%\) W\(^{-1}\)cm\(^{-2}\).

1. Introduction

Lithium niobate on insulator (LNOI) is an emerging photonic integrated circuit (PIC) platform that offers similar integration densities as platforms based on silicon nitride (SiN) and silicon on insulator (SOI), with the advantage of having a strong second order nonlinear optical and electro optical effect [1,2]. Low loss optical waveguides have been achieved in this platform by etching the lithium niobate directly form a ridge/rib or wire waveguide [3,4] and by optical loading the lithium niobate thin film with a strip of material that has a higher refractive index compared to silica [5-7]. One of the most commonly used optical loading material is SiN, due to the wide transparency window and the ease of deposition and patterning. The crystal orientation of the lithium niobate thin-film plays an important role in the waveguide design. The most common crystal orientation for the lithium niobate thin-film is either X cut or Y cut with the crystallographic Z axis is in the plane of the lithium niobate thin-film, with the strongly electro-optic \((r_{33})\) or nonlinear optic \((d_{13})\) tensor components oriented laterally across the waveguides. This orientation makes it possible to use coplanar electrodes placed symmetrically on either side of a waveguide to modulate the waveguide index [8,9] or to use similar electrodes with higher voltage to pole waveguides and achieve quasi-phase matching structures for nonlinear optical applications [5,10]. These properties enabled record breaking demonstration, such as optical modulation with a voltage length product of 2.8 Vcm [8] and a second-harmonic generation (SHG) efficiency of 2600% W\(^{-1}\)cm\(^{-2}\) in periodically poled waveguides [10].

The SHG efficiency of 2600% W\(^{-1}\)cm\(^{-2}\) [10] was achieved by etching the lithium niobate directly, which is effective, but requires dedicated fabrication approaches. Furthermore, the quasi-phase matching wavelength is strongly dependent on the exact waveguide dimensions, which makes it prone to fabrication tolerances. A way to avoid these challenges is to form waveguides in un-etched thin films of lithium niobite by dielectric loading with a thin strip of moderately high index material. Silicon nitride (SiN) is an attractive choice having sufficiently high index for relatively compact waveguide, but harnessing the mature and CMOS compatible fabrication techniques of the SiN as only the nitride needs to be deposited and etched [11]. 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$^{-2}$) [5]. 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 SiN strip loaded LNOI and find that the generated second harmonic (SH) can leak into the slab modes due to TE to TM conversion, 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 peak conversion efficiency of ~1160% W$^1$ cm$^{-2}$.

2. Simulation and design

Lateral leakage describes an effect where light from a shallow etched waveguide mode radiates into orthogonally polarized slab modes that have higher effective refractive indices. In photonics, this effect was first observed in silicon on insulator (SOI), when the waveguide was excited with a TM mode (see illustration in Fig. 1a) [12-15]. In this case, the TM waveguide mode can have a lower effective refractive index compared to the orthogonally polarized TE slab modes, because the TM waveguide mode has a strong evanescent field outside of the waveguide. The angle Θ under which the TM waveguide mode couples to the TE slab modes depends on the phase matching ($n_{TE} \sin(\Theta) = n_{TM}$) [16]. This means that if a shallow etched SOI ridge waveguide is excited with a TM waveguide mode, then the waveguide will radiate beams of TE light into the slab on each side of the waveguide under an angle Θ. The strength of radiation at each wall is determined by the geometry of that wall [17]. This effect can be seen as a contribution to waveguide loss, which is unwanted in most cases.

In SOI lateral leakage can only occur in ridge waveguides when they are excited with a TM mode, as the orthogonally polarized TE slab modes can have a significantly higher effective refractive index. However, this is not the case in LNOI. Here, the crystal orientation and the orientation of the light polarization needs to be carefully considered, as lithium niobate is birefringent. The birefringence means that the lithium niobate crystal exhibits an extraordinary refractive index ($n_e$) of ~2.138 and an ordinary refractive index ($n_o$) of ~2.211, for a wavelength of 1.55 µm.

![Fig. 1. (a) In SOI lateral leakage of TE slab modes can occur when a ridge waveguide is excited with a TM mode. (b) Can lateral leakage of TM slab modes occur when a LNOI ridge waveguide is excited with a TE mode?](image)

As mentioned in the introduction, it is common to have the polar Z-axis in the plane of the lithium niobate thin-film, if one wants to utilize either the strongest electro-optical effect or fabricate periodically poled nonlinear optical waveguide in LNOI by using electrodes on either side of the waveguide. This also requires the excitation of the waveguide with a TE mode, to align the polarization of the light with the polar Z crystal axis (to use either $r_{33}$ or $d_{33}$). To investigate if LNOI can exhibit lateral leakage, we calculated the effective index difference between the TE polarized waveguide mode and the TM polarized slab mode by $\Delta n_{eff} = n_{TE,wg} - n_{TM,slab}$. Lateral leakage can only occur when the effective refractive index of the waveguide mode is lower than the orthogonally polarized slab mode. For negative effective index difference values, one can therefore expect that lateral leakage can take place, which would manifest as additional source of waveguide loss, as illustrated in Fig. 1b.

2.1 Lithium niobate etched ridge waveguides in LNOI
C. Wang et al. [10] demonstrated periodically poled LNOI waveguides with an efficiency of 2600% W^{-1}cm^{-2}, which is close to the theoretical efficiency of these waveguides of ~4000% W^{-1}cm^{-2}. This indicates that these waveguides did not suffer from lateral leakage at the fundamental and the SH wavelength. To investigate if this is indeed the case, we simulated the difference between the effective index of the guided TE waveguide mode and the radiating TM slab mode for a LNOI ridge waveguide with a width of 1.4 µm and a etch depth of 300 nm (similar to C. Wang et al. [10]), as a 2D function of the wavelength and the LN thin-film thickness. The results are shown in Fig. 2a. For convenience we plotted a line in the graph that indicates where the effective index difference is zero. It can be seen that for nearly all wavelengths and lithium niobate thicknesses the TE waveguide mode has an effective refractive index that is higher than the TM radiating mode with the difference getting higher for thinner lithium niobate thicknesses and shorter wavelengths. Only in the top left corner (for short wavelengths and thick LN thin-film thickness) a negative refractive index difference can be observed. These results indicate that for most of the investigated waveguide cross-sections lateral leakage will not take place, this includes both the fundamental and SH wavelengths for the cross-section from C. Wang et al. [10], when using a LN thickness of 600 nm.

Next, we investigated the effective refractive index difference in the case that the etch depth is reduced to only 150 nm. This shallower ridge waveguide might be attractive for low-loss waveguides as less field from the optical mode would interact with the waveguide sidewall. Fig. 2b shows the difference of effective refractive indices as a function of the wavelength and the LN thin-film thickness. It can be seen that the curve indicates that a refractive index difference of zero has moved from the top left corner further to the center of the graph. This means that a larger distribution of waveguide cross-sections (for short wavelengths and thick LN thin-film thicknesses) can have TE waveguide modes with index lower than the radiating TM slab around them. This indicates that the TE waveguide mode for these parameters can suffer from lateral leakage, which will manifest as an addition loss. If one wants to design nonlinear optical waveguides with such an etch depth, one needs to consider this. For example, periodically poled LNOI waveguides for SHG with a fundamental wavelength of 1.55 µm would require a LN thickness of below ~500 nm.

Fig. 2. Effective refractive index difference between the TE waveguide mode and the TM slab mode as a 2D function of the wavelength and the LN thickness, for an etched lithium niobate ridge width of 1.4 µm and an etched depth of 300 nm (a) or 150 nm (b).

2.2 Silicon nitride loaded ridge waveguides in LNOI
L. Chang et al. [5] demonstrated a nonlinear optical conversion efficiency of 160% W\(^{-1}\)cm\(^2\) for SiN loaded ridge waveguides in LNOI. This value is approximately one order of magnitude lower than the theoretically predicted conversion efficiency. To investigate if these waveguides suffered from lateral leakage we calculated the effective refractive index differences for SiN loaded LNOI ridge waveguides with similar dimensions. We chose a SiN ridge width of 2 µm, a SiN ridge thickness of 400 nm and an etch depth of 380 nm. The resulting effective refractive index difference between the TE waveguide mode and the TM slab mode is presented in Fig. 3a as a function of wavelength and lithium niobite film thickness. It can be seen that short wavelengths and thick LN thicknesses can have a negative effective refractive index difference of the modes, significantly more so than the LN ridge waveguides simulated in Section 2.1. This indicates that TE waveguide modes are more susceptible to lateral leakage, which will manifest as an additional loss. It can also be seen that for a LN thin-film thickness of 700 nm, the SHG wavelength (775 nm) is far in the area with a negative refractive index contrast and can therefore suffer from lateral leakage. This could explain the observed lower SHG efficiency in Ref. [5], as some of the generated SH would leak into the unguided TM slab mode where it would start to expand away from the waveguide. This loss of intensity of light at the second harmonic would counter the parametric growth, resulting in far less efficient nonlinear conversion than what would be expected if the second harmonic were fully confined within the waveguide. One can also see that the waveguides may even suffer from lateral leakage for a wavelength of 1.55 µm. This was not observed in Ref. [5] and will be further investigated in Section 3.1.

To reduce the chance of waveguides with lateral leakage, one might consider increasing the thickness of the SiN loading, as this might increase the refractive index difference of the TE waveguide mode to the TM slab mode. To investigate this, we calculated the effective index difference between TE guided and TM radiating modes for SiN loading thickness of 600 nm and a etch depth of 580 nm. The results are presented in Fig. 3b. It can be seen that increasing the SiN loading thickness moves the zero effective refractive index line slightly towards the top left corner of the graph. However, it becomes clear that increasing the SiN loading thickness helps a bit, but not as much as one might anticipate. This can be explained by the fact that most of the optical mode in the vertical direction is confined in the lithium niobate and only a small component is in the SiN loaded area. Increasing the SiN thickness has therefore only a very small effect on the overall effective refractive index of the TE waveguide mode. According to Fig 3a and 3b, the most effective way to reduce lateral leakage in these waveguides is to reduce the thickness of the lithium niobate.
Fig. 3. Effective refractive index difference between the TE waveguide mode and the TM slab mode as a 2D function of the wavelength and the LN thickness, for a SiN ridge width of 2 μm. (a) shows the results for a SiN thickness is 400 nm and has a etch depth of 380 nm and (b) shows the results for a SiN thickness is 600 nm and has a etch depth of 580 nm.

3. Experimental results and discussion

As a first step, we experimentally investigate lateral leakage in SiN loaded LNOI waveguides that have a similar cross-section to Ref. [5]. This investigation is described in Section 3.1. Afterwards (in Section 3.2), we investigate a waveguide cross-section with a 300 nm thick LN thin-film, which should not suffer from lateral leakage at the fundamental and SH wavelength for efficient SHG.

3.1 Measurement of lateral leakage loss in silicon nitride loaded ridge waveguide

In Section 2.2 we predicted that the waveguides from Ref. [5], which had a LN thin-film thickness of 700 nm, may exhibit lateral leakage at the fundamental and SH wavelength. To investigate if the waveguides used in Ref. [5] does indeed exhibit lateral leakage, we fabricated an array of similar waveguides and investigated the waveguide transmission as a function of wavelength close to the fundamental wavelength of 1550 nm. The waveguide length was approximately 5 mm. We used a tunable laser to measure the transmission of the waveguides as a function of wavelength for the TE and the TM mode. Light was coupled in and out of the waveguide by lensed fibers.

The measured transmission spectrum of the waveguide is shown in Fig. 4. It can be seen that both polarizations have periodic oscillations (magnified green spectral area is shown in Fig. 4b). The period of the oscillation is approximately 0.11 nm, which matches well with the expected free spectral range of the Fabry-Perot resonance caused by the reflectivity of the waveguide end facets and the cavity length of 5 mm. It can further be observed that the power of the TM mode stays quite constant over the whole wavelength range, however for the TE mode one can observe a sharp drop in transmission for wavelengths below ~1.485 μm (blue highlighted area). The additional loss for these wavelengths is approximately 9 dB/cm. From the simulation results in Fig. 3a one would expect lateral leakage to occur at wavelengths of below 1.6 μm and cause additional losses in the waveguide which is higher than the observed wavelength at which increase loss occurs in Fig. 4. This discrepancy may be caused by fabrication tolerances (e.g. the LN thin-film thickness was lower than 700 nm) as well as slight differences of the material refractive indices and the assumed Sellmeier equations for the materials [18,19].

Next, we investigated the waveguide behavior for a wavelength of ~780 nm that is close to the SH wavelength for a frequency doubler in this platform. For this we launched the TE and TM mode from an external cavity 780 nm diode laser in the waveguide and measured the transmission. We found that the transmitted power for the TM mode is 16.9 ± 5.8 dB higher than for the TE mode. This indicates that significant leakage takes place in these waveguides at the SH wavelength and may explain the significantly reduced second harmonic efficiency observed with this geometry.
Avoidance of lateral leakage for efficient second harmonic generation

According to Fig. 3a, it should be possible to avoid lateral leakage by reducing the thickness of the lithium niobite. If lateral leakage can be eliminated at the second harmonic, then the efficiency of the second harmonic generation should improve dramatically. To eliminate lateral leakage at a wavelength of 780 nm, we chose a LN thin-film thickness of 300 nm (following Fig. 3a). We fabricated the waveguides and used the fabrication steps described in Ref. [5]. We adjusted the poling period of the domain pattern to 4.98 µm to account for the slightly different effective refractive indices of the fundamental and SH mode. The waveguide length was 4.8 mm. After fabricating the devices, we characterized them using a tunable laser, with a pump power of approximately 1 mW inside of the waveguide. On the output we split the SH and the fundamental wavelength using a wavelength division multiplexer (WDM), before detecting the power with appropriate power meters.

Fig. 5 shows the SHG efficiency as a function of the pump wavelength. One can see strong oscillations in the efficiency, caused by the Fabry-Perot resonances of the fundamental and SH wavelength, which experience a reflection at the end facets of 9.7% and 11.6%, respectively, according to our simulations. The SHG efficiency has an envelope that approximately follows a sinc² function. The bandwidth of the sinc² envelope is approximately 2.1 nm, which is slightly wider than the theoretical bandwidth of 1.8 nm, predicted using the equation from Ref. [20]. The peak conversion efficiency of this waveguide is ~1160% W⁻¹cm². The theoretical conversion efficiency of the periodically poled LNOI waveguide is 1070% W⁻¹cm². However, the Fabry-Perot resonance can increase the fundamental power in a cavity by a factor of (1-Rw)² [21], where Rw is the reflectivity of the waveguide end facets. This corresponds to an increase the fundamental power by 22.5% inside the cavity and results in an increased theoretical peak conversion efficiency of 1606% W⁻¹cm² due to square power dependency.

The lower peak conversion efficiency of the fabricated nonlinear optical waveguides as well as the wider bandwidth can be explained by not considering the waveguide losses, which we estimate to be 0.6 dB/cm for the fundamental wavelength as well as not having a perfect duty cycle of the poling pattern. Nevertheless, the nonlinear optical performance of the waveguide shows that if one avoids lateral leakage at the SH wavelength that one can achieve a high nonlinear optical conversion efficiency in LNOI ridge/rib waveguides.
4. Conclusion

We have shown that lateral leakage can take place not only for TM waveguide modes in SOI, but also for TE waveguide modes in LNOI. The occurrence of lateral leakage for a TE waveguide mode can be explained by the birefringence of lithium niobate. Hence, lateral leakage must be considered for linear and nonlinear optical ridge/rib waveguides in LNOI as it can cause undesired waveguide losses. Lateral leakage in LNOI ridge/rib waveguides is more likely for shorter wavelengths and thicker LN thin-film thicknesses for a given ridge/rib height.

We also discovered that the nonlinear optical waveguides in Ref. [5] suffered from lateral leakage at the SH wavelength. This helped explain the significantly lower conversion efficiency that was observed in these waveguides than was expected. By choosing an appropriate waveguide cross-section we could avoid lateral leakage in SiN loaded LNOI waveguides, which enabled us to demonstrate a peak SH efficiency of $\sim 1160\%$ W$^{-1}$ cm$^2$.

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