Periodically Poled Lithium Niobate Waveguides for Quantum Frequency Conversion

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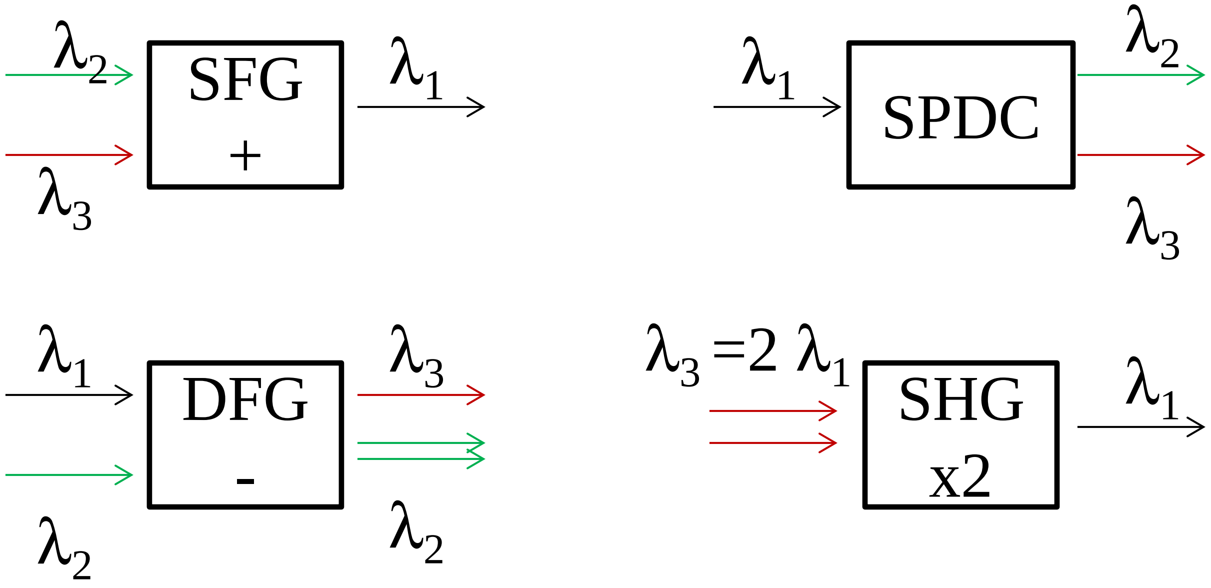
Introduction/Overview

- 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

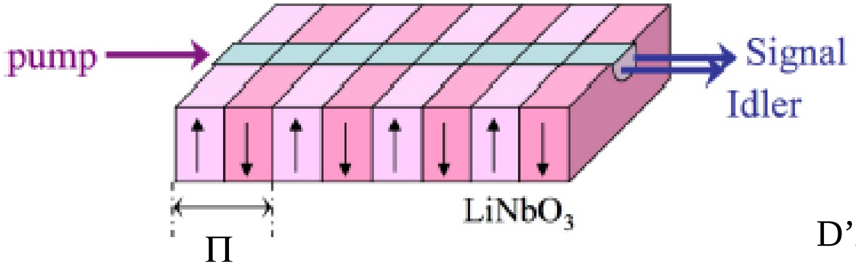
- For a frequency conversion process to occur efficiently, momentum must be conserved

$$\frac{n_1}{\lambda_1} = \frac{n_2}{\lambda_2} + \frac{n_3}{\lambda_2}$$

- 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



D'Auria, et al., *Proc. SPIE* **8172** (2011)

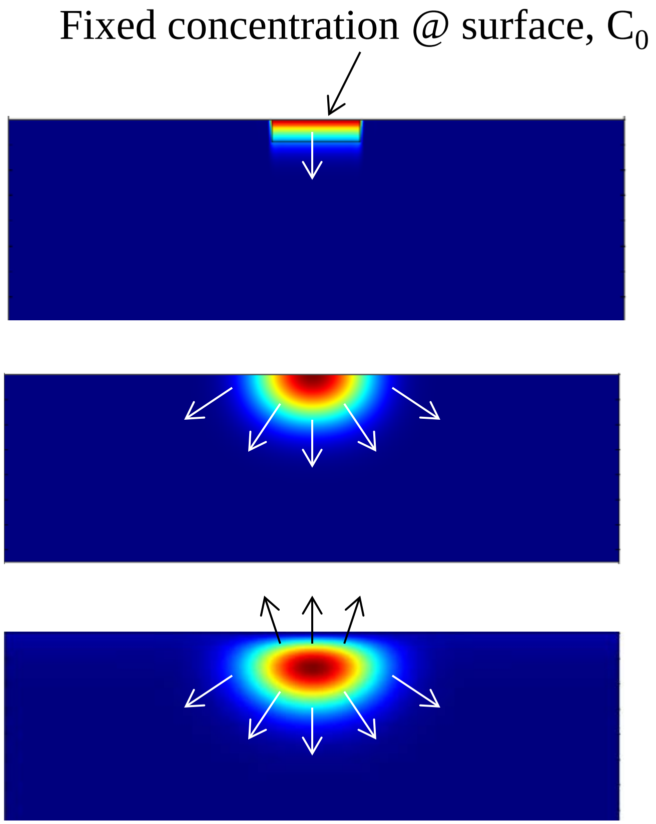
- Momentum conservation condition becomes

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

Diffused Waveguide Modeling in Comsol

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

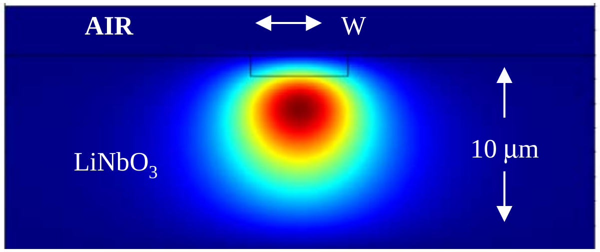
$$D_e(T) = D_{0e} e^{-Q/RT}$$



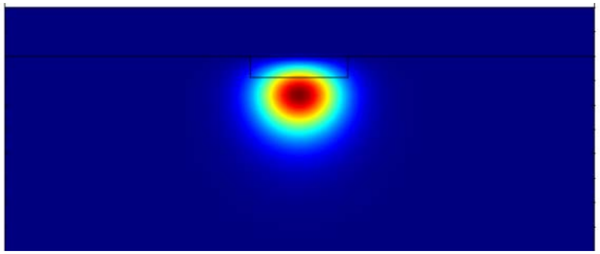
Diffused Waveguide Modeling in Comsol

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

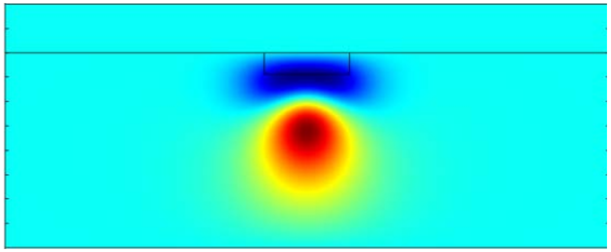
@ λ_2



@ λ_1

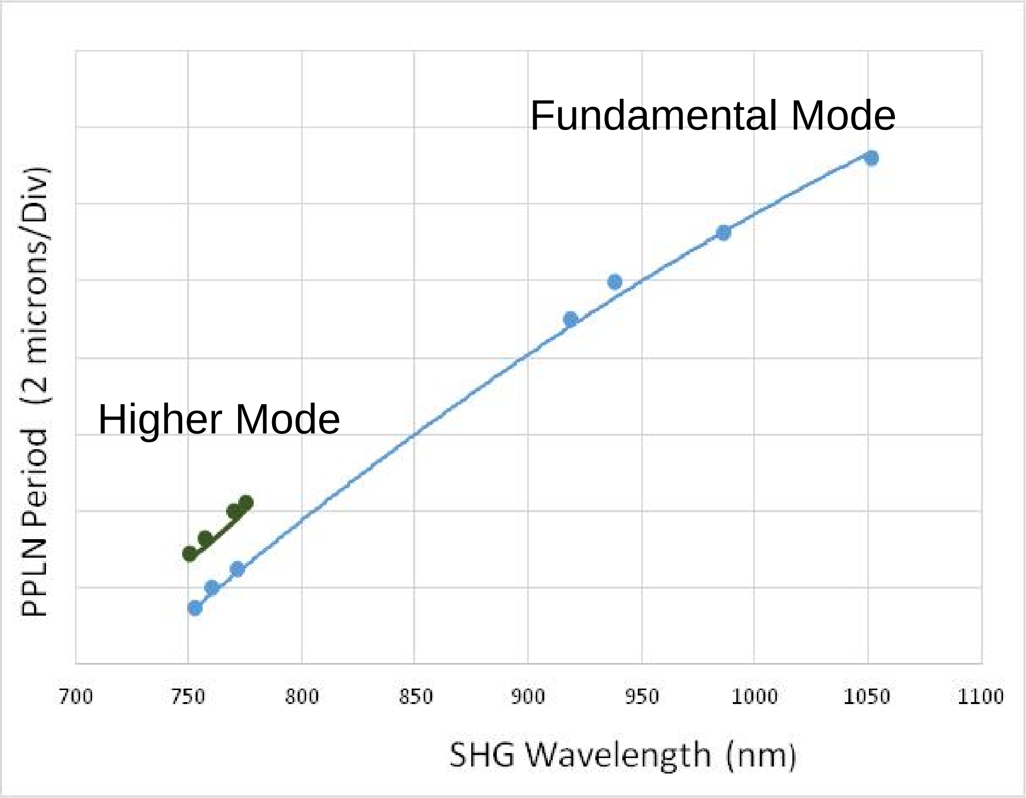


Fundamental mode



Higher-order mode

SHG Peak Wavelength vs. QPM Period: Model & Measurements



Conversion Efficiency

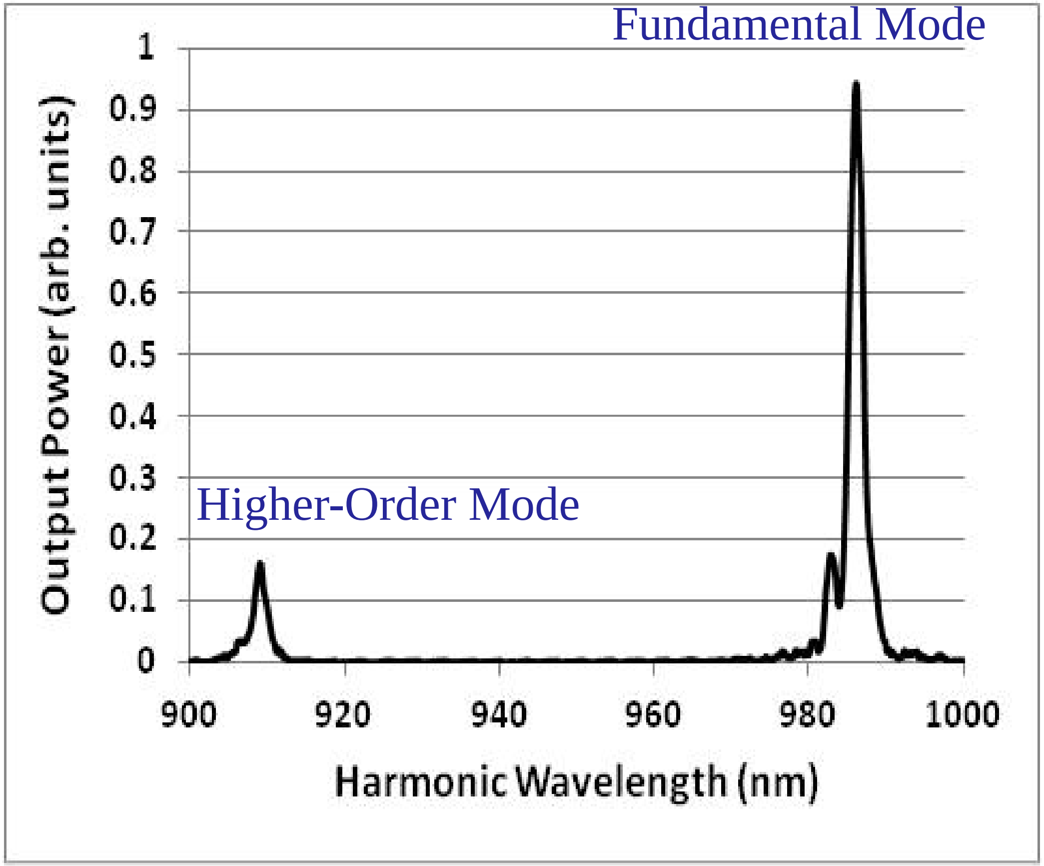
$$\eta_0 = \frac{8\pi^2 d_{eff}^2}{n_1 n_2 n_3 c \epsilon_0 \lambda_3^2} \qquad [\text{Power}^{-1}]$$

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

ηx100% = slope efficiency in % / (W m^2)

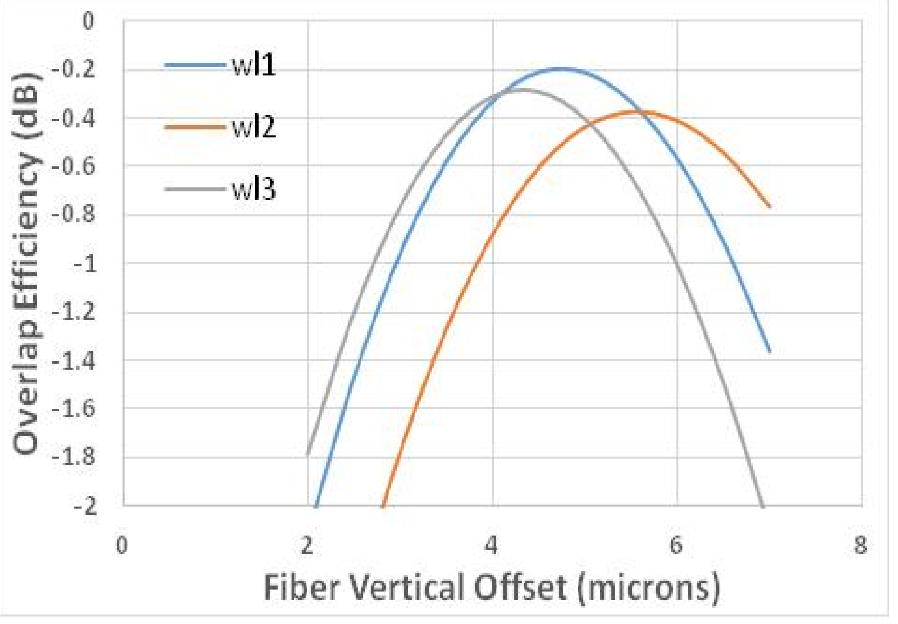
ηL^2x100% = efficiency in %/W

Measured SHG Spectrum



External Coupling Efficiency to Single-Mode Fiber

$$\eta_{\text{coup}} = \frac{\left| \int_{-\infty}^{\infty} dx \int_{-\infty}^{\infty} dy\, \hat{E}_1(x,y) e^{-(y-y_0)^2/\sigma^2} \right|^2}{\left| \int_{-\infty}^{\infty} dx \int_{-\infty}^{\infty} dy\, e^{-(y-y_0)^2/\sigma^2} \right|^2}$$



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