Periodically Poled Lithium Niobate Waveguides for Quantum Frequency Conversion

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Introduction/Overview

• Quantum Communication (e.g. Quantum Key Distribution)

• Requires Single-Photon Sources and Detectors
  – These work best at wavelengths around 800 nm

• Requires Low-Loss Transmission Over Optical Fiber
  – Works best around 1550 nm

• Need to Convert Between Wavelengths While Preserving Quantum State
Second-Order Nonlinear Processes

\[ \frac{1}{\lambda_1} = \frac{1}{\lambda_2} + \frac{1}{\lambda_3} \]
Phase Matching

• For a frequency conversion process to occur efficiently, momentum must be conserved

\[
\frac{n_1}{\lambda_1} = \frac{n_2}{\lambda_2} + \frac{n_3}{\lambda_2}
\]

• Dispersion means that \( n_1, n_2 \) and \( n_3 \) are likely to be different

• In bulk crystals, angle phase matching is used; but in waveguides…
Quasi-Phase Matching

• Periodically reverse the nonlinear optical coefficient by inverting the crystal axis

\[
\frac{n_1}{\lambda_1} - \frac{n_2}{\lambda_2} - \frac{n_3}{\lambda_3} = \frac{1}{\Pi}
\]

Diffused Waveguide Modeling in Comsol

- Diffusion Step 1: Proton Exchange
- Diffusion Step 2: Annealing
- Diffusion Step 3: Reverse Proton Exchange

\[ D_e(T) = D_0 e^{-Q/RT} \]
Diffused Waveguide Modeling in Comsol

- Optical Mode Computation
  - Assumes $\Delta n = \alpha C$

@ $\lambda_1$

@ $\lambda_2$

Fundamental mode

Higher-order mode
SHG Peak Wavelength vs. QPM Period: Model & Measurements

![Graph showing SHG Peak Wavelength vs. QPM Period](image)
Conversion Efficiency

\[ \eta_0 = \frac{8\pi^2 d_{\text{eff}}^2}{n_1 n_2 n_3 c \varepsilon_0 \lambda_3^2} \quad \text{[Power}^{-1}] \]

\[ \eta = \eta_0 \left| \int_{-\infty}^{\infty} dx \int_{-\infty}^{\infty} dy \ \hat{E}_1(x, y) \hat{E}_2(x, y) \hat{E}_3^*(x, y) \right|^2 \quad \text{[Area}^{-1}] \]

\[ \eta \times 100\% = \text{slope efficiency in \%} / (\text{W m}^2) \]

\[ \eta L^2 \times 100\% = \text{efficiency in \%} / \text{W} \]
Measured SHG Spectrum

![Graph showing Measured SHG Spectrum with peaks labeled Fundamental Mode and Higher-Order Mode.]}
External Coupling Efficiency to Single-Mode Fiber

\[ \eta_{\text{coup}} = \frac{\left| \int_{-\infty}^{\infty} dx \int_{-\infty}^{\infty} dy \, E_1(x,y) e^{-\frac{(y-y_0)^2}{\sigma^2}} \right|^2}{\left| \int_{-\infty}^{\infty} dx \int_{-\infty}^{\infty} dy \ e^{-\frac{(y-y_0)^2}{\sigma^2}} \right|^2} \]
Conclusions

• Comsol Multiphysics was used to simulate a multi-step diffusion process for waveguide fabrication and compute the corresponding optical modes

• Good agreement with experiment was achieved with one fitting parameter