# Periodical poling in congruent lithium niobate with slanted polar axis 

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Periodically poled lithium niobate (PPLN) crystals are widely used in nonlinear optics as frequency mixers for wide wavelength range [1]. The typical thickness of such optical element ranges from 0.5 to 1.0 mm . The development of femtosecond lasers with high average and peak power (> 10 W ) boosted the interest to large aperture ( $\sim 1 \mathrm{~cm}$ ) frequency mixers. Formation of periodical domain structure in $1-\mathrm{cm}$-thick Congruent Lithium Niobate (CLN) crystals is a challenging task due to threshold field about $21 \mathrm{kV} / \mathrm{mm}$ [2]. Alternative solution is the so-called "slanted poling" technique [3], which represents formation of periodical domain structure in nonpolar cut plate. For optimal cut, the angle between polar Z-axis and crystal surface is $25^{\circ}$ and X -axis is parallel to sample surface. In this case the pump beam propagates with extraordinary polarization along X-axis thus realizing the maximum nonlinear coefficient $d_{33}$. However, the CLN wafers with optimal cut are rare on the market and quite costly.

Here we propose to apply the concept of slanted poling on CLN wafers with widespread cuts for surface acoustic wave applications (slanted CLN), which are much more affordable.


Figure 1. Scheme of periodically poled slanted CLN. $\theta_{\mathrm{s}}$ is a slant angle. $\Lambda_{\text {mask }}$ is a mask period. $\delta$ is angle between mask direction and X -axis.
The large-aperture frequency mixers were designed for: $36^{\circ} \mathrm{Y}$-cut and $64^{\circ} \mathrm{Y}$-cut. The slanted crystals are oriented, so the Y-axis is in the crystal surface and an angle between polar Zaxis and surface sample is called slant angle $\theta_{\mathrm{s}}$ (Fig. 1). The flat domain walls in CLN crystal with $\mathrm{C}_{3 \mathrm{v}}$ symmetry can be parallel to one of two YZ-planes inclined relative to the sample surface [4].

The poling mask period was calculated using angular quasi-phase matching (AQPM) conception [5] for optical parametric amplification (OPA) process for: $\lambda_{\text {pump }}=1030 \mathrm{~nm}$, $\lambda_{\text {signal }}=1542 \mathrm{~nm}, \lambda_{\text {idler }}=3100 \mathrm{~nm}$. We considered that all interacting beams are collinear. The mask period $\Lambda_{\text {mask }}=33.2 \mu \mathrm{~m}$ at an incident angle $\theta_{i} \approx 35^{\circ}$ and the angle between an incident plane and X-axis located in the sample plane $\alpha=270^{\circ}$ for $36^{\circ} \mathrm{Y}$-cut; and $\Lambda_{\text {mask }}=18.3 \mu \mathrm{~m}$ at $\theta_{i} \approx 45^{\circ}$ and $\alpha=270^{\circ}$ for $64^{\circ} \mathrm{Y}$-cut. The area covered by periodical mask was $2 \times 2 \mathrm{~mm}^{2}$.

The periodical domain structure was produced by electrical field poling using liquid (saturated aqueous solution of LiCl ) and metal electrodes combination [6]. The photoresist mask was created by photolithography on $\mathrm{Z}_{\mathrm{s}}{ }^{+}$surface using photoresists with thickness ranging from 1.8 to $3.8 \mu \mathrm{~m}$. The instantaneous domain images during poling visualized by optical microscopy were recorded by high-speed CMOS camera (Photron Mini UX100, Japan) with frame rate up to 1000 fps . The field pulses with magnitude ranged from 21.5 to $34.5 \mathrm{kV} / \mathrm{mm}$ were applied. The thickness of the samples was ranged from 265 to $500 \mu \mathrm{~m}$.

The period of photoresist pattern was varied from 40.2 down to $18.3 \mu \mathrm{~m}$. It was demonstrated that the $64^{\circ} \mathrm{Y}$-cut wafers demonstrate better poling results with formation of more homogeneous structures with small number of imperfections. It was shown that decrease the poling period leads to decrease of structure switching time, increase of the field required for polarization reversal and increase of the density of imperfections. The influence of sample and photoresist thickness on the poling quality has been discussed.


Figure 2. Optical image of the domain structure with period $40.2 \mu \mathrm{~m}$ in 0.5 mm -thick $64^{\circ} \mathrm{Y}$-cut CLN.
The OPA process efficiency was measured in periodically poled $500-\mu \mathrm{m}$-thick $64^{\circ} \mathrm{Y}$-cut CLN with $\Lambda_{\text {mask }}=18.3 \mu \mathrm{~m}$ and $265-\mu \mathrm{m}$-thick $36^{\circ} \mathrm{Y}$-cut CLN with $\Lambda_{\text {mask }}=33.2 \mu \mathrm{~m}$ using 1030 nm fs-laser with pulse duration 350 fs , frequency 100 kHz and average power 11 W . Broadband seed beam with wavelength range from 1200 to 2000 nm was generated using Yttrium Aluminum Garnet (YAG) crystal pumped by the same fs-laser. The diameter of the pump beam was about $400 \mu \mathrm{~m}$. The maximal OPA gain ( $\approx 300$ ) was reached for periodically poled $64^{\circ} \mathrm{Y}$-cut CLN.

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