High energy, single-mode, all-solid-state and tunable UV laser transmitter

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Laser Risk Reduction Program (LRRP)

- NASA began Laser Risk Reduction Program (LRRP) in 2002 to develop reliable, robust, and compact laser technologies for lidar applications from space based platforms
  - **Program:** Joint operation of Langley Research Center and Goddard Space Flight Center
  - **Goal:** 1 micron and 2 micron lasers and wavelength conversion technology
  - **Applications:** Four Lidar Techniques—altimetry, Doppler, Differential Absorption Lidar (DIAL), backscatter lidar
  - **Measurements:** 6 priority Earth Science measurements:
    1. Surface and ice mapping
    2. Horizontal vector wind profiles
    3. Carbon-di-oxide (CO₂) profiles
    4. Ozone (O₃) profiles
    5. Aerosol/clouds
    6. River currents
UV Task Objectives

- The objective of the UV Task is to develop an efficient, all-solid-state, diode pumped, conductively cooled, single longitudinal mode and high energy 1-micron to UV wavelength conversion technology.
- The emphasis is to generate UV wavelengths of 308 nm and 320 nm for ozone sensing using Differential Absorption Lidar (DIAL) technique from space.
- Performance Goals:
  - Output energy at UV wavelengths: $\geq 200 \text{ mJ}$
  - Pulselength: 10 - 25 ns
  - PRF: 50 Hz
- High pulse energy allows enhanced performance during strong daylight conditions.
- UV Task is a collaborative effort among Sandia National Labs, Fibertek, and NASA LaRC.
Technical Approach to UV generation

- Basic Scheme comprises of a Nd:YAG laser pumped nonlinear optics based converter comprising of a second harmonic generation (SHG), optical parametric oscillator, (OPO) and sum frequency generation (SFG) processes.

![Diagram of UV generation process]

- Nd:YAG Pump Laser
  - Pulse duration: $\tau_{\text{pulse}} = 10 - 20 \text{ ns}$

- SHG
  - 1064 nm $\rightarrow$ 532 nm

- OPO
  - 532 nm $\rightarrow$ 803 nm $+ 1576 \text{ nm};$ 731.5 nm $+ 1950 \text{ nm}$

- SFG
  - 532 nm $+ 803 \text{ nm}$ $\rightarrow$ 320 nm
  - 532 nm $+ 731.5 \text{ nm}$ $\rightarrow$ 308 nm
UV Wavelength Conversion -Experimental Results-

- The nonlinear optics based technology to efficiently generate UV wavelengths has been established using a flash lamp pumped Nd:YAG laser.
- The scheme utilizes a novel (Rotated Image Singly Resonant Twisted RectAngle) RISTRA OPO to generate 803 and 731.5 nm wavelengths pumped using a 532 nm pump source.
- A type-I BBO crystal is used in the RISTRA OPO and a LBO crystal is used for SFG.
- Single mode operation is obtained through pulsed seeding technique with temporally matched pump and idler pulse profile.
- Pulse idler seeding is obtained by a tunable laser diode and RISTRA OPO in tandem as seed sources.
- For 803 nm:
  - A small or low energy RISTRA OPO that is locked by Pound-Drever-Hall (PDH) technique and seeded by New Focus tunable diode laser operating at 803 nm.
  - The 1.5x scaled big RISTRA OPO that is pulse seeded at 1576 nm from the small OPO and locked by energy stabilization technique.
Latest Results on the UV conversion

- State-of-the-art conversion efficiencies have been demonstrated using a flash lamp pumped Nd:YAG laser with a round top-hat profile

- Greater than 90% pump depletion obtained
- At 320 nm, >200 mJ extra cavity SFG with good beam quality
  - IR to UV efficiency > 21% (27% for 1 mJ seed)
- At 320 nm, up to 160 mJ intra-cavity SFG
  - IR to UV efficiency up to 24%
- Fluence ≥1 J/cm² for most beams
Solid-State Nd:YAG Pump laser

- For future space applications, an all solid-state, diode pumped Nd:YAG pump laser has been developed in collaboration with Fibertek, Inc.
  - The pump laser is an upgrade of ~300 mJ/pulse Nd:YAG laser developed under NASA funded ATIP program
  - Two amplifiers have been added to the NASA ATIP laser to achieve up to 1.2 J/pulse
An all solid-state diode-pumped laser transmitter featuring:

<table>
<thead>
<tr>
<th>Feature</th>
<th>Benefit</th>
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<tbody>
<tr>
<td>Injection seeded ring laser</td>
<td>Improves emission brightness ($M^2$)</td>
</tr>
<tr>
<td>Diode-pumped zigzag slab amplifiers</td>
<td>Robust and efficient design for use in space</td>
</tr>
<tr>
<td>Advanced E-O phase modulator material</td>
<td>Allows high frequency cavity modulation for improved stability injection seeding</td>
</tr>
<tr>
<td>Alignment insensitive / boresight stable 1.0 $\mu$m cavity and optical bench</td>
<td>Stable and reliable operation over environment</td>
</tr>
<tr>
<td>Conduction cooled</td>
<td>Eliminates circulating liquids w/in cavity</td>
</tr>
<tr>
<td>Space-qualifiable component designs</td>
<td>Establishes a path to a space-based mission</td>
</tr>
</tbody>
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Single Frequency Laser Ring Laser Design

Optical Schematic

- Near stable operation allows trading beam quality against output energy by appropriate choice of mode limiting aperture
  - 30 mJ TEM$_{00}$, $M^2 = 1.2$ at 50 Hz
  - 30 mJ TEM$_{00}$, $M^2 = 1.3$ at 100 Hz
  - 50 mJ square supergaussian, $M^2 = 1.4$ at 50 Hz
- Injection seeding using an RTP phase modulator provides reduced sensitivity to high frequency vibration
- PZT stabilization of cavity length reduces sensitivities to thermal fluctuations
- Zerodur optical bench results in high alignment and boresight stability

Design Features

1. Reverse wave suppressor
2. Cube polarizer
3. Odd bounce slab
4. Steering wedge
5. $\lambda/2$ waveplate
6. Mode limiting aperture
7. RTP phase modulator
8. 45° Dove prism
9. Non-imaging telescope
10. RTP q-switch

Final Zerodur Optical Bench (12cm x 32cm)
Amplifier Design Configuration

3 Bounces-Rectangular Shape-2 sided pumping in the TIR axis, 2 sided conduction cooling, Pump faces uncoated (~10% loss)

2-Sided Pumped & Cooled Amplifier

Prototype Two-Sided Pumped and Cooled Head Design

Dimensions
- 6.8 x 13.0 x 75.3 mm³
- Near Brewster (57°)

Extraction
- 100% at full aperture

Aperture
- 11.5 x 6.8 mm² (internal)
- 7.1 x 6.8 mm² (external)

Doping Level
- 0.5 ± 0.1 % Nd³⁺

Pump Diodes
- 192 ea. 50 watt QCW bars (12 ea. 16 bar arrays)

Input
Output
First Stage
Second Stage

4.9 cm
7.1 cm
8.4 cm
Final System Configuration

Optical layout

Diode Bars and slabs are conductively coupled to the heat sink.

For space applications, one can use heat pipes or radiators.
Amplifier Upgrade
2-Sided Pumped & Cooled Amplifier

Dual Stage Amplifier Modeling

Model is based on Franz-Nodvic result for a amplifying a square (in time) pulse

Model includes all key parameters explicitly
- Number of pump diodes (192)
- Peak diode power (75 W)
- Diode pulse width
- Input oscillator pulse energy (60 mJ)
- Input beam diameter
- Gain path length in amp
- Slab volume

Accounts for reduced gain for second pass

1 J per pulse output is predicted for 210 µs diode pump pulses

Modeled output of dual 2-sided pumped and cooled amplifiers for 60 mJ input to first stage

Dual 2-sided pumped amplifiers meet the requirements of most space-based direct detection wind lidars designs
Pump Laser Performance

- The laser is now operational at 50 Hz PRF with maximum pulsewidths around 22 ns
- The output beam profile is rectangular super gaussian

- **Oscillator Configuration**
  - 100 µs pump pulse
  - 55 W/bar
  - 100 bars
  - Oscillator Output
    - 50 mJ/pulse
    - PRF = 50 Hz
    - 0.41 cm x 0.41 cm square beam
    - $M^2 = 1.2$

- **Amplifier Configuration**
  - Vary pump pulse width
  - 55 W/bar
  - 112 bars/amp
  - Peak Dual Amplifier Output
    - 350 mJ/pulse
    - $M^2 = 1.6$

- **Input** = 280 mJ
  - First Stage Output > 700 mJ
  - PRF = 50 Hz
  - Pulsewidth = ~16 ns
  - Spatial Mode = Rect. Super Gaussian
  - $M^2 = 2$
  - Optical Eff. >11%
  - Wall Plug Eff. >7%

- **Input** = 700 mJ
  - Second Stage O/P > 1100 mJ
  - PRF = 50 Hz
  - Pulsewidth = 22 ns
  - Spatial Mode = SG
  - $M^2 = 2.5$
  - Optical Eff. = 11%
  - Wall Plug Eff. = 7%
Nd:YAG Pump Laser
- Typical Output Characteristics -

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Specification</th>
<th>Goal</th>
<th>Design/Performance</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pulse Energy (mJ)</td>
<td>900</td>
<td>1200</td>
<td>1040</td>
</tr>
<tr>
<td>M²</td>
<td>NA</td>
<td>2</td>
<td>2.5</td>
</tr>
<tr>
<td>Laser head package</td>
<td>Single breadboard</td>
<td>NA</td>
<td>Single breadboard in custom enclosure</td>
</tr>
<tr>
<td>Cooling</td>
<td>Conductive to diodes and slabs</td>
<td>NA</td>
<td>Conductive to diodes and slabs</td>
</tr>
<tr>
<td>Seeding</td>
<td>Ramp &amp; fire</td>
<td>NA</td>
<td>Ramp &amp; fire</td>
</tr>
<tr>
<td>Electronics</td>
<td>Separate custom module</td>
<td>NA</td>
<td>Separate custom module</td>
</tr>
</tbody>
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Typical pulsewidth = 22 ns. Max. Pulse Energy achieved = 1.2 J. Electrical to optical efficiency >7% was achieved with only 58 W peak power per diode bar pumping the amplifiers.

Average power at 50 Hz of 51.0 W (1020 mJ/pulse)
Temporal Characteristics

Oscillator Only: 16.5 ns

Oscillator + Preamp 1 + Preamp 2: 19.5 ns

Oscillator + Amp 1 + Amp 2: 20.9 ns

Full System: Pulsewidth ~ 22 ns
Full System Results Beam Quality

50 Hz, Full Power Beam Quality Measurements

\[ M_x^2 = 2.5, \quad M_y^2 = 2.5, \]

\[ M^2 \text{ data} \]
Full Nd:YAG Laser Unit

- The dimensions of this laser unit, including a SHG module, is 34” x 22” x 8”
- With latest diode bars and modified opto-mechanical components, the above package can be reduced to less than a quarter of its size
Custom power supplies and control electronics for the upgrade have been built:

- Control electronics consists of two 19" rack mountable boxes.
- All power supplies are contained in two 19" rack mountable power supply modules.
- Each amplifier can be individually set between high power and low power operation to allow the user to achieve a wide range of output powers at 50 Hz.
Currently, we are generating a few mJ with limited pump energy of 280 mJ/pulse
  - The elliptical beam allows reduced overlap inside the nonlinear crystal of RISTRA module hence reduces the conversion efficiency
Spatial fluence profile & RISTRA

- RISTRA OPO requires round, top-hat spatial pump profile -

Flat pump profiles have facilitated high pump depletion & hence high OPO conversion efficiency

Results Using refined Flash Lamp pump laser

OPO signal near-field spatial fluence profile, Fresnel Number > 450

Self-seeded oscillation in two-crystal RISTRA ~85% pump depletion

Results Using Diode pumped Nd:YAG laser

Pump Beam at the Big OPO

Reduced Pump Depletion
On-Going Work

- Improve the Beam Quality of the Diode Pumped Nd:YAG Laser
  - The goal is to achieve a Round, Top Hat spatial fluence profile with wavefront aberration less than 0.5

- Refinements to the ring oscillator cavity, pre amplifiers and amplifiers of the diode-pumped Nd:YAG laser to improve beam quality and reduce pulsewidth is nearing completion
Summary and Conclusions

• A high energy, single mode, all solid-state Nd:YAG laser primarily for pumping an UV converter is developed
• Greater than 1 J/pulse at 50 HZ PRF and pulsewidths around 22 ns have been demonstrated
• Higher energy, greater efficiency may be possible
  – Refinements are known and practical to implement
• Technology Demonstration of a highly efficient, high-pulse-energy, single mode UV wavelength generation using flash lamp pumped laser has been achieved
  – Greater than 90% pump depletion is observed
  – 190 mJ extra-cavity SFG; IR to UV efficiency > 21% (> 27% for 1 mJ seed)
  – 160 mJ intra-cavity SFG; IR to UV efficiency up to 24%
  – Fluence ≤ 1 J/cm² for most beams
• The pump beam quality of the Nd:YAG pump laser is being refined to match or exceed the above UV converter results
• Currently the Nd:YAG pump laser development is a technology demonstration
  – System can be engineered for compact packaging