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 patterned electric field, one can change a single crystal of SLT into a patterned material, periodically poled SLT (PPSLT); this patterning leads to an increase in the nonlinear optical performance of the material ("quasi-phasematching", QPM)
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 from the other end
Periodic Poling Apparatus: Schematic and Photograph

- 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

- Voltage turned off automatically when desired charge or pulse length has been reached
Scaling to Short Periods: Macroscopic View

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

- Reproducible, wafer-scale poling process
Scaling to Short Periods: Microscopic View

- Magnified pictures taken of the minus-Z face (the face which did not contain the patterned photoresist)
- QPM gratings with periods 10.8 \( \mu m \) (left), 7.6 \( \mu m \) (right); useful for generating yellow and green radiation, respectively
- Reasonable quality for these periods over a 50-mm length
Scaling to Still-Shorter Periods: Microscopic View

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

- More work needed to achieve (or better) this quality on wafer scale
Scaling to 2 mm Thickness: 
Macroscopic, Microscopic Views

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

- 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**

- 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

- PPSLT crystals with three different lengths (10, 20, 30 cm) mounted inside resistively-heated oven
Laser Testing: Phase-Matching Curve

- 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

- 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

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

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

where \( \omega_{1\text{h}} \) is the frequency of the fundamental beam, \( d_{\text{eff}} \) is the effective nonlinear coefficient, \( L \) is the interaction length, \( n_{1\text{h}} \) and \( n_{2\text{h}} \) are indices of refraction, and \( W_0 \) is the laser spot size
- Calculated value of \( d_{\text{eff}} \) 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 \( d_{\text{eff}} \) can be used in predictions of device performance
- For comparison, periodically poled lithium niobate (PPLN) devices can have \( d_{\text{eff}} = 17 \) pm/V, but suffer from stability, power handling, and UV transparency issues

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**Laser Testing: Summary of Performance in Continuous-Wave Regime**

<table>
<thead>
<tr>
<th>Quantity</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fundamental wavelength</td>
<td>1047 nm</td>
</tr>
<tr>
<td>Chip length, L</td>
<td>3.0 cm</td>
</tr>
<tr>
<td>$\eta_{dev}$</td>
<td>1.0%/W</td>
</tr>
<tr>
<td>$\eta_{nor} = \eta_{dev}/L$</td>
<td>0.3%/W-cm</td>
</tr>
<tr>
<td>Fundamental power</td>
<td>5.5 W</td>
</tr>
<tr>
<td>Second-harmonic power</td>
<td>300 mW</td>
</tr>
</tbody>
</table>

- 300 mW of green radiation generated, with no evidence of beam distortion due to photorefraction
Laser Testing: Conversion Efficiency in Pulsed Regime

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

- 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

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

<table>
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<tr>
<th>Quantity</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fundamental wavelength</td>
<td>1047 nm</td>
</tr>
<tr>
<td>Laser repetition rate</td>
<td>20 KHz</td>
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<tr>
<td>Laser pulse length</td>
<td>100 ns</td>
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<tr>
<td>Chip length</td>
<td>2.0 cm</td>
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<tr>
<td>Peak conversion efficiency</td>
<td>31%</td>
</tr>
<tr>
<td>Fundamental peak intensity</td>
<td>20 MW/cm²</td>
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<tr>
<td>Fundamental average power</td>
<td>2.5 W</td>
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<tr>
<td>Fundamental pulse energy</td>
<td>125 µJ</td>
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<tr>
<td>Second-harmonic average power</td>
<td>780 mW</td>
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<tr>
<td>Second-harmonic pulse energy</td>
<td>39 µJ</td>
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</table>
MWIR Absorption Spectra of SLT, CLN

- 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

- 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