Laser Technologies for Deep Space Optical Communications

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Outline

- Introduction to free space optical communications
- Requirements
  - Technology development for JPL/NASA missions
- Laser development
  - Diode and fiber based MOPA devices for high data rates
  - Solid state lasers with high peak powers
  - Status of solid state laser performance
  - Technology challenges
  - Laser characteristics - efficiency, pulse jitter
- Summary

Advantages & Challenges of Lasercomm

- Higher date rates
  - For example, near Earth RF typically limited to 10 - 100s Mbps but ⇒ Gbps with complex modulation schemes
- Lower beam divergence ⇒ smaller transmit aperture
  ⇒ lower mass
- No bandwidth allocation restrictions - severe limitation for high BW RF modulation

- Challenges
  - clouds - availability of coverage
    ⇒ *site diversity*
  - atmospheric induced scintillation effects - beam breakup and wander
    ⇒ *adaptive optics, aperture averaging*
  - stringent acquisition, pointing and tracking requirements
    ⇒ *spread beam, fast steering mirrors etc*

JPL/NASA Mission Requirements

- Mission determines distance and data rate or volume
  ⇒ drives size, aperture, transmit power required

- Near Earth:
  - LEO / GEO - ground
  - Example:
    - ISS demonstration: LEO - ground, λ = 1.5 um, > 1 Gbps, 200 mW laser power, 10cm → 1m, unidirectional link with ground beacon acquisition

- Deep Space:
  - Planetary to Interstellar missions, distances AU - > 100 AU
  - Example:
    - Mars downlink, 20 kHz, P_{peak} ~ 30 kW, P_{avg} ~ 1 W, λ = 1-1.5 um, 30cm → 1m apertures

Laser Requirements

- High rate optical channel using direct detection determined by application:
- Near Earth links:
  - high data rates desired, 100 Mbps - 10 Gbps
  - high average power sufficient, 1-5 W
  - ⇒ Semiconductor diode or fiber based lasers with OOK modulation
- Deep space links:
  - maximize photon efficiency ⇒ high average and peak powers, kW - MW/pulse
  - medium data rates, 10 kbps - 1 Mbps
    - ⇒ Diode pumped solid state lasers with PPM techniques

Both require compact, efficient, reliable, rad. hard lasers with good beam quality

Laser Requirements (cont.)

Link Analysis

	Mars downlink	ISS downlink
• Link Range	1.5 AU (2.10^8 km)	1000 km
• Data rate	1 Mbps	1.2 Gbps
• Modulation	PPM, coding	OOK
• Transmit power, avg.	3 W	200 mW
• Transmit aperture	30 cm	10 cm
• Losses - space, pointing, atmospheric	25% +dist (-368 dB)	25 % + dist (-258 dB)
• Receiver gain - telescope	10 m	1 m
• Required power - detector sensitivity	3 nW	0.2 uW
• Link margin	3 dB	5 dB

Link Analysis

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Mars(Down,X2000)

Link Summary

Link Range		km	1.00 AU		
Data rate		kbps	PPM (M = 256)		
Coded BER			Reed-Solomon Coding		
Transmit power	1.00	W average	3.19 kW (peak)	65.04	dBm
Transmit losses	57.0	% transmission		-2.44	dB
Transmitter gain	6.3	urad beamwidth		116.03	dB
Pointing losses				-0.97	dB
Space loss				-364.97	dB
Atmospheric losses	67.2	% transmission		-1.72	dB
Receiver gain	3.50	m aperture diameter		140.24	dB
Receiver optics losses	25.3	% transmission		-5.96	dB
Received signal	1.98E+02	photons/pulse	3.36 nW (peak)	-54.74	dBm
Background signal level	7.60E+00	photons/slot	0.10 nW		
Required signal level	7.32E+01	photons/pulse	1.24 nW (peak)	-59.06	dBm
Allowances and Adjustments				-1.00	dB
Link Margin				**3.31**	**dB**

Detailed Link Table

Transmitter (Mars)

Laser (pulsed Q-switched Nd:YV04)					
Peak power			3.19 kW	65.04	dBm
Average power		W			
Wavelength	1.06	um			
Pulse width	11.00	ns			
Pulse width to slot width ratio	0.80				
Slot width or integration time	13.75	ns			
Dead time	31.62	us			
Pulse repetition rate	28.46	kHz			

Descanso, Sept 1999 MWW 7/total

Deep Space Laser Requirements

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	Jupiter 6 AU	Interstellar Probe 200 AU
Downlink Laser		
Average Power, W	3	15
Peak Power, MW	0.022	11.3
Repetition Rate, Hz	6650	135
Energy per pulse, mJ	0.44	110
Pulse width, nsec	20	10
Uplink Laser		
Average Power, W	7.3	135
Peak Power, MW	1.46	12000
Repetition Rate, Hz	250	1.1
Energy per pulse, J	0.04	120
Pulse width, nsec	25	10

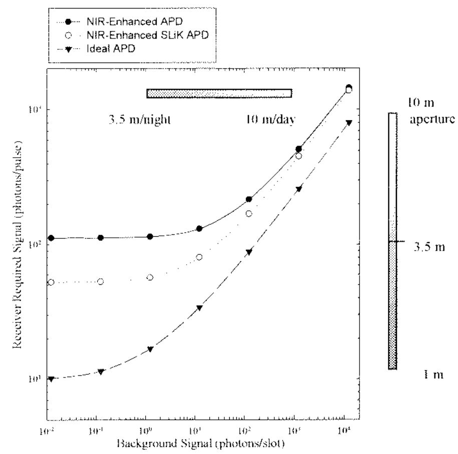
Assume: 30 cm aperture on spacecraft, 10 m on ground

Descanso, Sept 1999 MWW 8/total

JPL Detector/Link Requirements

Laser requirement also driven by detector capabilities:

- Transmitter:
  - **1 Watt Q-switched Nd:YAG laser**
  - 1064 nm
  - 25 ns pulse width
  - 10^{-5} modulation extinction ratio
  - 10 cm telescope
  - 27.8 % transmitter optics losses
  - 16 kbps
  - 10^{-5} BER
  - PPM (M=256)
  - Reed-Solomon coding
- Channel:
  - **2 AU link range**
  - 32.8 % atmospheric loss
- Receiver:
  - Telescope diameter -various
  - 55.1 % receiver optics losses
  - Silicon APD Detector - various
  - High-Impedance Pre-amplifier
  - 31.25 ns slot width



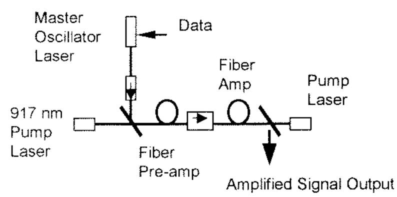
Depending on background level, link is viable with 3.5 or 10 m aperture

JPL Laser Development: High data-rate lasers

Lab Prototypes

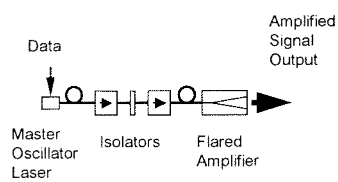
Fiber MOPA

- MO: InGaAs diode oscillator
- 5 W 2-stage YDFA
- 2.5 Gbps, OOK, 1070 nm
- Good beam quality



Diode MOPA

- MO: InGaAs FP oscillator capable of 10 Gbps
- InGaAs flared amplifier
- Packaged: 1 Watt InGaAs flared amplifier,
- 2.5 Gbps, OOK, λ = 960 nm, efficiency ~ 24%
- Table-top: 3.6 W at 2.5 Gbps
- Poor modulation extinction ratio due to ASE



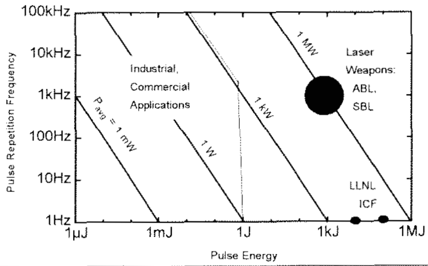
Current Solid State Laser Technology

Laser Transmitter:

- Good beam quality, ~ diffraction limited, $M^2 < 1.3$
- Reasonable overall efficiencies, ~ 6 - 10%
- Good modulation extinction ratio, 50 dB

Operational modes of Candidate Solid State Lasers:

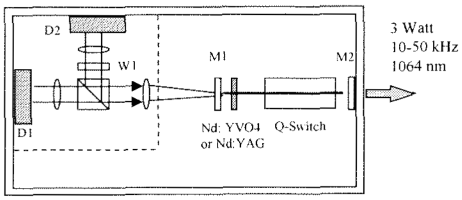
- Q-Switched ⇒ direct detection, limited to < 1 Mbps (100 kHz)
- Cavity dumping ⇒ direct detection, will support 1- 10 Mbps
- Continuous wave ⇒ coherent detection



Solid State lasers

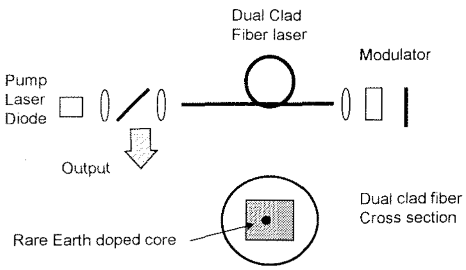
Bulk

Nd:YAG
Yb:YAG
$Nd:YVO_4$
Nd:YLF



Fiber based

- Fiber Amplifier or Laser
- Er or Yb/Er co-doped core
- Increased peak power with large effective area core

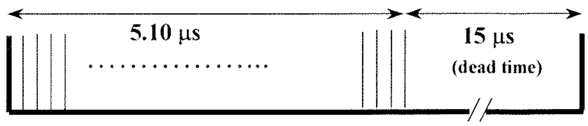


JPL Deep Space Laser Transmitter

Modulation techniques:

Pulse position modulation (PPM) provides a suitable modulation and detection scheme for solid state Nd:YAG type lasers

25 ns per slot (256 slots ⇒ 8 bit/pulse)



50 KHz rep rate Nd:YAG laser

- PPM requires:
  - that pulse width be < 20 ns slot width
  - that pulse jitter be such that probability of pulse over-shooting intended slot be minimized
  - slot width is restricted in order to limit background photons
- Example: night time link from Mars using above modulation and 5 W of average laser power will result in a downlink of ~ 200 photons/pulse using a 10 m receiver on the ground

JPL Status of Laser Development

High Power Q-switched Lasers

	Nd:YAG 1.06 µm		Nd:YLF 1.05 µm	Yb:YAG 1.03 µm	Doubled .532 µm		YALO 1.08 µm
Pav/ W	10	690	29	280	120	175	140
Ppulse mJ	100						
PRF kHz	0.1	2.5	5	10	5	2.5	0.1
Pulsewidth ns	20	~100	20	30	-	~100	-
Efficiency %	6	?	6	6	2	?	1.8
BQ / D.L.	1.05	1.1	1.1	5	5	1.5	1.1
Comments		P~ kW with osc/amp					MOPA
Developer	ESA	TRW	SEO	LLNL	DOS	TRW	German

Status of Laser Development

High Power cw Solid State Lasers

	Nd:YAG				Nd:YLF	Yb:YAG		Doubled	
Wavelength nm	1060				1050	1030		532	
Pcw W	1	10	45	107	50	430	40	5	.2
Efficiency %	6.3	<8	6	11	8	6.3	2.5	0.4	~ 0.5
BQ / D.L.	~1	1.05	<1.3	5	~ 1.1	5	1.02	-	1.1
Linewidth kHz Timescale	10 10ms	Q.L.*	?	-	?	?	?	5000 50 ms	<10 1 ms
Comments		Freq. Stable	300 W poor BQ	147 W BQ=45 $\eta \sim 14$			T=100K	commercial	commercial NPRO†
Developer	JPL	Japan	German	Japan	SEO	LL NL	DOS	Coh.	Light-wave

* Injection locked to a single frequency NPRO laser.
Frequency noise $2 \times 10^{-5} / \sqrt{Hz}$ at 300 Hz. Shot noise limited above 1 MHz.

† Two 40 mW Nd:YAG devices frequency locked to high finesse Fabry-Perot cavity: $\Delta\nu = 330$ mHz.

Laser Dev. for X2000 Laser Requirements

Specifications		*Continuum* EPO 5000	*Q-peak* 1047Q	*Spectra-Physics* B10-106Q	*Uniphase* Stablelight
Material		YAG	YLF	YVO_4	YLF YAG
λ nm	**~ 1000**	1064	1047	1064	1064 1047
$P_{average}$ W	**1**	1	10	3	2
PRF kHz	**1.5-20**	0 ~ 5	3-100	-50	0-70
P_{peak} kW	**30 @ 3kHz**	83	50	18	25
Pulse width ns @ freq.	**< 25** **1,5,20**	3	40 75	10 10 12	10 10 20
Pulse energy μJ	**> 300** **1,5,20**	250 200	2000 1000 500	180 180 130	250 250 110
Beam Quality	**1.1**	< 2	< 1.2	TEM_{00}	TEM_{00}
Air cooled	**Yes**	yes	no	yes	no/yes
Efficiency %	**10**	~ 1	~ 3	.75 (8 - cool)	~ 0.7
Q-switch	**E.O.**	E.O.	A.O.	A.O.	A.O.
End-Pumped	**yes**	yes	no	yes	
Comment		Single Diode	8W YVO_4 air cooled. end pumped. 20 kHz	Remote diode bar	
Customize	**yes**	~ no	yes - YVO4	no	Yes

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Technology Challenges

Issues in High Power Solid Sate Laser Development

- Nd:YAG — well established technology, robust, peak output at PRF ~ 5 kHz
- Nd:YLF — no thermal birefringence but lower thermal fracture strength which limits high power capability, gain peaks at PRF ~ 2 kHz
  - Peak absorption ~797 nm so less absorption from 808 nm pump diode energy
  - Longer upper state lifetime therefore higher output energy for given pump energy
- Nd:YVO_4 — high gain and high absorption
  - Suitable for high PRF as able to maintain high pulse energy
  - Short pulsewidths possible due to short upper state lifetimes
  - Not as robust thermally, start to lose BQ at high PRF
- Yb:YAG — broader absorption band at 940 nm relaxes diode λ constraint
  - quasi 3 level system
  - InGaAs pump diodes have less heating and higher efficiency from lower quantum defect with potentially increased reliability
- Fiber laser — Peak power limited but can increase fiber area
  - High efficiency
  - Good thermal design

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Laser Efficiency

Efficiency	Ideal	Expected at High Power	Demonstrated
η_P - diode	.65	.35	.3-.5
η_T - transfer	.95	.85	.7-.93
η_a - absorption.	.9	.9	
η_s - q. defect	.76	.76, .89*	
η_Q – q. conversion	.95	.95	$\eta_{opt-opt}$ = .4 -.5
η_E – extraction	.9	.8	
η_B – beam overlap	.9	.85	
η_{PS} – power supply	.9	.9	.9
η_D - doubler	(0.6)	(0.45)	(.3-.5)
Total η	.29 (.17)	.14 (.06)	.02-.14 (<.07)

* Yb

Strategies to increase efficiencies:

- To obtain maximum diode efficiency, provide better thermal management, improved material quality $\Rightarrow$ > 40 % at high power
- Increase diode coupling by novel optical techniques such as microlens design
- ηopt-opt limited by gain medium; can be increased by using Yb, end pumping, and improved resonator design for mode matching. Side pumping required for > 50 W due to thermal stress though.

Deep Space Laser Pulse Measurements

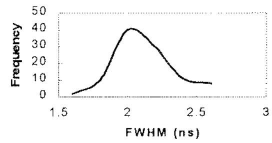
• A Nd:YVO4 master oscillator (Lightwave Electronics) along with a diode pumped amplifier was modulated using a custom PPM modulator

•Three types of detectors used

Detector	BW	Area (μm)	QE	Pulse Jitter	FWHM ns	Sensitivity Photons
InGaAs PIN	1.0 GHz	100	78%	+/- 8 ns	2+/- .5	11000
Si APD	500 MHz	500	4-5 %	+/- 9 ns	1.2-3	100
Si SPCM APD	-	120	2-3 %	+/- 6 ns	8.7	600

Extremum of pulse jitter + pulse width ~ 21 ns

InGaAs PIN



Summary

- JPL lasercomm development
  - Near Earth ⇒ high data rate diode or fiber based laser transmitters
  - Deep space ⇒ DPSS laser transmitters

- Laser development:
  - *Diode and fiber based lasers:*
    - High efficiency, good beam quality, high data rates
    - High ASE degrades modulation extinction ratio
    - Commercial devices available that meet near Earth requirements
  - *Solid State lasers*:
    - High peak power, good beam quality, high modulation extinction ratio
    - Medium data rates, improvements in efficiency being explored
    - Commercial systems meet requirements for various missions
    - With the right detector, a PPM modulated Nd:YVO_4 can provide the power and timing characteristics needed for a Mars link