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VG04-123

Periodic Poling of Stoichiometric Lithium Tantalate for High-Average Power Frequency Conversion

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Poster Presentation

PPSLT: A New Nonlinear Optical Material

- **AFRL has supported the development of high-average power solid state lasers, often with operating wavelengths in the near-infrared region of the spectrum**
- **PPSLT can be used to shift the output wavelengths of these laser systems to other regions of the spectrum to fill specific needs**
- **Shifting to shorter wavelengths (into the visible region of the spectrum) is useful for adaptive optics (589 nm sodium guide-star radiation); compact visible sources also have great commercial potential (projection displays, biomedical instruments, etc.)**
- **Shifting to longer wavelengths (into the mid-infrared region of the spectrum) is useful for infrared counter-measures and remote chemical sensing**

Physical Properties Responsible for the Promise of PPSLT

- **Stoichiometric lithium tantalate (SLT) is a ferroelectric material, which means the unit cell of the crystal has a permanent electric dipole moment and can be re-oriented by applying an electric field ("domain inversion")**

- **By applying a <u>patterned</u> electric field, one can change a single crystal of SLT into a <u>patterned</u> material, periodically poled SLT (PPSLT); this patterning leads to an increase in the nonlinear optical performance of the material ("quasi-phasematching", QPM)**

Physical Properties Responsible for the Promise of PPSLT (Continued)

- **In comparison with other ferroelectric materials, SLT has these advantages:**
  - it is less susceptible to optical damage, leading to more stable output power at a given temperature and to lower operating temperatures
  - lower electric fields are needed to achieve domain inversion, making it possible to produce thicker crystals with higher power-handling capability
  - it has better transparency in the ultraviolet region of the spectrum, leading to the production of radiation with shorter wavelengths

How to Fabricate and Test PPSLT Devices

- **Procure wafer of stoichiometric lithium tantalate (SLT) from an appropriate vendor**
- **Cover one surface of wafer with a patterned insulator, then apply a metal overcoat to that pattern**
- **Apply a pulse of high voltage**
- **Etch the wafer in hydrofluoric acid to reveal the domain pattern**
- **Dice the wafer into chips and polish the end faces**
- **Shine a high-power near-infrared laser into one end of the crystal and measure the visible radiation coming out the other end**

Periodic Poling Apparatus: Schematic and Photograph

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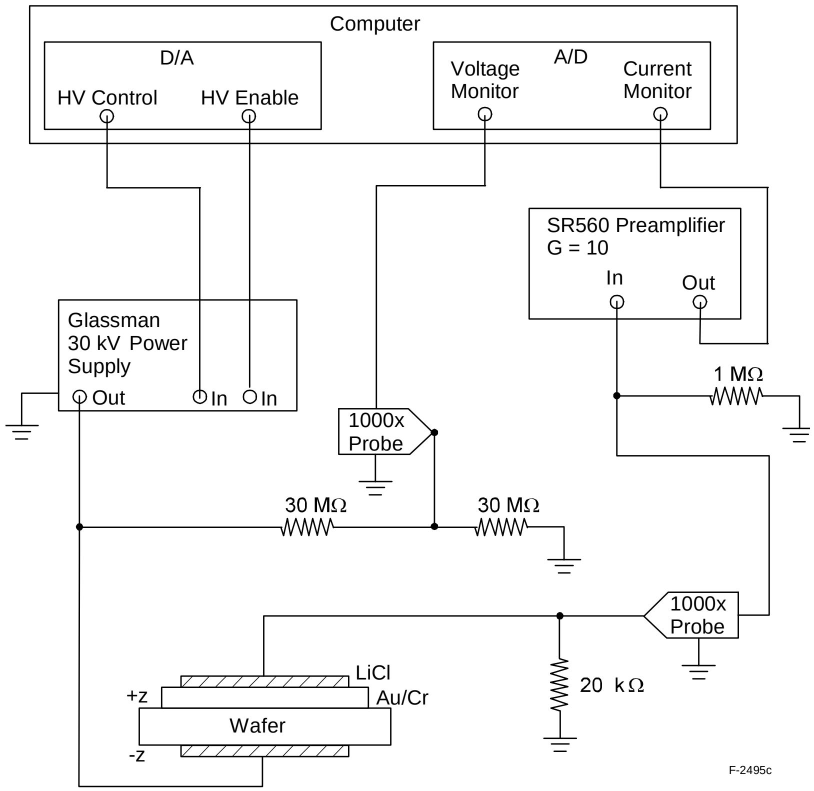
- **Computer-controlled system for creating high-voltage pulses, recording current and voltage**
- **Wafer covered with patterned photoresist, Cr/Au on the plus-Z face; electrical contact using electrolyte-soaked lens tissue**



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- **Voltage turned off automatically when desired charge or pulse length has been reached**

Scaling to Short Periods: Macroscopic View

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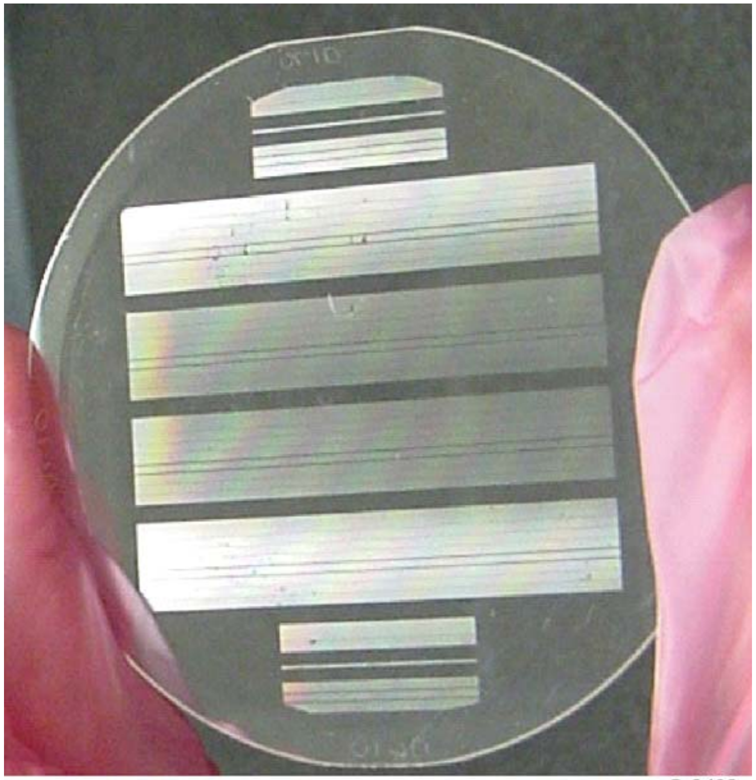
- **Three-inch diameter, 0.5 mm thick wafers from Deltronic Crystal Industries**
- **Pattern (revealed by etching) contains grating-like structures with periods ranging from 5.8 μm to 11.2 μm**



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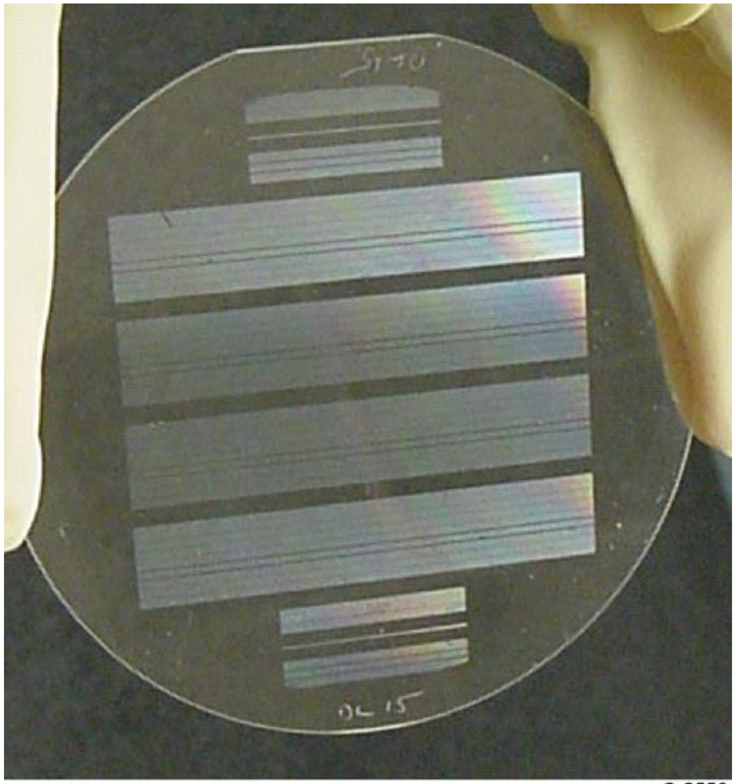

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- **Reproducible, wafer-scale poling process**

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Scaling to Short Periods: Microscopic View

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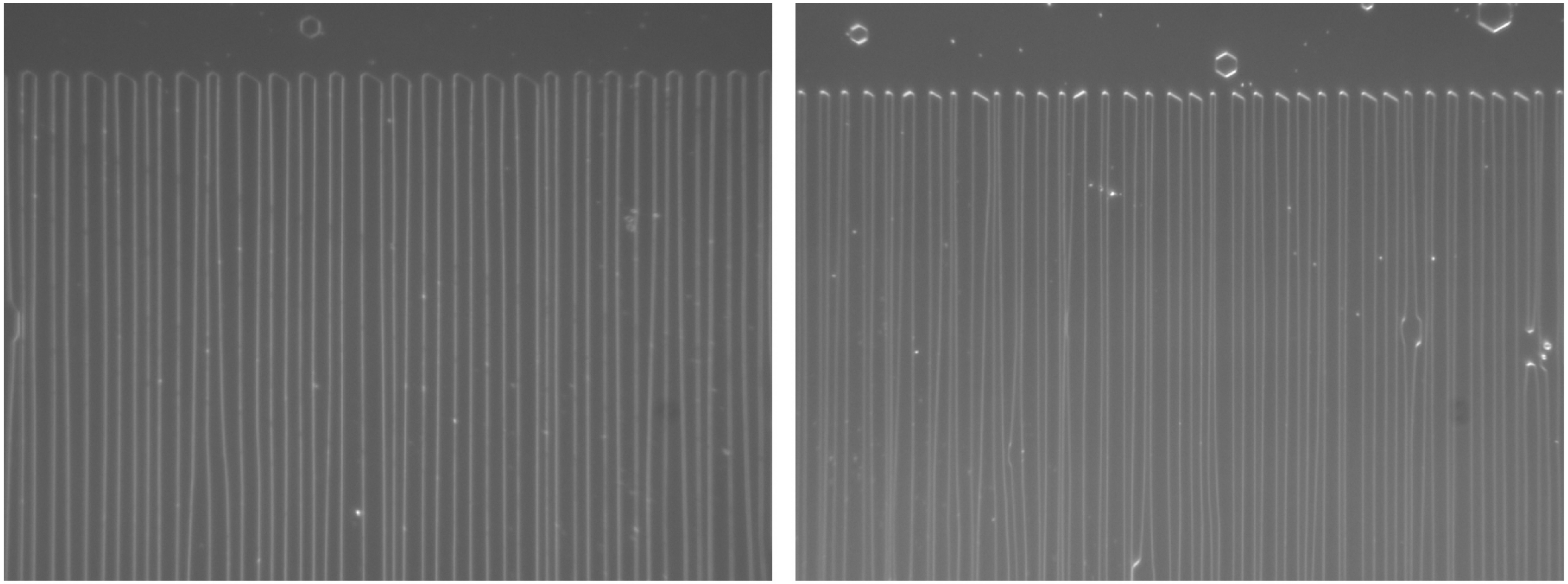
- **Magnified pictures taken of the minus-Z face (the face which did not contain the patterned photoresist)**
- **QPM gratings with periods 10.8 μm (left), 7.6 μm (right); useful for generating yellow and green radiation, respectively**



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- **Reasonable quality for these periods over a 50-mm length**

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Scaling to Still-Shorter Periods: Microscopic View

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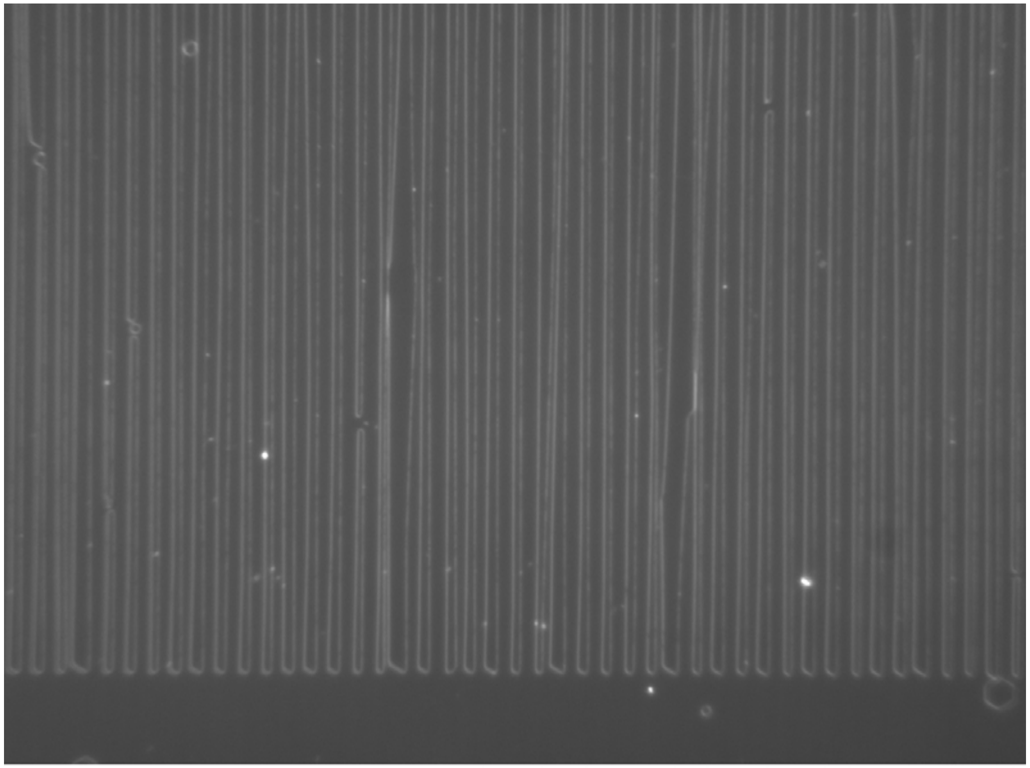
- **QPM period = 6.0 μm; useful for generating blue-green radiation**



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- **More work needed to achieve (or better) this quality on wafer scale**

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Scaling to 2 mm Thickness: Macroscopic, Microscopic Views

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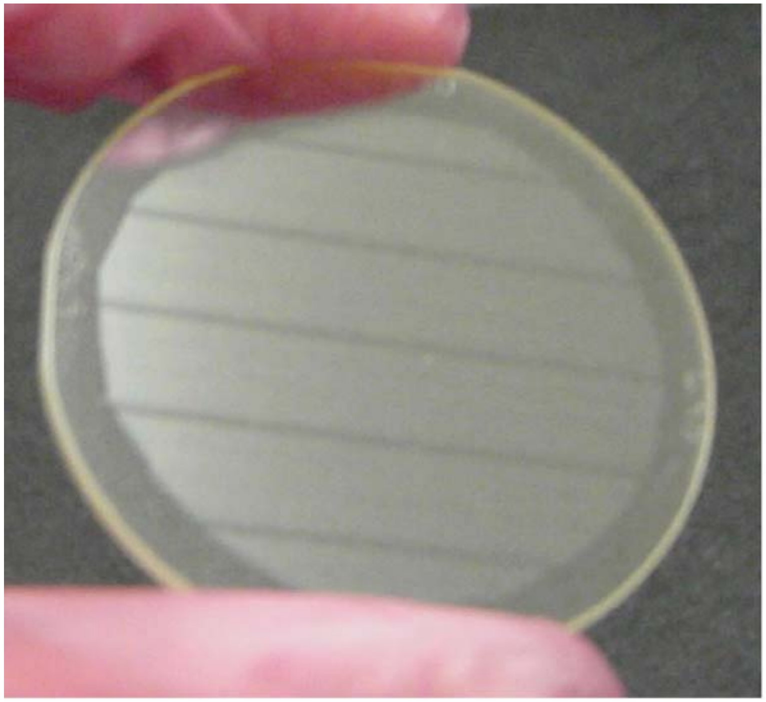
- **50 mm diameter, 2 mm thick wafers used**
- **QPM period = 17.4 μm; useful for frequency-doubling of telecom lasers**



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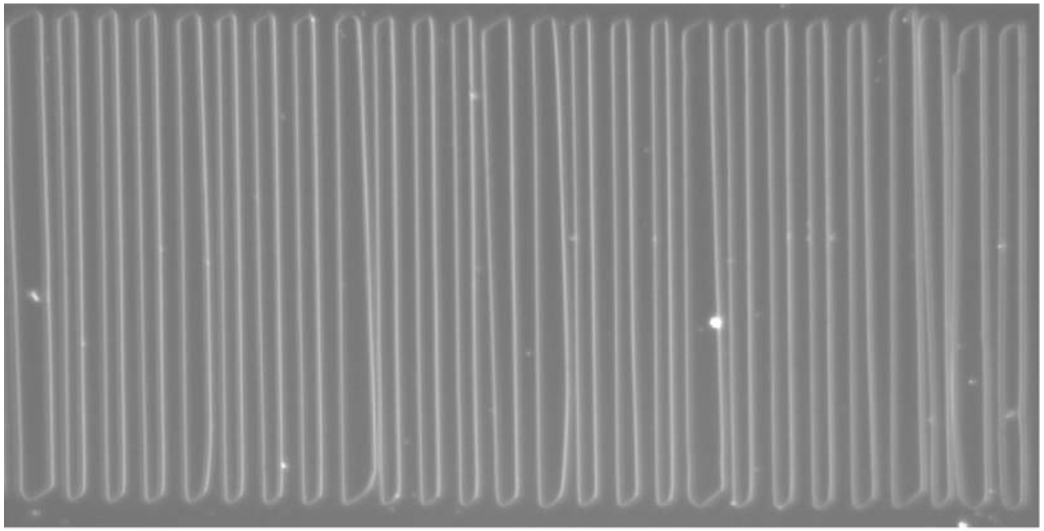

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- **Further work needed to minimize domain merges on wafer scale, and to scale the wafer diameter from 50 mm to 76.2 mm**

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High Power Laser Tests: Schematic and Photograph

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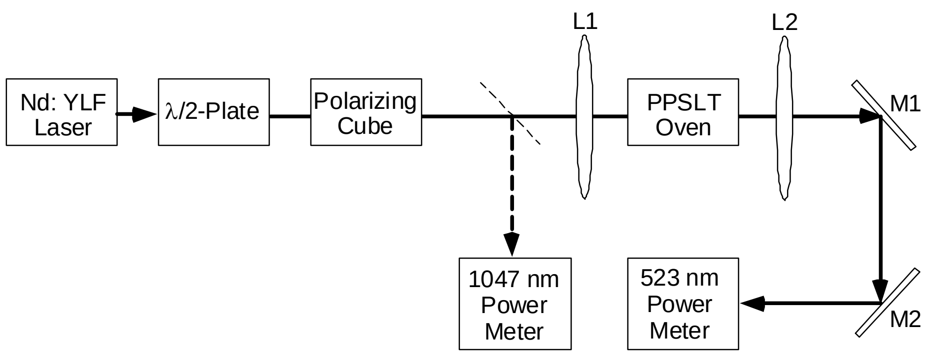
- **Q-Peak Nd:YLF input laser based on multi-pass slab (MPS) technology**
- **Average power up to 6 W at 1047 nm; can be operated in continuous-wave mode, or in a variety of pulse formats**



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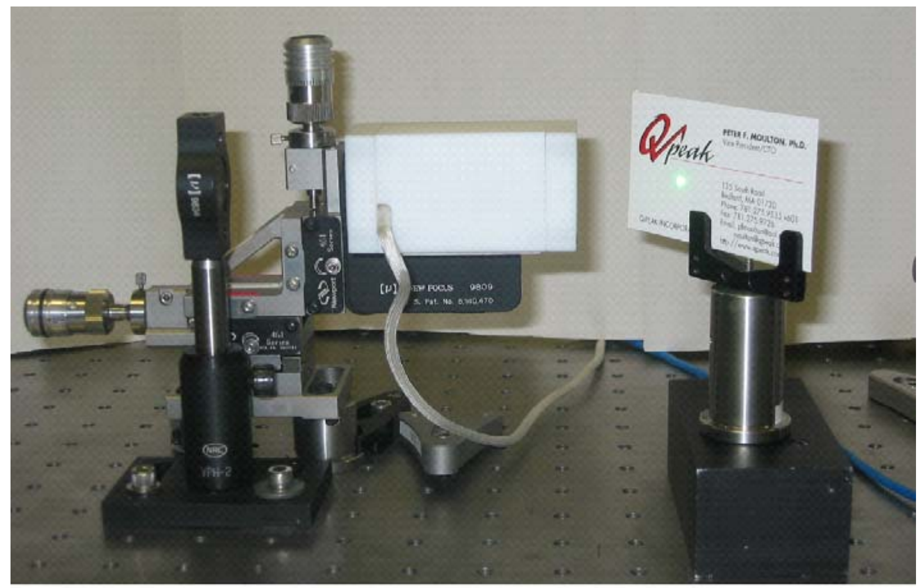

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- **PPSLT crystals with three different lengths (10, 20, 30 cm) mounted inside resistively-heated oven**

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Laser Testing: Phase-Matching Curve

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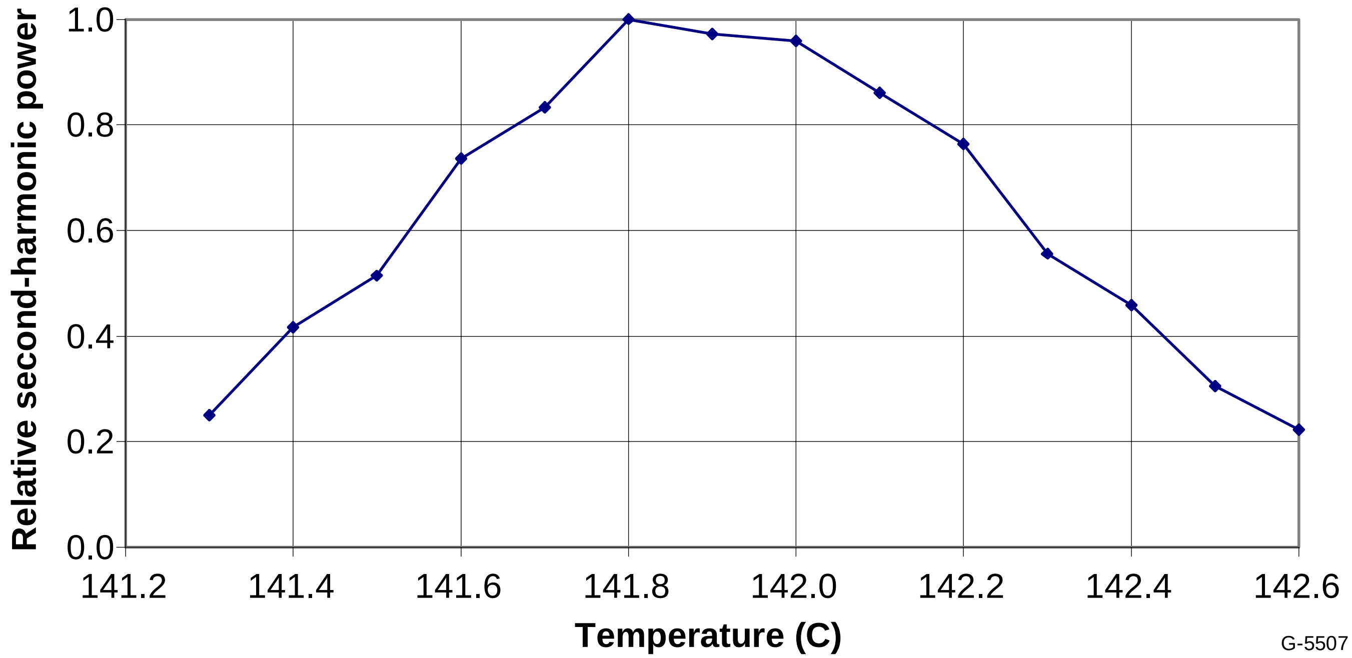
- **SHG converts 1047 nm input radiation to 523.5 nm**
- **Power at 523.5 nm monitored as a function of temperature of PPSLT crystal; QPM grating with period of 7.4 μm, length of 30 mm**



- **Phase-matching temperature and bandwidth agree reasonably well with predictions based on published Sellmeier equation of Bruner et al. (*Optics Letters*, 28, 194-196 (2003))**

Laser Testing: Conversion Efficiency in Continuous-Wave Regime

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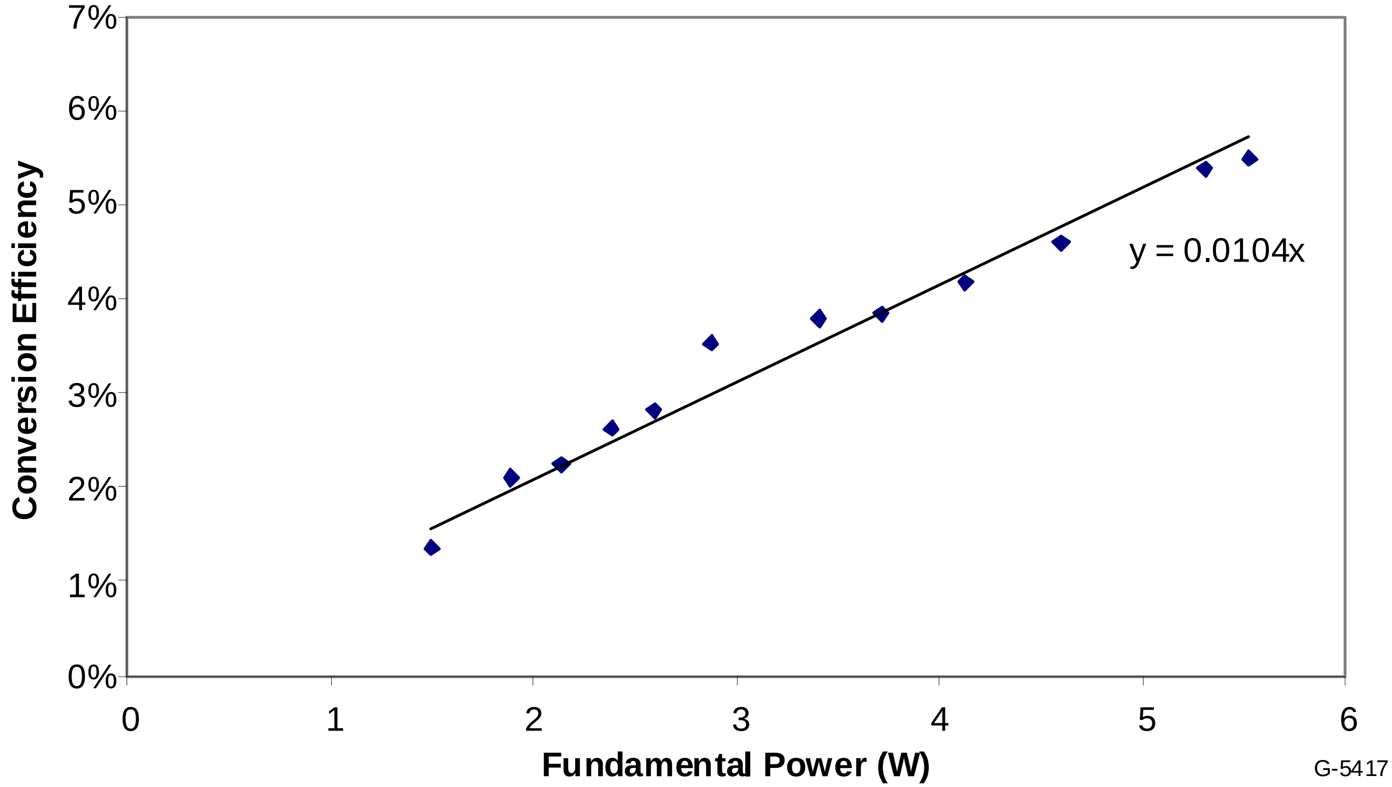
- **SHG efficiency measured as a function of incident power at 1047 nm**
- **Measured powers corrected for Fresnel reflection losses**



- **Linear relationship observed, as expected when the input beam is not depleted by the interaction**
- **Fitted slope gives a device efficiency of 1.0%/W**

Laser Testing: Calculation of Effective Nonlinear Optical Coefficient

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- **Spatial profile of weakly-focused laser beam calculated from known beam properties using Gaussian beam propagation formulas**
- **Device efficiency given by the following equation:**

$$\eta_{dev} = \frac{2\omega_{1h}^2 d_{eff}^2 L^2}{\pi n_{1h}^2 n_{2h} \varepsilon_0 c^3 W_0^2}$$

where ω_{1h} is the frequency of the fundamental beam, d_{eff} is the effective nonlinear coefficient, L is the interaction length, n_{1h} and n_{2h} are indices of refraction, and W_0 is the laser spot size

- **Calculated value of d_{eff} is 7.4 pm/V, close to the expected value of 10.2 pm/V for an ideal QPM structure with perfect uniformity and perfect phasematching**
- **This value of d_{eff} can be used in predictions of device performance**
- **For comparison, periodically poled lithium niobate (PPLN) devices can have d_{eff} = 17 pm/V, but suffer from stability, power handling, and UV transparency issues**

Laser Testing: Summary of Performance in Continuous-Wave Regime

Quantity	Value
Fundamental wavelength	1047 nm
Chip length, L	3.0 cm
η_{dev}	1.0%/W
$\eta_{nor} = \eta_{dev}/L$	0.3%/W-cm
Fundamental power	5.5 W
Second-harmonic power	300 mW

- **300 mW of green radiation generated, with no evidence of beam distortion due to photorefraction**

Laser Testing: Conversion Efficiency in Pulsed Regime

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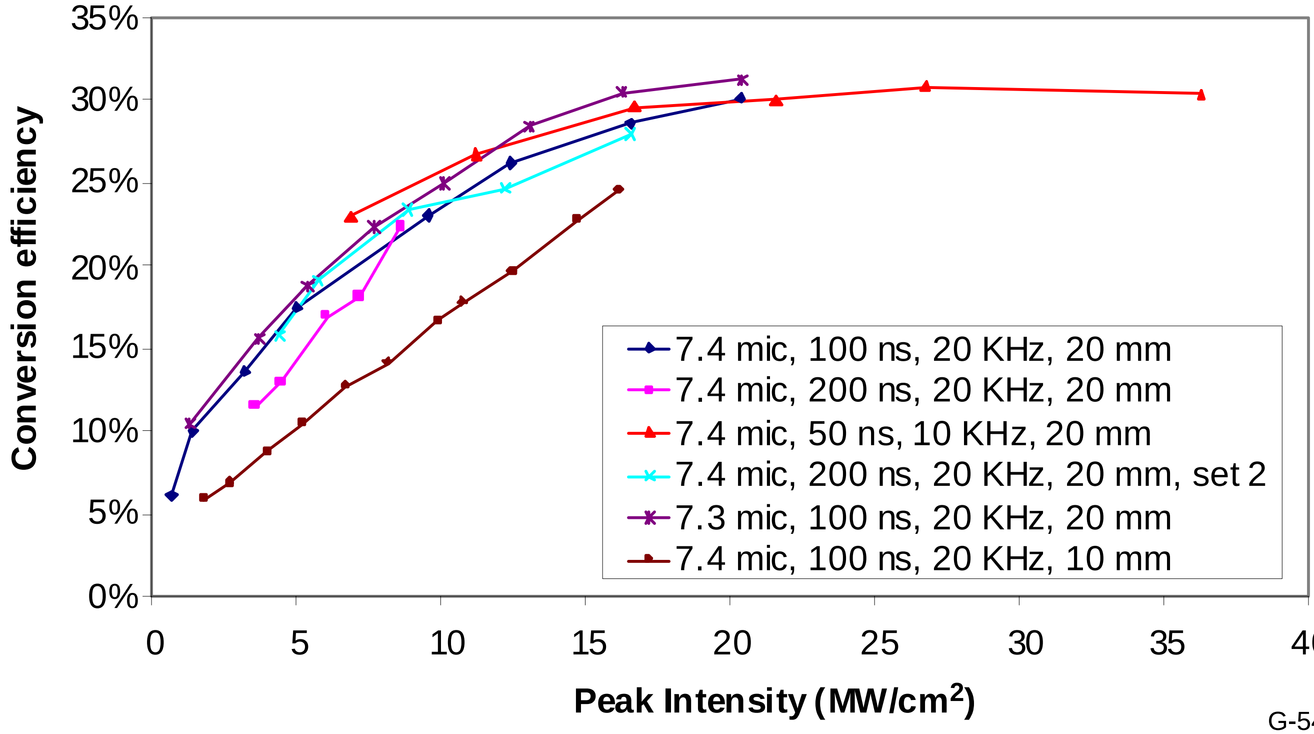
- **Data obtained for a variety of QPM periods, pulse formats, and crystal lengths**



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- **Conversion efficiency levels off at ~30% in the 20 mm long chip, lower than expected based on the cw results; small phase-matching errors in the depleted-pump regime may be responsible**

Laser Testing: Summary of Best Performance in Pulsed Regime

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Quantity	Value
Fundamental wavelength	1047 nm
Laser repetition rate	20 KHz
Laser pulse length	100 ns
Chip length	2.0 cm
Peak conversion efficiency	31%
Fundamental peak intensity	20 MW/cm^2
Fundamental average power	2.5 W
Fundamental pulse energy	125 μJ
Second-harmonic average power	780 mW
Second-harmonic pulse energy	39 μJ

- **780 mW of green radiation generated**
- **Optical damage (surface and bulk) observed at the highest intensities; more work needed to understand its cause**

MWIR Absorption Spectra of SLT, CLN

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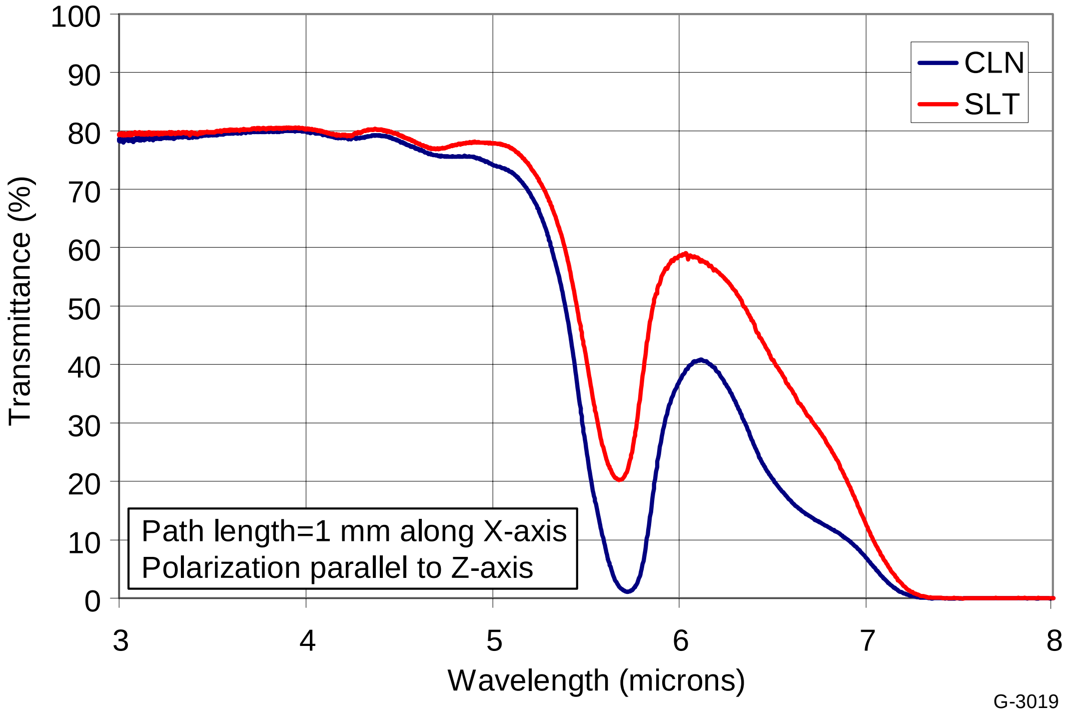
- **Optical parametric oscillators (OPOs) based on congruent lithium niobate (CLN) are limited to wavelengths less than 4 microns because of absorption; reliable absorption data for SLT are not available in the literature**
- **FTIR spectra taken on X-cut, 1 mm thick wafers of SLT, CLN**



- **SLT not significantly more transparent than CLN in the 4.0-4.5 micron wavelength range; therefore, PPSLT is not promising for extending OPOs to longer wavelengths**

Summary and Conclusions

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- **Periodic poling of commercially available SLT wafers from two suppliers (Oxide Corporation and Deltronic) carried out**
- **Wafer-scale poling achieved for periods as short as 7.3 μm on 0.5 mm thick substrates**
- **Promising results obtained for periods as short as 5.8 μm on 0.5 mm thick substrates, and for periods as short as 17.4 μm on 2.0 mm thick substrates**
- **SHG of a Nd:YLF laser in PPSLT has produced 300 mW of average green power in the cw regime, with a device efficiency of 1.0%/W**
- **SHG has also produced 780 mW of average green power in the pulsed regime, with a conversion efficiency of 31%**
- **Future work will include extending short-period poling to thicker substrates, examining scaling to higher average powers**