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Towards Noncritical Phasematching in Thin-film Lithium Niobate Frequency Converters

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Abstract: We present a study of noncritical phasematching in thin-film, periodically poled lithium niobate waveguides. Noncritical phasematching relaxes fabrication tolerances and is needed for long devices or when ideal tuning curves are required.

There is growing interest in periodically poled, thin-film lithium niobate (LN) for nonlinear optical frequency conversion [1–3]. The tight optical confinement produced by the lithium-niobate and silica-dioxide thin films allows high modal overlap between the interacting waves for efficient frequency conversion [1, 2] while also enabling group-velocity engineering [4]. Thin-film LN is also attractive as a platform for integrated quantum photonics as entangled photon pair sources [3] and modulators can be combined on a single chip. While some initial considerations [3] have been given to identifying waveguide geometries that are more tolerant to fabrication variations, to our knowledge, a systemic study of noncritical phasematching [5, 6] has not been performed for thin-film periodically poled lithium niobate (PPLN) waveguides. Here, we present such a study.

Nonlinear frequency conversion requires uniform phasematching over the entire length of the device. Phasematching depends on the local refractive index, which is affected by waveguide width, waveguide thickness and other properties. If there is significant variation in the local indices of refraction (for example, from poorly controlled fabrication), then the phasematching wavelength may vary over the length of the device, which results in a distorted tuning curve and may limit conversion efficiency. Proton-exchanged PPLN waveguides have been designed to be noncritically phasematched where the phasematching is to first order independent of the waveguide width [5, 6]. If noncritical phasematching is not possible, then we can choose geometries that minimize the dependence on the dimensional parameter.

We used COMSOL to simulate light propagating in thin-film LN waveguides. We modeled waveguides etched in x-cut MgO:$LiNbO_3$ films (total LN thickness between 300 nm and 700 nm) sitting above a 2 micron thick SiO_2 layer with 75° sloped sidewalls [1, 3]. We varied the total LN film thickness, the etch depth and the waveguide top width. We examined second-harmonic generation with fundamental wavelength at 1570 nm using TE-polarized modes (to utilize the d_{33} nonlinear coefficient of LN). From the effective indices, we calculated the required quasi-phasematching (QPM) periods.

Figure 1a shows the calculated fundamental and second-harmonic modes for an example waveguide. Figures 1b and 1c plot the QPM period as a function of top waveguide width and total LN film thickness with the etch depth set to 50 nm and 350 nm, respectively. We see that the QPM period generally increases with both total LN thickness and waveguide width. Contour lines that are perfectly horizontal or vertical represent waveguide geometries that are noncritically phasematched in waveguide width or in LN film thickness, respectively. We see that for the 50 nm etched waveguides (Fig. 1b), the contours are nearly horizontal, which means that the phasematching is quite

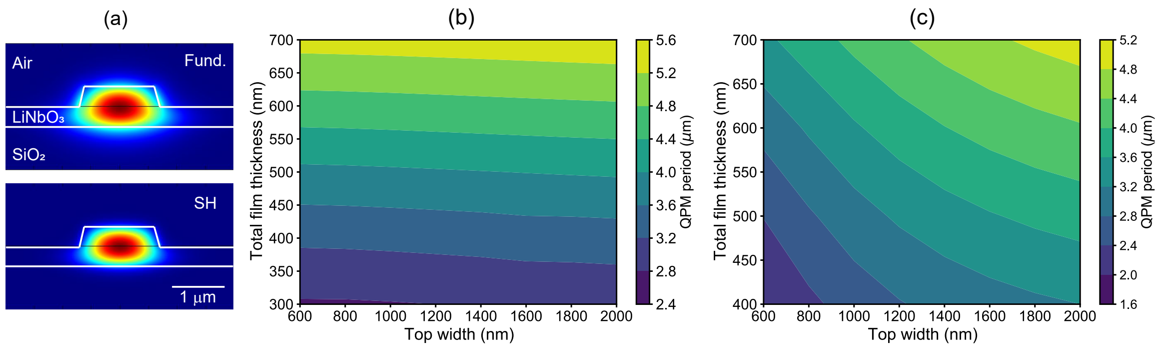

Fig. 1. (a) Calculated fundamental and second-harmonic TE modes. Required QPM period for different waveguide widths and thicknesses where etch depth is fixed to (b) 50 nm and (c) 350 nm.

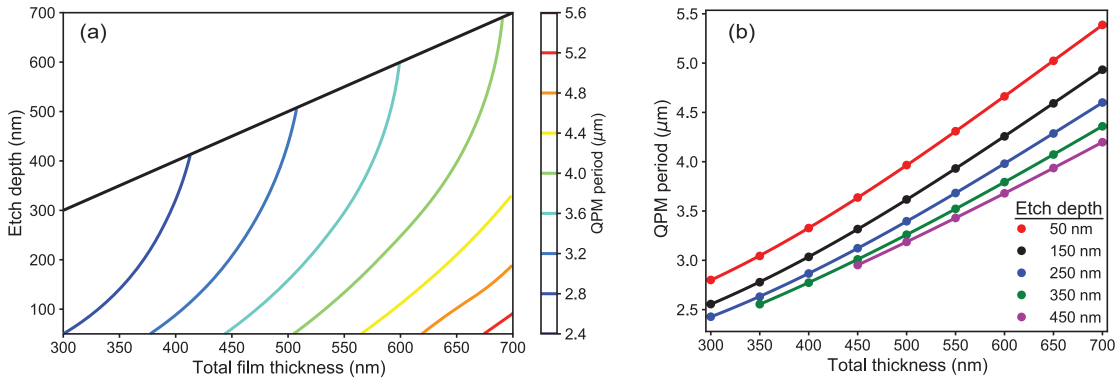

Fig. 2. (a) Required QPM periods as a function of LN film thickness and etch depth with waveguide width set to 1200 nm. The top left portion of the plot above the solid black line represent unphysical structures. (b) Dependence of QPM period on total LN film thickness (1200 nm waveguide top width) for different etch depths. We observe a decrease in slope with larger etch depths.

insensitive to waveguide width. However, for the 350 nm deep etch, there is more curvature in the contours and noncritical phasematching occurs at large waveguide widths ($> 2\ \mu$m).

In thin-film LN devices, the largest source of dimensional uncertainty is typically the LN film thickness. This thickness uncertainty can be as high as 40 nm, while the waveguide width and etch depth are typically controlled with higher precision. After etching, any variation in the total LN film thickness is transferred into waveguide height variations. In Fig. 2a, we fix the waveguide top width to 1200 nm and calculate the required QPM period as a function of etch depth and total LN film thickness. Plots at different waveguide widths are qualitatively similar. From these calculations, we could not identify waveguide geometries where the contours are perfectly horizontal, that is, where the QPM period is (to first order) independent of LN film thickness. Therefore, the strategy is to minimize the dependence of the phasematching on film thickness. Figure 2b plots the QPM period as a function of LN film thickness for different etch depths and waveguide width set to 1200 nm. We see the slope of the curves decrease with larger etch depths, which suggests that more deeply etched waveguides will have more noncritical-like behavior and hence, less dependence on film thickness imperfections.

In conclusion, we present a study of noncritical phasematching behavior in periodically poled thin-film LN waveguides. Since film thickness is the least controlled dimension, our study suggests larger etch depths will provide less sensitivity to thickness variations. Minimizing sensitivity to fabrication errors will be important for realizing long PPLN waveguide devices, such as those needed for high-efficiency frequency conversion (for instance, in quantum frequency) and for realizing narrow, well-controlled tuning curves.

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