Spaceborne Laser Technology for Lidar Remote Sensing

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Outline

- Laser requirement for Lidar remote sensing
- History of spaceborne laser
- Design of spaceborne solid-state laser
- Examples of developing spaceborne laser
- Laser components in space environment
- Conclusion
Outline

- Laser requirement for Lidar remote sensing
- History of spaceborne laser
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- Conclusion
Application of Spaceborne laser

Application of Space Laser

Earth observation with Lidar
• Aerosol and dust
• Cloud
• Atmospheric composition
• Atmospheric dynamics
• Earth topography

Space Science and Metrology
• Gravitational waves
• Cold atomic clock
• Optical clock
• Atom interferometer
• Time metrology

Space measurement and communication
• Deep space detection
• Laser communication
• Formation flying
• Rendezvous and docking
Application of Spaceborne laser

- Space laser interferometer
- Space laser ranging
- Formation flying
- Space laser communication
- Laser link for navigation
Application of Spaceborne laser

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Space Science and Metrology
- Gravitational waves
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Light Detection And Ranging—Lidar

TRANSMITTER OPTICS

LASER

D

Atmospheric gases, clouds, aerosols, molecules

D

DETECTOR

RECEIVER OPTICS
Atmospheric Vertical profile

MSIS90 Temperature

Resonant Fluorescence From Metal Atoms
Rayleigh Scattering From Air Molecules
Mie Scattering From Aerosols

Range Determined From Time-of-Flight: \( R = c \cdot \Delta t / 2 \)
## Classification of Lidar

<table>
<thead>
<tr>
<th>Lidar Type</th>
<th>Principle</th>
<th>Values</th>
<th>Target</th>
</tr>
</thead>
<tbody>
<tr>
<td>Laser altimeter, Laser bathymetry</td>
<td>Back reflecting</td>
<td>Time</td>
<td>Topography, Depth</td>
</tr>
<tr>
<td>Doppler Lidar</td>
<td>Doppler</td>
<td>Frequency Shift</td>
<td>Wind speed</td>
</tr>
<tr>
<td>Different Absorption Lidar</td>
<td>Atomic, molecular absorption</td>
<td>Intensity</td>
<td>Atmospheric composition</td>
</tr>
<tr>
<td>Fluorescence Lidar</td>
<td>Fluorescence</td>
<td>Wavelength, Intensity</td>
<td>Atmospheric composition</td>
</tr>
<tr>
<td>Raman Lidar</td>
<td>Raman scattering</td>
<td>Wavelength, Intensity</td>
<td>Atmospheric composition, temperature</td>
</tr>
<tr>
<td>Mie Lidar</td>
<td>Mie Scattering</td>
<td>Intensity</td>
<td>Aerosol, cloud</td>
</tr>
<tr>
<td>Rayleigh Lidar</td>
<td>Rayleigh Scattering</td>
<td>Intensity</td>
<td>Temperature, molecule density</td>
</tr>
</tbody>
</table>
Cross-section of different principle

- **Mie Scattering**
- **Atomic Fluorescence**
- **Molecular Absorption**
- **Rayleigh Scattering**
- **Raman Scattering**

### Rayleigh
\[
\frac{d\sigma}{d\Omega} = \sigma_R \propto \frac{1}{\lambda^4}
\]

### Resonance Fluorescence
\[
\frac{d\sigma}{d\Omega} = \frac{\sigma_{\text{eff}}}{4\pi} = \frac{\int_{-\infty}^{+\infty} \sigma_{\text{abs}}(\nu, \nu_0) \cdot g_L(\nu, \nu_L) \, d\nu}{4\pi}
\]
Spaceborne Lidar for Earth Observation

- Spaceborne Lidar is the lidar operated at space platform, such as satellite, space station, space shuttle.

- Spaceborne Lidar is used to remote sensing the properties of earth’s atmosphere, surface, ocean, et.al.
Spaceborne Lidar

- Spaceborne lidar needs receive enough return power and enough ratio of signal to noise to retrieve information of earth.
- Cross-section, laser power and receiver’s area is closely relative to Lidar’s return.

1. L. Bonino, Lidar concepts for space applications, Thales Alenia Space Italy
## Classification of Lidar

<table>
<thead>
<tr>
<th>Lidar Type</th>
<th>Principle</th>
<th>Values</th>
<th>Target</th>
</tr>
</thead>
<tbody>
<tr>
<td>Laser altimeter, Laser bathymetry</td>
<td>Back reflecting</td>
<td>Time</td>
<td>Topography, Depth (very shallow)</td>
</tr>
<tr>
<td>Doppler Lidar</td>
<td>Doppler</td>
<td>Frequency Shift</td>
<td>Wind speed</td>
</tr>
<tr>
<td>Different Absorption Lidar</td>
<td>Atomic, molecular absorption</td>
<td>Intensity</td>
<td>Atmospheric composition</td>
</tr>
<tr>
<td><strong>Fluorescence Lidar ?</strong></td>
<td>Fluorescence</td>
<td>Wavelength, Intensity</td>
<td>Gas composition Mesosphere</td>
</tr>
<tr>
<td>Raman Lidar</td>
<td>Raman scattering</td>
<td>Wavelength, Intensity</td>
<td>Atmospheric composition, temperature</td>
</tr>
<tr>
<td>Mie Lidar</td>
<td>Mie Scattering</td>
<td>Intensity</td>
<td>Aerosol, cloud</td>
</tr>
<tr>
<td>Rayleigh Lidar</td>
<td>Rayleigh Scattering</td>
<td>Intensity</td>
<td>Temperature, molecule density</td>
</tr>
</tbody>
</table>
What’s requirement of space laser for different Lidar?
**Backscattering Spaceborne Lidar (direct detection)**

1. Backscattering Lidar – Aerosol, molecule optical thickness, cloud top height, and optical thickness
2. Laser requirement: high energy, 2~3 wavelengths

**CALIPSO**

**Cloud**

**Aerosol**
Backscattering Spaceborne Lidar

- High spectrum resolution Lidar
Laser requirement of space HRSL Lidar

\[ P(R) = P_0 \frac{c \tau}{2} AK \frac{G(R)}{R^2} [\beta_a(R) + \beta_M(R)] \exp \left[ -2 \int_{r_0}^{r} \left[ \alpha_a(R') + \alpha_M(R') \right] dR' \right] \]

Laser requirement for HSRL:
- Single frequency with narrow linewidth
- Frequency stability: ~ 20 MHz
- High energy: ~ 100 mJ
- Two wavelengths
Doppler Lidar: Wind

- Direct direction measurement: ALADIN
- Coherent measurement
Laser requirement of space Doppler Lidar

- **Laser for Doppler wind Lidar**
  - Single frequency, narrow linewidth
  - Frequency stability: ~ 1 MHz
  - High pulse energy with middle repetition rate
  - Usually in UV or 2 micrometer

Mie detection with Fizeau Filter

Molecule detection with double FP filter
Spaceborne DIAL Lidar
Laser requirement of space DIAL Lidar

**Laser for DIAL Lidar:**
- Exact single wavelength to match absorption line of molecule
- Usually two or multi-wavelengths
- Long term wavelength stability
- Narrow linewidth, such as CO2
- High spectrum purity
- High Energy with middle repetition rate
Spaceborne topography Lidar

- From single beam to multi-beam
- From analog detection to photon counting
Laser requirement for topography Lidar

- **Analog detection:**
  - Pulse energy: ~ 70 mJ
  - Pulse width: ~7 ns
  - Repetition rate: < 100 Hz

- **Photon counting:**
  - Narrow pulse width: < 1 ns
  - High repetition rate: ~10 kHz
  - Low pulse energy: 0.1~ 1 mJ
Requirement of laser for Earth Observation Lidar

- **HSRL Lidar**
  - Frequency Stability

- **DIAL Lidar**
  - Narrow LineWidth

- **Doppler Lidar**
  - Single Frequency

- **Laser altimeter**
  - Pulsed
  - High repetition Rate

- **CO2, CH4**
  - 2051nm
  - Frequency stable, narrow linewidth, pulsed OPO, OPA
  - Or Frequency stable 2μ solid-state laser

- **Aerosol, cloud**
  - 1645 nm

- **Topography**
  - 1572 nm
  - Single frequency, frequency stable pulsed Nd: YAG laser

- **Ocean Mix layer**
  - 1064 nm

- **Wind**
  - 532 nm
  - High Repetition rate, narrow pulse width solid-state of fiber laser

- **Doppler Lidar**
  - 355 nm

- **Laser altimeter**
## Typical Requirement of space laser for Earth Observation

<table>
<thead>
<tr>
<th>Sensor</th>
<th>Application</th>
<th>Parameters of laser</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Imaging Lidar</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Earth Imaging</td>
<td>Wavelength: 1 μm, Pulse energy: &gt; 150 mJ, PRF: 1~40 Hz</td>
<td></td>
</tr>
<tr>
<td>Planetary Imaging</td>
<td>Wavelength: 1 μm, Pulse energy: &gt; 50 mJ, PRF: 1~20 Hz</td>
<td></td>
</tr>
<tr>
<td>Topography</td>
<td>Wavelength: 1 μm, Pulse energy: &gt; 100 μJ, PRF: 5~10 kHz, Beam number: 1000</td>
<td></td>
</tr>
<tr>
<td><strong>Atmospheric Lidar</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Wind Detection</td>
<td>Wavelength: 0.35 μm, Single frequency, narrow linewidth, Pulse energy: &gt; 150 mJ, PRF: &gt; 100 Hz</td>
<td></td>
</tr>
<tr>
<td>Coherent Detection</td>
<td>Wavelength: 2.05 μm, Single frequency, narrow linewidth, Pulse energy: &gt; 1 J, PRF &gt; 50 Hz</td>
<td></td>
</tr>
<tr>
<td>Backscattering</td>
<td>Wavelength: 0.35 μm, 0.5 μm, 1.0 μm, Single frequency, Pulse energy: &gt; 100 mJ, PRF: 20~50 Hz</td>
<td></td>
</tr>
<tr>
<td>(Cloud, aerosol)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>DIAL CO₂</td>
<td>Wavelength: 1.57 μm / 2.05 μm, Frequency stability: &lt; 0.3 MHz, Pulse energy: &gt; 50 mJ, PRF: &gt; 50 Hz</td>
<td></td>
</tr>
<tr>
<td>CH₄</td>
<td>Wavelength: 1.65 μm, Frequency stability: &lt; 0.9 MHz, Pulse energy: &gt; 20 mJ, PRF: &gt; 50 Hz</td>
<td></td>
</tr>
</tbody>
</table>
Outline

- Laser requirement for Lidar remote sensing
- **History of spaceborne laser**
- Design of spaceborne solid-state laser
- Examples of developing spaceborne laser
- Laser components in space environment
- Conclusion
History of spaceborne lidar

- Spaceborne lidar has a history more than 40 years.
- Up to now, almost all spaceborne lidar used solid-state laser.
History of spaceborne laser

Apollo 15 Laser altimeter (USA, 1971)

- **Moon explorer**

Lamp Pumped Ruby laser
- Wavelength: 694.3 nm
- Pulse energy: 200 mJ
- Pulse width: 10 ns
- Pulse repetition rate: 3.75/min.

Clementine laser altimeter (USA, 1994)

- **Moon explorer**

Diode pumped Nd:YAG
- Wavelength: 1064 nm
- Q-switch: LiNbO₃
- Pulse energy: 171 mJ
- Pulse width: 8 ns
- PRF: 1-8 Hz

History of spaceborne laser

**Diode Pumped Nd:YAG**
- Q-switch: LiNbO$_3$
- Wavelength: 1064 nm
- Pulse energy: 100 mJ
- Pulse width: 15 ns
- PRF: 1 Hz

**SELENE Laser altimeter (Japan, 2007)**
Moon explorer

**Diode Pumped Nd:YAG**
- Q-switch: KD*P
- Wavelength: 1064 nm
- Pulse energy: 150 mJ
- Pulse width: 7ns
- PRF: 1 Hz

**CE-1 Laser altimeter (China, 2007)**
Moon explorer

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History of spaceborne laser

LLRI laser Altimeter (India, 2008)

Moon explorer

- Diode pumped Nd:YAG
  - Q-switch: Actively, LiNbO3
  - Pulse Energy: 10 mJ
  - Pulse energy: 2 ns
  - PRF: 10 Hz

LOLA laser Altimeter (USA, 2008)

Moon explorer

- Diode pumped Nd:YAG
  - Q-switch: Passively, Cr:YAG
  - Pulse energy: 2.7 mJ
  - PRF: 28 Hz
  - Five beams

History of spaceborne laser

Diode Pumped Nd:YAG
- Q-switch: Active, LiNbO3
- Pulse Energy: 42mJ
- Pulse Energy: 8 ns
- PRF: 10 Hz

Diode pumped Nd:YAG
- Q-switch: Passive, Cr:YAG
- Pulse energy: 20 mJ
- PRF: 8 Hz

MOLA Mars Laser altimeter (USA, 1996)
Mars explorer

Mercury Laser altimeter (USA, 2004)
Mercury Explorer

Lidar for earth observation

- The Lidar In-space Experiment (LITE), flown on the Space Shuttle in 1994, demonstrated the ability of lidar to measure the vertical distributions of clouds and aerosols.

A deep layer of biomass smoke (light blue) is seen under multiple cirrus layers (white) in this LITE data taken over southwest Africa.

The lidar penetrates upper level clouds to reveal lower level cloud structure, as shown in this data from the Pacific Ocean.

- LITE is first lidar to observe atmosphere of earth on space shuttle; Milestone
- It run only 21 days. It was a successful demonstration of lidar for earth remote sensing.
- **Lamp pumped** Nd:YAG at 1064 nm, 532 nm, and 355 nm
Lidar for earth observation

- Output 1064 nm, 532 nm, 355 nm
- Folded cavity with porro prism, actively Q-switched
- MOPA
- Lamp pumped
- SHG and THG
History of spaceborne laser

GLAS - Laser altimeter
Diode pumped, Passive Q-switch, MOPA Nd:YAG
- Wavelength: 1064 nm & 532 nm
- Pulse energy: 75 mJ @ 1064 nm
  35 mJ @ 532 nm
- Pulse width: < 10 ns
- PRF: 40 Hz

CALIPSO – backscattering Lidar
Diode pumped, EO Q-switched Nd:YAG
- Wavelength: 1064 nm & 532 nm
- Pulse energy: 110 mJ @ 1064 nm
  110 mJ @ 532 nm
- PRF: 20 Hz

## Lunched spaceborne laser (Laser altimeter)

<table>
<thead>
<tr>
<th>Sensor</th>
<th>year</th>
<th>Laser specification</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Earth</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>SLA-01</td>
<td>1996</td>
<td>Nd:Cr:YAG, 40 mJ, 10 ns, 10 Hz, 1064 nm</td>
</tr>
<tr>
<td>SLA-02</td>
<td>1997</td>
<td>Nd:Cr:YAG, 40 mJ, 10 ns, 10 Hz, 1064 nm</td>
</tr>
<tr>
<td>MPL/DS2</td>
<td>1999</td>
<td>lost</td>
</tr>
<tr>
<td>Icesat/GLAS</td>
<td>2003</td>
<td>Nd:YAG, 74 mJ/35 mJ, 5 ns, 40 Hz, 1064 nm/532 nm</td>
</tr>
<tr>
<td><strong>Moon</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>clementine</td>
<td>2004</td>
<td>Nd:Cr:YAG, 170 mJ, 10 ns, 1 Hz, 1064 nm</td>
</tr>
<tr>
<td>SELENE/LALT</td>
<td>2007</td>
<td>Nd:YAG, 100 mJ, 15 ns, 1 Hz, 1064 nm</td>
</tr>
<tr>
<td>CE-1</td>
<td>2007</td>
<td>Nd:YAG, 150 mJ, 7 ns, 1 Hz, 1064 nm</td>
</tr>
<tr>
<td>Chandrayaan/LLR</td>
<td>2007</td>
<td>Nd:YAG, 10 mJ, 10 Hz, 1064 nm</td>
</tr>
<tr>
<td>LOLA</td>
<td>2009</td>
<td>Nd:YAG, 2.7 mJ, 7 ns, 28 Hz, 1064 nm, 5 beams</td>
</tr>
<tr>
<td>CE-2</td>
<td>2010</td>
<td>Nd:YAG, 75 mJ, 7 ns, 3 Hz, 1064 nm</td>
</tr>
<tr>
<td>CE-3</td>
<td>2013</td>
<td>Nd:YAG, 45 mJ, 7 ns, 5 Hz, 1064 nm</td>
</tr>
<tr>
<td><strong>Mars</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>MOLA 1</td>
<td>1992</td>
<td>Lost</td>
</tr>
<tr>
<td>MOLA 2</td>
<td>1996</td>
<td>Nd:Cr:YAG, 42 mJ, 8 ns, 10 Hz, 1064 nm</td>
</tr>
<tr>
<td><strong>Mercury</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Messenger/MLA</td>
<td>2004</td>
<td>Nd:Cr:YAG, 20 mJ, 8 ns, 8 Hz, 1064 nm</td>
</tr>
<tr>
<td><strong>Mercury</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Bepicolombo</td>
<td>TBD</td>
<td>actively Q-switched, diode laser pumped Nd:YAG, 50 mJ, 3<del>8 ns, 1</del>10 Hz</td>
</tr>
</tbody>
</table>
# Lunched spaceborne laser (Lidar)

<table>
<thead>
<tr>
<th>Earth</th>
<th>Mission</th>
<th>Agency</th>
<th>Year</th>
<th>Laser Configuration</th>
<th>Details</th>
</tr>
</thead>
<tbody>
<tr>
<td>LITE</td>
<td>NASA</td>
<td>1994</td>
<td>Nd:Cr:YAG 1064 nm/532 nm/355 nm</td>
<td>Lamp pumped</td>
<td></td>
</tr>
<tr>
<td>BALKAN</td>
<td>Russia</td>
<td>1995</td>
<td>Nd:Cr:YAG, 1064 nm/532 nm</td>
<td>lamp pumped</td>
<td></td>
</tr>
<tr>
<td>GLAS</td>
<td>NASA</td>
<td>2003</td>
<td>Nd:YAG, 74 mJ/35mJ, 5 ns, 40 Hz, 1064 nm/532 nm</td>
<td></td>
<td></td>
</tr>
<tr>
<td>CALIPSO</td>
<td>NASA</td>
<td>2006</td>
<td>Nd:YAG, 110 mJ@1064 nm &amp; 532 nm</td>
<td>20Hz</td>
<td></td>
</tr>
<tr>
<td>ALADIN</td>
<td>ESA</td>
<td>TBD</td>
<td>Single frequency Nd:YAG, 150 mJ @355 nm, 100 Hz</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Mars</td>
<td>Phoenix</td>
<td>NASA</td>
<td>2007</td>
<td>Nd:YAG, 30 mJ, 15 ns, 1 Hz, 1064 nm, 532 nm</td>
<td></td>
</tr>
</tbody>
</table>
# Lunched spaceborne laser (Others)

<table>
<thead>
<tr>
<th>Application</th>
<th>Sensors</th>
<th>year</th>
<th>Parameters of laser</th>
</tr>
</thead>
<tbody>
<tr>
<td>Laser Communication</td>
<td>SILEX/ESA</td>
<td></td>
<td>AlGaAs Diode laser, 847 nm/819 nm, 100 mw</td>
</tr>
<tr>
<td></td>
<td>TerraSAR-X</td>
<td>2007</td>
<td>Nd:YAG+fiber amplifier, 1064 nm, 1.2 W, SLM</td>
</tr>
<tr>
<td></td>
<td>ALphsat and</td>
<td>2013</td>
<td>Nd:YAG + fiber amplifier, 1064 nm, 2.5 W, SLM</td>
</tr>
<tr>
<td></td>
<td>Sentine 1+2</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>LLCD</td>
<td>2013</td>
<td>Er:Fiber, 0.5 W, 1550 nm</td>
</tr>
<tr>
<td>RVD Lidar</td>
<td>ETS-VII</td>
<td>1998</td>
<td>Laser diode</td>
</tr>
<tr>
<td></td>
<td>XSS-11</td>
<td>2005</td>
<td>Cr,Nd:YAG, 1064 nm, 10 kHz, 1 ns,</td>
</tr>
<tr>
<td>Gravitational-Wave</td>
<td>LISA, eLISA</td>
<td>TBD</td>
<td>NPRO Nd:YAG</td>
</tr>
<tr>
<td>Cold atomic clock</td>
<td>PHARAO</td>
<td>TBD</td>
<td>Cs stabled 852 nm, diode laser</td>
</tr>
<tr>
<td></td>
<td>CCAC</td>
<td>2016</td>
<td>Rb stabled 780 nm, diode laser</td>
</tr>
<tr>
<td></td>
<td>CAL</td>
<td>TBD</td>
<td>Rb, K, 780 nm, 852 nm, 767 nm, Diode laser or Frequency doubled Fiber laser (1560 nm or 1534 nm)</td>
</tr>
</tbody>
</table>
More than 30 solid-state lasers were launched into space for lidar measurement.

Performance of CALIPSO’s laser

- Folded Porro cavity
- Diode side pumped SLAB
- KD*P Q-switch
- KTP frequency doubled
- Operated in air sealed container
Performance of CALIPSO’s laser
Performance of MLA’s laser

- Linear Porro cavity oscillator + power amplifier
- Cr:YAG passively Q switched
- Side pumped SLAB for oscillator and amplifier
- Operated in vacuum
Performance of MLA’s laser

Mercury laser altimeter form 2011

Performance of GLAS’s laser

- Linear hemi-porro cavity
- Cr:YAG passively Q-switched
- Double pass Pre-amplifier + power amplifier
- Side pumped SALB
- Frequency doubled
- Operated in vacuum
Performance of GLAS’s laser

Near Future Mission

✓ ALADIN in ADM (ESA)
  – It will be the **first Doppler Lidar** in the world
  – An UV, single frequency pulsed laser (Frequency trebled Nd:YAG)

✓ ATLID in EarthCARE (ESA)
  – It will be the **first high spectrum resolution Lidar**
    to measure atmospheric molecule and high altitude cloud
  – An UV, single frequency pulsed laser (laser (Frequency trebled Nd:YAG)
ALADIN’s laser

- Injection Seeding, MOPA
- Folded linear cavity
- Double pre-amplifier+ power amplifier
- Sided pumped SLAB
- Frequency trebled
- Operated in vacuum? Or with O2 to avoid optics damage

1. UV CHARACTERIZATION OF ENGINEERING QUALIFICATION MODEL OF ALADIN LASER TRANSMITTER INTERNATIONAL CONFERENCE ON SPACE OPTICS 2006
ATLID’s laser

- Similar design with ALADIN with modified cooling system and structure
- Operated in sealed air pressurized environment

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Type</td>
<td>Solid-state laser</td>
<td>Frequency jitter</td>
<td>&lt; 10 MHz rms Aladin TXA</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>&lt; 50 MHz rms Atlid TxA</td>
</tr>
<tr>
<td>Laser cooling</td>
<td>Conductively, via cold plate</td>
<td>Output beam diameter</td>
<td>&lt; 7.5 mm Aladin TXA</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>&lt; 16 mm Atlid TxA</td>
</tr>
<tr>
<td>Emission wavelength</td>
<td>355 nm</td>
<td>Output beam divergence</td>
<td>&lt; 0.4 mrad full angle Aladin TXA</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>&lt; 0.3 mrad full angle Atlid TxA</td>
</tr>
<tr>
<td>Pulse energy</td>
<td>120 mJ Aladin TXA</td>
<td>Pointing jitter</td>
<td>&lt; 0.04 mrad Aladin TXA</td>
</tr>
<tr>
<td></td>
<td>40 mJ Atlid TxA</td>
<td></td>
<td>&lt; 0.02 mrad Atlid TxA</td>
</tr>
<tr>
<td>Pulse repetition rate</td>
<td>51 Hz</td>
<td>Output wavelength tunable</td>
<td>± 7.5 GHz Aladin TXA</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>± 5 GHz Atlid TxA</td>
</tr>
<tr>
<td>Pulse width</td>
<td>20 ns at 355 nm</td>
<td>Lifetime in space</td>
<td>39 months</td>
</tr>
<tr>
<td>Spectral width (FWHM)</td>
<td>&lt; 50 MHz</td>
<td>Total laser pulses</td>
<td>5 Giga-shots</td>
</tr>
</tbody>
</table>

Alberto Cosentino, Alessandro D’Ottavi, Adalberto Sapia, Enrico Suetta, Spaceborne Lasers Development for ALADIN and ATLID Instruments, IGARSS 2012
Bright future of spaceborne laser

✔ NASA, ESA and China are developing spaceborne lidar to sound atmospheric aerosol, cloud, composition, wind, etc.

✔ In the next decades, there are several lidars to be launched into space.

✔ Reliability and lifetime of spaceborne laser has been improved greatly during past 40 yrs.

✔ Laser is still a great challenge for spaceborne lidar.
Outline

- Application of Lidar remote sensing
- History of spaceborne Laser
- **Design of spaceborne solid-state Laser**
- Examples of developing spaceborne laser
- Laser Components in Space Environment
- Conclusion
Special characteristics of spaceborne laser

✓ Compact, robust;
✓ high efficiency and conductively cooling;
✓ Long lifetime under space environment (vacuum, radiation, Temperature);
✓ High beam point stability after vibration, TVAC testing, and it is most important for lidar, especially.
Typical Lasers for Space Application

- Most launched spaceborne lasers are **solid-state lasers**.
- Solid-state laser has merits of **electronically droved, compact**.
- Solid-state laser is divided into:
  - Diode pumped buck solid-state laser (Rod, Slab)
  - Fiber laser and fiber laser amplifier

**thermal lens & thermal stress-induced birefringence**

**reduced thermo-optical distortions**
Design items of spaceborne laser

- Requirement analysis
- Scheme design and optics simulation
- Structure design and mechanical analysis
- Thermal design and simulation
- Driver electronics design
- Reliability design
- Test and validation
Concept of Solid-state laser

Different Lidar requires different options:
① Oscillator only (CW, QCW, pulsed)
② Oscillator + Amplifier
③ Single frequency
④ Other wavelengths by nonlinear converter.
Typical Solid-state Laser -1

Buck Oscillator

Fiber Oscillator
Typical Solid-state Laser-2

Fiber Amplifier

Master Oscillator Power Amplifier (MOPA) with single frequency and SHG

Design of solid-state laser (1)--Oscillator

**Optical Resonator**
- 1. Cavity Length
- 2. Mode Size
- 3. Cavity Stability
- 4. Output Coupling

**Gain medium**
- ✓ 1. Gain Material
- ✓ 2. Pump Volume in Gain Medium
- ✓ 3. Pump Coupling Scheme Heat Removal
- ✓ 4. Intracavity Thermal Lensing
- ✓ 5. Thermal Lensing Compensation

1. System Efficiency
2. Output Energy
3. Beam Quality
4. Single Frequency
Design of solid-state laser (1)--Oscillator

• Modeling & Simulation

Optical Resonator
- Modeling & Software (ie. LASCAD, GLAD)
  - Resonator Configuration
  - Thermal Effect

Gain Medium
- Ray Tracing (ie. Zemax)
  - Thermal Analysis (ie. ANSYS)
  - Thermo-Optic Effects
  - Data Process (ie. MATLAB)

Laser Output
- Energy
- Beam Quality
- Single Frequency
Design of Oscillator--Cavity

Folded or linear cavity with cross Porro prism (LOLA, Clementine, Messenger—MLA)

\[ R = M_{prp}^e M_{prp} = \cos^2\left(\frac{P}{2}\right) + \sin^2\left(\frac{P}{2}\right)\cos^2(2\beta) \]

Design of Oscillator-- Cavity

Compact linear cavity (CE-1, Selene, Bepicolombo)

Design of Oscillator- Cavity

- Ring cavity with injection seeding.
- It is designed for single frequency laser typically, such as Doppler lidar, high spectral resolution Lidar.

Design of Oscillator-- Q-switch

Space laser is usually operated in pulse mode, therefore it has a Q-switcher to get huge pulse.

a. During pumping duration, Q of cavity is low;
b. Just after pumping, the population of inversion is maximum, then Q-switcher is opened;
c. Q of cavity is increased immediately;
d. The energy is released in a short time.
e. Huge laser pulse is generated with a pulse width around several ten ps to several hundred ns.
Design of Oscillator-- Q-switch

✓ Actively Q-switching:
  – EO Q-switcher with LiNbO3, KD*P, RTP.
  – AO Q-switcher is rarely used due to higher power consumption.

✓ Passively Q-switching:
  – Cr4+:YAG is widely used.

<table>
<thead>
<tr>
<th></th>
<th>KD*P</th>
<th>LN</th>
<th>RTP</th>
<th>BBO</th>
<th>LGS</th>
</tr>
</thead>
<tbody>
<tr>
<td>KD2PO4</td>
<td>LiNBO3</td>
<td>RTP</td>
<td>RbTiOPO4</td>
<td>β-BaB2O4</td>
<td>La3Ga5SiO14</td>
</tr>
<tr>
<td>Wavelength (µm)</td>
<td>0.2~1.6</td>
<td>0.42~5.2</td>
<td>0.35~4.5</td>
<td>0.19~3.5</td>
<td>0.24~2.4</td>
</tr>
<tr>
<td>Electro-optic coefficient (pm/V)</td>
<td>r_{63}=26.4</td>
<td>r_{33}=32, r_{31}=10, r_{22}=6.8</td>
<td>r_{33}=38.5 (Y), r_{33}=35, r_{23}=12.5, r_{13}=10.6 (X)</td>
<td>r_{22}=2.7</td>
<td>r_{11}=2.3, r_{41}=1.8</td>
</tr>
<tr>
<td>Damage threshold (GW/cm²)</td>
<td>0.5</td>
<td>0.1</td>
<td>2.5</td>
<td>1.5</td>
<td>&lt;1</td>
</tr>
<tr>
<td>Extinction Ratio</td>
<td>1000:1</td>
<td>&gt;400:1</td>
<td>&gt;100:1</td>
<td>&gt;500:1</td>
<td>&gt;100:1</td>
</tr>
</tbody>
</table>
Design of Oscillator-- Q-switch

Actively Q-Switch rate equation

\[ \frac{dN}{dt} = -\gamma \sigma c N \phi, \]
\[ \frac{d\phi}{dt} = \frac{2 \sigma l N \phi}{t_1} - \phi \frac{t_1}{t_c} \]

\[ N_0 = \frac{P t_p \alpha \epsilon \chi \eta}{V h \nu} \]

\[ \eta = [1 - \exp(-t_p/t_{spon})] t_{spon}/t_p, \]
\[ L = 2 \sigma l + \ln \left( \frac{1}{\prod_i T_i^2} \right) \]
\[ L(t) = L[1 + \exp(-t/\tau)], \]

P : peak pump power
Tp: Pump duration
\( \alpha \): absorbed fraction,
X: pump coupling efficiency
\( \chi \): quantum efficiency
hu: photon energy
V : volume of laser crystal
Design of Oscillator-- Q-switch

Passively Q-Switch rate equation

\[
\frac{dn}{dt} = -\gamma \sigma c n \phi \\
\frac{d\phi}{dt} = \left[2\sigma l_{slab} n - 2\sigma_{gs} n_{gs} l_{pcs} - \left(\text{loss}_{\text{cav}} + \ln \left(\frac{1}{R}\right)\right)\right] \frac{\phi}{t_r} \\
\frac{dn_{gs}}{dt} = -\sigma_{gs} c \phi n_{gs} \\
\frac{dn_{es}}{dt} = \sigma_{es} c \phi n_{es}
\]

\[
T_{\text{opt}} = G_0 \frac{\phi_{\text{opt}}}{1-\delta}, \quad \phi_{\text{opt}} = \frac{1}{1 - \frac{1}{\rho_{\text{opt}} \left(1 - e^{-\rho_{\text{opt}}}ight)}} \\
R_{\text{opt}} = G_0^{-\psi_{\text{opt}}}, \quad \psi_{\text{opt}} = 2 \left[1 - \frac{L}{2 \ln G_0} - \frac{\phi_{\text{opt}}}{1 - \delta}\right] \\
E_{\text{opt}} = \frac{h \nu A \ln(G_0)}{\gamma \sigma} \frac{\rho_{\text{opt}} \psi_{\text{opt}}}{2} = F_{\text{sat}} \ln(G_0) A \frac{\rho_{\text{opt}} \psi_{\text{opt}}}{2}
\]

Design of Solid-state Amplifier

Consideration

- Efficiency, Energy Storage & Exaction Efficiency
  - Thermo-optic Effects
  - Optical-damage Threshold
  - SE & ASE

Design Contents

- Gain Medium
- Pump Design
- Cooling Systems
- Compensation Systems

Optimum Design: High Efficiency & Beam Quality
Design Model of Amplifier

- Diode operating parameters
  - Current pulse length
  - Prf pulse length
- Diode spectrum of ensemble of arrays
  - Center λ shifts 0.3 nm/°C
- Diode - slab transmission efficiency
- Nd absorption spectrum
- Convolve diode and Nd spectra vs T
- Pump absorption efficiency
- Gain and extraction model
- Slab and beam path parameters
  - Emission cross section
  - Fluorescence lifetime
  - Zig-zag geometry

- Losses
  - Stored energy
  - Fluorescence
  - Slab thermal load
  - Gain
  - Extraction efficiency
- 3D finite element slab model
  - Slab fracture limit
  - Slab temperature profile
  - Slab stress distribution
  - Stress safety factor
- Ray trace dn/dT dL/dT stress optic coefficients

- Thermal OPD
- Thermal birefringence
Characters of the amplifiers

The Predicated Output Energy $E_{out}$

$$E_{out} = E_{sat} A \cos(\theta) f(2 - f) \times \ln \left\{ 1 + \left[ \exp \left[ \frac{E_{in}}{AE_{sat} \cos(\theta) f(2 - f)} \right] - 1 \right] \exp \left[ \frac{E_{stored}}{AE_{sat} \cos(\theta)} \right] \right\}$$

- $E_{in}$ - the input signal energy,
- $A$ - the active cross sectional area of the zig-zag slab,
- $\theta$ - the complementary angle,
- $f_{eff}$ - the effective overlap factor
- $E_{stored}$ - the stored energy
Efficiency - Energy Storage

The Stored Energy

\[ E_{stored} = \eta_a \eta_t \eta_s \eta_{qd} \eta_c \eta_q \eta_{spon} E_{LD} \]

- \( \eta_a \) Absorption efficient of slab
- \( \eta_t \) Transfer efficient from diode to slab
- \( \eta_s \) Store efficient
  \[ \eta_s = \frac{1 - \exp(-t_p/\tau)}{t_p/\tau} \]
- \( \eta_{qd} \) Stokes efficient
- \( \eta_c \) Overlap efficient between laser mode and laser medium
- \( \eta_q \) Quantum efficient
Efficiency - Energy Extraction

◆ The output fluence of a solid-state power amplifier:

\[ F_{\text{out}} = \eta_{\text{overlap}} F_{\text{sat}} \times \ln\left\{ 1 + \left[ e^{F_{\text{in}} / F_{\text{sat}}} - 1 \right] e^{g_{0}l_{\text{eff}}} \right\} \]

- \( \eta_{\text{overlap}} \) - the spatial mode-overlap efficiency,
- \( F_{\text{out}} \) - the output fluence,
- \( F_{\text{in}} \) - the input signal fluence,
- \( l_{\text{eff}} \) - the signal optical path length.

➤ The extraction efficiency:

\[ \eta = \eta_{\text{overlap}} \frac{F_{\text{out}} - F_{\text{in}}}{F_{\text{sat}} g_{0}l_{\text{eff}}} \]

Limit of Energy Exaction: input signal fluence,
spatial mode-overlap efficiency,
pump energy & configuration
optical surface damage
Efficiency - Energy Extraction

- Diode pumped Nd:YAG ZigZag SLAB amplifier

Optical Efficiency

\[ \eta_{o-o} = \eta_{\text{transfer}} \eta_{\text{absorb}} \eta_{\text{quantum}} \eta_{\text{stokes}} \eta_{\text{store}} \eta_{\text{extraction}} \eta_{\text{overlap}} \]

14.5% 90% 90% 91% 76% 73% 50% 70%
Design of different wavelength output

\[ P = \varepsilon_0 \chi^{(1)} E + \varepsilon_0 \chi^{(2)} EE + \varepsilon_0 \chi^{(3)} EEE + \cdots , \]

\( \varepsilon_0 \): the permittivity of free space
\( \chi \): *the linear susceptibility representing* the linear response of the material.

✓ Second order nonlinearity \( \chi^{(2)} \)
  ➢ *Second harmonic generation*
  ➢ Sum- and Difference-Frequency Generation
  ➢ Parametric amplification

✓ Third order nonlinearity \( \chi^{(3)} \)
  ➢ *Third harmonic generation*
  ➢ Kerr effect
  ➢ Stimulated Raman Scattering
Design of Harmonic Generation

- Important factors:
  - Type I or Type II selection
  - Crystal selection
  - Damage threshold
  - Beam divergence

\[
\frac{P_{2\omega}}{P_{\omega}} = l^2 K \frac{P_{\omega}}{A}.
\]

\[
K = 2Z^3 \omega^2 d_{\text{eff}}^2.
\]

Type I \(d_{\text{eff}} = d_{14} \sin 2\phi \sin \Theta_m\).

Type II \(d_{\text{eff}} = d_{14} \cos 2\phi \sin 2\Theta_m\).

\(d_{\text{eff}}\) is the effective nonlinear coefficient
## Design of Harmonic Generation

<table>
<thead>
<tr>
<th>Crystal</th>
<th>Phase matching type</th>
<th>$d_{\text{eff}}$ (pm/V)</th>
<th>$\theta$ (deg)</th>
<th>$\Phi$ (deg)</th>
<th>Walk-off angle (mrad)</th>
<th>$\Delta\Phi/\Delta\theta$ (deg) $l = 1\text{cm}$</th>
<th>Temperature bandwidth (K) $l = 1\text{cm}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>LBO (SHG)</td>
<td>I</td>
<td>0.836</td>
<td>90</td>
<td>10</td>
<td>6.03</td>
<td>0.27/2.63</td>
<td>5.8-6.7</td>
</tr>
<tr>
<td>BBO (SHG)</td>
<td>I</td>
<td>2.01</td>
<td>22.9</td>
<td></td>
<td>55.8</td>
<td>0.021</td>
<td>37-51</td>
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<tr>
<td>BiBO (SHG)</td>
<td>I</td>
<td>3.00</td>
<td>168</td>
<td>90</td>
<td>27.55</td>
<td>0.04</td>
<td>1.3</td>
</tr>
<tr>
<td>KTP$_{gr}$ (SHG)</td>
<td>II</td>
<td>3.56</td>
<td>90</td>
<td>24.3</td>
<td>4.28</td>
<td>0.58/1.82</td>
<td>20</td>
</tr>
<tr>
<td>LBO (THG)</td>
<td>II</td>
<td>0.52</td>
<td>44.4</td>
<td>90</td>
<td>9.5</td>
<td>0.79/0.16</td>
<td>6</td>
</tr>
<tr>
<td>BBO (THG)</td>
<td>I</td>
<td>2.01</td>
<td>31.4</td>
<td></td>
<td>72.24</td>
<td>0.011-0.015</td>
<td>16</td>
</tr>
<tr>
<td>BiBO (THG)</td>
<td>I</td>
<td>3.9</td>
<td>145.7</td>
<td>90</td>
<td>68.6</td>
<td>0.051/0.024</td>
<td>0.9</td>
</tr>
</tbody>
</table>

Ciapponi Alessandra, Riede Wolfgang, Tzeremes Georgios, etc. Non-linear optical frequency conversion crystals for space applications ,Proc. SPIE 7912, Solid State Lasers XX: Technology and Devices, 791205
Design of Parametric Oscillators

\[
\frac{1}{\lambda_p} = \frac{1}{\lambda_s} + \frac{1}{\lambda_i},
\]

\[
\frac{n_p}{\lambda_p} - \frac{n_s}{\lambda_s} - \frac{n_i}{\lambda_i} = 0
\]

\[
\Delta k = k_p - k_s - k_i = 0
\]

- KTP/PPKTP
- KTA
- LN/PPLN
- PPLT
Other design of space laser

✓ Mechanics design:
  – Light weight and good stability;
  – lower stress deformation;
  – Pressured structure;
  – Good thermal conductivity

✓ Thermal controlling
  – Survive in a relative wide temperature range
  – Operate with stable output in a certain temperature range
Examples of mechanics and thermal design
Summary

- Type of cavity, Q-switcher, amplifier and new wavelength generation must be designed in detail.
- The performance of space laser must be estimated by numerical simulation;
- Mechanics and thermal controlling is also very important to manufacture space laser.

- Walter Koechner, *Solid-state laser engineering*
Outline

- Laser requirement for Lidar Remote Sensing
- History and Example of Spaceborne Laser
- Design of Spaceborne Solid-state Laser
- Examples of developing spaceborne laser
- Laser Components in Space Environment
- Conclusion
EXAMPLES

1. Solid-state laser at 1 μm
   a) Lasers for Chinese moon explorer, soft-landing: laser altimeter
   b) Single frequency, pulsed oscillator and power amplifier for lidar to remote sensing atmosphere: Doppler, DIAL, HSRL Lidar
   c) Nonlinear output: DIAL Lidar

2. Solid-state at 2 μm
Spaceborne lasers under developing in SIOM

- **Low power laser @ 1μm, 1.5μm**
  - Laser range finder: Low PRF, Low, Mid-energy
  - Laser imaging lidar: High PRF, Low energy
  - Laser communication: High PRF or CW

- **High energy laser @ UV, Green, IR**
  - Earth Observation Lidar: Multi-wavelength, High Energy
  - EO or passive Q-switched
  - Pulsed MOPA Fiber laser
  - Single mode Fiber laser
  - Single frequency SLAB MOPA
  - Nonlinear frequency
Example 1: Laser Sensors for Chinese moon explorer

- **Laser altimeter**: to measure the real time altitude during landing
- **Laser imaging lidar**: to scanning landing spot to confirm flat surface
- **Doppler Lidar**: to measure landing velocity
Solid-state Laser for CE-3 Altimeter

- **Configurations**
  - **Crystal**: Cr, Nd:YAG
  - **Cavity**: Linear, porro & plano mirror
  - **Pump head**: Φ4 × 45 mm with diode side pumping
  - **Q-switch**: actively, LiNbO3

- **Specification**
  - **Wavelength**: 1064.36 nm
  - **Energy**: 45mJ
  - **Energy stability**: 0.2mJ
  - **Pulse width**: 4.8ns@45mJ
    - 5.5ns@15mJ
  - **Repetition rate**: 2 Hz
  - **Beam divergence**: 0.9mrad
  - **Point stability**: X, y: 3.1μrad
  - **Weight**: 1.3kg
Solid-state Laser for CE-3 Altimeter
Principle of Imaging Lidar

- Two axis scanning with 16 beam simultaneously

16 beams
## Requirements of Laser for image lidar

- **Wavelength:** 1064nm ±2nm;  
- **Rise time 10～90%:** <4ns;  
- **Repetition rate:** 50 kHz;  
- **Pulse energy:** ≥80μJ@50 kHz;  
- **Energy stability:** ±5%;  
- **Beam divergence:** <1mrad;  
- **Point stability:** <50μrad;  
- **Dimension:** 228mm x 60mm x 215mm  
- **Weight:** <2.6kg  
- **Power:** Average: <20W

What kind of laser will be selected?

*Candidate*

- Passive Q-switched solid-state laser  
- AO Q-switched solid-state laser  
- Pulsed fiber laser amplifier
Selection of laser type

Case 1: Passive Q-switched Nd:YAG

Case 2: AO Q-switched Nd:YVO4

Case 3: Modulated Laser diode with fiber amplifier
Test Results of different lasers

**Passive Q-switch laser Nd:YAG Laser**
- High energy
- Low PRF less than 20 kHz, Low efficiency

**AO Q-switch Nd:YVO4**
- High PRF
- Middle efficiency, Low peak power and wider pulse width

**Fiber laser amplifier**
- High PRF, high efficiency
- Middle energy but enough
- Very robust and compact.
Results of fiber amplifier for imaging Lidar

Average power up to 4 W

Spectrum width of 0.9 nm

Pulse width of 7 ns

M2 <1.3
Single frequency laser for Doppler Lidar

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Specification</th>
</tr>
</thead>
<tbody>
<tr>
<td>Wavelength</td>
<td>1550nm±1nm</td>
</tr>
<tr>
<td>Linewidth of seeder</td>
<td>≤30kHz</td>
</tr>
<tr>
<td>RIN of seeder (30K~1MHz)</td>
<td>≤2×10⁻¹³/Hz</td>
</tr>
<tr>
<td>Local laser power</td>
<td>100~120µW</td>
</tr>
<tr>
<td>Output power</td>
<td>≥2W</td>
</tr>
<tr>
<td>Output fiber</td>
<td>3 local lasers, 3 transmitters</td>
</tr>
<tr>
<td>Weight</td>
<td>≤1.2kg</td>
</tr>
</tbody>
</table>

Linewidth < 9 kHz
Example 2: Single frequency, pulsed high energy solid-state laser for Atmospheric Lidar

✓ Laser for Lidar to remote sensing aerosol, wind or CO2.

✓ High energy, single frequency, narrow linewidth, middle repetition rate

✓ Configuration:
  – Injection Seeding, EO Q-switched oscillator
  – Multi-slab power amplifier

✓ Design and results are demonstrated.
Example 2: Single frequency, pulsed high energy solid-state laser

Single frequency Oscillator + multi-stage amplifier
Example 2: Single frequency operation

- How to get pulsed single frequency output for solid-state laser?
  - Mode selection in cavity with FP etalon, prism, grating, and other narrow line spectrum filter;
  - Enhance capability of mode competition, and Pre-lasing;
  - Injection seeding to pulsed cavity
  - CW single frequency +pused modulated+ amplifier
Example 2: Single frequency operation

Mode selection

Pre-lasing

Frequency selection

Pre-lasing

Injection seeding method

Injection seeder

$\frac{c}{2L}$
Example 2: Single frequency operation

• Requirement of seeder:
  – Single frequency, narrow linewidth (<10 kHz), low intensity noise, stable, compact;

• Candidate:
  – A NPRO (non-planar ring cavity) Nd:YAG laser
  – A short cavity DFB Fiber laser
  – External cavity diode laser

• It is also applied in laser interferometer for gravitational-wave missions.
Example 2: Single frequency operation

Fig. 2. Free-running frequency (left) and relative intensity (right) noise spectra of various single-frequency lasers. PW-ECL: PLANEX from Redfern Integrated Optics (1542 nm), NPRO: Model 125
Example 2: Single frequency operation

Tom Kane, R. L. Byer
“Monolithic, unidirectional Single-mode Nd:YAG ring laser”

✓ Small size NPRO Nd:YAG for large tunable frequency
✓ Frequency lock diode to pump NPRO to reduce intensity noise
Example 2: Single frequency operation

- **Graph:**
  - Laser output power vs. pump power (mW).
  - Graph shows a linear relationship.

- **Image a:**
  - Image of beam parameters with M2=1.1.

- **Graph b:**
  - PER (dB) vs. time (h).
  - Power vs. frequency (Hz).
  - Laser frequency vs. time (h).
  - Data indicates frequency stability with FWHM<2kHz.
Example 2: Single frequency operation

Injection Seeding Design

Modifized Ramp and Fire Technique

Modifized Ramp and Fire Technique

Example 2: Single frequency operation
Example 2: Injection seeding End pumped Oscillator

M1 and M2: mirrors
QW: quarter-wave plate
HW: half-wave plate
PZT: piezo actuator
P: polarizer.

Injection Seeding, EO Q-switch, folded cavity, end-pumping Nd:YAG laser
Example 2: End pumped Rod Oscillator

- Nd:YAG slab
  - Dimension: 4x4x20-mm
  - Dopant Concentration: 0.7at.%
  - Pump Configuration: End-pumped by Fiber coupled LD array
  - LDA: Peak power of 300W, D.C. of 2%

![Diagram of Nd:YAG oscillator with filter and LDA components]
Example 2: End pumped Rod Oscillator

Results of Resonator calculation--LASCAD

\[ f_1 = -45 \text{mm}, \quad f_2 = 70 \text{mm}, \quad f_c = 130 \text{mm}, \quad L_1 = 220 \text{mm}, \quad L_2 = 12.5 \text{mm}, \quad L_3 = 50 \text{mm}, \quad L_4 = 50 \text{mm} \]
Example 2: End pumped Rod Oscillator

Experiment’s Results of oscillator

<p>| | |</p>
<table>
<thead>
<tr>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Repetition</td>
<td>100 Hz</td>
</tr>
<tr>
<td>Pulse energy</td>
<td>10 mJ</td>
</tr>
<tr>
<td>Pulse duration</td>
<td>13 ns</td>
</tr>
<tr>
<td>Longitudinal mode</td>
<td>Unique (SLM)</td>
</tr>
<tr>
<td>Beam quality ($M^2$)</td>
<td>1.2</td>
</tr>
</tbody>
</table>

 rms = 0.493 MHz
Example 2: Laser Amplifier Configuration

- Input signal
- Isolator
- Expansion scope
- Preamplifier 1
- Preamplifier 2
- Power amplifier 1
- Power amplifier 2
- Laser output
## Example 2: The Slabs Dimensions & Parameters

<table>
<thead>
<tr>
<th>Brief description</th>
<th>Preamplifier1&amp;2</th>
<th>Power-Amplifier1</th>
<th>Power-Amplifier2</th>
</tr>
</thead>
<tbody>
<tr>
<td>Slab length, mm</td>
<td>119.35</td>
<td>119.43</td>
<td>120</td>
</tr>
<tr>
<td>Slab width, mm</td>
<td>5</td>
<td>8</td>
<td>10</td>
</tr>
<tr>
<td>Slab thickness, mm</td>
<td>5</td>
<td>6</td>
<td>8</td>
</tr>
<tr>
<td>Apex angle on both ends, deg</td>
<td>28.78</td>
<td>50</td>
<td>40</td>
</tr>
<tr>
<td>Nd+3 doping concentration, %</td>
<td>1.1</td>
<td>1</td>
<td>0.9</td>
</tr>
<tr>
<td>Signal input pulse energy, mJ</td>
<td>10 &amp; 60</td>
<td>180</td>
<td>500</td>
</tr>
<tr>
<td>Gaussian beam waist size, mm</td>
<td>3</td>
<td>6</td>
<td>8</td>
</tr>
<tr>
<td>Stored energy, J</td>
<td>1</td>
<td>1.9</td>
<td>1.6</td>
</tr>
</tbody>
</table>
Example 2: Bounce Pump for High Efficiency

Preamplifier 1&2

Power-amplifier1

Power-amplifier2
Example 2: Thermal Effect Analysis

- Temperature Distribution
- Temperature Induced Bending
- Temperature Induced Stress

To calculate thermal lens, wave front distortion, depolarization
Example 2: Thermal Effect Analysis

Depolarization results

Depolarization in the Zigzag Direction

Depolarization Perpendicular Zigzag Direction
Example 2: Comparison of experiment and simulation of thermal lens

<table>
<thead>
<tr>
<th>100Hz thermal lens</th>
<th>Experiment results</th>
<th>Modeling Results</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>Index Gradient induced lens (m)</td>
</tr>
<tr>
<td>50A</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Zigzag direction</td>
<td>7.4</td>
<td>7</td>
</tr>
<tr>
<td>Perpendicular zigzag direction</td>
<td>3</td>
<td>7</td>
</tr>
<tr>
<td>100A</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Zigzag direction</td>
<td>*</td>
<td>*</td>
</tr>
<tr>
<td>Perpendicular zigzag direction</td>
<td>1.5</td>
<td>2.2</td>
</tr>
</tbody>
</table>
Example 2: Compensation of thermal lens

<table>
<thead>
<tr>
<th>Laser Beam (mm)</th>
<th>Preamplifier 1</th>
<th>Preamplifier 2</th>
<th>Power amplifier 1</th>
<th>Power amplifier 2</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>B</td>
<td>C</td>
<td>A</td>
<td>B</td>
</tr>
<tr>
<td>3.3</td>
<td>3.4</td>
<td>2.8</td>
<td>3.02</td>
<td>3.87</td>
</tr>
<tr>
<td>Gauss beam (mm)</td>
<td>3.2</td>
<td>3.2</td>
<td>2.56</td>
<td>2.7</td>
</tr>
<tr>
<td>Ideal beam</td>
<td>3mm</td>
<td>3 mm</td>
<td>6 mm</td>
<td>8 mm</td>
</tr>
</tbody>
</table>

Gauss beam (mm): 3.2, 2.56
Ideal beam: 3mm, 3 mm
Example 2: Predication of output energy

- **Preamplifier 1**
- **Power Amplifier 1**
- **Preamplifier 2**
- **Power Amplifier 2**

Graphs show the relationship between pump energy (mJ) and output energy, with different stages indicated by arrows.
Example 2: Results of amplifier

![Graphs showing the results of amplifier models and experiment comparisons for Pre-amplifier 1, Pre-amplifier 2, Main -amplifier 1, and Main -amplifier 2.](image)

- **Pre-amplifier 1**
- **Pre-amplifier 2**
- **Main -amplifier 1**
- **Main –amplifier 2**
Challenges of space laser technology

- CO2 lidar needs long term frequency stability and high spectrum purity.
- High energy UV laser in space is still a challenge due to optics damage.
- New spaceborne Lidar pushes new space laser technology:
  - Such as multi beam high spectrum resolution Lidar: high repetition rate, planar waveguide solid-state laser is proposed.
  - Lidar or laser range finder with fs laser is a new technology, spaceborne fs laser is frontier.
  - O2, H2O, Lidar: Special wavelength without mature laser crystal.
Outline

- Laser requirement for Lidar remote sensing
- History and example of spaceborne Laser
- Design of spaceborne solid-state Laser
- Examples of developing spaceborne laser
- Laser components in space environment
- Conclusion
Many photonics and optics are assembled in solid-state lasers
Any components are related with the failure of laser, and must be qualified for space environment.

Qualification of laser’s components

Qualification of laser’s components

Radiation condition

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Condition</th>
<th>Units</th>
</tr>
</thead>
<tbody>
<tr>
<td>Orbital Altitude</td>
<td>100 - 1000</td>
<td>Km</td>
</tr>
<tr>
<td>Dose Rate, Typical</td>
<td>~0.1</td>
<td>Krad/year</td>
</tr>
<tr>
<td>Total Dose* (2-year mission)</td>
<td>&lt; 0.2</td>
<td>Krad</td>
</tr>
<tr>
<td>Particle Impact</td>
<td>11 to 26</td>
<td>Impacts/m²/year</td>
</tr>
<tr>
<td>UV Radiation</td>
<td>2220 to 5800</td>
<td>ESH/year*</td>
</tr>
<tr>
<td></td>
<td>118</td>
<td>W/m²</td>
</tr>
<tr>
<td>Atomic Oxygen</td>
<td>10¹¹ - 10¹²</td>
<td>Atoms/m³</td>
</tr>
<tr>
<td></td>
<td>4.3 to 4.4</td>
<td>EV</td>
</tr>
<tr>
<td>Charged Plasma</td>
<td>3e4 to 9e5</td>
<td>cm⁻³</td>
</tr>
<tr>
<td></td>
<td>0.1 to 0.2</td>
<td>EV</td>
</tr>
<tr>
<td>GCR¹ Fluences – Fe*, CREME96, Solar Minimum</td>
<td>10⁻⁶ - 0.002</td>
<td>Particles/cm²/day/MeV/nuc</td>
</tr>
<tr>
<td></td>
<td>10⁻³ - 10⁻⁵</td>
<td>MeV/nucleon</td>
</tr>
<tr>
<td>GCR¹ Integral LET¹ Spectra*, CREME96, Solar Minimum</td>
<td>10⁻⁸ - 150</td>
<td>Particles/cm²/day</td>
</tr>
<tr>
<td></td>
<td>0.1 - 20</td>
<td>MeV·cm²/mg</td>
</tr>
<tr>
<td>Solar Protons, CREME96</td>
<td>10⁻¹³ - 10⁻⁶</td>
<td>Protons/cm²/sec/MeV</td>
</tr>
<tr>
<td></td>
<td>~10² - 10⁵</td>
<td>MeV</td>
</tr>
</tbody>
</table>

## Main laser medium

<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Wavelength</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>/nm</td>
<td>1064</td>
<td>914.4</td>
<td>930</td>
<td>1053(σ)</td>
<td>912.2</td>
<td>1062</td>
<td>1062</td>
<td>1064</td>
<td>1030</td>
</tr>
<tr>
<td></td>
<td>1064.3</td>
<td>1079</td>
<td>1341</td>
<td>1047(π)</td>
<td>1063.1</td>
<td></td>
<td></td>
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<td></td>
</tr>
<tr>
<td></td>
<td>1342</td>
<td></td>
<td></td>
<td></td>
<td>1340.6</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>Index</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>(λ=1.06μm)</td>
<td>1.82</td>
<td>1.96</td>
<td>1.94</td>
<td>1.448</td>
<td>1.97</td>
<td>1.892</td>
<td>1.94</td>
<td>1.83</td>
<td>1.82</td>
</tr>
<tr>
<td></td>
<td>nₒ=1.96</td>
<td>nₑ=2.18</td>
<td>nₒ=1.448</td>
<td>nₑ=2.19</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>nₒ=1.96</td>
<td>nₑ=2.18</td>
<td>nₒ=1.448</td>
<td>nₑ=2.19</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>Cross section</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>/10⁻¹⁹cm²</td>
<td>σ₉₄₆=0.37</td>
<td>σ₀₉₄₆=0.48</td>
<td>σ₀₉₃₀=0.41</td>
<td>σ₁₀₇₉=4.6</td>
<td>σ₁₃₄₁=2.2</td>
<td>σ₀₉₁₂=0.66</td>
<td>σ₁₀₆₃=7.6</td>
<td>σ₁₃₄₀=1.8</td>
<td>σ₁₀₆₂=1.14</td>
</tr>
<tr>
<td></td>
<td>σ₀₆₄₆=2.8</td>
<td>σ₁₀₆₄=15.6</td>
<td>σ₁₃₄₂=2.8</td>
<td>σ₁₃₄₁=2.2</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>1.2(σ)</td>
<td>1.8(π)</td>
<td>1.2(σ)</td>
<td>1.8(π)</td>
<td>1.2(σ)</td>
<td>1.8(π)</td>
<td>1.2(σ)</td>
<td>1.8(π)</td>
<td>1.2(σ)</td>
</tr>
<tr>
<td><strong>Lifetime</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>/μs</td>
<td>230</td>
<td>100</td>
<td>170</td>
<td>480</td>
<td>90</td>
<td>254</td>
<td>289</td>
<td>277</td>
<td>951</td>
</tr>
<tr>
<td><strong>Pumping</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>wavelength /nm</td>
<td>807.5</td>
<td>808.5</td>
<td>803</td>
<td>792(/C)</td>
<td>808.5</td>
<td>806</td>
<td>809</td>
<td>809</td>
<td>942</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>796(⊥c)</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>CTC/[W/(m·K)]</strong></td>
<td>14</td>
<td>5.23(/C)</td>
<td>11</td>
<td>6.3</td>
<td>11.7(沿&lt;110&gt;)</td>
<td>9</td>
<td>6</td>
<td>9.6</td>
<td>7</td>
</tr>
<tr>
<td></td>
<td></td>
<td>5.1(⊥c)</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>CTE</strong>/10⁻⁶ K⁻¹</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>7.7-8.2</td>
<td>a: 2.2</td>
<td>a: 4.2</td>
<td>a: 13</td>
<td>a: 1.5</td>
<td>-</td>
<td>7.4</td>
<td>6.13</td>
<td>7.7-8.2</td>
</tr>
<tr>
<td></td>
<td></td>
<td>c: 8.4</td>
<td>b: 11.7</td>
<td>c: 8</td>
<td>c: 7.3</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>c: 5.1</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>dn/dT(10⁻⁶ K⁻¹)</strong></td>
<td>7.3</td>
<td>2.7</td>
<td>a: 9.75±0.07</td>
<td>-2.0 (σ)</td>
<td>4.7</td>
<td>17.6±0.8</td>
<td>10.5</td>
<td>8.3</td>
<td>7.3</td>
</tr>
<tr>
<td>(λ=1.06μm)</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

CTC: coefficient of thermal conductivity
CTE: coefficient of thermal expansion
Main laser medium

Laser Fiber:
- Yb Doped Fiber
- Er Doped Fiber
- Yb,Er: Doppler fiber
- Tm Doped Fiber
- Ho Doped Fiber
Radiation performance of laser crystals

Radiation performance of laser crystals

- Most laser crystals have good radiation performance;
- Absorption spectrum in UV and visible is changed larger than that in near infrared after radiation;
- Some co-doped crystal can improve radiation hardness, such as Cr,Nd:YAG.
- Diode pumping, and Q-switch operation is better to improve radiation performance than lamp pumping and CW operation.
Radiation performance of Doped fibers

Radiation induced absorption (RIA) of Er doped fiber with different Al

<table>
<thead>
<tr>
<th>Fiber Name</th>
<th>NB Al</th>
<th>LB NP</th>
<th>Al NP</th>
<th>Si NP</th>
<th>Si+</th>
</tr>
</thead>
<tbody>
<tr>
<td>Erbium absorption (dB/m@ 1530 nm)</td>
<td>4.7</td>
<td>12.3</td>
<td>23</td>
<td>2</td>
<td>3.2</td>
</tr>
<tr>
<td>Aluminum (wt%)</td>
<td>&lt;1</td>
<td>6-8</td>
<td>4-6</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>Pump power (dBm)</td>
<td>23</td>
<td>23</td>
<td>21</td>
<td>23</td>
<td>21</td>
</tr>
<tr>
<td>Optimal Length (m)</td>
<td>25</td>
<td>6</td>
<td>2.5</td>
<td>45</td>
<td>22</td>
</tr>
<tr>
<td>Output signal (dBm)</td>
<td>17</td>
<td>18</td>
<td>16</td>
<td>17</td>
<td>15</td>
</tr>
<tr>
<td>RIA at 1550 nm (dB/m/Gy)</td>
<td>5.5e-4</td>
<td>7e-3</td>
<td>5e-3</td>
<td>2.2e-4</td>
<td>2.8e-4</td>
</tr>
<tr>
<td>RIA at 980 nm (dB/m/Gy)</td>
<td>1.2e-3</td>
<td>2e-2</td>
<td>3e-2</td>
<td>3e-4</td>
<td>3e-4</td>
</tr>
</tbody>
</table>

Radiation performance of Doped fibers

✓ All doped fiber has relative larger RIA than laser crystal;
✓ Yb Doped and Er: Doped has similar performance under radiation;
✓ Fiber without Al has better performance than that with Al;
✓ Ce co-doped fiber can harden radiation;
✓ H2 treatment can improve radiation performance
Radiation effect of nonlinear crystals

Radiation effect of nonlinear crystals

100 krad

10.8 MeV

LiNbO$_3$:Y (0.46 wt%)

LiNbO$_3$:Mg (0.27 wt %)

LiNbO$_3$:Gd (0.004 wt %)
Laser diode in space environment

✓ Laser diode is the most important module for all solid-state laser.
  • Lifetime in vacuum;
  • Performance after $\gamma$ and proton radiation
## Example of laser diode used in vacuum

<table>
<thead>
<tr>
<th>Satellite</th>
<th>Sensor</th>
<th>Number/wavelength/type</th>
<th>Parameters</th>
<th>status</th>
</tr>
</thead>
<tbody>
<tr>
<td>MGS (1996-2001)</td>
<td>MOLA</td>
<td>44/808 nm/array</td>
<td>vacuum 150 μs, 10 Hz, 60 A</td>
<td>Success</td>
</tr>
<tr>
<td>ICESat (2003~2010)</td>
<td>GLAS</td>
<td>54/808 nm/array</td>
<td>vacuum 200 μs, 40 Hz, 100 A</td>
<td>Lifetime</td>
</tr>
<tr>
<td>MESSAGER (2006-present)</td>
<td>MLA</td>
<td>10/808 nm/array</td>
<td>vacuum 160 μs, 8 Hz, 100 A</td>
<td>Success</td>
</tr>
<tr>
<td>LRO (2008-present)</td>
<td>LOLA</td>
<td>2/808 nm/array</td>
<td>vacuum 200 μs, 28 Hz, 90 A</td>
<td>Success</td>
</tr>
<tr>
<td>CALIPSO (2006-present)</td>
<td>CALIOP</td>
<td>192/808 nm/array</td>
<td>Pressure sealed 150 μs, 20 Hz, 60 A</td>
<td>Success</td>
</tr>
</tbody>
</table>

No efficient proof to show that laser diode has low lifetime in vacuum. While, laser diode occurs problem in vacuum incidentally.
Failure example of laser diode

- No evidence to show laser diode can not be used in vacuum.
- Hard solder can be running for long lifetime in vacuum.
Lifetime test in vacuum

Air

1E-5 Torr

Lifetime test in vacuum for Indium and gold solder
Radiation performance of laser diode

- High power Laser diode array has very good performance under radiation.
- Lower power such as DFB, DRB has a little effect of wavelength stability

### Other components of laser

- Isolator, combiner, modulator, fiber grating are also key components in space laser, especially for space fiber laser.

<table>
<thead>
<tr>
<th>Item</th>
<th>Parameter to Monitor</th>
<th>Type of Measurement</th>
<th>Dominant Failure Modes</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fiber (all)</td>
<td>IL of core, Absorption rate of clad at pumpλ, Absorption and emission spectra</td>
<td>Active, Occasional</td>
<td>Increase in IL leading to optical damage during operation at peak power (catastrophic)</td>
</tr>
<tr>
<td>Combiner (ITF, JDSU)</td>
<td>IL, thru fiber, IL, three of multimode input ends</td>
<td>Active, Before and after</td>
<td>Decrease in transfer efficiency from the pump arm to output cladding and overheating of combiner</td>
</tr>
<tr>
<td>Pump LD (JDSU)</td>
<td>Output Power, λ &amp; spectrum, Threshold</td>
<td>Active, Before and after</td>
<td>Gradual degradation or sudden failure with radiation exposure. High environmental temp may lead to wavelength drift.</td>
</tr>
<tr>
<td>Pump-Combiner Module (Altlight)</td>
<td>Output power at max current, λ and spectrum at max current, TEC current at 20°C, Power vs. current, Isolation</td>
<td>Active, Before and after</td>
<td>Gradual degradation with radiation. Overheating at high environmental temp may lead to wavelength drift. Combiner may have thermal drift.</td>
</tr>
<tr>
<td>Fiber Bragg Grating (FBG, SPI, Cervis)</td>
<td>Reflectivity, Reflectivity spectrum, Sideband reflectivity</td>
<td>Occasional, Before and after</td>
<td>Athermal property may get damaged leading to wavelength drift (catastrophic). IL degradation with radiation damage.</td>
</tr>
<tr>
<td>Laser Seed Source (Sacher)</td>
<td>Output power at max current, Output spectra, Output power vs. current, TEC current at 20°C</td>
<td>Active, Occasional, Before and after test</td>
<td>Wavelength drift. Gradual or sudden failure due to high thermal operation or radiation exposure.</td>
</tr>
<tr>
<td>Isolator, fiber pigtailed (Novawave)</td>
<td>IL, Isolation</td>
<td>Active, Before and after test</td>
<td>Increase in IL with vibration, thermal or radiation exposure.</td>
</tr>
<tr>
<td>Isolator, free space (EOT)</td>
<td>IL, Isolation</td>
<td>Before and after test</td>
<td>Increase in IL with radiation. Degradation of Isolation. Misalignment with vibration.</td>
</tr>
</tbody>
</table>

Reliability of optics for spaceborne laser

✓ Self-focus of solid-state laser (large scale, small scale) is a big problem to affect reliability of space laser.

✓ Optical design to avoid optics damage:
  – Small Scale Self Focusing
  – Large Scale Self Focusing
  – Longitudinal Mode Beating
  – Small Scale Thermal Lensing

✓ Avoiding self-focus is very important for space laser with following methods:
  • Operated under single frequency
  • Non strong modulation on laser pulse
  • No diffraction in laser cavity
  • Reduce laser power density on optics
Reliability of optics for spaceborne laser

- CID (Contamination Induced Damage) is another big problem of space laser.
- Contamination controlling is very important for developing space laser in every steps.

Damage in vacuum with contamination
Reliability of optics for spaceborne laser

Many damage cases were found in vacuum and pure N2 environment.

Environment with O2 is found it is useful to prevent damage.

Space laser is sealed in a air container or an environment with O2.

LBO damage threshold is down into 1Mw/cm² in vacuum

Optics damage in pure N2 environment

Reliability of optics for spaceborne laser

- Critical polishing and cleaning of optics glass or crystal’s surface before coating; And keeping cleaning during coating;
- It is prefer to use ion beam deposition;
- Careful cleaning and check with high power microscope (> 200 x) to avoid any defect on surface before assembling;
- Assembling laser in 100 class cleaning room.
- Make sure that the power density on optics around 1/3 of it’s damage threshold;
- Enough pre-shot is necessary, around $1 \times 10^7$ shots.
Outline

- Laser requirement for Lidar remote sensing
- History of spaceborne Laser
- Design of spaceborne solid-state Laser
- Examples of developing spaceborne laser
- Laser components in space environment
- Conclusion
Conclusion

✓ Spaceborne Lidar is a powerful tools to remote sensing atmosphere of earth and other planets;
✓ Laser is the most important device in a spaceborne Lidar;
✓ Many lasers were lunched into space successfully;
✓ While ,very high reliability is required for space laser. Special design and qualified components must be implemented to access high reliability.
✓ It is still a challenge to develop a high reliability and long lifetime spaceborne laser.
Thanks for your attention!