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WINTER COLLEGE ON OPTICS ON OPTICS AND PHOTONICS IN NANOSCIENCE AND NANOTECHNOLOGY

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"Nonlinear Optical Waveguides" - I

presented by:

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Nonlinear Waveguides in Microstructured Media: Materials, Devices, and Applications

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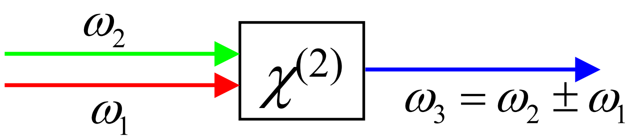
Waveguide Nonlinear Optics

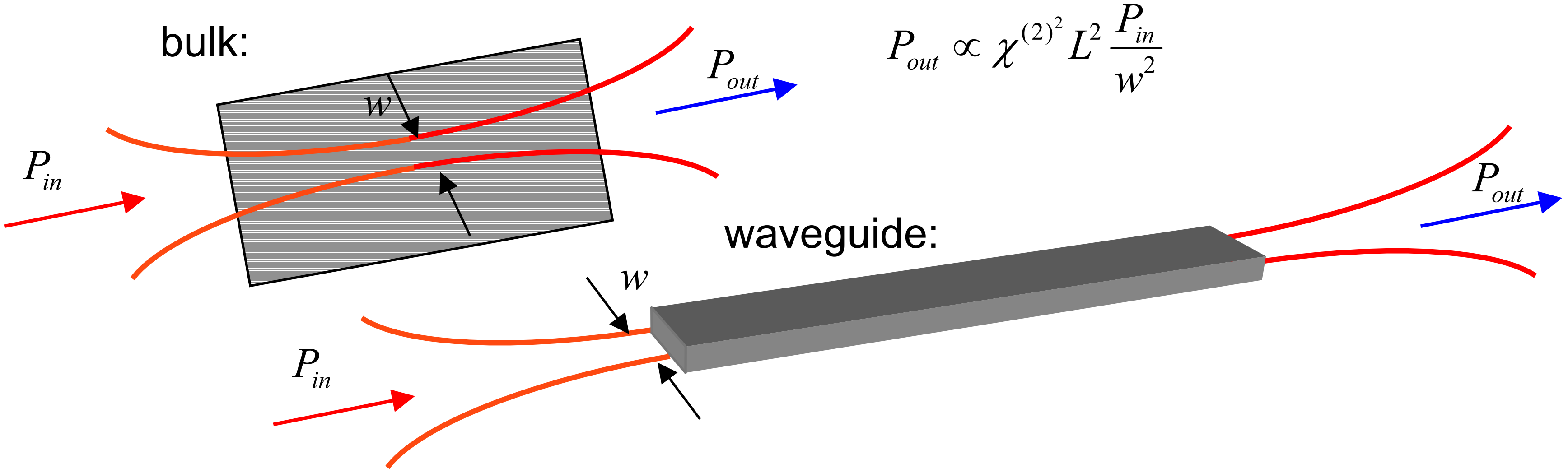
- Nonlinear optics $P \propto \chi^{(1)}E + \chi^{(2)}E^2 + \chi^{(3)}E^3 + \ldots$



$\chi^{(2)}$ mixes frequencies
  harmonic generation
  sum/difference
  parametric amplification

- Why waveguide nonlinear interactions?

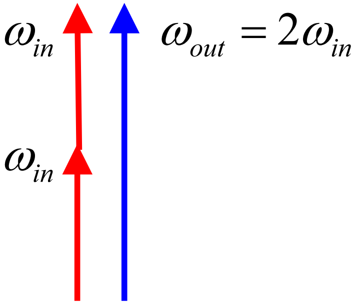
$$P_{out} \propto {\chi^{(2)}}^2 L^2 \frac{P_{in}}{w^2}$$

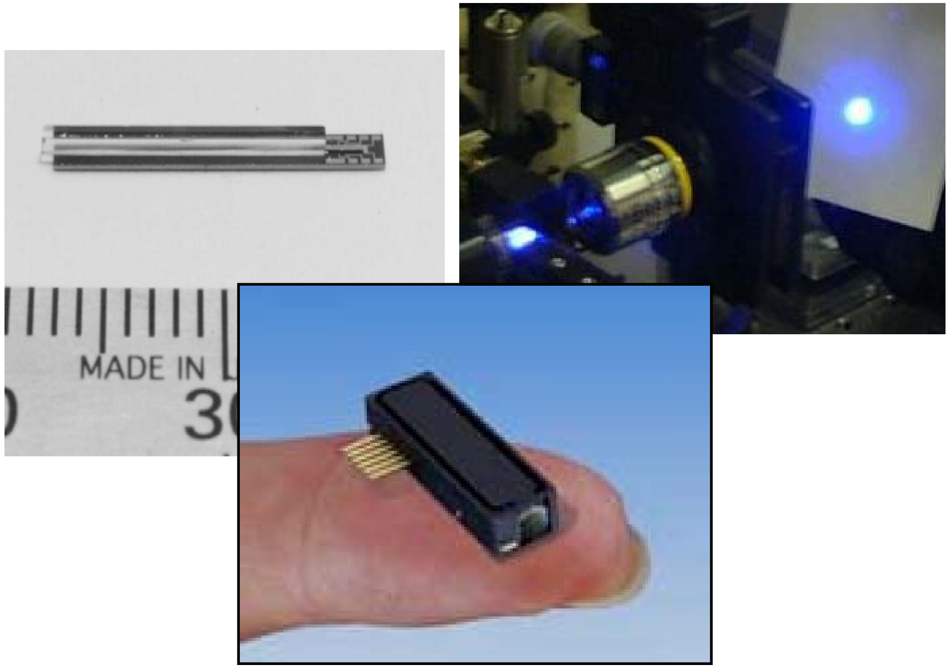


  - waveguide confinement enhances efficiency
  - efficient operation with milliwatt powers

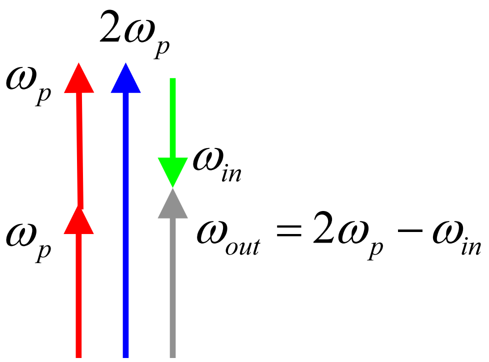
Typical Waveguide $\chi^{(2)}$ Devices

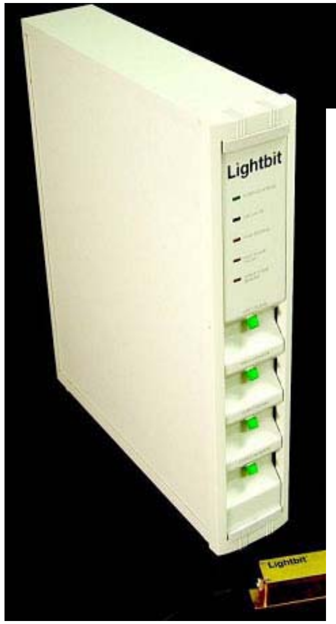
- Generation of coherent radiation
  - SHG: $\omega_{out} = 2\omega_p$
  - 810 nm → 405 nm
  - NGK-Matsushita for ODS

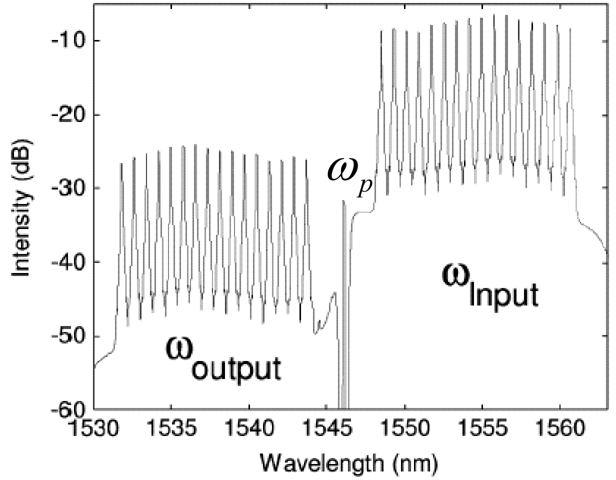




- Optical signal processing
  - Cascaded DFG: $\omega_{out} = 2\omega_p - \omega_{in}$
  - convert within 1.5 μm band
  - Lighbit for telecom applications



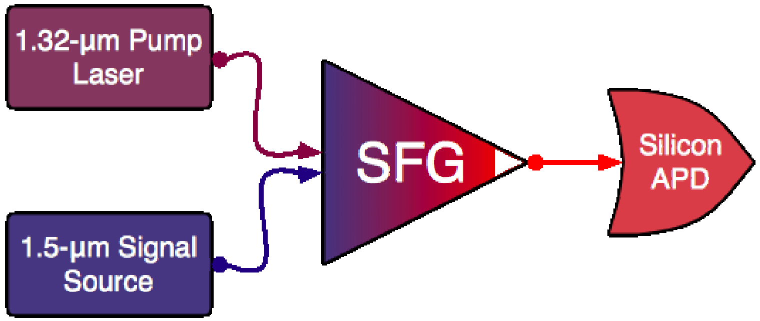


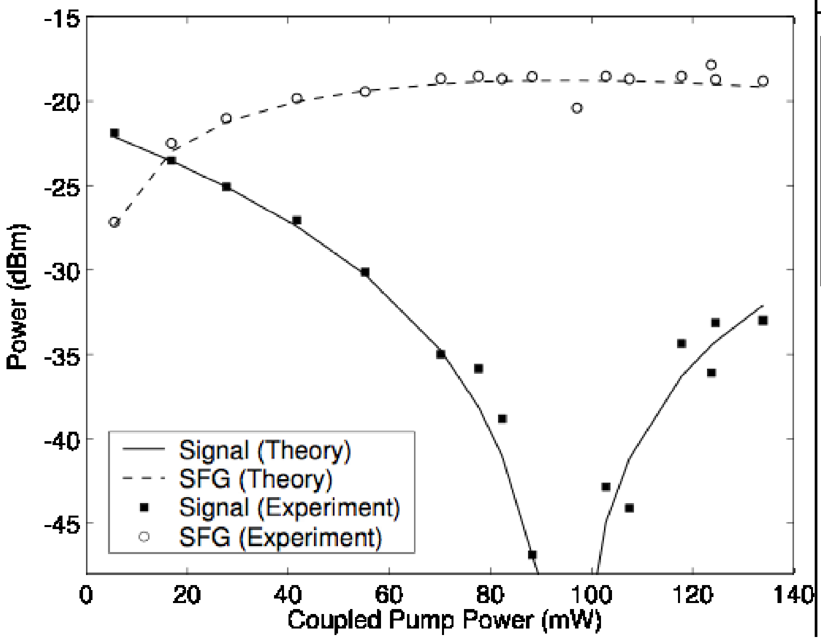


Examples of Applications of Highly Nonlinear Waveguides

99.9% photon conversion

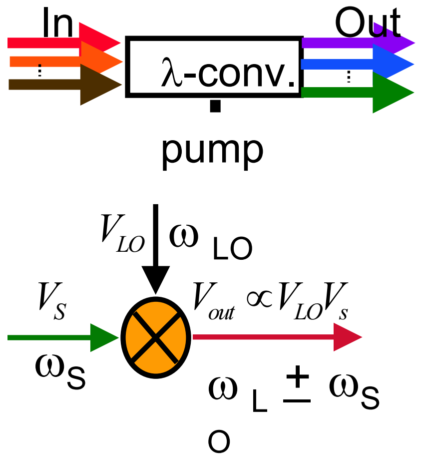
enable 1.5-μm photon counting

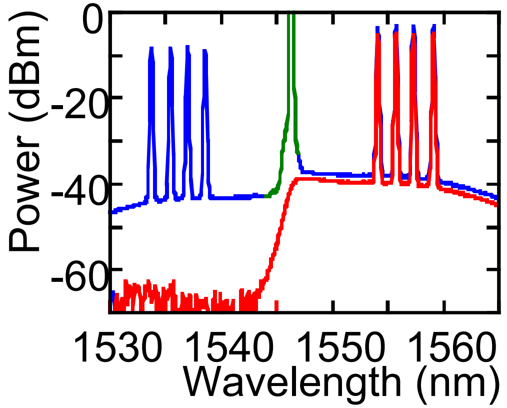




Efficient waveguide mixers for telecom

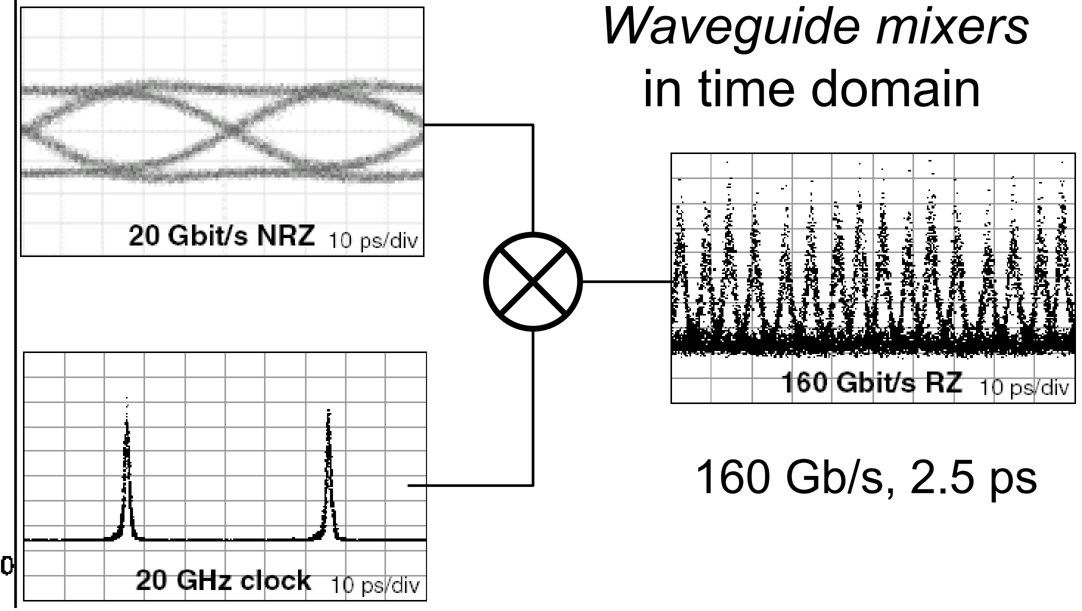
various signal processing functions





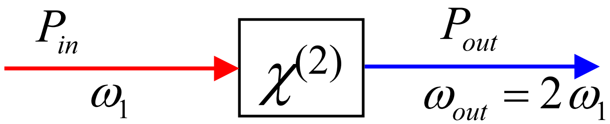
Waveguide mixers

in time domain



160 Gb/s, 2.5 ps

Key Concepts

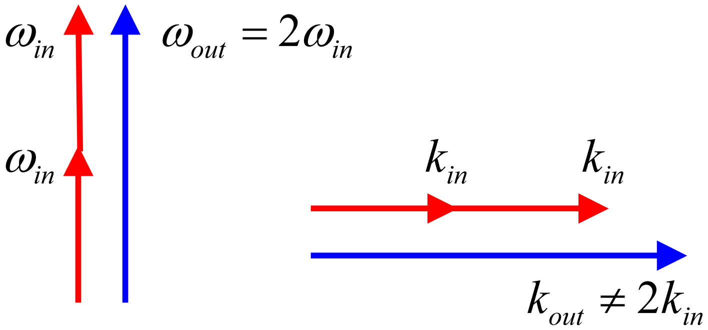


- Efficiency
  - how much output for given inputs
  - evade limitations imposed by inherently small nonlinearities
  - enabled by waveguide devices

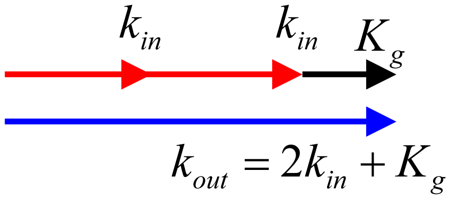
$$\eta \equiv \frac{P_{out}}{P_{in}}$$

- Phasematching
  - momentum must be conserved
  - not unless medium dispersionless

$$k = n\omega / c \qquad n_{2\omega} \neq n_{\omega}$$



- Quasi-phasematching
  - periodic structure compensates for mismatch
  - micron-scale features needed
  - microstructured materials essential



How to incorporate nonlinearity into EM equations?

Total polarization response: $P \propto \chi^{(1)}E + \chi^{(2)}E^2 + \chi^{(3)}E^3 + \ldots$

$$\mathbf{D}(\mathbf{r},t) = \varepsilon\varepsilon_0\mathbf{E}(\mathbf{r},t) + \mathbf{P}_{NL}(\mathbf{r},t)$$

separate out "interesting" nonlinear contribution to the total polarization. Lump linear response into $\varepsilon = 1 + \chi^{(1)}$

Can manipulate Maxwell equations into forced wave equation:

$$\frac{\varepsilon}{c^2}\frac{\partial^2\mathbf{E}(\mathbf{r},t)}{\partial t^2} - \nabla^2\mathbf{E}(\mathbf{r},t) = -\mu_0\frac{\partial}{\partial t}\left[\mathbf{J}(\mathbf{r},t) + \frac{\partial\mathbf{P}_{NL}(\mathbf{r},t)}{\partial t}\right]$$

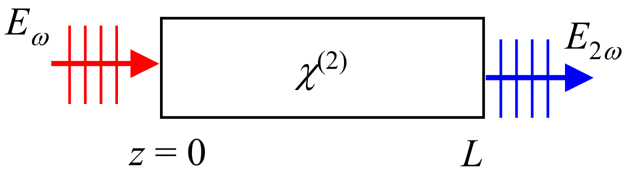
note that time dependent polarization acts like a current:

$$\partial\mathbf{P}_{NL}/\partial t \leftrightarrow \mathbf{J}$$

Monochromatic: $e^{i\omega t}$

$$\boxed{\omega^2\frac{\varepsilon}{c^2}\mathbf{E}(\mathbf{r}) + \nabla^2\mathbf{E}(\mathbf{r}) = -\omega^2\mu_0\mathbf{P}_{NL}(\mathbf{r})}$$

Plane-Wave Second Harmonic Generation (SHG)

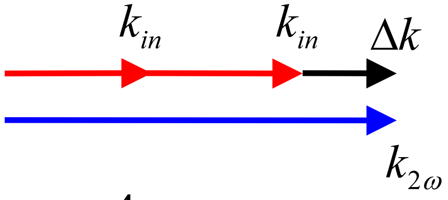


$$E(x,y,z)e^{i\omega t} = E_\omega(z)e^{-ik_\omega z}e^{i\omega t}$$

nonlinear polarization: $P_{2\omega} \propto \chi^{(2)}\, E_\omega^2\, e^{-i2k_\omega z}$

field evolution: $\dfrac{dE_{2\omega}}{dz} \propto \omega P_{2\omega} \propto \omega\chi^{(2)}\, E_\omega^2\, e^{ik_{2\omega}z}$

phase mismatch: $\Delta k = k_{2\omega} - 2k_\omega$



$$\Delta k = \frac{4\pi}{\lambda}(n_{2\omega} - n_\omega)$$

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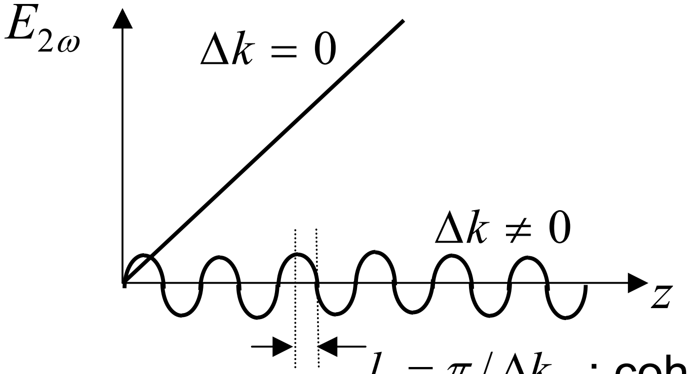
phasematched: $\Delta k = 0$

$$E_{2\omega}(L) \propto \chi^{(2)}\, E_\omega^2\, L$$



$l_c = \pi / \Delta k$: coherence length

not phasematched: $\Delta k \neq 0$

$$E_{2\omega}(L) \propto \int_0^L E_\omega^2\, \chi^{(2)} \exp(i\Delta k\, z)\, dz$$

$$\rightarrow E_\omega^2 \chi^{(2)}\, \sin(\Delta k\, L2)/\Delta k$$

$$\sim E_\omega^2\, \chi^{(2)} L\, \mathrm{sinc}(\Delta k\, L/2)$$

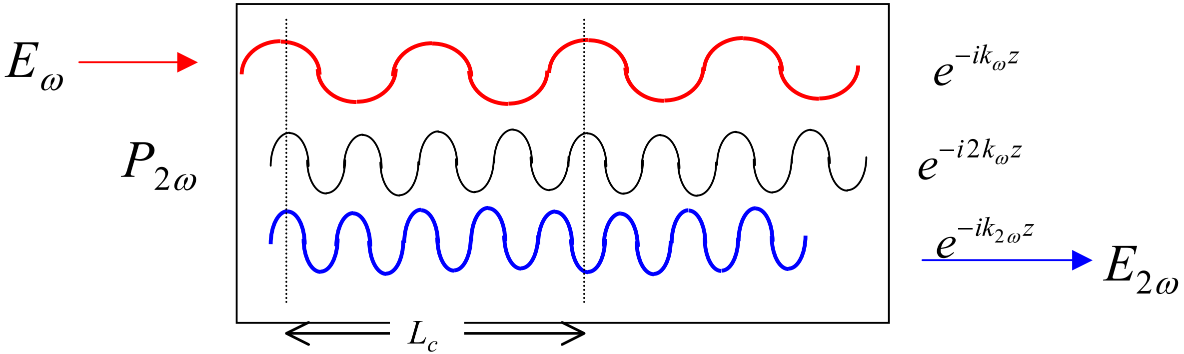
Phase velocity matching essential

Second Harmonic Generation

- Nonlinear polarization ≈ oscillating current

$$P_{2\omega} \propto \chi^{(1)} E_{2\omega} + \chi^{(2)} E_{\omega}^{2} + \ldots \qquad j_{2\omega} \propto \dot{P}_{2\omega}$$

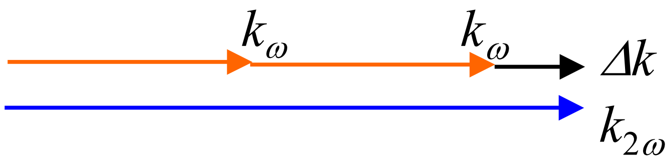
- Output field is sum of contributions from whole crystal



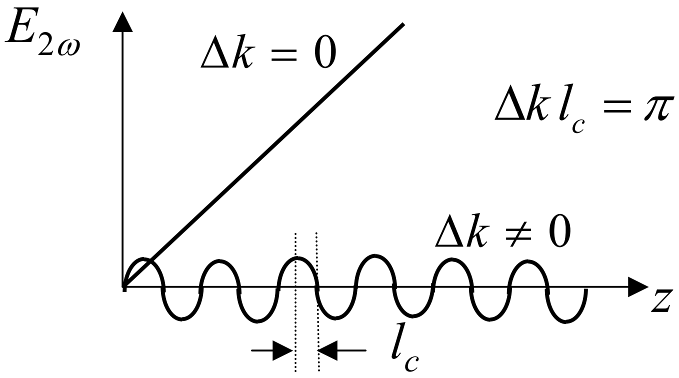
$$E_{2\omega}(L) \propto \int_0^L E_{\omega}^{2}\, \chi^{(2)} \exp(i\Delta k\, z)\, dz$$

$$\to E_{\omega}^{2} \chi^{(2)}\ \sin(\Delta k\, L/2)/\Delta k$$

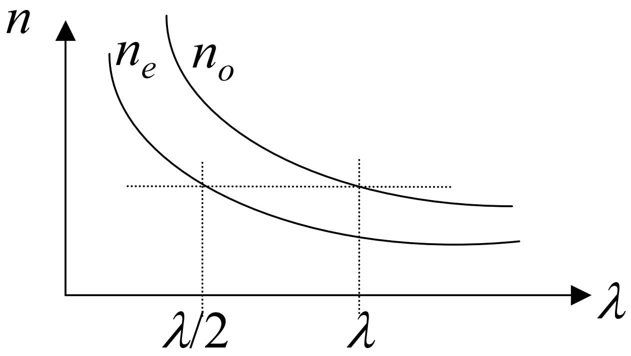
$$\Delta k = k_{2\omega} - 2k_{\omega} = (2\pi/\lambda)(n_{2\omega} - n_{\omega})$$



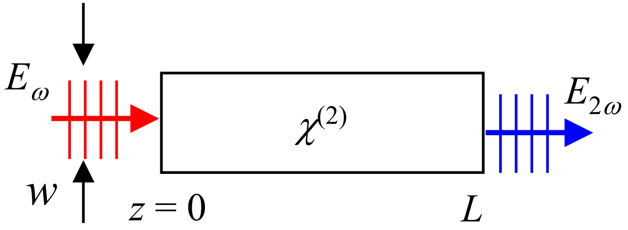
Phase velocity matching essential



Birefringence conventionally used



Undepleted Pump SHG



$$E_{2\omega}(L) = \frac{i\omega}{2n_2 c} \int_0^L \chi^{(2)} E_\omega^2 \, e^{i\Delta k\, z} \, dz$$

- Undepleted pump: $E_\omega(z) \approx \mathrm{const}$
  uniform nonlinear coefficient, $\chi^{(2)} = \mathrm{const}$

$$E_{2\omega}(L) = \frac{i\omega}{2n_2 c} \chi^{(2)} E_\omega^2 \int_0^L e^{i\Delta k\, z} \, dz$$

- Phasematched case: $\Delta k = 0$
  - field grows linearly with L
  - intensity grows quadratically with L
  - material parameter C^2 $[\mathrm{W}^{-1}]$
  - convenient form for efficiency η
    plane wave efficiency η_0

$$E_{2\omega}(L) = \frac{i\omega}{2n_2 c} \chi^{(2)} E_\omega^2 \, L$$

$$I_2(L) = C^2 \, L^2 \, I_1^2$$

$$C^2 = \frac{2\pi^2 \chi^{(2)2}}{n_2 n_1^2 c \varepsilon_0 \lambda^2}$$

$$\eta \equiv I_2 / I_1 = \eta_0 = C^2 \, L^2 \, I_1$$

$$\eta = \frac{P_{2\omega}}{P_\omega} = C^2 L^2 \frac{P_\omega}{\pi w^2}$$

Phase-mismatched SHG

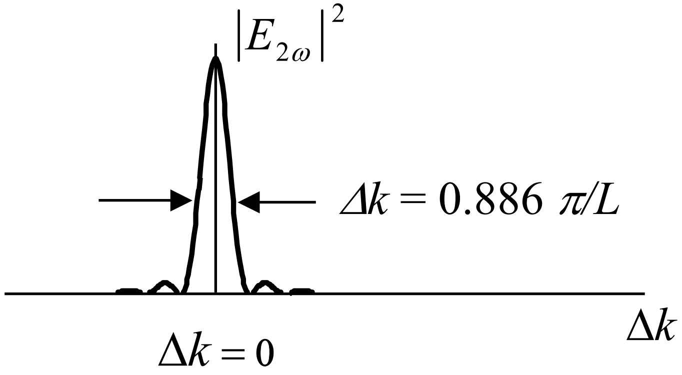
- Allow nonzero mismatch: $\Delta k_0 \neq 0$
  - retain undepleted pump assumption
  - can be written conveniently with plane wave efficiency η_0

$$E_{2\omega}(L) = \frac{i\omega}{2n_2 c}\chi^{(2)}E_\omega^2 \int_0^L e^{i\Delta k\, z}\, dz$$

$$E_{2\omega}(L) = \frac{i\omega}{2n_2 c}\chi^{(2)}E_\omega^2\, L\, \mathrm{sinc}(\Delta k\, L/2)$$

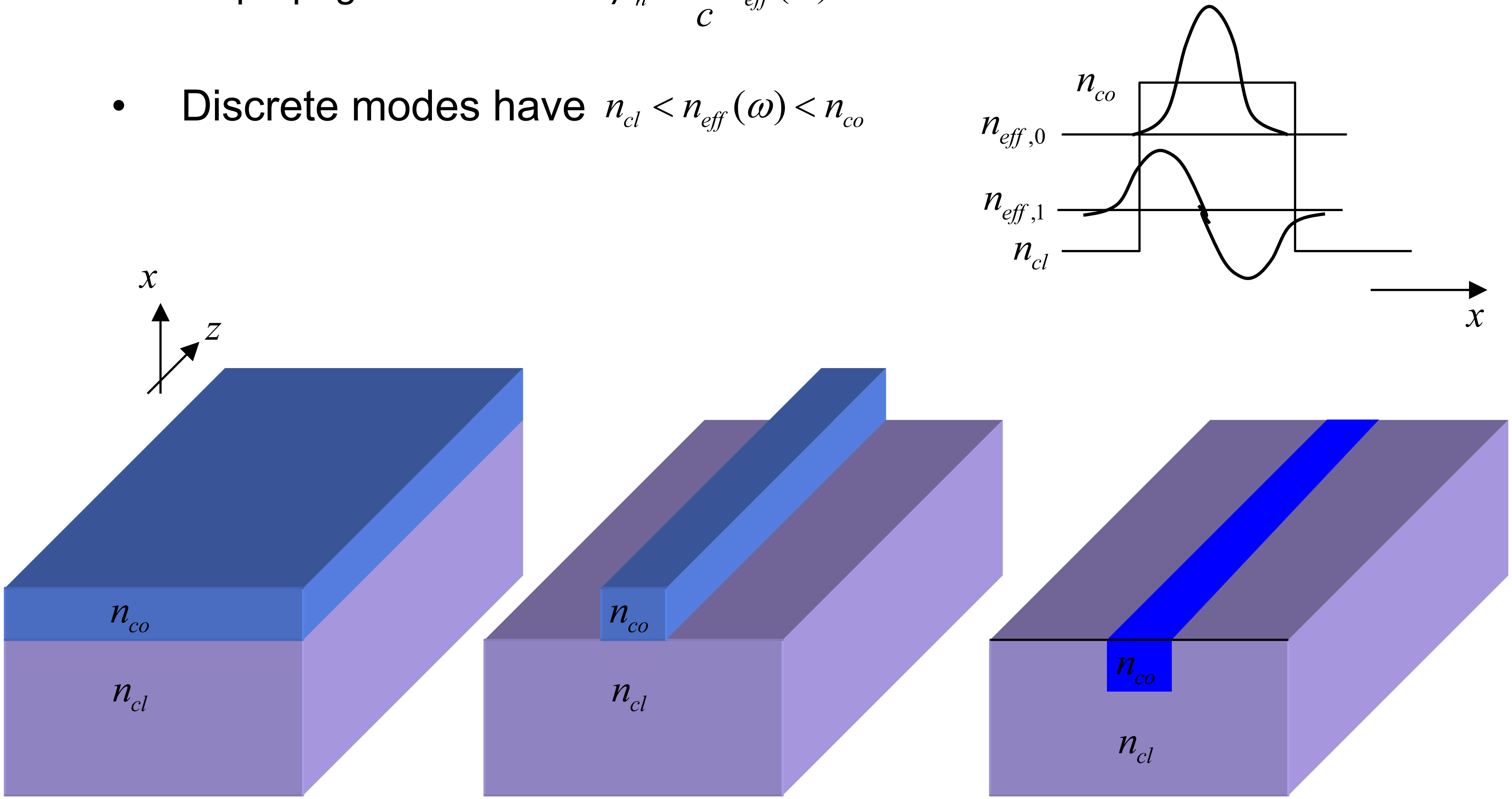
$$\eta = \eta_0\, \mathrm{sinc}^2(\Delta k L/2)$$

- General properties
  - conversion sharply peaked at $\Delta k = 0$
  - width scales inversely with length

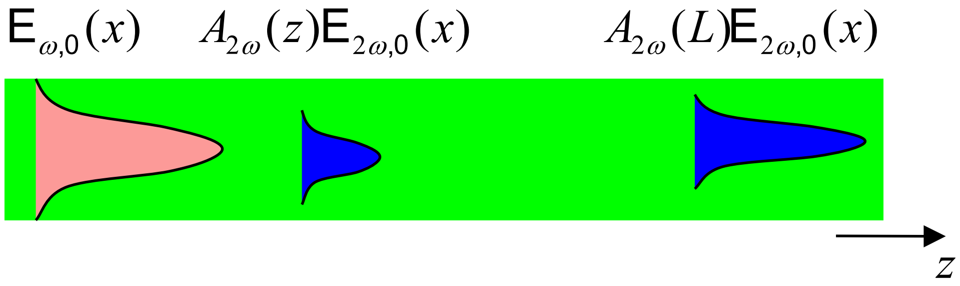


Waveguide concepts

- Dielectric waveguide: $n(x,y,z) = n_{cl} + (n_{co} - n_{cl})\, f(x,y)$
- Supports discrete eigenmodes: $E_n(x,y,z)e^{i\omega t} = \mathrm{E}_n(x,y)e^{-i\beta_n z}\, e^{i\omega t}$
  - modal field $\mathrm{E}_n(x,y)$
  - propagation constant $\beta_n \equiv \frac{\omega}{c} n_{eff}(\omega)$
- Discrete modes have $n_{cl} < n_{eff}(\omega) < n_{co}$



Map PW NLO onto WG



- Waveguide case maps simply onto plane-wave description

- Describe evolution in terms of z-dependent amplitude, $A(z)$

$$E_n(x,y,z)e^{i\omega t} = A(z)\,\mathsf{E}_\mathrm{n}(x,y)e^{-i\beta_n z}\,e^{i\omega t}$$

- Propagation equation for amplitudes:

$$\frac{dA_{2\omega}}{dz} \propto \chi^{(2)}\,J\,A_\omega^2\,e^{i\Delta\beta z}$$

vs plane wave:

$$\frac{dE_{2\omega}}{dz} \propto \chi^{(2)}(z)\,E_\omega^2\,e^{i\Delta kz}$$

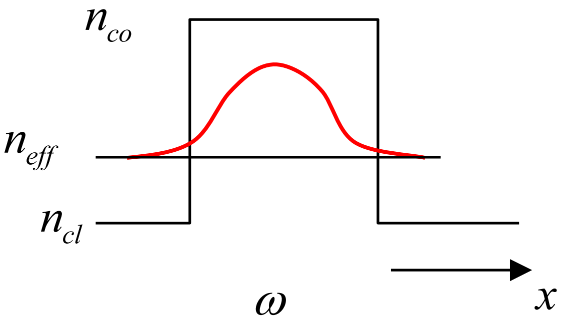
modal phase mismatch: $\Delta\beta \equiv \beta_{2\omega} - 2\beta_\omega$

$\Delta k \equiv k_{2\omega} - 2k_\omega$

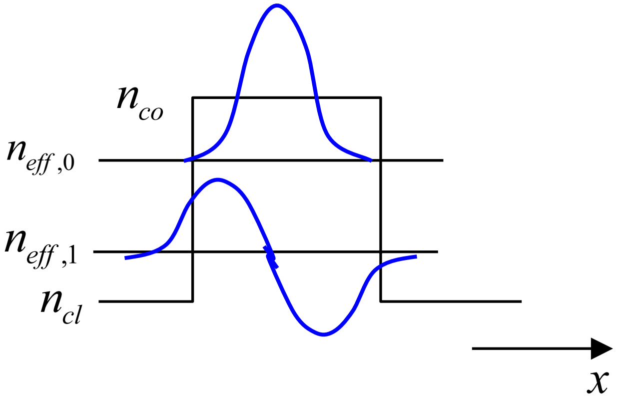
modal overlap: $J \equiv \int \mathsf{E}_{2\omega}(x,y)\mathsf{E}_\omega^2(x,y)\,dx\,dy$

Two Major Waveguide Effects on NLO

- Waveguide dispersion
  - intramodal dispersion is “normal” -- adds to material dispersion
    does not help for phasematching
  - intermodal dispersion
    can be used for phasematching between modes
    usually difficult to use
      output in undesirable high-order mode
  - imperfect waveguide geometry spoils phasematching
    contributes to tight fabrication tolerances



ω



2ω

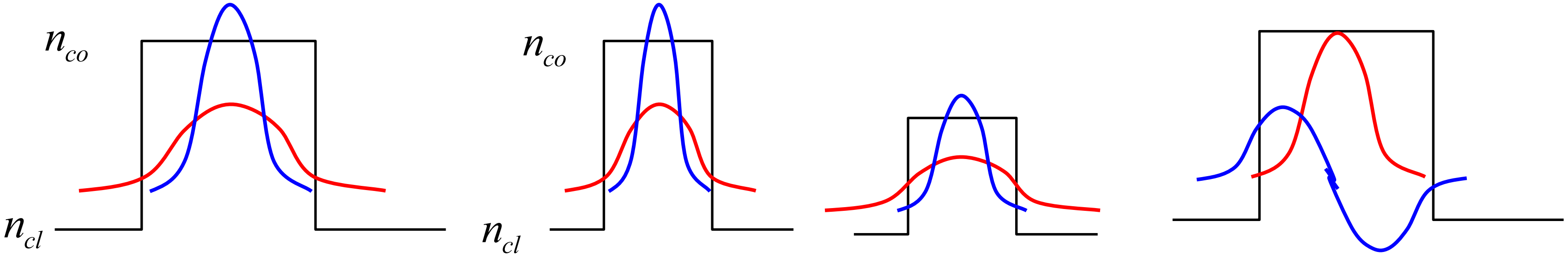
modal phasematching only possible if $n_{co}(2\omega) - n_{co}(\omega) < n_{co} - n_{cl}$

Two Major Waveguide Effects on NLO

- Modal overlap
  - large mode overlap J important for efficiency
  - favors fundamental mode, tight confinement
  - some interactions (odd-even mode) forbidden
  - can state as “effective area”
    area of a plane wave that would have the same efficiency

$$A_{eff} \propto \frac{1}{\int \mathrm{E}_{2\omega}(x,y)\mathrm{E}^2_{\omega}(x,y)\,dx\,dy} \qquad \frac{P_{2\omega}}{P_\omega} = C^2 L^2 \frac{P_\omega}{A_{eff}}$$

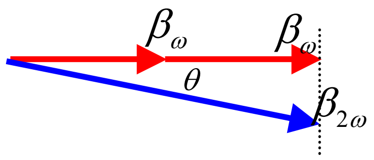
$$\boxed{\frac{P_{2\omega}}{P_\omega} = \kappa\ [\%/\,\mathrm{W\text{-}cm}^2]\ L^2\, P_\omega}$$

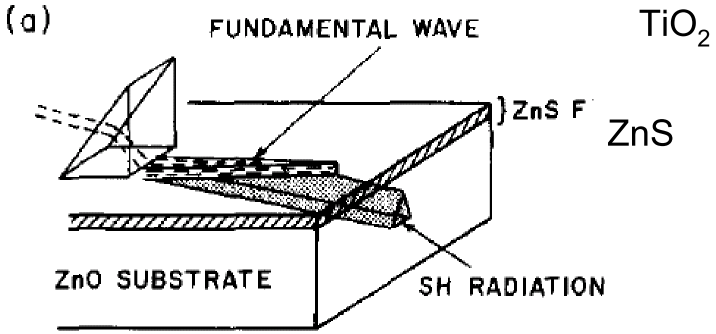


Early Work in Waveguide NLO

- Frequently used linear waveguide on nonlinear substrate

- "Cerenkov" phasematching
  - generate radiation mode
  - low efficiency
  - complicated beam patterns



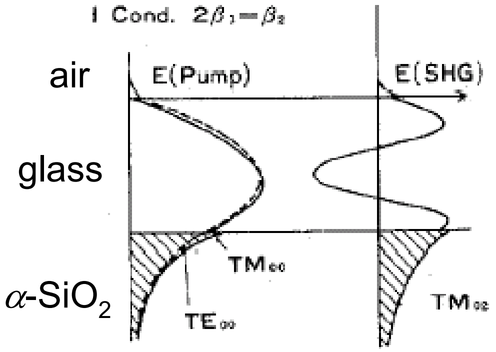


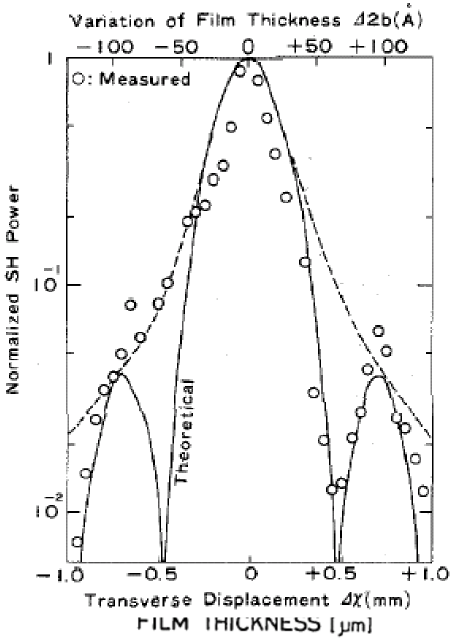
P.K. Tien, *Appl. Phys. Lett.* **17** 447 (1970).

- Multilayer films for modal phasematching
  - engineer dispersion with thicknesses
  - better efficiency than Cerenkov
  - modal overlap still low
  - tight tolerances (10's Å)
  - difficult focusing

- Early work reviewed in:

G. Stegeman, *Appl. Phys. Lett.* **58** R57 (1985).



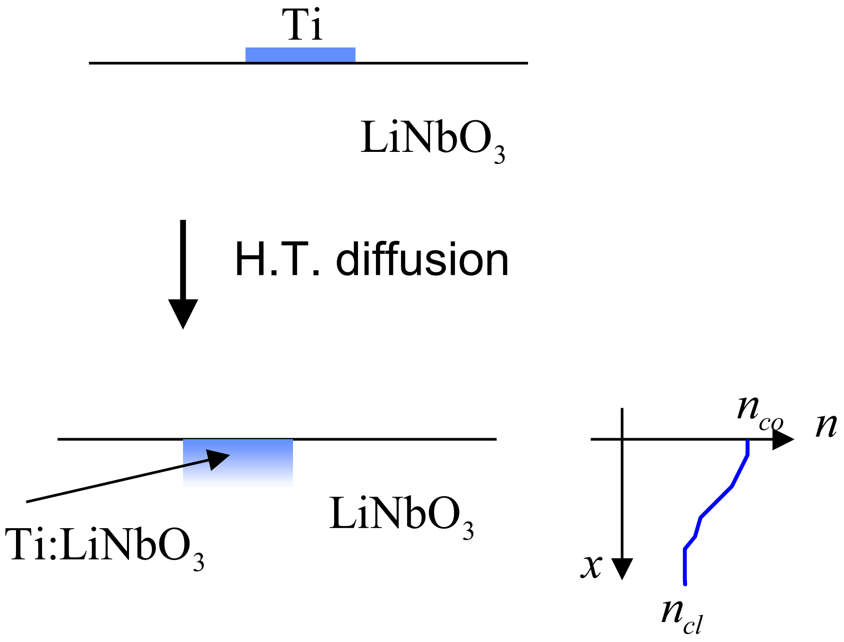


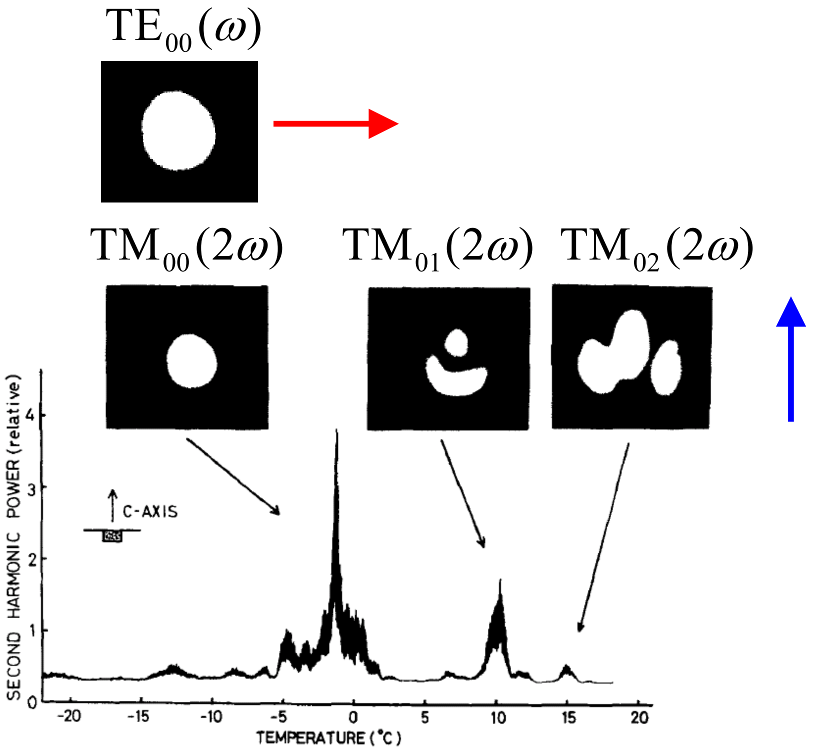
Y. Suematsu, *IEEE JQE* **10** 222 (1974)

Early Waveguide NLO 2

- Diffused waveguides in crystalline substrates soon used
  - could take advantage of birefringent crystals for phasematching
  - combination of birefringence and modal dispersion for PM
  - better overlap
  - looser tolerances
  - operating range limited by birefringence

- Common process: indiffuse Ti film
  - raises refractive index in doped region



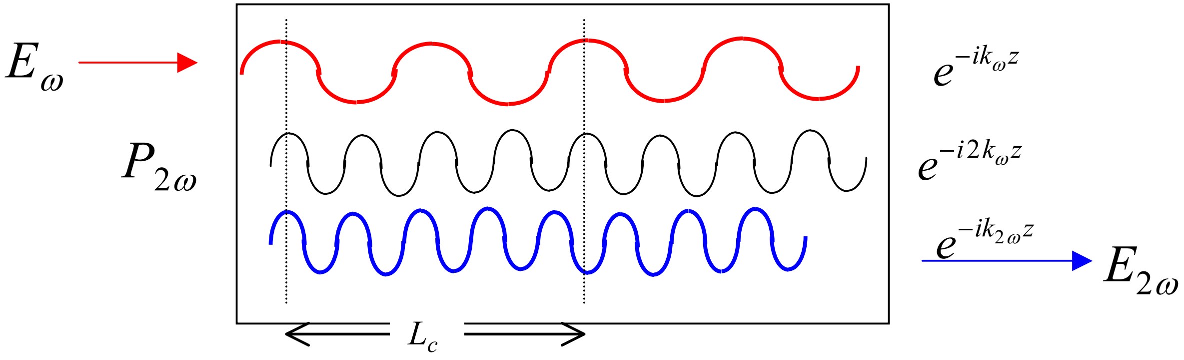


N. Uesugi, *Appl. Phys. Lett* **29** 572 (1976)

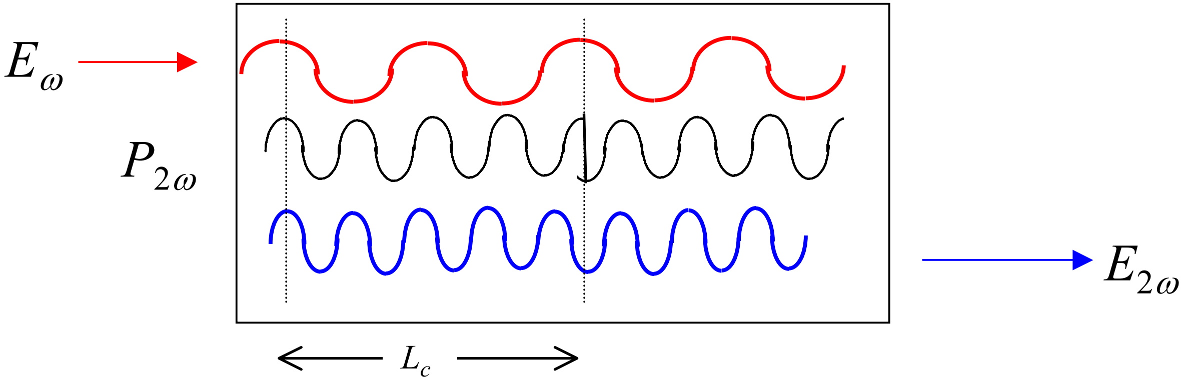
tune birefringence with temperature

Alternative to True Phasematching

- Problem was due to slip of phase between $P_{2\omega}$ and $E_{2\omega}$
  - due to phase velocity mismatch



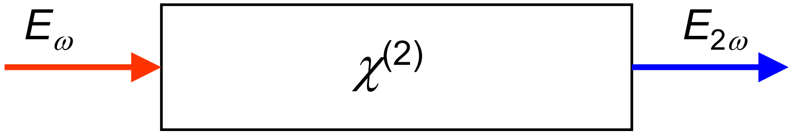
- Introduce an abrupt phase shift in $P_{2\omega}$ after phase slip of π
  - field and polarization now in phase, and growth continues



- Since $P_{2\omega} \propto \chi^{(2)} E_\omega^2$, sign change in $\chi^{(2)}$ gives desired result
  - repeat periodically every coherence length

Phasematching and Quasi-phasematching

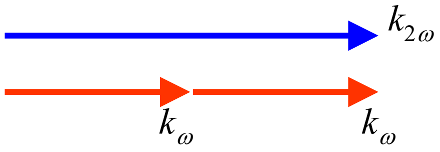
SHG:



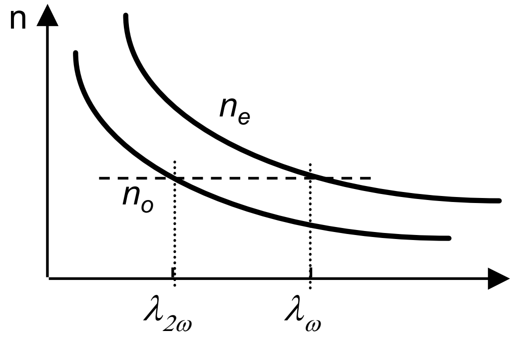
$$dE_{2\omega}/dz \propto \chi^{(2)} E_\omega^2 e^{-i\Delta kz} \qquad E_{2\omega} \propto E_\omega^2 \int \chi^{(2)} e^{-i\Delta kz} dz$$

BPM: [Giordamine, Maker 1962]

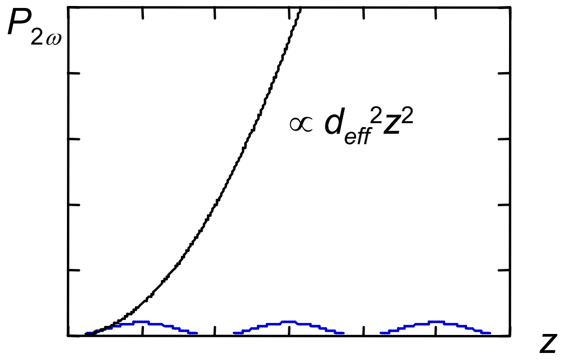
$\Delta k = 0$:



birefringence:

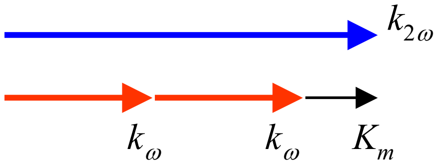


Power:



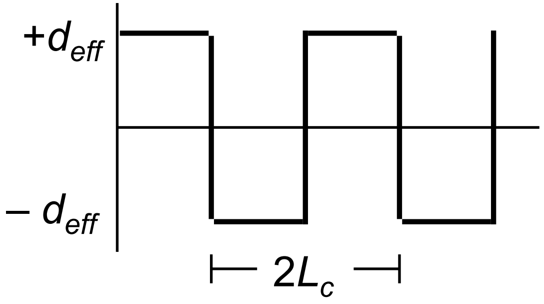
QPM: [Bloembergen 1962]

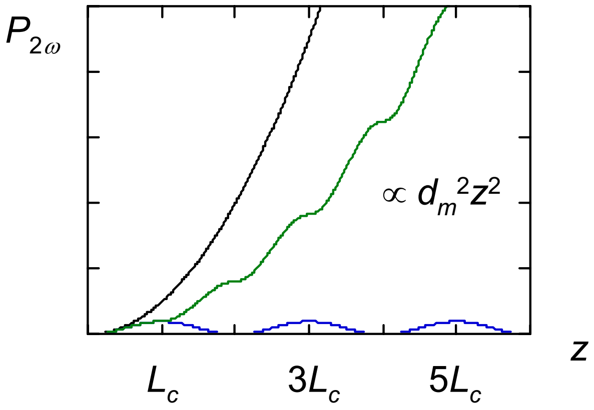
$$d_{eff} = d_m e^{iK_m z}$$



pattern d_{eff}

$$d_m = \frac{2}{m\pi} d_{eff}$$

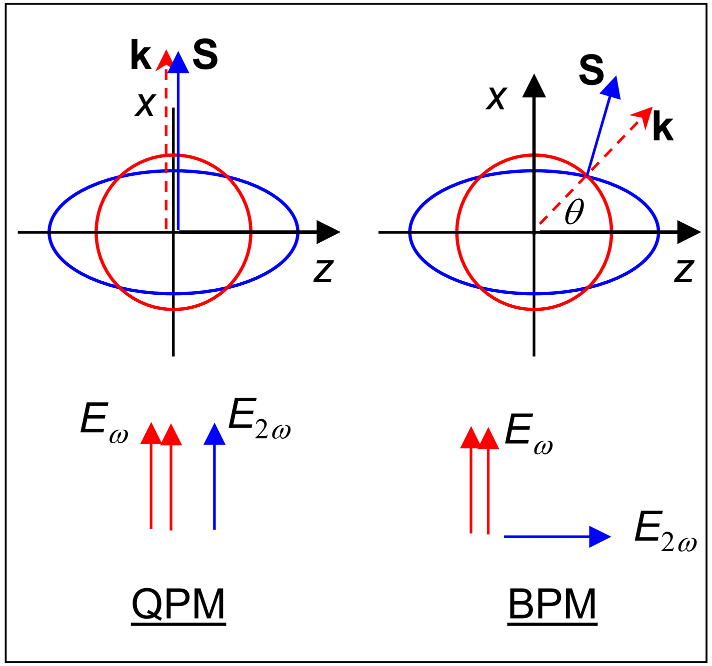




Armstrong, Bloembergen, Ducuing, Pershan, *Phys. Rev.* **127**, 1918 (1962)

Advantages of QPM

Eliminates dependence on birefringence for phasematching



- Any interaction within transparency range
  - even in non-birefringent materials
- Noncritical phasematching
  - eliminates Poynting vector walkoff
  - especially important for OPOs
- Any desired polarizations
  - use large diagonal nonlinear coefficients
  - for $LiNbO_3$: $d_{33}/d_{31} = 7$
- *Aperiodic gratings*
  - shape temporal, spatial, spectral response
- One material can be tailored for many applications
  - base technology on readily available commodity material

Generic Nonlinear Material

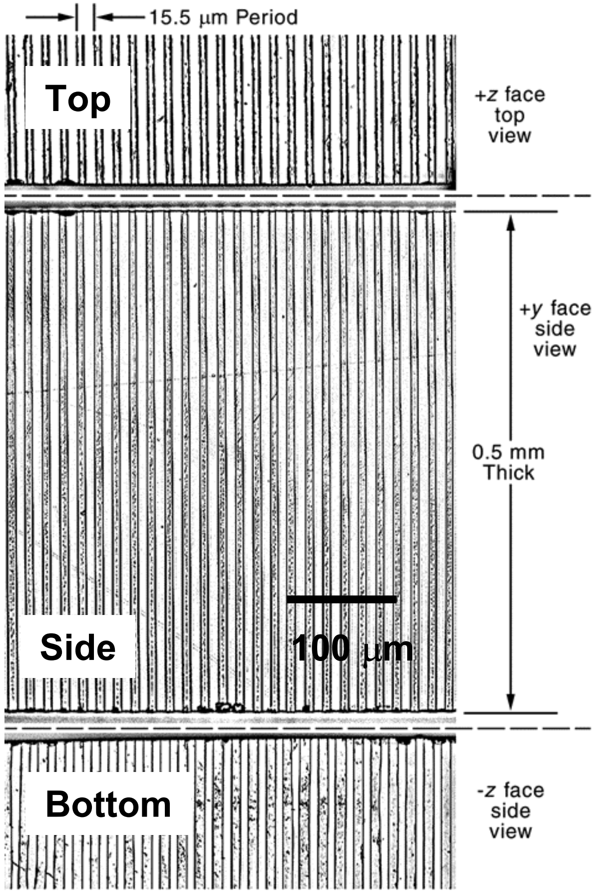
BUT: need patternable material

for micron scale features

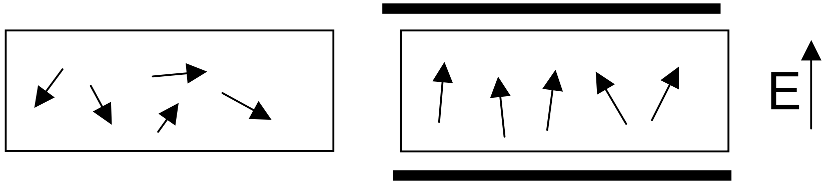
Fejer, Magel, Jundt, Byer, *IEEE-JQE* **28**, 2631 (1992)

Microstructured Materials Essential for QPM

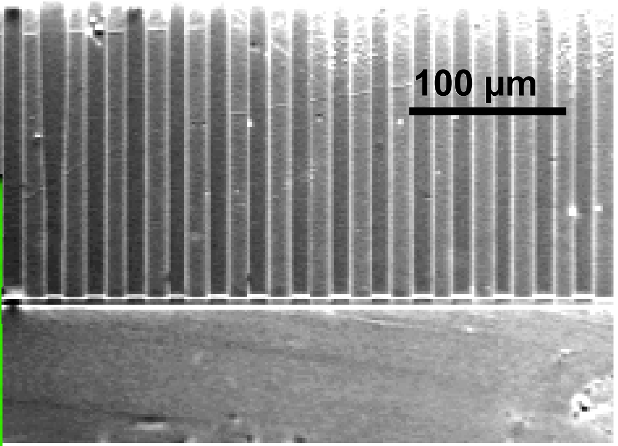
Ferroelectrics

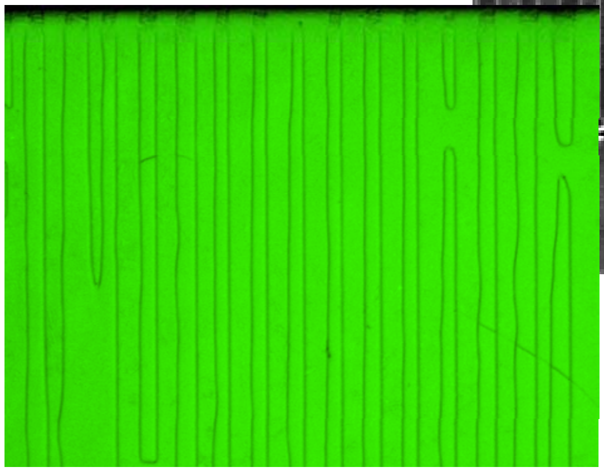


Oriented chromophores in polymers



Orientation-patterned GaAs

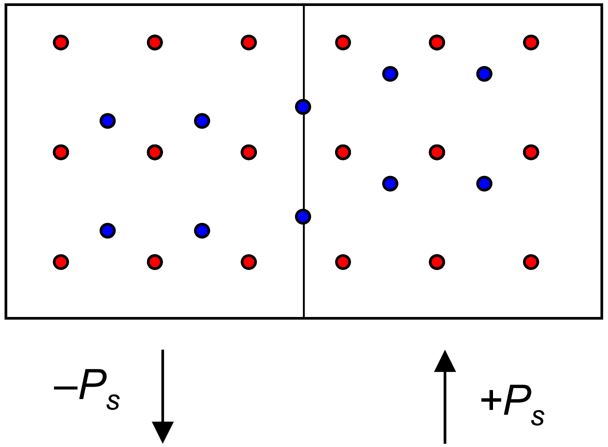




Crystal quartz (ferrobielastic)

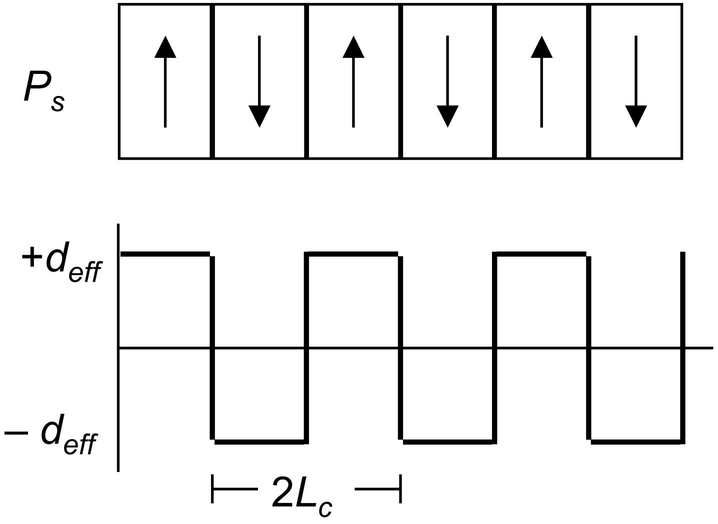
Ferroelectrics

- Spontaneous electric dipole moment, P_s
  - appears below Curie temperature
  - forms into domains
  - "poling": reorients for applied field > E_c
  - analogous to ferromagnets
- Domain reversal like 180° rotation
  - changes sign of odd-rank tensors
  - electrooptic, piezoelectric, nonlinear



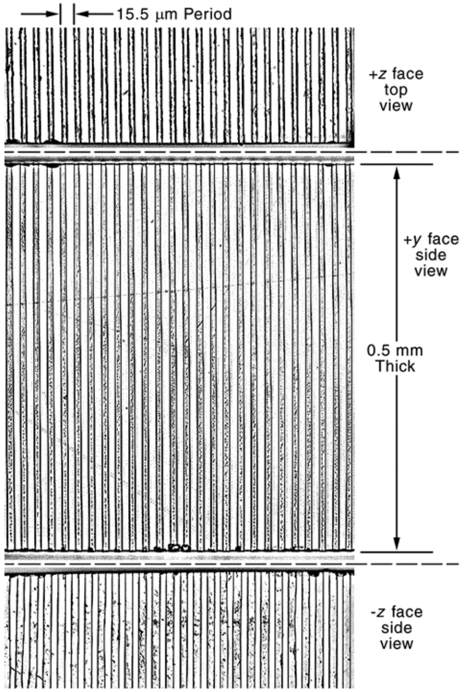
Lines and Glass, *Principles and Applications of Ferroelectrics,* Oxford 1977

- Periodic domain array for QPM:
  - periodic sign change in d_{eff}
- Early work based on periodically perturbed growth
  - control again difficult
- Current techniques use lithographic control
  - micron scale patterning
  - periodic electrode controls domain pattern

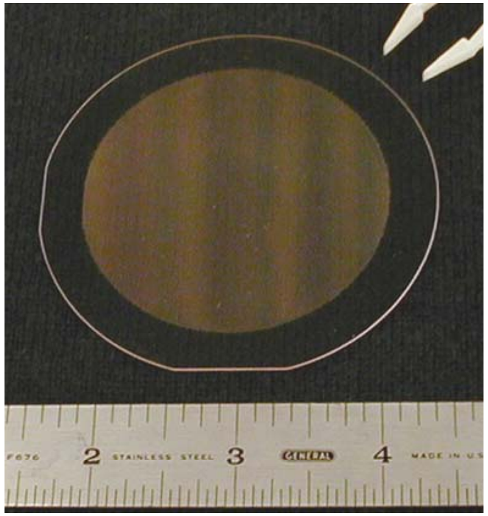


Microstructured Ferroelectrics Important for QPM

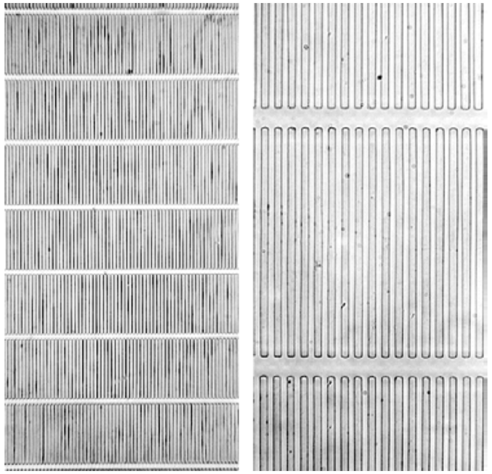
Large Aspect Ratio Structures
Volume patterning by surface lithography on ferroelectrics



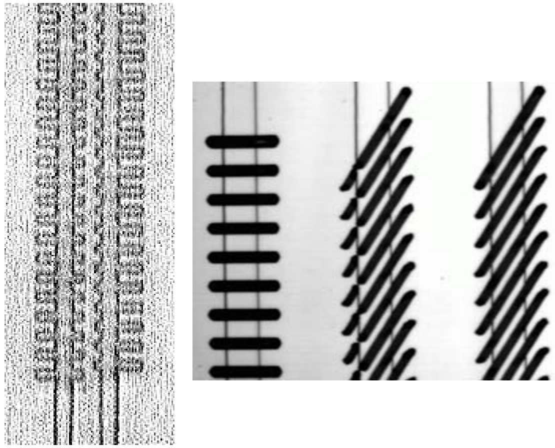
Large Areas
Scalable production



Complex Patterns
Enhanced functionality



Waveguide Devices
Processing compatible

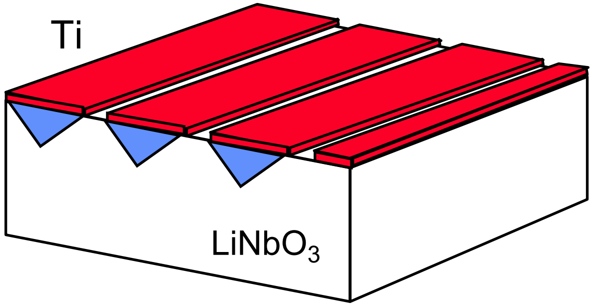


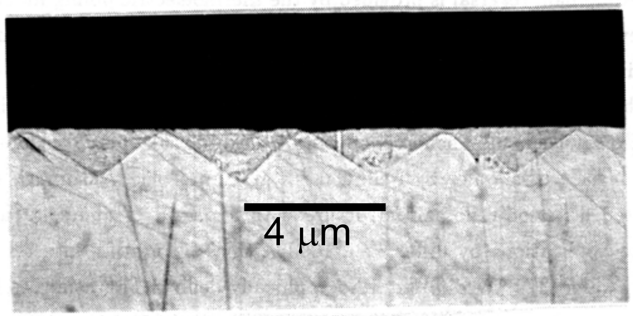
Early Work on Lithographically Patterned Ferroelectrics

- Early work in lithographic patterning based on indiffused dopants
  - Ti in $LiNbO_3$ [Lim 1989]
  - Li in $LiNbO_3$ [Webjorn 1989]
  - H in $LiTaO_3$ [Mizuuchi 1991] [Ahlfeldt 1991]
  - Ba,Rb in $K(TiO)PO_4$ (KTP): [van der Poel 1990]
  - early work reviewed in Fejer [1992b]

- Generally created shallow domain inverted regions
  - suited to waveguide, but not bulk interactions

- Waveguide devices
  - annealed proton exchange in $LiNbO_3$ and $LiTaO_3$
  - Ba, Rb exchange in KTP
  - powers 1 - 10 mW
  - efficiencies 50 - 100%/W-cm^2 demonstrated
    limitations due to overlap of modes with shallow domains

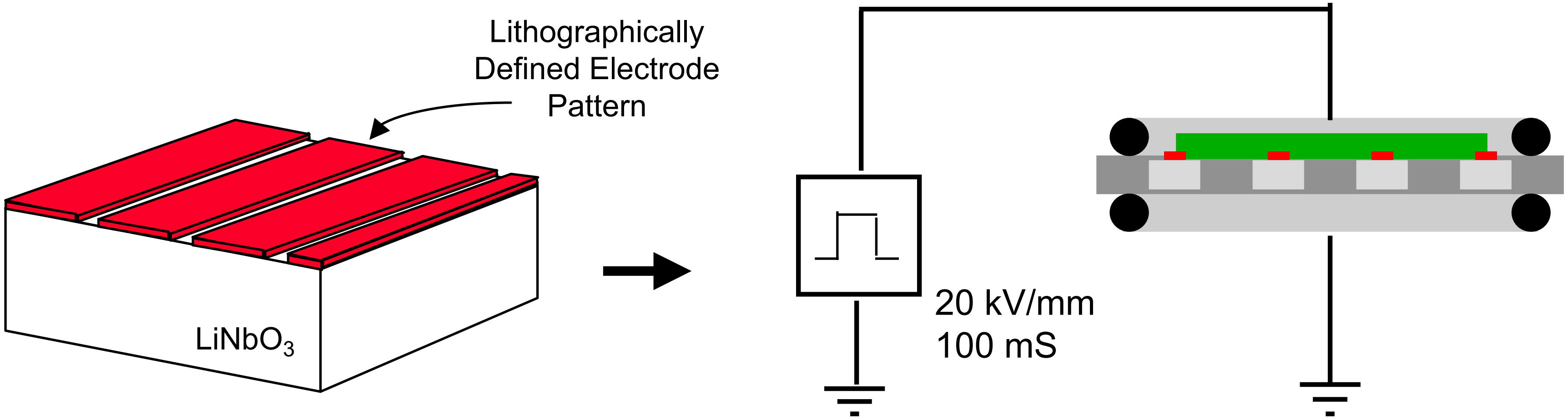


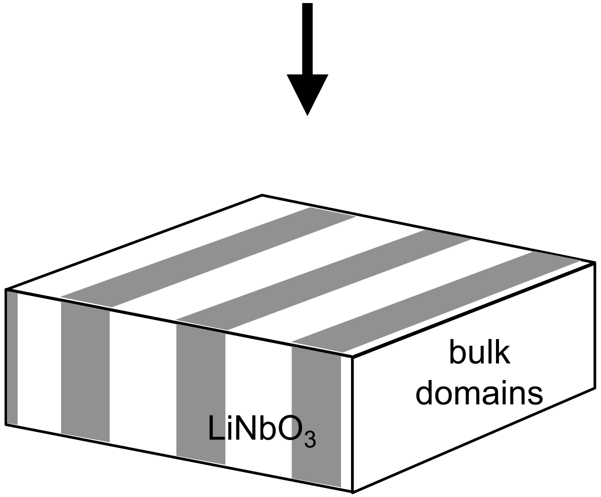


Next major breakthrough: electric field poling

discuss after QPM background

Electric Field Poling of $LiNbO_3$

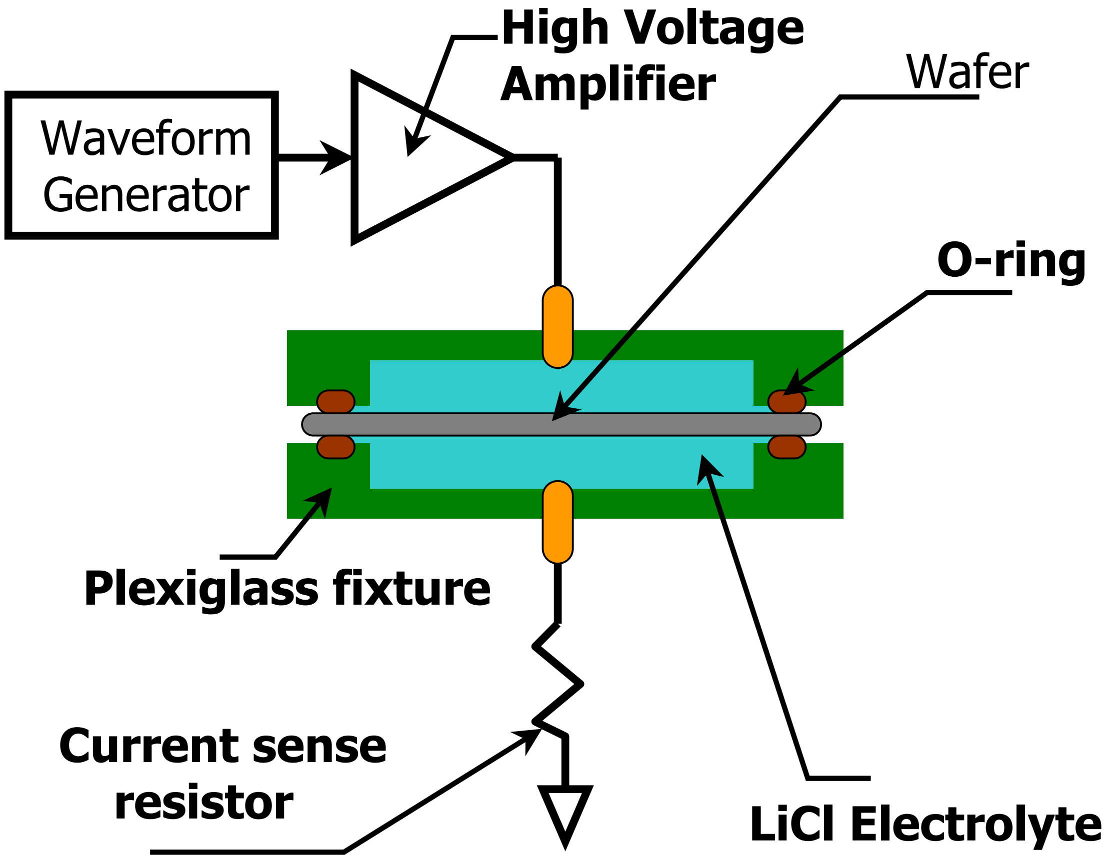




- Lithographic electrodes
- Pulsed high voltage
- Bulk (0.5 - 1 mm) domains
- Periods to < 4 µm
- Entire 3” dia. wafers poled
- $LiNbO_3$, $LiTaO_3$, KTP

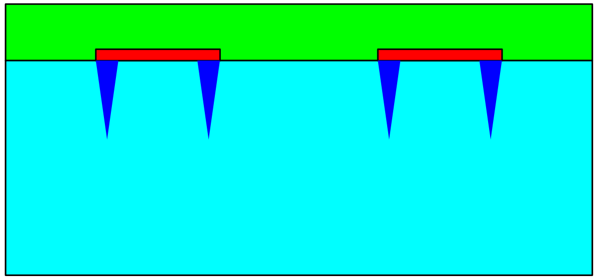
Basic HV Technology for Poling

- High voltage
  - 20 - 60 kV/mm
  - short shaped pulses
    1- 1000 ms
- Thin wafer
  - 0.2 - 1 mm
- Electrode affects pattern
- Fixture design
  - low fringe fields
  - resists corona
  - liquid contact
  - holds off 60 kV/mm

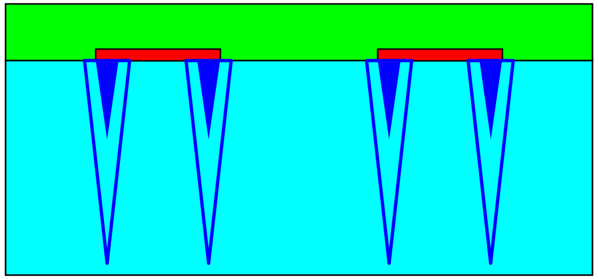


Stages in Periodic Poling

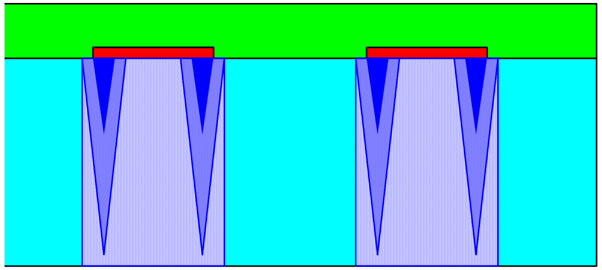
Nucleation



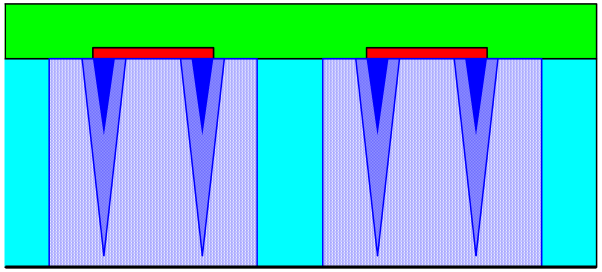
Tip
Propagation

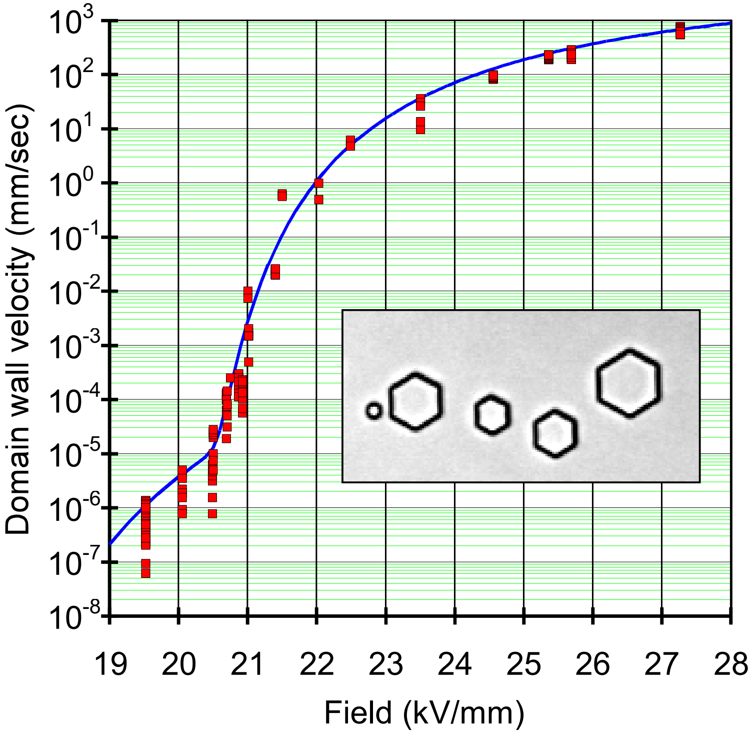


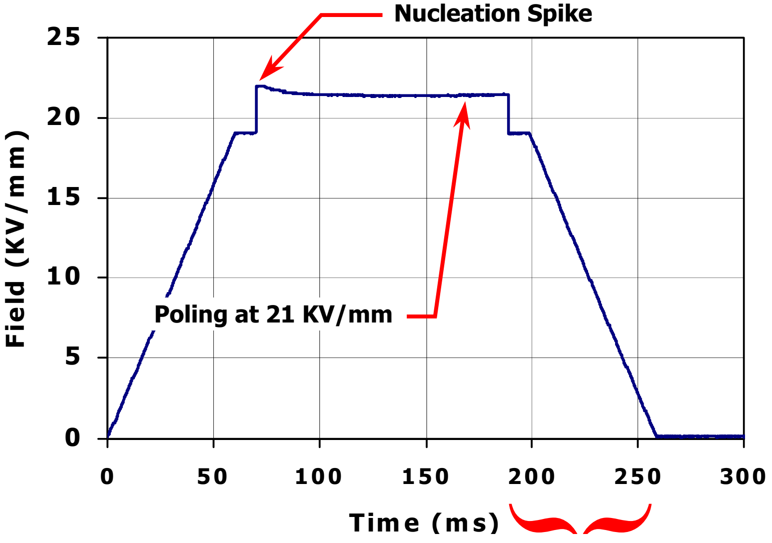
Lateral
Growth



Termination/
Stabilization

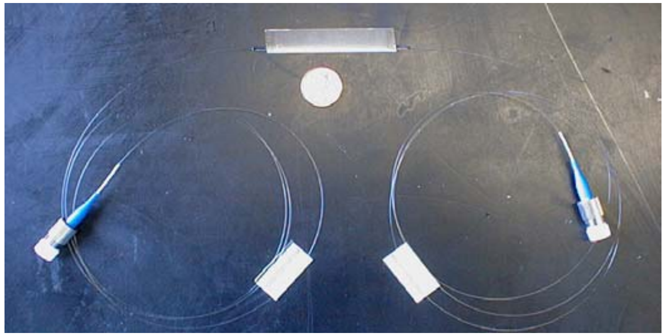


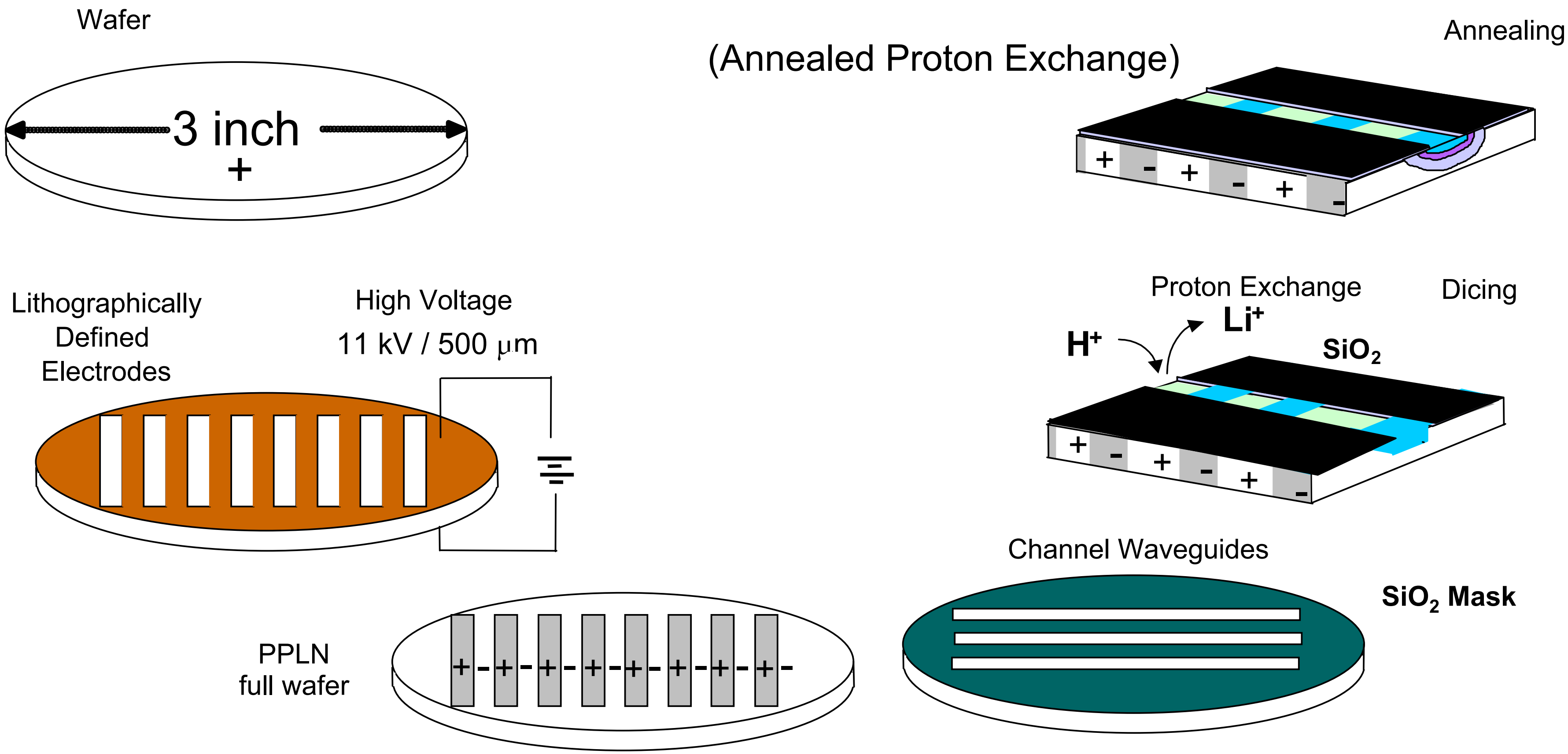



Nucleation Spike

Poling at 21 KV/mm

Fabrication of APE PPLN Waveguides





$LiNbO_3$ Wafer

3 inch

Lithographically Defined Electrodes

High Voltage 11 kV / 500 μm

PPLN full wafer

Channel Waveguides

SiO_2 Mask

Proton Exchange

Dicing

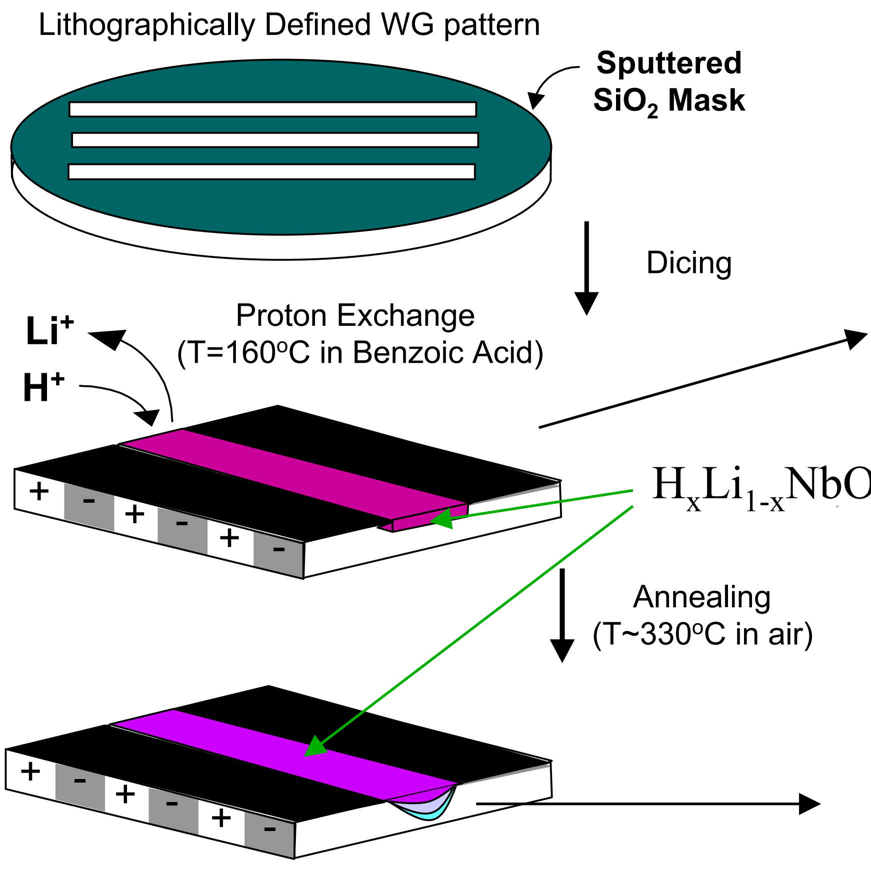
(Annealed Proton Exchange)

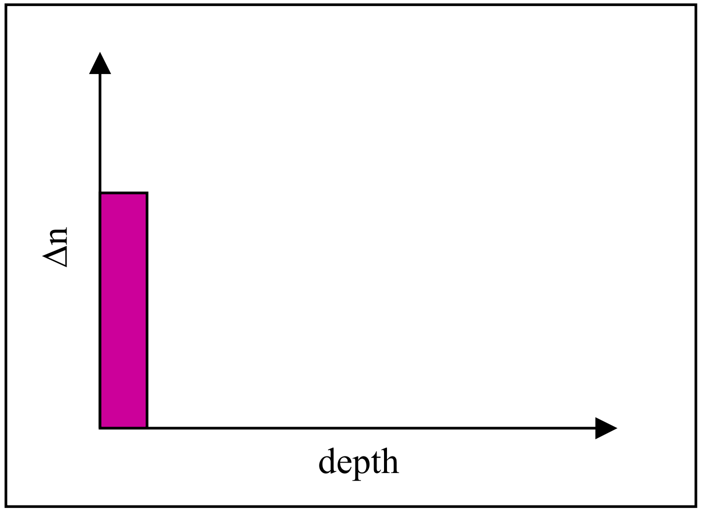
Annealing

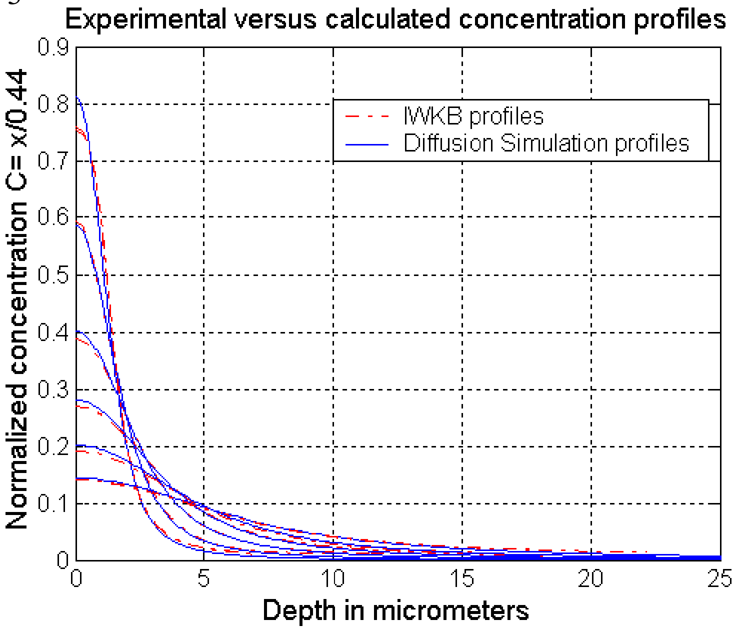
Keys to efficient waveguide devices

- Confinement / overlap of modes
  - systematic design requires waveguide model [Bortz 1994]
  - proton diffusion, index change vs concentration
- Device length
  - length ^{2} scaling
- Homogeneity (of waveguide)
  - waveguide lithography: +/- 0.1 µm (3 cm)
    full wafer processing required
  - proton exchange (PE): +/- 0.03 °C (3 cm)
  - waveguide anneal: +/- 0.05 °C (3 cm)
- Transverse mode control (more later)
  - multimoded waveguide at pump wavelength in DFG devices

APE PPLN Fabrication Process



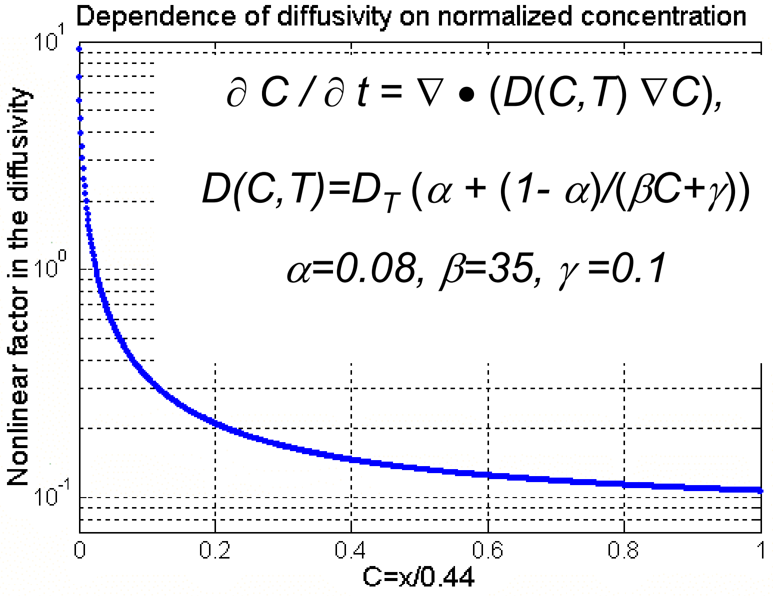




Diffusion Process:

$$\partial C / \partial t = \nabla \bullet (D(C,T)\ \nabla C)$$

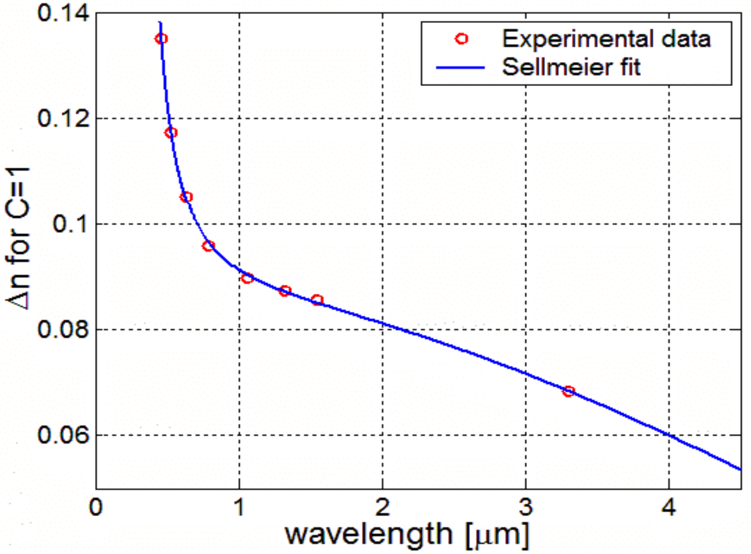
Process Model Valuable for Systematic Design

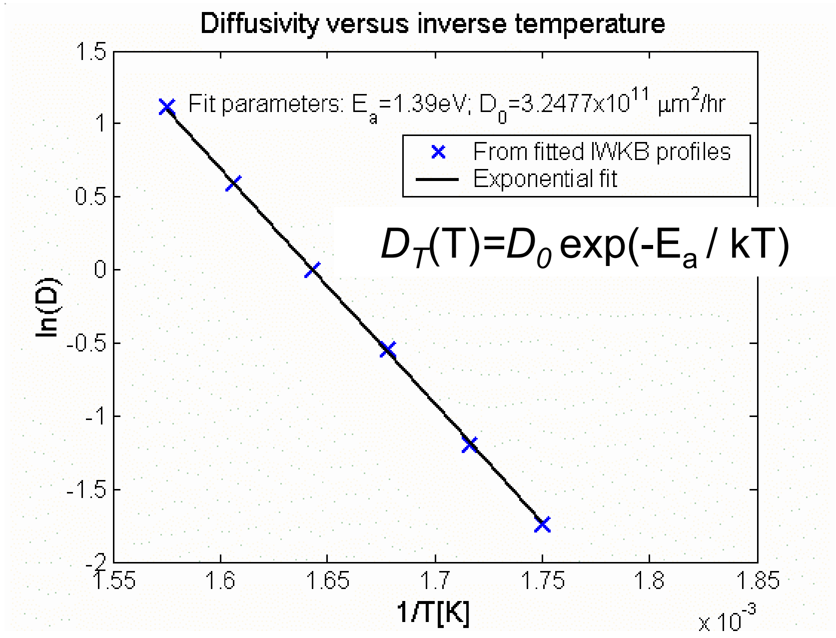


$$\partial C / \partial t = \nabla \bullet (D(C,T)\, \nabla C),$$

$$D(C,T)=D_T\,(\alpha + (1-\alpha)/(\beta C+\gamma))$$

$$\alpha=0.08,\ \beta=35,\ \gamma=0.1$$





$$D_T(T)=D_0\exp(-E_a / kT)$$

Temperature range from 300 to 360 °C

$$\Delta n(\lambda,1)=\sqrt{a_1+\frac{a_2}{\lambda^2-\lambda_0{}^2}-a_3\lambda^2}-n_{sub}(\lambda)$$

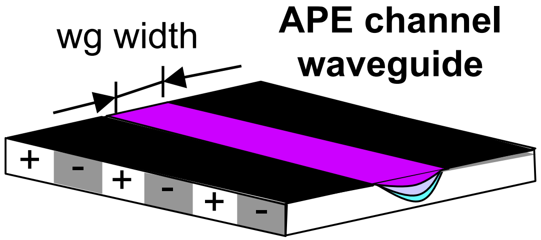
$$a_1=4.945,\ a_2=0.1354,\ a_3=0.0278,\ \lambda_0=0.2324$$

$$\Delta n(\lambda,C)= C\,\Delta n(\lambda,1)$$

C=x/0.44 in $H_xLi_{1-x}NbO_3$

$$\Delta n(0.6328,C=1) = 0.105$$

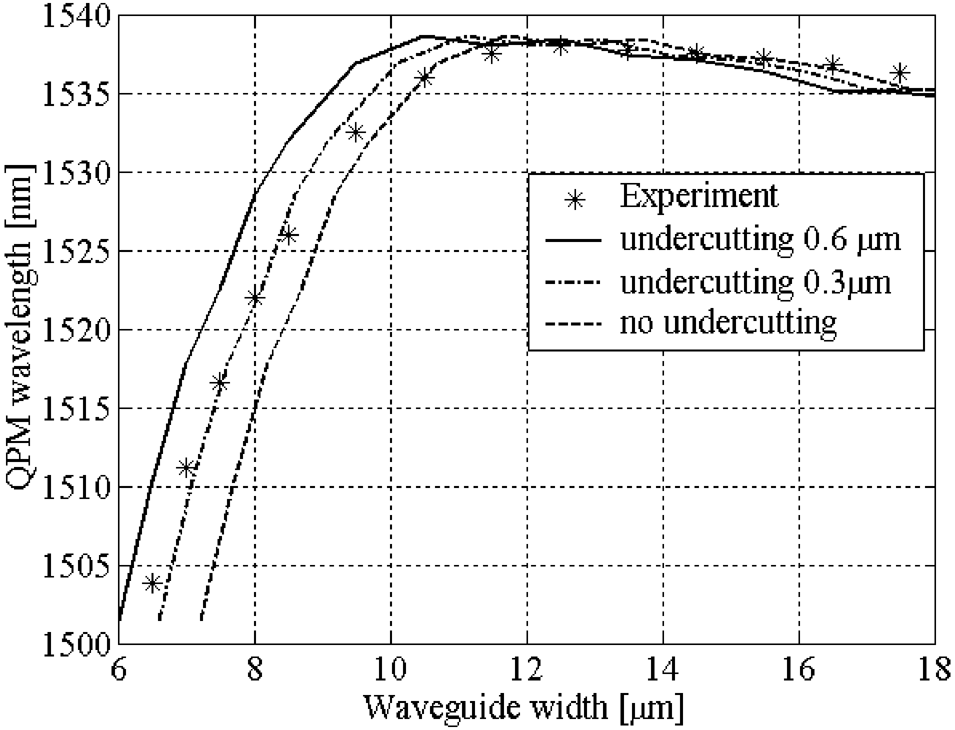
Test of model



Channel APE waveguide SHG

QPM period Λ=14.75 μm

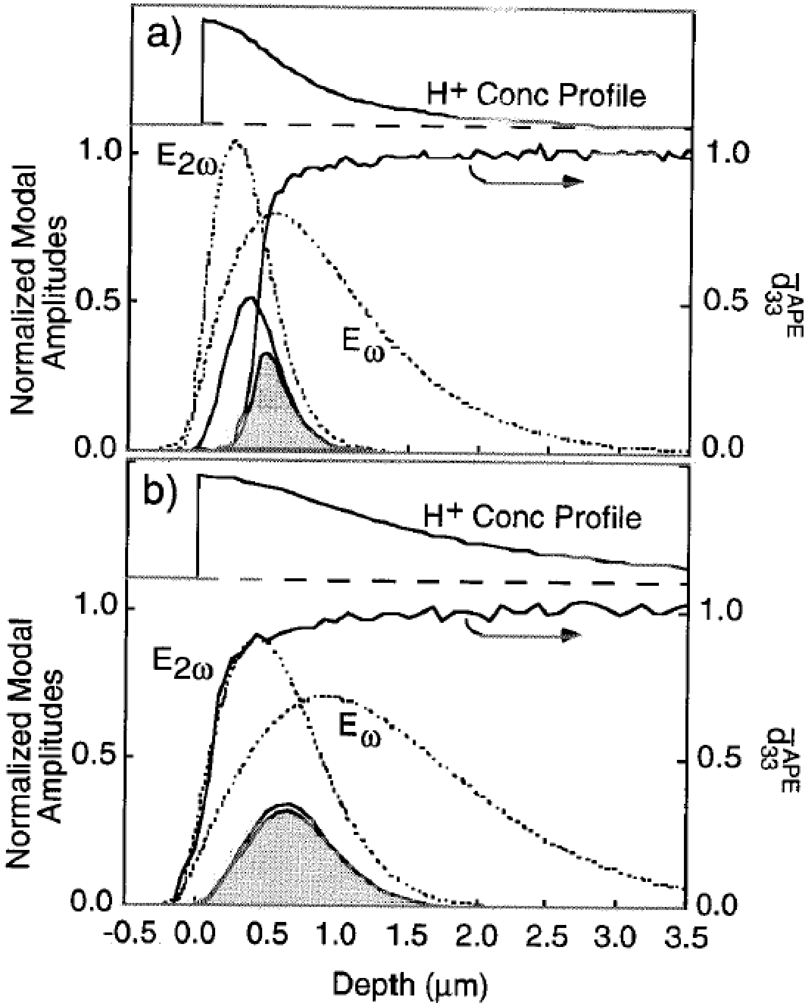
λ_{qpm}= 2 Λ ($n_{eff}(2\omega) - n_{eff}(\omega)$)



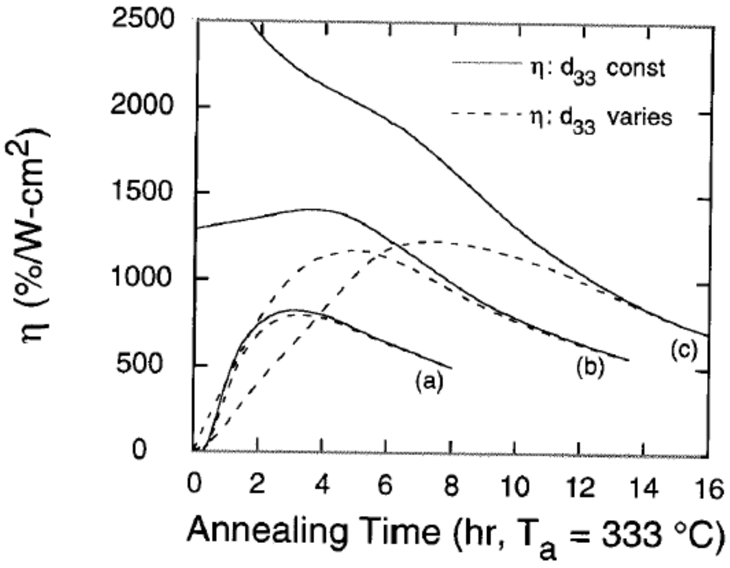
$\delta\lambda_{qpm}$ ~ 1nm $\Rightarrow$

$\delta(n_{eff}(2\omega) - n_{eff}(\omega))$~ 3×10^{-5}

Mode Overlaps



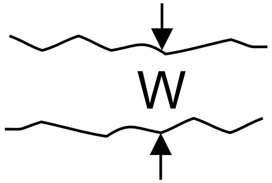
- With refractive index profile, can calculate modes
- With modes and nonlinear coefficient vs depth can calculate overlap integrals
- Nonlinear coefficient near zero in exchanged layer, unchanged below
- Requires looser confinement so modes overlap in region with recovered nonlinear coefficient



[Bortz 1993] [Bortz 1994]

Noncritical Designs

- A 5-cm long device is ~5×10^4 wavelengths long
  - a variation of 10^{-5} in the effective index will lead to a π phase shift
  - will spoil the quasi-phasematching
  - limits useful length of the device
  - leads to very strict tolerances on process



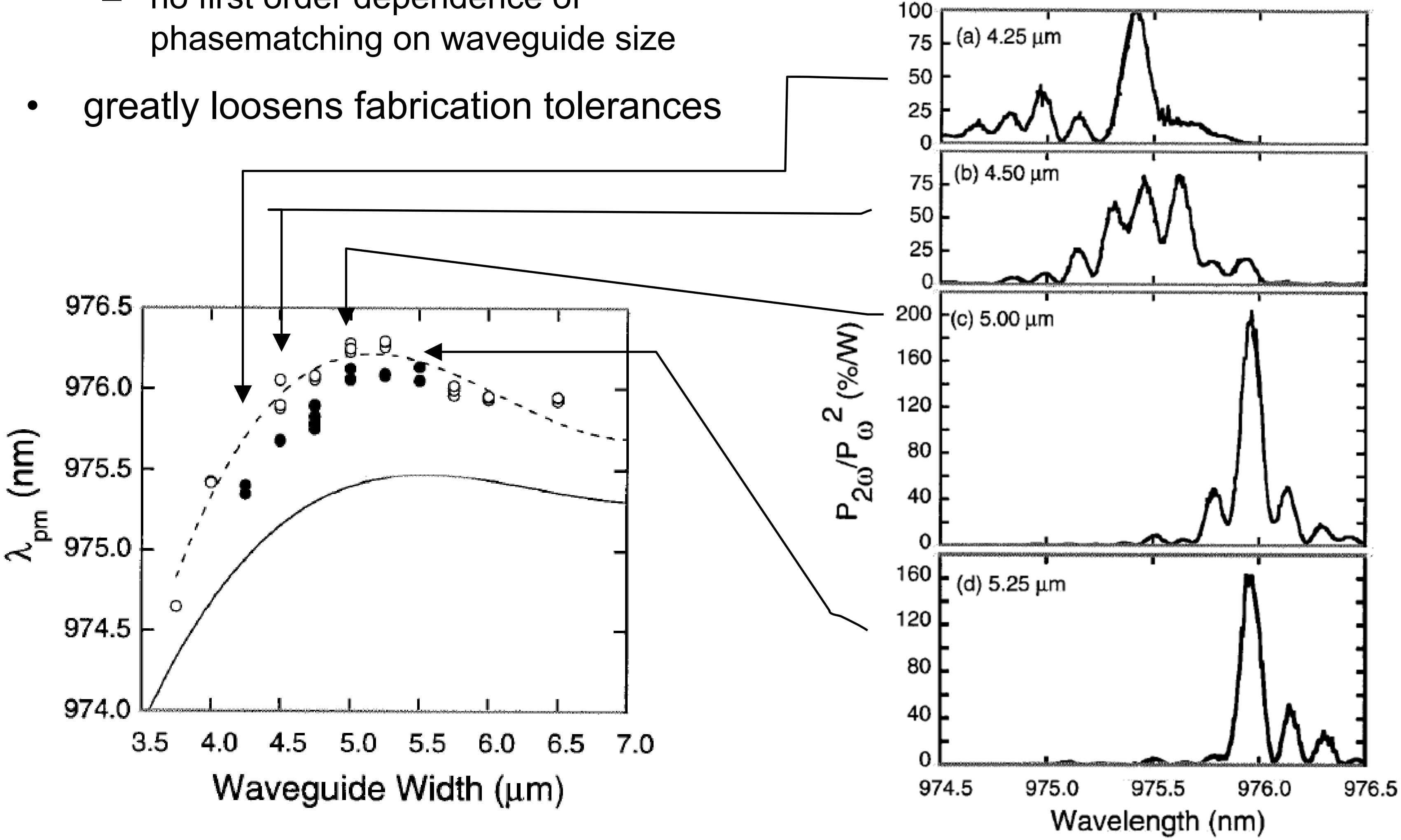
- Solution: noncritical designs
  - QPM depends only on difference of propagation constants $n_{eff,2\omega} - n_{eff,\omega}$
  - non-critical design has

$$\frac{d(n_{eff,2\omega} - n_{eff,\omega})}{dw} = 0$$

  - thus no first order dependence on errors in waveguide size
  - greatly facilitates fabrication

Noncritical Designs for Fabrication Tolerance

- Knowledge of waveguide dispersion allows “noncritical design”
  - no first order dependence of phasematching on waveguide size
- greatly loosens fabrication tolerances



[Bortz 1994]   detailed discussion: [Khanarian 2001]

Annealed Proton Exchange

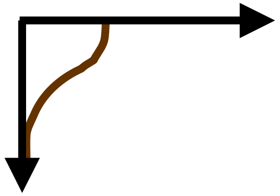
- Annealed proton exchange creates monotonic refractive index profile
- Asymmetry of refractive index profile limits overlap of modal fields

Index Profile

$H_xLi_{1-x}NbO_3$

$\boxed{\Delta n \propto x}$

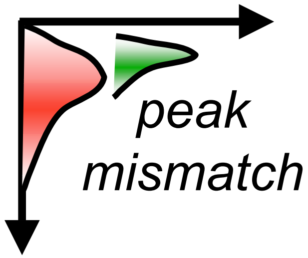
APE

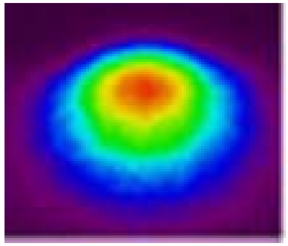


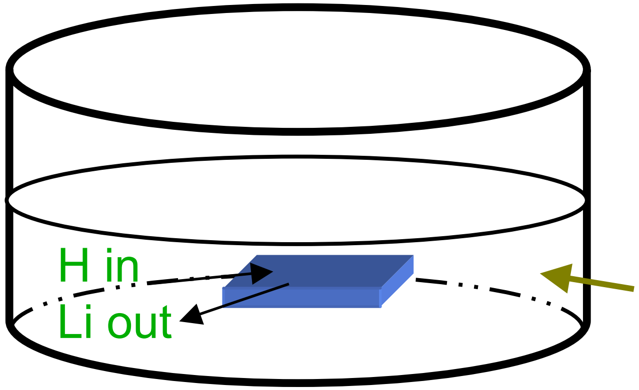
Modal Fields

— ω

— 2ω







Proton-rich melt:
benzoic acid

Reverse Proton Exchange

- Reverse proton exchange creates buried refractive index profile
  - protons removed from surface of APE waveguide
- Modal fields symmetric in depth
  - modal overlap improved

Index Profile

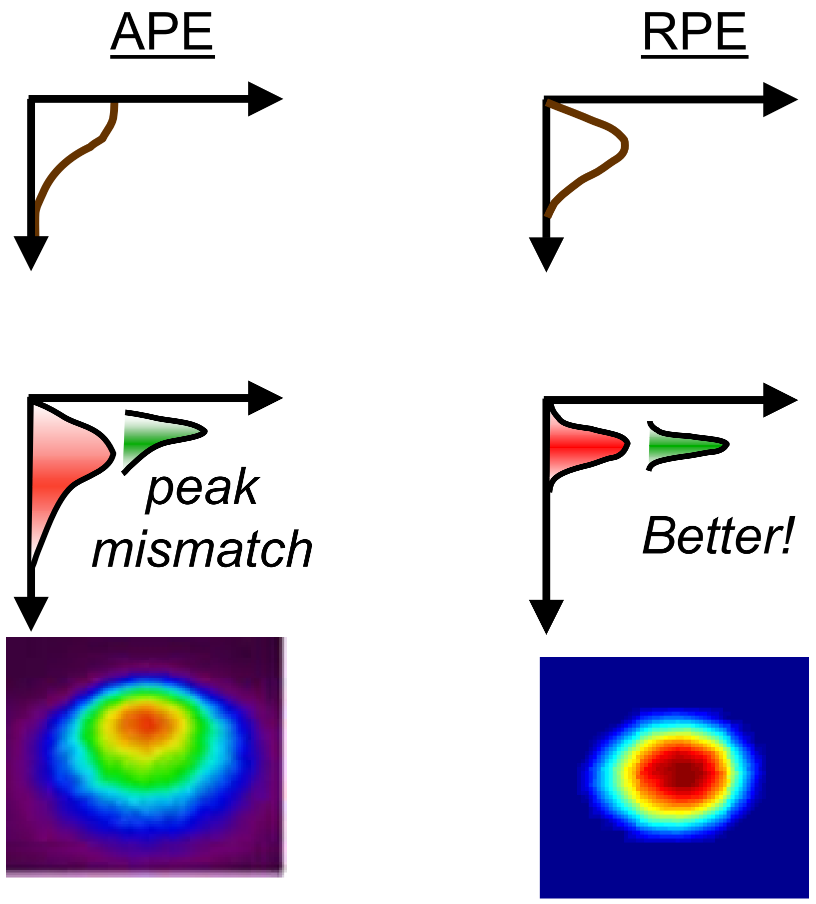
$H_xLi_{1-x}NbO_3$

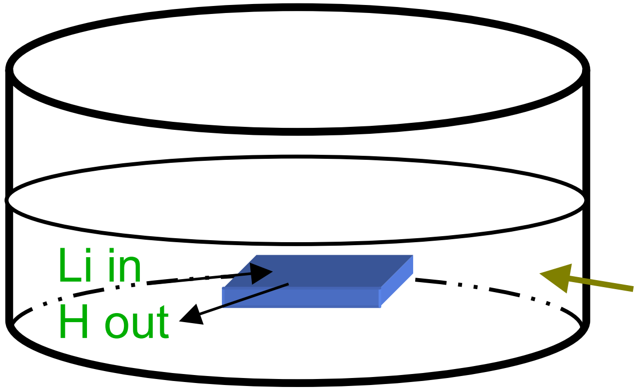
$\boxed{\Delta n \propto x}$

Modal Fields

🟥 ω

🟩 2ω

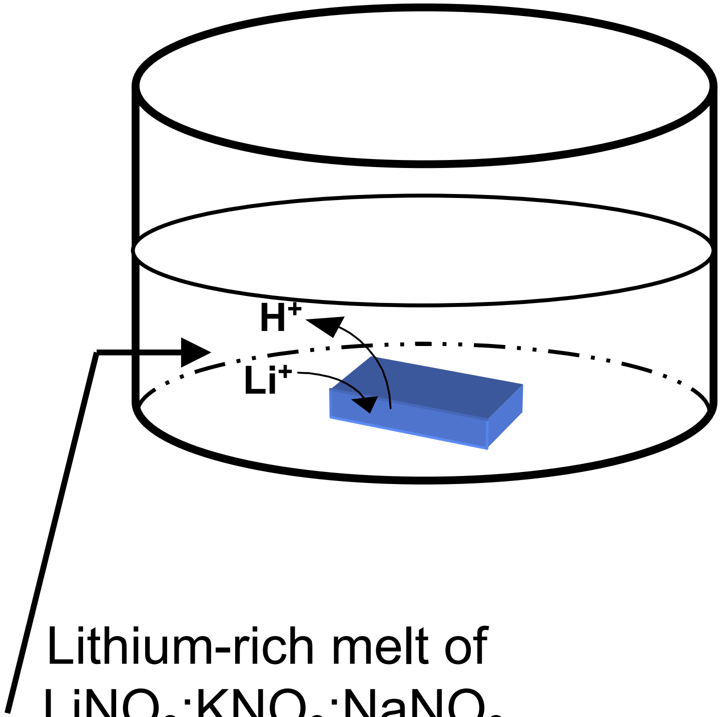




Lithium-rich melt of $LiNO_3$:KNO_3:$NaNO_3$

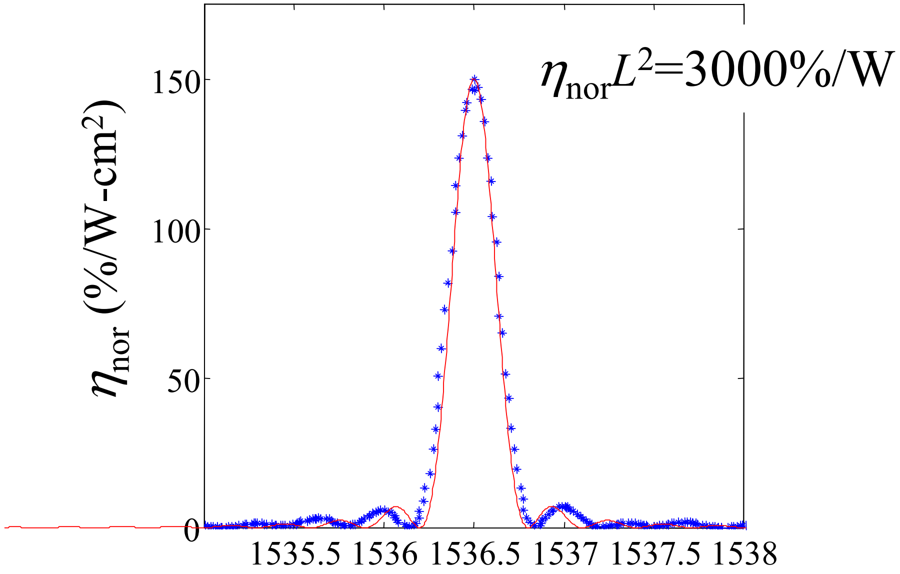
RPE Waveguides

- After annealing, sample is immersed in a lithium-rich melt
- Protons diffuse *out*, and Li^+ ions diffuse *in*
- $LiNO_3$ alone damages sample surface - other nitrates prevent this
- Beaker placed in a cylindrical tube furnace at 328°C
  (this is close to the annealing temperature, facilitating design)



Lithium-rich melt of
$LiNO_3$:KNO_3:$NaNO_3$

Proposed by [Korkishko 1998]



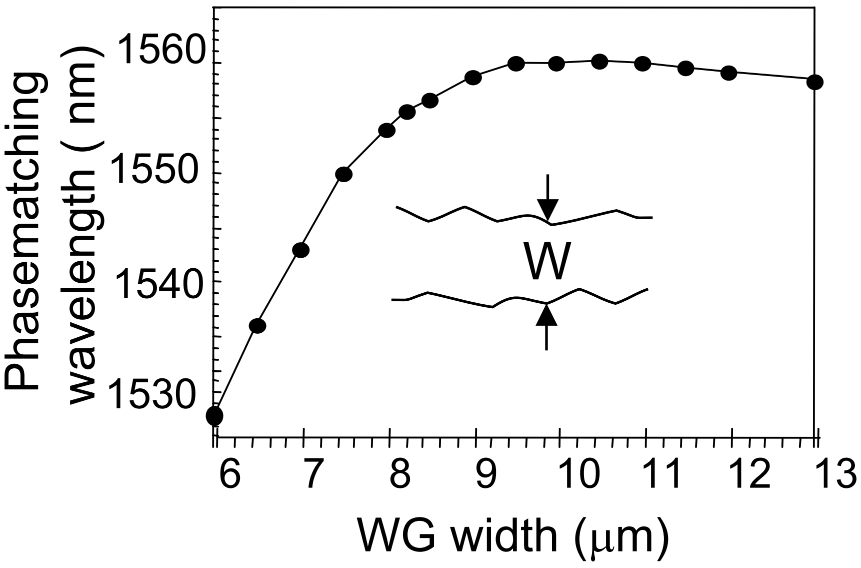
[Parameswaran 2002]

- Curve is nearly ideal
  ➨ good phasematching over entire 3.3 cm length
- η_{nor} = 150 %/W-cm^2
  > 3 times that of APE waveguides!

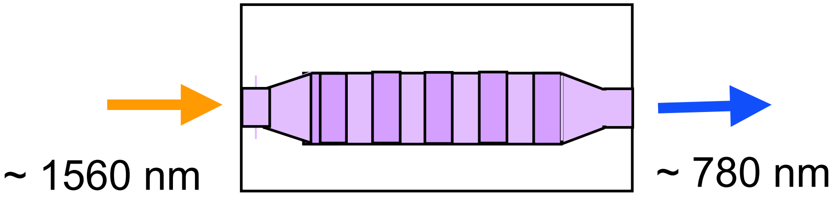
High efficiency PPLN Waveguides

- PPLN for WG application
  - domain uniformity
  - surface quality
- WG fabrication
  - Loss
  - Homogeneity over 5 cm (10^4~10^5 x λ)

waveguide lithography:	+/- 0.1 µm
proton exchange (PE):	+/- 0.02 °C
waveguide anneal:	+/- 0.03 °C

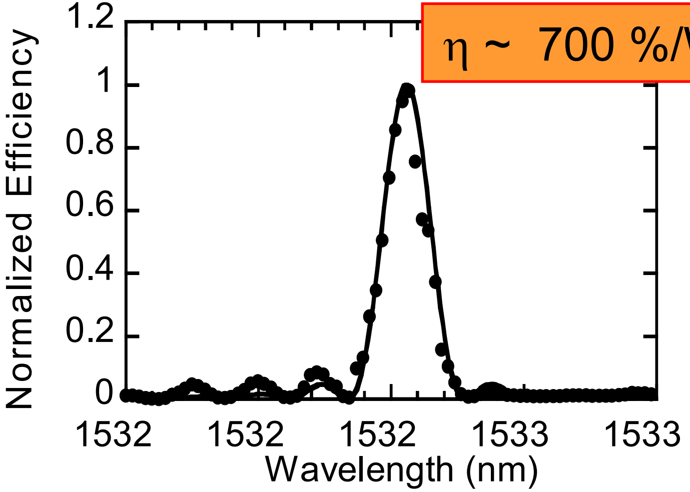


Improved process and WG design :
high efficiency and high yield



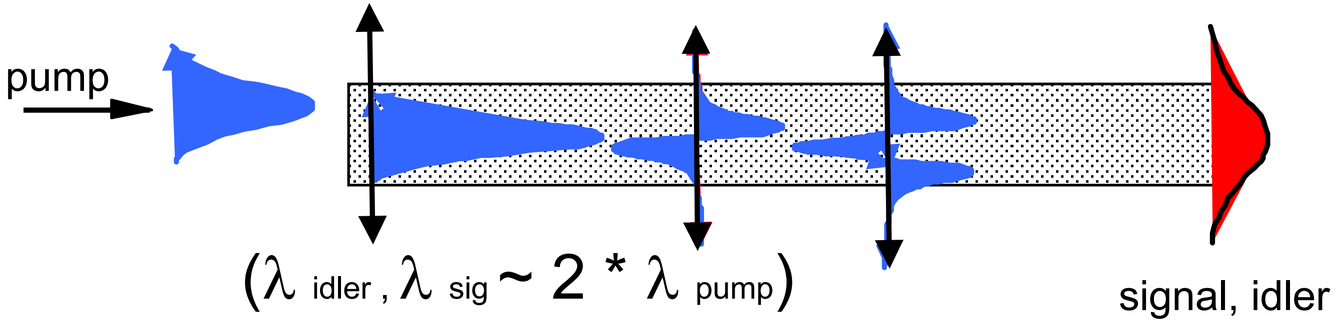
$$P_{out} \approx \eta P_{LO} P_s \,\mathrm{sinc}^2\left(\frac{\Delta k L}{2}\right)$$

η ~ 700 %/W

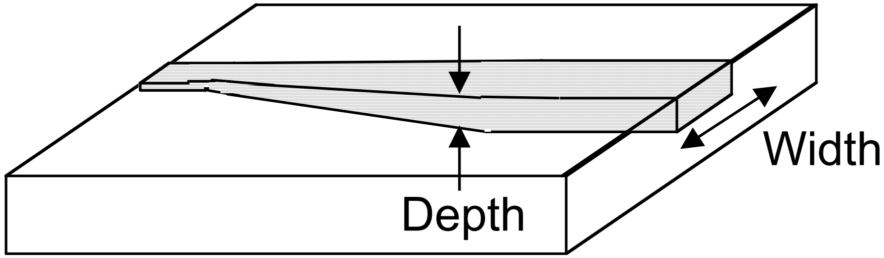


Multimode coupling

- Issue: Mode launching for multi-wavelength device
  - single-mode for signal and idler ⇒ multimode for pump



- Solution: adiabatically tapered waveguide
  - Issue: fabrication difficultly

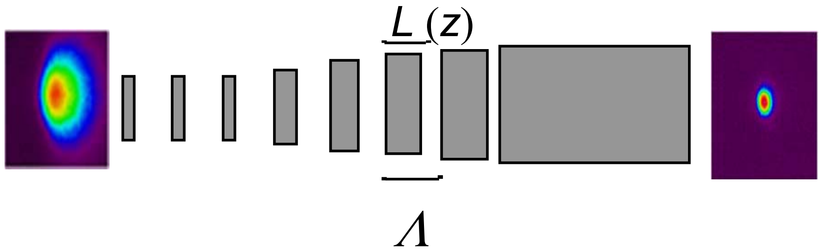


Width: by lithography

Depth: difficult

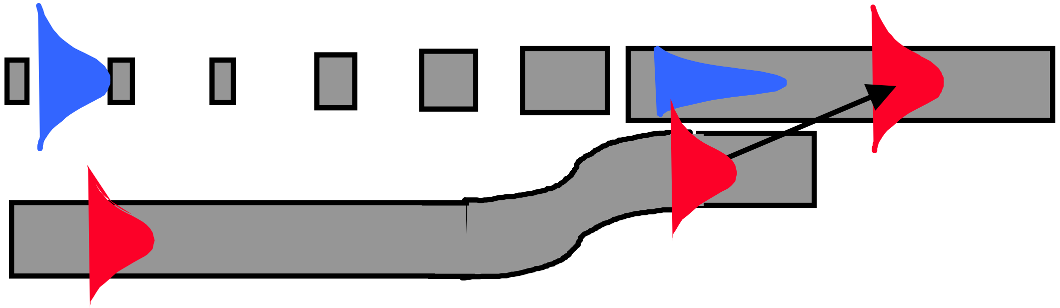
Key mode launching components: taper and coupler

- Adiabatic taper
  - arbitrary mode size/number transformation
  - implemented with periodically segmented waveguides
  - allows independent optimization of coupling and mixing regions



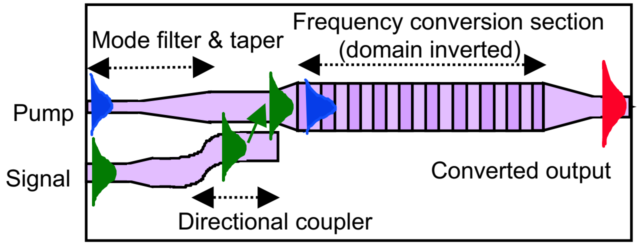
$$\Delta n_{eq}(z) = [L(z)/\Lambda]\Delta n$$

- WDM coupler
  - taper is cut-off for signal
  - combine local oscillator and signal with coupler



[Chou 1996]

Typical Device Fabrication



- Annealed proton exchange waveguides
  - 10 μm channel in SiO_2 mask
  - 15 hours at 160ºC in benzoic acid
  - 27 hour anneal at 325ºC
- Mode size
  - 2 μm x 6 μm in mixing region
  - 1/*e* field 8.5 μm in input coupling region (1.3:1 ellipticity)
- Passive insertion loss:
  - approx 2 dB fiber to fiber at 1.5 μm for 5 cm long device
- Mixing region “noncritical”
  - no first order dependence on mask dimension

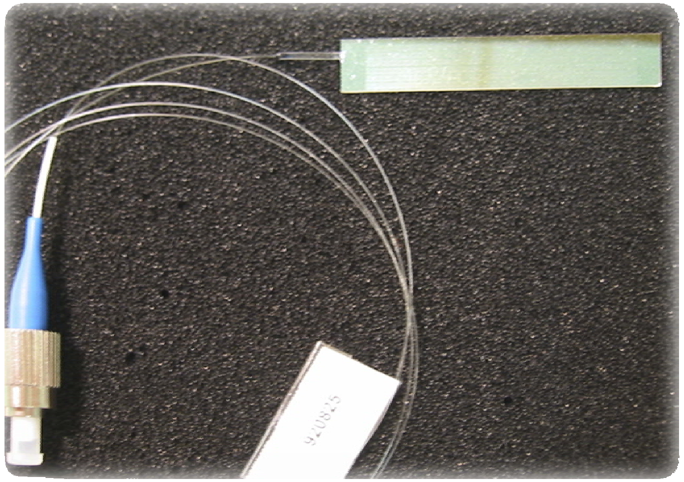
[Chou 1998]

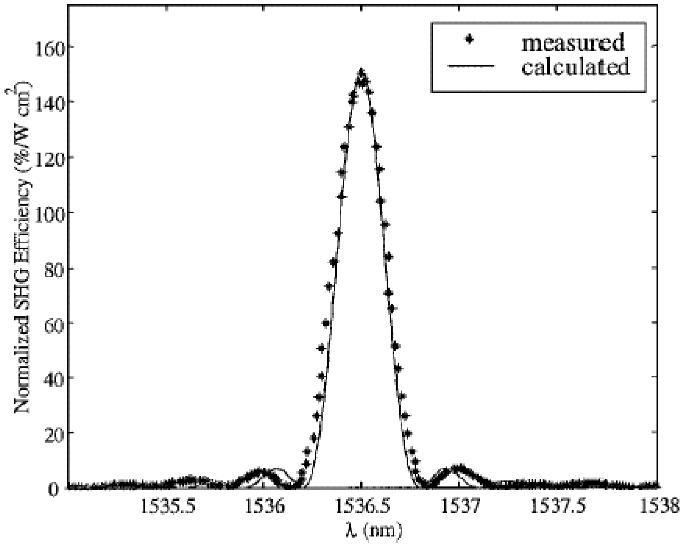
Basic Device Performance

- Combining all these methods:

- Efficiency at 1.5 μm:
  - 150%/W-cm^2
  - ~3000%/W in 5-cm device

- Insertion loss
  - 0.1 -- 0.2 dB/cm loss
  - ~2 dB fiber-fiber

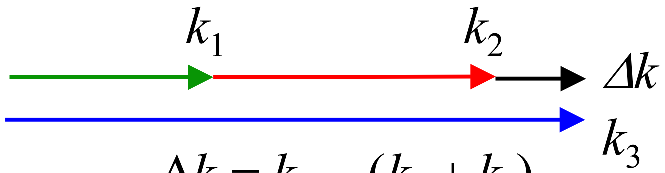




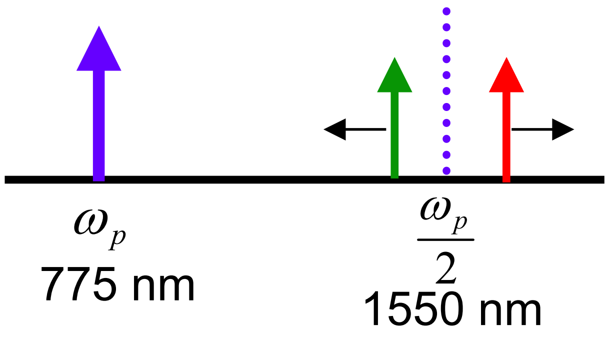
•Will look at applications to optical signal processing in next lecture

Narrow vs wide tuning

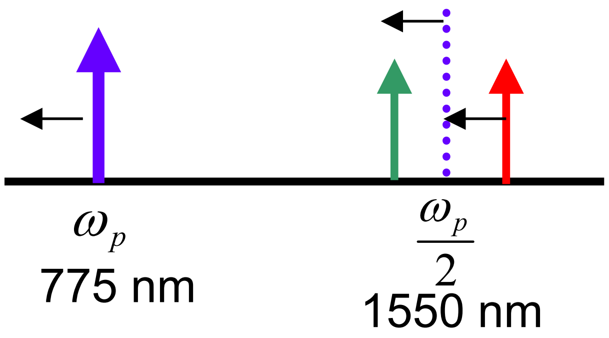
- Bandwidth depends on tuned parameter
  - very broad for tuning signal at fixed pump
  - narrow for tuning pump at fixed signal



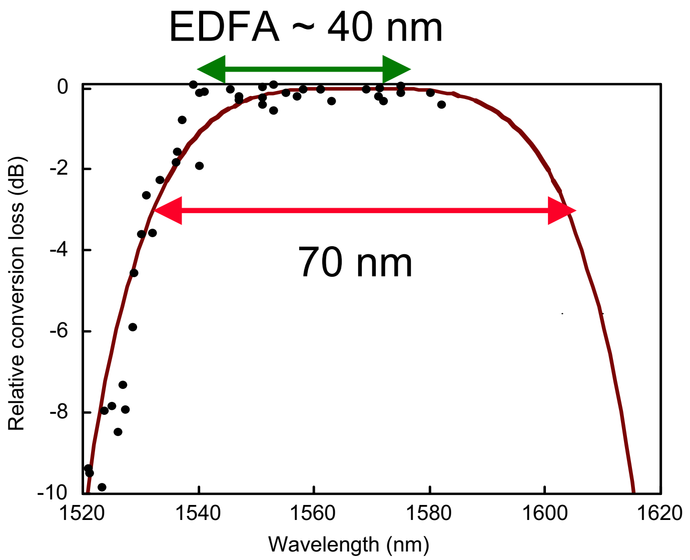
$$\Delta k = k_p - (k_s + k_i)$$

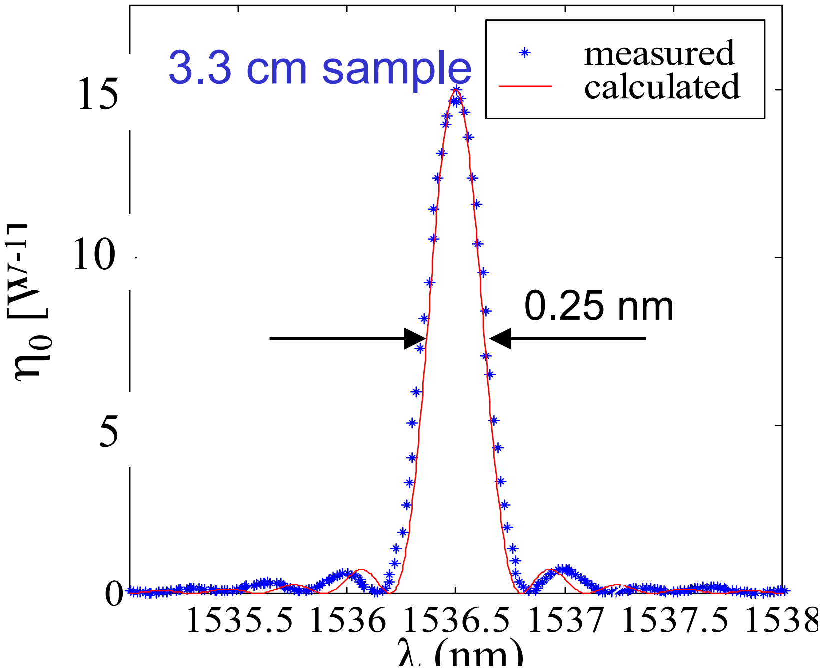


$$\Delta k = k_p - (k_s + k_i) \sim \text{constant}$$



$$\Delta k = k_p - (k_s + k_i) \text{ changes}$$





Performance Issues

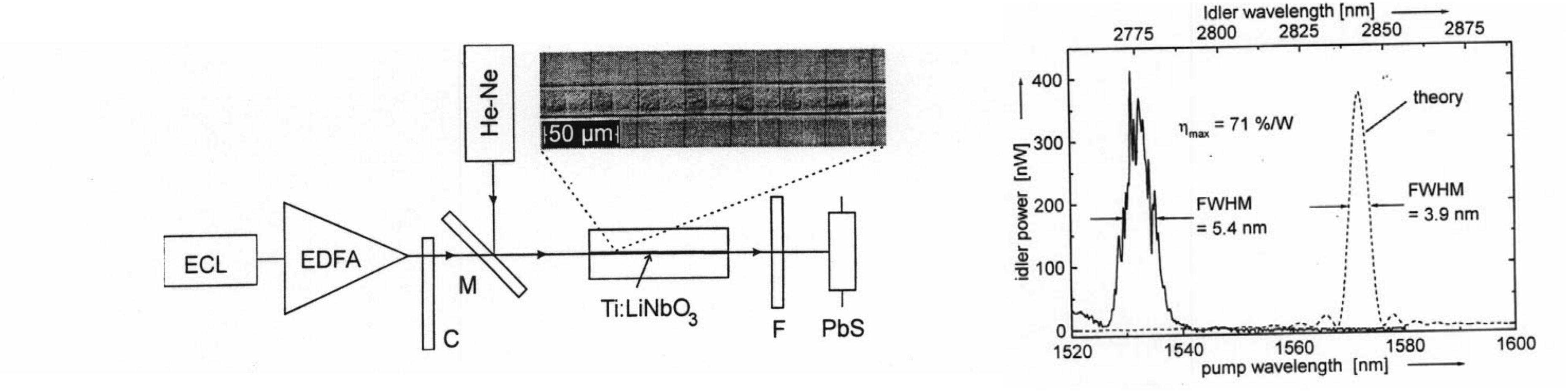
- Remarkably nonlinear devices
  - 3000%/W $\Rightarrow$ 50% efficiency for 16 mW pump
  - 10^3 -- 10^4 higher than bulk media

- Some issues remain:
- Notably lifetime
  - OK in IR
  - “photorefractive” effects limit lifetime with visible light devices
- Size (several cm) inconvenient in some contexts

- Alternative media attempt to address these and related issues

DFG in Ti:PPLN Waveguides

- Ti:LiNbO$_3$ waveguides attractive for QPM
  - well developed technology
  - low-loss
  - guide both polarizations
- Recent work demonstrates compatibility with PPLN
- DFG of 2.8 μm with efficiency of 71%/W in 5 cm waveguide



Hofman, Schreiber, Haase, Herrmann, Ricken, Sohler, Opt. Lett. 1999

APE PPLN results comparable: ~100 μW @ 4 μm [Petrov 2000]

Toward Commercial UV Source

- Ongoing effort at Matsushita to produce practical SHG diode for DVD
- $MgO:LiNbO_3$ chosen for photorefractive damage resistance and substrate availability
  - in-plane poling required for packaging with TE-polarized diode lasers
  - presents challenge for conventional poling
  - two-d field application on x-cut substrate creates appropriate domains
- 17 mW at 426 nm for 55 mW diode pump (31% efficient)
  - 1 cm long waveguide -- 800%/W-cm^2 (1500%/W-cm^2 with multimode Ti:S)

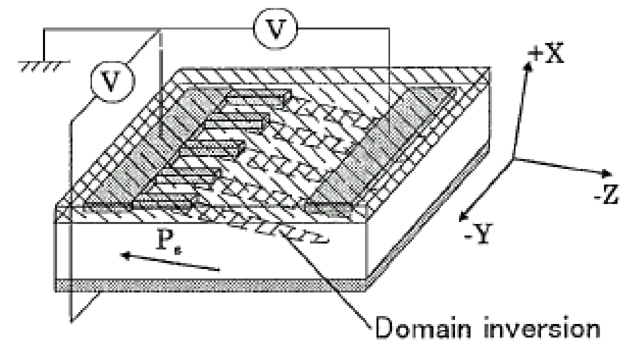
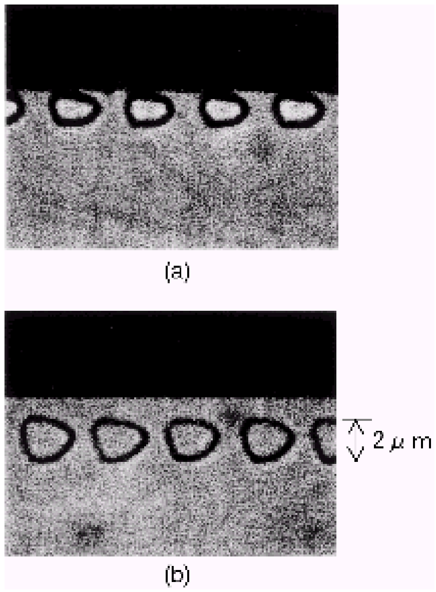
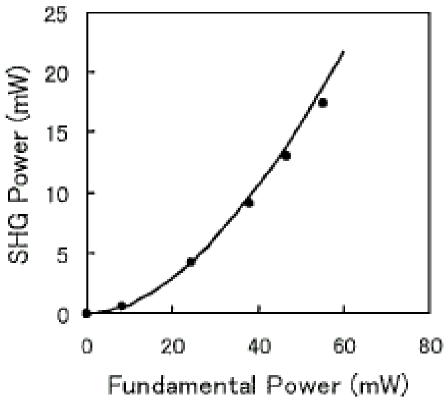


Fig. 1. Schematic diagram of the experimental setup for two-dimensional high-voltage application for an off-cut $MgO:LiNbO_3$.

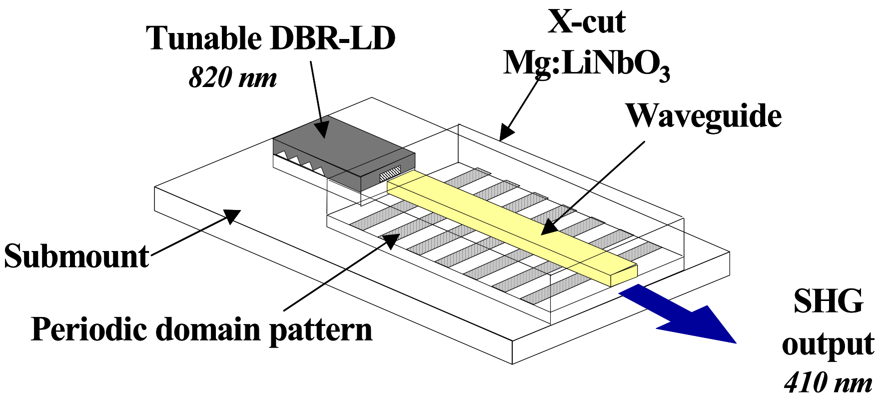


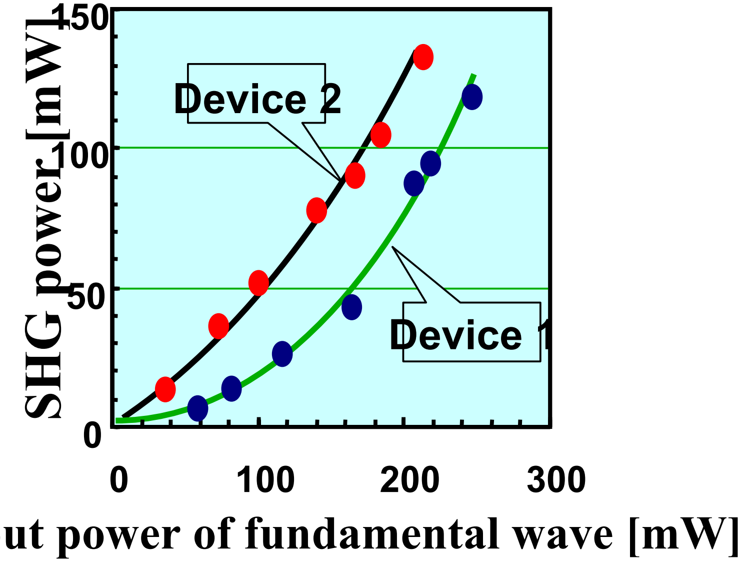


[Sugita 1999] [Sugita 2001] (100 mW!)

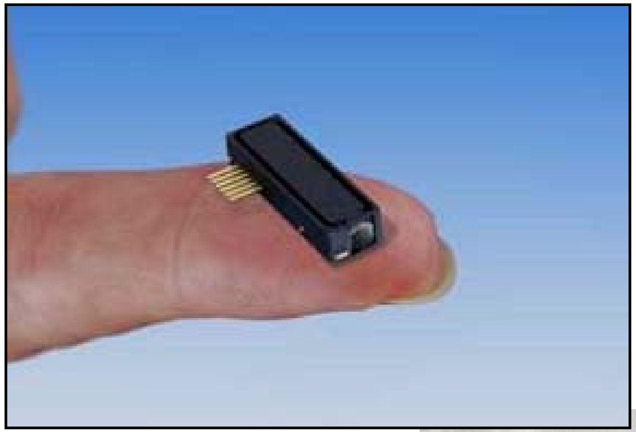
Packaging important for practical use

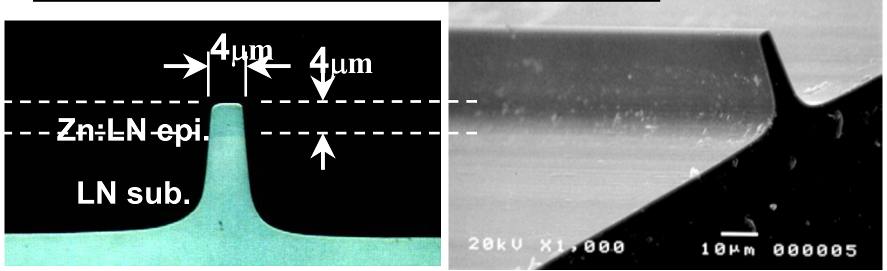
- NGK/Matsushita developed package for violet DVD source
  - 3 piece: silicon submount with laser butt-coupled to SHG chip
  - temperature tracking of laser wavelength and QPM peak obviate temp. control

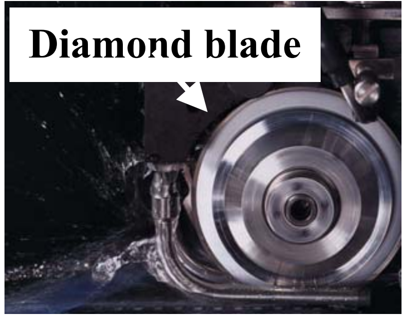




[Imaeda 2003] [Sugita 2001]





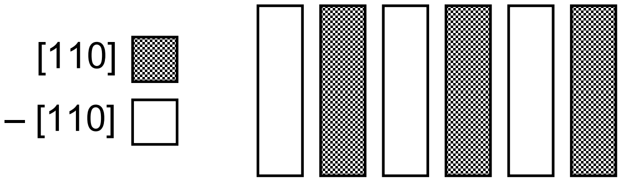


Novel machined ridge waveguide

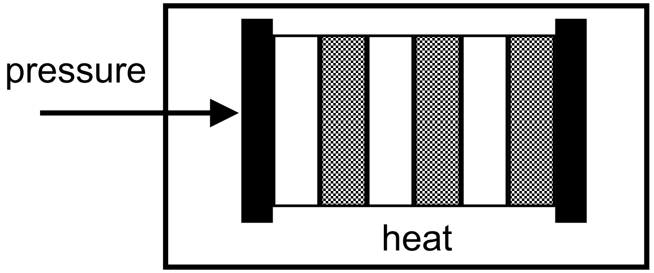
QPM techniques in Semiconductors

90° rotation changes sign of d_{eff}

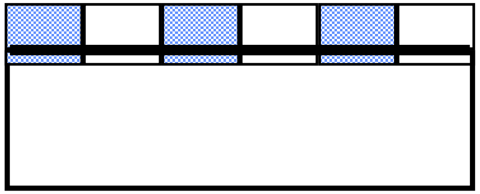
- Stack of plates
  - rotate to change sign of d_{eff}
  - difficult assembly, lossy



- Diffusion-bonded stacks
  [Gordon 1993] [Lallier 1998]
  - intimate bond reduces losses
  - difficult assembly



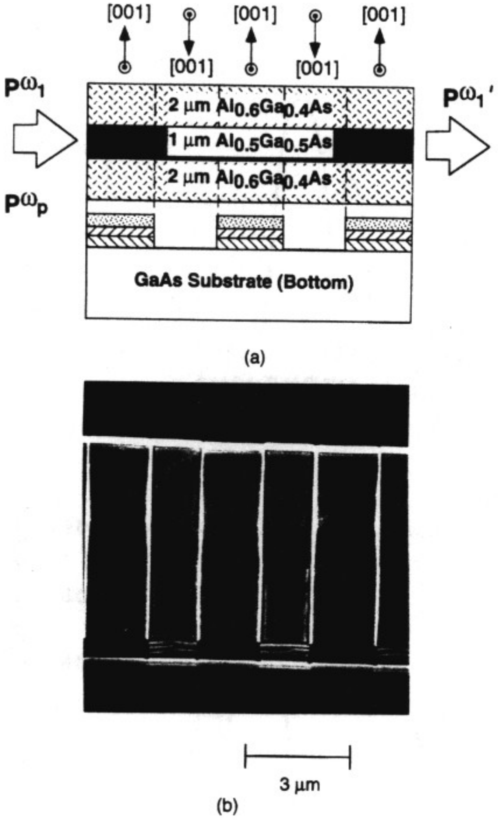
- Patterned film growth
  - template substrate forces twinning
  - lithographic patterning
  - growth techniques emerging



Gordon, Woods, Eckardt, Route, Feigelson, Fejer, Byer, *Elec. Lett.* **29**, 1942 (1993)
Lallier, Brevignon, Ledoux, *Opt. Lett.* **23**, 1511 (1998)

Orientation Patterned GaAs Waveguides

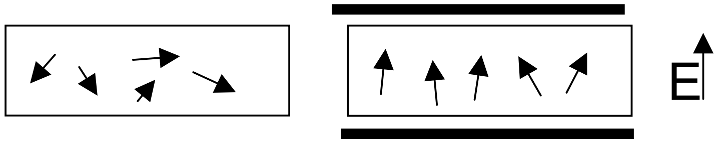
- OMCVD film grown on template substrate
- Substrate lithographically patterned on wafer-bonded thin film
- Device used for waveguide DFG
  - wavelength converter for telecom application
- Waveguide corrugations contribute significant loss
- All-epitaxial template offers potentially attractive alternative for thick and thin films



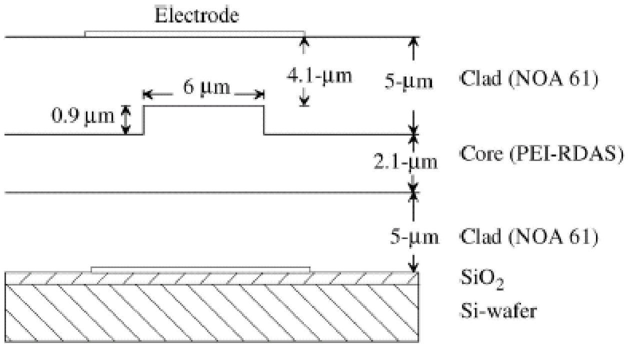
Yoo, *Appl. Phys. Lett.* **68**, 2609 (1996)

Polymers

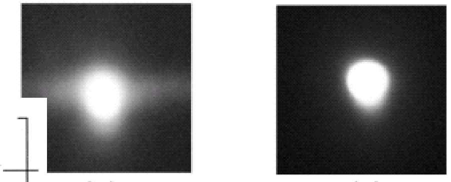
- Polymer films attractive: easy fabrication
  - orient random chromophores to induce patterned $\chi^{(2)}$
    apply electric field to align dipoles
  - typically suffer high losses, low nonlinearity



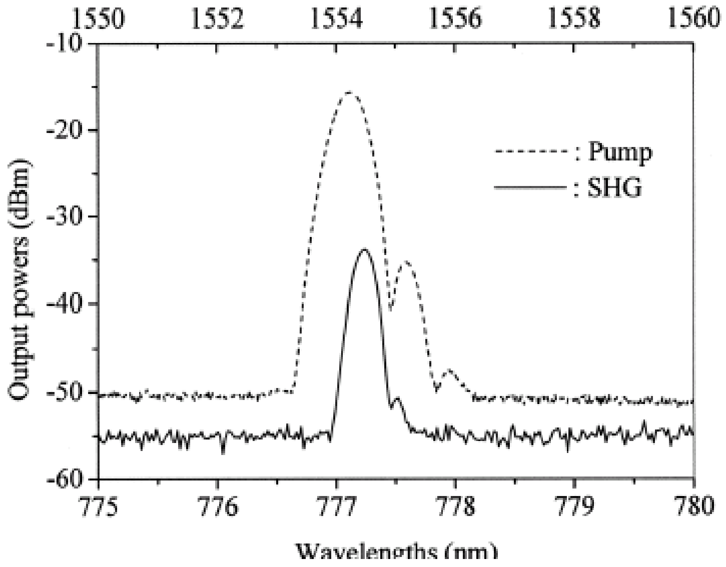
- Recent result with PEI-DAS among best
  - 14 pm/V for 100 V/μm poling field
  - absorption: 1.8 dB/cm @ 1.5 μm, 3.2 dB/cr
  - waveguide loss: 2.1 dB/cm @ 1.5 μm, 7 dB/cm
  - overall, efficiency 2.2%/W-cm^2

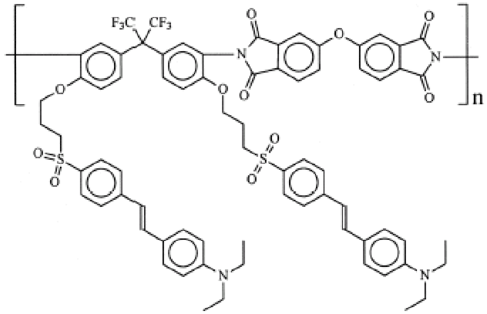


(a)



(b) (c)



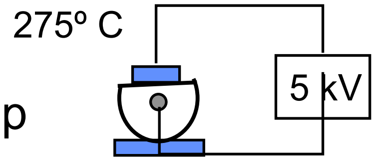


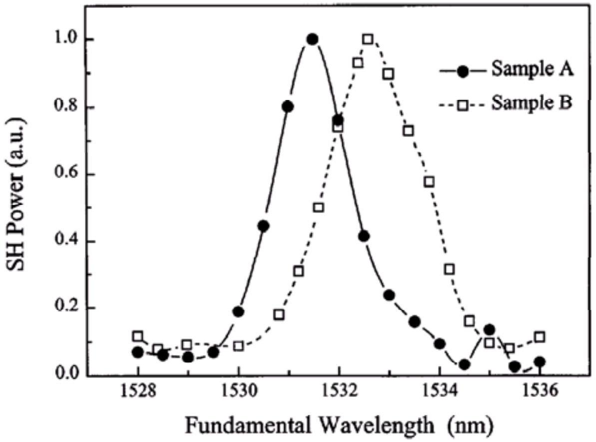
(a)

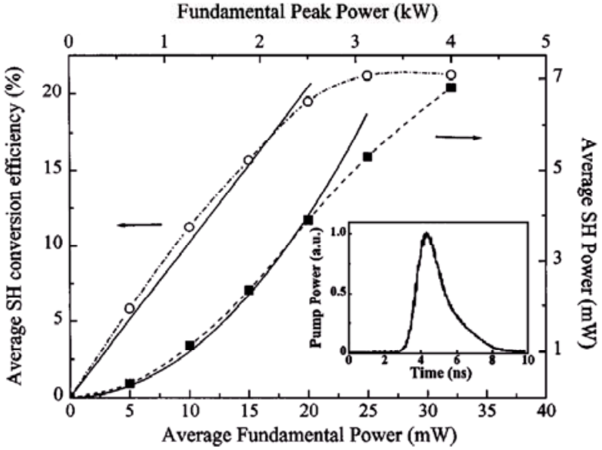
Jung Jin Ju, *Opt. Lett.* **29**, 89 (2004)

Fused Silica for QPM

- Application of large electric fields induces a $\chi^{(2)}$ in fused silica
  - thermal poling: fiber held at elevated temperature during poling
    induced nonlinearity ≈ <1 pm/V
  - UV poling: fiber irradiated with 193 nm during poling
    induced nonlinearity 6 pm/V reported
- Poling with periodic electrode can be used for QPM
- Single-mode fibers attractive as medium for QPM
  - long lengths, low loss
  - low dispersion, low thermooptic effects
  - easy interface to fiber sources and systems
- Recent SHG experiment with 2 ns 4 kHz seeded EDFA pump
  - 30 % efficiency, 7 mW 780 nm output







Pruneri, Bonfrate, Kazansky, Richardson, … , *Opt. Lett.* **24**, 208 (1999)

[Bonfrate 1999] parametric fluorescence in QPM fiber | Chen [2003], UV generation

Optical Signal Processing

- These highly nonlinear devices can be used for all-optical signal processing

- Look at this application and devices modified to suit these needs in next lecture