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, (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: \( \geq 200 \text{ mJ} \)
  - Pulsewidth: \( 10 - 25 \text{ ns} \)
  - PRF: \( 50 \text{ Hz} \)
- 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

\[
\begin{align*}
\text{Nd:YAG Pump Laser} & \quad \tau_{\text{pulse}} = 10 - 20 \text{ ns} \\
2\omega & \quad \text{KTP} \\
120 - 150 \text{ mJ} & \quad 803 \text{ nm} \\
> 200 \text{ mJ} & \quad 532 \text{ nm} \\
\sim 200 \text{ mJ UV} & \quad 320 \text{ nm} \\
\omega_1 + \omega_2 & = \omega_3 \\
1064 \text{ nm} & \quad \text{SHG} \\
532 \text{ nm} & \quad \text{OPO} \\
532 \text{ nm} + 803 \text{ nm} & \quad \text{SFG} \\
532 \text{ nm} + 731.5 \text{ nm} & \quad \text{SFG} \\
532 \text{ nm} + 803 \text{ nm} + 1576 \text{ nm} & \quad 731.5 \text{ nm} + 1950 \text{ nm} \\
532 \text{ nm} + 731.5 \text{ nm} & \quad 320 \text{ nm} \\
532 \text{ nm} + 731.5 \text{ nm} & \quad 308 \text{ nm}
\end{align*}
\]
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$1 J/cm$^2$ 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
**Nd:YAG Pump Laser**  
-Summary of Technical Approach-

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

- **Injection seeded ring laser**  
  Improves emission brightness ($M^2$)

- **Diode-pumped zigzag slab amplifiers**  
  Robust and efficient design for use in space

- **Advanced E-O phase modulator material**  
  Allows high frequency cavity modulation for improved stability injection seeding

- **Alignment insensitive / boresight stable 1.0 $\mu$m cavity and optical bench**  
  Stable and reliable operation over environment

- **Conduction cooled**  
  Eliminates circulating liquids w/in cavity

- **Space-qualifiable component designs**  
  Establishes a path to a space-based mission
Single Frequency Laser Ring Laser Design

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
Near Brewster (57°)
100% at full 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)
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%

Second Stage Amplifier

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>
</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.**
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

$M_x^2 = 2.5, M_y^2 = 2.5,$
• 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.