Investigation of periodic poling in LNOI

(Student paper)

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Lithium niobate on insulator (LNOI) is a material platform of growing interests due to its outstanding properties. We investigate periodic poling in LNOI to quasi-phase match our nonlinear optical processes. For this purpose, we use finger electrodes and show their fabrication. We also show our periodic poling results and demonstrate finally a second harmonic generation process in a periodically-poled waveguide.
Keywords: *LNOI, periodic poling, second harmonic generation, domain inversion*

INTRODUCTION

Quantum optics is a field of research that explores the behavior of light and matter at the quantum level. The study of quantum optics is motivated by the desire to understand the fundamental nature of light and its interactions with matter and the potential for developing new technologies based on these interactions. Explicitly integrated quantum optics focuses on integrating multiple quantum optical elements, such as lasers, detectors, and nonlinear crystals, into a single system. This approach allows for the manipulation and control of light at the quantum level, leading to new possibilities for quantum computing, communication, and metrology. Additionally, this approach allows for exploring new phenomena such as quantum entanglement and quantum teleportation.

Overall, the field of quantum optics and explicitly integrated quantum optics are motivated by the desire to understand and control the behavior of light at the quantum level, which has the potential to lead to new technologies and a deeper understanding of the natural world. Typically, quantum optical setups are bulky setups that occupy whole tables and require very tightly controlled environments to achieve the required stability. More advanced applications require an increasing number of components and stability. However, integrated photonic systems are inherently more stable and scalable, allowing for more complex applications to be developed in a fraction of the footprint. One material of choice for integrated photonic application is lithium niobate, due to its outstanding properties which enable e.g., low propagation losses [1] and high optical nonlinearities [2].

Although significant improvements have been made in integrated optical devices in lithium niobate, the miniaturization progress has reached the realms of integrated optics and quantum photonics. One of the most promising opportunity to overcome this limitation is the so-called silicon on insulator (SOI) platform. Due to its special design, the refractive index change between the waveguide and the substrate is immense [3] and offers great possibilities for miniaturization. Nevertheless, due to its inversion symmetry, silicon offers no second order nonlinearity [4]. Consequently, only third order nonlinear processes can be used in SOI. The corresponding nonlinear optical coefficient $\chi^{(3)}$, which is a measure of the strength of nonlinear optical interactions, is up to 12 orders of magnitude smaller than the one of the second order nonlinearity [5] of lithium niobate. Therefore, lithium niobate on insulator (LNOI) which combines the excellent properties of lithium niobate, including a second order nonlinearity, and the advantages of SOI platform is the best choice for quantum devices.

The key components for integrated photonics and quantum optics in LNOI are waveguides, modulators and nonlinear interactions achieved via periodic poling. Periodic poling is utilized for quasi-phase matching processes, which are needed for efficient frequency conversions, which is the critical component in LNOI. In recent years, significant progress has been made in periodic poling in LNOI. However, structured analyses of the poling behavior and efficient poling over several millimeters lengths, are still lacking. We want to take this step and present our current results on structural periodic poling in LNOI.

RESULTS

Quasi-phase matching is essential for efficient frequency conversion, requiring periodically-poled structures in LNOI. For our experiments, we use commercially available x-cut LNOI (NANOLN). The domain inversion happens along the z-axis of the crystal. We use so-called finger electrodes where domain inversion is realized by applying high-voltage pulses. Therefore, high-quality electrodes are a crucial component for periodic poling. We characterize the final results via second harmonic (SH) microscopy and finally measure in a frequency conversion process in a waveguide. The propagation direction is perpendicular to the poling. Consequently, we fabricate our waveguides along the y-axis.

FINGER ELECTRODES

For finger electrode fabrication, we spin coat resist onto an LNOI sample in the first step. The resist is structured subsequently via laser lithography or electron-beam lithography. After developing, chromium and gold is deposited as finger electrodes. As a last step, a lift-off process is done.

Laser lithography provides the possibility of efficient production due to the high writing speed of the system. To the best of our knowledge, we are the first group to use laser lithography to fabricate finger electrodes. Typically, electron-beam lithography is chosen for this purpose since it offers a higher resolution. The higher resolution of the electron-beam lithography compared with laser lithography can be seen in figure 1, which shows the resulting finger electrodes for a laser lithography (left) and for electron-beam lithography (right) based process.

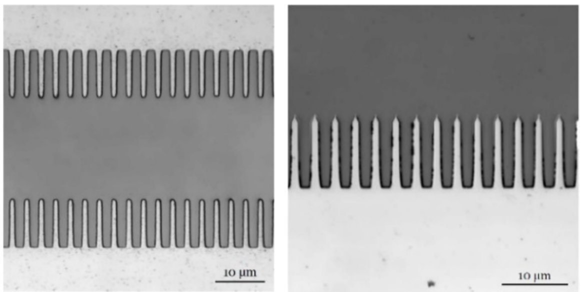

Fig. 1. Finger electrodes after fabrication. On the left the fabrication process is done by using a laser lithography system and on the right the process is done via an electron-beam lithography.

Irrespectively from which lithography system is used, it is essential for high-quality poling that the finger electrodes are stable, adhesive and homogenous along the entire length. Since the efficiency of quasi-phase-matched processes increases within the length of the periodically-poled area, long periodically-poled areas are desirable, which clearly require long electrodes.

PERIODIC POLING

For periodic poling, we invert the domains periodically in the crystal by applying a high-voltage pulse to the finger electrodes. A deep understanding of the complex interaction between the poling parameters is essential to achieve high-quality periodic poling. This includes a structured analysis of the crucial parameters like the poling pulse, especially the voltage and the time, the electrodes' geometry, the metal used for the finger electrodes and the lithium niobate thin-film layer itself.

We investigated the shape of the poling pulse and focused on the interaction between the applied voltage and the time. For this purpose, we tested different parameter combinations and visualize the domains via SH microscopy. One example of such an SH microscope image is shown in figure 2 (left), in which the domain walls (yellow) between the inverted and non-inverted domains can be seen.

DISCUSSION

The quality of fabricated poling structures can be inferred from their SH microscope images, as discussed above. Thus, the shape of the domain walls provides a deeper insight into the switching behavior of lithium niobate upon poling. Utilizing the findings from those measurements allows us to optimize and tailor the poling process to such a degree that homogeneous and reproducible fabrication of periodically poled structures becomes feasible. Yet, those images can also be used for exhibiting the limits of our current fabrication methods, and thus allows a profound comparison to the work of different research groups. Here, the poled structure becomes a key issue, as well as maximum length at which those structures can be fabricated reproducibly. Maximizing the poled length is crucial for increasing conversion efficiencies for both classical photonics and quantum conversion processes.

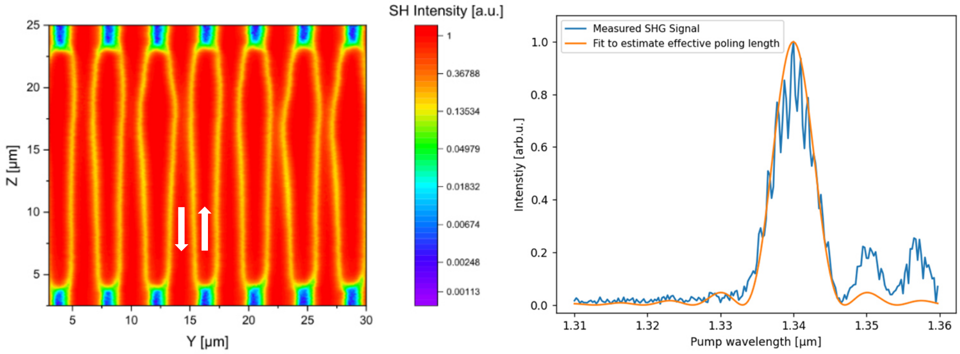

Fig. 2. Example for an SH microscope image of a periodically-poled LNOI sample with a poling period of 3 µm in which the domain walls (yellow) are visualized (left). The arrows indicate the direction of the spontaneous polarization. Measured SHG signal for our 7.5 mm long periodically-poled sample (blue) with a poling period of 2.8 µm and a fit function (orange) to estimate the effective poling length (right).

Therefore, we poled LNOI with a poling period of 3 µm along 5 mm periodically, which is also the maximum poling length that is shown by other research groups [6]. Furthermore, we investigate our inverted domains via SH microscopy to check whether the domains looked uniform over the whole length or not. We saw a few discrepancies between the domains at the middle of the electrode and the ones at the edges of the electrode, which indicates once again the special challenge of poling a long area periodically. Despite that, our results are promising since we managed periodic poling. Thus, we also tested periodic poling over 7.5 mm with different poling periods (2.9 µm, 2.8 µm and 2.7 µm).

To analyze our periodic poling result for 7.5 mm, we do SH microscopy. Moreover, we do an optical study by investigating the nonlinear properties via a second harmonic generation (SHG) process. Our measured SHG signal for a poling period of 2.8 µm is shown in figure 2 (right). We use a sinc-function to identify the effective poling length of our sample, which measures the quality of the poling.

Whenever poling was perfect, the effective length should equal to the length of the electrode. Our sample's calculated effective poling length is 567 µm which is lower than the finger electrodes' physical length. The discrepancy between the physical and effective poling lengths shows that using the same poling pulse for short and long poling areas does not result in the same quality of periodic poling.

By gaining a deeper understanding of the interaction of the parameters relevant to periodic poling, adaptive poling is feasible. This knowledge can be used to estimate the poling parameters better. Furthermore, this knowledge is beneficial to adapt the poling parameter to pole an extended area periodically. A homogenous and reproducible domain inversion is one of the most significant challenges for periodic poling along several millimeters.

Overall, we show our fabrication process for finger electrodes, which includes the use of a laser lithography system and an electron-beam one. Furthermore, we show the latest results of our periodic poling investigation of different poling lengths. Additionally, we demonstrate that poling lengths up to 7.5 mm are possible and show our nonlinear optical conversion analysis.

Acknowledgements: Funded by the Deutsche Forschungsgemeinschaft (DFG, German Research Foundation) – SFB-Geschäftszeichen TRR142/3-2022 – Projektnummer 231447078 and FOR5044 – Projektnummer 426703838.

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