NASA Space Laser Technology

Michael A. Krainak

Representing the work of hundreds of people

NASA Goddard Space Flight Center
Laser & Electro-Optics Branch
Code 554

September 15, 2014
NASA Space Laser Technology
AGENDA

I. Overview of existing and near-term space laser systems

II. Monolithic solid state lasers

I. Future missions
Space Laser Altimetry Instruments

- **Apollo - moon**
  NASA (1971-1972)
  Ruby lasers, 5,000 shots

- **Clementine - moon**
  LLNL/NRL (1994)
  Nd:YAG laser, ~72,000 shots

- **NEAR/NLR - Eros**
  JHU/APL (1996-2001)
  Nd:YAG laser, 11 million shots

- **MESSENGER/MLA - Mercury**
  NASA GSFC (2004-present)
  Nd:YAG laser, 35 Million shots to date

- **LRO/LOLA - moon**
  NASA GSFC (2008-present)
  Nd:YAG laser, 400 million shots to date

- **SELENE/LALT - moon**
  Japan (2007-2009)
  Nd:YAG laser

- **Chang'E - moon**
  China (2007-present)
  Nd:YAG laser

- **Chandrayaan/LLRI - moon**
  India (2008-2010)
  Nd:YAG laser

- **ICESat/GLAS - Earth**
  NASA GSFC (1992-2010)
  Nd:YAG laser

- **MGS/MOLA - Mars**
  Nd:YAG laser, 670 million shots

- **MESSENGER/MLA**
  Mercury, NASA GSFC (2008-present)
  Nd:YAG laser

- **LRO/LOLA**
  Moon, NASA GSFC (2018-present)
  Nd:YAG laser

- **SELENE/LALT**
  Moon, Japan (2017-present)
  Nd:YAG laser

- **Chang'E**
  Moon, China (2019-present)
  Nd:YAG laser

- **Chandrayaan/LLRI**
  Moon, India (2020-present)
  Nd:YAG laser

- **ICESat-2/ATLAS**
  Earth, NASA GSFC (2020-present)
  Nd:YAG laser

**Current and future missions...**

- **BELA/BepiColumbo**
  Mercury, ESA (launch in 2016)
  Nd:YAG laser

- **GEDI**
  Earth, NASA GSFC (launch in 2019)
  Nd:YAG Laser
<table>
<thead>
<tr>
<th>Instrument</th>
<th>GLAS</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mission</td>
<td>ICESat</td>
</tr>
<tr>
<td>Laser type</td>
<td>Cr:Nd:YAG, passive q-switch</td>
</tr>
<tr>
<td>Laser Architecture</td>
<td>Porro-Mirror resonator passively Q-switched with two stage amplifiers</td>
</tr>
<tr>
<td># of lasers</td>
<td>3</td>
</tr>
<tr>
<td>Laser Wavelength</td>
<td>$\lambda_1$ $1064.5 \text{ nm } \pm 100 \text{ pm}$</td>
</tr>
<tr>
<td>Laser pulse energy</td>
<td>$\lambda_1$ = 75 mJ</td>
</tr>
<tr>
<td>Laser Pulse Repetition Rate</td>
<td>40 $\pm$ 0.1 Hz</td>
</tr>
<tr>
<td>Laser Pulsewidth</td>
<td>$\leq$ 6 ns</td>
</tr>
<tr>
<td>Laser Beam quality</td>
<td>TEM00</td>
</tr>
<tr>
<td>Laser Divergence</td>
<td>110 $\mu$rad (+23, -10)</td>
</tr>
</tbody>
</table>
Mercury Laser Altimeter (MLA)

MLA Laser Transmitter - derivative of GLAS laser MOPA design, 8Hz, 20 mJ
Detector - same as GLAS, SiAPD
Lunar Orbiter Laser Altimeter (LOLA)

First multi-beam Space-based Altimeter Instrument

Laser Transmitter – Derivative of GLAS Master Oscillator,
Two lasers on a single bench for redundancy
Receiver – Same as GLAS, MLA - SiAPD

Equal-Area projection of lunar topography developed from 1 billion LOLA measurements
Resolution: N/S = 20m, E/W = 0.1 deg (4.5km at equator, 200m at >85 Lat)
ICESat-2 ATLAS Instrument

Multi-beam Micropulse Laser Altimeter
- Single laser beam split into 6 beams
- 10 m ground footprints
- 10 kHz rep. rate laser (~1mJ)
- Multiple detector pixels per spot
- On-board boresight alignment system
- Laser Reference System gives absolute laser pointing knowledge

Ground Track and Footprint
- 6.61 mR (3.3km)
- Weak (1) Weak (1) Weak (1)
- Strong (4) Strong (4) Strong (4)
- Track Direction
- 5 mR (2.5 km)
ICESat-2 Flight Lasers

• Significant increase in laser technology compared to previous space missions
  – High repetition rate
  – High power
  – Short pulse width
  – $10^{12}$ shot lifetime

• Frequency doubled Master Oscillator/Power amplifier architecture
  – $>1$ mJ of 532 nm output at 10 kHz.

• Qualification laser is currently in EMI testing and is scheduled to complete testing in by Oct.

• Flight lasers are on track for delivery in late 2014.
Global Ecosystem Dynamics Investigation (GEDI)

Instrument and Mission Requirements For Carbon Estimation

GEDI Lidar, Class C Mission
International Space Station (ISS)
- Platform provides coverage of nearly all tropical and temperate forests
Self-contained Laser Altimeter
- 3 lasers produce 14 ground tracks
- Precise ranging, attitude and position sensors
Active Pointing Control System
- Provides pointing isolation and enables complete coverage of 500 m grid cells

Payload
The waveform lidar technique utilized by GEDI Lidar is the only remote sensing technique that has demonstrated the ability to provide 3-D canopy profile information at the required resolution and accuracy across the full range of canopy cover and environmental conditions.

JEM-EF on ISS, equatorial-to-mid-latitude orbit
High Output Maximum Efficiency Resonator

- The HOMER Laser - A highly efficient, TRL6, solid-state laser transmitter for altimetry and lidar.
- Several copies have been produced for TRL advancement. Current systems still operational:
  - HOMER-1 - TRL5 sealed unit for lifetest and flight-like components
  - HOMER-2 - TRL6, flight-like processes, environmental and life testing
  - HOMER ETU - flight ready design for ISS, ready for fabrication
- HOMER Development Goals from 2001 to present:
  - Reduce part count (2/3 reduction from similar systems)
  - Achieve highest reported efficiency.
  - Demonstrate > 10B shots (5X – 10X other systems)
  - Simplify design for reliable assembly.
  - Demonstrate unmatched lifetime.
  - Demonstrate unmatched decay rate.
  - Employ no Beryllium.
  - Survive GEVS vibration and TVAC.

<table>
<thead>
<tr>
<th>Specification</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Output power</td>
<td>13 mJ (1064 nm) in far field central lobe</td>
</tr>
<tr>
<td>Wavelength</td>
<td>1064.3 nm +/- 0.2 nm</td>
</tr>
<tr>
<td>Pulse width</td>
<td>10 ns +/- 2 ns (FWHM)</td>
</tr>
<tr>
<td>Pulse Repetition Freq.</td>
<td>241 Hz</td>
</tr>
<tr>
<td>Temp range (Operating)</td>
<td>±2°C (recorded at the LDA pedestal base)</td>
</tr>
<tr>
<td>Spatial Mode</td>
<td>Single Gaussian spatial mode, radially symmetric (TEM00)</td>
</tr>
<tr>
<td>Temporal Mode</td>
<td>Gaussian with trailing edge pulse porch ≤ 2% of pulse peak amplitude</td>
</tr>
<tr>
<td>Divergence (after BX)</td>
<td>57.5 mrad +/- 5 mrad (374 km altitude)</td>
</tr>
<tr>
<td>Pointing Jitter</td>
<td>Shot to shot jitter (1 sigma) &lt; 5 mrad</td>
</tr>
<tr>
<td>Lifetime per Laser</td>
<td>&gt; 8 Billion Shot @ 35% Duty Cycle over 3 yr Mission (minimum)</td>
</tr>
</tbody>
</table>

HOMER Flight Transmitter

Fabrication begins on HOMER ETU, the final generation of a decade-long HOMER hardware evolutionary process, in Jan 2015.

Dr. D. Barry Coyle & Paul R. Stysley / GSFC – Code 554
barry.coyle@nasa.gov; paul.r.stysley@nasa.gov
GRACE follow-on (Gravity Recovery And Climate Experiment)

- Measurement of earth’s gravitational field
- Measurement of 1 nm variation in length over 100 sec and 50 km
- Required frequency noise: ~10Hz/rtHz (at 1mHz~100mHz) after pre-stabilization
GRACE-FO Laser (Baseline)

- Non-planar ring oscillator (NPRO) Nd:YAG laser provides tunability for locking to cavity
  - Laser wavelength adjusted by changing dimensions of YAG crystal using PZT glued to crystal and thermal adjustment
- Space-qualified NPRO laser available from Tesat Spacecom
Lunar Laser Communications Demonstration (LLCD)

- NASA’s first high rate (625 Mbps downlink - 20 Mbps uplink) space laser communications demonstration
- Space terminal integrated on the Lunar Atmosphere and Dust Environment Explorer (LADEE)
- Launched on 6 September 2013 from Wallops Island on Minotaur V
  - Completed 1 month transfer
  - 1 month lasercomm demo @ 400,000 km
    - 250 km lunar orbit
  - 3 months science
    - 50 km orbit
    - 3 science Payloads
      - Neutral Mass Spectrometer
      - UV Spectrometer
      - Lunar Dust Experiment
LLCD diode oscillator/fiber amplifier
MOPA laser transmitter
(built by MIT-LL)
Mission Concept

- Orbit: Geosynchronous
  - Longitude TBD between 162°W to 63°W
- 2 years mission operations
- 2 operational GEO Optical Relay Terminals
- 2 operational Optical Earth Terminals
- Optical relay services provided
  - Ability to support a LEO User
- Hosted Payload
- Launch Date: Dec 2017
I. Overview of existing and near-term space laser systems

II. Monolithic solid state lasers

I. Future missions
ATLAS laser – is there a “better” way?
Non-Planar Ring Oscillator (NPRO)
(T. Kane, R. Byer – Stanford U. -1984)

A unidirectional laser is to include a polarizer, a Faraday rotator, and a nonmagnetic polarization rotator, such as the Nd:YAG laser. This laser is constructed with a pump-limited, single-mode operation of Nd:YAG. The laser oscillator is monolithic and totally internally reflecting.

Most ring lasers use a resonator that is entirely within a plane. There are sometimes advantages to a non-planar geometry that are worth a greater complexity. Dorschke at Raytheon has described a nonplanar helium-neon ring laser that, when used as a gyroscope, overcomes the problem of self-locking or lock-in.

Researchers in the Soviet Union have built nonplanar Nd:YAG ring lasers and have studied the mode structure, temporal dynamics, and polarization of these lasers. Biraben suggested that single-mode dye lasers have been achieved with semimode.

Single-frequency Q-switched ring laser with an antiresonant Fabry-Perot saturable absorber

B. Braun and U. Keller

Received January 2, 1985

We present: A Q-switched monolithic Nd:YAG ring laser (MISER) using a monomode wave coupled antiresonant Fabry-Perot saturable absorber. Single-frequency, 0.7 μs pulses with a pulse width below 100 ns at an ~1-MHz repetition rate are demonstrated. Pulse width and repetition rate can be varied by changing the distance and thus the coupling strength between the crystal and the absorber.

Fig. 1. Layout of the MISER with an A-FPSA coupled to a total-internal-reflection point and (at the right) a schematic of the interface between the MISER and the A-FPSA.
1.6 W of single-mode output power from a novel power-scaling scheme for monolithic nonplanar ring lasers

Hagen Zimer and Ulrich Wittrock
Photonics Laboratory, University of Applied Sciences Münster, Stegerwaldstrasse 39, 48565 Steinfurt, Germany

Received January 13, 2004

A novel monolithic ring laser with high potential for power scaling, the disk nonplanar ring oscillator, is presented. We achieved power scaling by reducing the pump-light-induced aberrations. The basic idea of our approach is to attach a thin Nd:YAG disk to an undoped nonplanar YAG ring resonator while the other side of the disk is mounted on a heat sink. First promising experiments have demonstrated a single-frequency cw output power of 1.6 W at 1.06 μm with a slope efficiency of 49%. Power scaling to several watts seems to be possible. © 2004 Optical Society of America

OCIS codes: 140.3570, 140.3480, 140.3560, 140.3410, 140.3580, 140.3530.

Fig. 1. (a) Nd:YAG disk NPRO, (b) front view into the BCD plane, (c) enlarged section of the disk about TIR point C.
## Monolithic laser advantages

<table>
<thead>
<tr>
<th>Parameters</th>
<th>Single element monolithic laser and multi-element laser array</th>
</tr>
</thead>
<tbody>
<tr>
<td>Spectral</td>
<td>DBR/DBR helps with spectral narrowing, spectral stability and single frequency operation.</td>
</tr>
<tr>
<td>Spatial</td>
<td>Thermal lens and passive q-switching provides soft aperturing to ensure high beam quality.</td>
</tr>
<tr>
<td>Temporal</td>
<td>Short cavity means short optical pulses.</td>
</tr>
<tr>
<td>Energy/Power</td>
<td>Design to produce 50 μJ; also per design to produce 8.4 kHz - average power ~0.42W</td>
</tr>
<tr>
<td>Repetition Rate</td>
<td>Pump power driven, also affected by Yb concentration, need iterative processes to optimize concentration for gain and rep rate</td>
</tr>
<tr>
<td>Passive QS</td>
<td>Discrete SA element or co-dope with Yb in PTR, no high voltages as in Active QS</td>
</tr>
<tr>
<td>Coatings</td>
<td>Bragg mirrors serve as high reflector and output coupler, no coating except for AR to minimize Fresnel reflection for pump and lasing wavelength, avoid the issue of optical damage to coating.</td>
</tr>
<tr>
<td>Nonlinear Effects</td>
<td>No detrimental nonlinear effects.</td>
</tr>
<tr>
<td>Reliability</td>
<td>Use highly fiber coupled pump lasers used in telecom industry. Multiple lasers mean losing one laser can still do majority of science - built in redundancy.</td>
</tr>
<tr>
<td>Pump configuration</td>
<td>Fiber coupled pumps for compact and robust design. Using microlens array for coupling pump light into laser array.</td>
</tr>
<tr>
<td>Laser Cavity</td>
<td>Closed cavity immunes to contamination inside laser cavity, which usually has the highest fluence. Monolithic design to minimize number of components.</td>
</tr>
<tr>
<td>Pointing Stability</td>
<td>End gratings formed the lasing axis, thermal lensing and soft aperturing from PQS provides additional pointing stability.</td>
</tr>
<tr>
<td>Alignment Sensitivity</td>
<td>Monolithic design means robustness. No to low misalignment concerns with laser resonator.</td>
</tr>
<tr>
<td>Thermal Control</td>
<td>Will examine the use of embedding loop heat pipes (LHP) or microchannel cooler (MCC) into the laser array for efficient thermal management. LHP has been used successfully in spaceflight lasers and MCC has been used extensively in packaging of high power semiconductor laser arrays.</td>
</tr>
</tbody>
</table>
Solid state monolithic laser with Volume Bragg Grating mirrors

Possible geometry of a monolithic solid state laser in PTR glass doped with rare earth ions. 1 - rear-earth doped PTR-glass wafer; 2 – high efficiency VBG as a feedback coupler; 3 – low efficiency VBG as an output coupler; 4 - pumped volume in active PTR-medium; 5 - pumping beam from LD bars.
Monolithic Yb:glass CW solid state laser

DBR and DFB lasers in neodymium- and ytterbium-doped photothermorefractive glasses

A. Ryasnyanskiy,1,* N. Vorobiev,2 V. Smirnov,1 J. Lumeau,2,3 L. Glebova,1 O. Mokhun,1 Ch. Spiegelberg,1 Michael Krainak,1 A. Glebov,1 and L. Glebova4

1 OptiGrate Corp, 502 South Econ Circle, Oviedo, Florida 32765, USA
2 CREOL—The College of Optics and Photonics, University of Central Florida, Orlando, Florida 32816-2700, USA
3 Aix-Marseille Université, CNRS, Centrale Marseille, Institut Fresnel, UMR 7249, Marseille 13013, France
4 NASA Goddard Space Flight Center, 8500 Greenbelt Rd., Greenbelt, Maryland 20771, USA

*Corresponding author: ariasnyanskiy@optigrate.com

Received January 3, 2014; revised March 3, 2014; accepted March 10, 2014; posted March 11, 2014 (Doc. ID 204149); published March 31, 2014

The first demonstration, to the best of our knowledge, of distributed Bragg reflector (DBR) and monolithic distributed feedback (DFB) lasers in photothermorefractive glass doped with rare-earth ions is reported. The lasers were produced by incorporation of the volume Bragg gratings into the laser gain elements. A monolithic single-frequency solid-state laser with a linewidth of 250 kHz and output power of 150 mW at 1064 nm is demonstrated. © 2014 Optical Society of America
Monolithic Master Oscillator Power Amplifier (MOPA)

Semiconductor Monolithic MOPA

Solid-state (crystal/glass) MONOLITHIC MOPA

High-power diffraction-limited semiconductor sources have been sought after for a number of years. Semiconductor lasers have demonstrated operation to high output powers, in excess of 120 W CW from a single monolithic chip [1]; however, coherent operation of semiconductor lasers has been limited to significantly lower output powers. Several monolithic approaches have been studied with the goal of demonstrating coherent output powers in excess of 1 W CW including anti-guide laser arrays [2-4], monolithically integrated active cavity master oscillator power amplifiers (MAG-MOPA).
Yb:YAG Microchip Laser with Passive Q switch (Raytheon)

**Laser Output Beam Parameters**
- Pulse Energy: 0.1 mJ
- Repetition Rate: 10 kHz
- Wavelength: 1030.2 nm
- Linewidth: 17 pm
- Polarization Ext: 25 dB
- Pulsewidth: 0.83 nsec
- Beam Quality M2: 1.3
- 0-0 Efficiency: 25%

**Laser Operating point**
- Diode Current: 4.5 A
- Diode Output Power: 3.9 W
- Chiller Temp: 29.8 °C
- Diode Temp: 31 °C
- μChip Temp: 17.8 °C
- VBG Temp: 20 °C
Planar waveguide power amplifier
Solid state MOPA (Raytheon)

- Weight < 27 lb (dry)
- Volume ~260 m³

Wavelength ~1030.2 nm;
<20 pm spectral width

NF Image at ~84 cm from
MOPA Output
FW1/e² size: 2.6 mm × 3.3 mm

MO Nominal Operating Point
- Pulse Energy 0.1 mJ
- Repetition Rate 10 kHz
- Wavelength 1030.2 nm
- Linewidth 0.018 nm
- Polarization ER 25 dB
- Pulsewidth 0.8 nsec
- Beam Quality M² ~1.3
- Opt-Opt Efficiency 25.6%
- El-Opt Efficiency 12.8%

MOPA Nominal Operating Point
- Pulse Energy 2.2 mJ
- Repetition Rate 10 kHz
- Wavelength 1030.2 nm
- Linewidth 0.02 nm
- Polarization ER 18 dB
- Pulsewidth 0.8 nsec
- Beam Quality M² ~1.1
- Opt-Opt Efficiency 24%
- El-Opt Efficiency 11%
Fig. 1. (a) Schematic of fs-laser inscription process in Yb:YAG ceramics for the double cladding waveguides, and their cross sectional microscope images, which consist of tubular central structures with 30 μm diameter, and concentric larger size tubular claddings with diameters of (b) 200, (c) 150 and (d) 100 μm, respectively.
Double clad monolithic laser
Performance

Fig. 4. (a) Laser pulse energy at 1.06 μm versus energy of the pump pulse incident on the DWG-1 waveguide. The near-field distributions are shown at the maximum laser pulse energy (OCM with $T = 0.10$) for emission in (b) DWG-1 ($E_p = 3.4$ mJ) and (c) bulk Nd:YAG ($E_p = 5.5$ mJ).
Optical waveguides in smartphone "Gorilla" glass!

Fig. 1. Laser writing of a photonic device in a smartphone screen. The photograph shows that the waveguide (a horizontal line from the left side) cannot be seen by the naked eye. The white light comes from the plasma generated by the nonlinear absorption of the focused laser.

Fig. 7. Loss of the 30 cm multimode waveguide (with a loss of 0.027 dB/cm) with different launch NAs. More modes appear as the NA increases. At an NA of ~0.012, only the $L_{P01}$ mode is seen, and at an NA of 0.25 all modes are seen at the waveguide output by altering the launch conditions.
Graphene waveguide modulator

Fig. 1. Top view of device, light was coupled using grating couplers (left). Isometric view of device showing graphene layer on top of Si waveguide (top right). Cross-sectional view of device with graphene layers separated by 94 nm aluminum oxide (bottom right).

Fig. 3. Relative electro-optical response of the modulator as a function of frequency. $f_{\text{m}}$ is 670 MHz. The inset shows the output signal of the modulator at 50 MHz (yellow line) for an AC input voltage $V_{AC} = 4$ V (purple and cyan lines represent the reference signals).
Q-switched monolithic laser
Passive and active Q-switches

Fig. 2. Schematic plot of the experimental setup for the pulsed laser generation in the double-cladding Nd:YAG ceramic waveguides.

Fig. 1. The experimental scheme for the indirect interaction graphene Q-switched waveguide laser generation.
Planar Waveguide Amplifier for Power Scaling

35 mm long laser amplifier for a 16 W laser at IR
(~9 W in green – same as ATLAS laser)

Yb:YAG waveguide core, 40 μm thick, sandwiched by undoped YAG
Highly efficient continuous wave blue second-harmonic generation in fs-laser written periodically poled Rb:KTiOPO₄ waveguides

Fig. 1. Second harmonic power (black squares) and conversion efficiency (red dots) versus incident fundamental power at 943.18 nm. Theoretical square-fit of the measured data points (solid line).
AGENDA

I. Overview of existing and near-term space laser systems

II. Monolithic solid state lasers

I. Future missions
"Earth" application – Not just monolithic but monolithic with "compatible" material/process. Cost driven SiN waveguide lasers for CMOS (MIT and UCSB)

CMOS-compatible 75 mW erbium-doped distributed feedback laser

Fig. 1. Waveguides used in this work. (a) Layers used for constructing the waveguide structure within wafer-scale fabrication flow. High-definition masks are used to create waveguides and gratings in the SiN layer, and an erbium-doped glass is deposited as a blanket film. (b) Intensity profile of an inverted ridge waveguide mode with a 4 μm SiN core. The 1563 nm mode is mainly confined in the erbium-doped glass.

Fig. 2. On-chip DFB laser performance. (a) Single-mode laser emission from the DFB with more than 60 dB suppression of the amplified spontaneous emission (ASE), measured with an OSA with 0.02 nm resolution. The peak around 1588 nm is due to the Kman-shifted residual pump. (b) Power as a function of launched pump power for two lasers with equal corrugation (x = 300), but different grating length (L = 23 and 15 mm), lasing at 1563 nm. The cavity with the longer grating shows higher slope efficiency and a lower threshold.
# Upcoming approved NASA missions with a space-based laser

<table>
<thead>
<tr>
<th>Mission</th>
<th>Laser</th>
<th>Launch Date</th>
</tr>
</thead>
<tbody>
<tr>
<td>Gravity Recovery And Climate Experiment-Follow On (GRACE-FO) NASA-JPL</td>
<td>Nd:YAG Monolithic NPRO</td>
<td>2017</td>
</tr>
<tr>
<td>Laser Communication Relay Demonstration (LCRD) NASA-GSFC/JPL/MIT-LL</td>
<td>Diode oscillator-erbium fiber amplifier MOPA</td>
<td>2018</td>
</tr>
<tr>
<td>Geodynamics of the Earth, Dynamics of Ice (GEDI) NASA-GSFC</td>
<td>Nd:YAG laser (IR)</td>
<td>2019</td>
</tr>
</tbody>
</table>
Upcoming “hopeful” NASA missions with a space-based laser (start before 2024)

<table>
<thead>
<tr>
<th>Mission</th>
<th>Laser</th>
</tr>
</thead>
<tbody>
<tr>
<td>Jupiter Europa topography</td>
<td>Nd:YAG MOPA (similar to Mercury Laser Altimeter)</td>
</tr>
<tr>
<td>Laser communication terminal International Space Station (to LCRD)</td>
<td>Diode oscillator-erbium fiber amplifier MOPA</td>
</tr>
<tr>
<td>Deep-space Optical Terminal (JPL)</td>
<td>Diode oscillator-erbium fiber amplifier MOPA</td>
</tr>
<tr>
<td>Robotic Servicing</td>
<td>Nd:YAG or Diode oscillator-erbium fiber amplifier MOPA</td>
</tr>
<tr>
<td>Earth atmospheric carbon dioxide</td>
<td>Diode oscillator-erbium fiber amplifier MOPA or 2 micron Tm:YAG</td>
</tr>
<tr>
<td>Earth atmospheric methane</td>
<td>Nd laser pumped diode oscillator/seed OPA/OPO or Diode oscillator Er:YGG amplifier</td>
</tr>
<tr>
<td>Improved Earth gravity - Gravity Recovery And Climate Experiment 2 (GRACE-II)</td>
<td>Nd:YAG Monolithic NPRO or ?</td>
</tr>
<tr>
<td>Precision time transfer – improved Global Positioning System (GPS)</td>
<td>Fiber frequency comb ?</td>
</tr>
</tbody>
</table>
SUMMARY

1. Over the past two decades NASA has deployed diode, solid state and fiber lasers based instruments for new spacecraft systems and science discoveries.

1. A second generation of space laser instruments will benefit from further monolithic laser manufacturing techniques.

2. NASA needs US industry and University help in developing robust, monolithic high power lasers for future space laser instruments.
Acknowledgement

The authors would like to thank

NASA ESTO;

NASA ASTID program;

GSFC IRAD program;

GSFC SBIR program

and the

Instrument and Science Teams of:

MOLA, ICESat/GLAS, Calipso, MLA, LOLA, ICESat-2, LIST SDT,

ASCENDS, GRACE-FO, GRACE-II, LADEE, LLCD & LCRD
Satellite clock synchronization
Atomic Clock Ensemble in Space (ACES) on ISS in 2016 - European Space Agency

ACES payload

ELT (European Laser Timing)

PHARAO (Project d'Horloge Atomique à Refroidissement d'Atomes en Orbite): a laser-cooled cesium atomic clock