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

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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, (b) Horizontal vector wind profiles (3) Carbon-di-oxide (CO₂) profiles (4) Ozone (O₃) profiles (5) Aerosol/clouds and (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: $\geq 200$ mJ
  – Pulsewidth: 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.

\[
\begin{align*}
\text{Nd:YAG Pump Laser} & \quad \tau_{\text{pulse}} = 10 - 20 \text{ ns} \\
2\omega & \quad \text{KTP} \\
\text{OPO} & \quad \text{SFG crystal(s)}
\end{align*}
\]

\[
\omega_1 + \omega_2 = \omega_3
\]

\[
\begin{align*}
1064 \text{ nm} & \quad \text{SHG} \quad 532 \text{ nm} \\
532 \text{ nm} & \quad \text{OPO} \quad 803 \text{ nm} + 1576 \text{ nm}; \ 731.5 \text{ nm} + 1950 \text{ nm} \\
532 \text{ nm} + 803 \text{ nm} & \quad \text{SFG} \quad 320 \text{ nm} \\
532 \text{ nm} + 731.5 \text{ nm} & \quad \text{SFG} \quad 308 \text{ nm}
\end{align*}
\]

\[
\sim 900 \text{ mJ} \ 1064 \text{ nm} \quad \text{120} - 150 \text{ mJ} \ 803 \text{ nm} \quad \sim 200 \text{ mJ} \ \text{UV} \ 320 \text{ nm}
\]
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 $\geq$1 J/cm² for most beams
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.
**Nd:YAG Pump Laser**

*Summary of Technical Approach*

An all solid-state diode-pumped laser transmitter featuring:

<table>
<thead>
<tr>
<th>Feature</th>
<th>Description</th>
</tr>
</thead>
<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 µm 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>
</table>
Single Frequency Laser Ring Laser Design

Optical Schematic

Design Features

- 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
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
- Incident Angle: 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)
- Pump faces uncoated (~10% loss)
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
$M^2 \approx 2$
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>$M^2$</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>
</table>

**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

\[ M^2_x = 2.5, \quad M^2_y = 2.5, \]

\[ \text{M}^2 \text{ data} \]
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.

Single Power Supply Module

Control electronics
• 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