Periodic Poling of X-Cut Thin-Film Lithium Niobate

The Route to Submicrometer Periods

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***Abstract*—Ultra-short poling periods of 1 µm and below in lithium niobate will allow nonlinear optical devices with operation to the UV regime or narrow-band counter-propagating single-photon generation. However, fabrication of such periods in bulk Lithium Niobate penetrating the complete modal areas of waveguides has been challenging. In this work, we demonstrate the fabrication of periodic domain grids with submicrometer periodicity in 300 nm x-cut thin-film lithium niobate. The poling was achieved through application of a single, shaped electrical pulse and electrodes fabricated with a combination of electron- and direct laser-writing lithography. The poling results were investigated with piezo-response force microscopy and second-harmonic microcopy and indicate the poled domains to penetrate across the complete film thickness. This will enable the fabrication of novel nonlinear optical devices combining the high efficiency of thin films with ultra-short domain periods.**

Keywords—Thin film Lithium Niobate, nonlinear optics, periodic poling, SH microscopy, PFM

I. Introduction

The large nonlinear optical coefficients, its broad transparency from 320 nm up to 5000 nm and its wide availability makes Lithium niobate (LN) an ideal candidate for nonlinear, integrated optics [1]. Nonlinear optical effects have many applications ranging from single photon generation, ie. parametric down conversion, frequency conversion, or amplification. Efficient nonlinear optical interactions require phase matching between the interacting beams, which can be achieved in LN through quasi-phase matching in periodically inverted domain structures. Many applications, like mirrorless OPOs [2], counter-propagating single photon generation or conversion of light between UV and telecom ranges, require short poling periods of around 1 µm and even below. However, the fabrication of domain grids with periods of 1 µm penetrating several µm deep through the complete modal area of an indiffused waveguide in bulk LN is challenging, as domains will quickly merge laterally during forward growth. Currently, the shortest poling periods for bulk LN waveguides, that are reported, are on the order of 1.7-2.3 µm. [3,4]

Over the last decade, single crystalline thin films of LN (TFLN) with thicknesses down to 200 nm became available on wafer scale. The small thicknesses and the high index contrast of LN on a SiO_2 buried oxide layer enables waveguides with sub-wavelength confinement and tight bending radii. The improvement in confinement and scale compared to its bulk counterparts results in an increase of one to two orders of magnitude in the nonlinear conversion efficiency [5]. TFLN is also very attractive for ultra-short periodic domain patterns, because the inverted regions can be as thin as the film thickness, therefore preventing merging of neighboring domains during growth. So far, the demonstrated structures in TFLN feature poling periods in the range of 2.67 to 5 µm [5,6], which is comparable to the shortest bulk periods, while first reports indicate the potential to fabricate periods of 1 µm and below [7] in TFLN.

In this work we have systematically investigated the fabrication of periodically-poled x-cut TFLN with periods ranging from several microns into the sub-micrometer range using a single-poling pulse and lithographically structured electrodes.

II. Methods

For fabrication we used commercially available 5%-MgO-doped x-cut TF-LN with 300 nm thickness on a 1.8 µm SiO_2 buried oxide layer and silicon substrate (NanoLN, Jinan Jingzheng Electronics Co.,Ltd.). The sample geometry is shown in Fig. 1. The poling electrodes were fabricated in a two-step process. First, the finger electrodes of the desired poling period were structured using electron beam lithography, followed by metal deposition and lift off. Here, electrodes with periods down to 600 nm were realized. In a second step, large rectangular contact pads were structured with standard optical lithography and a second metal

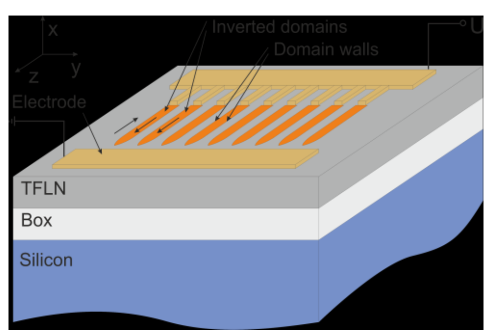

Fig. 1. Sketch of the TFLN sample geometry showing the electrode design.

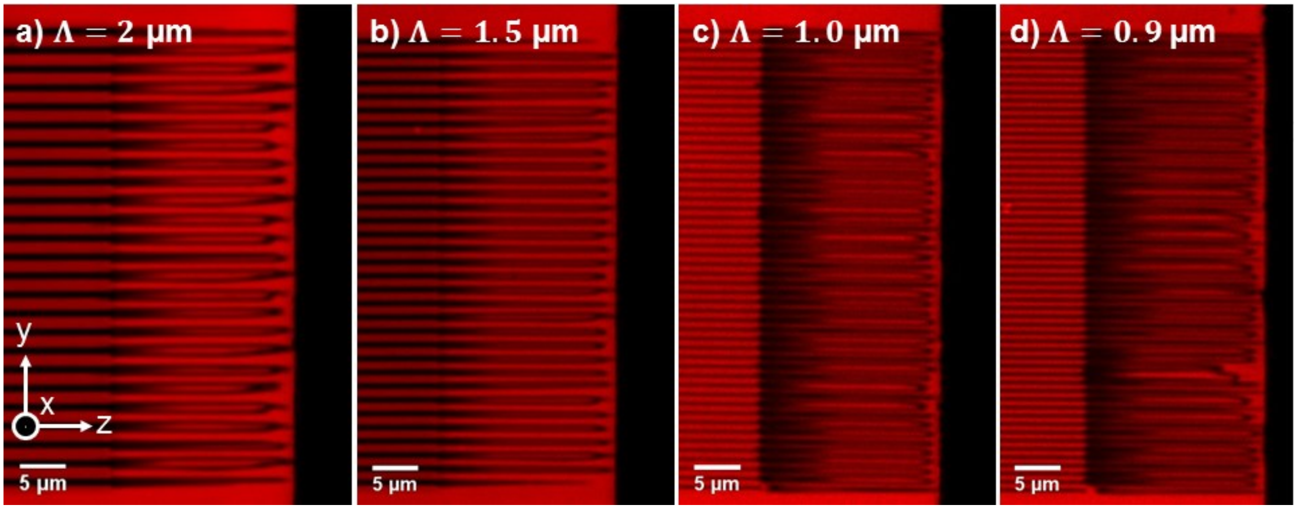

Fig. 2. SH images of fabricated domain structures with periods ranging from (a) 2.0 µm, (b) 1.5 µm, (c) 1.0 µm to (d) 0.9 µm.

deposition and lift-off process. The poling was performed with a single electrical pulse applied to the electrodes, using a typical poling waveform [8]. The waveform features a fast ramping up to facilitate nucleation. Then, the voltage was kept for around 1 ms above the coercive field to allow growth of the new domains. Subsequently, the voltage was ramped down slowly (> 30 ms) to allow for stabilization of the poled domains. The pulse form was optimized for each poling period in an iterative process of poling and subsequent imaging with SH microscopy. Further, details on the poling setup can be found in previous work [8]. SH microscopy was performed on a Leica SP5 MP microscope at an operating wavelength of λ=920 nm. The immersion oil objective (NA 1.4) allows for a <200 nm lateral resolution. For detailed images on structures of 1 µm period and below, piezo response force microscopy (PFM) was performed using a Cypher AFM (Asylum Research - Oxford instruments) and full metal Ir/Pt tips (Rocky Mountain Nanotechnology, LLC).

III. DISCUSSION

Fig. 2 shows SH microscopy images of poled structures with (a) 2 µm, (b) 1.5 µm, (c) 1.0 µm and (d) 0.9 µm periods, respectively. The electrodes appear as dark stripes and dark regions on the top and bottom of the images respectively, as the gold features no second-order nonlinearity in the optical regime. The domain walls appear as dark lines spanning from the positive to the ground electrodes along the crystallographic z-axis, while the SH signal magnitude in both the unpoled and inverted domain is the same, as shown previously [9]. Therefore, our results indicate that the domains do penetrate the complete film thickness, which is a key requirement for efficient nonlinear devices. The calculated duty cycles are between 40 to 60 % for the 2 µm down to 900 nm periods, which is similar to duty cylces in successful nonlinear SHG devices based on TFLN [5]. The PFM results confirm these findings. For submicron structures, we observe indications for domain-to-domain interactions leading to every second domain being narrower than its neigbors.

IV. ONCLUSIONS

In this work periodic poling of TFLN over periods ranging from 2.0 µm down to 600 nm with a similar poling protocol has been investigated. Our results show periodic poling down to 600 nm period. The SH and PFM results indicate that the domains do penetrate the film thickness, which is an important prerequisite for successful nonlinear device fabrication.

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