Optimizing the efficiency of a periodically poled LNOI waveguide using in situ monitoring of the ferroelectric domains

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ABSTRACT
Lithium niobate on insulator (LNOI) is a unique platform for integrated photonic applications and especially for high-efficiency nonlinear frequency converters because of the strong optical field confinement. In this work, we fabricated a 6-mm-long periodically poled LNOI ridge waveguide with an optimized duty cycle (50:50) using an active domain structure monitoring method. The performance of the single-pass second-harmonic generation and difference-frequency generation in the nanophotonic waveguide was characterized, and the normalized conversion efficiencies were 80% of the theoretical values. These high-quality frequency conversion devices can pave the way for the application of LNOI in nonlinear integrated photonics.

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The lithium niobate on insulator (LNOI) platform has drawn increasing attention in recent years. LNOI inherits the excellent material properties of lithium niobate (LiNbO3) single crystals, such as a wide low-loss transparency window, a strong electro-optic (EO) coefficient,1 and high second-order nonlinearity. Most importantly, an LNOI platform offers stronger optical confinement compared to conventional weakly confining LiNbO3 waveguides, such as proton exchanged and titanium in-diffused waveguides,3,4 which leads to improved optical signal processing capabilities and enhanced light-matter interactions. Because of these advantages, photonic devices based on LNOI can be more compact and efficient. LNOI has been employed to construct many photonic devices, including high-performance LiNbO3 integrated EO modulators working at CMOS-compatible voltages,5,6 high-Q micro-resonators,7,8 photonic crystal micro-cavities,9,10 and photonic crystal micro-cavities.10

LiNbO3 has been widely used for second-order nonlinear frequency conversion in nonlinear optics because of its high second-order nonlinear coefficient. To realize efficient frequency conversion in LNOI waveguides, phase-matching is a key aspect. To date, several schemes have been used to achieve phase-matching in LNOI-based nonlinear optical elements, such as modal phase matching,11-13 metasurface-assisted phase-matching,14 quasi-phase matching (QPM). Among these methods, quasi-phase-matched LNOI waveguides can offer several advantages such as phase-matching arbitrary second-order nonlinear optical processes within the transparency range of the crystal, access to the largest nonlinear coefficient, and phase-matching of interactions between the TE00 modes that exhibit the tightest mode confinement. Periodically poled ferroelectric domain structures have been fabricated on LNOI platforms, and they have been implemented to demonstrate quasi-phase-matched second-order nonlinear processes such as second-harmonic generation (SHG),15,16 sum-frequency generation (SFG),17 difference frequency generation (DFG), and spontaneous parametric downconversion (SPDC).18 Because of sub-wavelength optical confinement, ultrahigh-efficiency frequency conversion, e.g., 2200%–2600% W cm−2 normalized efficiencies for SHGs in the communication C-band, was reported with such nanophotonic waveguides that were several millimeters long.1,7,19 However, the measured efficiencies were only ~60% or lower than the
theoretically obtainable value. In this work, we provide a detailed
description for the fabrication of high-quality periodically poled LNOI
ridge waveguides, where the poling fidelity was actively monitored via
confocal microscopy. The fabricated nanophotonic waveguide was
characterized via SHG and DFG in the communication band, and the
normalized conversion efficiencies were ~80% that of the theoretical
values over the 6-mm waveguide length.

The fabrication process of the periodically poled LNOI waveguide
could roughly be divided into two stages. The electric field poling tech-
nique was applied to obtain the ferroelectric domain structure; then, the
sample was dry etched to form the ridge waveguide structure. The
specific processing steps are shown in Fig. 1(a). First, a comb-shaped metal
electrode was deposited on a 600-nm-thick X-cut LiNbO3 thin film with
Si as the substrate (NANOLN), and the spacing between the in-plane
positive and negative electrodes was 6 μm. Then, high-voltage pulses
were applied to fabricate the ferroelectric domain structure defined by
the patterned electrode. After this, the electrode was removed and the
ridge waveguide was fabricated using electron beam lithography (EBL)
followed by an Inductively Coupled Plasma (ICP) etching process to
produce the periodically poled LNOI ridge waveguide.

The conventional electric field poling technique was applied to
fabricate the domain structure in the LNOI. During and after the poling
process, confocal second-harmonic (SH) microscopy was used to non-
destructively characterize the inverted ferroelectric domain structure.
The coercive field of the X-cut LNOI was higher than that of the bulk
LiNbO3 crystal. For bulk LiNbO3, the coercive field was ~21 kV/mm,
while for the LiNbO3 thin film, it could be as high as 30 kV/mm. In
the domain structure fabrication process, the applied electric field was
~40 kV/mm and the pulse duration was several tens of milliseconds.
The duty cycle of the fabricated structure was controlled by adjusting
the number of applied high-voltage pulses. Figure 1(b) shows the evolu-
tion of the domain inversion with an increasing number of applied high-voltage pulses. When 2 pulses were applied, domain inversion
began to occur; when the number of pulses reached 8, the domain gradu-
ally expanded outside the electrode area; when 12 pulses were applied,
the duty cycle of the domain-inverted region was observed to be ~50:50
near the positive electrode; and excessive poling was observed when 40
pulses were applied, and the neighboring domains tended to merge.

Through this intuitive and nearly real-time domain structure visualization
scheme, we could control the number of pulses to obtain a periodi-
cally poled LiNbO3 thin film with an optimized duty cycle. After the
ferroelectric domain structure was fabricated, a ridge waveguide was
obtained via dry etching of the LiNbO3 thin film. The width of the inverted
domain was 6 μm, while the width of the ridge was smaller. One
advantage of this process sequence, i.e., poling followed by etching,
was that we could select the poled region with the best poling quality for
the subsequent ICP etching process, as shown in the dashed area in Fig.
1(d). The geometry of the ridge waveguide is shown in Fig. 1(e). The
top width of the ridge waveguide was 1.4 μm and the etched depth was
~350 nm, with the angle of the waveguide sidewall being 60°. After
periodic poling and dry etching, the chip was cleaved to expose the
waveguide facets, and a subsequent focused ion beam (FIB) etching pro-
cess was applied to polish both the waveguide facets.

The poling period was determined by the modal dispersion of the
LiNbO3 thin-film ridge waveguide, together with the momentum
conservation condition. During the fabrication process, the errors for
the etching depth and waveguide width were 20 nm and 100 nm,
respectively, which led to a large deviation between the predicted and
measured phase-matching wavelength because of the strong modal
dispersion in such thin-film waveguides. To obtain a reliable poling
period design, we prepared 11 periodically poled waveguides in paral-
lel on the LNOI chip, and the poling periods of the waveguides were in
the range 3.9–4.3 μm with equal intervals. In the experiment, we could
switch among the channels to determine the most suitable one for
phase-matching the given wavelength. In addition, the 11 waveguides
were individually poled based on the active monitoring method to
ensure good poling quality.

A schematic setup for the experiment is shown in Fig. 2. The
pump wave from a continuous-wave (CW) Ti:sapphire laser was gath-
ered into a single-mode fiber and then combined with the signal from a
CW fiber laser (SANTECH, TSL-550) using a wavelength division
multiplexer (WDM). The polarization of the interacting three modes
was chosen to be TE, which corresponds to a type-0 phase-matching
diagram, and the pump and the signal pass through the polarization
controller to ensure excitation of the TE modes in the waveguide.
Then, both beams were coupled to the thin film waveguide using a
lensed fiber and the fiber-to-chip coupling loss was ~10 dB. The light
was coupled out of the waveguide using an aspherical mirror with an
optimized focal length of 4 mm, and the coupling loss off the chip was
estimated to be ~1 dB (including Fresnel reflection at the end facet).
Fibers were placed behind the aspherical mirror for the measurement
of the generated waves.

The SHG performance was characterized using a waveguide with a
poling period of 4.3 μm on the nanophotonic chip. The CW fiber

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**Fig. 1.** (a) Fabrication procedure for the periodically poled LNOI ridge waveguide. (b) Evolution of inverted domain growth with the number of applied high-voltage pulses. (c) Magnified view of the domain-inverted region in the LiNbO3 thin film recorded via SH confocal microscopy, where domain inversion occurred in the red dotted box. (d) Ridge waveguide was selectively fabricated in the domain inverted-region with a duty cycle close to 50:50, as shown in the red dotted box. (e) The cross section of the LNOI ridge waveguide.
laser, which is tunable near 1470 nm, was utilized as the fundamental light source in the measurement. The measured and theoretical wavelength tuning curves are shown in Fig. 3(a). The first zeros of the ideal curve were at 1467 nm and 1473 nm, while the measured curve had two non-zero dips around the two points, which can be attributed to the excitation of the high-order modes in the SHG. The full width at half maximum (FWHM) of the spectrum was 4.24 nm, which is slightly larger than the predicted value of 3.2 nm. When the wavelength of the fundamental wave (FW) was tuned to 1469.6 nm, a maximum output power of 1.62 mW for the SH wave was obtained, with an FW power of 397 μW. Because of fabrication errors, the observed SHG wavelength differed significantly from the calculated value of 1520 nm. Figure 3(b) shows the output power of the SH as a function of the square of the power of the FW, which is a linear relation in theory. The normalized SHG conversion efficiency can be calculated according to $g_{\text{SHG}} = P_{\text{SH}} / (P_{\text{FW}} \cdot L^2)$, in which $P_{\text{FW}}$ and $P_{\text{SH}}$ represent the powers of the FW and SH waves, respectively, and $L = 6 \text{ mm}$ is the length of the poled waveguide. Using the fitted slope from Fig. 3(b), the normalized SHG conversion efficiency was calculated to be 3061% W$^{-1}$ cm$^{-2}$, which is 75% that of the theoretical value 4000% W$^{-1}$ cm$^{-2}$. The power relationship of the DFG process was characterized as well; when the wavelength of the pump and signal light was fixed at 735 nm and 1397.5 nm, respectively, the corresponding wavelength of the idler was 1550 nm. Figure 4(b) gives the relation of the power dependence of the idler on the product of the pump and the signal, which indicates a nearly linear relationship. In addition, we measured the DFG tuning characteristics when the wavelength of the pump was fixed at 737 nm, while the signal wavelength was scanned from $1380$ to $1430$ nm.
1380 to 1430 nm in the E-band. In this case, the wavelength of the idler was tuned in the C-band from 1524 to 1581 nm, as shown in Fig. 4(c).

To conclude, we fabricated a periodically poled LNOI using the electrical field poling technique followed by dry etching to form a ridge waveguide. The duty cycle was controlled to be close to 50:50 by adjusting the number of applied high-voltage pulses. SH confocal microscopy was used to actively reveal the inverted ferroelectric domain structure. The periodically poled LNOI waveguide was characterized by SHG at 1470 nm with the normalized conversion efficiency being 3061% W−1 cm−2, which is > 80% of the theoretical value. In addition, DFG was realized with a pumping wavelength at ~730 nm in the visible part of the spectrum, and the spectral tuning range of the generated idler in the C-band was ~50 nm. The normalized DFG conversion efficiency reached about 75% of the predicted one. The results obtained in this work show that active monitoring of the poling fidelity during the fabrication process can yield LNDO3 nanophotonic devices with conversion efficiencies comparable to the theoretically obtainable values, which can promote the use of LNOI for integrated photonic applications. Because of the strong geometric dispersion and the fabrication errors, the LNOI platform needs further development to improve the reliability and repeatability, thus alleviating a substantial testing in the creation of devices. The fabrication process should be improved, and one possible solution is to use a different process sequence, e.g., periodical poling after ridge waveguide fabrication; thus, a more accurate poling period can be obtained based on the measured geometric parameters of the nanophotonic waveguide from the previous procedure. Moreover, designing of new photonic structures with high tolerance to the fabrication errors might be an alternative direction.

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REFERENCES