Second-Harmonic Generation via Quasi-Phase Matching in Periodically Poled Lithium Niobate

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Background

Current laser technology is limited to certain wavelengths of light due to the fixed set of known lasing mediums. Many optical applications, however, require high intensity coherent light sources at specific wavelengths that cannot be produced with lasers alone. The development of frequency conversion devices relieves the restrictions to certain wavelengths and opens doors to various biomedical, telecom, and optical applications.

Periodically poled lithium niobate (PPLN) is a nonlinear crystal photonic technology used for efficient frequency conversion. By using PPLN in combination with common lasers, it is possible to access a large number of wavelengths in the visible and infrared spectrum.

Why Lithium Niobate?

Ferroelectricity

Lithium niobate is a ferroelectric crystal – it's crystal structure possesses a electric polarization that can be reversed via the application of an external electric field.

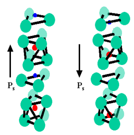


Figure 2. Polarity is reversed in $LiNbO_3$ due to movement of lithium ions within the crystal structure from one stable position to another.

Nonlinear Material

The relationship between polarization density (P) and electric field (E) in a nonlinear medium can be expressed as

$$P(r,t) = \varepsilon_0 \chi E(r,t) + \varepsilon_0 \chi^{(2)} E^2(r,t) + \varepsilon_0 \chi^{(3)} E^3(r,t) + \ldots$$

- Particularly high 2nd order nonlinear susceptibility constant ($\chi^{(2)}$) which introduces the prospect of second-harmonic generation (SHG).

Second-Harmonic Generation

- A nonlinear optical process where some energy of an input wave of frequency ω_1 is converted into a polarization wave of frequency $\omega_2 = 2\omega_1$.
- Photons of same frequency interact with nonlinear material, "combine" to generate photons with twice the initial frequency.
- Only allowed in materials without inversion symmetry.

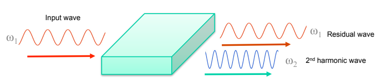


Figure 6. A graphical representation of second-harmonic generation via a nonlinear crystal photonic device.

Fabrication Process

- Periodic grating pattern is precisely defined using a lithographic mask via conventional microfabrication techniques.
- Ferroelectric domain reversal, or poling, is achieved via the application of a large external electric field.
- Crystal sample is annealed and polished.

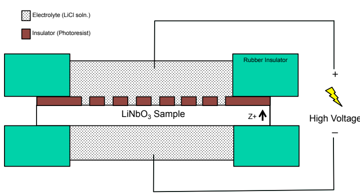
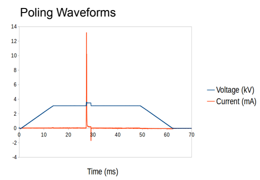


Figure 1. Electrode configuration for the poling process. The electrolyte connects both surfaces of the sample to the voltage source and forms an isopotential surface that helps control electric field fringing.

Reversing the Domains

- Large potential (21kV) is applied across the crystal for a short duration of time.
- The voltage is ramped, and a "peak" in voltage induces the reversal.

In successful poling, the voltage peak will cause a spike in current, indicating that lithium ions have moved and the domain polarity has reversed.



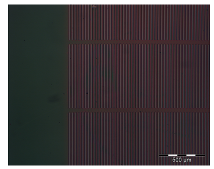


Figure 1. Laser-written domain grating pattern on a Si sample seen in a photolithographic mask.

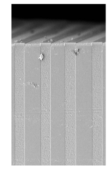


Figure 3. SEM image of an HF-etched PPLN sample. Etching occurs at different rates on the positive and negative Z-faces of $LiNbO_3$, allowing for the visualization of the domain patterns.

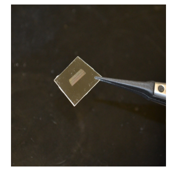


Figure 3.1. $LiNbO_3$ wafer after the poling process. The final device will be polished down to the edges of the grating period to allow a light wave to be coupled into the grating laterally.

Quasi-Phase Matching

- Waves ω_1 and ω_2 propagate at different phase velocities, determined by n_1 and n_2, respectively.
- Distance over which the relative phase of both waves changes by π is known as the coherence length.
- Invert the phase of wave ω_2 at each maximum (every odd number of coherence lengths) so the second-harmonic wave will grow continuously.

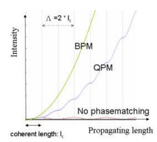


Figure 5. A comparison of polarization wave intensity in perfect phase matching, quasi-phase matching, and no phase matching.[4]

- Reverse phase of second-harmonic wave by inverting the ferroelectric domain of the medium every coherence length along the direction of propagation.
- Required inversion period for QPM can be expressed by the equation

$$\Lambda = \frac{\lambda_0}{2(n_2 - n_1)}$$

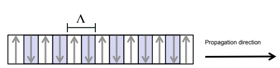
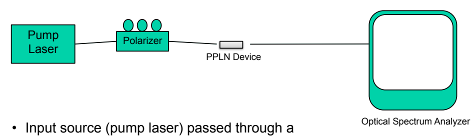


Figure 7. A diagram of a medium with periodically reversed nonlinear coefficient. The domain orientation inverts with a period Λ, which is an integer multiple of the material's coherence length.

Experimental Procedure



- Input source (pump laser) passed through a polarizer.
- Laser input is then coupled into a polished edge of the device.
- Output frequencies coupled back into fiber and passed to Optical Spectrum Analyzer.
- Successful SHG will be indicated by a spectral peak centered on the frequency corresponding to half the input wavelength.
- SHG success also largely dependent on the coupling of the input source into the device. Focusing the intensity of the input wave as it propagates will greatly effect SHG efficiency.

Device Performance

- Performance is a measure of measured second-harmonic wave intensity relative to input wave intensity.
- SHG efficiency highly dependent on the precision with which the grating period can be implemented.

Domain Broadening
During the fabrication process, domains can undergo broadening due to electric field fringing when voltage is applied.

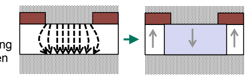


Figure 8. A depiction of domain broadening due to fringing field lines during the poling process.

Conclusions and Future Work

As most of the parameters for PPLN devices can be optimized theoretically, the bulk of our research efforts are concerned with the non-trivial PPLN fabrication process.

The majority of the issues that were encountered involved the fabrication process, rather than experimental results. Further experimentation with PPLN devices is limited by a lengthy and unpredictable fabrication process, so the priority for future work will involve improving the reliability and precision with which grating patterns can be engineered into $LiNbO_3$ crystal.

Improving Electrode Configuration
The poling process is the most critical step in PPLN devices, yet it is also the most unreliable (around 50% success rate). Poling success rate could be improved by finding better, more robust electrode configurations regarding insulation and electrical contact with the crystal surface.

Implementing a Channel Waveguide
Due to diffraction within the material, the power of the output wave will be less focused after passing through the device. A waveguide could increase the measured output power by maintaining beam focus throughout the device.

Handling Domain Broadening
The issue of domain broadening could be compensated for via approximations during grating period calculations, or could be lessened by reducing the distance the field lines span (fabricate much thinner $LiNbO_3$ samples).

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