Prospects and Issues for Short Wavelength Sources

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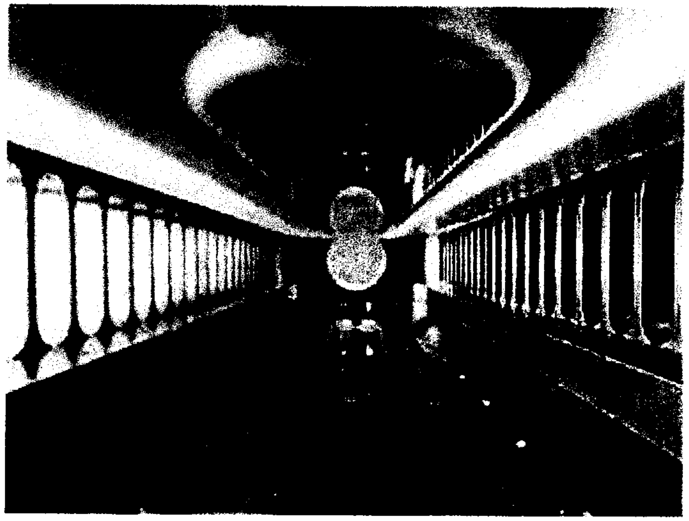
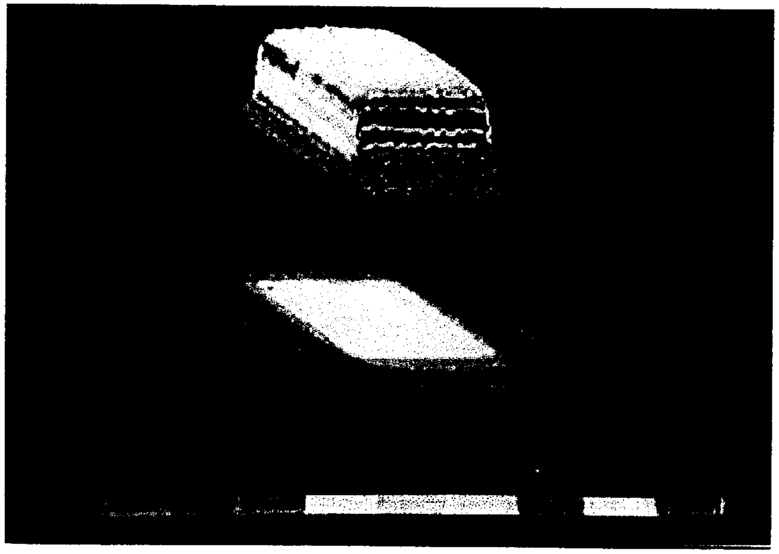
Short Wavelength Sources Are of Interest

- Several advantages
  - higher responsivity $\propto \lambda^{-1}$
  - smaller delay line mirrors $\propto \sqrt{\lambda}$
  - lower loss in core optics (in some cases)
- Several issues
  - higher loss in core optics (in some cases)
  - tighter tolerances on figure, scatter, etc.
  - no good visible/UV lasers
- How to make 10 - 1000 W of VIS/UV?
  - short wavelength laser
    only realistic option is gas laser -- not very realistic
  - nonlinear frequency conversion of available 1 μm lasers
    second harmonic generation (SHG)
    sum frequency generation (SFG)

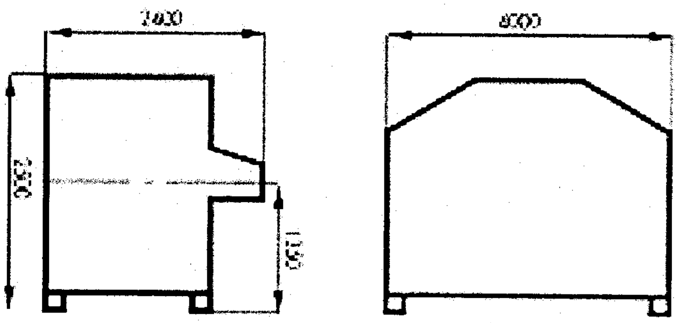
Very high Energy Excimer Laser (VEL)

- > 1 kW ouput power (308 nm)
  - 15 J pulses
  - 100 Hz





VEL 1 K



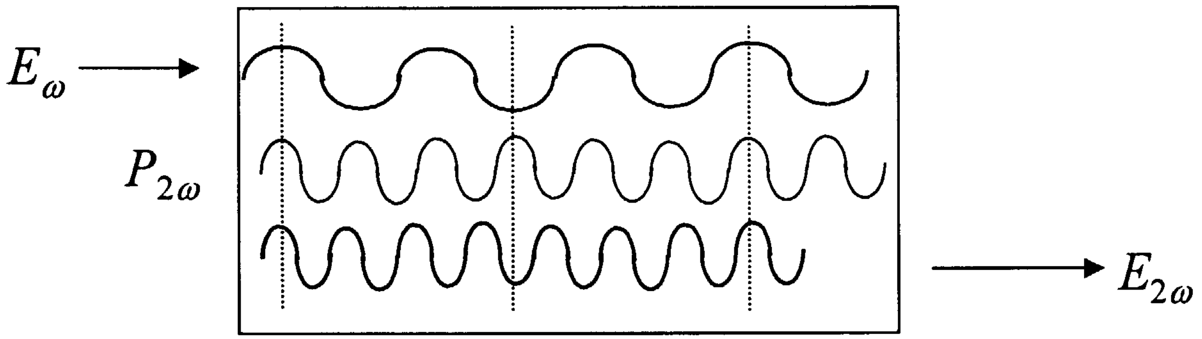
SOPRA

Second Harmonic Generation

- Nonlinear polarization ≈ oscillating current

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

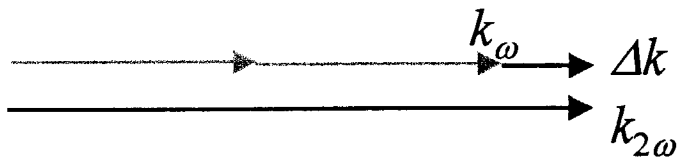
- Output field is sum of contributions from whole crystal



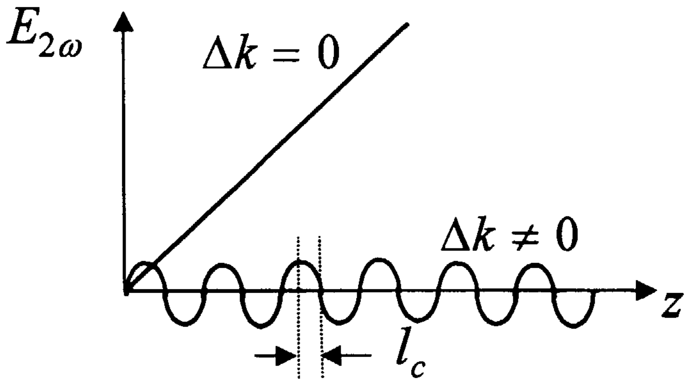
$$E_{2\omega}(L) \propto \int_0^L E_\omega^2\, \chi^{(2)}(z) \exp[i(k_{2\omega} - 2k_\omega)z]\, dz$$

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

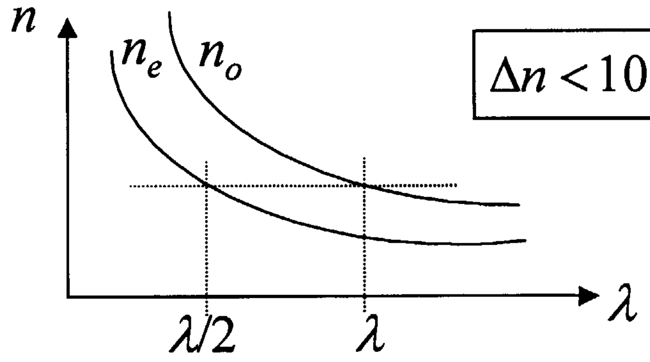
$$\Delta k = k_{2\omega} - 2k_\omega = (2\pi/\lambda)(n_{2\omega} - n_\omega)$$



Phase velocity matching essential



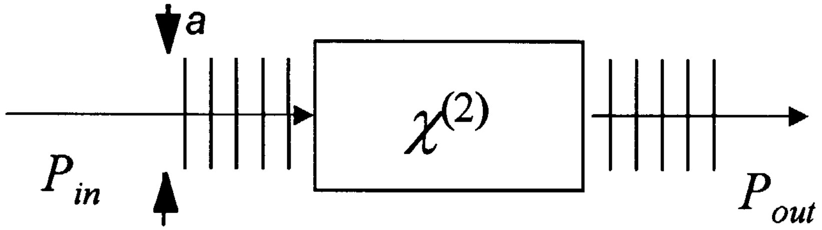
Birefringence generally used



$$\boxed{\Delta n < 10^{-5} - 10^{-6}}$$

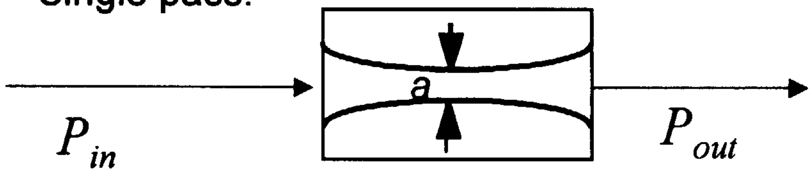
Efficiency Scaling for SHG

Plane wave:



$$\eta \equiv \frac{P_{out}}{P_{in}} \propto \chi^{(2)2} \frac{P_{in} \cdot L^2}{\lambda^2 a^2}$$

Single pass:

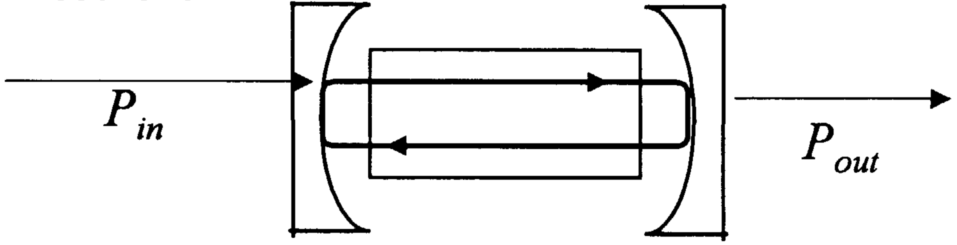


$$a^2 \propto \lambda \cdot L$$

$$\eta = \eta_{norm}\,[\%/W - cm]\;\; P_{in} \;\; L$$

- 0.01 – 10%/W-cm in visible

Resonant:



$$P_{circ} \propto P_{in} / loss$$

$$\eta = \eta_{norm}[\%/W - cm]P_{in}L/loss^2$$

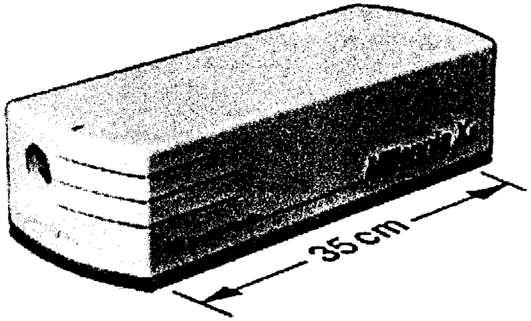
- typical 1%/mW

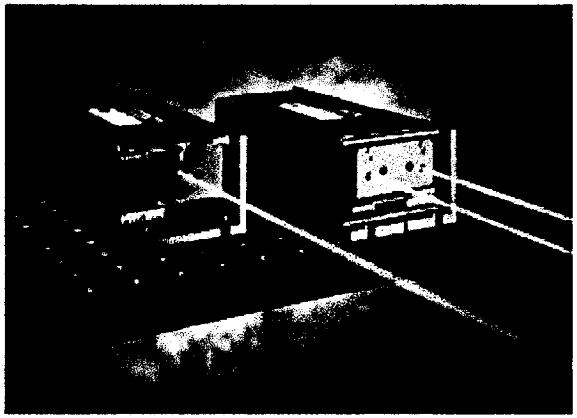
Outline

- SHG Basics and Power Scaling
- Current Results
  - commercial and research
- Materials Issues
- Thermal Loading
- Device Configurations

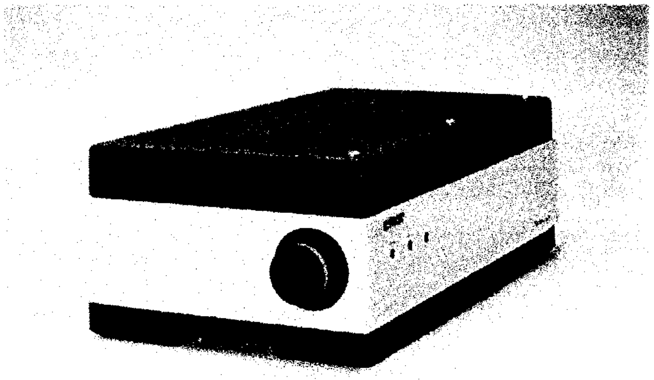
Current Commercial Results

- SP, Coherent: 5 - 10 W CW 532 nm source
  - intracavity doubled





- LWE: 200 mW CW 532 nm source
  - external cavity
  - single frequency NPRO pump



- SONY: 30 mW CW 266 nm source
  - SHG intracavity + SHG external cavity

Research Results

- Pulsed visible: > 300 W
  - LBO SHG of high rep rate Q-switched Nd:YAG

- Pulsed UV: > 20 W

- CW external cavity 532 nm: > 10 W
  - LBO pumped by CW Nd:YAG

- CW single-pass SHG: 2 W
  - PPLN pumped by CW Nd:YAG

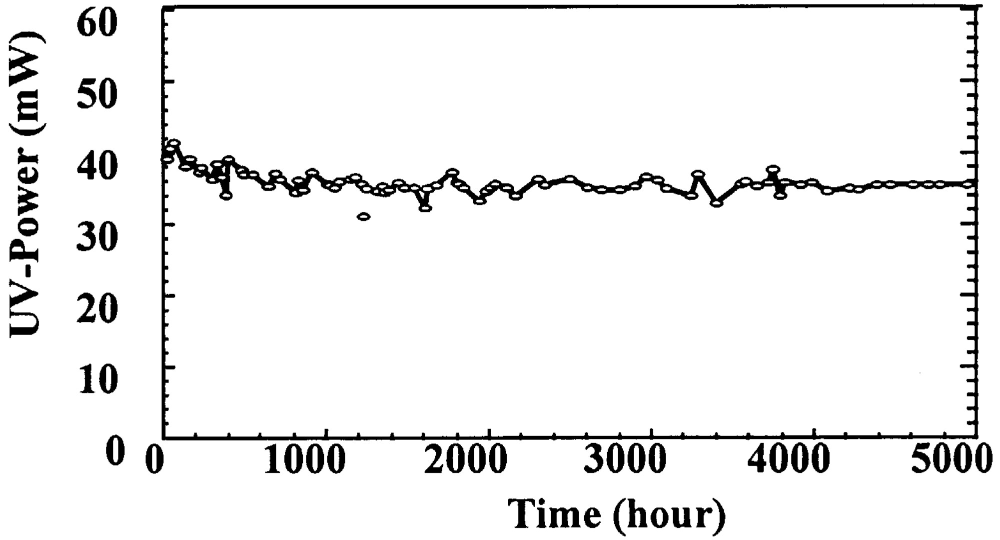
All-Solid-State Deep Ultraviolet Laser

- **Compact, reliable UV SS lasers becoming available**
  - improved pump diodes
  - improved nonlinear materials
  - improved processing
  - improved coatings ...

415 x480 x170 mm^3

SONY "COBALT" Laser

Wavelength	266 nm
Output power(CW)	10 mW, 20 mW
Noise	0.5 % rms or less
Average life	> 5000 h
Power consumption	260 W



SONY

UV Damage in BBO

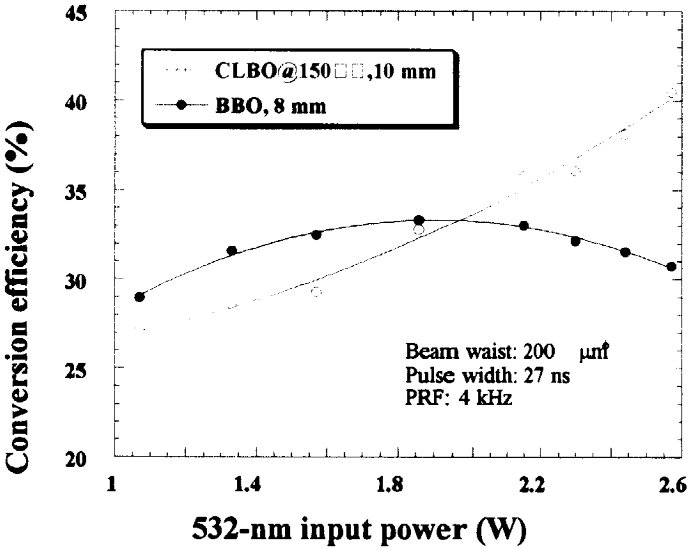
- Scattering Sources along 266-nm Beam Propagation Direction

(Observed with Laser Scanning Tomography)

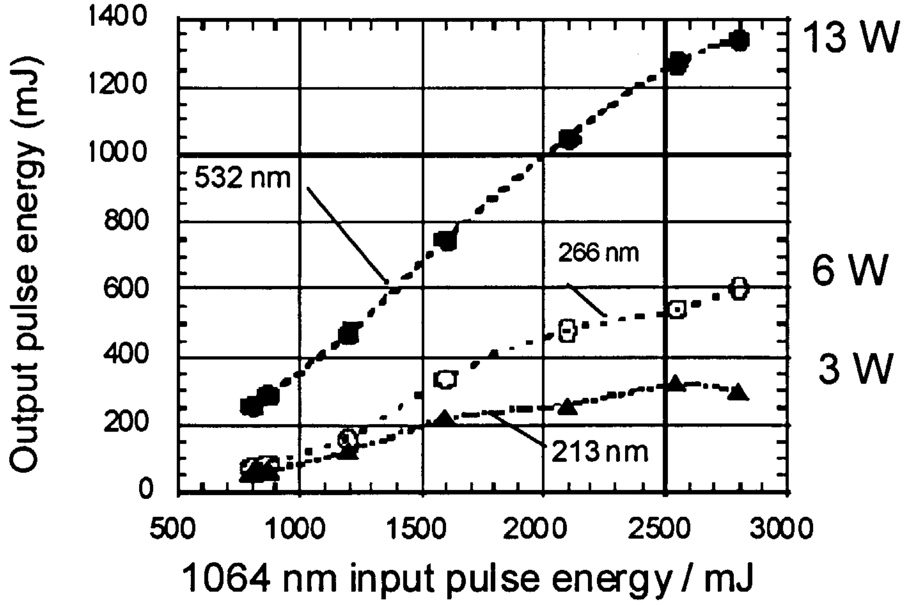
Thermal Loading Affects High Average Power Devices

- Average power loading
  - efficiency rolls over at high powers
  - thermal dephasing
  - thermal beam distortion
- Premium on materials with:
  - high nonlinearity/loss
  - low photothermal response
  - no one material property by itself tells the story

4HG CLBO vs BBO



SHG, 4HG, 5HG in CLBO



Material Requirements

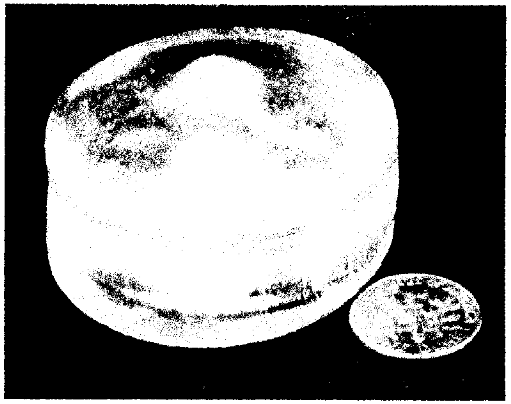
Complex Set of Material Requirements

- Adequate nonlinear coefficient
  - importance often overestimated
- Phasematching
  - noncritical strongly preferred
- Thermal properties
  - high thermal conductivity
  - small photothermal coefficients
- Low absorptivity
- Low scatter
- Growable
- Processable
- Environmentally stable
- No quirks
  - photorefractive effects
  - photochromic effects…

Extrinsic effects:
Difficult to quantify and control

UV Nonlinear Materials

- Borate materials widely used for NLO in UV



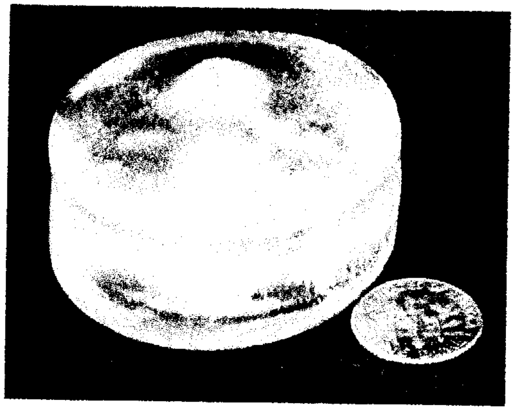
- BBO, LBO
  - standard commercial materials
  - challenging growth and processing
  - aging?

- CLBO
  - promising material
  - easy to grow
  - processing issues being solved
  - high UV powers demonstrated

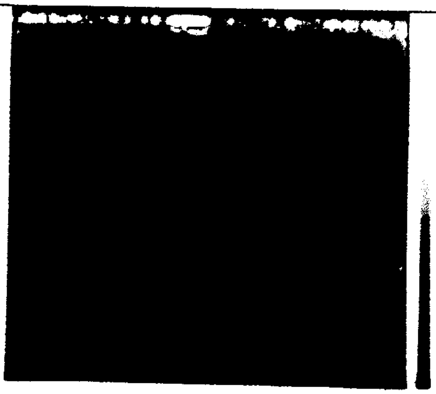
Sasaki/Mori Lab, Osaka U.

Crystal Growth of β-BBO

- Excellent UV Nonlinear Crystal
  - Transmission to 190 nm
  - SHG phase matching to 205 nm
  - Physically Robust
- Long term aging in conventional crystals
- Improved growth leads to longer lifetime

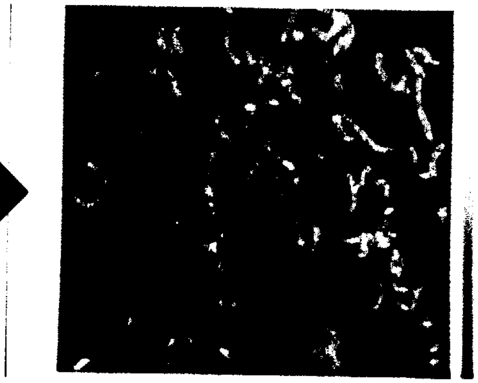


Czochralski Grown BBO



No Visible Scattering

Conventional TSSG Grown BBO



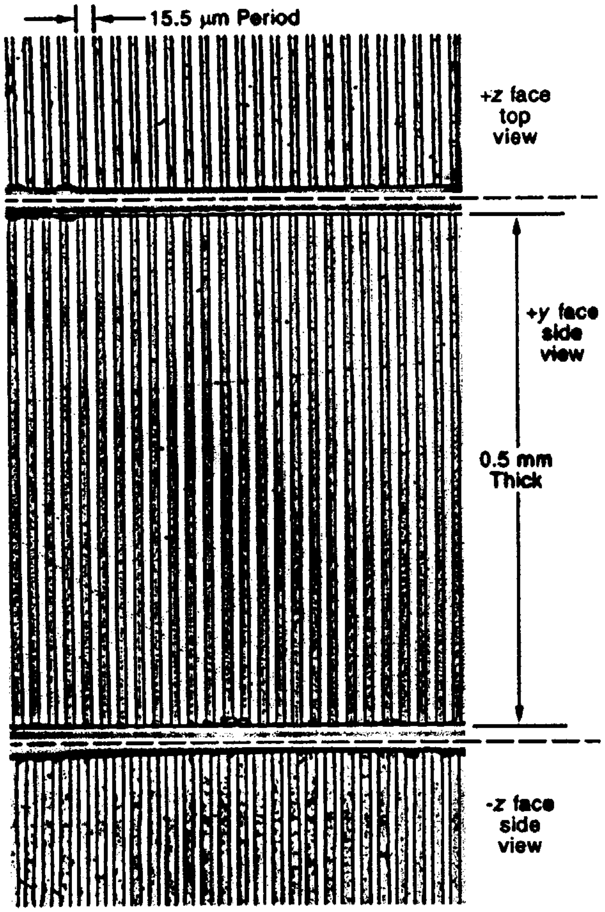
Flux & Inclusions

SONY

Periodically-Poled Ferroelectrics

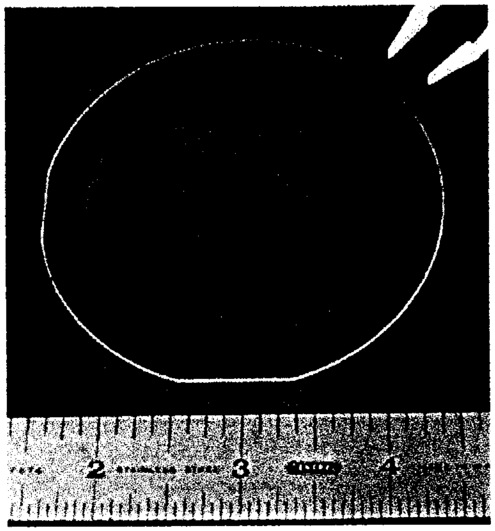
Large Aspect Ratio

2 μm domains in 0.5 mm sample



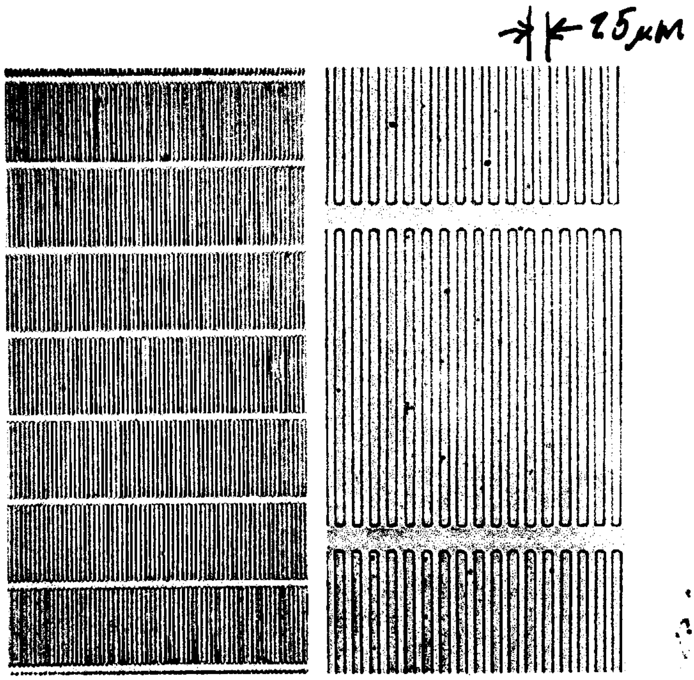
Large Areas

full 3 inch wafers



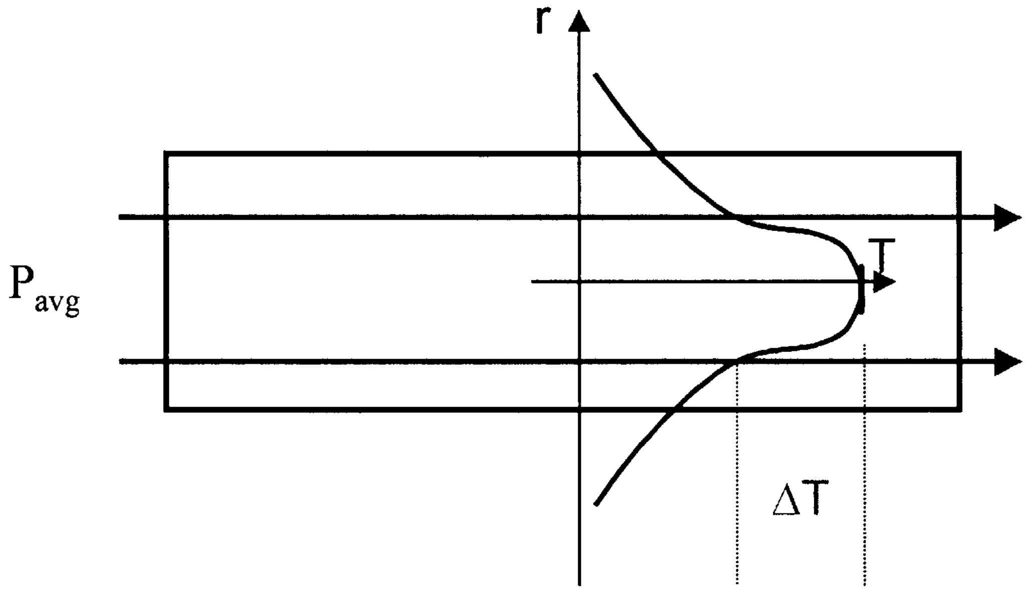
Complex Patterns

follows mask pattern



Temperature Rise in High Power NLO

- Absorbed optical power inhomogeneously heats crystal
  - produces radially varying temperature



$$\Delta T = \frac{\alpha P_{avg}}{4\pi k_{th}}$$

- Temperature rise across beam *independent* of spot size
- Leads to radially varying index: $\Delta n = \beta_T \Delta T$ $\quad \beta_T = {dn}/{dT}$
- Leads to radially varying phase on optical beam: $\Delta\phi = 2\pi \Delta n L / \lambda$

$$\boxed{\Delta\phi = \frac{\alpha \beta_T}{2k_{th}} L P_{avg}}$$

Power Limits from Thermal Effects

- Radially varying phase limits allowable power
  - spoils phasematching
  - thermally focuses beams
  - longitudinal variation also spoils phasematching
- Define maximum allowable thermal phase distortion, $\Delta\phi_{\max} = M\pi \simeq \frac{\alpha\beta_T}{2k_{th}} L P_{max}$
  - gives maximum allowable power
  - proportional to material figure of merit
  - inversely proportional to length of crystal

$$P_{\max} L = 2\pi M \frac{k_{th}}{\alpha\,\beta_T}$$

- Efficiency is scales similarly

$$\eta = \gamma_{conf}\, P\, L$$

  - so there is a maximum attainable efficiency

$$\eta_{\max} = 2\pi M \frac{\gamma_{conf}\, k_{th}}{\alpha\,\beta_T}$$

  - and an overall material figure of merit

$$FOM_{HP} = \frac{d^2\, k_{th}}{n^2\, \alpha\,\beta_T}$$

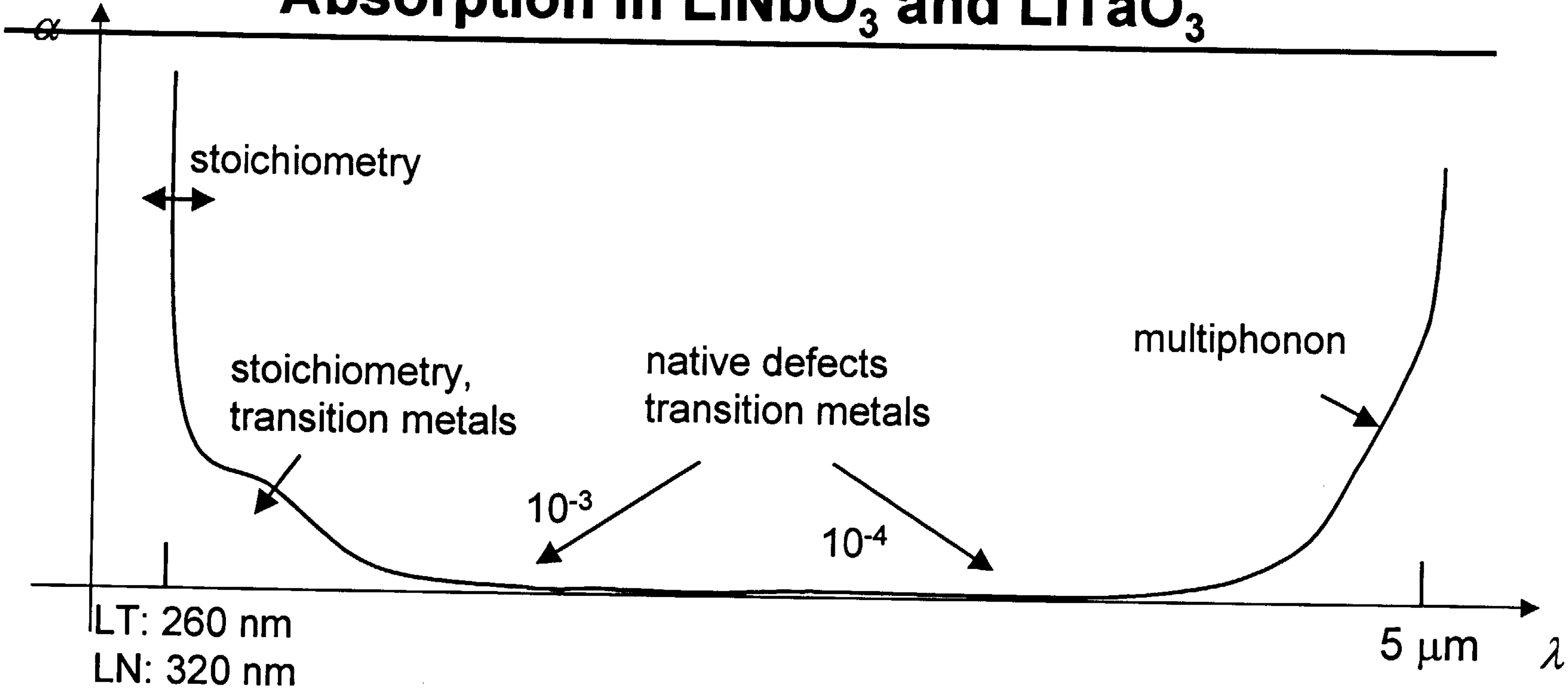
Typical Parameters for 1 μm SHG

		KTP	LBO	BBO	PPLN
	d_{eff} [pm/V]	3.2	0.85	1.9	19
	C^2 [GW^{-1}]	47	4.6	22	1200
	dn/dT [K^{-1}]	1.6	0.8	1.7	3.8
	k_{th} [W/m-K]	3	3	1	6
	α [cm^{-1}]	?	?	?	?
Neglecting α:	$\frac{\text{FOM}}{\text{FOM(KTP)}}$	1	0.2	0.14	22

Perhaps neglecting α is a bad idea

- Tabulation of absorption is difficult
  - typically an extrinsic property -- varies from sample to sample
  - can be strongly wavelength dependent
  - can be power dependent
  - one wavelength can influence another
  - can be time dependent

Absorption in $LiNbO_3$ and $LiTaO_3$



- Band edge: Li/Nb ratio
- Shoulder: Li/Nb, Cr^{3+}, Fe^{3+}
- Visible: Cr^{3+}, Fe^{2+}, bipolaron $(Nb_{Li} + e^-) + (Nb_{Nb} + e^-)$
- Near-IR: polaron $(Nb_{Li} + e^-)$ + ?
- Mid-IR: multiphonon

Can influence shoulder, visible, near-IR with growth and processing

Material Issues

- Absorption effects are complicated
  - processing dependent
  - nonlinear
  - hysteretic
  - nonlocal
  - wavelength(s) dependent
  - difficult to characterize with a single number, but:

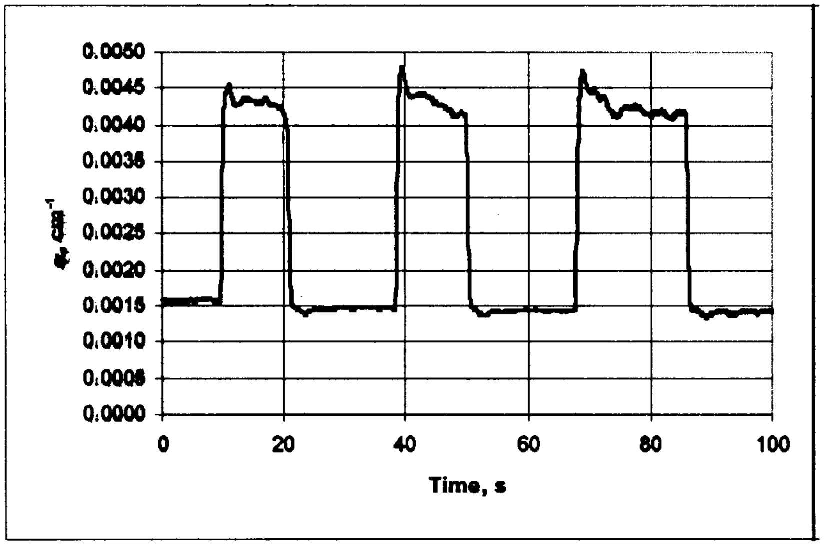
Lower is Better

- Quirky effects can be serious (and complicated)
  - photochromic effects
  - photorefractive effects
  - induced scattering
  - surface degradation ...
- Crystal growth and processing studies are ongoing
- Device designs must be adapted to peculiarities of given material
  - general scaling rules often fail

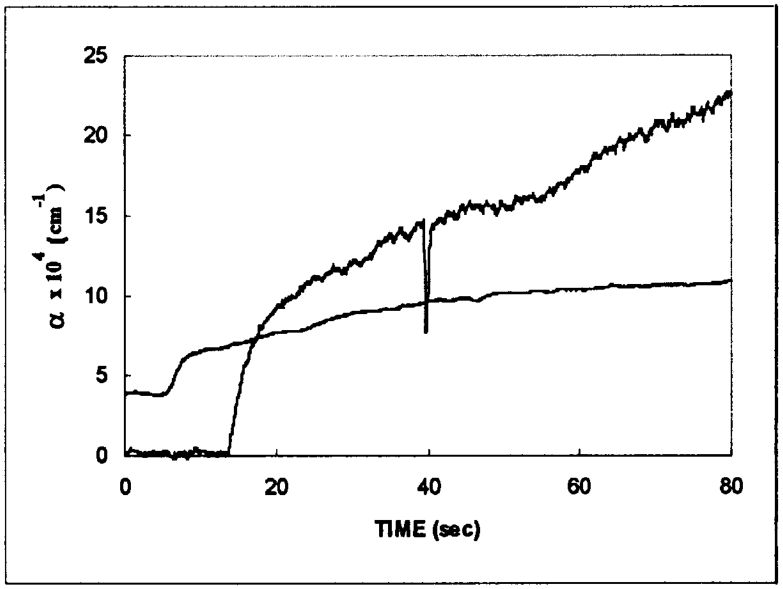
Absorption Can Be Complicated

- Absorption effects have varied manifestations
  - can vary widely for nominally identical samples
- Irradiance at one wavelength alters absorption at another
  - Green-Induced IR Absorption in $LiNbO_3$ (GRIIRA)
- Time dependent absorption at a single wavelength
  - grey track formation in KTP

GRIIRA in $LiNbO_3$

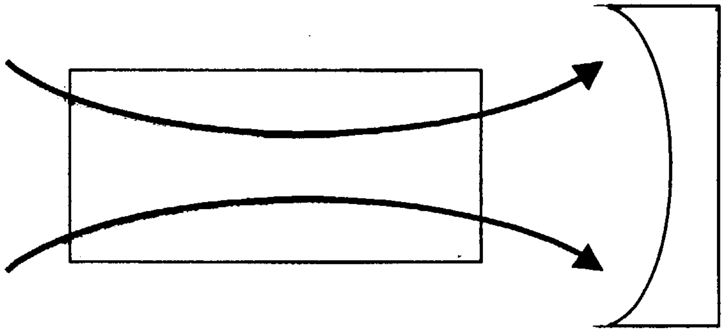


Gray Track Formation in KTP



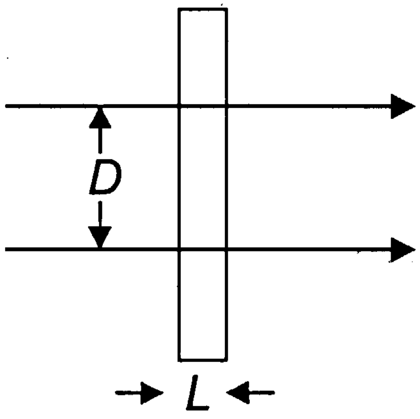
Device Configurations for Power Scaling

- Double pass
  - increase effective length
  - reimage through crystal
  - correct thermal focusing
  - 4 x efficiency of one pass



- Slab/multibounce geometries
  - engineer thermal field

- Face Pumping
  - longitudinal heat flow for high average power
  - requires $D > L$
  - requires highly nonlinear material



Summary

- Short wavelength sources potentially advantageous for advanced interferometers
- Nonlinear conversion of solid-state lasers best route to high power
- Rapid progress in commercial and research demonstrations
  - commercial CW green 10 W
  - multi-hundred Watt pulsed green SHG lasers demonstrated
- Scaling to CW >100 W green and UV realistic but challenging
  - appropriate IR pump lasers are well along
  - must develop robust, low-absorption nonlinear crystals
  - implement appropriate thermal and optical device configurations