Space Lasers 1

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Space Lasers?
Outline of Presentations

• **Space Lasers 1 – Applications & Laser Requirements**

• **Space Lasers 2 – Development of Tunable Alexandrite Lasers for Remote Sensing (+ other)**

• **A Commercial Laser Story – Midaz Lasers Ltd**
Outline of Space Lasers 1

- Laser Applications in Space Domain
- Lasers for Remote Sensing (Lidar)
- Laser Specification for Applications
- Engineering Challenges for Space Environment
Space Application Sectors

Space Science

Earth Observation

Satellite Telecom

“Downstream” data-services
Gravitational Interferometers
Gravitational Interferometers in Space

Arm length: \( L = 5M \text{ km} \)
Laser Communications in Space

- High data rates (optical vs RF)
- Low optical power requirement
- Secure (point-to-point)

Satellite to Earth

\[ \phi = \frac{\lambda}{D} \]

\[ \phi_{\text{Earth}} > \phi_{\text{sat}} \]
\[ P_{\text{Earth}} > P_{\text{sat}} \]

The “shower curtain” effect

NASA – Oct 2013
- 622 Mb/s (0.5W)
- 239,000 miles
The Internet of Space
Free-space satellite-based laser communication links

Quantum Key Distribution over 1200 km –using entangled photons from Chinese satellite (2017)
Space Lasers for Remote Sensing

- lasers can reach out to great distances and acquire valuable scientific data!
What is Remote Sensing?

The acquisition of information about an area, object or phenomenon without the need for direct physical contact

- **Passive techniques** – e.g. objects lit by sunlight
- **Active techniques** – radiation (e.g. laser) is actively emitted from instrument to act as a probe

- Light Detection And Ranging (LIDAR)
- Laser Altimetry
- LIBS
- SAR (Radar)
LIDAR Technique

LIDAR Instrument = Transmitter (Laser pulses) + Receiver (with detection equipment)
Mars “Curiosity” Rover

Quite short-range remote sensing: 1 – 7 m

The Mars Science Laboratory mission’s “Curiosity” rover carries the tunable laser spectrometer (TLS), which will investigate isotope ratios in carbon, hydrogen, and oxygen to assess present-day habitability and whether Mars ever supported life.

But on Mars!!
LIBS (Laser-Induced Breakdown Spectroscopy)

- Q-switched Nd:KGW laser (1067nm)
  - 10mJ / 5ns pulse (2MW)
  - Focused to >1 GW/cm² at target

Laser Pulse ablates small amount of material, as hot plasma that emits light.

Spectrometer identifies material by its spectral lines.
Satellite-based Remote Sensing

Quite long-range remote sensing: >400 km!

- Satellite-based Earth Observation is a powerful global mapping tool for:
  - surface mapping (altimetry)
  - weather monitoring and prediction;
  - environmental research (atmospheric modelling, climate change science);
  - environmental monitoring (e.g. pollution);
  - monitoring and management of natural resources (e.g. vegetation);
  - disaster mitigation

Some Issues to address:
- Ice cap melting,
- Vegetation; agriculture
- Weather
- Aerosols/clouds; radiation balance,
- $O_3$ Ultraviolet shield and smog, human health
- $CO_2$, $CH_4$ Greenhouse gases, global warming
- $O_2$ Atmospheric temperature measurement,
Laser Altimetry

*Time-of-Flight (TOF) provides a precise measurement of range*

\[ t = \frac{2z}{c} \]

Use GPS for satellite reference

1\,\text{ns} = 15\,\text{cm}
Laser Resolution

Beam Size (Foot-print) at target determines lateral spatial resolution

\[ \theta = \frac{\lambda}{\pi W_0} \]

<table>
<thead>
<tr>
<th>Beam size</th>
<th>Divergence ((\theta))</th>
<th>Size Increase @ 400 km</th>
</tr>
</thead>
<tbody>
<tr>
<td>1 mm</td>
<td>1 mrad</td>
<td>400 m</td>
</tr>
<tr>
<td>1 cm</td>
<td>0.1 mrad</td>
<td>40 m</td>
</tr>
<tr>
<td>1 m</td>
<td>1 (\mu)rad</td>
<td>(\sim) 0.4 m</td>
</tr>
</tbody>
</table>
NASA Laser Altimeters - MLA, MOLA, LOLA

• Mission Objectives: Time-of-flight mapping of surface topography.

**MLA**
Mercury Laser Altimeter
• Diode pumped, passively Q-switched
  Cr:Nd:YAG laser @ 1064nm, 20mJ, 6ns, 8Hz
• Mission scheduled to end in March 2012

**MOLA**
Mars Orbiter Laser Altimeter
• Diode pumped, actively Q-switched
  Cr:Nd:YAG laser @ 1064nm, 48mJ, 10Hz
• Collected altimetry data 1996 - 2001

**LOLA**
Lunar Orbiter Laser Altimeter
• Diode pumped, passively Q-switched
  Cr:Nd:YAG @ 1064nm, 2.7mJ, 6ns, 28Hz
Laser Altimeter - LOLA

Passive Radiator

Transmitter

Receiver

Detectors

Lunar Surface

Laser Pulse

DOE

Signal

Time

Transmit

Return

Energy (Reflectance)

Pulse Width

(Roughness)

Range = \frac{(t_r - t_x)c}{2}

5 Laser beams w/500 μrad separation and 100 μrad divergence

Beam Expander

Laser (w/cold spare)

Diffractive Optical Element (DOE)

Laser Electronics Assembly

2.4mJ, 28Hz

λ = 1064nm

Receiver

Telescope

14cm aperture

Det. Assy.

Det. Assy.

Det. Assy.

Det. Assy.

Digital Electronics Unit

400 μrad Detector FOV’s

5 x 200μm Fiber Optics

Power Converter-Electronics
Space Lidar for Earth Observation

- Atmospheric vertical (3-D) profiles of wind / clouds / aerosols...
  - global coverage (on satellite platform)
  - ranging information
  - day/night operation
Laser-Based Lidar principles

Light Detection And Ranging (LIDAR)

Doppler wind lidar
\[ \Delta f \quad V = \frac{\lambda}{2} \cdot \Delta f \]

Backscatter lidar: cloud/aerosol profiles
Extinction = \( \frac{I_R}{I_T} \)

Differential absorption lidar (DIAL)
Trace gas concentration
\[ = \log \left( \frac{I_{\lambda, on}}{I_{\lambda, off}} \right) \]
Small signal return from atmosphere requires high pulse energy lasers
Satellite-based LIDAR Missions (ESA)

**ADM AEOLUS Mission:**
- Acquire global wind profiles for climate & weather mapping.

**ALADIN - Doppler Wind Lidar**
- Nd:YAG 3ω (UV - 355nm)

**EARTHCARE Mission:**
- Acquire vertical profiles of clouds & aerosols.

**ATLID - Backscatter Lidar**
- Nd:YAG 3ω (UV - 355nm)
Space Laser Technology - Altimeter

BEPI COLOMBO Laser Altimeter

Q-switched Nd:YAG laser
@ 1064nm, 50mJ, 5ns, 1-10 Hz
Laser (LIDAR) Instrument - Space Qualification is Hard

Laser Specification
- High pulse energy / pulse rate
- Ultra-narrow/stable frequency
- High Efficiency

Structural Tests
- Vibrations
- Acceleration (~40 g)
- Thermal cycling
- Leak tests

Radiation Tests
- 100 kRad (gamma & proton)

Rigorous Lifetime Tests
- Whole system & sub-components
- Electrical tests
- Laser-induced damage tests
ALADIN - Doppler Wind Lidar Instrument
Nd:YAG 3ω (UV - 355nm)

<table>
<thead>
<tr>
<th>Transmitter (Nd:YAG)</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Wavelength</td>
<td>355 nm</td>
</tr>
<tr>
<td>Pulse energy</td>
<td>120 mJ</td>
</tr>
<tr>
<td>Repetition rate</td>
<td>100 Hz</td>
</tr>
<tr>
<td>Line width</td>
<td>30 MHz</td>
</tr>
<tr>
<td>Duty cycle</td>
<td>42 %</td>
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| Transmit-receive Telescope | 1.5 m |

Low Wall-plug efficiency ~ 2%

[Alves et al., ESA, ICSO, 2010]
Space Laser Technology - LIDAR

- SiC mirror

- Power Laser Heads (PLH)
- Reference Laser Heads (RLH)
- Optical Bench Assembly (OBA)
Demanding space requirements for laser

*has meant Nd:YAG is nearly only space-deployed laser*

**Altimetry:** (1064nm) Surface mapping of Earth, Mercury (MLA, BELA), Mars (MOLA), Moon (LOLA)

**Lidar:** GLAS (1064/532nm); CALIOP (1064/532nm); ATLID (355nm); ALADIN (355nm)
The Need for New Space Laser Technology

Higher efficiency

• Reduced on-board power requirement
• Reduced heat dissipation issues

Versatile tunable wavelength

• Superior information gathering capability (Resonantly detect atmospheric species)
• Better spectral match to application (e.g. ~ 800nm for vegetation altimetry)
Imperial College led-programme supported by ESA

.....to enable new / better space-borne Remote Sensing
Nd:YAG laser and its harmonics has limitations.....

In particular......

- no wavelength tunability
- entirely missing regions of the spectrum
- limited efficiency & high heat dissipation

OPO nonlinear optical conversion can be used to fill gaps – but significant further loss of efficiency & significant added reliability issues!
Alexandrite is a tunable solid-state laser

Alexandrite has broad lasing band ~700-850nm

- accesses new wavebands in near-IR and UV/blue (with SHG)
- offers continuous wavelength tunability
- excellent laser properties favourable to high pulsed power operation

Fixed wavelength(s) ➔ Choose your wavelength(s)!
Flexible wavelength enables new/better LIDAR Sensing

Molecular Resonant:
BS Lidar & DIAL

H$_2$O @ 730nm / 820nm
O$_2$ @ 761 nm
K @ 770nm
Fe @ 248nm
### Atmospheric LIDAR Specification

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Specification</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pulse Energy</td>
<td>100mJ</td>
</tr>
<tr>
<td>Pulse Duration</td>
<td>&lt; 100ns</td>
</tr>
<tr>
<td>Pulse Repetition Rate</td>
<td>100Hz</td>
</tr>
<tr>
<td>Central Wavelength Band</td>
<td>720 – 820nm</td>
</tr>
<tr>
<td>Spectral Width</td>
<td>&lt; 0.0001nm (50MHz)</td>
</tr>
<tr>
<td>Spatial Beam Quality</td>
<td>$M^2 &lt; 1.5$</td>
</tr>
</tbody>
</table>

- **Signal-to-noise**
- **Vertical Resolution**
- **Lateral Resolution**
- **Spectral Resolution**
- **Spatial Resolution**
Alexandrite for Vegetation Lidar

Alexandrite operates across the red-edge band of vegetation.

“...see the woods and the trees!”

Red-edge change is a sensitive indicator of health/stress in vegetation.
# Vegetation LIDAR Specification

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Specification</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pulse Energy</td>
<td>0.1mJ (single-photon counting detection)</td>
</tr>
<tr>
<td>Pulse Duration</td>
<td>&lt; 3ns</td>
</tr>
<tr>
<td>Pulse Repetition Rate</td>
<td>10 kHz</td>
</tr>
<tr>
<td>Central Wavelength Band</td>
<td>720 – 820nm</td>
</tr>
<tr>
<td>Spectral Width</td>
<td>-</td>
</tr>
<tr>
<td>Spatial Beam Quality</td>
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- **Signal-to-noise**
- **Vertical Resolution**
- **Lateral Resolution**
- **Spectral Resolution**
- **Spatial Resolution**
Status of Alexandrite?

**Tunable (λ)**
~700-850nm

**High Power (P)**
~100W

**High Energy (E)**
>1J

**Lamp-Pumped**

Cosmetic medical market
(Red) Diode-Pumping of Alexandrite is Possible!

Diode-Pumped

High efficiency
compact
long lifetime

Space Compliant

Alexandrite Absorption Spectrum

Red diode pumps
(AlGaInP)

x10 increase in efficiency!
Alexandrite and Space Qualification

A very long road....

First Alexandrite Breadboard Project

Validated UV Lidar Laser Technology

Validated Space-designed Lidar Laser

Space Instrument Deployed

Full laser spec:
- Power
- Tunable (UV)
- Inject-seeding
- Full modelling

TECHNOLOGY PHASE

SPACE DESIGN

SPACE IMPLEMENTATION

2011
And beyond?

NEW SCIENCE

REMOTE SENSING

OTHER APPLICATIONS