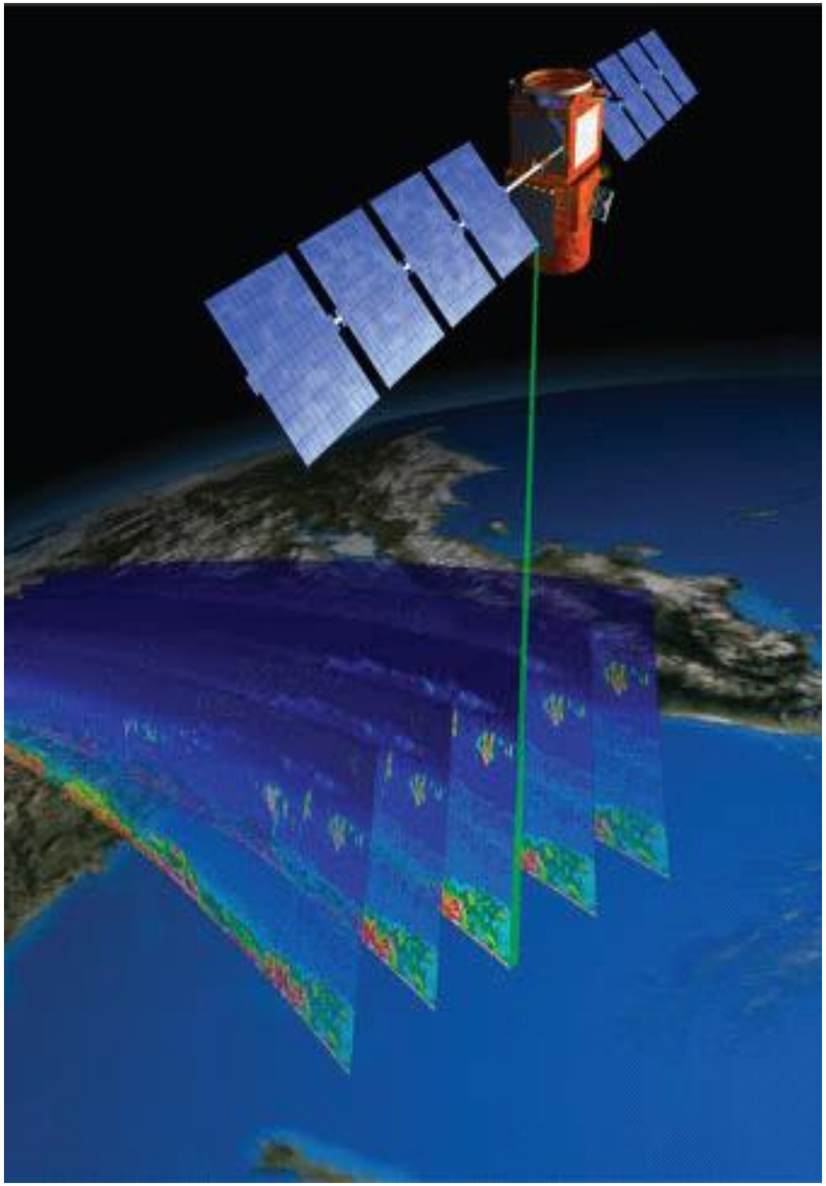
The Abdus Salam International Centre for Theoretical Physics

Winter College on Optics

Light: a bridge between Earth and Space

Spaceborne Laser Technology for Lidar Remote Sensing



Weibiao Chen

Shanghai Institute of Optics and fine Mechanics, Chinese Academy of Sciences

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
- Design of spaceborne solid-state laser
- Examples of developing spaceborne laser
- Laser components in space environment
- Conclusion

Application of Spaceborne laser

Application of Space Laser

Earth observation with Lidar

- Aerosol and dust
- Cloud
- Atmospheric composition
- Atmospheric dynamics
- Earth topography

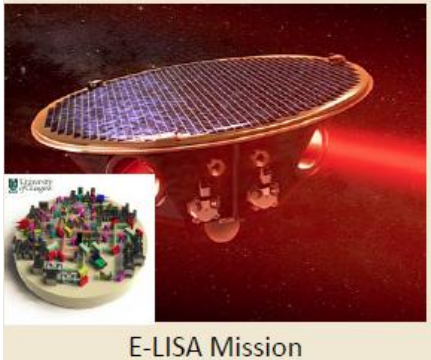
Space Science and Metrology

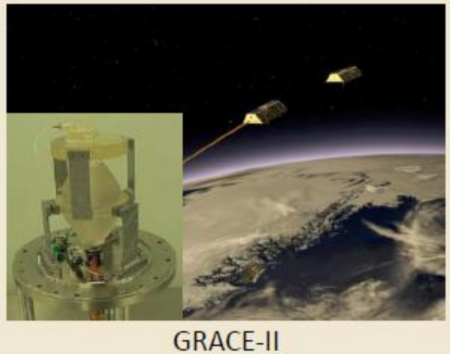
- Gravitational waves
- Cold atomic clock
- Optical clock
- Atom interferometer
- Time metrology

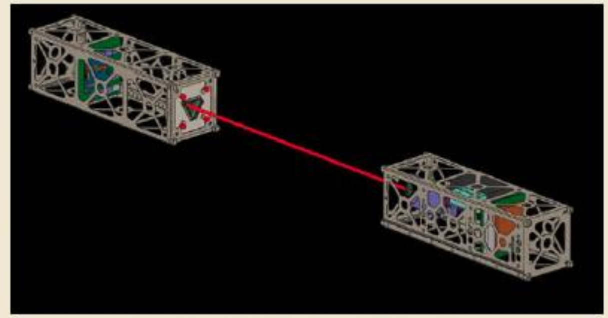
Space measurement and communication

- Deep space detection
- Laser communication
- Formation flying
- Rendezvous and docking

Application of Spaceborne laser



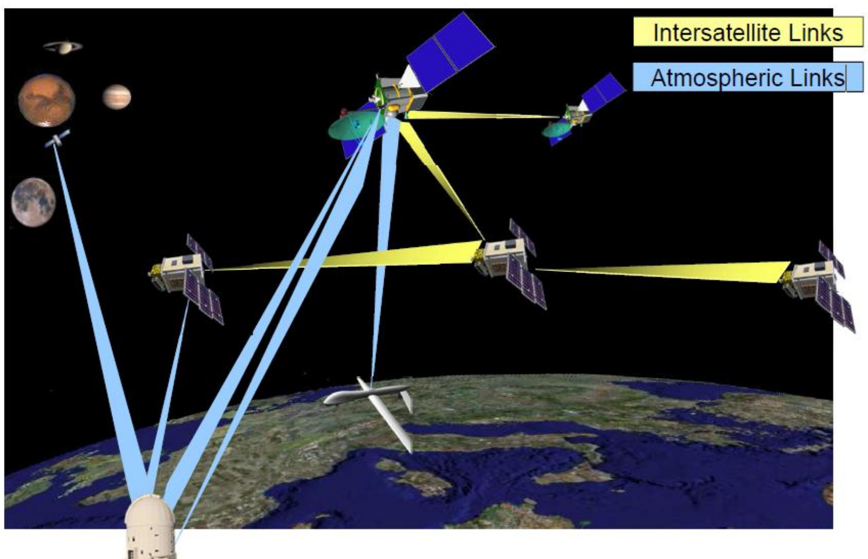




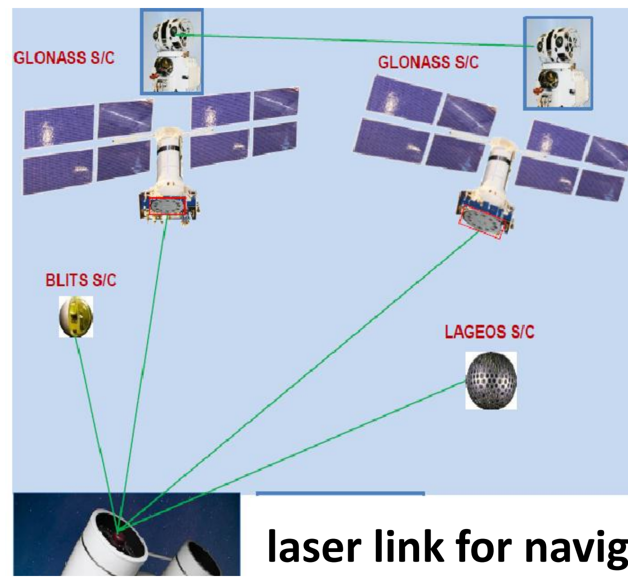
Formation flying

Space laser interferometer

Space laser ranging



Space laser communication



laser link for navigation

Application of Spaceborne laser

Application of Space Laser

Earth observation with Lidar

- Aerosol and dust
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Space Science and Metrology

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Space measurement and communication

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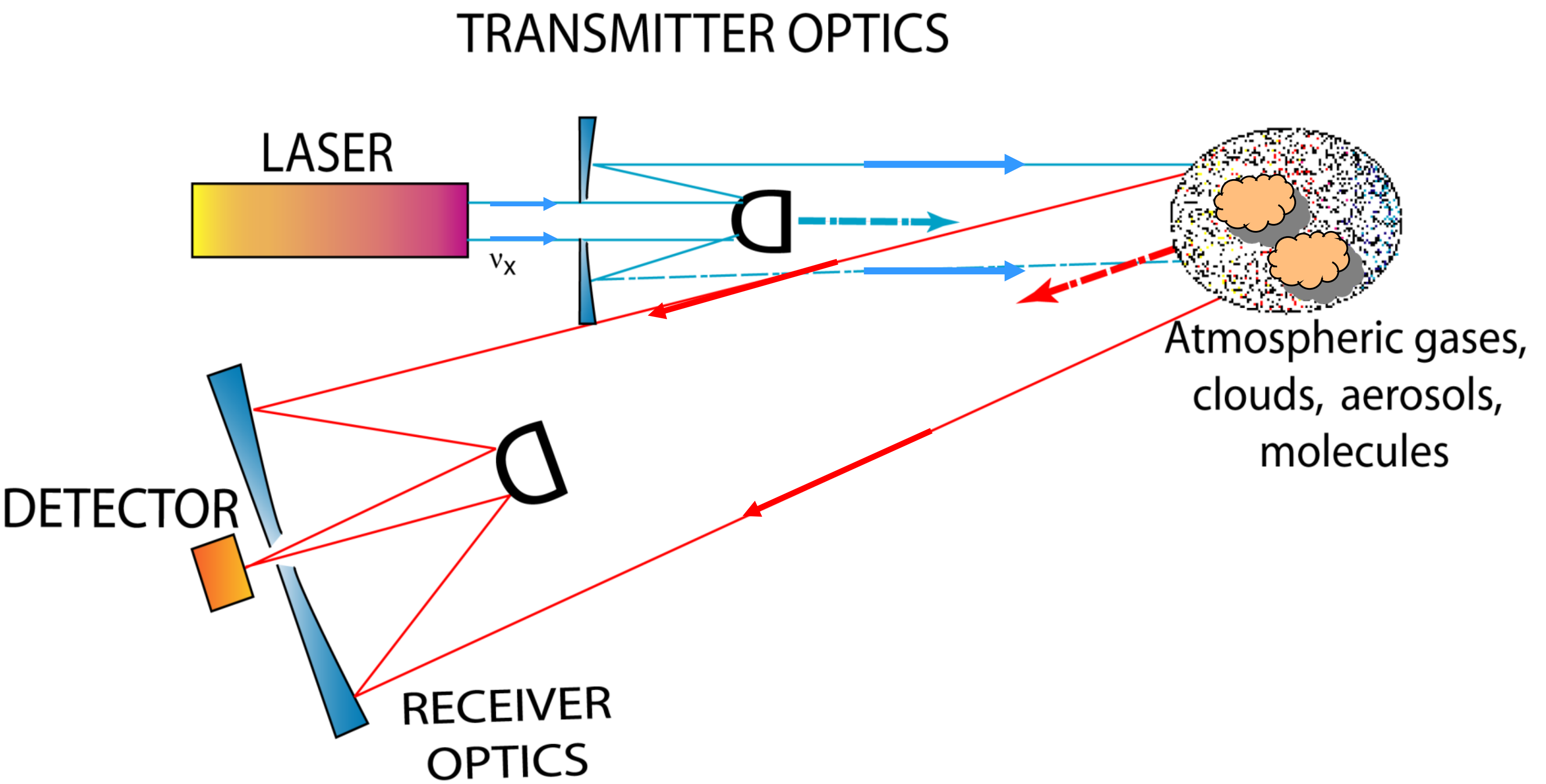
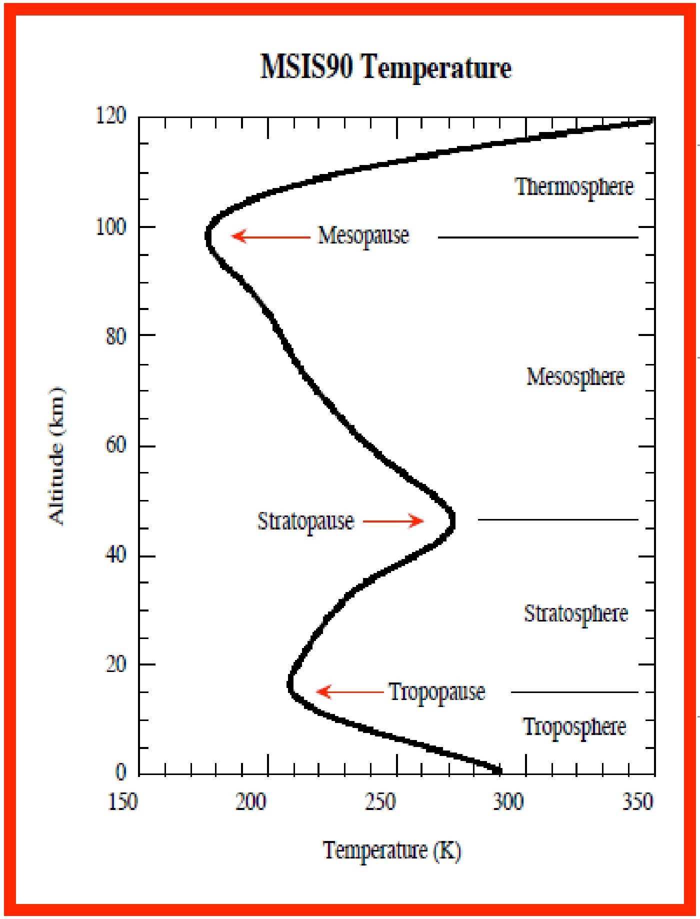
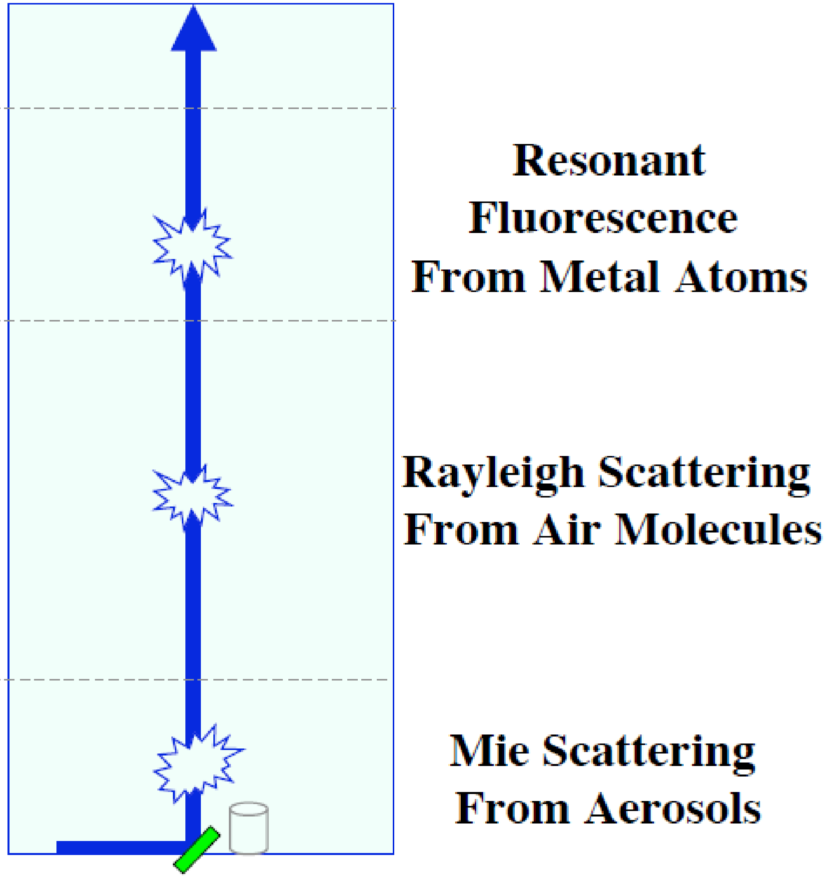
Light Detection And Ranging-- Lidar



Atmospheric Vertical profile



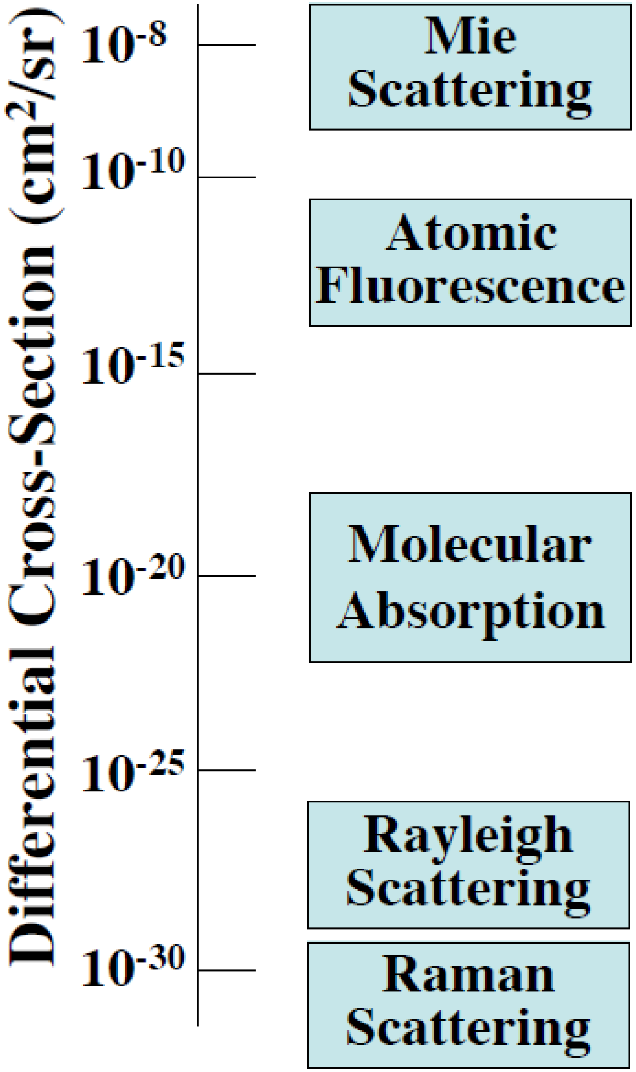


Range Determined From Time-of-Flight: $R = c \cdot \Delta t / 2$

Classification of Lidar

Lidar Type	Principle	Values	Target
Laser altimeter, Laser bathymetry	Back reflecting	Time	Topography, Depth
Doppler Lidar	Doppler	Frequency Shift	Wind speed
Different Absorption Lidar	Atomic, molecular absorption	Intensity	Atmospheric composition
Fluorescence Lidar	Fluorescence	Wavelength, Intensity	Atmospheric composition
Raman Lidar	Raman scattering	Wavelength, Intensity	Atmospheric composition , temperature
Mie Lidar	Mie Scattering	Intensity	Aerosol, cloud
Rayleigh Lidar	Rayleigh Scattering	Intensity	Temperature, molecule density

Cross-section of different principle



$$\beta(\lambda, \lambda_L, z) = \sum_i \left[\frac{\mathrm{d}\sigma_i(\lambda_L)}{\mathrm{d}\Omega} n_i(z) p_i(\lambda) \right]$$

Rayleigh $$\frac{d\sigma}{d\Omega} = \sigma_R \propto \frac{1}{\lambda^4}$$

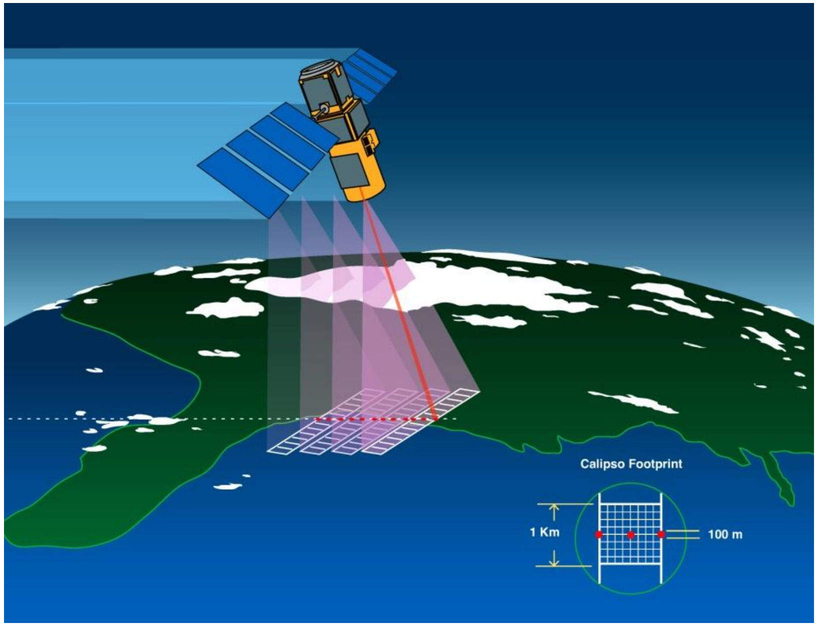
Resonance Fluorescence

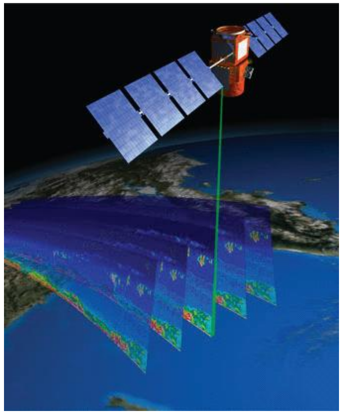
$$\frac{d\sigma}{d\Omega} = \frac{\sigma_{eff}}{4\pi} = \frac{\int_{-\infty}^{+\infty} \sigma_{abs}(\nu, \nu_0) \cdot g_L(\nu, \nu_L)\, \mathrm{d}\nu}{4\pi}$$

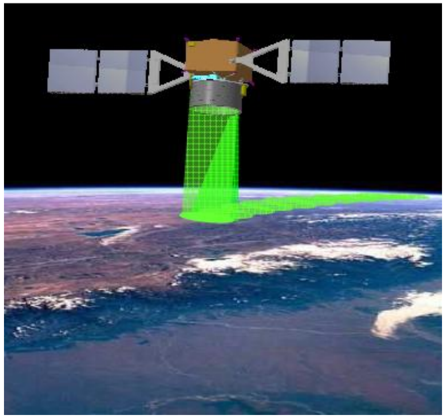
Spaceborne Lidar for Earth Observation

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

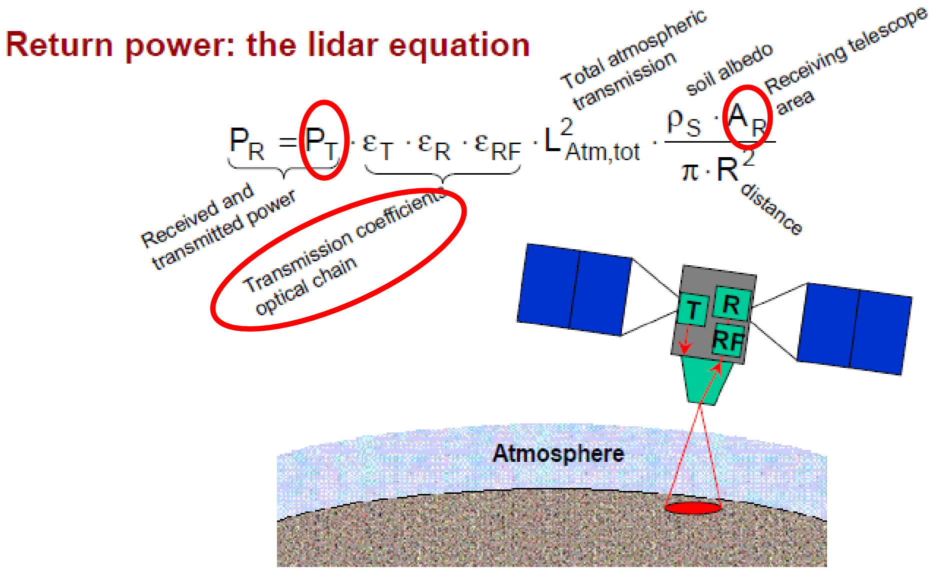
- Spaceborne Lidar is used to remote sensing the properties of earth’ s atmosphere, surface, ocean, et.al.

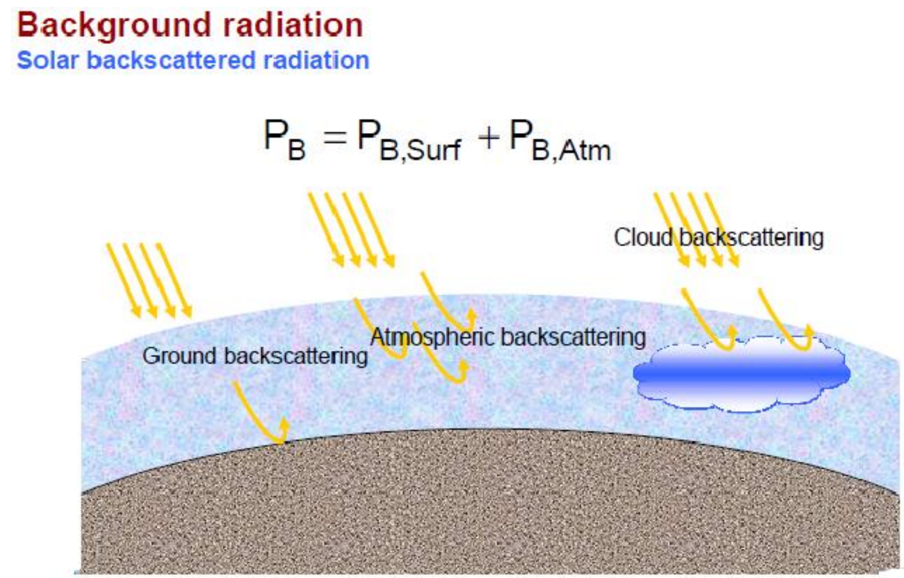






Spaceborne Lidar





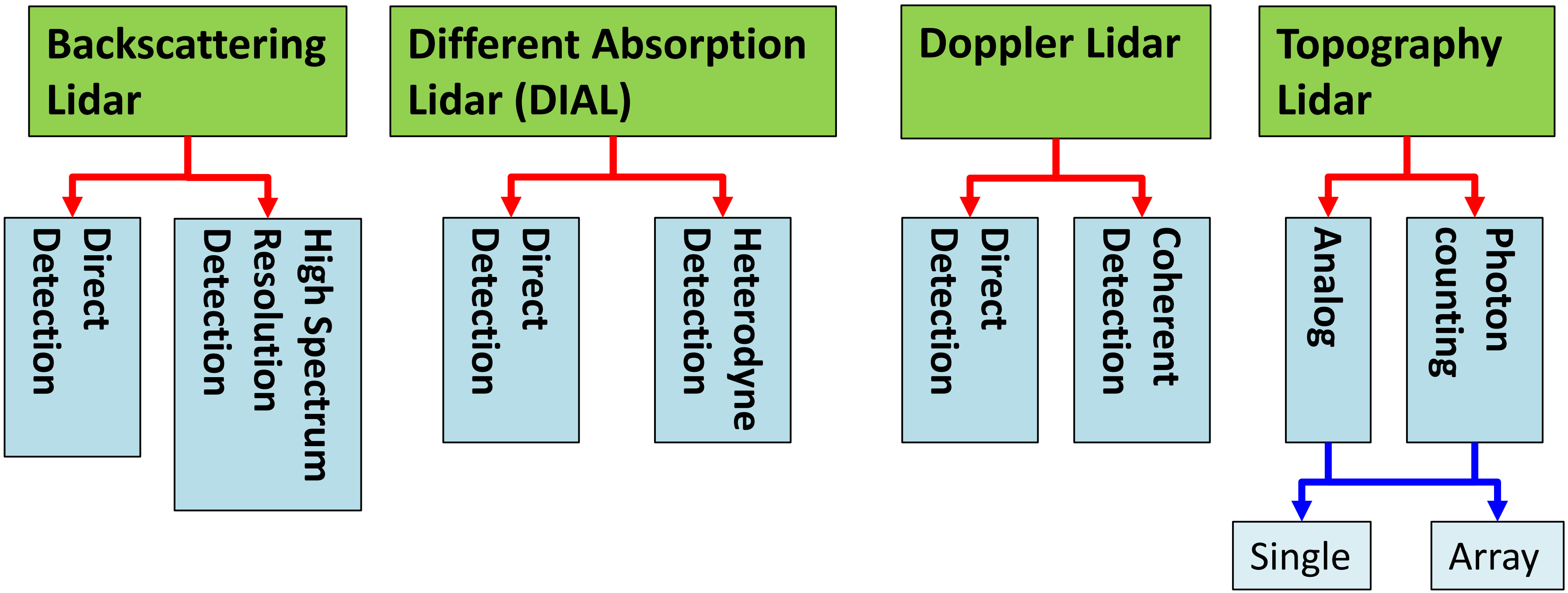
- Spacrborne lidar needs receive enough return power and enough ratio of signal to noise to retrieve information of earth.
- Cross-section, laser power and receiver's area is closely relative to Lidar's return.

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

Classification of Lidar

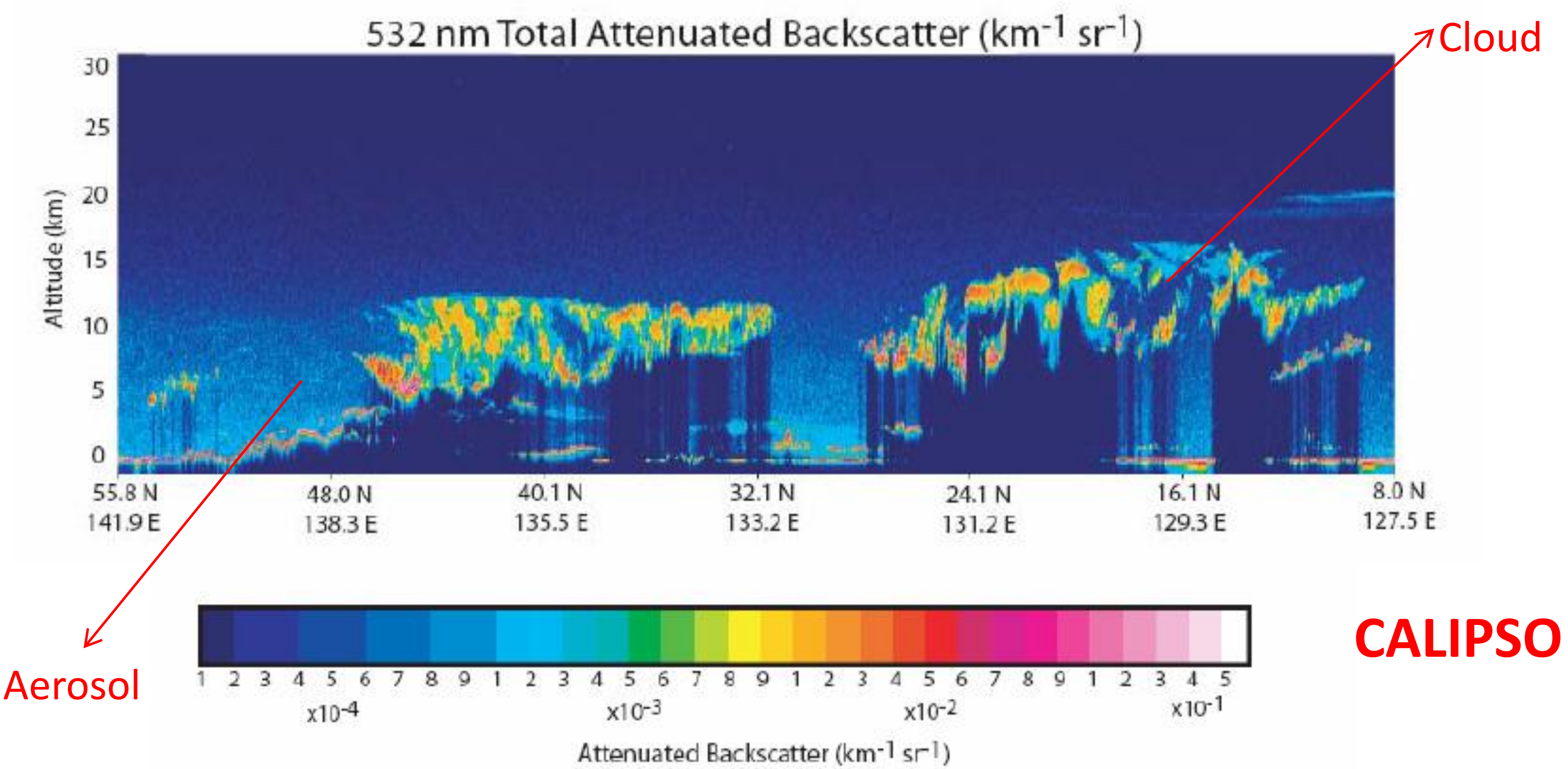
Lidar Type	Principle	Values	Target
Laser altimeter, ~~Laser bathymetry~~	Back reflecting	Time	Topography, Depth (very shallow)
Doppler Lidar	Doppler	Frequency Shift	Wind speed
Different Absorption Lidar	Atomic, molecular absorption	Intensity	Atmospheric composition
Fluorescence Lidar ?	Fluorescence	Wavelength, Intensity	Gas composition Mesosphere
~~Raman Lidar~~	Raman scattering	Wavelength, Intensity	Atmospheric composition, temperature
Mie Lidar	Mie Scattering	Intensity	Aerosol, cloud
Rayleigh Lidar	Rayleigh Scattering	Intensity	Temperature, molecule density

Spaceborne Lidar for Earth Observation



What's requirement of space laser for different Lidar?

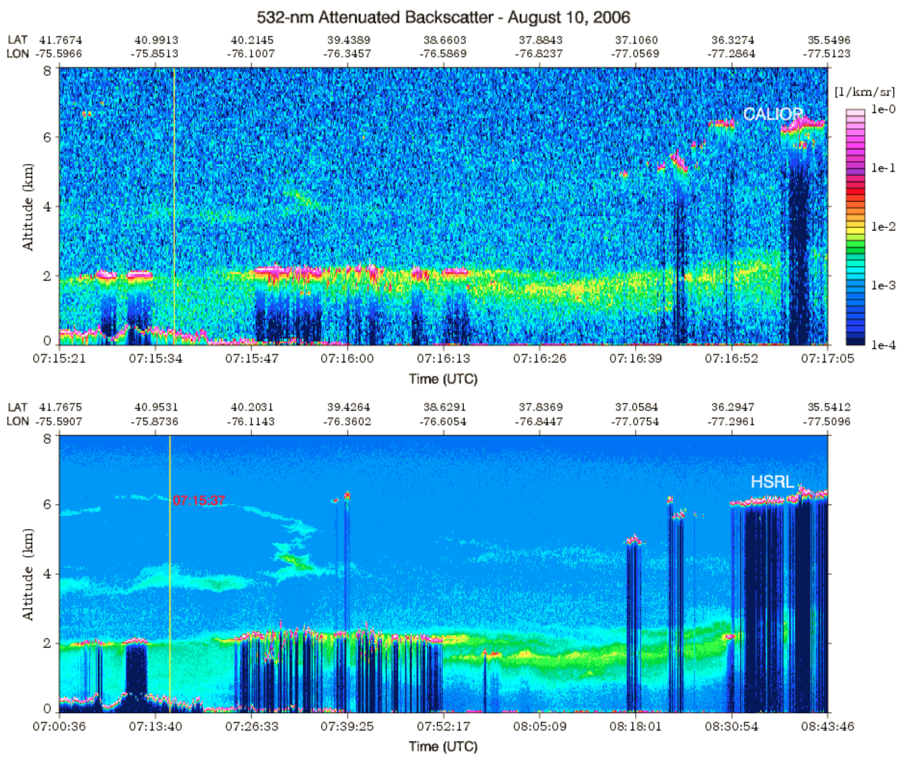
Backscattering Spaceborne Lidar (direct detection)

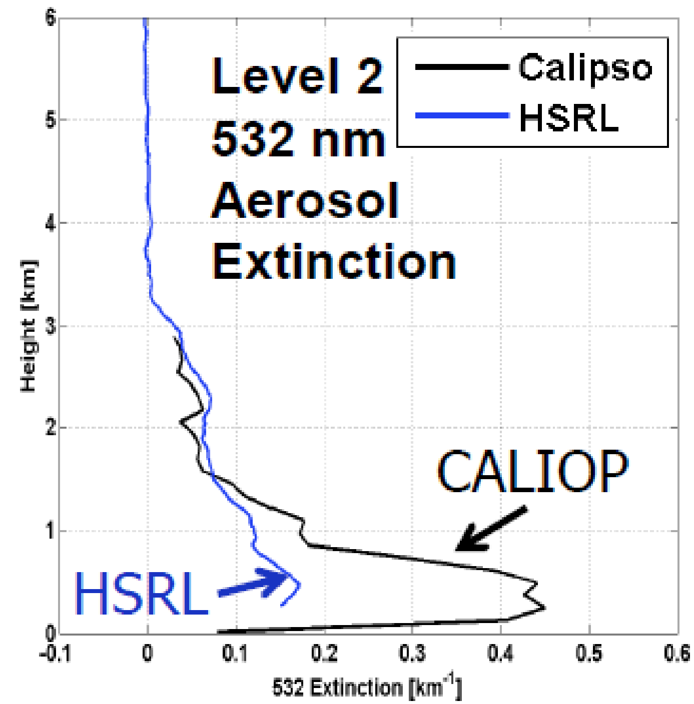


Backscattering Lidar –**Aerosol, molecule optical thickness, cloud top height, and optical thickness**

Laser requirement: high energy, 2~3 wavelengths

Backscattering Spaceborne Lidar

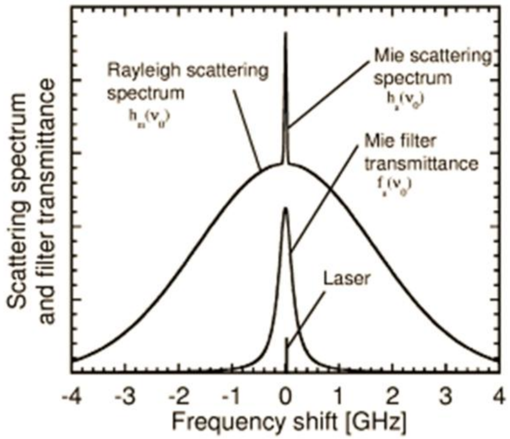


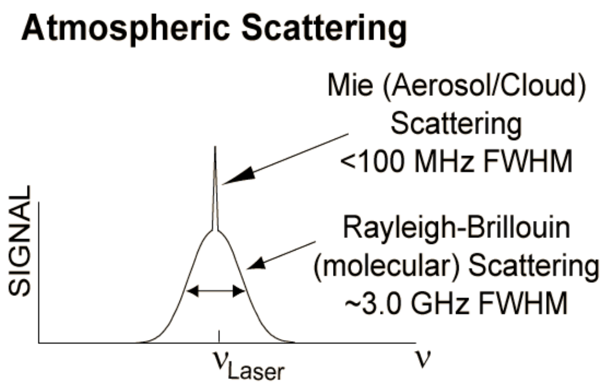


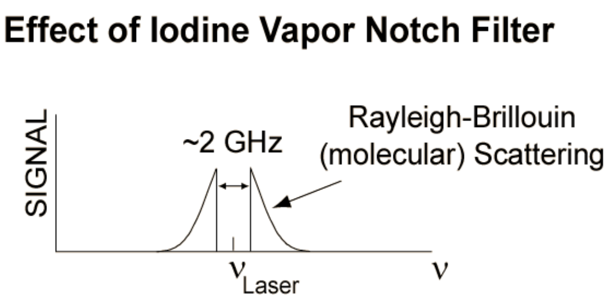
- High spectrum resolution Lidar

Laser requirement of space HRSL Lidar

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





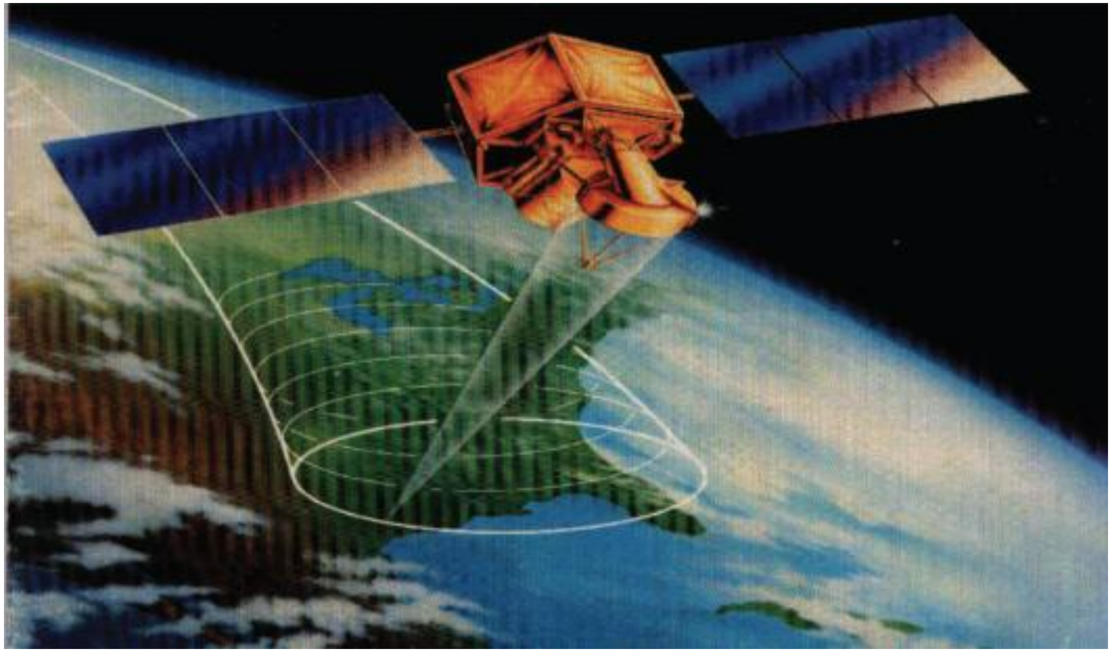


Laser requirement for HSRL:

- ✓ **Single frequency with narrow linewidth**
- ✓ **Frequency stability: ~ 20 MHz**
- ✓ **High energy: ~ 100 mJ**
- ✓ **Two wavelengths**

Rich Ferrare, Chris Hostetler, Ed Browell, John Hair, Spaceborne Aerosol and Ozone Lidars for Air Quality ApplicationsNCAR Community Workshop on Air Quality Remote Sensing from Space, February, 2006

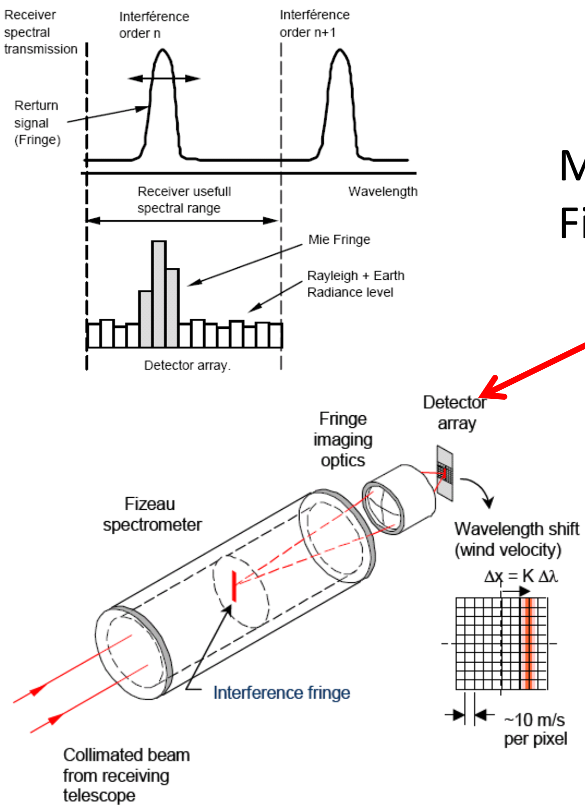
Spaceborne Doppler Lidar



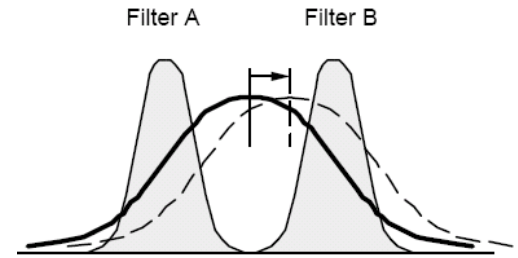
Doppler Lidar: Wind

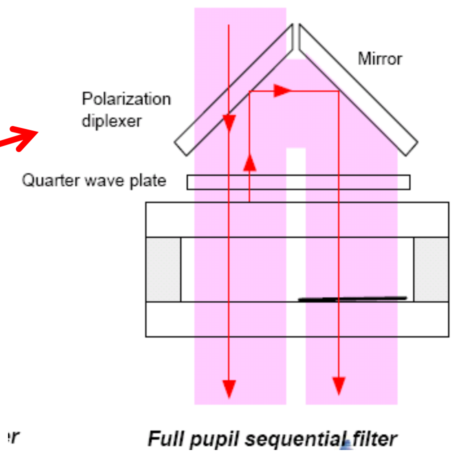
- ✓ Direct direction measurement : ALADIN
- ✓ Coherent measurement

Laser requirement of space Doppler Lidar



Mie detection with Fizeau Filter

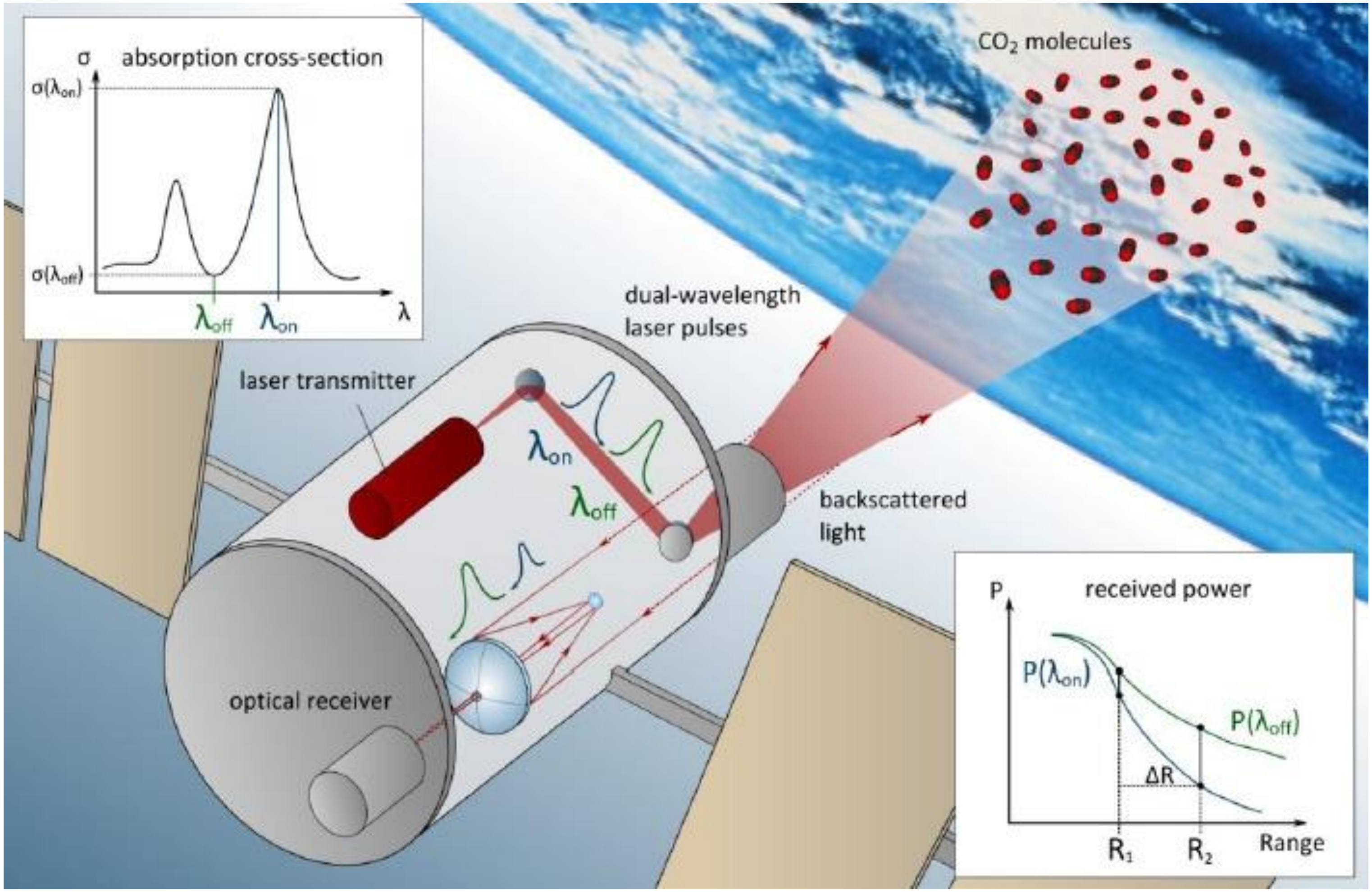




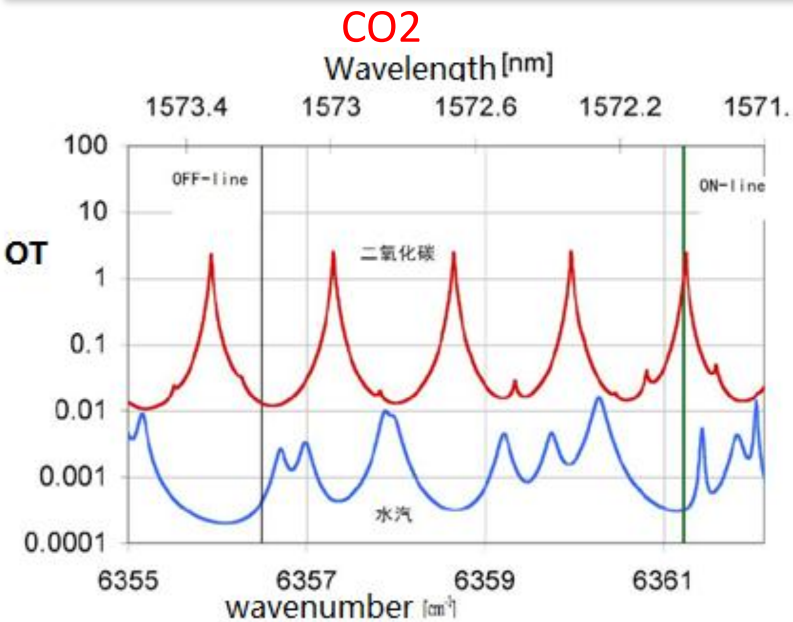
Molecule detection with double FP filter

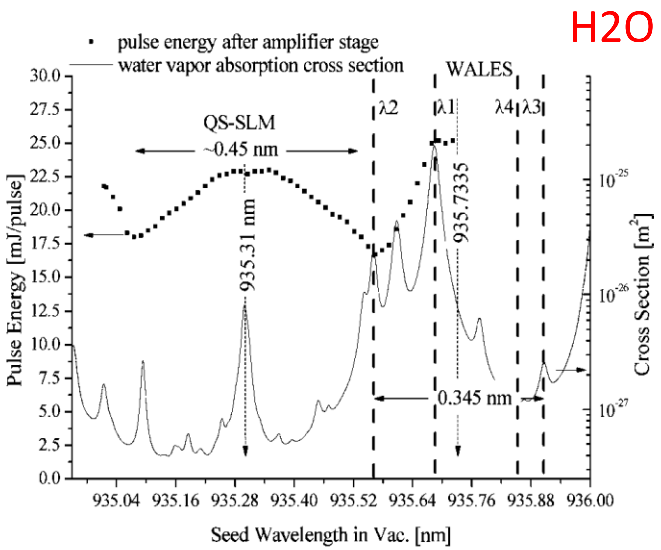
- **Laser for Doppler wind Lidar**
  - **Single frequency, narrow linewidth**
  - **Frequency stability: ~ 1 MHz**
  - **High pulse energy with middle repetition rate**
  - **Usually in UV or 2 micrometer**

Spaceborne DIAL Lidar

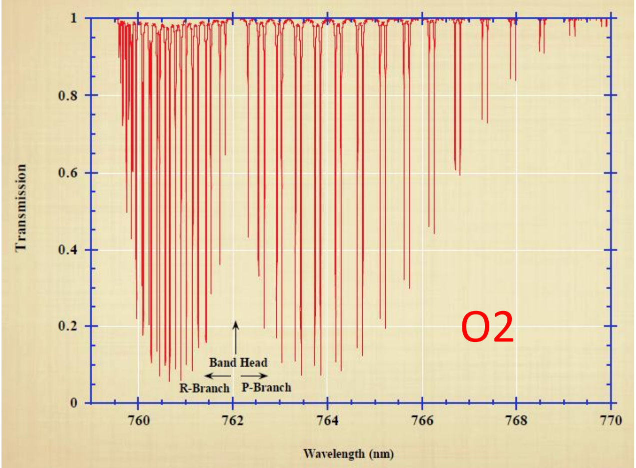


Laser requirement of space DIAL Lidar

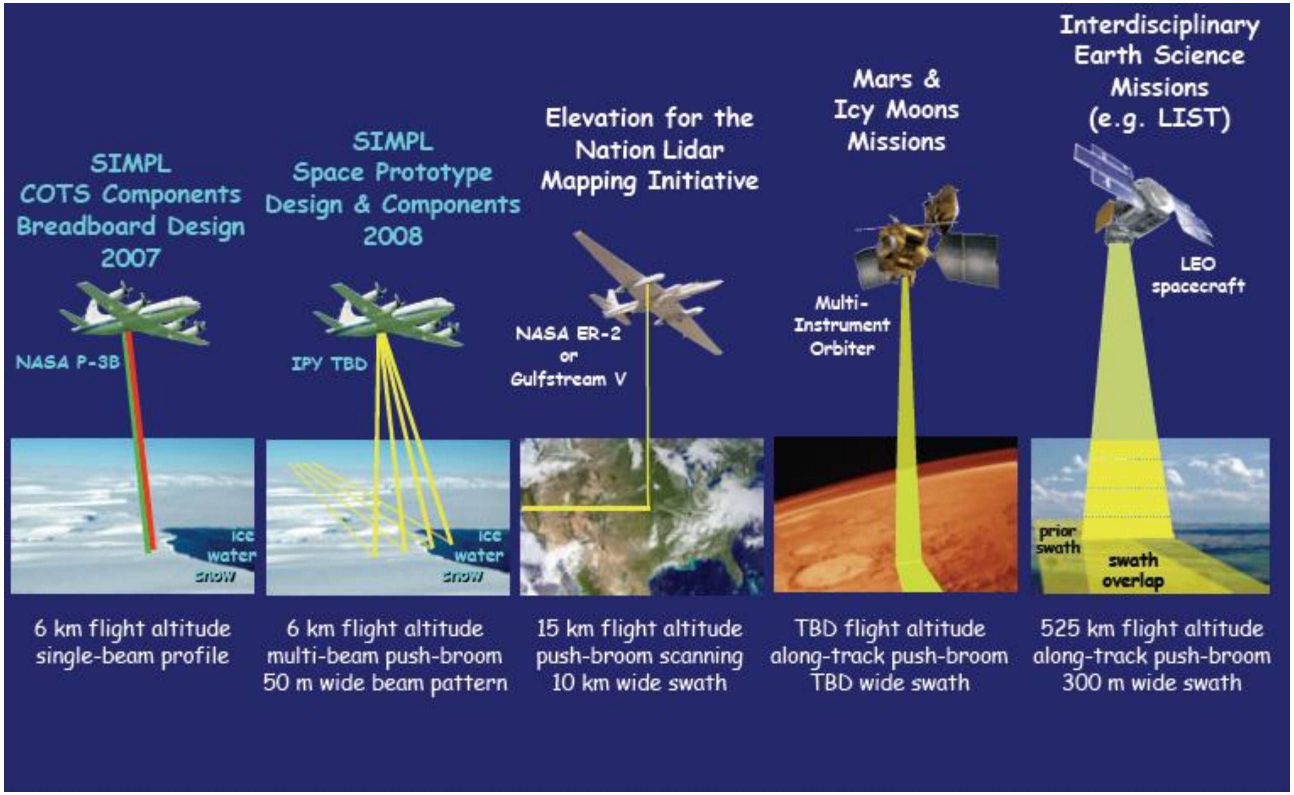




- **Laser for DIAL Lidar:**
  - Exact single wavelength to match absorption line of molecule
  - Usually two or multi-wavelengths
  - Long term wavelength stability
  - Narrow linewidth, such as CO2
  - High spectrum purity
  - High Energy with middle repetition rate



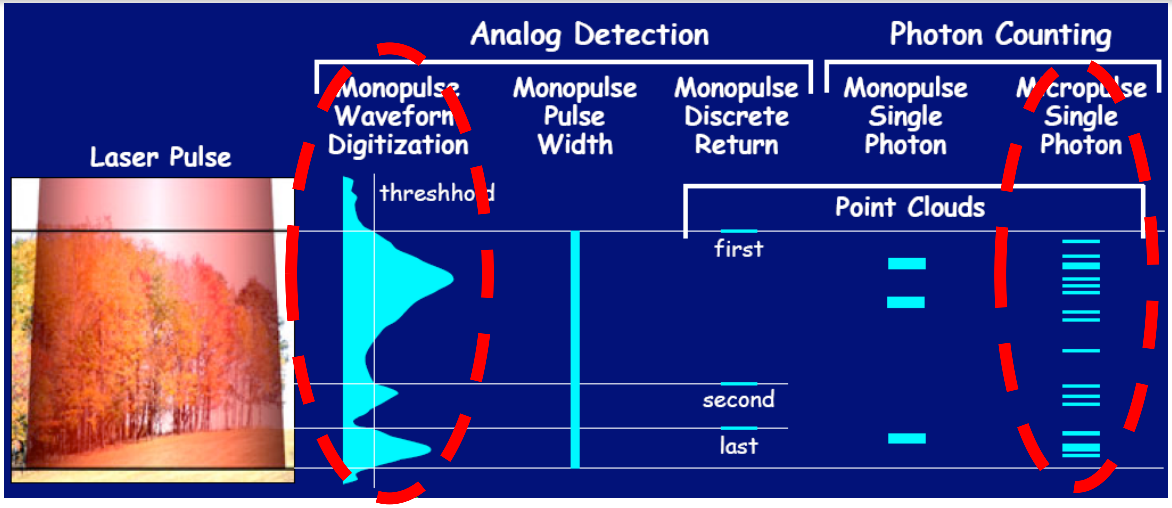
Spaceborne topography Lidar



✓From single beam to multi-beam

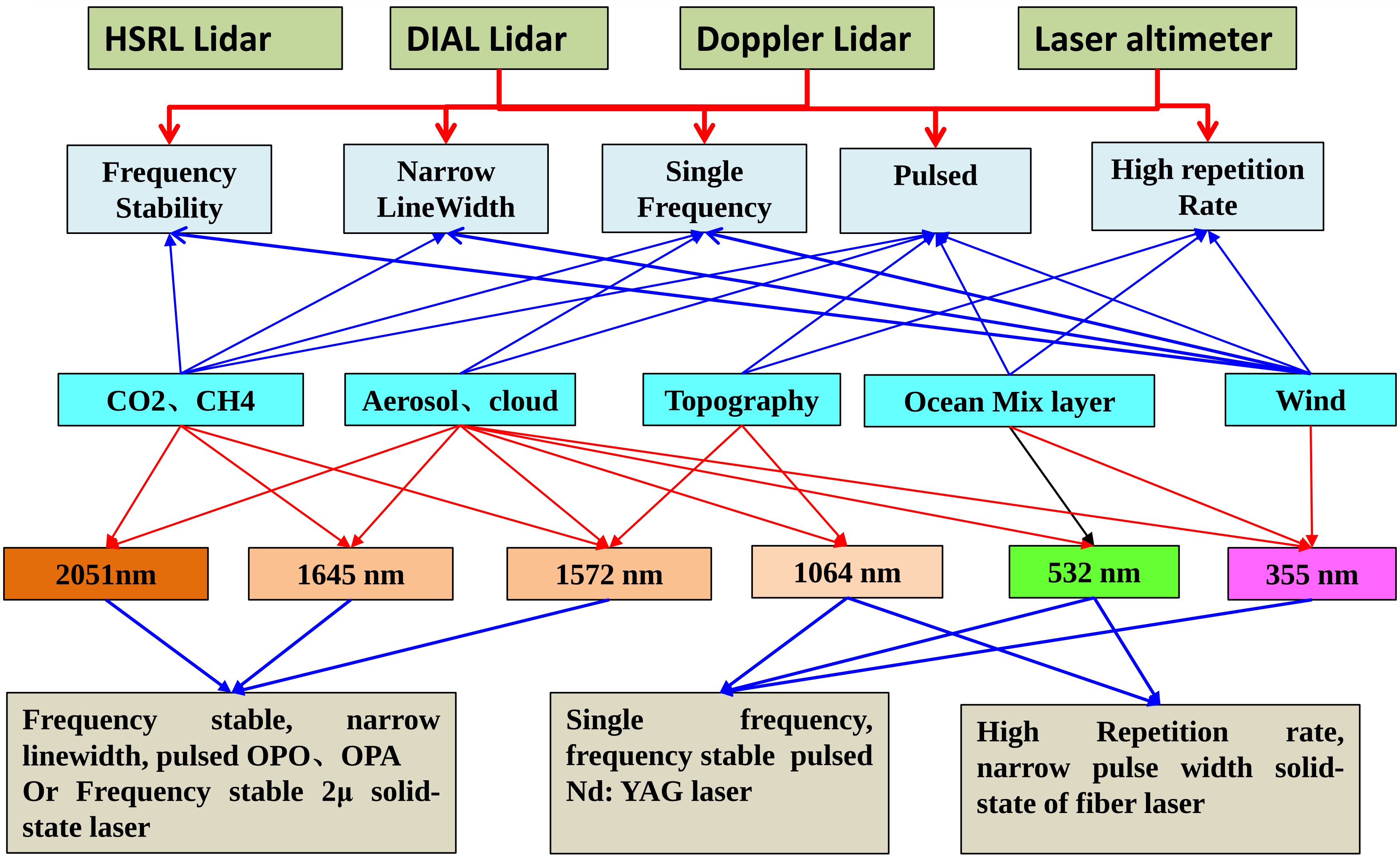
✓From analog detection to photon counting

Laser requirement of space topography Lidar



- ✓ **Laser requirement for topography Lidar**
  - **Analog detection :**
    - **Pulse energy: ~ 70 mJ**
    - **Pulse width: ~7 ns**
    - **Repetition rate: < 100 Hz**
  - **Photon counting:**
    - **Narrow pulse width: < 1ns**
    - **High repetition rate: ~10 kHz**
    - **Low pulse energy: 0.1~ 1 mJ**

Requirement of laser for Earth Observation Lidar



Typical Requirement of space laser for Earth Observation

Sensor	Application		Parameters of laser
Imaging Lidar /laser altimeter	**Earth**		Wavelength: 1 μm, Pulse energy:> 150 mJ, PRF:1~40 Hz
	Planetary		Wavelength: 1 μm, Pulse energy:> 50 mJ, PRF: 1~20 Hz
	Topography		Wavelength: 1 μm， Pulse energy:> 100 μJ PRF: 5~10 kHz， Beam number:1000
Atmospheric Lidar	**Wind**	**Direct Detection**	Wavelength: 0.35 μm， Single frequency, narrow linewidth, Pulse energy: >150 mJ， PRF: >100 Hz
		Coherent Detection	Wavelength: 2.05 μm, Single frequency, narrow linewidth, Pulse energy: >1 J, PRF>50 Hz
	Backscattering （Cloud, aerosol		Wavelength: 0.35 μm， 0.5 μm， 1.0 μm， Single frequency, Pulse energy: >100 mJ, PRF: 20~50 Hz
	DIAL	**CO_2**	Wavelength:1.57 μm /2.05 μm, Frequency stability:<0.3 MHz, Pulse energy: >50 mJ, PRF: > 50 Hz
		CH_4	Wavelength: 1.65 μm , Frequency stability: < 0.9 MHz Pulse energy: >20 mJ, PRF: > 50 Hz

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.

Patricia Daukantas

Lidar in SPACE:

From Apollo to the 21st Century

Over the last four decades, spaceborne lidar instruments have evolved beyond their original application—altimetry—to tracking glacier melting, gauging wind speeds and spotting snow on Mars.

When laser-ranging technology was first developed in the 1960s, no one could have envisioned that it would become a key tool for exploring Earth and its neighboring planets from space. From hundreds of kilometers away, lidar systems can give scientists a broad overview of features that would have escaped notice from lower altitudes.

Whether the platform is a spacecraft, an aircraft or a base on the ground, the components of lidar systems are the same: a laser and scanning optics, a receiver (often a telescope equipped with a photodetector) and position and navigation systems. As in radar, with its radio-frequency pulses, lidar sends out laser pulses that reflect off a certain target and register as a signal back in the system's detector. Frequencies range from near-infrared to ultraviolet, depending on the need.

In space, lidar systems have taken careful measurements of other solar system bodies and have even collected data on martian weather. From low Earth orbit, lidar has tracked the shrinkage of glaciers and the movement of clouds, and, in the next few years, the technology will tackle the three-dimensional profiling of wind—a critical missing component from short-term meteorological and long-term climate-change models.

Space lidar started with the ruby laser, but the Nd:YAG laser has become the light source of choice, especially since its fundamental, doubled and tripled frequencies can sense aerosol particles as well as macroscopic surfaces. In meteorology, geology and even forestry, lidar systems flying on airplanes and spacecraft

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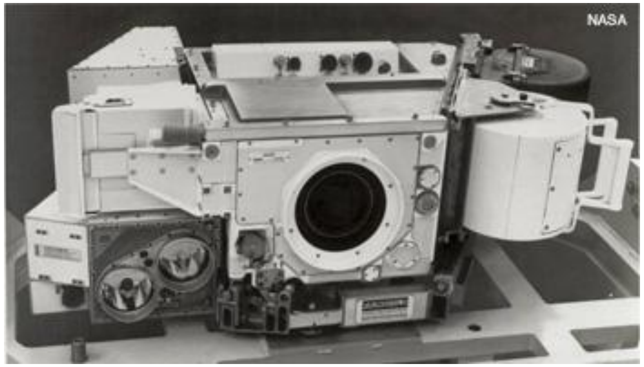
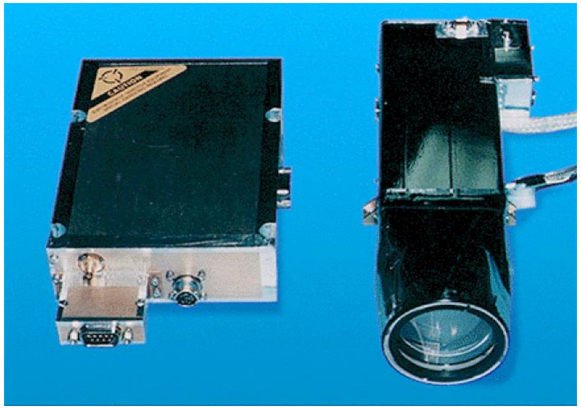
History of spaceborne laser



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.



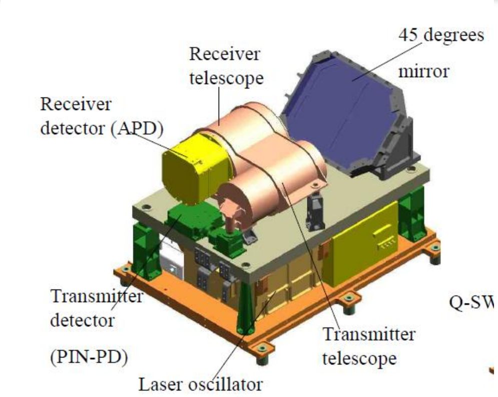
Clementine laser altimeter (USA, 1994)

Moon explorer

Diode pumped Nd:YAG
- Wavelength: 1064 nm
- Q-switch : $LiNbO_3$
- Pulse energy :171 mJ
- Pulse width: 8 ns
- PRF: 1-8 Hz

1. Roberson FL, Kaula WM. Apollo 15 laser altimeter [C]. Apollo 15: Preliminary Science Report. 1972:48.
2. Nozette Stewart, Rustan P, Pleasance LP, etc. The Clementine mission to the Moon: Scientific overview [J]. Science, 1994, 266(5192): 1835-1839.

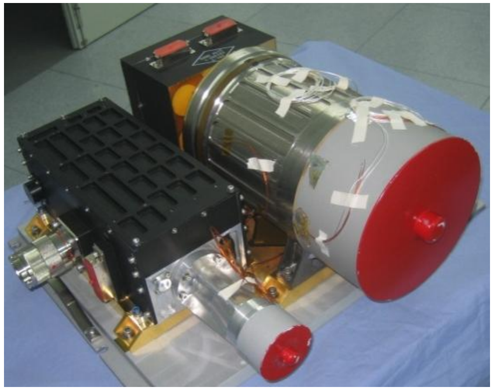
History of spaceborne laser



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



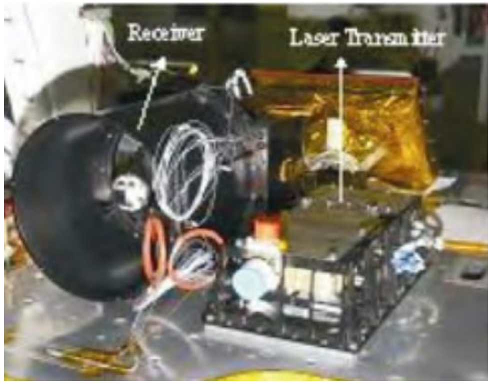
Diode Pumped Nd:YAG

- 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

1. KASE Teiji, ABE Kikuo, HOTTA Tomomi, etc. LALT: Laser Altimeter for luna exploring satellite SELENE: Active and passive sensors for remote sensing [J]. NEC research & development, 2003, 44(2): 175-180.
2. J. Wang, S. Rong, W. Chen, CE-1 Laser altimeter, Science bulletin of China , 2010, (8): 1063-1070.

History of spaceborne laser

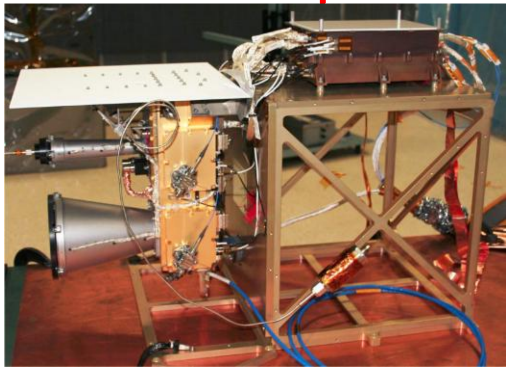


LLRI laser Altimeter (India, 2008)

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**

1. Kamalakar JA, Prasad AS Laxmi, Bhaskar KVS, etc. Lunar laser ranging instrument (LLRI): a tool for the study of topography and gravitational field of the moon [J]. Curr. Sci, 2009, 96(4): 512-516.
2. Smith David E, Zuber Maria T, Jackson Glenn B, etc. The lunar orbiter laser altimeter investigation on the lunar reconnaissance orbiter mission [J]. Space Science Reviews, 2010, 150(1-4): 209-241.

History of spaceborne laser

Diode Pumped Nd:YAG

- **Q-switch: Active, LiNbO3**
- **Pulse Energy:42mJ**
- **Pulse energy : 8 ns**
- **PRF: 10 Hz**

MOLA Mars Laser altimeter (USA, 1996)

Mars explorer

Diode pumped Nd:YAG

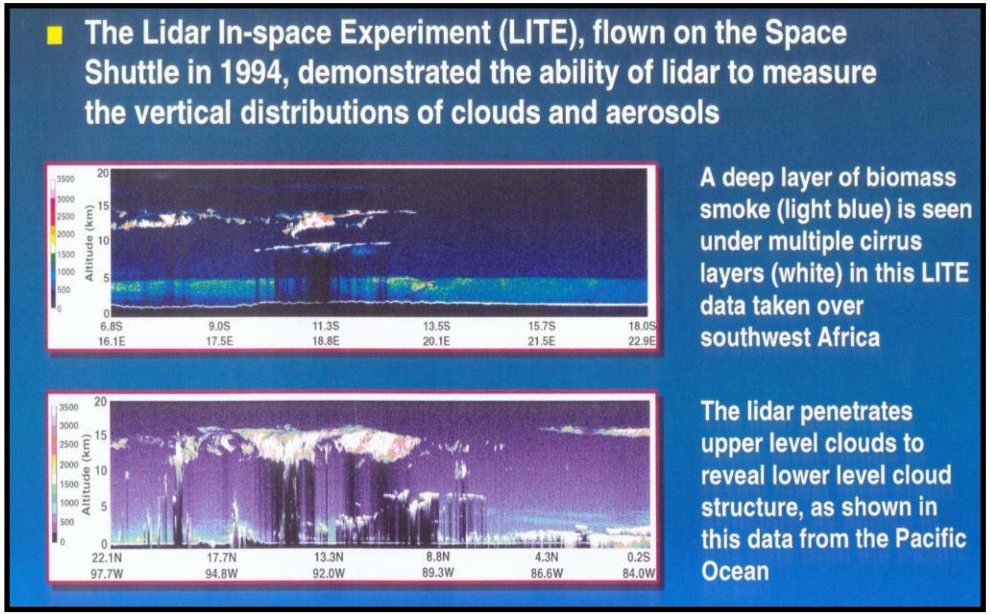
- **Q-switch: Passive, Cr:YAG**
- **Pulse energy: 20 mJ**
- **PRF: 8 Hz**

Mercury Laser altimeter (USA, 2004)

Mercury Explorer

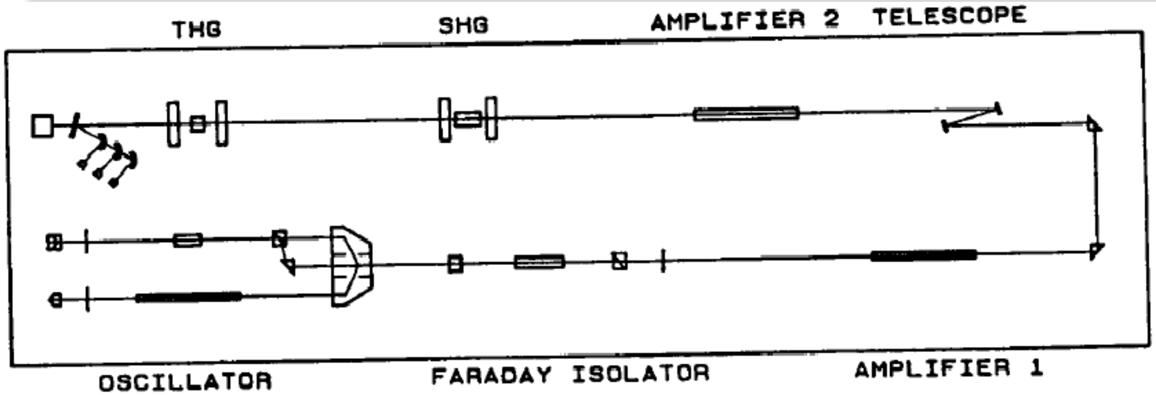
1. Afzal Robert S. Mars observer laser altimeter: laser transmitter [J]. Applied Optics, 1994, 33(15): 3184-3188.
2. Zuber Maria T, Smith David E, Solomon Sean C, etc. Laser altimeter observations from MESSENGER's first Mercury flyby [J]. Science, 2008, 321(5885): 77-79.

Lidar for earth observation

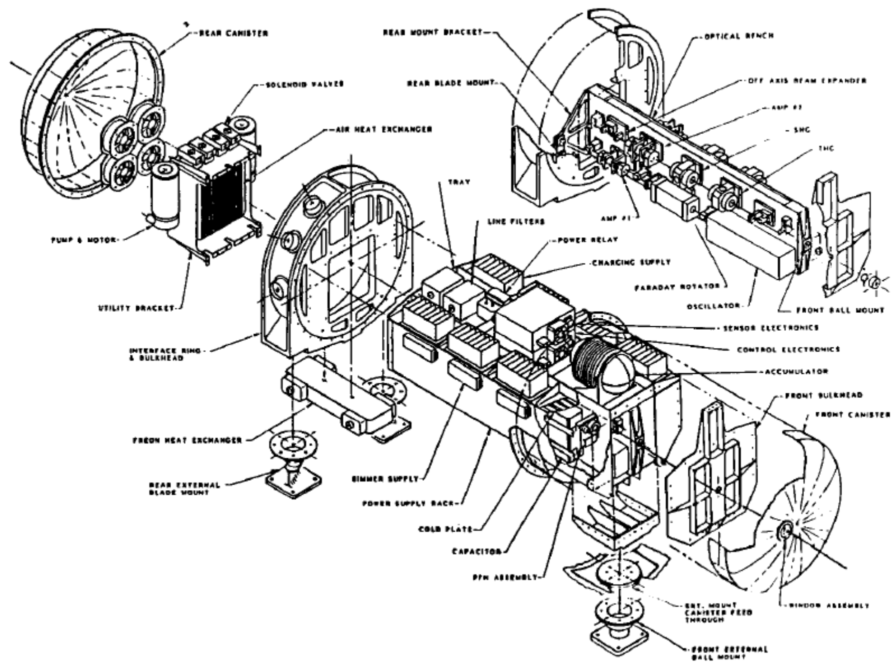


- ✓ LITE is first lidar to observe atmosphere of earth on space shuttle; Milestone
- ✓ It run only 21 days. It was a successful demonstration of lidar for earth remote sensing.
- ✓ **Lamp pumped** Nd:YAG at 1064 nm, 532 nm, and 355 nm

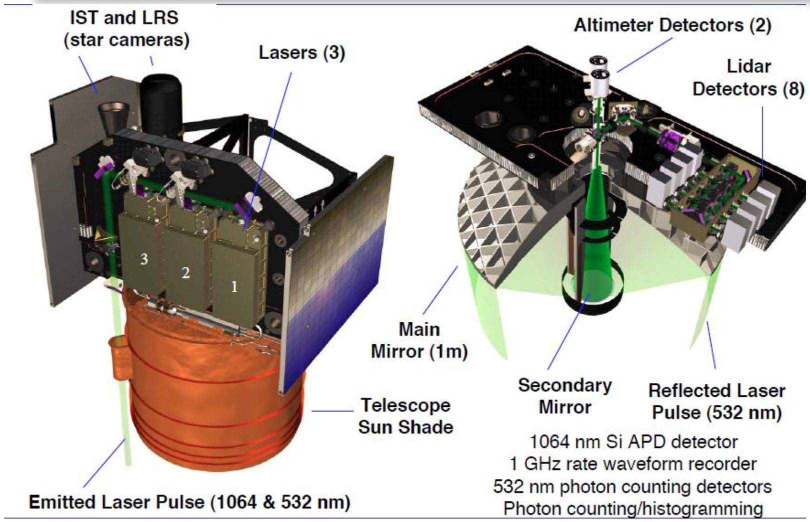
Lidar for earth observation



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



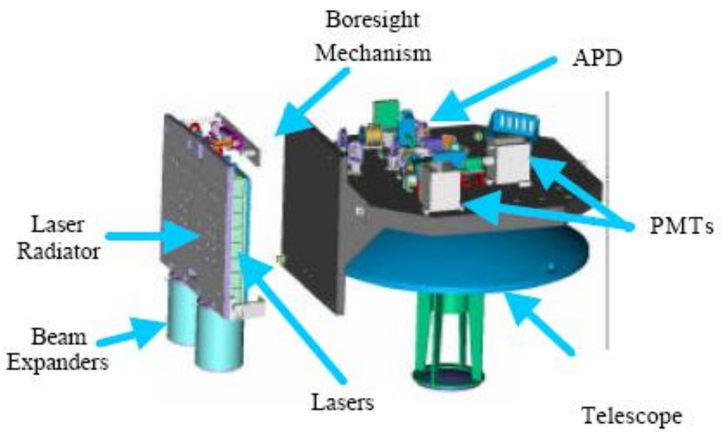
History of spaceborne laser



GLAS- Laser altimter

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**

1. Abshire James B, Ketchum EA, Afzal RS, etc. The geoscience laser altimeter system (GLAS) for the ICEsat mission [C]. Lasers and Electro-Optics, 2000.(CLEO 2000). Conference on. IEEE, 2000:602-603.
2. Winker David M, Hunt William H, Hostetler Chris A. Status and performance of the CALIOP lidar [C]. Remote Sensing. International Society for Optics and Photonics, 2004:8-15.

Lunched spaceborne laser (Laser altimeter)

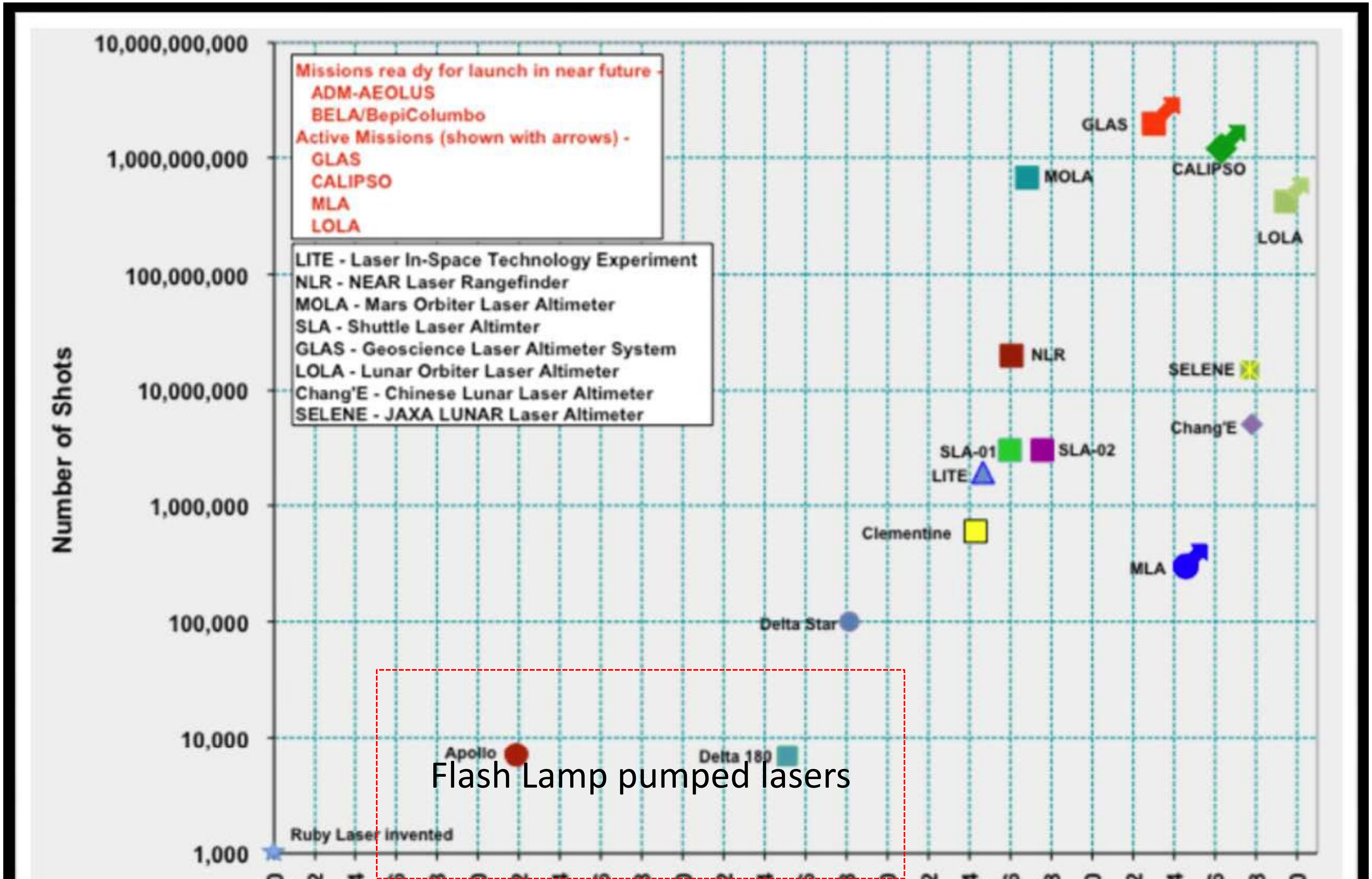
	Sensor		year	Laser specification
Earth	SLA-01	NASA	1996	Nd:Cr:YAG，40 mJ，10 ns，10 Hz， 1064 nm
	SLA-02	NASA	1997	Nd:Cr:YAG，40 mJ，10 ns，10 Hz， 1064 nm
	MPL/DS2	NASA	1999	lost
	Icesat/GLAS	NASA	2003	Nd:YAG，74 mJ/35mJ，5 ns，40 Hz，1064 nm/532 nm
Moon	clementine	NASA	2004	Nd:Cr:YAG，170 mJ，10 ns，1 Hz，1064 nm
	SELENE/LALT	Japan	2007	Nd:YAG，100 mJ，15 ns，1 Hz，1064 nm
	CE-1	China	2007	Nd:YAG，150 mJ，7 ns，1 Hz，1064 nm
	Chandrayaan/LLRI	India	2007	Nd:YAG，10 mJ，10 Hz，1064 nm
	LOLA	NASA	2009	Nd:YAG，2.7 mJ，7 ns，28 Hz，1064 nm，5 beams
	CE-2	China	2010	Nd:YAG，75 mJ，7 ns，3 Hz，1064 nm
	CE-3	China	2013	Nd:YAG，45 mJ，7 ns，5 Hz，1064 nm
Mars	MOLA 1	NASA	1992	Lost
	MOLA 2	NASA	1996	Nd:Cr:YAG，42 mJ，8 ns，10 Hz, 1064 nm
Mercury	Messenger/MLA	NASA	2004	Nd:Cr:YAG，20 mJ，8 ns，8 Hz，1064 nm
Mercury	Bepicolombo	ESA	TBD	actively Q-switched, diode laser pumped Nd:YAG , 50 mJ, 3~8 ns, 1~10 Hz

Lunched spaceborne laser (Lidar)

Earth	LITE	NASA	1994	Nd:Cr;YAG 1064 nm/532 nm/355 nm ,Lamp pumped
	BALKAN	Russia	1995	Nd:Cr;YAG，1064 nm/532 nm，lamp pumped
	GLAS	NASA	2003	Nd:YAG，74 mJ/35mJ，5 ns，40 Hz，1064 nm/532 nm
	CALIPSO	NASA	2006	Nd:YAG，110 mJ@1064 nm & 532 nm，20Hz
	ALADIN	**ESA**	**TBD**	**Single frequency Nd:YAG,** **150 mJ @355 nm, 100 Hz**
Mars	Phoenix	NASA	2007	Nd:YAG，30 mJ，15 ns，1 Hz，1064 nm，532 nm

Lunched spaceborne laser(Others)

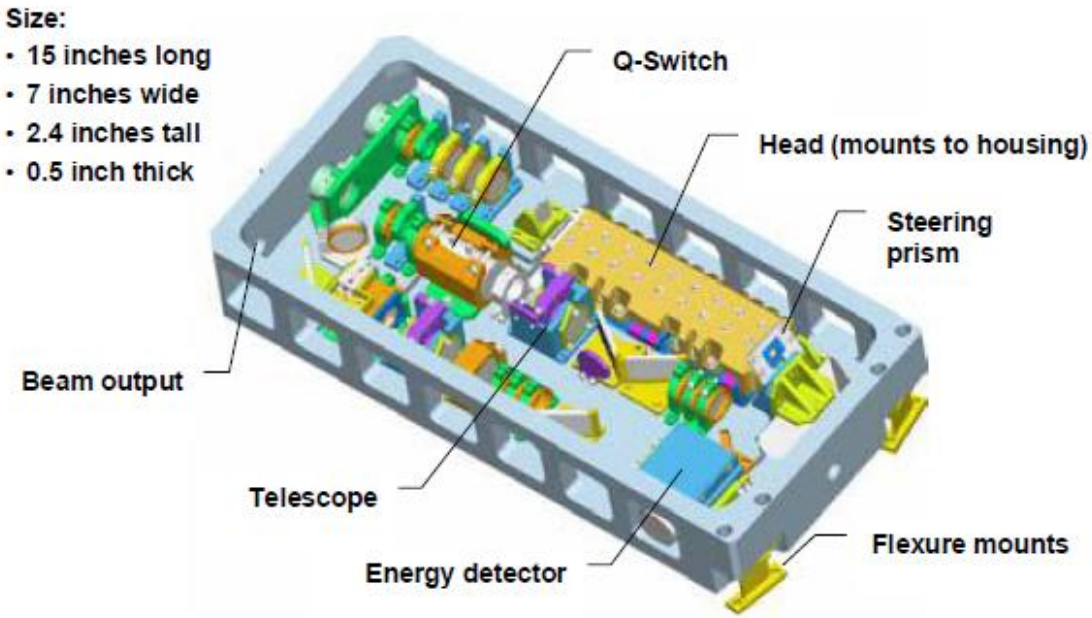
Application	Sensors		year	Parameters of laser
Laser Communication	SILEX/	ESA		AlGaAs Diode laser，847 nm/819 nm，100 mw
	TerraSAR-X	ESA	2007	Nd:YAG+fiber amplifier，1064 nm，1.2 W，SLM
	ALphsat and Sentine 1+2	ESA	2013	Nd:YAG + fiber amplifier，1064 nm，2.5 W，SLM
	LLCD	NASA	2013	Er:Fiber，0.5 W，1550 nm
RVD Lidar	ETS-VII	JAPAN	1998	Laser diode
	XSS-11	NASA	2005	Cr,Nd:YAG，1064 nm，10 kHz，1 ns，
Gravitational-Wave	LISA、eLISA	ESA	TBD	NPRO Nd:YAG
Cold atomic clock	PHARAO	ESA	TBD	Cs stabled 852 nm, diode laser
	CCAC	China	2016	Rb stabled 780 nm, diode laser
	CAL	NASA	TBD	Rb, K，780 nm，852 nm，767 nm，Diode laser or Frequency doubled Fiber laser (1560 nm or 1534 nm)

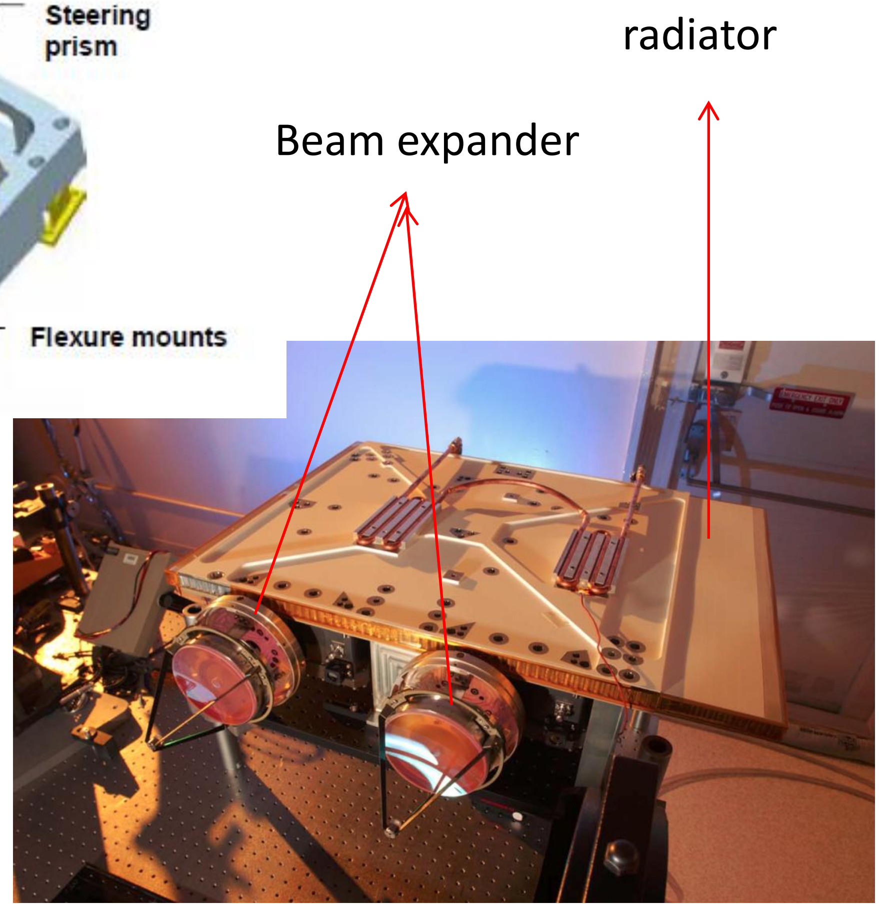


- More than 30 solid-state lasers were lunched into space for lidar measurement.

Robert S. Afzal, Review of Solid-State Lasers for Space Applications, Solid State Lasers XV: Technology and Devices, Proc. of SPIE Vol. 6100, 61001U, (2006)

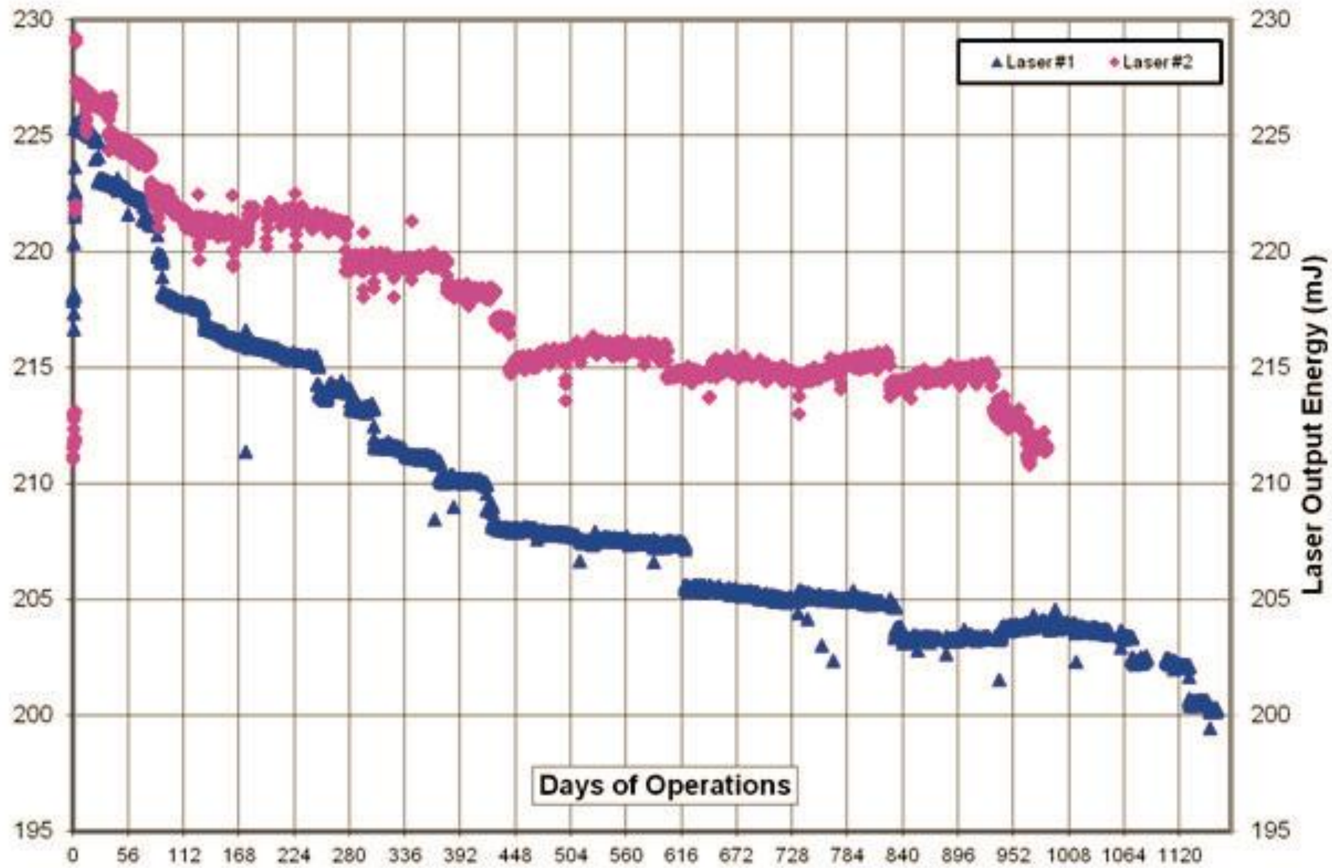
Performance of CALIPSO's laser





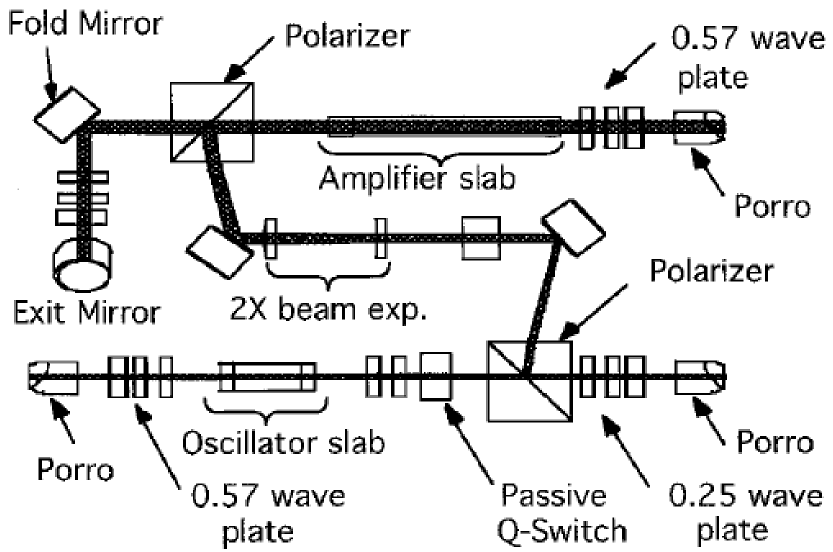
- ✓Folded Porro cavity
- ✓Diode side pumped SLAB
- ✓KD*P Q-switch
- ✓KTP frequency doubled
- ✓Operated in air sealed container

Performance of CALIPSO's laser

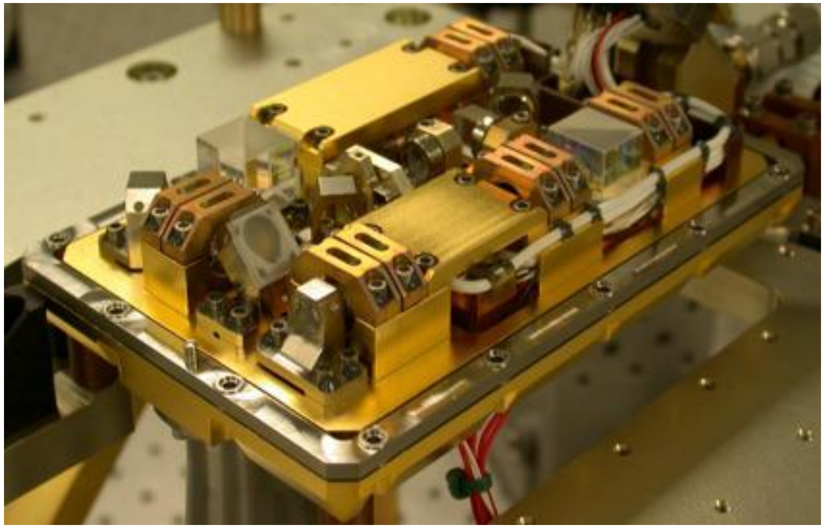


Floyd Hovis, THE LASER TRANSMITTERS FOR THE NASA/CNES CALIPSO AND NASA ICESAT-2 MISSIONS, IGARSS 2012

Performance of MLA's laser

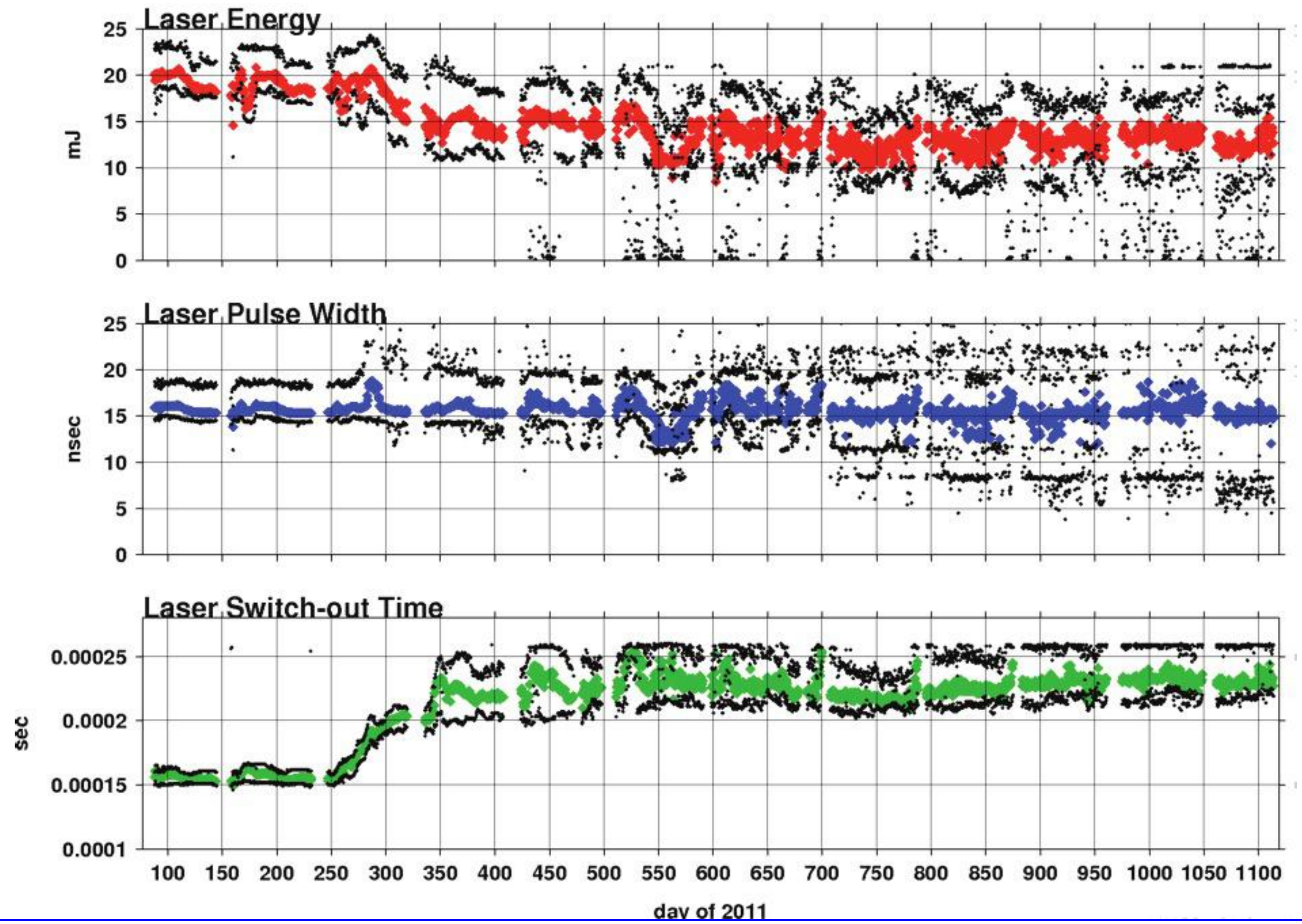


- ✓ **Linear Porro cavity oscillator +power amplifier**
- ✓ **Cr:YAG passively Q switched**
- ✓ **Side pumped SLAB for oscillator and amplifier**
- ✓ **Operated in vacuum**



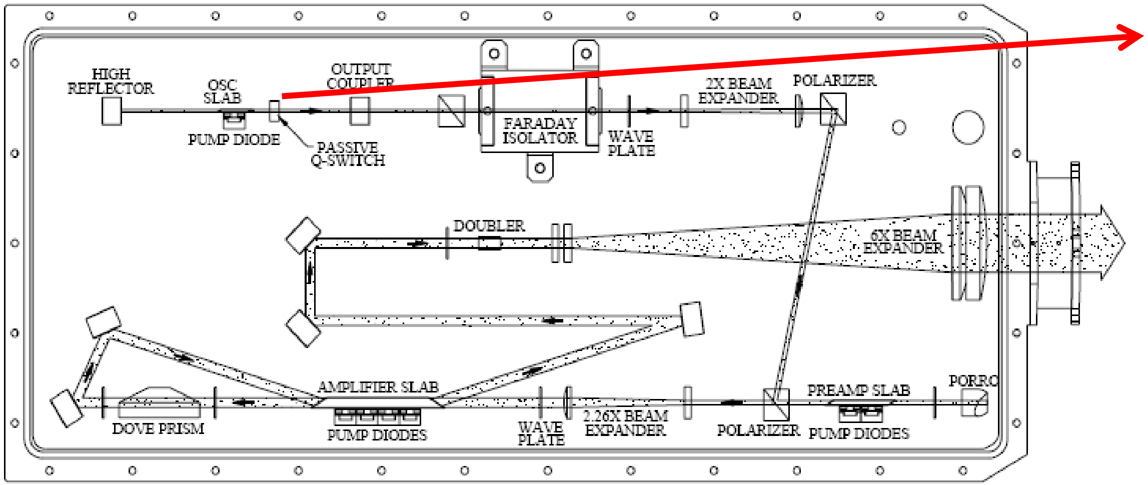
Performance of MLA's laser

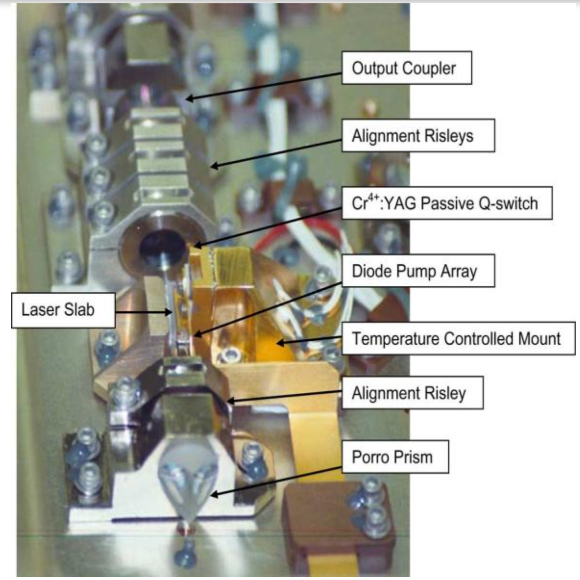
Mercury laser altimeter form 2011

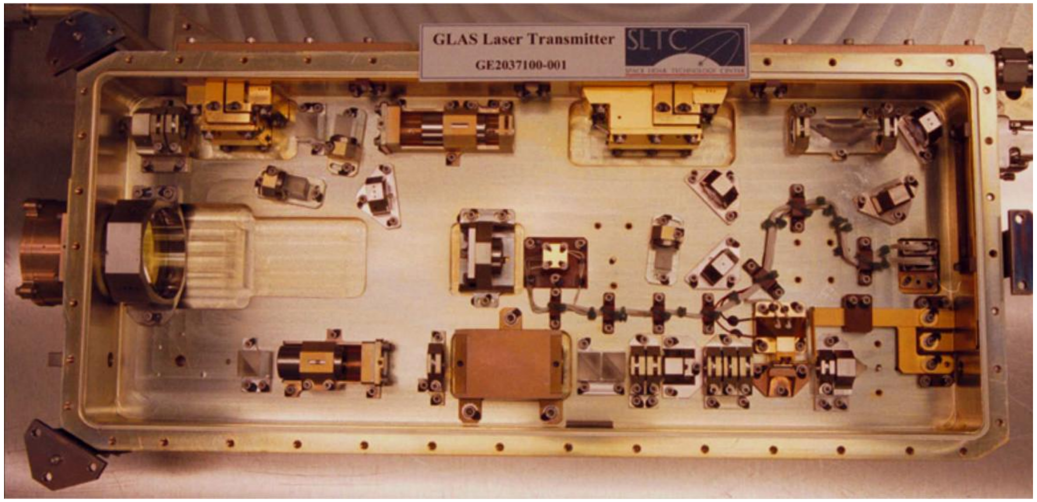


Anthony W. Yu1, Xiaoli Sun, Steven X. Li, John F. Cavanaugh, and Gregory A. Neumann, In-Flight Performance of the Mercury Laser Altimeter Laser Transmitter, Solid State Lasers XXIII: Technology and Devices,Proc. of SPIE Vol. 8959,

Performance of GLAS's laser

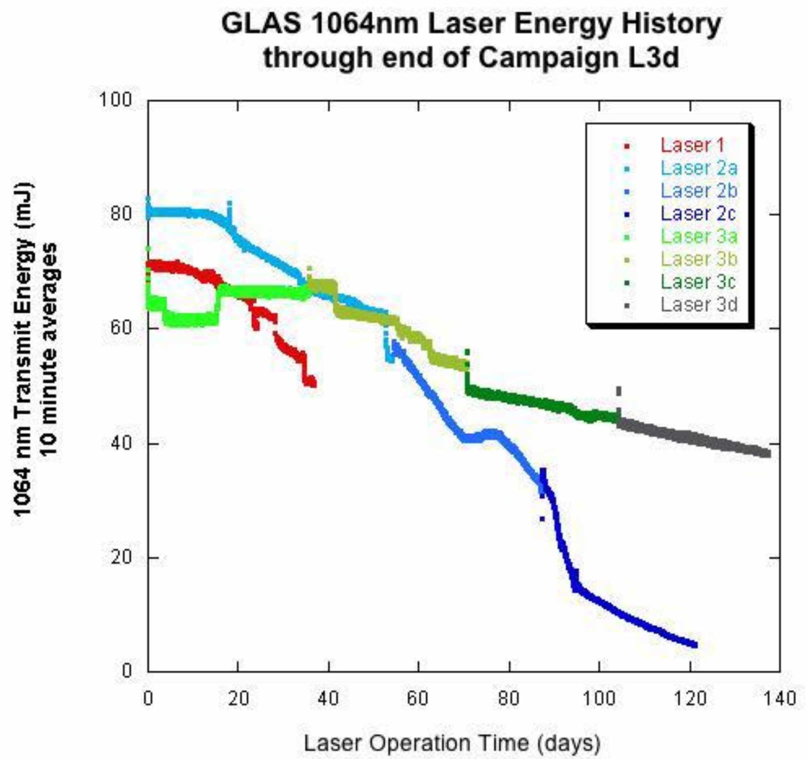


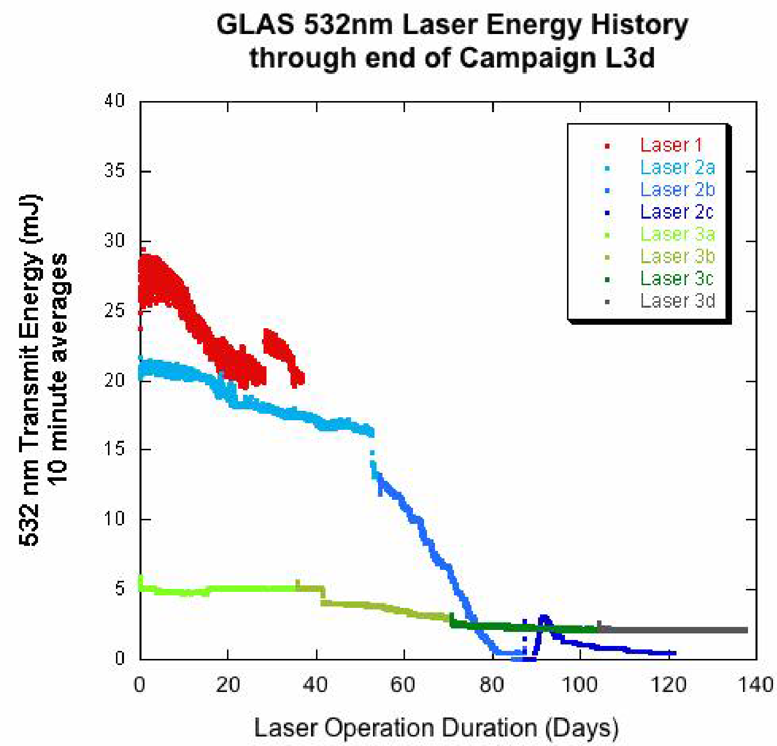




- ✓Linear hemi-porro cavity
- ✓Cr:YAG passively Q-switched
- ✓Double pass Pre-amplifier + power amplifier
- ✓Side pumped SALB
- ✓Frequency doubled
- ✓Operated in vacuum

Performance of GLAS's laser



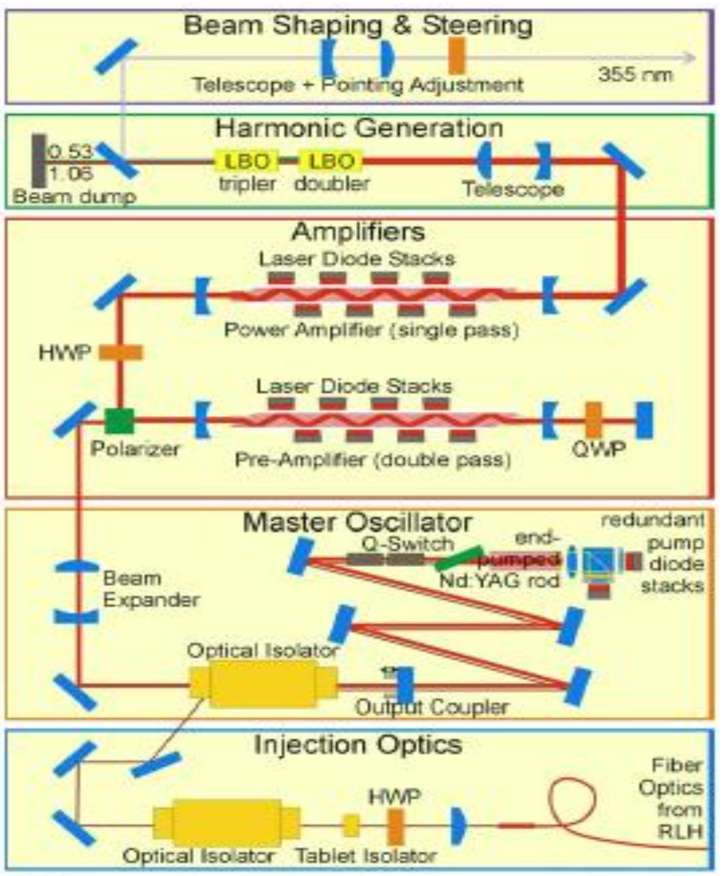


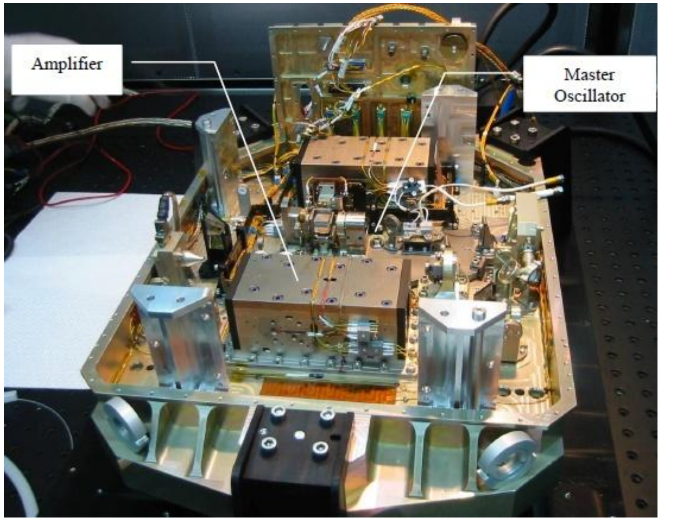
Performance of the GLAS Laser Transmitter, Solid State Lasers XV: Technology and Devices, Proc. of SPIE Vol. 6100, 610020, (2006)

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

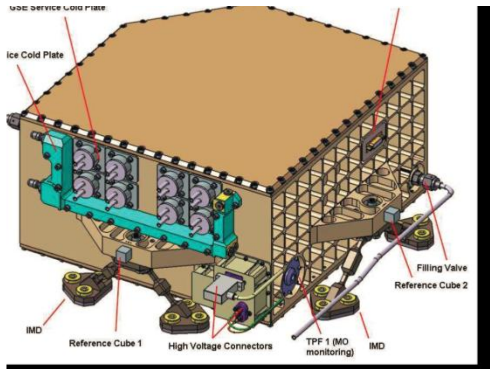


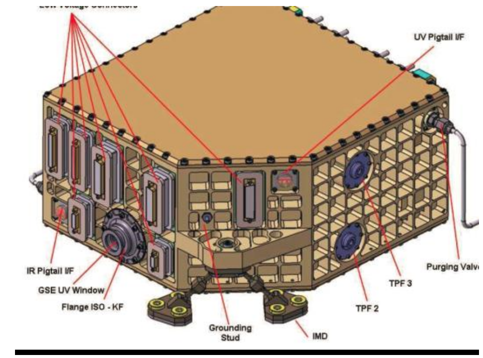


- ✓ **Injection Seeding, MOPA**
- ✓ **Folded linear cavity**
- ✓ **Double pre-amplifier+ power amplifier**
- ✓ **Sided pumped SLAB**
- ✓ **Frequency trebled**
- ✓ **Operated in vacuum? Or with O2 to avoid optics damage**

1. UV CHARACTERIZATION OF ENGINEERING QUALIFICATION MODEL OF ALADIN LASER TRANSMITTERINTERNATIONAL CONFERENCE ON SPACE OPTICS 2006
2. Didier Morançais, Frédéric Fabre, Martin Endemann, Alain Culoma, ALADIN Doppler Wind Lidar: Recent advances, Lidar Technologies, Techniques, and Measurements for Atmospheric Remote Sensing III,, Proc. of SPIE Vol. 6750, 675014, (2007)

ATLID's laser





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

✓ Similar design with ALADIN with modified cooling system and structure

✓ **Operated in sealed air pressurized environment**

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

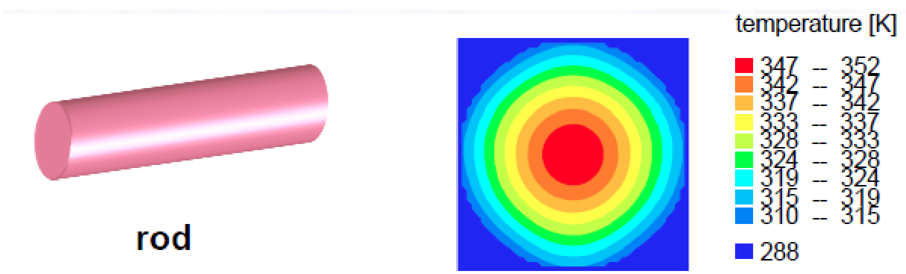
- Application of Lidar remote sensing
- History of spaceborne Laser
- **Design of spaceborne solid-state Laser**
- Examples of developing spaceborne laser
- Laser Components in Space Environment
- Conclusion

Special characteristics of spaceborne laser

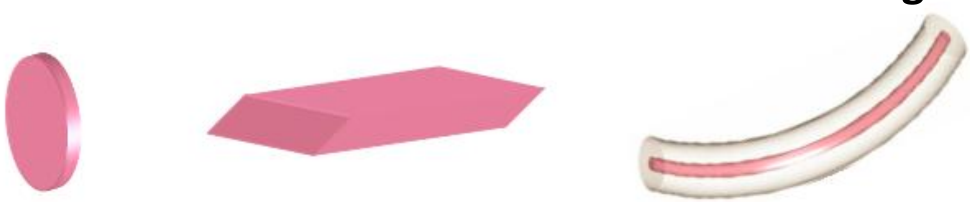
- ✓ **Compact, robust;**
- ✓ **high efficiency and conductively cooling**;
- ✓ **Long lifetime under space environment** (vacuum, radiation, Temperature)；
- ✓ **High beam point stability** after vibration, TVAC testing ,and it is most important for lidar, especially.

Typical Lasers for Space Application

- Most lunched 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**

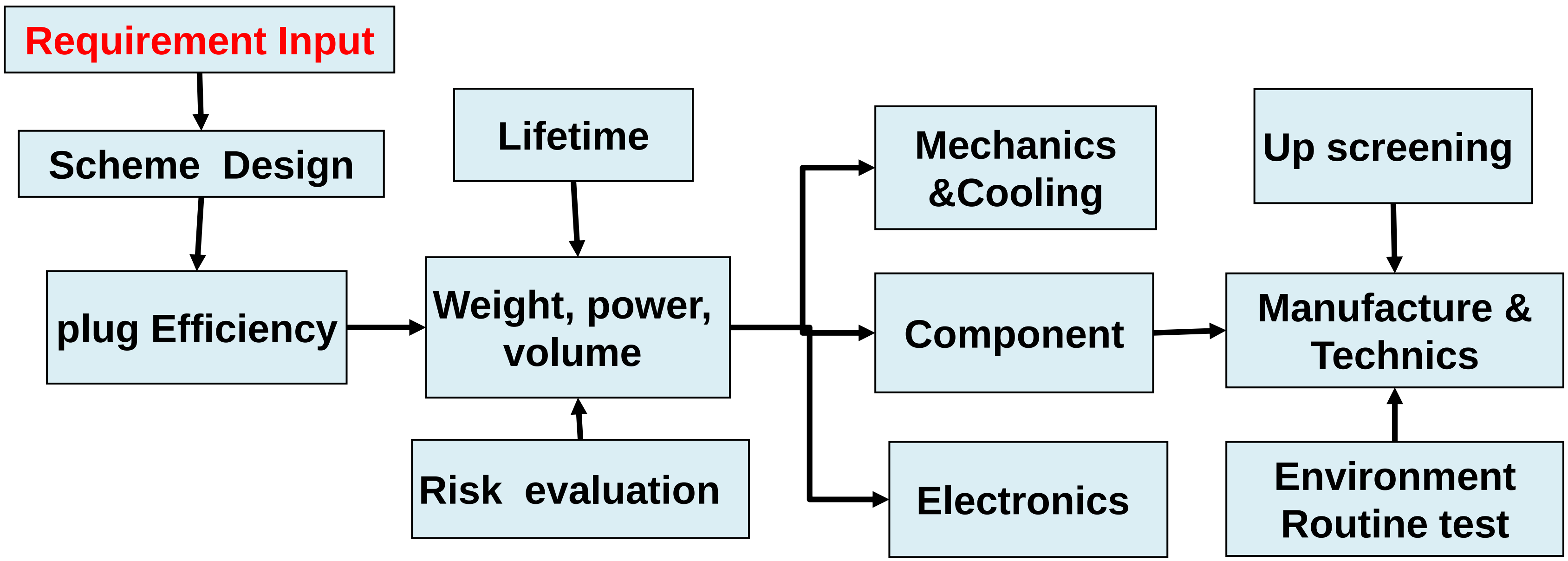


thermal lens & thermal stress-induced birefringence



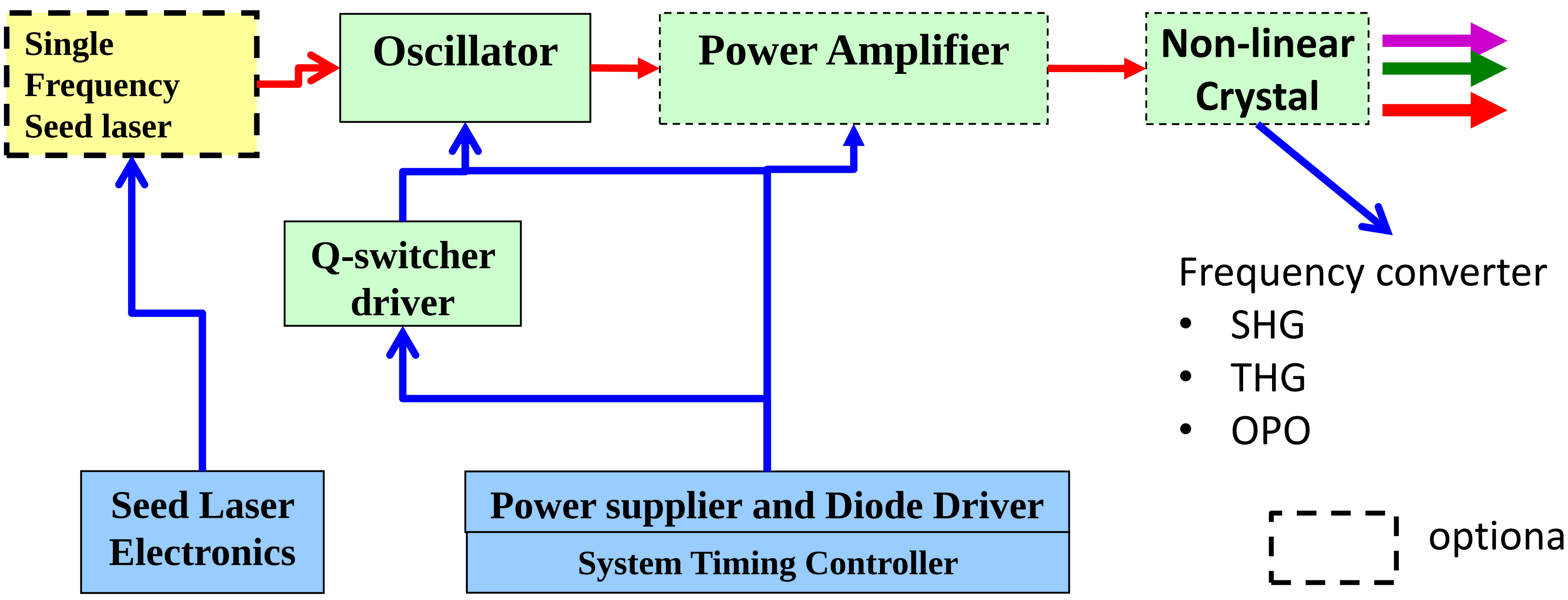
reduced thermo-optical distortions

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)

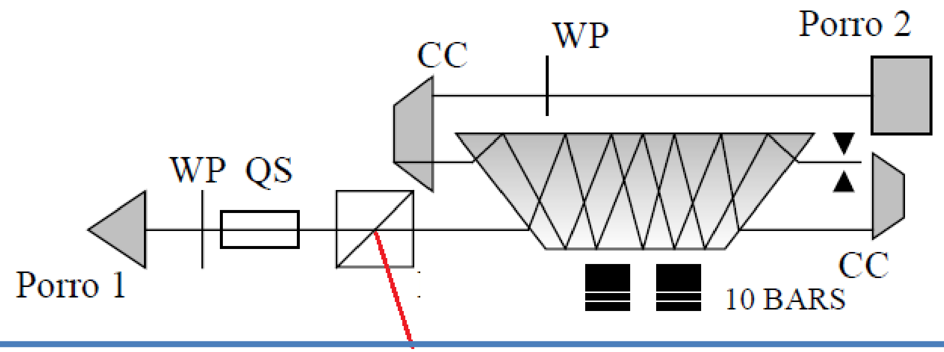
② Oscillator + Amplifier

③ Single frequency

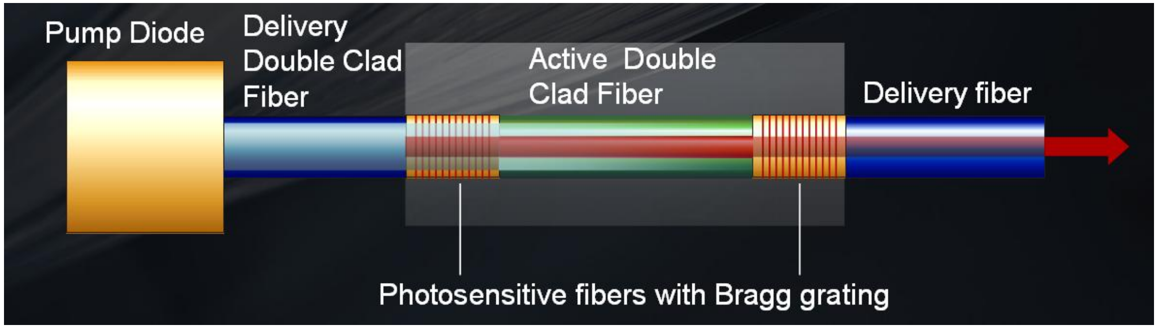
④ Other wavelengths by nonlinear converter.

Typical Solid-state Laser -1

Buck Oscillator

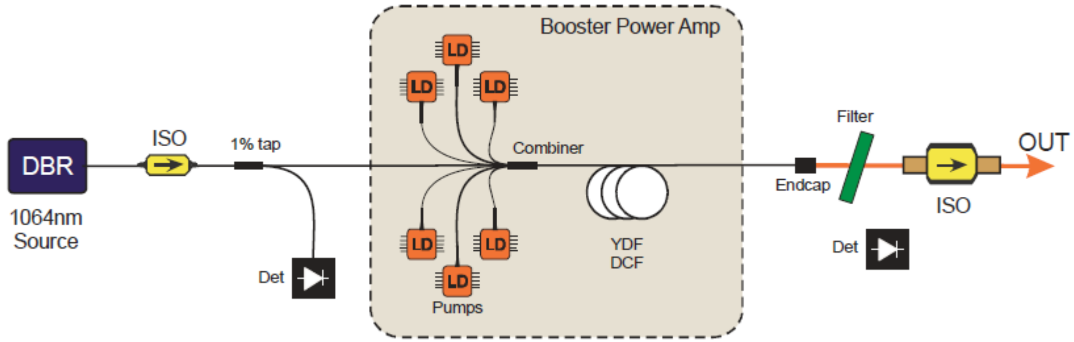


Fiber Oscillator

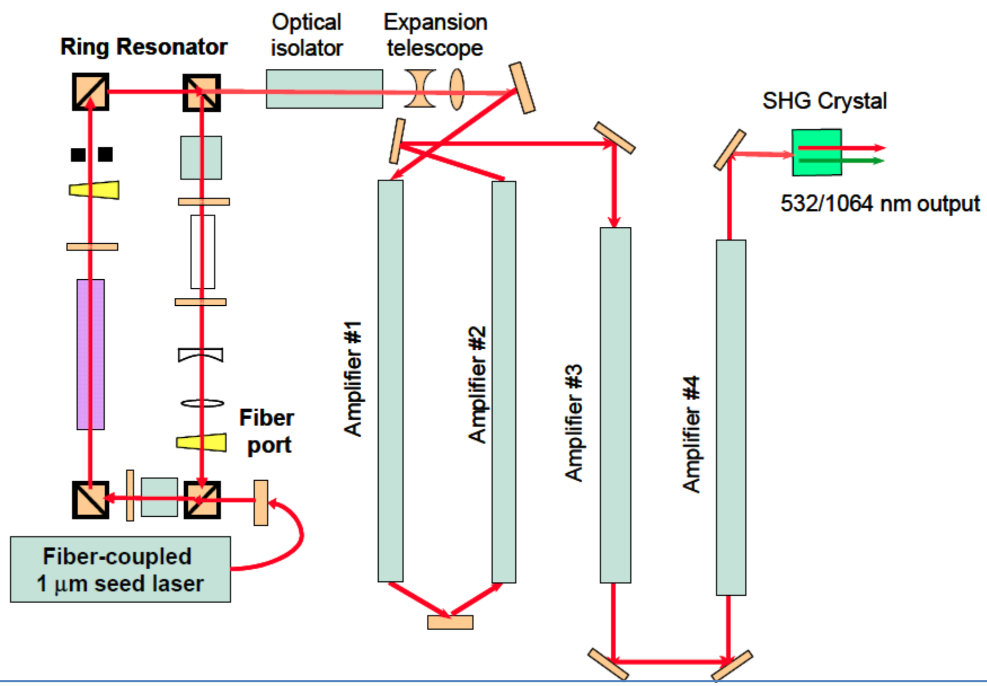


Typical Solid-state Laser-2

Fiber Amplifier



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



Narasimh S. Prasad, Upendr N. Singh, Floyd Hovis, Darrell J. Armstrong,**High energy, single-mode, all-solid-state and tunable UV laser transmitter,** Laser Radar Technology and Applications XI,Proc. of SPIE Vol. 6214, 62140T, (2006)

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

Optical Resonator

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

Gain medium

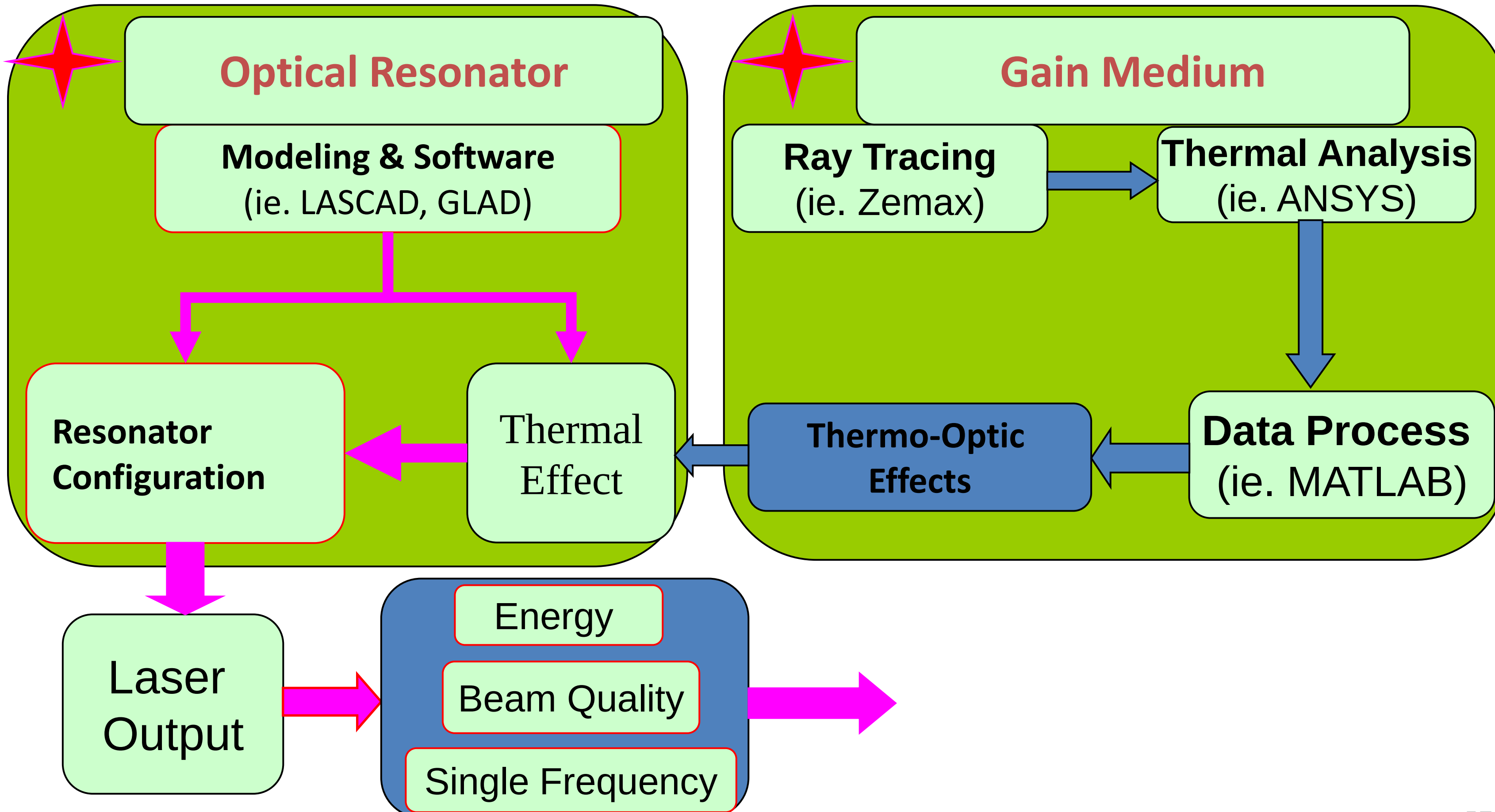
- ✓1.Gain Material
- ✓2.Pump Volume in Gain Medium
- ✓3.Pump Coupling Scheme Heat Removal
- ✓4.Intracavity Thermal Lensing
- ✓5.Thermal Lensing Compensation

→

1. **System Efficiency**
2. **Output Energy**
3. **Beam Quality**
4. **Single Frequency**

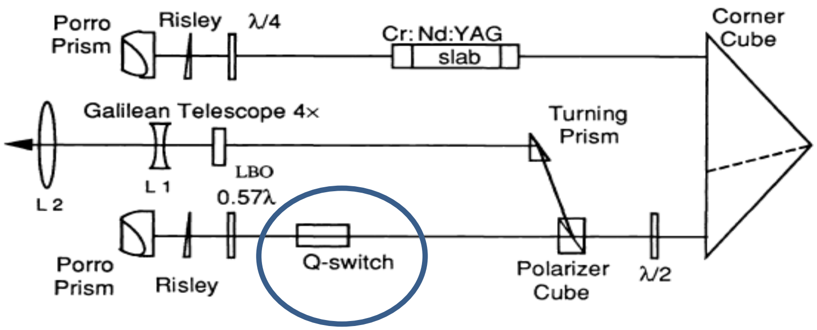
Design of solid-state laser (1)--Oscillator

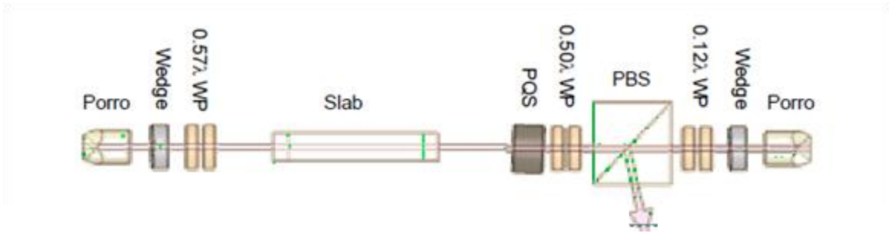
- **Modeling & Simulation**



Design of Oscillator--Cavity

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





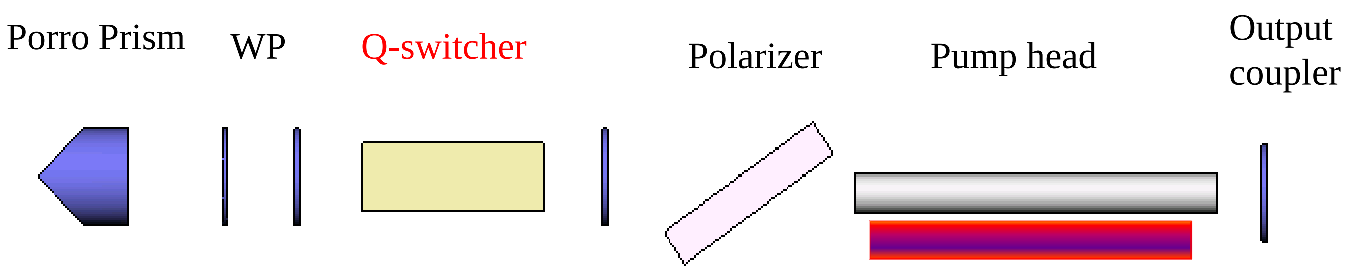
$$R = M^{*}_{prp} M_{prp} = \cos^2\left({}^{P}/_{2}\right) + \sin^2\left({}^{P}/_{2}\right)\cos^2(2\beta)$$

1. Kushina Mark E, Grote Michael G, Wiswall Charles E, etc. Clementine: Diode-pumped laser qualification [C]. Photonics West'95. International Society for Optics and Photonics, 1995:137-140.
2. Anthony W Yu, Novo-Gradaca Anne Marie, Shawa George B, etc. The lunar orbiter laser altimeter (LOLA) laser transmitter [C]. Lasers and Applications in Science and Engineering. International Society for Optics and Photonics, 2008:68710D-68710D-4.

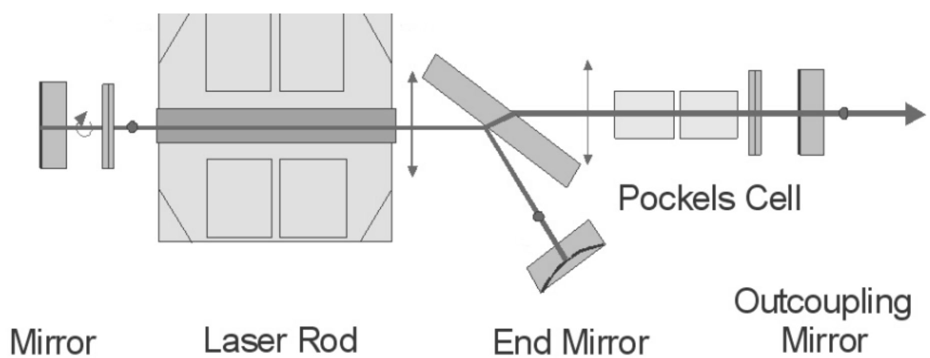
Design of Oscillator-- Cavity

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

CE-1 Laser



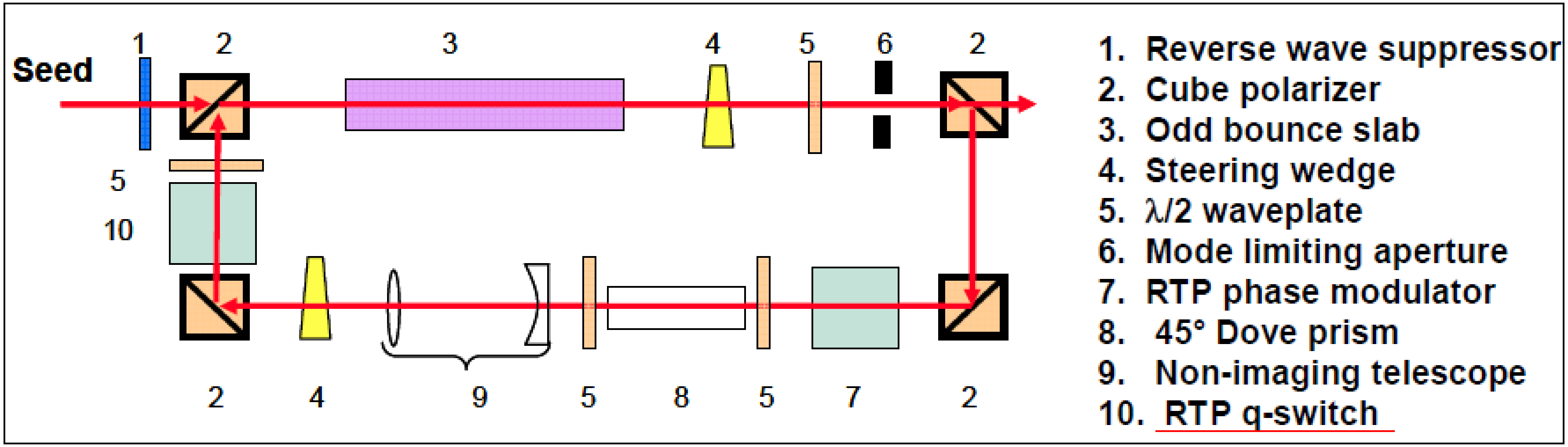
Bepicolombo



1. Qualification testing of the laser transmitter part for ESA's BepiColombo Laser Altimeter (BELA), Lidar Remote Sensing for Environmental Monitoring XII, Proc. of SPIE Vol. 8159, 815906

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

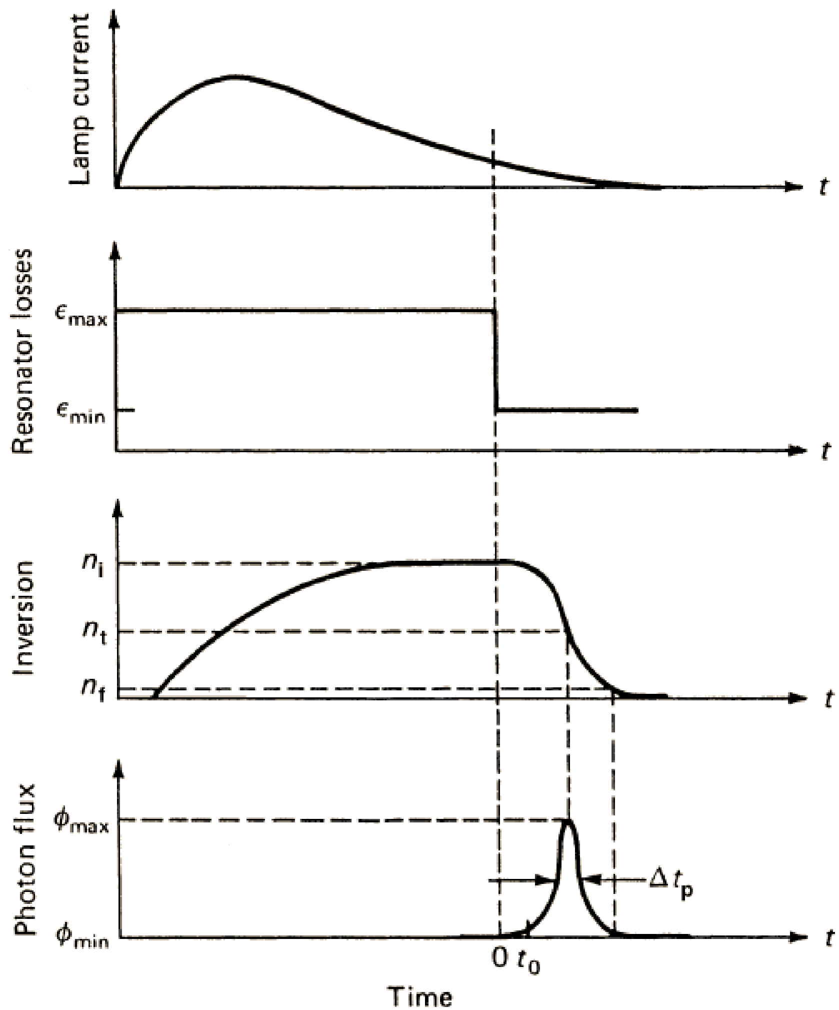


Narasimh S. Prasad, Upendr N. Singh, Floyd Hovis, Darrell J. Armstrong,**High energy, single-mode, all-solid-state and tunable UV laser transmitter,** Laser Radar Technology and Applications XI,Proc. of SPIE Vol. 6214, 62140T, (2006)

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.

	KD*P	LN	RTP	BBO	LGS
	KD_2PO_4	$LiNBO_3$	**$RbTiOPO_4$**	β-BaB_2O_4	$La_3Ga_5SiO_{14}$
Wavelength（μm）	0.2~1.6	0.42~5.2	**0.35~4.5**	0.19~3.5	0.24~2.4
Electro-optic coefficient （pm/V）	r_{63}=26.4	r_{33}=32 r_{31}=10 r_{22}=6.8	**r_{33}=38.5（Y） r_{33}=35，r_{23}=12.5 r_{13}=10.6（X）**	r_{22}=2.7	r_{11}=2.3 r_{41}=1.8
Damage threshold （GW/cm^2）	**0.5**	**0.1**	**2.5**	**1.5**	**<1**
Extinction Ratio	1000:1	>400:1	**>100:1**	>500:1	>100:1

Design of Oscillator-- Q-switch

,

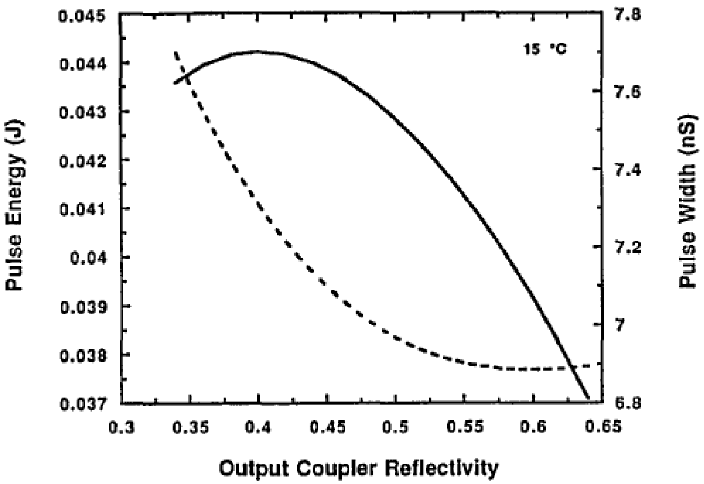
➢ Actively Q-Switch rate equation

$$\begin{cases} \frac{dN}{dt} = -\gamma\sigma c N \varnothing, \\ \frac{d\varnothing}{dt} = \frac{2\sigma l N \varnothing}{t_r} - \frac{\varnothing}{t_c} \end{cases}$$

$$N_o = \frac{P t_p \alpha \xi \chi \eta}{V h \nu}$$

$$\begin{cases} \eta = [1 - \exp(-t_p/t_{spon})] t_{spon}/t_p, \\ L = 2\alpha l + \ln\left(1 \Big/ \prod_i T_i^2\right) \\ L(t) = L[1 + \exp(-t/\tau)], \end{cases}$$

P : peak pump power
Tp: Pump duration
α: absorbed fraction,
X: pump coupling efficiency
X: quantum efficiency
hυ: photon energy
V : volume of laser crystal



Robert S. Afzal, Mars Observer Laser Altimeter: laser transmitter, APPLIED OPTICS / Vol. 33, No. 15 / 20 May 1994

Design of Oscillator-- Q-switch

➢ Passively Q-Switch rate equation

$$\frac{dn}{dt} = -\gamma\sigma c n \phi$$

$$\frac{d\phi}{dt} = \left[2\sigma l_{\mathrm{slab}} n - 2\sigma_{\mathrm{gs}} n_{\mathrm{gs}} l_{\mathrm{pqs}} - \left(\mathrm{loss}_{\mathrm{cav}} + \ln\left(\frac{1}{R}\right)\right)\right]\frac{\phi}{t_{\mathrm{r}}}$$

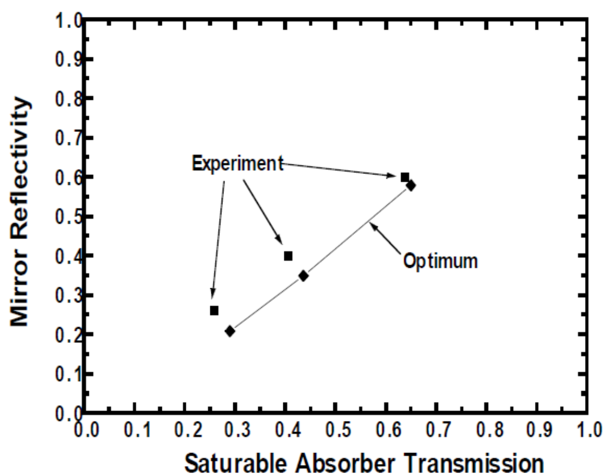
$$\frac{dn_{\mathrm{gs}}}{dt} = -\sigma_{\mathrm{gs}} c \phi n_{\mathrm{gs}}$$

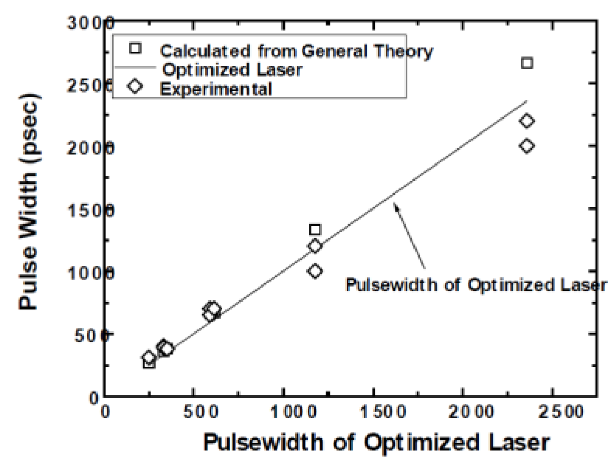
$$\frac{dn_{\mathrm{es}}}{dt} = \sigma_{\mathrm{es}} c \phi n_{\mathrm{es}}$$

$$T_{Opt} = G_0^{-\frac{\varphi_{opt}}{1-\delta}}, \varphi_{opt} = \frac{1 - \frac{1}{\rho_{opt}}(1-e^{-\rho_{opt}})}{1 - \frac{1}{\alpha\rho_{opt}}(1-e^{-\varepsilon\rho_{opt}})}$$

$$R_{opt} = G_0^{-\Psi_{opt}}, \Psi_{opt} = 2\left[1 - \frac{L}{2\ln G_0} - \frac{\varphi_{opt}}{1-\delta}\right]$$

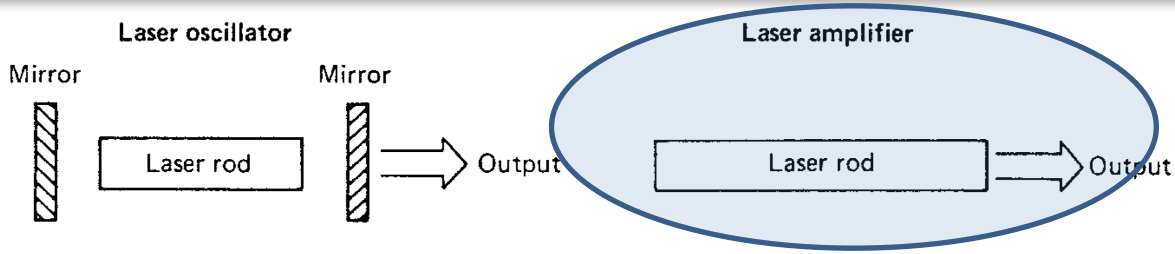
$$E_{opt} = \frac{h\nu A \ln(G_0)}{\gamma\sigma}\frac{\rho_{opt}\Psi_{opt}}{2} = F_{sat}^{gain}\ln(G_0) A \frac{\rho_{opt}\Psi_{opt}}{2}$$





Degnan John J. Optimization of passively Q-switched lasers [J]. Quantum Electronics, IEEE Journal of, 1995, 31(11): 1890-1901.

Design of Solid-state Amplifier



Consideration

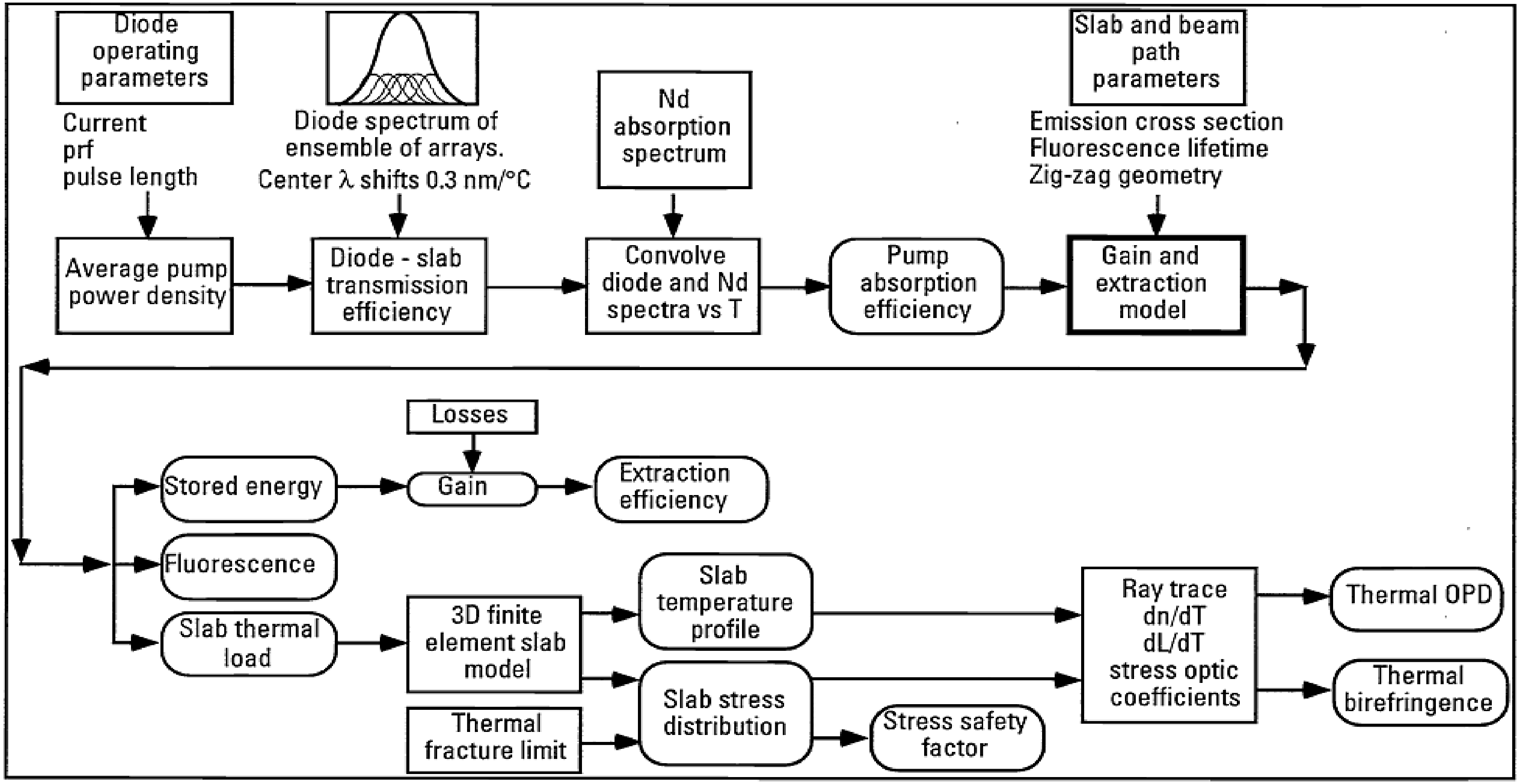
Design Contents

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

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

Optimum Design: High Efficiency & Beam Quality

Design Model of Amplifier



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,**

θ **- the complementary angle,**

f_{eff} **- the effective overlap factor**

E_{stored} **- the stored energy**

Efficiency- Energy Storage

The Stored Energy

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

η_a Absorption efficient of slab

η_t Transfer efficient from diode to slab

η_s Store efficient $\eta_s = \frac{1 - \exp(-t_p/\tau)}{t_p/\tau}$

η_{qd} Stokes efficient

η_c Overlap efficient between laser mode and laser medium

η_q Quantum efficient

Efficiency- Energy Extraction

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

$$F_{out} = \eta_{overlap} F_{sat} \times \ln\{1 + [e^{F_{in}/F_{sat}} - 1] e^{g_o l_{eff}}\}$$

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

➢ **The extraction efficiency:** $\eta = \eta_{overlap} \frac{F_{out} - F_{in}}{F_{sat} g_o l_{eff}}$

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 η_{o-o}

LD Optical Transfer | Absorption | Upper State | Stokes | Storage | Extraction | Beam Overlap

$$\eta_{o-o} = \eta_{transfer}\eta_{absorb}\eta_{quantum}\eta_{stokes}\eta_{store}\eta_{extraction}\eta_{overlap}$$

14.5%	**90%**	**90%**	**91%**	**76%**	**73%**	**50%**	**70%**

Design of different wavelength output

$$\mathbf{P} = \epsilon_0 \chi^{(1)} \mathbf{E} + \epsilon_0 \chi^{(2)} \mathbf{E}\mathbf{E} + \epsilon_0 \chi^{(3)} \mathbf{E}\mathbf{E}\mathbf{E} + \cdots,$$

ε_0: the permittivity of free space

χ*: 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 $\chi^{(2)}$

- **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

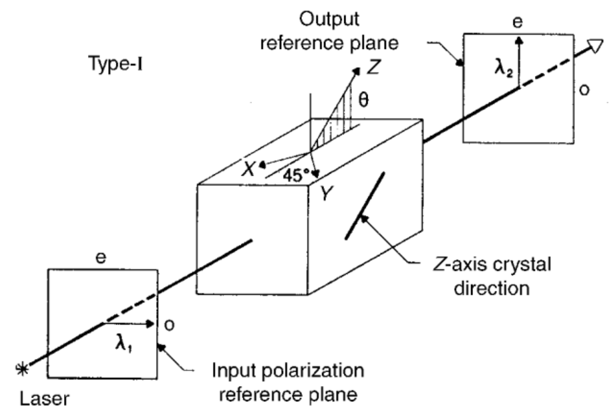
$$\frac{P_{2\omega}}{P_\omega} = l^2 K \frac{P_\omega}{A}.$$

$$K = 2Z^3 \omega^2 d_{\text{eff}}^2,$$

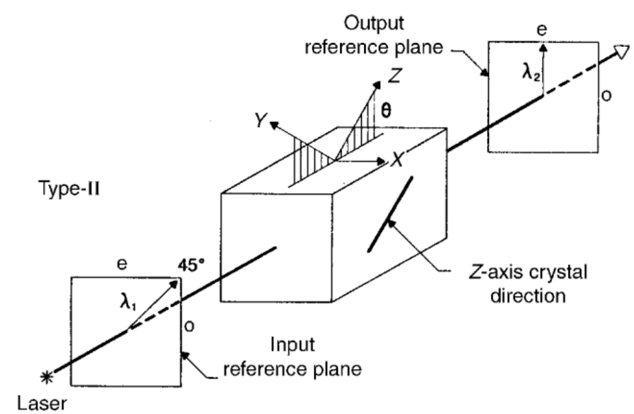
Type I $\quad d_{\text{eff}} = d_{14} \sin 2\phi \sin \Theta_{\text{m}}.$

Type II $\quad d_{\text{eff}} = d_{14} \cos 2\phi \sin 2\Theta_{\text{m}}.$

d_{eff} is the effective nonlinear coefficient



(a)



(b)

$$n_2^{\text{e}}(\Theta_{\text{m}}) = n_1^{\text{o}} \quad \text{type-I},$$

$$n_2^{\text{e}}(\Theta_{\text{m}}) = \tfrac{1}{2}[n_1^{\text{e}}(\Theta_{\text{m}}) + n_1^{\text{o}}] \quad \text{type-II},$$

Design of Harmonic Generation

Crystal	Phase matching type	d_{eff} (pm/V)	θ (deg)	Φ (deg)	Walk-off angle (mrad)	ΔΦ/Δθ (deg) l = 1cm	Temperature bandwidth (K) l = 1cm
LBO (SHG)	I	0.836	90	10	6.03	0.27/2.63	5.8-6.7
BBO (SHG)	I	2.01	22.9		55.8	0.021	37-51
BiBO (SHG)	I	3.00	168	90	27.55	0.04	1.3
KTP_{gr} (SHG)	II	3.56	90	24.3	4.28	0.58/1.82	20
LBO (THG)	II	0.52	44.4	90	9.5	0.79/0.16	6
BBO (THG)	I	2.01	31.4		72.24	0.011-0.015	16
BiBO (THG)	I	3.9	145.7	90	68.6	0.051/0.024	0.9

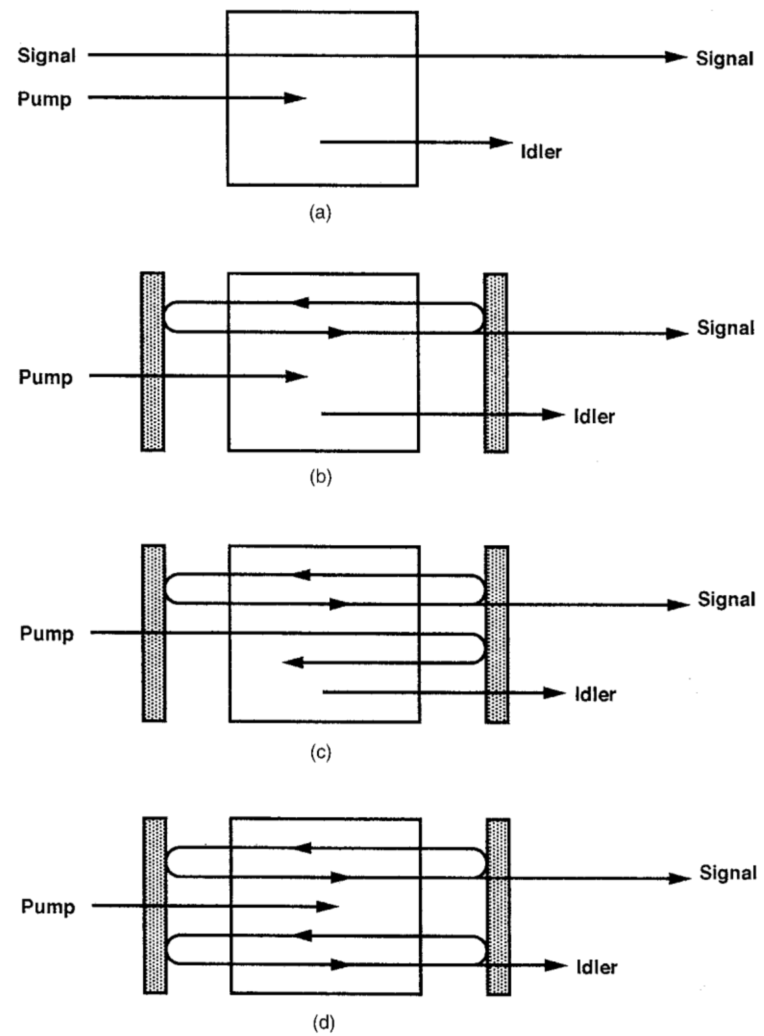
Ciapponi Alessandra, Riede Wolfgang, Tzeremes Georgios, etc. Non-linear optical frequency conversion crystals for space applications ,Proc. SPIE 7912, Solid State Lasers XX: Technology and Devices, 791205

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

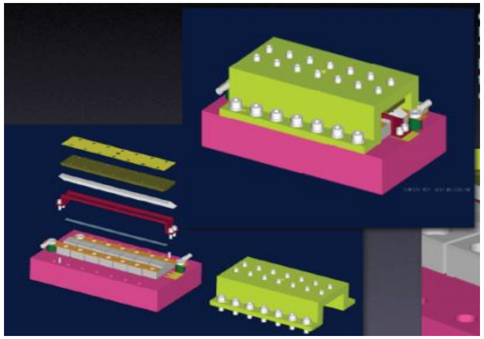
LN/PPLN

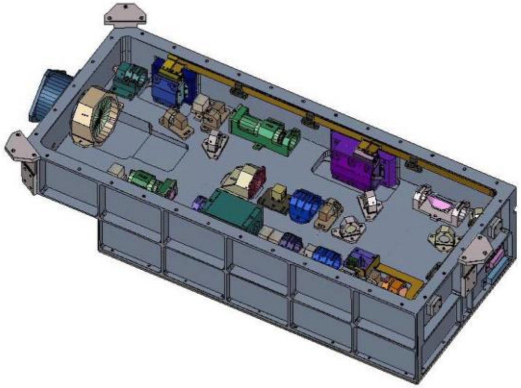
PPLT

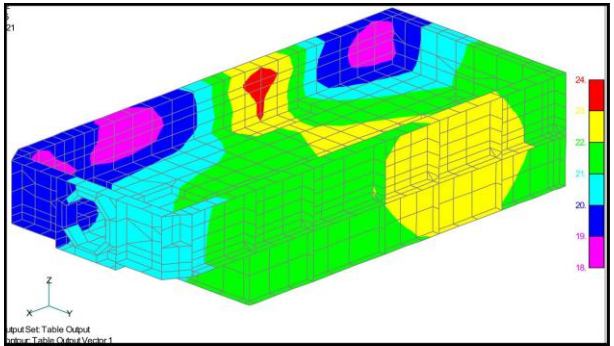
Other design of space laser

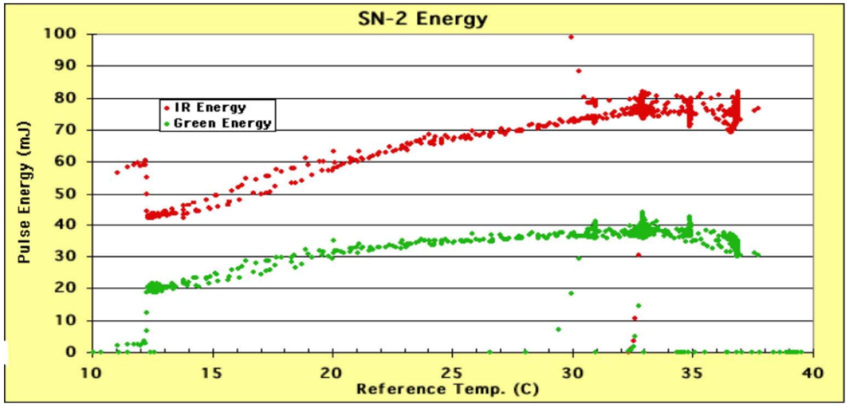
- ✓ Mechanics design:
  - – Light weight and good stability;
  - – lower stress deformation;
  - – Pressured structure;
  - – Good thermal conductivity
- ✓ Thermal controlling
  - – Survive in a relative wide temperature range
  - – Operate with stable output in a certain temperature range

Examples of mechanics and thermal design









Summary

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

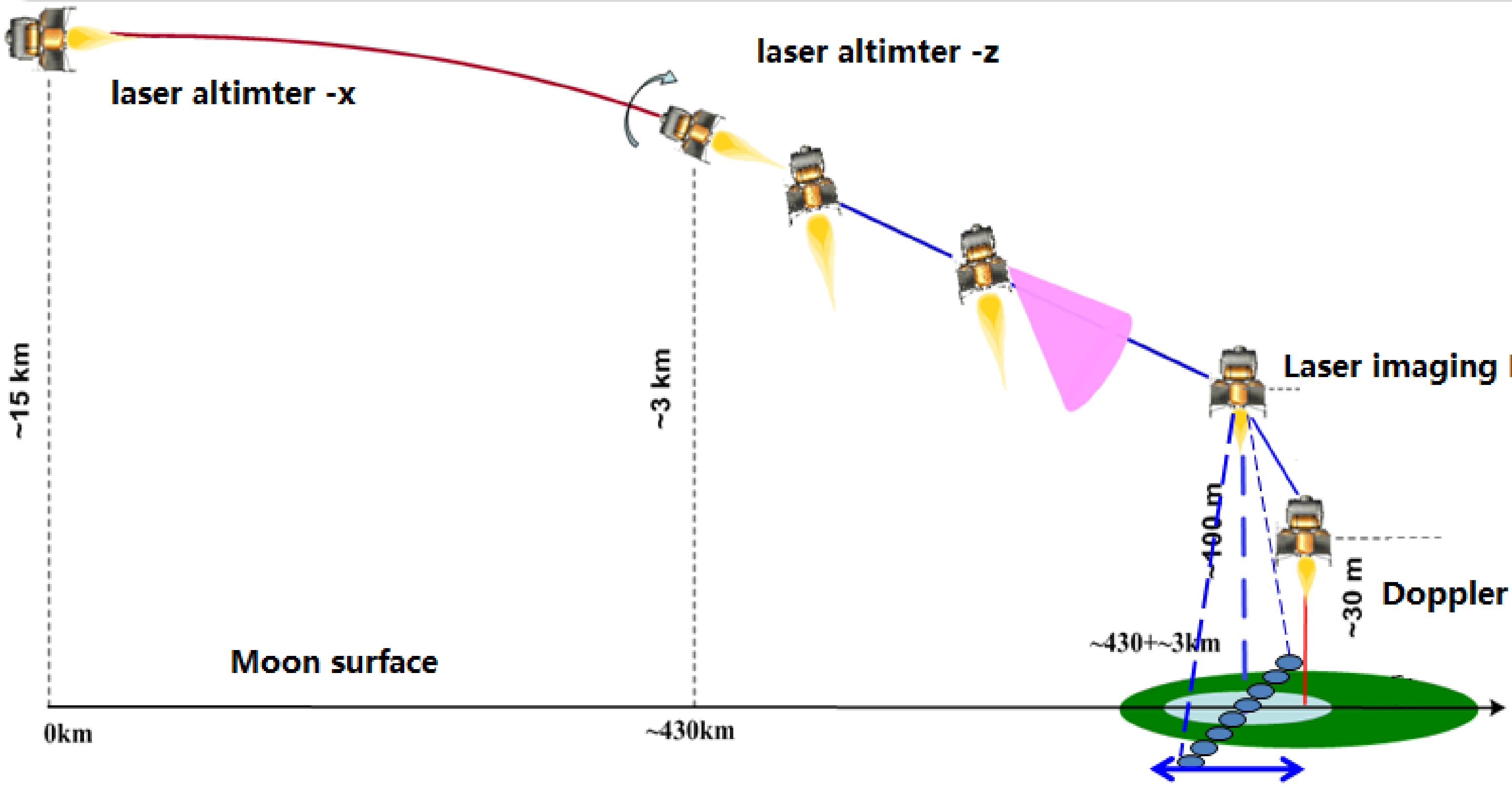
EXAMPLES

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

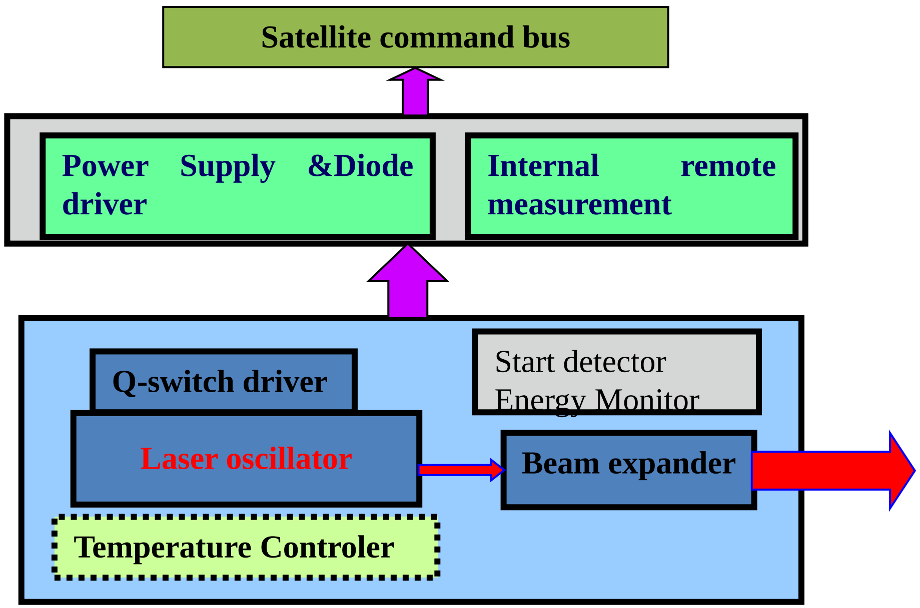
Low power laser @ 1µm, 1.5µm	Laser range finder	Low PRF Low , Mid-energy	EO or passive Q-switched
	Laser imaging lidar	High PRF Low energy	Pulsed MOPA Fiber laser
	Laser communication	High PRF or CW	Single mode Fiber laser
High energy laser @ UV, Green, IR	Earth Observation Lidar	Multi -wavelength High Energy	Single frequency SLAB MOPA Nonlinear frequency

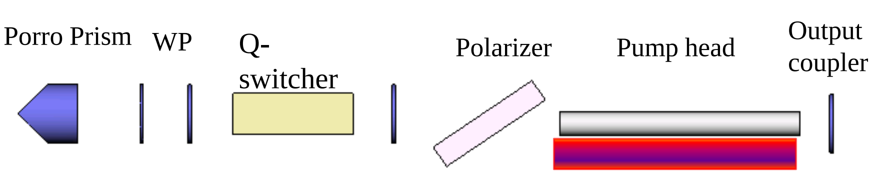
Example 1: laser Sensors for Chinese moon explorer



- **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

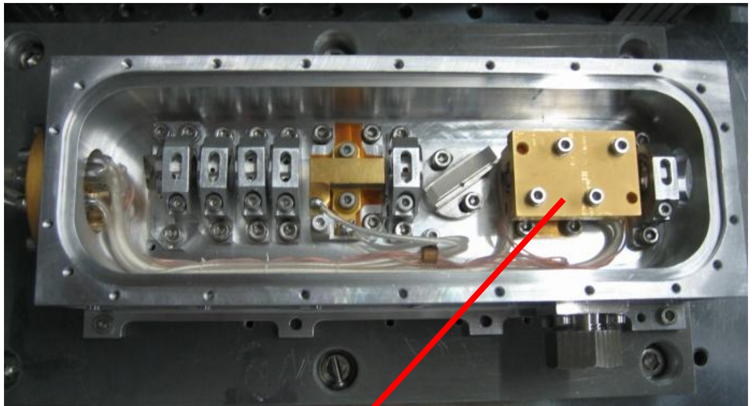


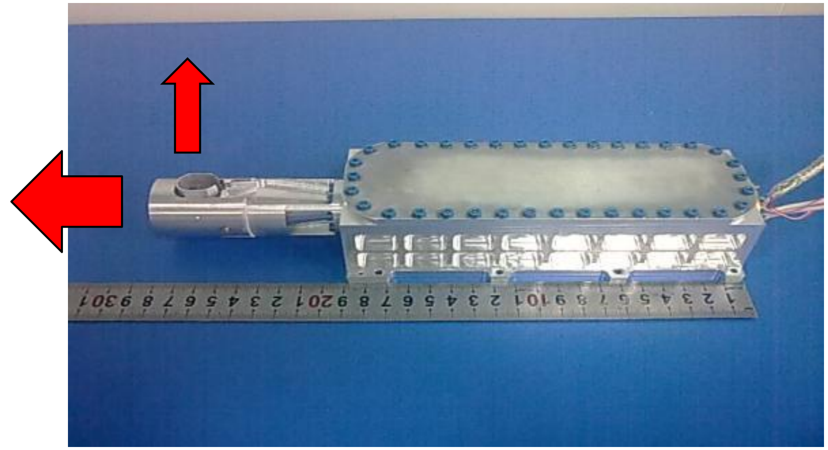


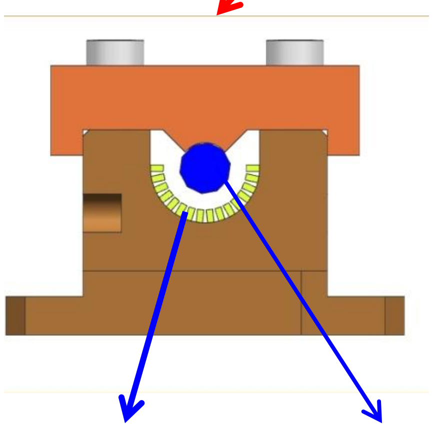
- **Configurations**
  - ✓ **Crystal:** Cr, Nd:YAG
  - ✓ **Cavity**: Linear, porro & plano mirror
  - ✓ **Pump head**: Φ4 ×45 mm with diode side pumping
  - ✓ **Q-switch**: actively, $LiNbO_3$

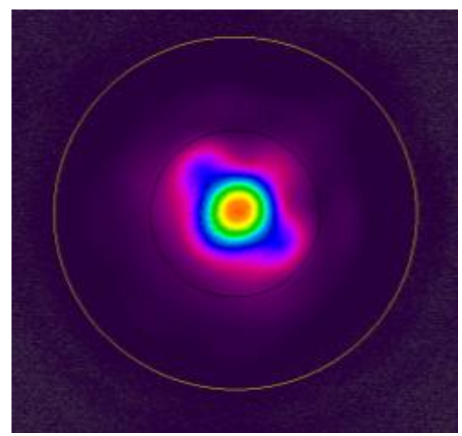
- **Specification**
  - ✓ Wavelength: 1064.36 nm
  - ✓ Energy : 45mJ
  - ✓ Energy stability: 0.2mJ
  - ✓ Pulse width: 4.8ns@45mJ
  - ✓ 5.5ns@15mJ
  - ✓ Repetition rate: 2 Hz
  - ✓ Beam divergence: 0.9mrad
  - ✓ Point stability: X, y： 3.1μrad
  - ✓ **Weight 1.3kg**

Solid-state Laser for CE-3 Altimeter

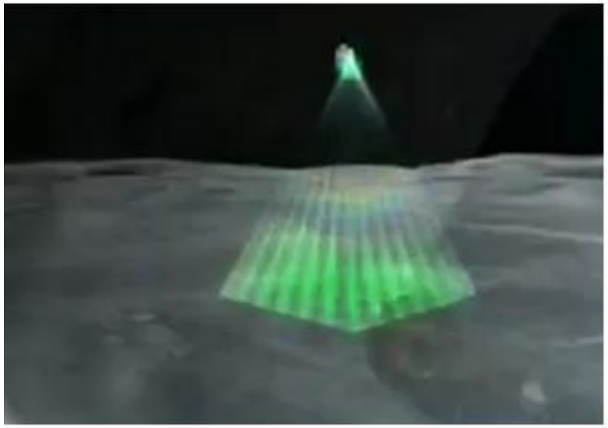


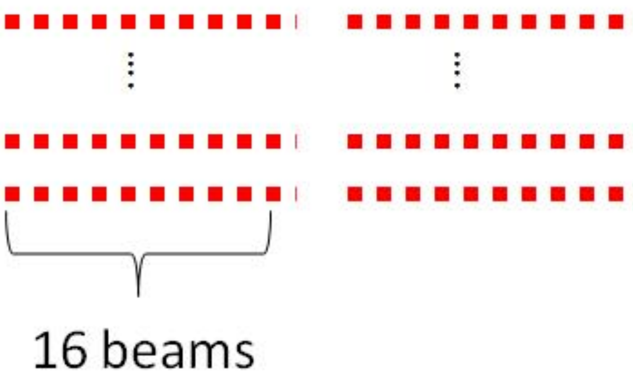


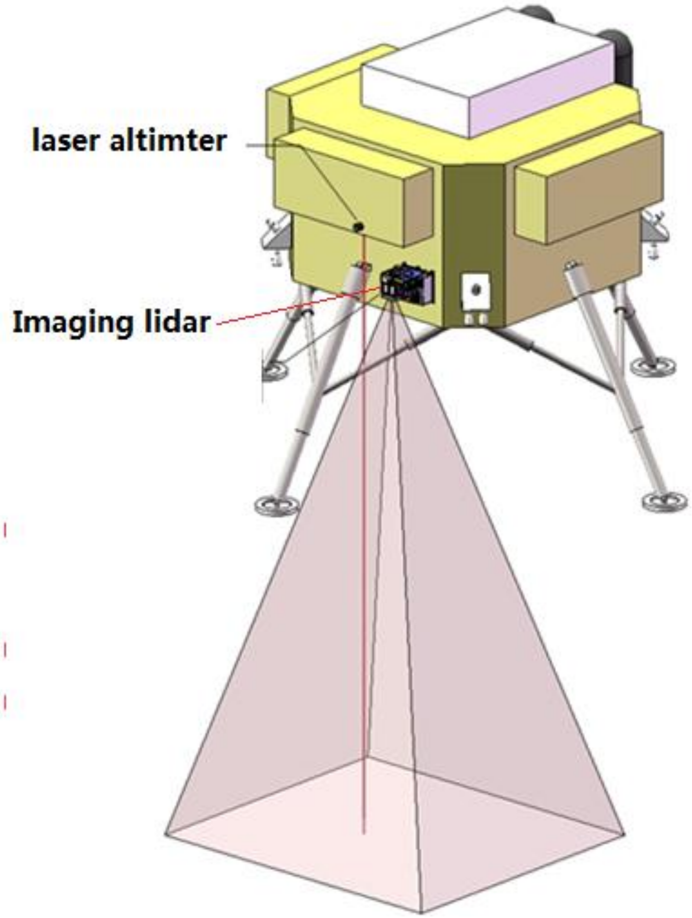




Principle of Imaging Lidar







- Two axis scanning with 16 beam simultaneously

Requirements of Laser for image lidar

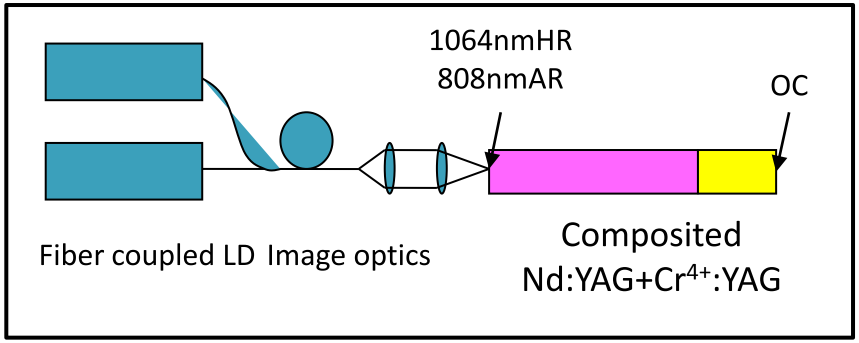
- Wavelength: 1064nm±2nm;
- Rise time 10～90%）: <4ns;
- Repetition rate: 50 kHz;
- Pulse energy: ≥80μJ@50 kHz;
- Energy stability: ±5%;
- Beam divergence: < 1mrad;
- Point stability : < 50μrad;
- Dimension : 228mm x 60mm x 215mm
- Weight: < 2.6kg
- Power : Average: <20W

What kind of laser will be selected ?

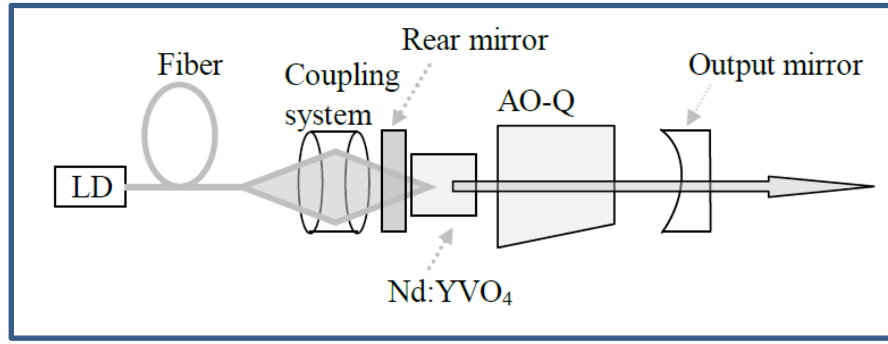
Candidate

- Passive Q-switched solid-state laser
- AO Q-switched solid-state laser
- Pulsed fiber laser amplifier

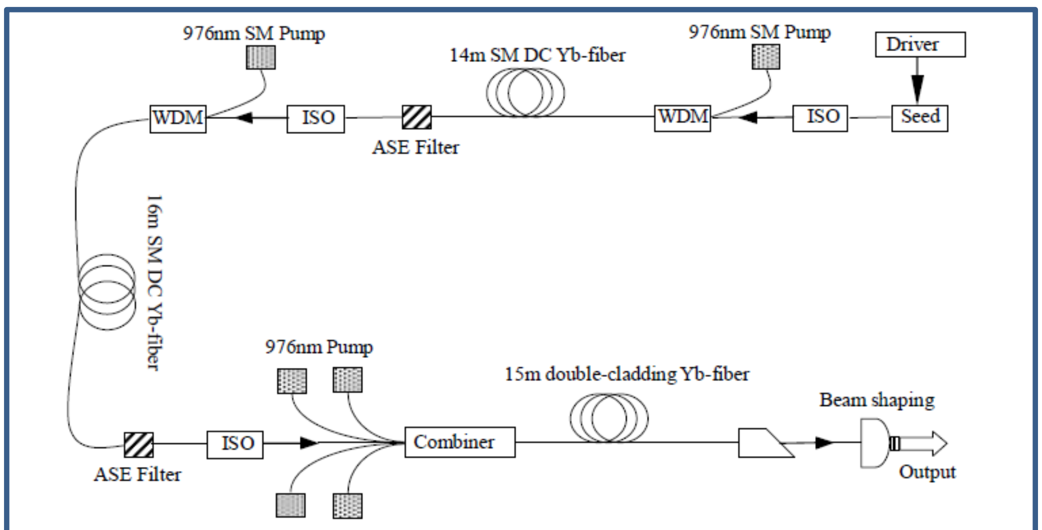
Selection of laser type



Case 1: Passive Q-switched Nd:YAG

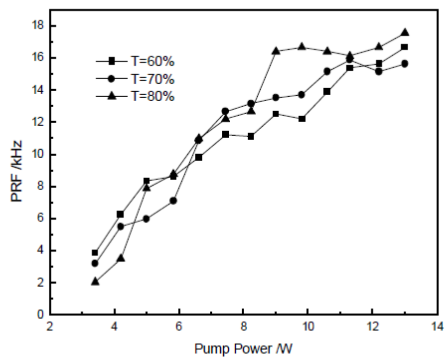


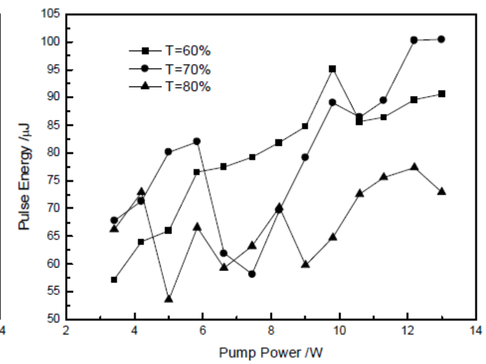
Case 2: AO Q-switched Nd:YVO4



Case 3: Modulated Laser diode with fiber amplifier

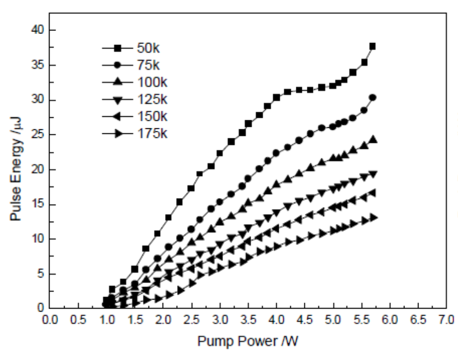
Test Results of different lasers

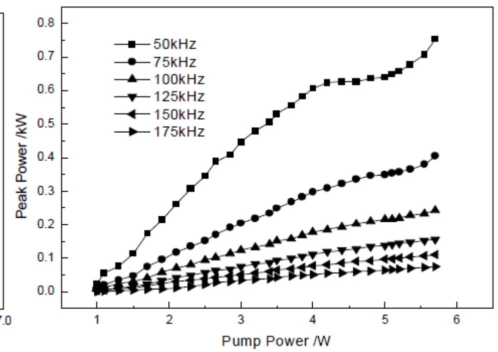




Passive Q-switch laser Nd:YAG Laser

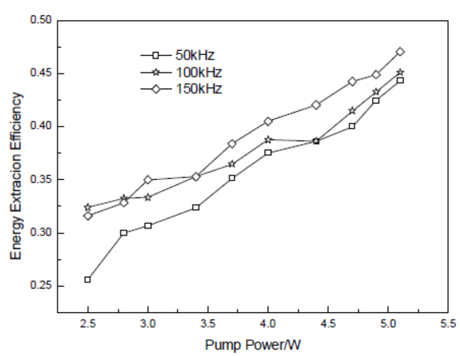
- High energy
- Low PRF less than 20 kHz, Low efficiency

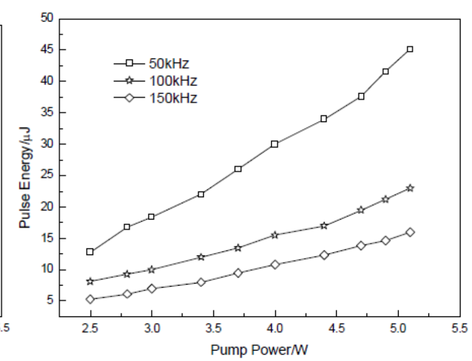




AO Q-switch Nd:YVO4

- High PRF
- Middle efficiency ,Low peak power and wider pulse width

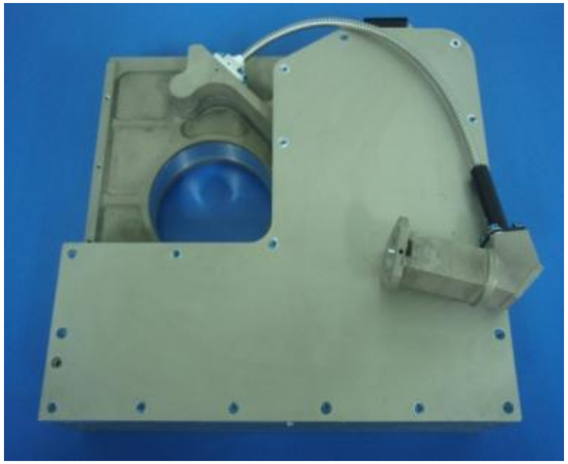


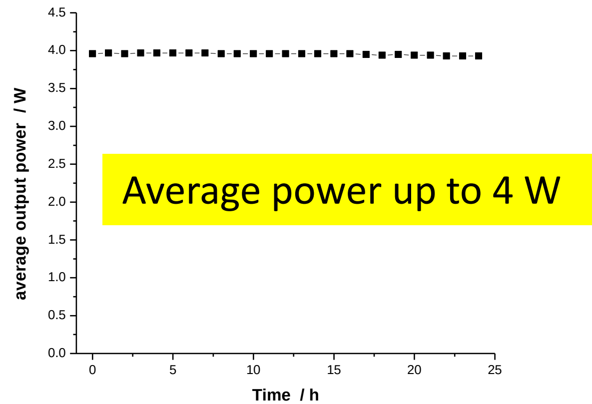


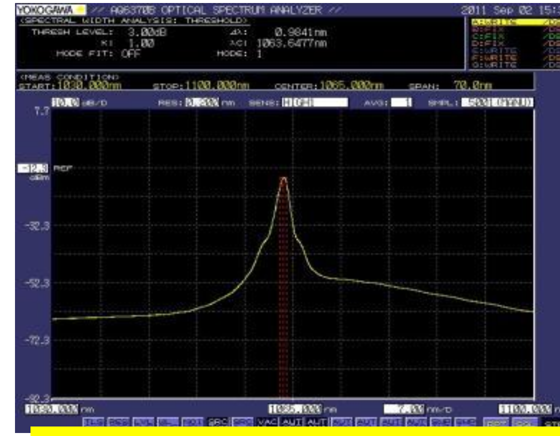
Fiber laser amplifier

- High PRF, high efficiency
- Middle energy but enough
- Very robust and compact.

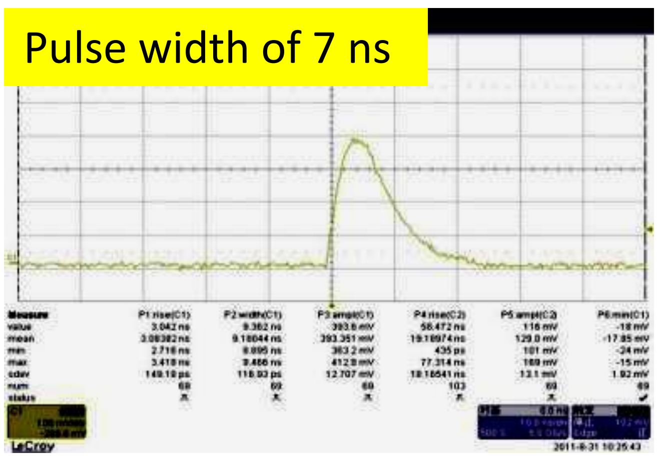
Results of fiber amplifier for imaging Lidar

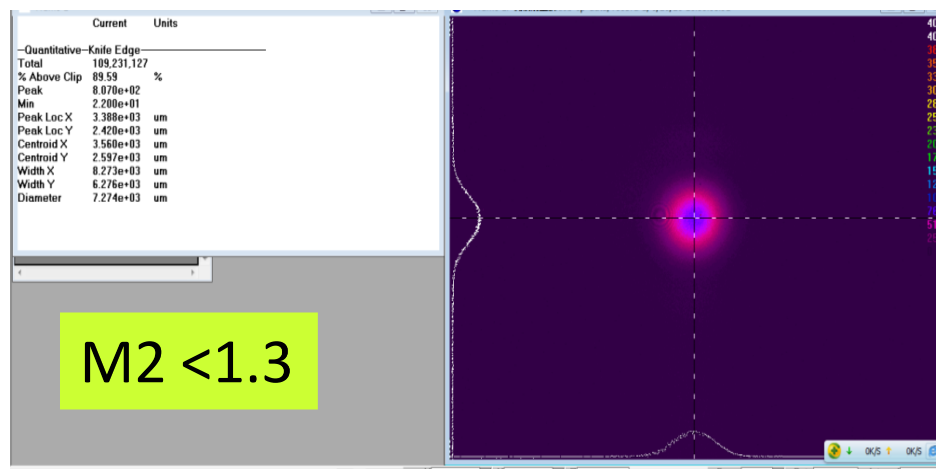




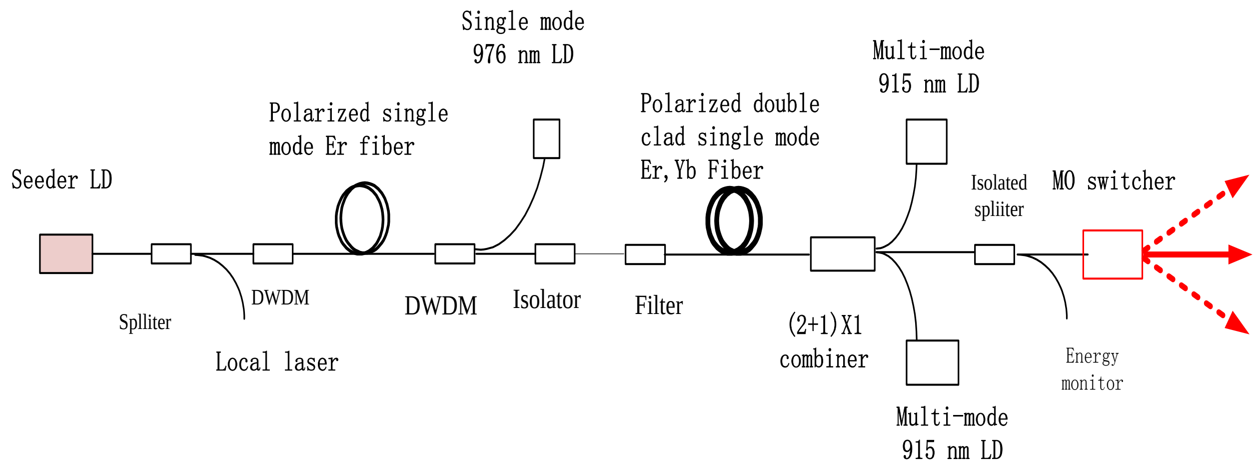


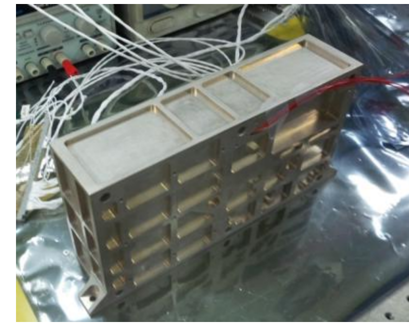
Spectrum width of 0.9 nm



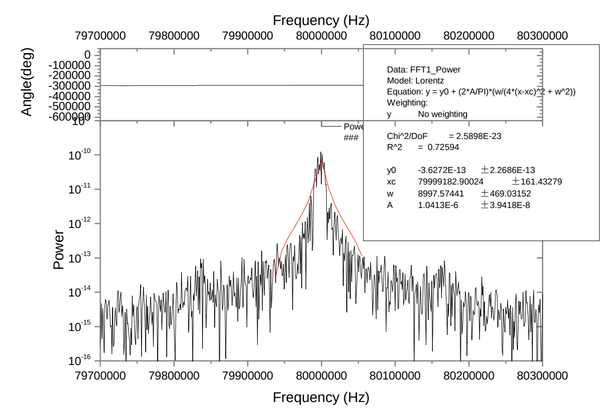


Single frequency laser for Doppler Lidar





Wavelength	**1550nm±1nm**
Linewidth of seeder	**≤30kHz**
RIN of seeder (30K~1MHz)	**≤2×10-13/Hz**
Local laser power	**100~120μW**
Output power	**≥2W**
Output fiber	**3 local lasers** **3 transmitters**
Weight	**≤1.2kg**

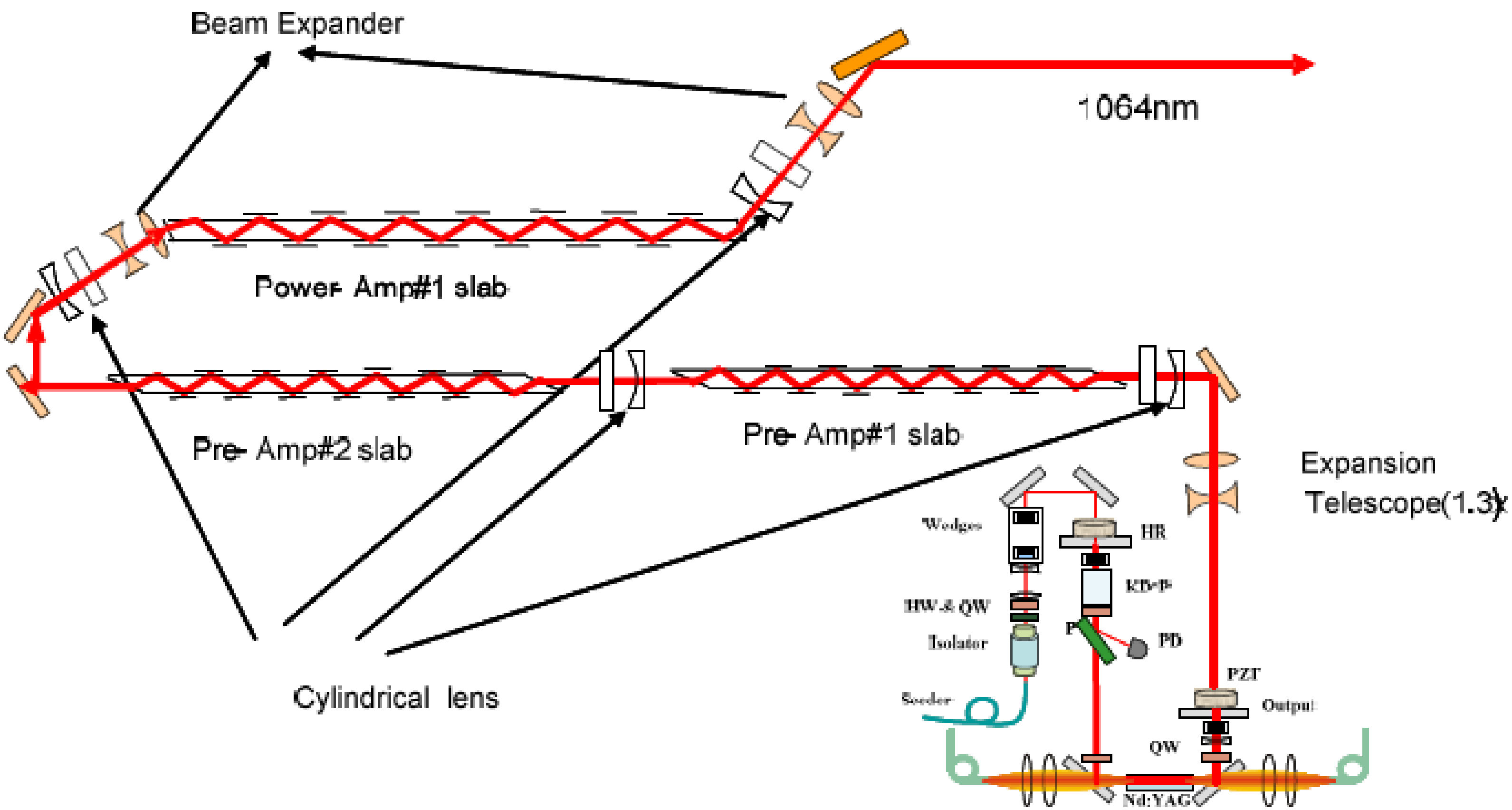


Linewidth < 9 kHz

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

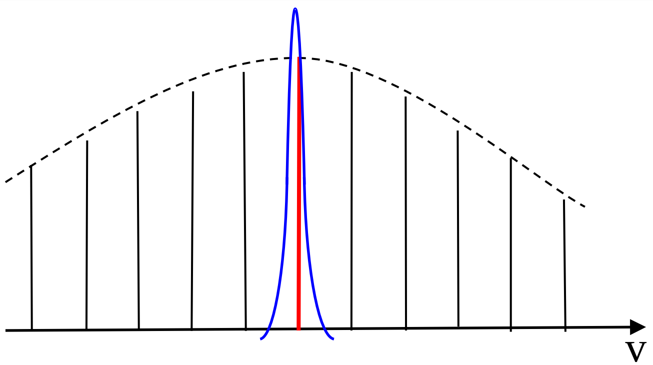


Single frequency Oscillator +multi-stage amplifier

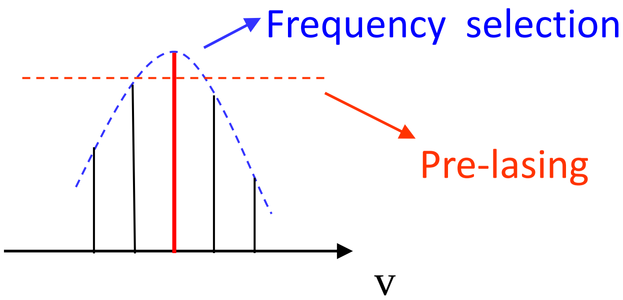
Example 2: Single frequency operation

- 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 pusled cavity
  - CW single frequency +pused modulated+ amplifier

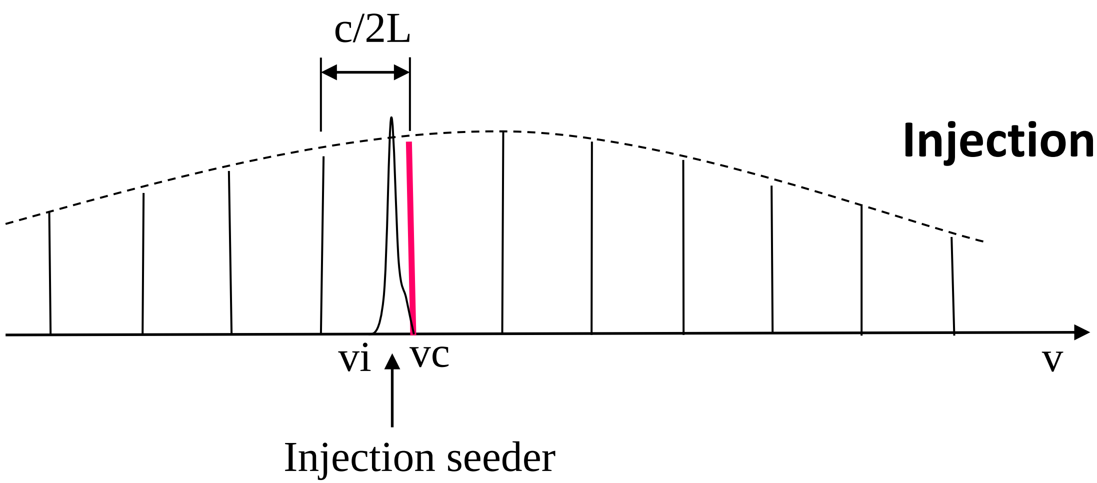
Example 2: Single frequency operation



Mode selection



Pre-lasing



Injection seeding method

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

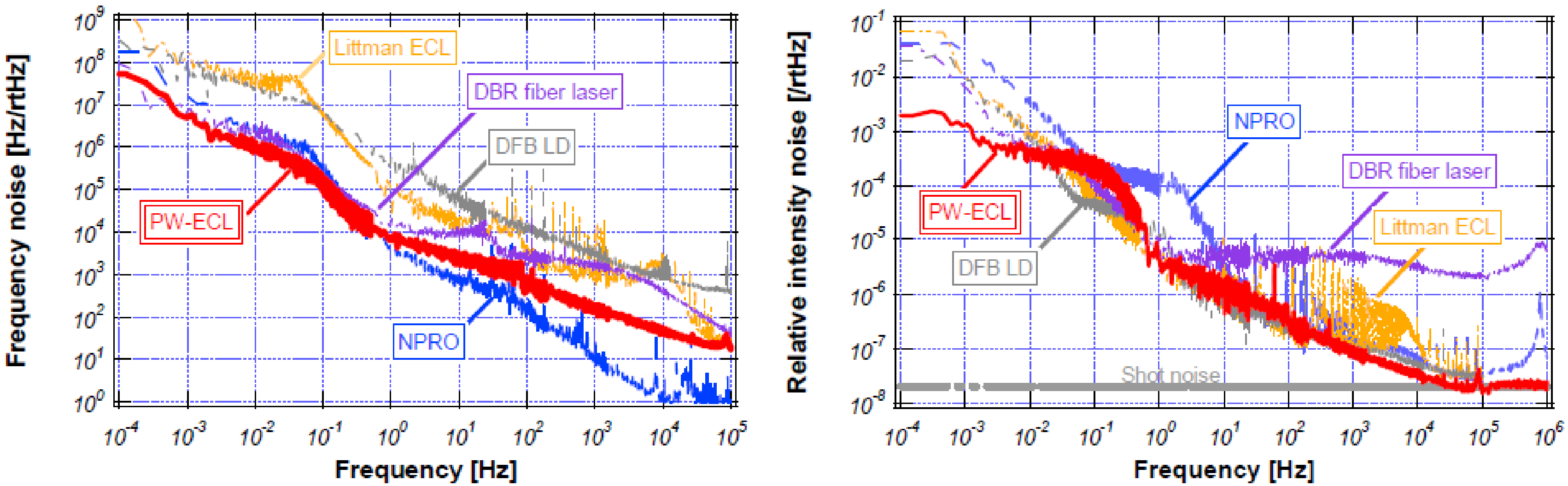
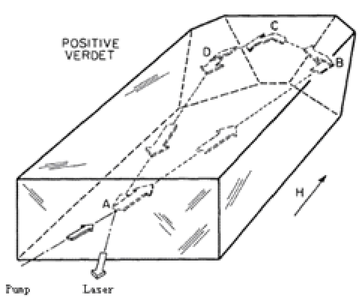
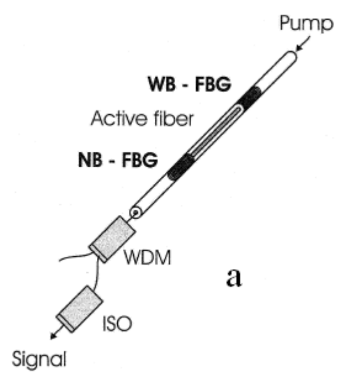
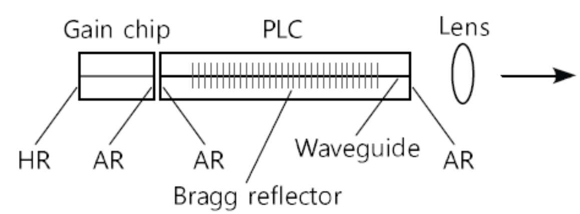


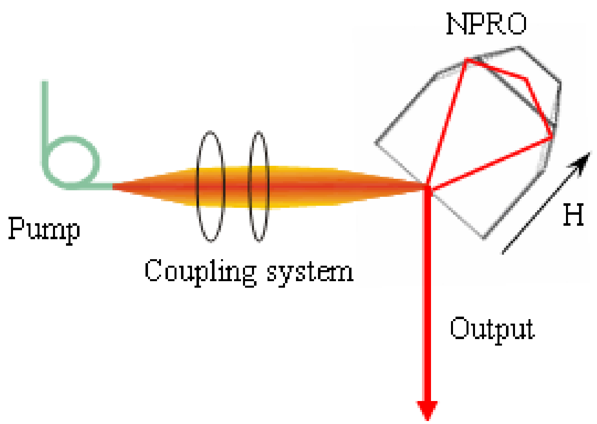
Fig.2. Free-running frequency (*left*) and relative intensity (*right*) noise spectra of various single-frequency lasers. PW-ECL: PLANEX from Redfern Integrated Optics (1542 nm), NPRO: Model 125

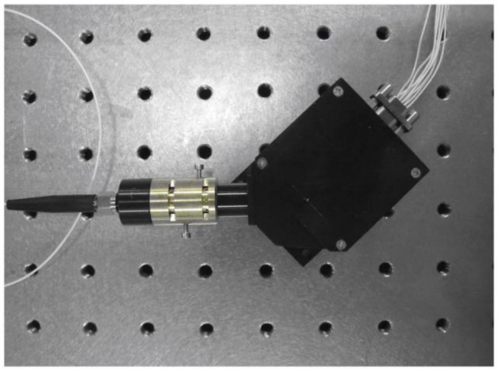




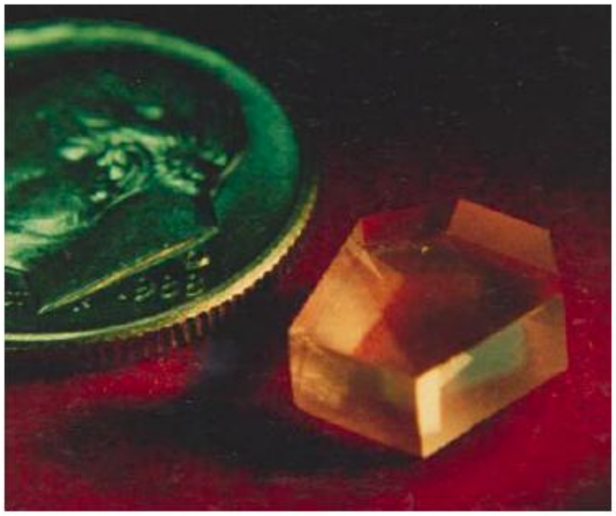


Example 2: Single frequency operation



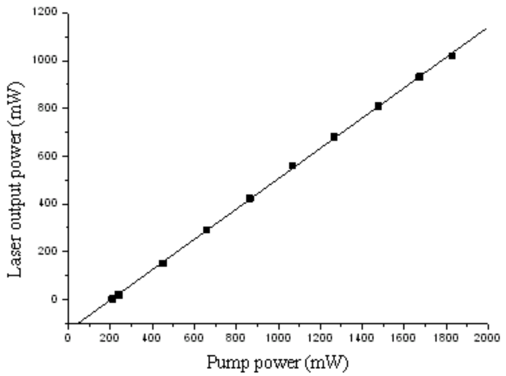


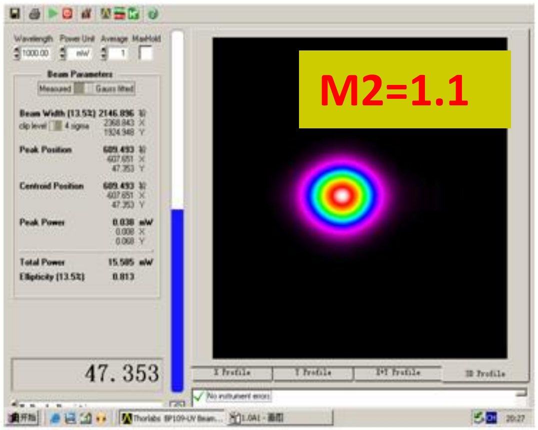
Tom Kane, R. L. Byer
"Monolithic, unidirectional
Single-mode Nd:YAG ring laser"
Opt. Lett. 10,65,1985



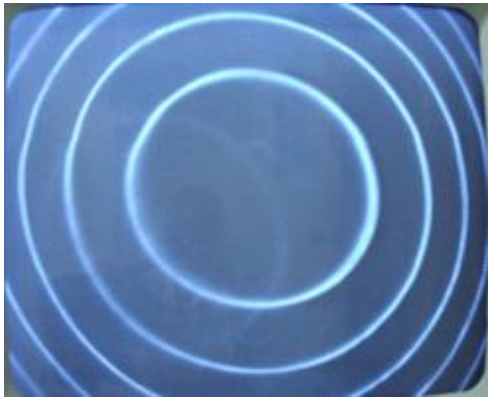
✓Small size NPRO Nd:YAG for large tunable frequency
✓Frequency lock diode to pump NPRO to reduce intensity noise

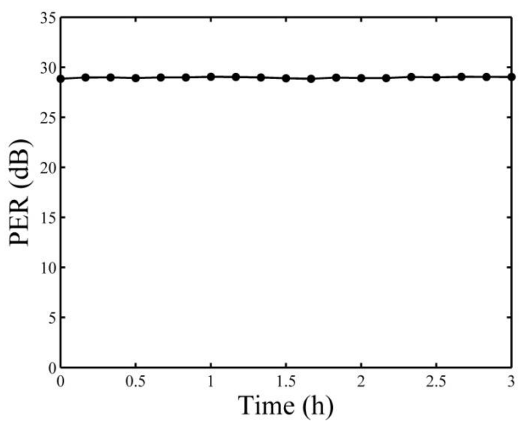
Example 2: Single frequency operation

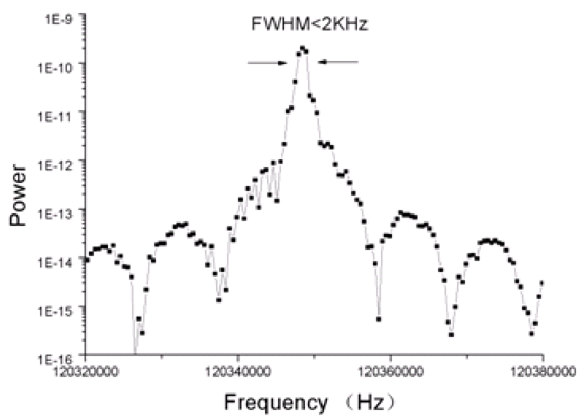


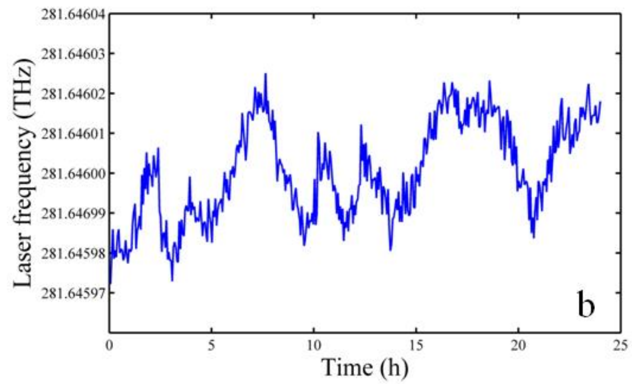


a





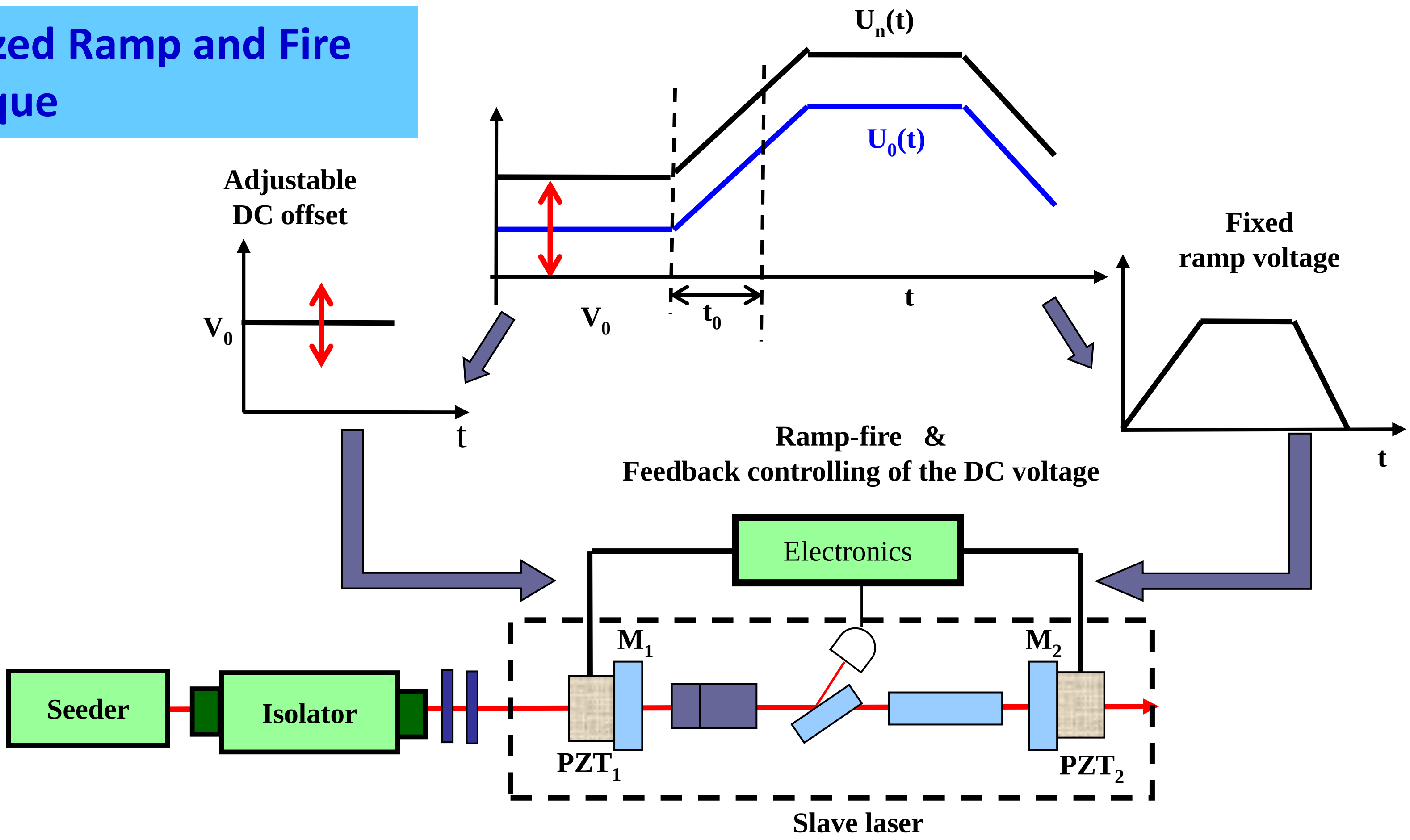




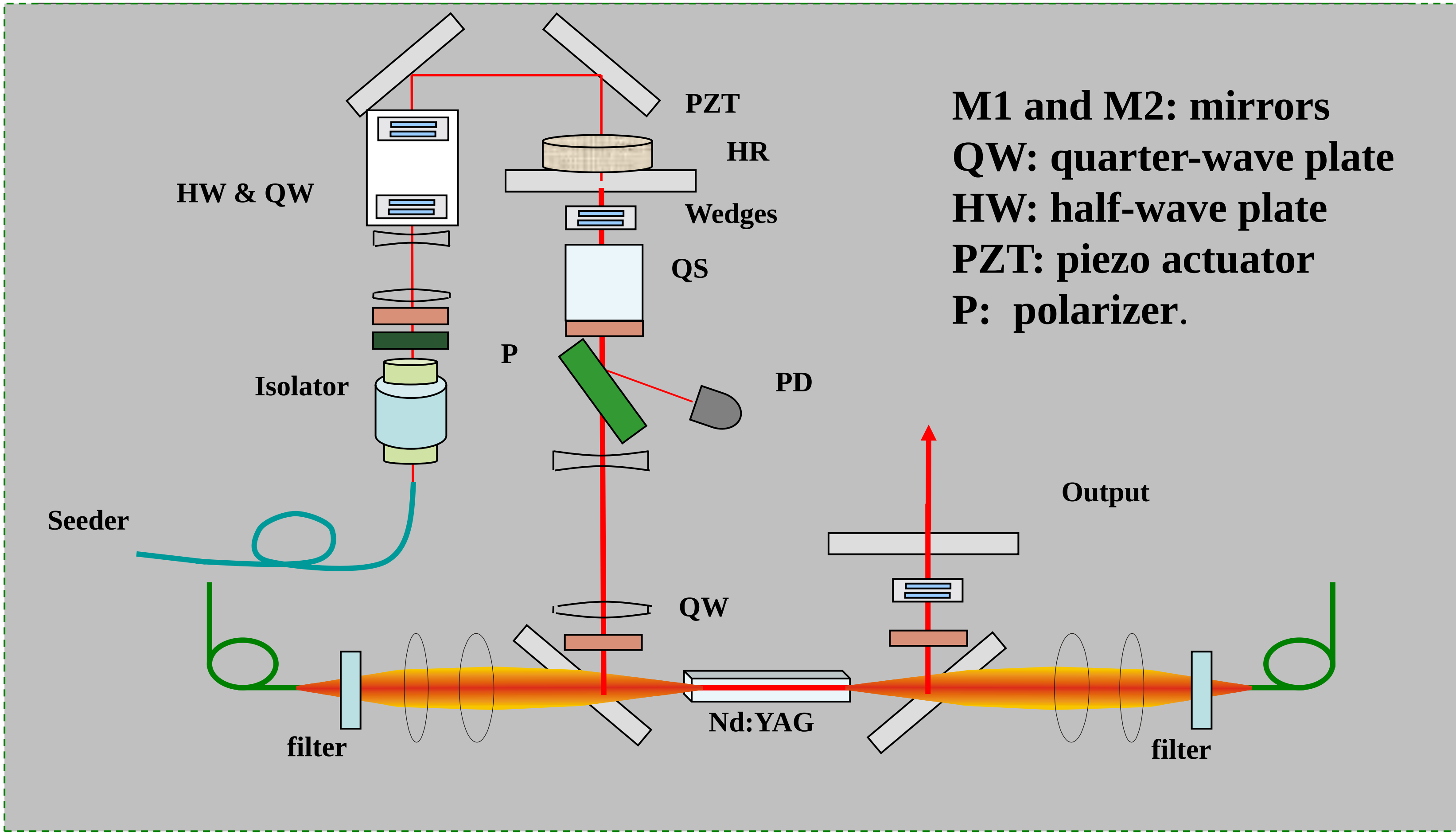
Example 2: Single frequency operation

Injection Seeding Design

Modified Ramp and Fire Technique



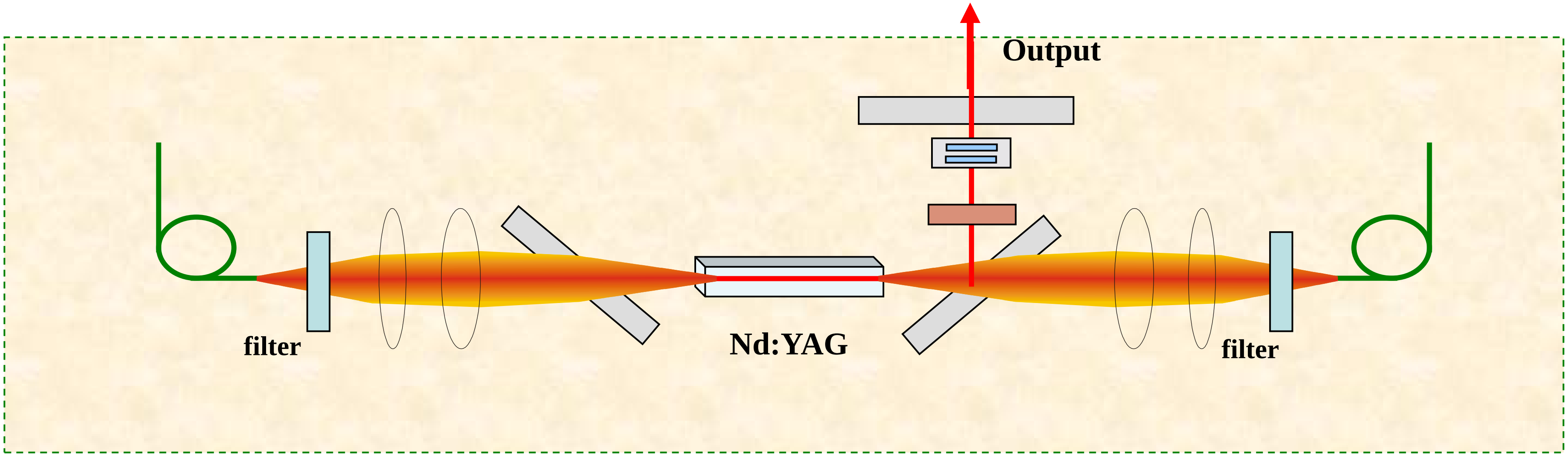
Example 2: Injection seeding End pumped Oscillator



Injection Seeding, EO Q-switch, folded cavity, end –pumping Nd:YAG laser

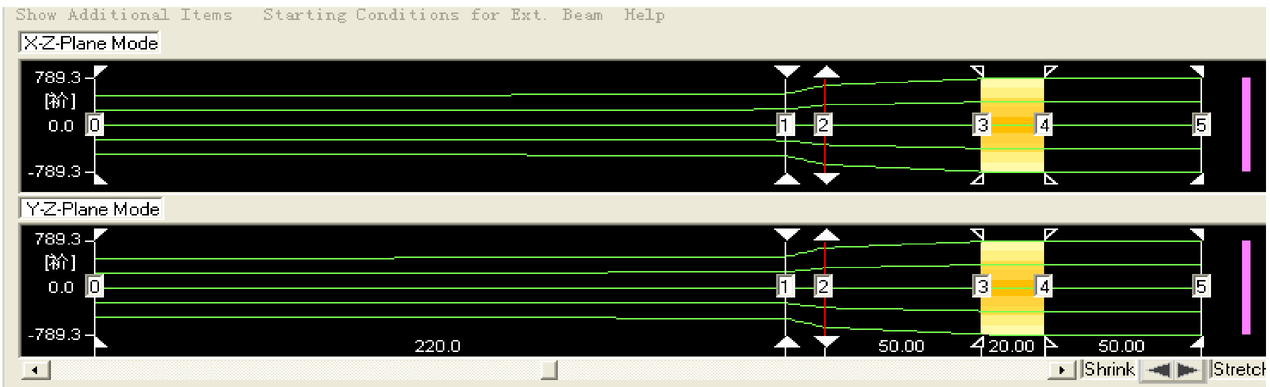
Example 2: End pumped Rod Oscillator

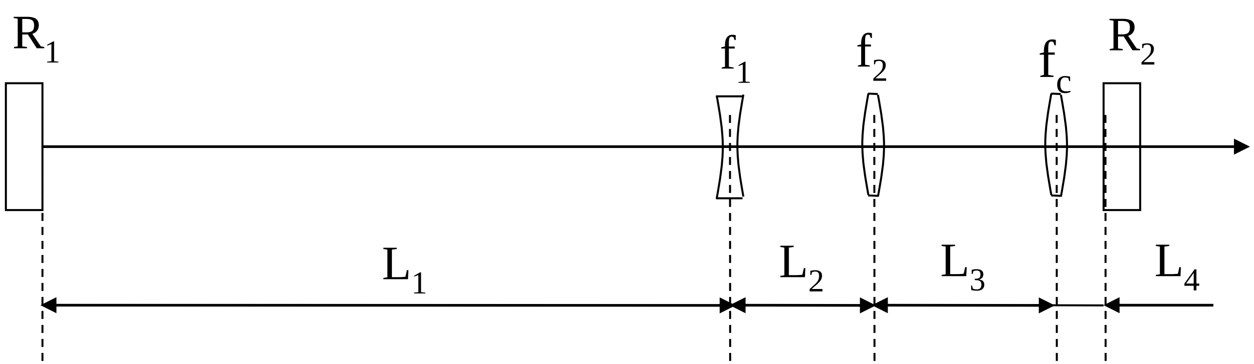
- **Nd:YAG slab**
  - **Dimension: 4x4x20-mm**
  - **Dopant Concentration: 0.7at.%**
  - **Pump Configuration: End-pumped by Fiber coupled LD array**
  - **LDA: Peak power of 300W, D.C. of 2%**



Example 2: End pumped Rod Oscillator

Results of Resonator calculation--LASCAD



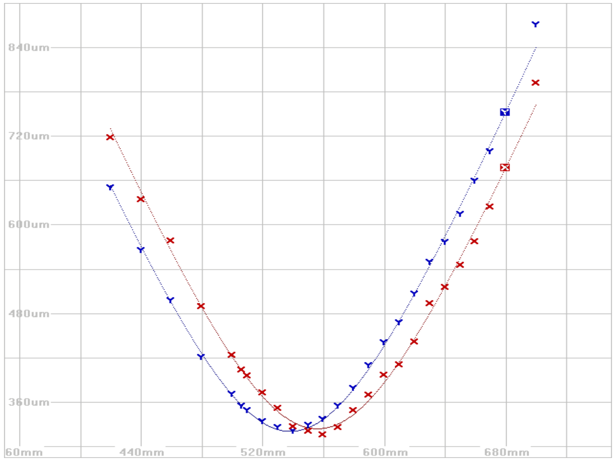


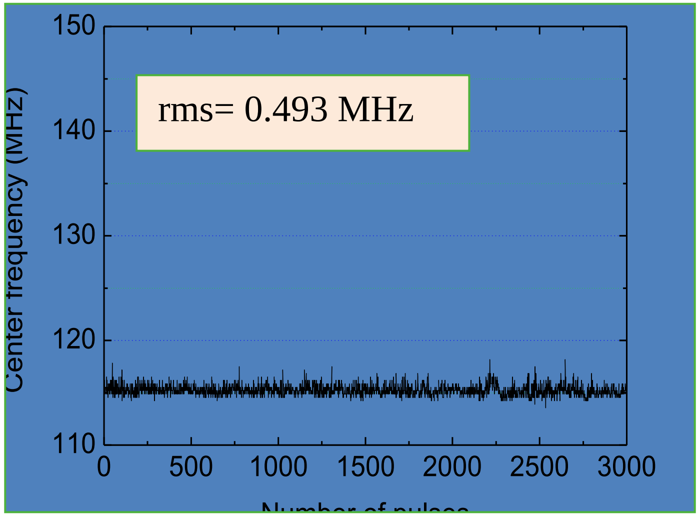
f_1=-45mm,
f_2=70mm,
f_c =130mm,
L_1=220mm,
L_2=12.5mm
L_3=50mm,
L_4=50mm

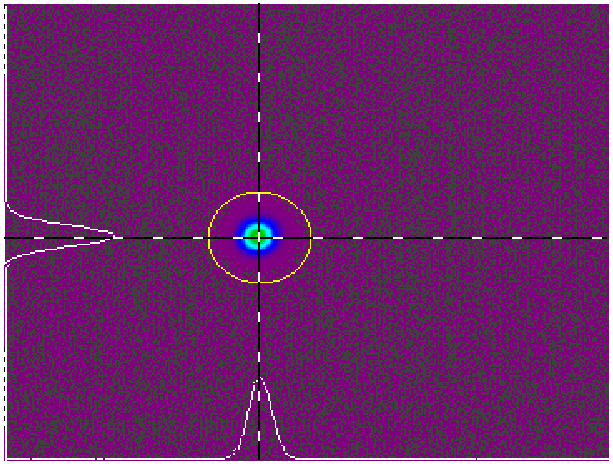
Example 2: End pumped Rod Oscillator

Experiment's Results of oscillator

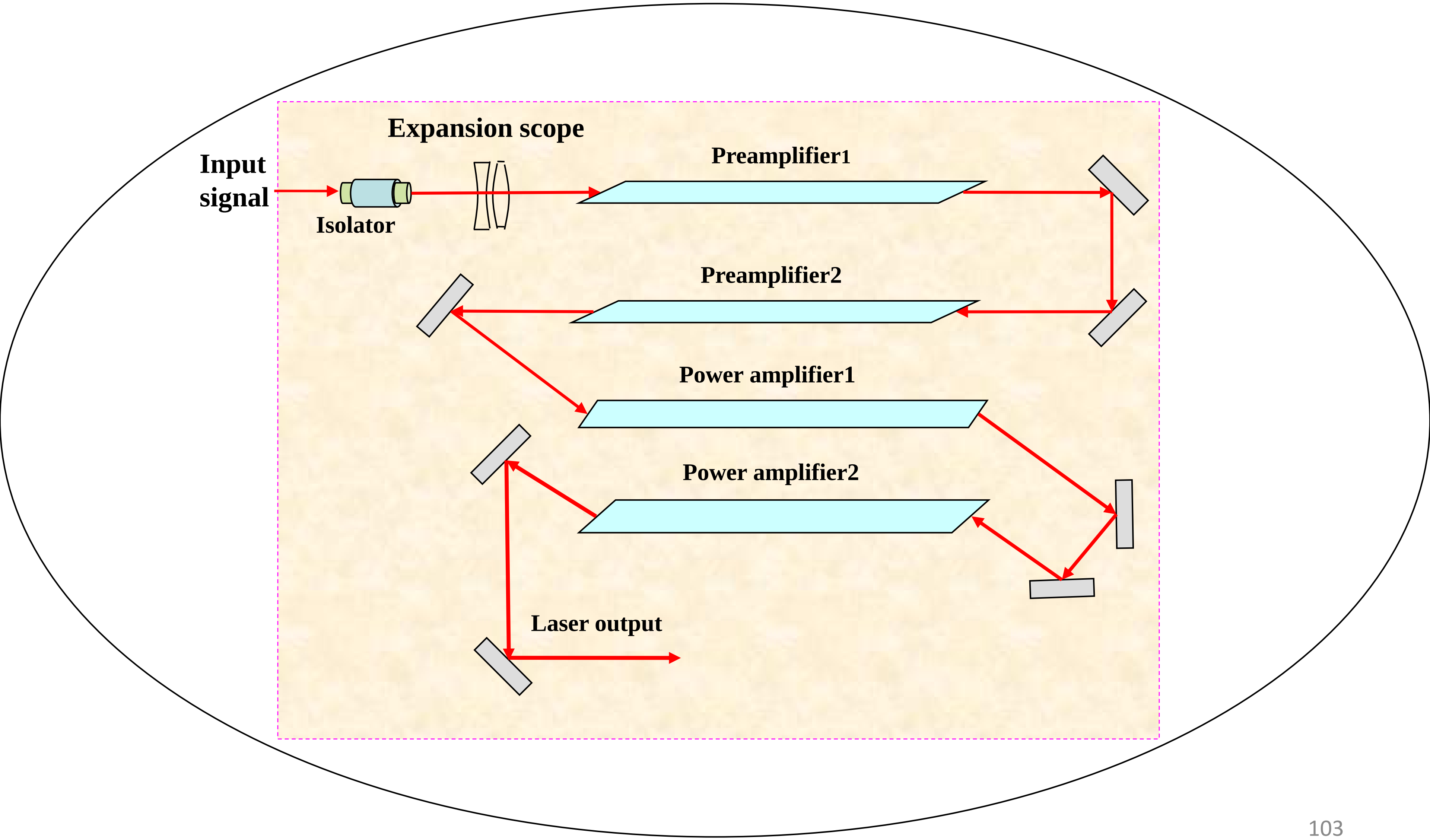
Repetition	100 Hz
Pulse energy	10 mJ
Pulse duration	13 ns
Longitudinal mode	Unique (SLM)
Beam quality (M^2)	1.2







Example 2: Laser Amplifier Configuration

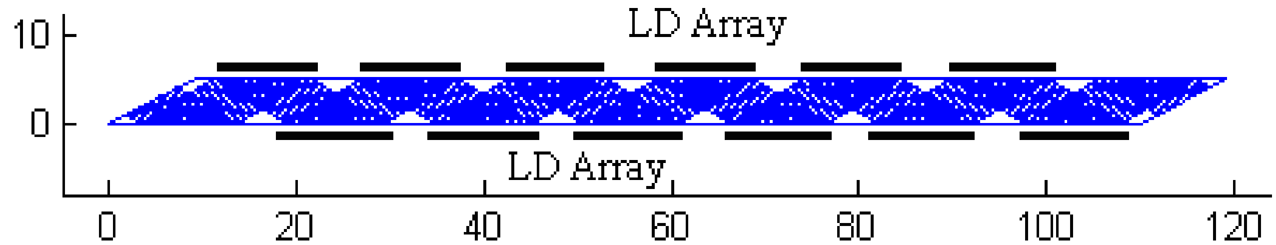


Example 2: The Slabs Dimensions & Parameters

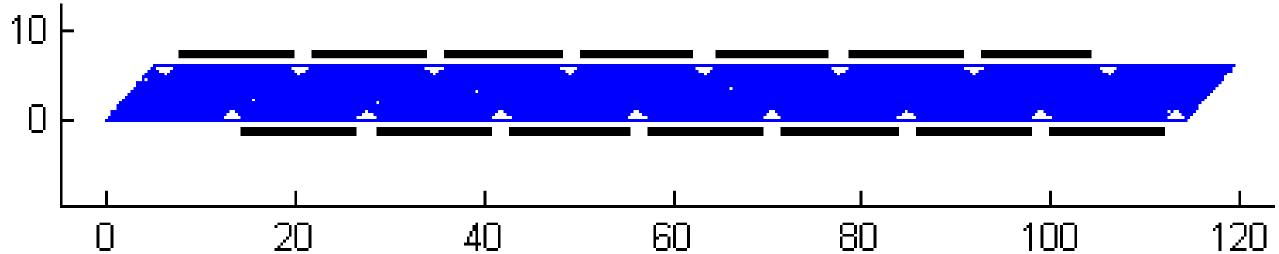
Brief discription	Preamplifier1&2	Power-Amplifier1	Power-Amplifier2
Slab length, mm	119.35	119.43	120
Slab width, mm	5	8	10
Slab thickness, mm	5	6	8
Apex angle on both ends, deg	28.78	50	40
Nd+3 doping concentration,%	1.1	1	0.9
Signal input pulse energy, mJ	10 & 60	180	500
Gaussian beam waist size, mm	3	6	8
Stored energy, J	1	1.9	1.6

Example 2: Bounce Pump for High Efficiency

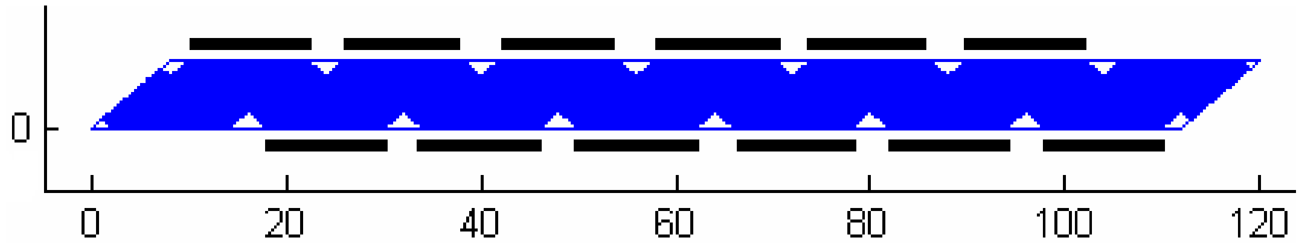
Preamplifier 1&2



Power-amplifier1

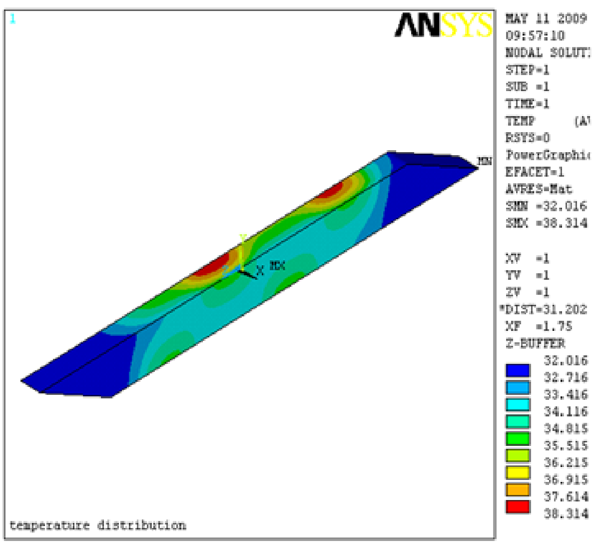


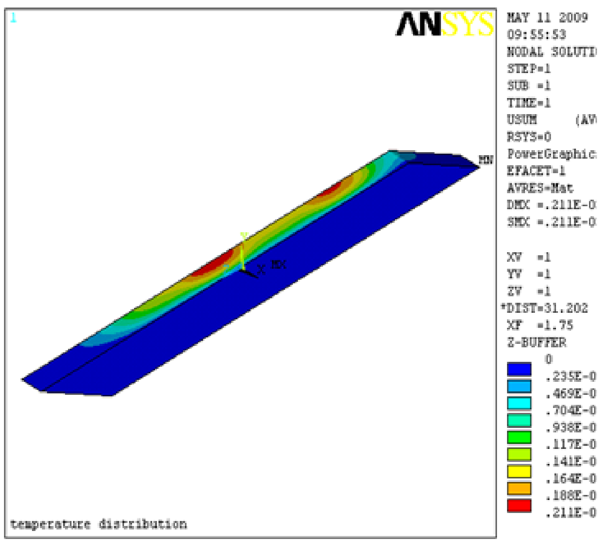
Power-amplifier2

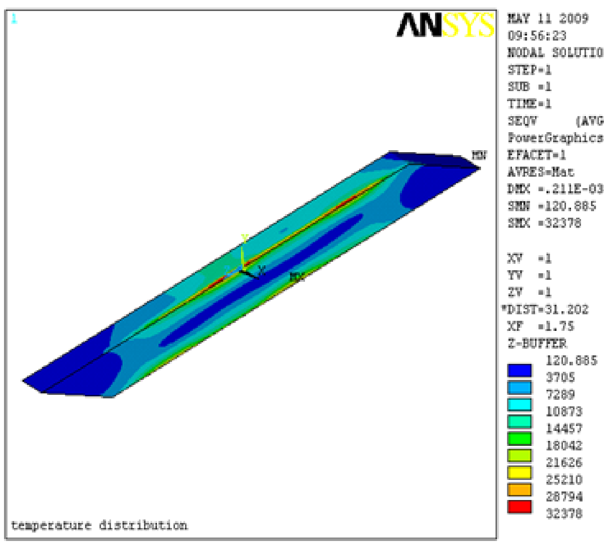


Example 2: Thermal Effect Analysis

- Temperature Distribution
- Temperature Induced Bending
- Temperature Induced Stress



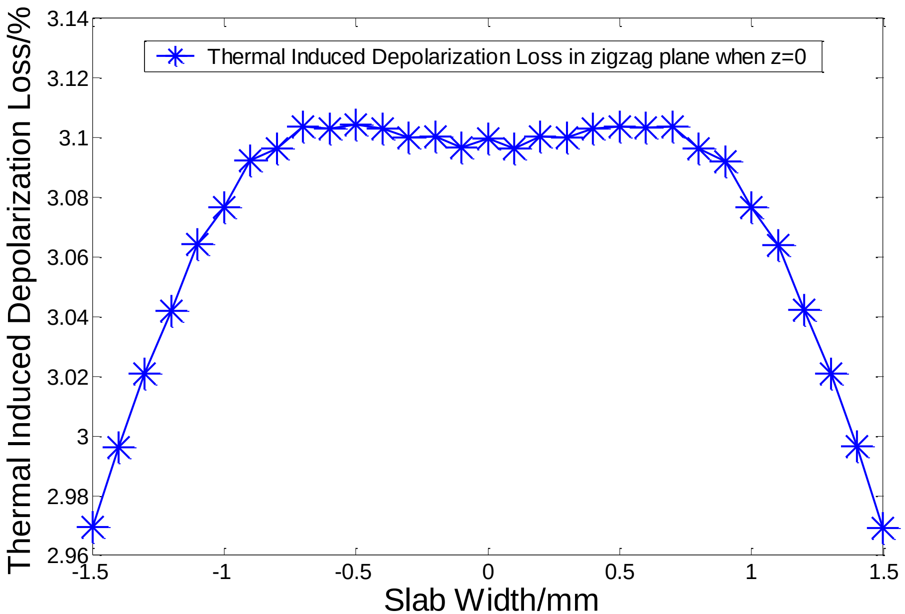




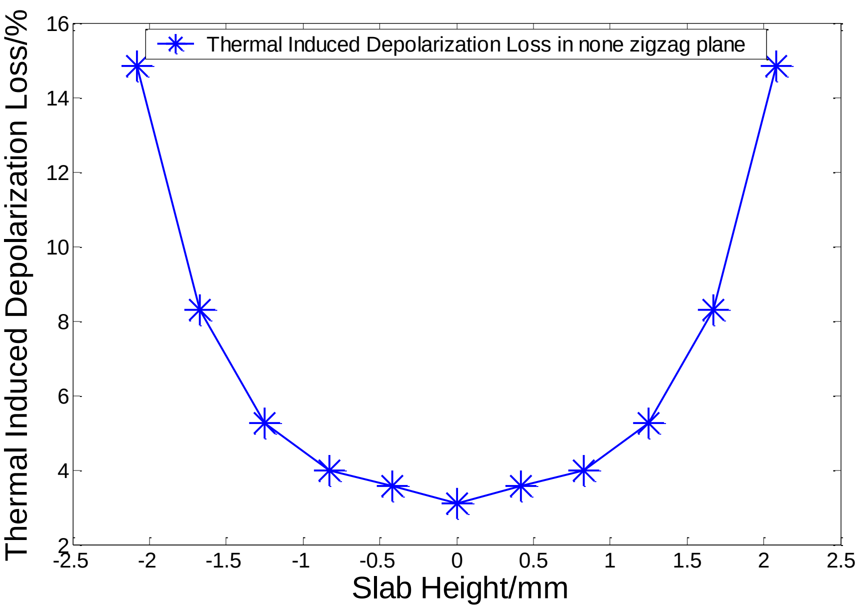
To calculate thermal lens, wave front distortion, depolarization

Example 2: Thermal Effect Analysis

Depolarization results



Depolarization in the Zigzag Direction

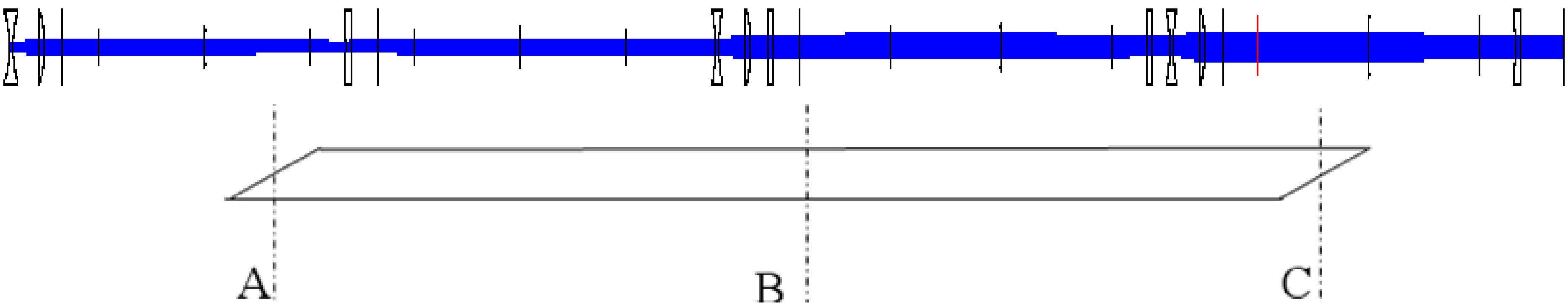


Depolarization Perpendicular Zigzag Direction

Example 2: Comparison of experiment and simulation of thermal lens

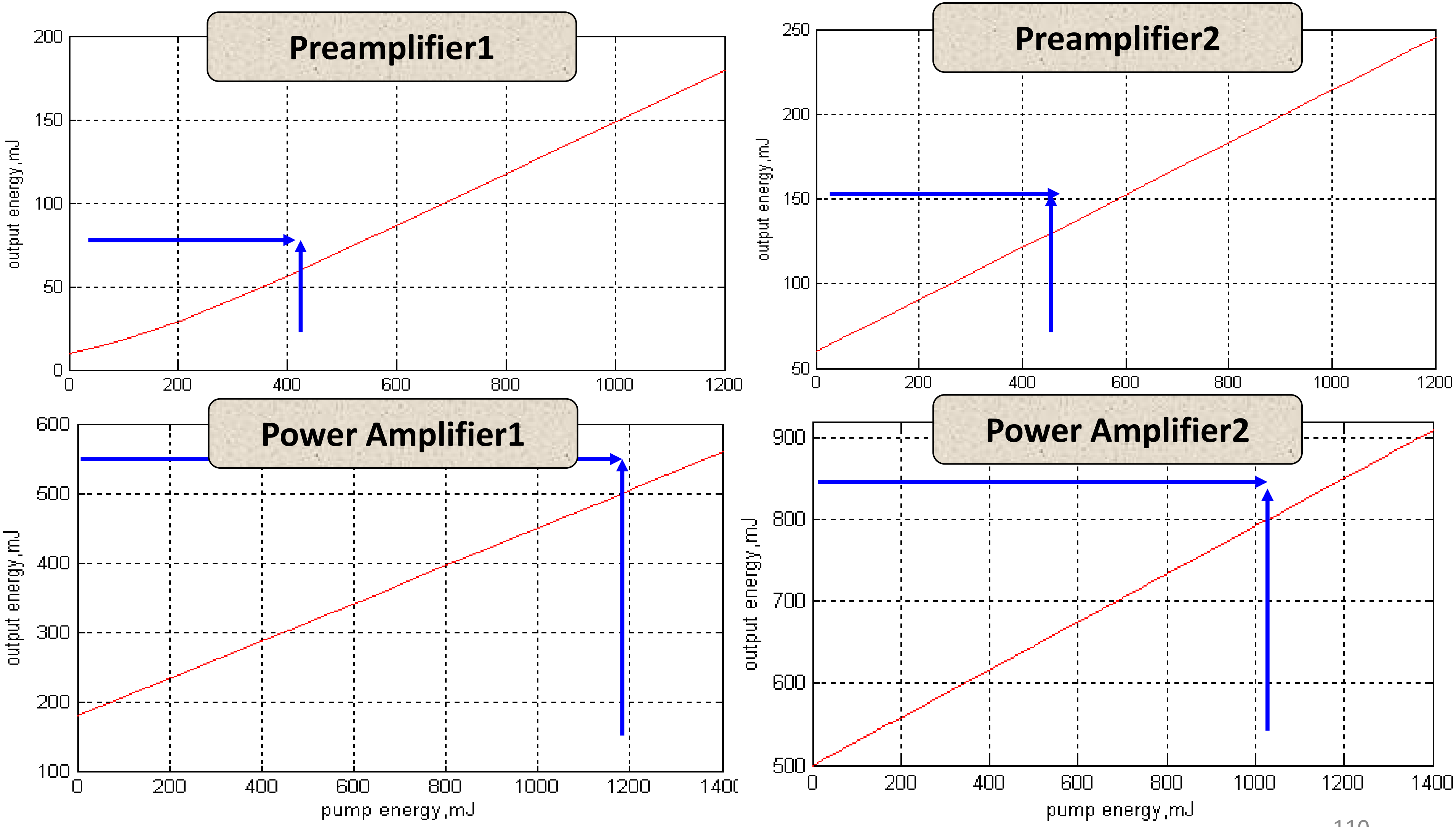
100Hz thermal lens		Experiment results	Modeling Results		
			Index Gradient induced lens (m)	Bending Induced lens (m)	Total lens (m)
50A	Zigzag direction	**7.4**	**7**	**-**	**7**
	Perpendicular zigzag direction	**3**	**7**	**5**	**2.9**
100 A	Zigzag direction	*	*	*	*
	Perpendicular zigzag direction	**1.5**	**2.2**	**3.1**	**1.3**

Example 2: Compensation of thermal lens

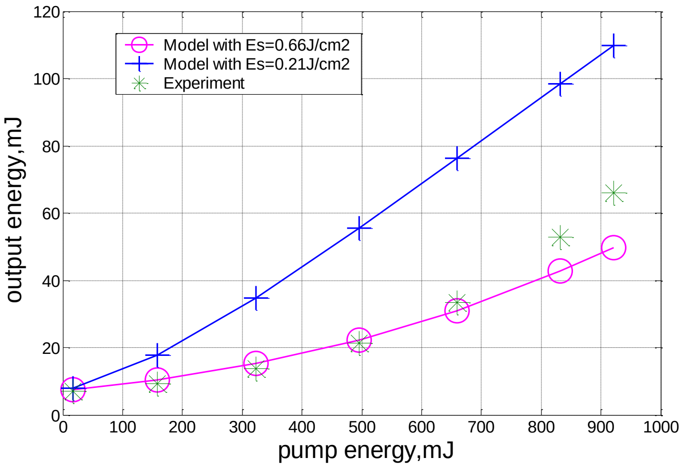


Laser Beam (mm)	Preamplifier 1			Preamplifier 2			Power amplifier 1			Power amplifier 2		
	A	**B**	**C**	**A**	**B**	**C**	**A**	**B**	**C**	**A**	**B**	**C**
	3.3	**3.4**	**2.8**	**3.02**	**3.87**	**3.87**	**6.47**	**6.73**	**5.2**	**7.51**	**7.54**	**6**
Gauss beam (mm)	**3.2**	**3.2**	**2.56**	**2.7**	**3.2**	**3.16**	**5.1**	**5.3**	**4**	**5.8**	**5.78**	**4.6**
Ideal beam	**3mm**			**3 mm**			**6 mm**			**8 mm**		

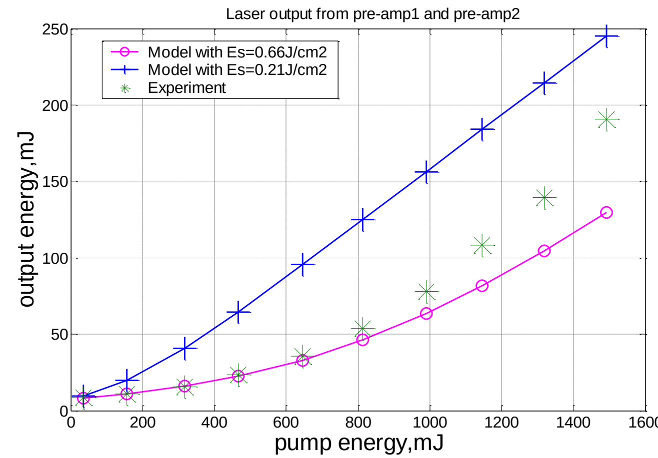
Example 2: Predication of output energy



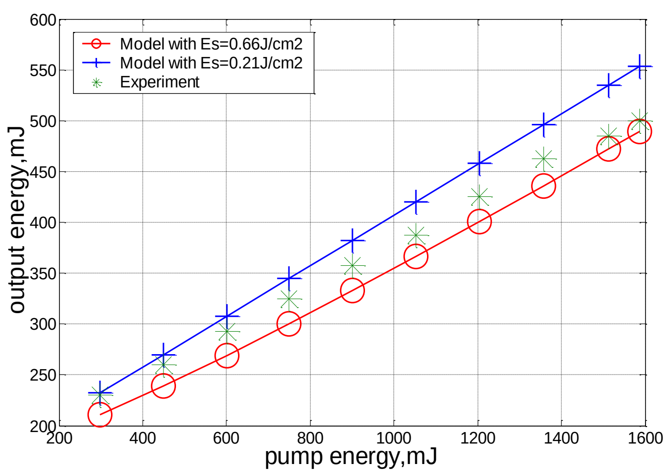
Example 2: Results of amplifier



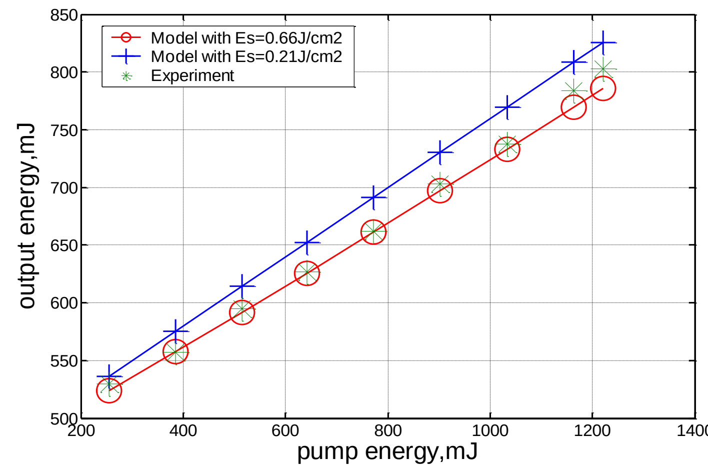
Pre-amplifier1



Pre-amplifier2



Main -amplifier1



Main –amplifier2

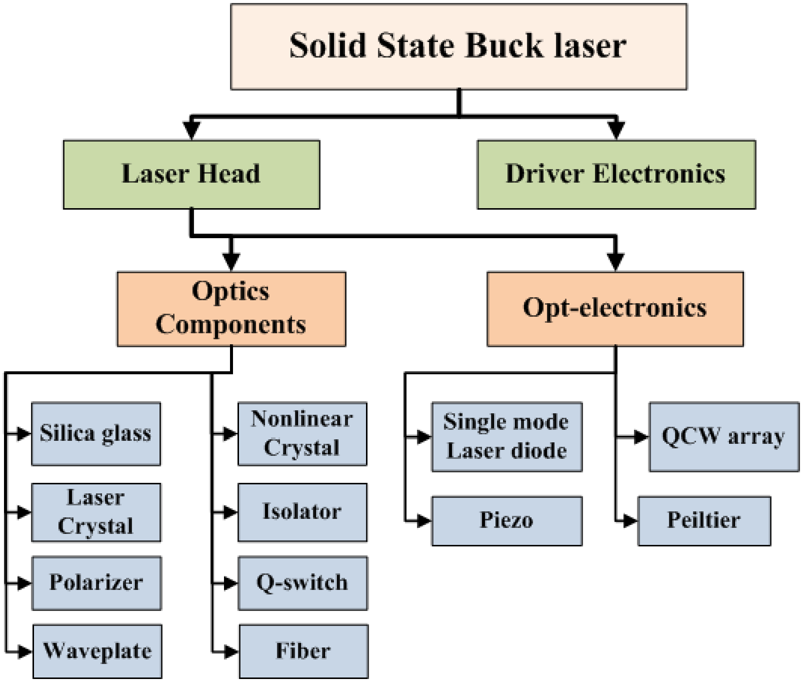
Challenges of space laser technology

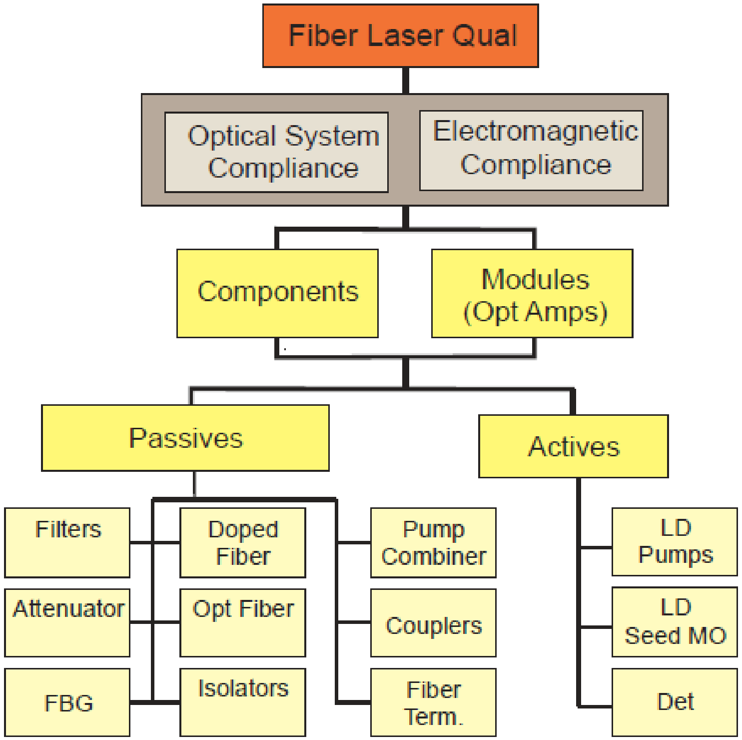
- ✓ CO_2 lidar needs long term frequency stability and high spectrum purity.
- ✓ High energy UV laser in space is still a challenge due to optics damage.
- ✓ New spaceborne Lidar pushes new space laser technology:
  - Such as multi beam high spectrum resolution Lidar: **high repetition rate, planar waveguide solid-state laser** is proposed.
  - Lidar or laser range finder with fs laser is a new technology, **spaceborne fs laser** is frontier .
  - O_2, H_2O, 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

Components of Solid-state Laser

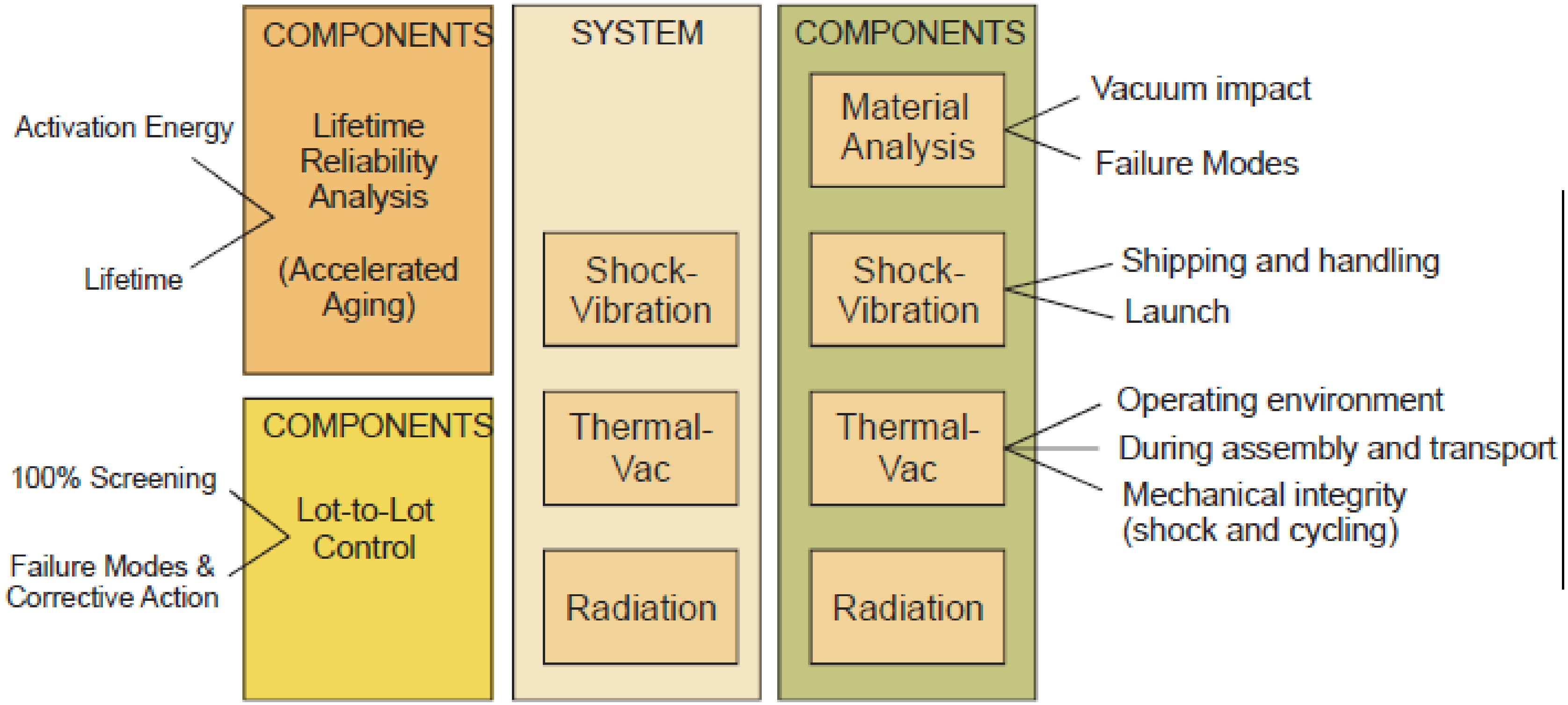




- Many photonics and optics are assembled in solid-state lasers
- Any components are related with the failure of laser, and must be qualified for space environment.

Qualification of Fiber Lasers and Fiber Optic Components for Space Applications, S. Hendow, S. Falvey, B. Nelson, L. Thienel, Maj. T. Drape, SPIE LASE 2006, 6102-59.

Qualification of laser's components

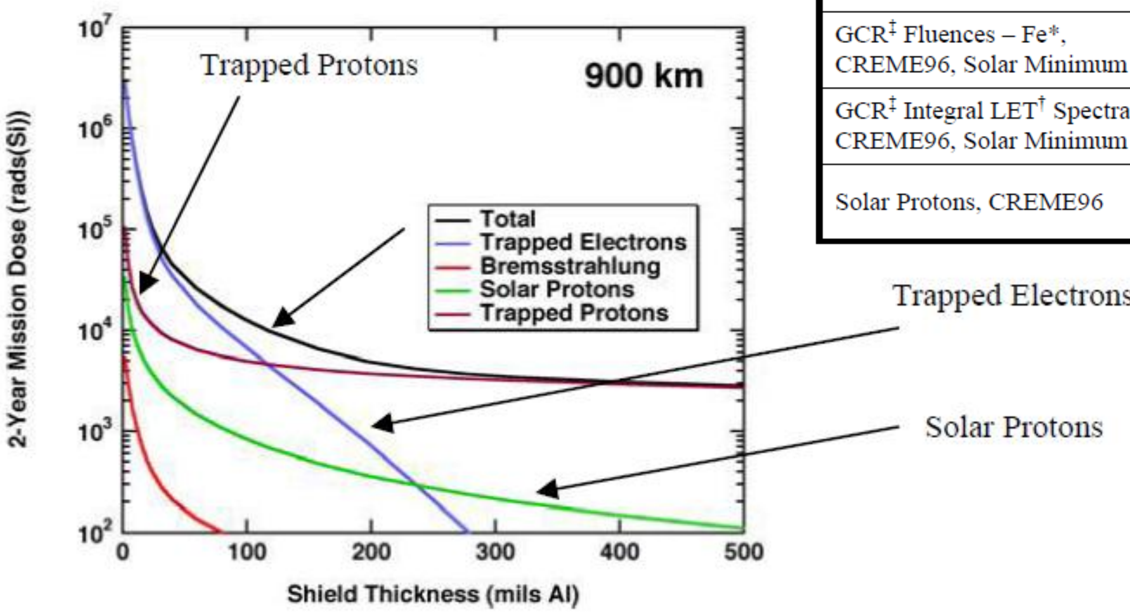


1. Sami Hendow, Suzzanne Falvey, and Burke Nelson, Overview of Qualification Protocol of Fiber Lasers for Space Applications, Solid State Lasers XV: Technology and Devices, Proc. of SPIE Vol. 6100, 61001Y, (2006)

Qualification of laser's components

Radiation condition

Parameter	Condition	Units
Orbital Altitude	100 - 1000	Km
Dose Rate, Typical*	~0.1	Krad/year
Total Dose* (2-year mission)	< 0.2	Krad
Particle Impact	11 to 26	Impacts/m^2/year
UV Radiation	2220 to 5800	ESH/year**
	118	W/m^2
Atomic Oxygen	$10^{11} – 10^{12}$	Atoms/m^3
	4.3 to 4.4	EV
Charged Plasma	3e4 to 9e5	cm^{-3}
	0.1 to 0.2	EV
GCR‡ Fluences – Fe*, CREME96, Solar Minimum	10^{-6} - 0.002	Particles/cm^2/day/MeV/nuc
	10^3 - 10^5	MeV/nucleon
GCR‡ Integral LET† Spectra*, CREME96, Solar Minimum	10^{-8} - 150	Particles/cm^2/day
	0.1 - 20	MeV-cm^2/mg
Solar Protons, CREME96	$10^{-13} – 10^{-6}$	Protons/cm^2/sec/MeV
	~10^2 - 10^5	MeV



Howard, Jim, "Space Radiation Environments and Effects", Presentation, Jackson & Tull, March 2005.

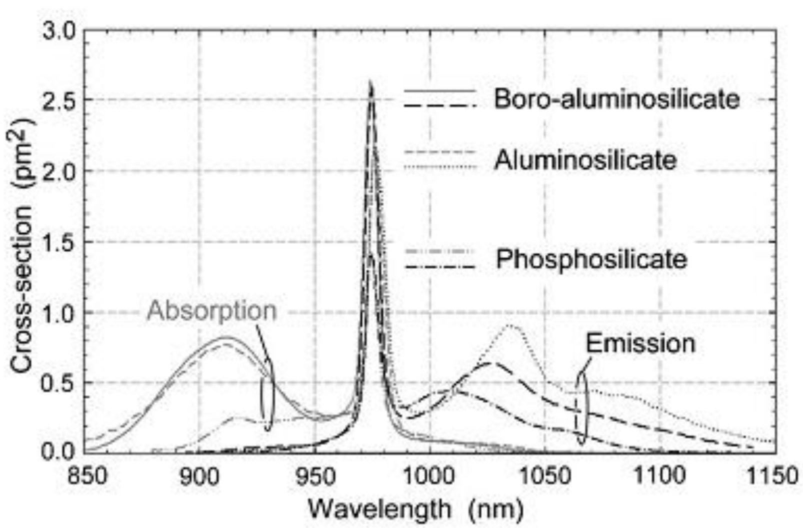
Main laser medium

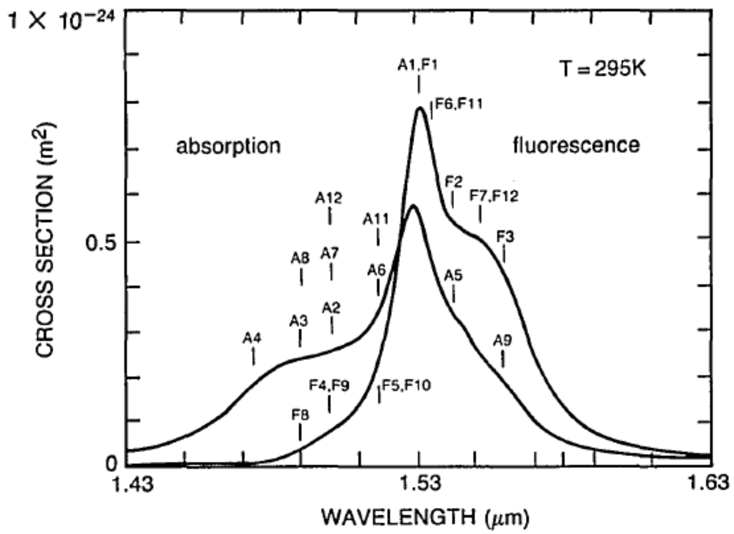
	Nd:YAG	Nd:YVO_4	Nd:YAP	Nd:YLF	Nd:$GdVO_4$	Nd:YGG	Nd:GSGG	Nd:LuAG	Yb:YAG
Wavelength /nm	1064	914.4 1064.3 1342	930 1079 1341	1053(σ) 1047(π)	912.2 1063.1 1340.6	1062	1062	1064	1030
Index (λ=1.06μm)	1.82	n_o=1.96 n_e=2.18	1.94	n_o=1.448 n_e=1.470	n_o=1.97 n_e=2.19	1.892	1.94	1.83	1.82
Cross section/$10^{-19}cm^2$	σ_{946} = 0.37 σ_{1064} =2.8	σ_{914}=0.48 σ_{1064}=15.6 σ_{1342}=2.8	σ_{930}=0.41 σ_{1079}=4.6 σ_{1341}=2.2	1.2(σ) 1.8(π)	σ_{912}=0.6.6 σ_{1063}=7.6 σ_{1340}=1.8	σ_{935}=0.15 σ_{938}=0.143 σ_{1062}=1.14	1.0	2.89	0.21
Lifetime /μs	230	100	170	480	90	254	289	277	951
Pumping wavelength /nm	807.5	808.5	803	792(//C) 796(⊥c)	808.5	806	809	809	942
CTC/[W/(m K)]	14	5.23(//C) 5.1(⊥c)	11	6.3	11.7(沿<110>)	9	6	9.6	7
CTE /10-6 K-1	7.7-8.2	a：2.2 c：8.4	a：4.2 b：11.7 c：5.1	a：13 c：8	a：1.5 c：7.3	-	7.4	6.13	7.7-8.2
dn/dT(10^{-6} K^{-1}) (λ=1. 06μm)	7.3	2.7	a：9.75±0.07 c：14.53±0.07	-2.0 (σ) -4.3 (π)	4.7	17.6±0.8	10.5	8.3	7.3

CTC: coefficient of thermal conductivity

CTE: coefficient of thermal expansion

Main laser medium

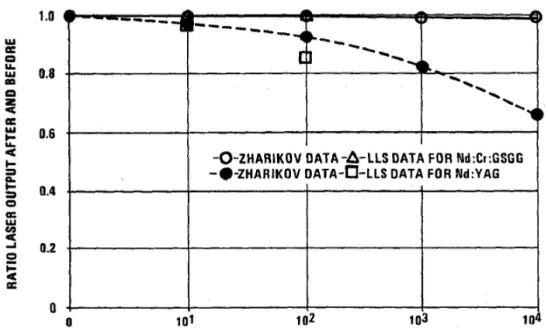


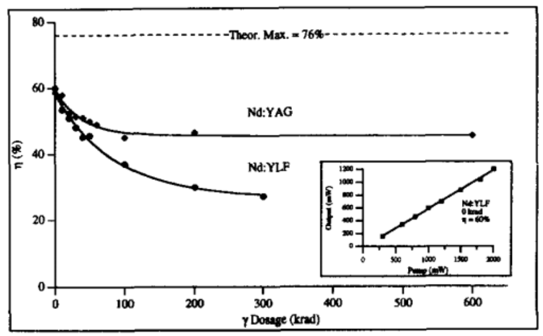


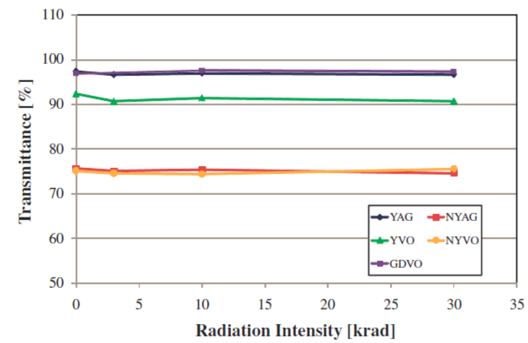
Laser Fiber:

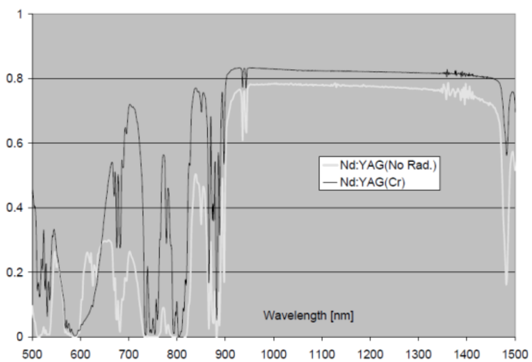
- Yb Doped Fiber
- Er Doped Fiber
- Yb,Er: Doppler fiber
- Tm Doped Fiber
- Ho Doped Fiber

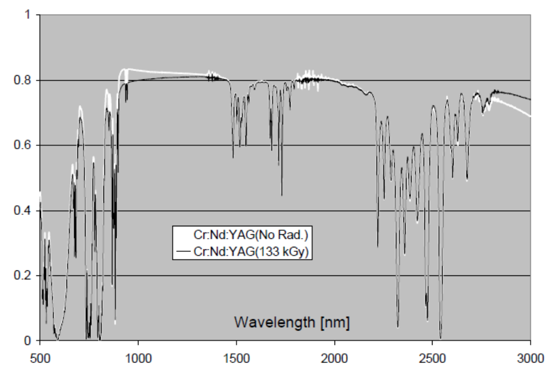
Radiation performance of laser crystals

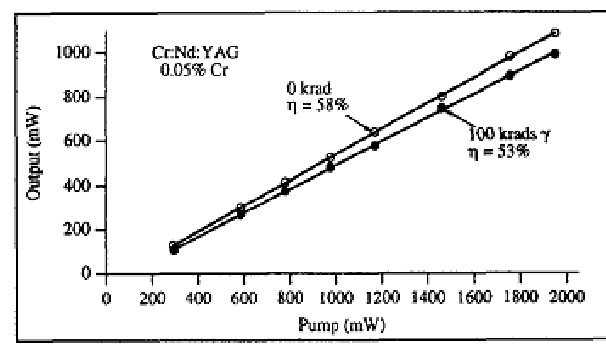












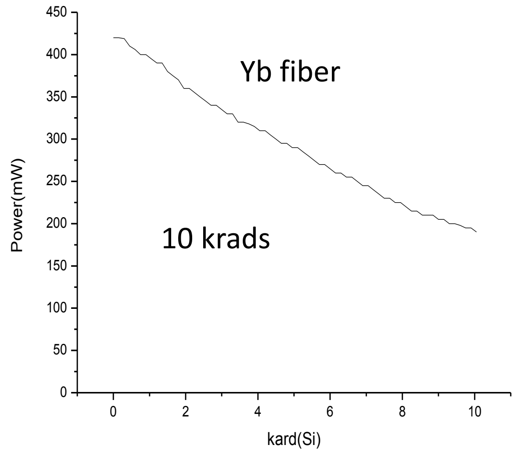
(a)

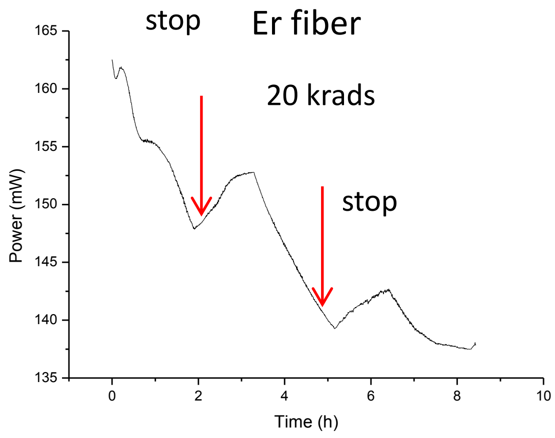
1. Acharekar MA, Kaplan MM, McCarthy DP. Radiation hardness of nd: Yag and nd: Cr: Gsgg laser rods. in Laser induced damage in optical materials. 1986. 1988.
2. Rose TS, Hopkins MS, Fields RA. Characterization and control of gamma and proton radiation effects on the performance of nd: Yag and nd: Ylf lasers [J]. Quantum Electronics, IEEE Journal of, 1995, 31(9): 1593-1602.
3. Ogawa Takayo, Kawasaki Yoshiya, Takizawa Yoshiyuki, etc. Radiation resistance of nd-doped laser crystals for space application [J]. Japanese Journal of Applied Physics, 2009, 48(8R): 088001

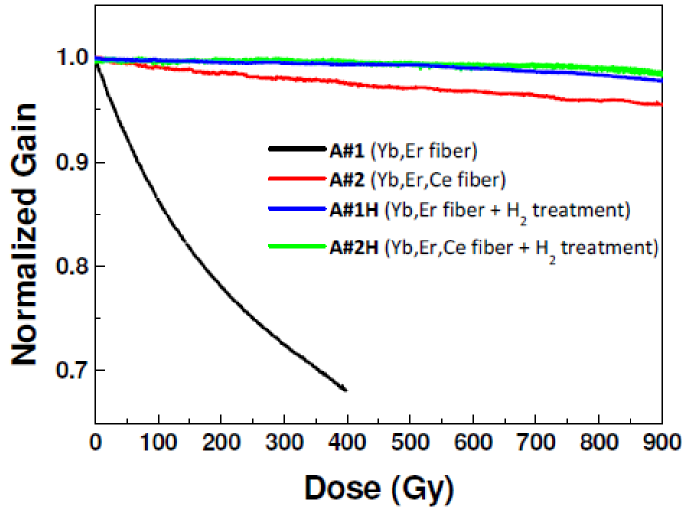
Radiation performance of laser crystals

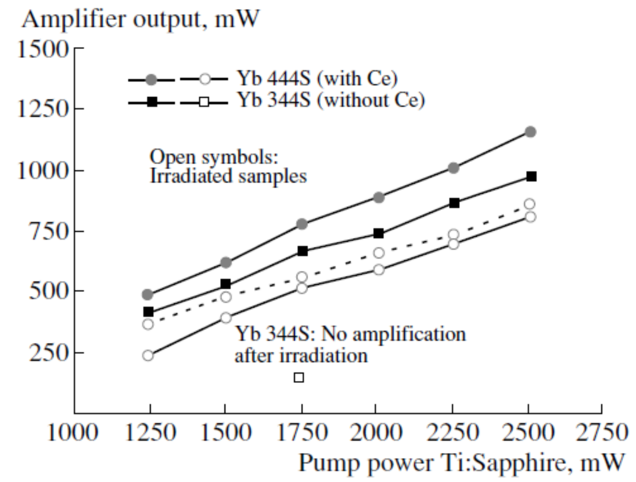
- ✓ Most laser crystals have good radiation performance;
- ✓ Absorption spectrum in UV and visible is changed larger than that in near infrade after radiation
- ✓ Some co-doped crystal can improve radiation hardness, such as Cr,Nd:YAG.
- ✓ Diode pumping, and Q-switch operation is better to improve radiation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

Radiation performance of Doped fibers



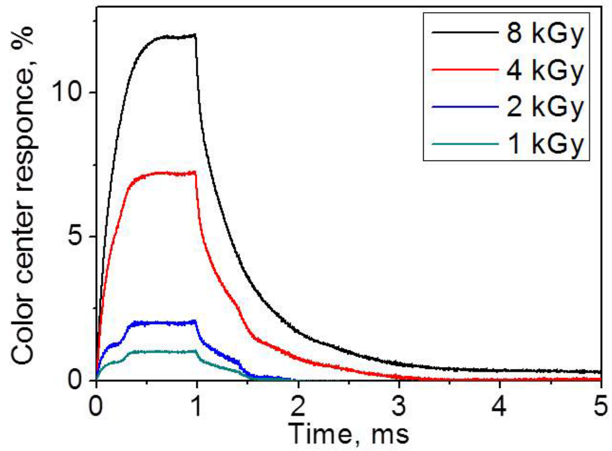


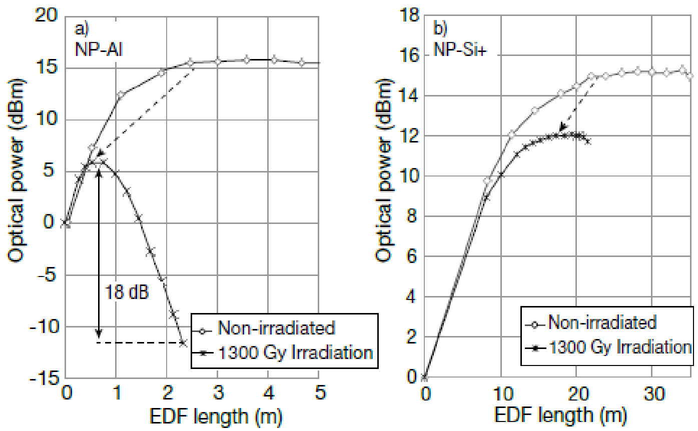




Girard Sylvain, Vivona Marilena, Laurent Arnaud, etc. Radiation hardening techniques for er/yb doped optical fibers and amplifiers for space application [J]. Optics Express, 2012, 20(8): 8457-8465.

Radiation performance of Doped fibers





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

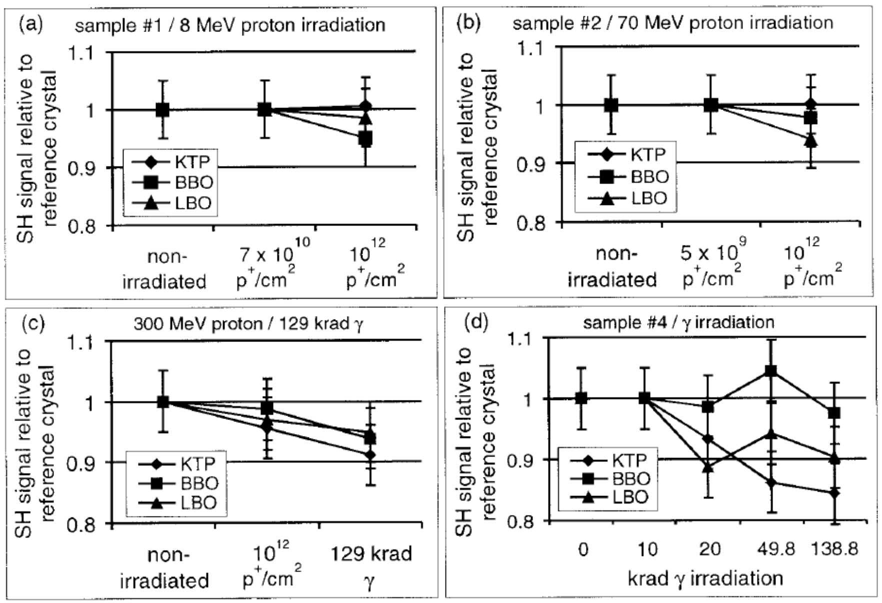
Fiber Name	NB Al	LB NP	Al NP	Si NP	Si+
Erbium absorption (dB/m@ 1530 nm)	4.7	12.3	23	2	3.2
Aluminum (wt%)	<1	6-8	4-6	0	0
Pump power (dBm)	23	23	21	23	21
Optimal Length (m)	25	6	2.5	45	22
Output signal (dBm)	17	18	16	17	15
RIA at 1550 nm (dB/m/Gy)	5.5e-4	7e-3	5e-3	2.2e-4	2.8e-4
RIA at 980 nm (dB/m/Gy)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

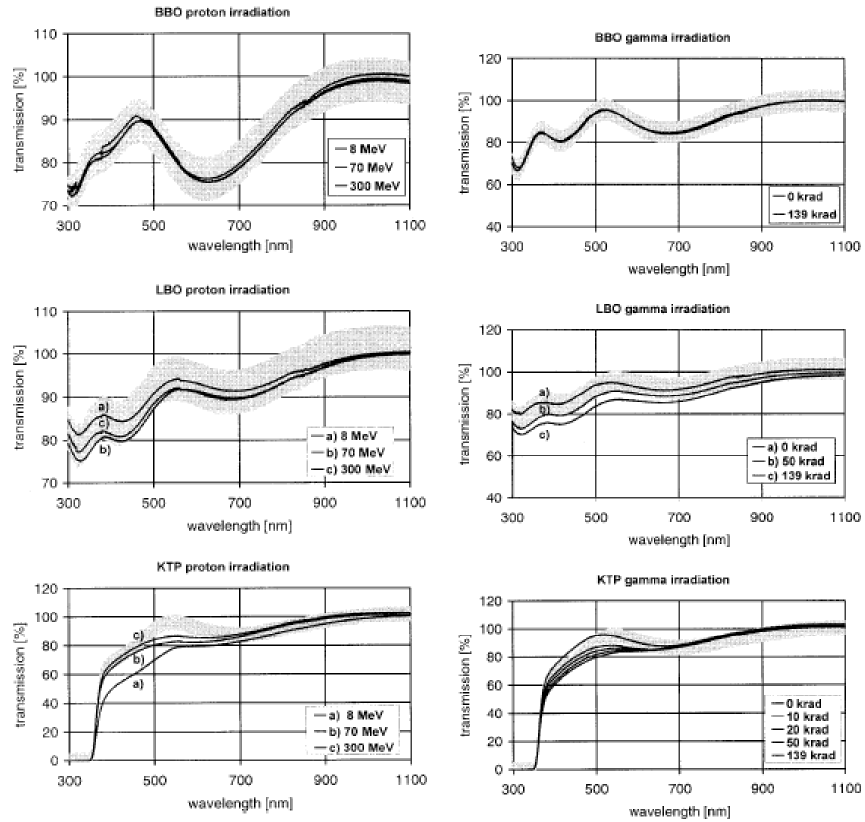
Ott Melanie. Radiation effects expected for fiber laser/amplifier rare earth doped optical fiber [J]. NASA GSFC, Parts, Packaging and Assembly Technologies Office Survey Report, 2004.

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

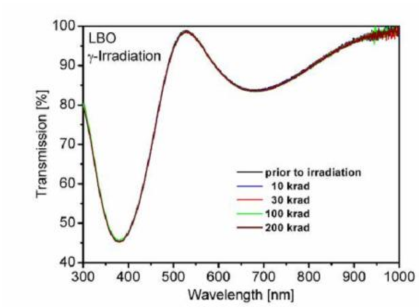
Radiation effect of nonlinear crystals

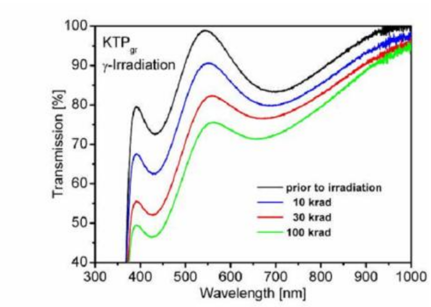




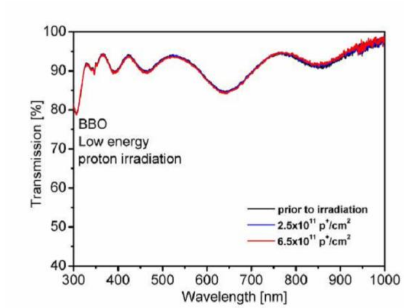
1. Roth Ulrich, Tröbs Michael, Graf Thomas, etc. Proton and gamma radiation tests on nonlinear crystals [J]. Applied Optics, 2002, 41(3): 464-469.
2. Ciapponi Alessandra, Riede Wolfgang, Tzeremes Georgios, etc. Non-linear optical frequency conversion crystals for space applications ,Proc. SPIE 7912, Solid State Lasers XX: Technology and Devices, 791205.

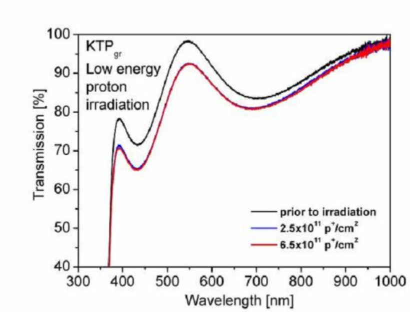
Radiation effect of nonlinear crystals



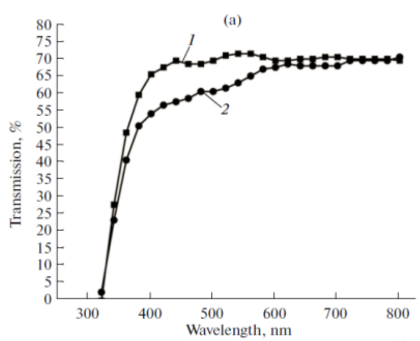


100 krad

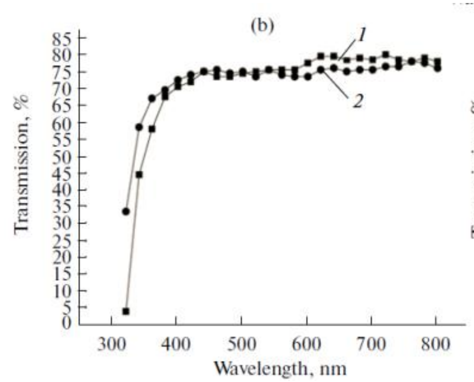


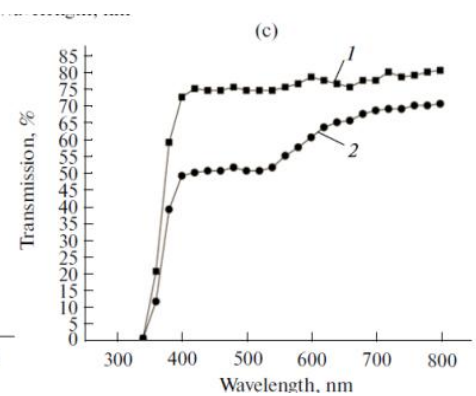


10.8 MeV



$LiNbO_3$: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;

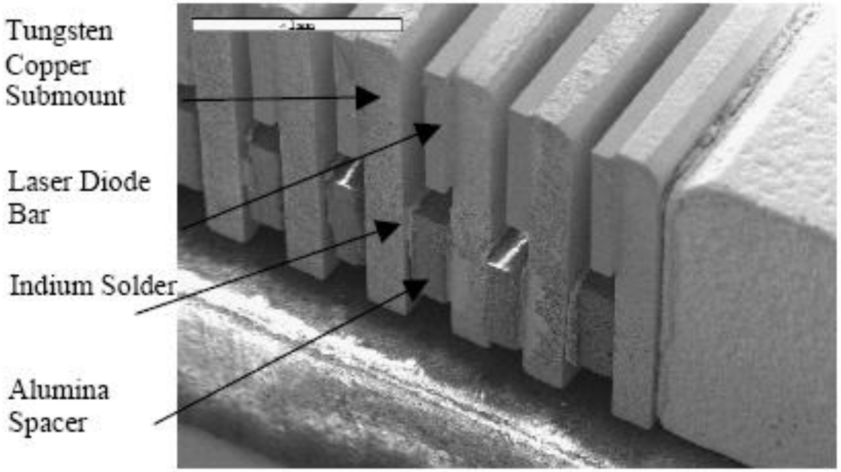
- Performance after ϒ and proton radiation

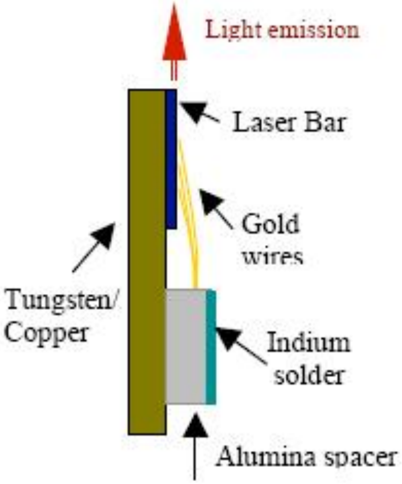
Example of laser diode used in vacuum

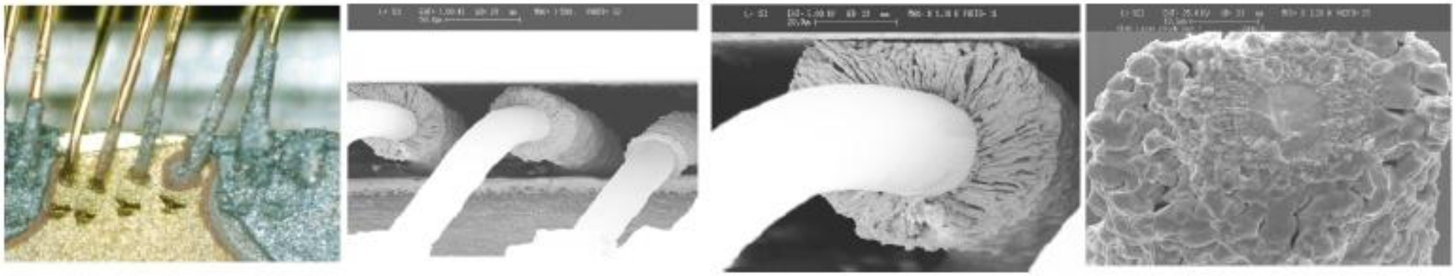
Satellite	Sensor	Number/wavelength/type	Parameters	status
MGS (1996-2001)	MOLA	44/808 nm/array	vacuum 150 μs， 10 Hz， 60 A	Success
ICESat (2003~2010)	GLAS	54/808 nm/array	vacuum 200 μs， 40 Hz， 100 A	**Lifetime**
MESSAGER (2006-present)	MLA	10/808 nm/array	vacuum 160 μs， 8 Hz， 100 A	Success
LRO (2008-presnt)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

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

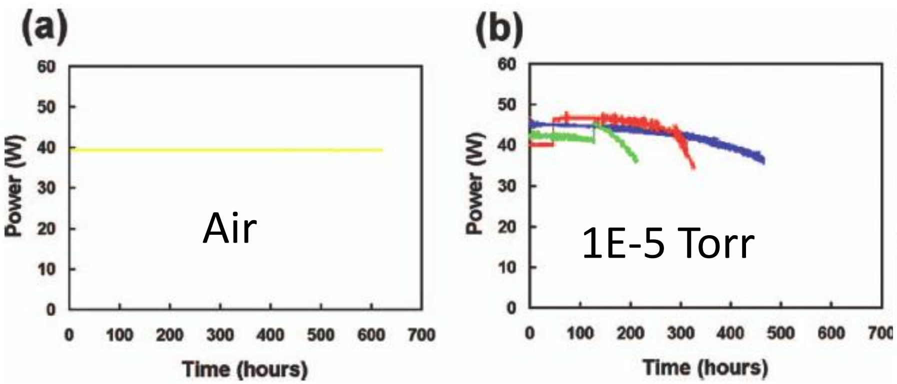


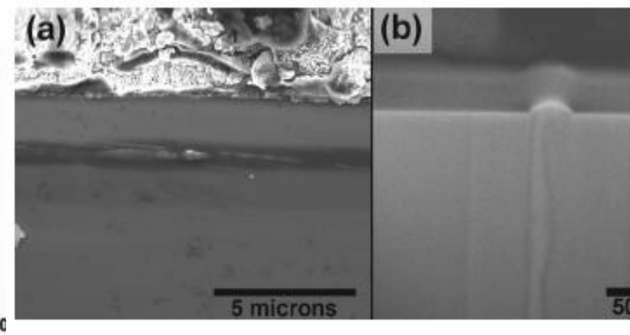


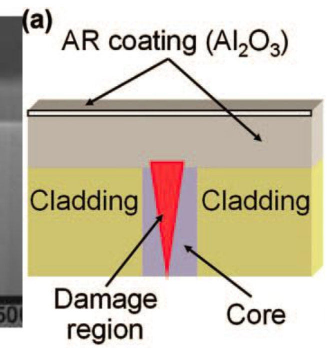


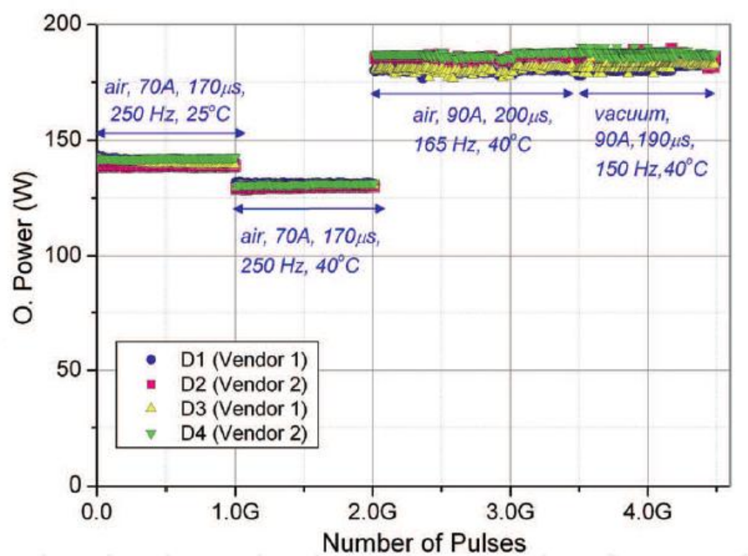
- No evidence to show laser diode can not be used in vacuum.
- Hard solder can be running for long lifetime in vacuum.

Lifetime test in vacuum

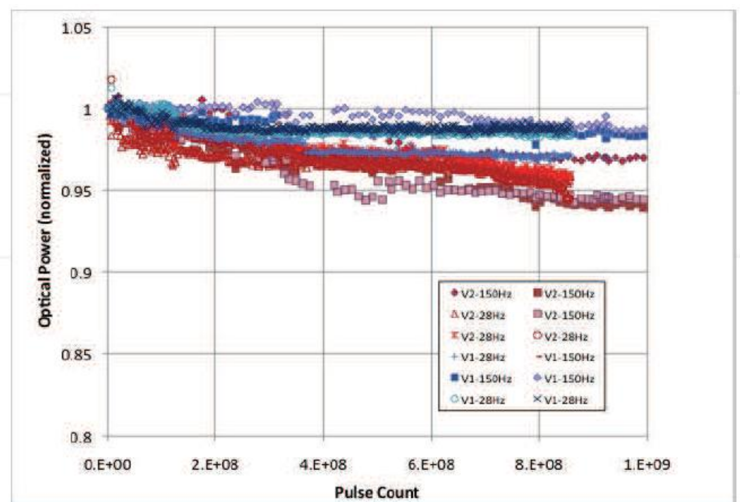






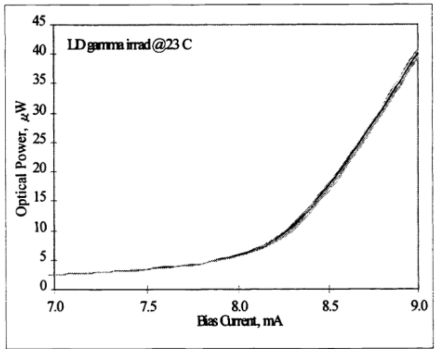


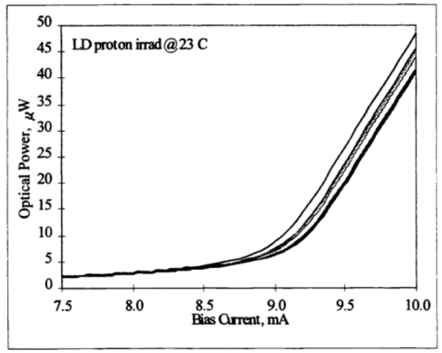
Lifetime test in vacuum

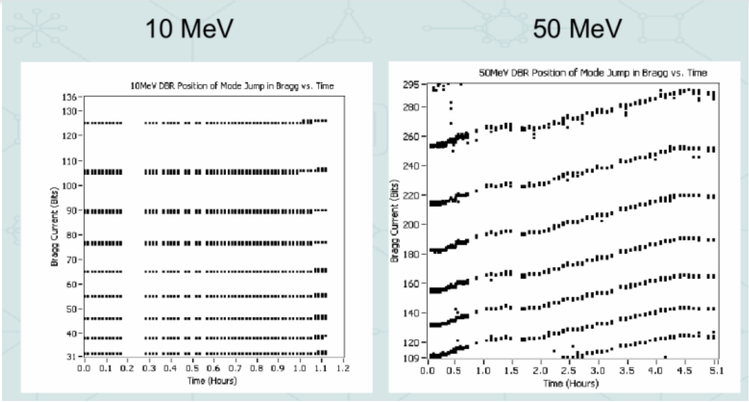


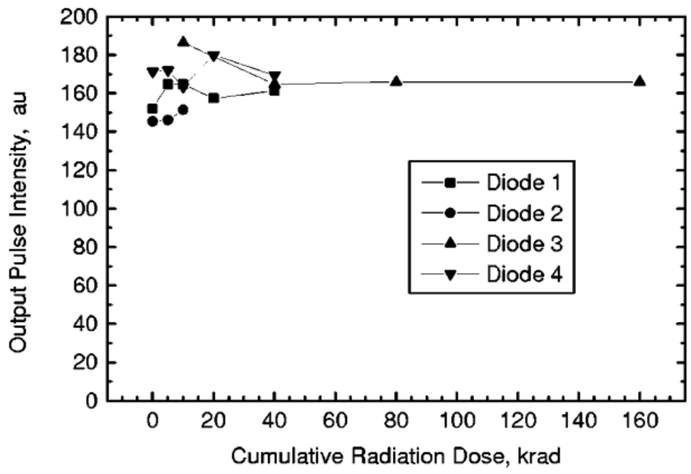
Lifetime test in vacuum for Indium and gold solder

Radiation performance of laser diode









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

1. Krishnan Kamala S, Smith W David, Hatch Joel M. Laser diode response to gamma and proton radiation [C]. Optical Science, Engineering and Instrumentation'97. International Society for Optics and Photonics, 1997:22-33.
2. Wright Malcolm W, Franzen Don, Hemmati Hamid, etc. Qualification and reliability testing of a commercial high-power fiber-coupled semiconductor laser for space applications [J]. Optical Engineering, 2005, 44(5): 054204-054204-8.

Other components of laser

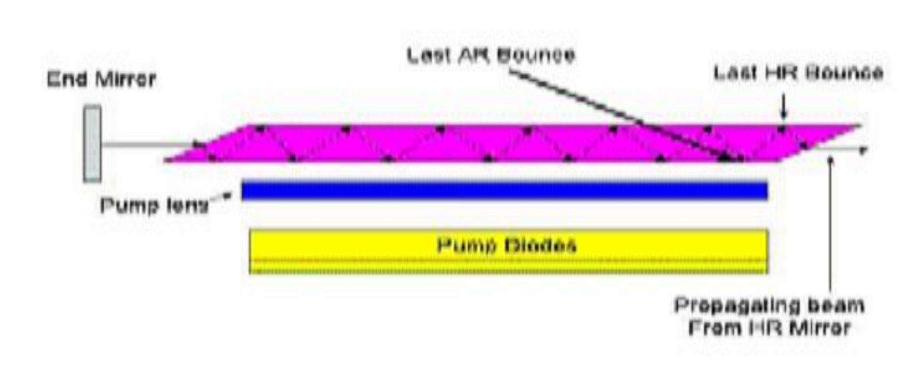
- Isolator, combiner, modulator, fiber grating are also key components in space laser, especially for space fiber laser.

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

Falvey Suzzanne, Buelow Marisol, Nelson Burke, etc. Fiber laser component testing for space qualification protocol development [C]. The Advanced Maui Optical and Space Surveillance Technologies Conference. 2006:30.

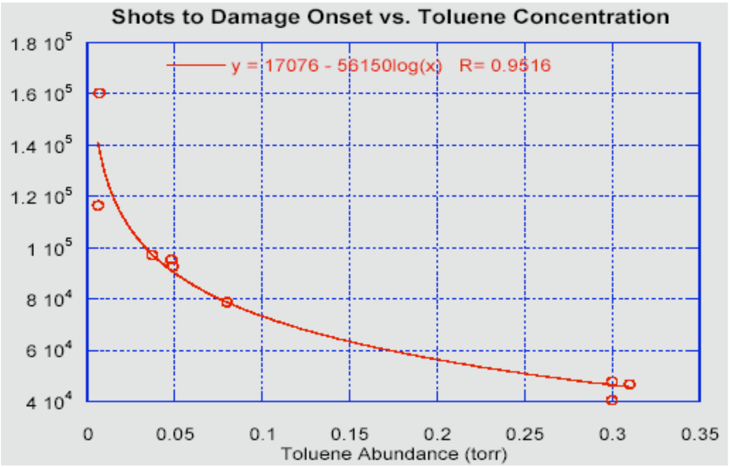
Reliability of optics for spaceborne laser

- ✓ 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**



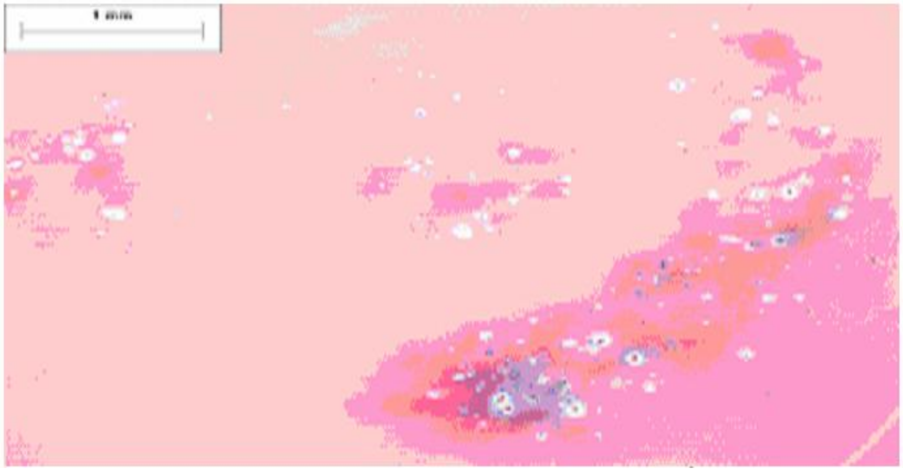
Reliability of optics for spaceborne laser

- ✓ 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



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

- ✓ 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.

Optics damage in pure N2 environment

1. Abdeldayem Hossin A., Dowdye Edward, Canham John, etc. Contamination and radiation effects on spaceflight laser systems [C]. 2005:589705-589705-13.
2. Hovis F. E., Shepherd B. A., Radcliffe C. T., etc. Contamination damage in pulsed 1 mu m lasers [J]. Laser-Induced Damage in Optical Materials: 1995, 1996, 2714: 707-716.
3. Hovis F. E., Shepherd B., Radcliffe C., etc. Mechanisms of contamination induced optical damage in lasers [J]. Laser-Induced Damage in Optical Materials: 1994, 1995, 2428: 72-83.

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 1×10^{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!