
Progress in Hybrid Fiber/Bulk Solid State Lasers

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Outline

- ❑ Motivation
- ❑ General Info on GSD lasers
 - Pump sources for GSD lasers
- ❑ Ho-properties – brief overview
- ❑ Tm: fiber Laser – Details
- ❑ Previous Results
 - Q-Peak' Previous Results
- ❑ Ho:YLF Laser – Details
- ❑ Conclusions

Motivation

- Development of an IR laser source:
 - High-energy (> 200 mJ)
 - High repetition rate (200-1000 Hz)
 - High beam quality (TEM₀₀)

- Immediate applications:
 - Pump source for OPOs
 - Lidar
 - Medical, industrial, military

Ground state depleted lasers

- ❑ Yb, Er, Ho, Tm lasers are examples of ground state depleted (GSD) lasers

- ❑ GSD laser operates as a quasi-4-level system:
 - Pumping is accomplished into the 1st excited manifold
 - Lower laser level belongs to the ground manifold and is partially populated at room temperature
 - GSD laser can not be [1-quantum-defect]-efficient at RT !!!

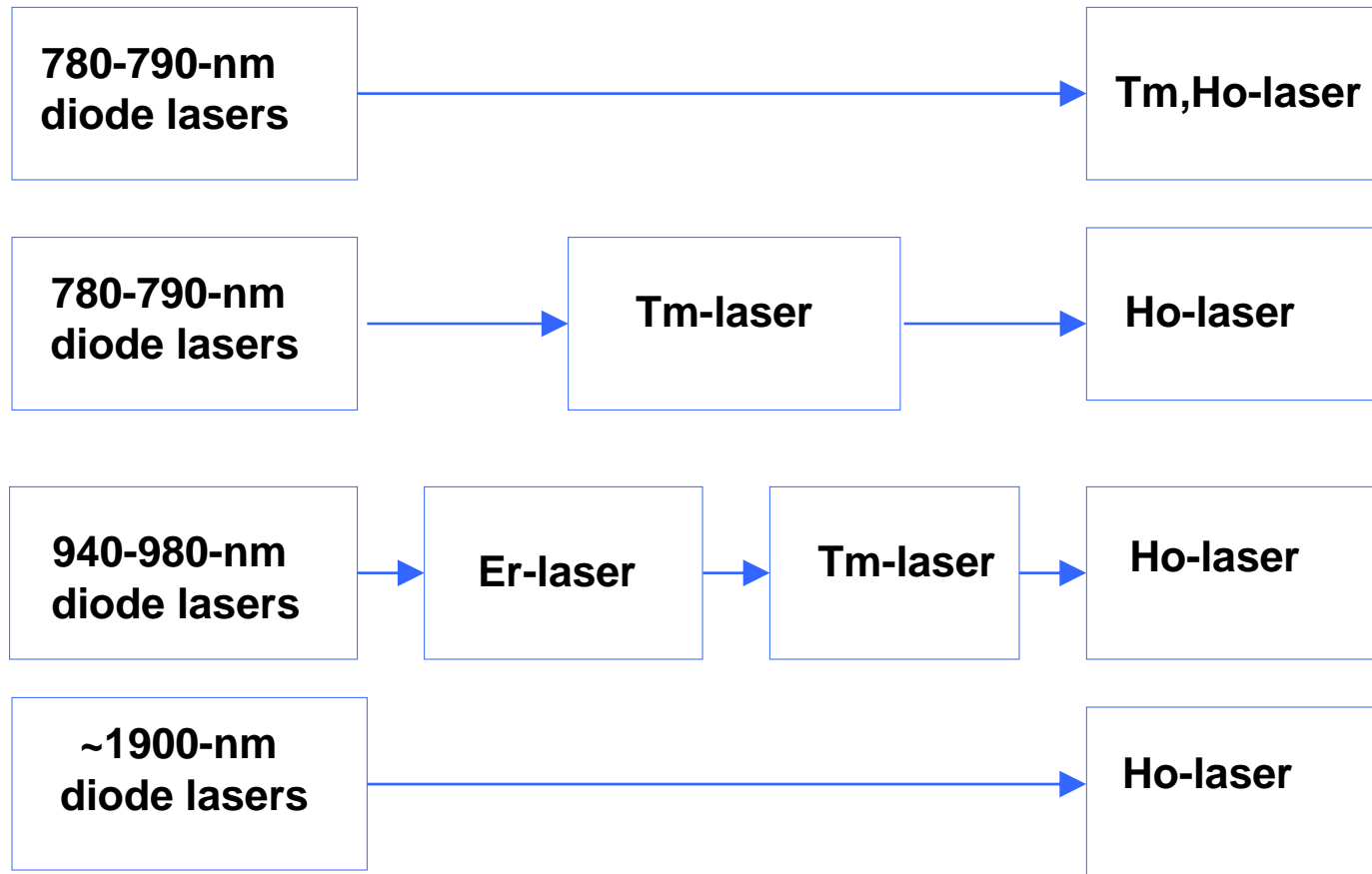
- ❑ Fundamental spectroscopic and laser properties pertinent to GSD lasers are systematically and quantitatively analyzed in prior work at LLNL
 - W.F. Krupke and L.L. Chase, Optical and Quantum Electron. 22, S1 (1990).
 - S.A. Payne, L.L. Chase, L.K. Smith, W.L. Kway and W.F. Krupke, IEEE J. Quantum Electron. 28, 2619 (1992).
 - L.D. DeLoach, S.A. Payne, L.L. Chase, L.K. Smith, W.L. Kway and W.F. Krupke, IEEE J. Quantum Electron. 29, 1179 (1993).

Why Ho-lasers?

- Most of the laser transitions in 2-um region have such a low gain cross-section that efficient, high-energy laser oscillation or amplification is impossible:
 - The energy fluence required for efficient extraction of stored energy in the laser material is so high that they will lead to optical damage of the laser crystal or associated optics.

- Only Ho-doped crystals, including Ho:YAG and Ho:YLF, have a large enough gain cross-section for effective high-energy operation.
 - Ho:YAG $\sigma_{em} \sim 1 \times 10^{-20} \text{ cm}^2$
 - Ho:YLF $\sigma_{em} \sim 2 \times 10^{-20} \text{ cm}^2$

Approaches to diode-pumping of Ho-doped lasers



Advantages of Tm-pumped Ho-laser

- Compared to diode-pumped Tm, Ho-co-doped laser:
 - Eliminates upconversion from Tm-Ho interaction that reduces efficiency and creates additional heating in crystal
 - Eliminates energy sharing between Tm and Ho that limits energy extraction in Q-switched mode

- Compared to direct-diode-pumped Ho-laser
 - Can operate at much higher power due to availability of high-power Tm-lasers

Pump sources for Ho-laser

- ❑ Relatively high-brightness sources are required (preferably $M^2 < 10$)
 - GSD laser pumping requires high optical density $\alpha L \gg 1$
- ❑ 1850-1950 nm wavelength range
- ❑ High power to achieve Ho-output $\gg 10$ W
- ❑ Possible alternatives:
 - Diode-pumped Tm-bulk solid state lasers
 - Diode-pumped Tm: fiber lasers Er or Tm

Ho-laser power scaling

- Cw Tm: fiber lasers with output >100 W emerge as an alternative to bulk Tm-laser:
 - Turn key operation
 - Cost-effective
 - Maintenance-free
 - Fiber delivery (no surprise!)
 - Excellent beam quality
 - Scalable power
 - Wide tuning range
 - Commercially available

Previous results – Ho-lasers

□ Tm:YLF pumped Ho:YAG

P. A. Budni et al., "High-power/high-brightness diode-pumped 1.9- μm Thulium and resonantly pumped 2.1- μm Holmium lasers," IEEE J. on Selected Topics in Quantum Electron., 6, 629-635 (2000).

- Tm:YLF pump
 - 36 W CW output at 1907 nm (σ -line)
 - Multimode, $M^2 \sim 2$
- Ho:YAG
 - CW: 19 W
 - QS: 16 W at 15 kHz

□ Tm:YLF pumped Ho:YLF

A. Dergachev, P.F.Moulton, "High-power, high-energy diode-pumped Tm:YLF-Ho:YLF-ZGP laser system", OSA TOPS Vol. 83, ASSP, (OSA, 2003), pp. 137-141

- Tm:YLF pump
 - 2 x ~25 W CW output at 1940 nm (σ -line)
 - $M^2 \sim 1.05 \times 7$
- Ho:YLF
 - CW: 21 W
 - QS: 16 W at 1 kHz

□ Ho-lasers pumped with Tm:fiber lasers:

- ORC, Univ. of Southampton, UK (Ho:YAG) ASSP'03 (A.Agdolvand et al., TOPS Vol.83, 7 (2003))
- NASA (Ho:YLF)
- FFI (Forsvarets forskningsinstitutt), Norway (Ho:YAG) ASSP'03 (E.Lippert et al., TOPS Vol.83, 292 (2003))
- BAE Systems (Ho:YAG)
- Q-Peak (Ho:YLF) ASSP'05

Ho:YLF vs Ho:YAG

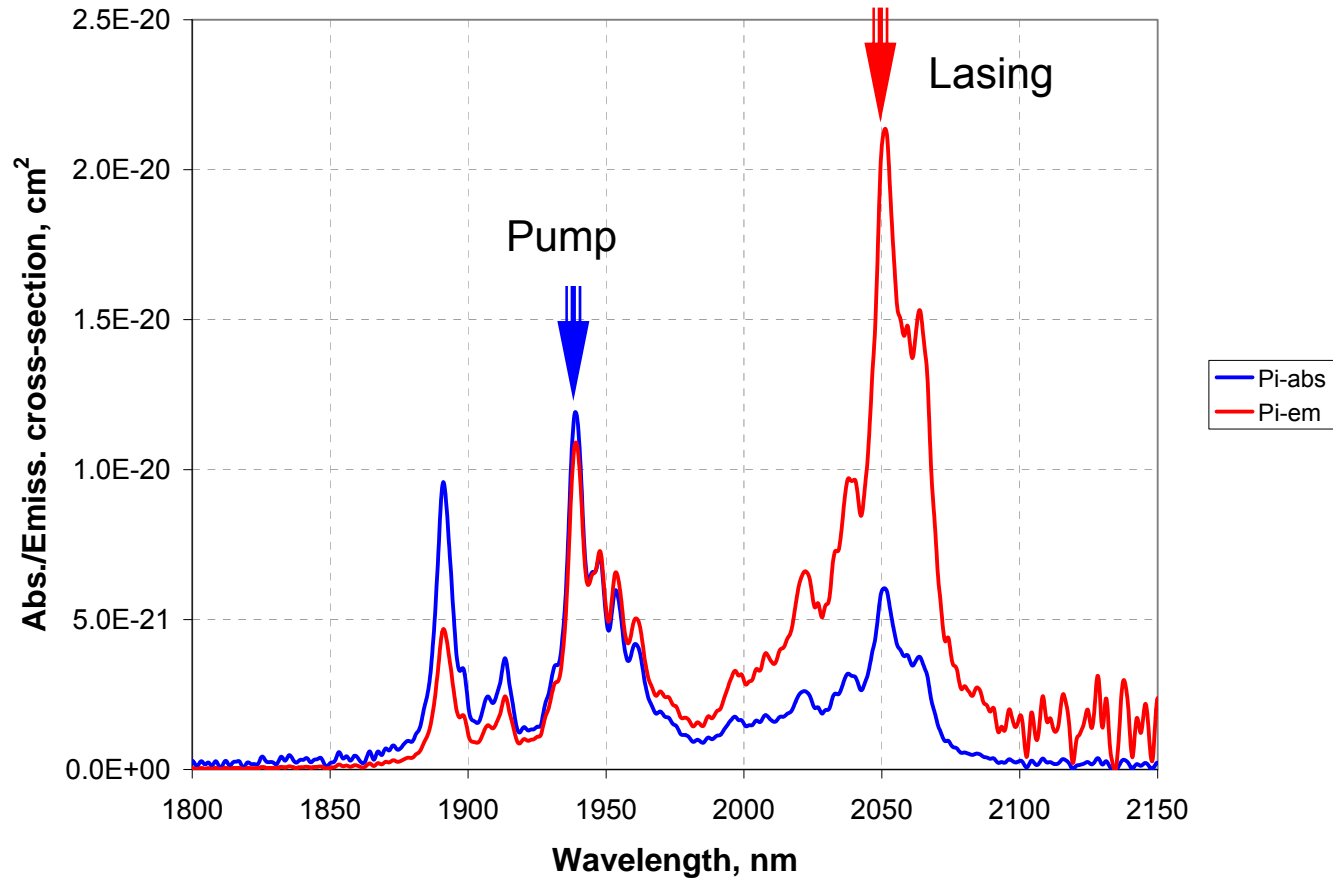
□ Ho:YLF

- Long upper laser level lifetime ~ 15 ms
- Higher emission cross-section
- Naturally birefringent material
- Low dn/dT → weak thermal lensing
- ~5% quantum defect

□ Ho:YAG

- Isotropic
- Lifetime (5I_7) 7 ms
- Strong thermal lensing
- Excellent thermo-mechanical properties
- ~10% quantum defect

Ho:YLF – Absorption/ Emission

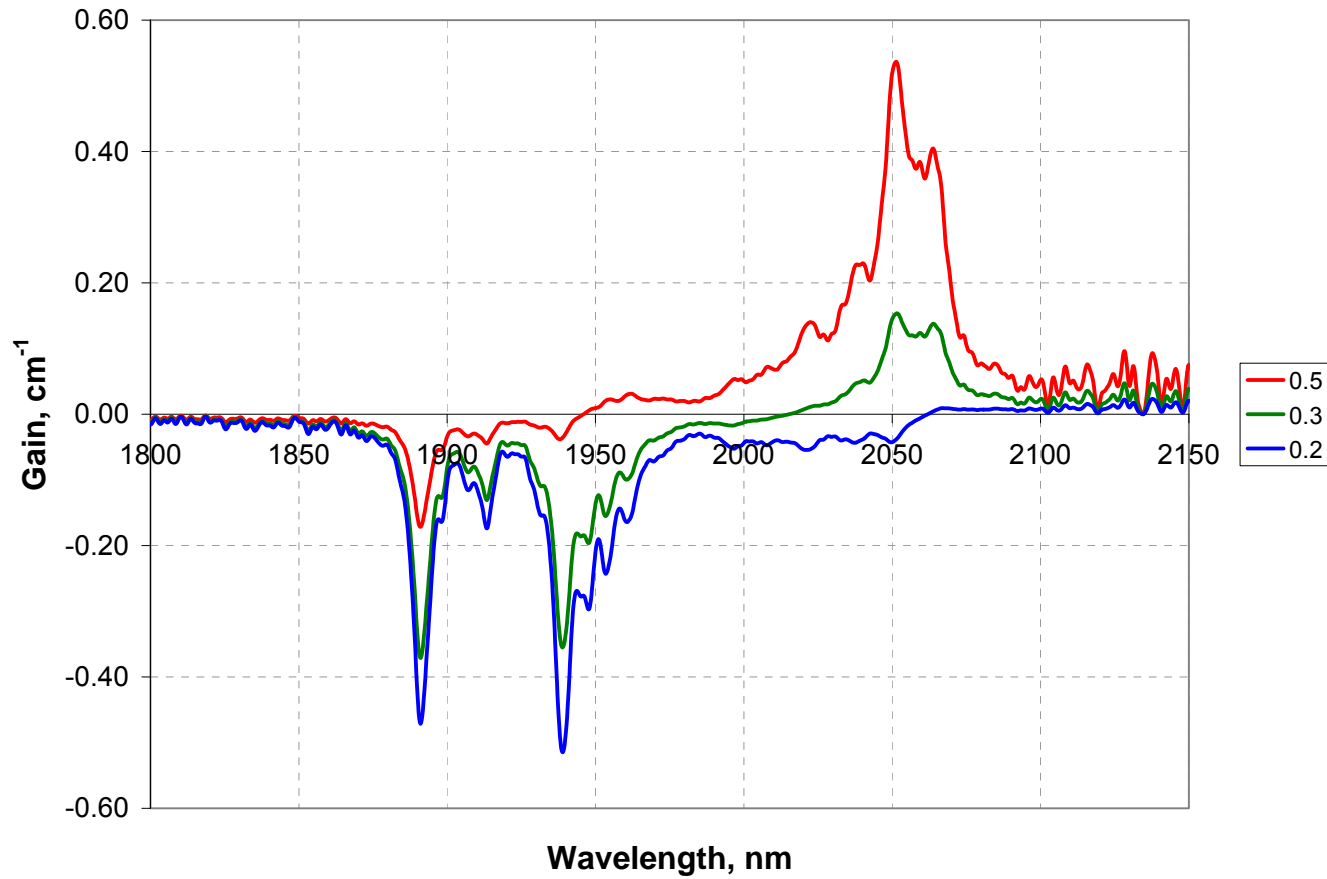


Cross-section determination - reciprocity method:

$$\sigma_{em}(\nu) = \sigma_{abs}(\nu) \left(\frac{Z_l}{Z_u} \right) \exp \left[\frac{(E_{ZL} - h\nu)}{kT} \right]$$

(Following S.A.Payne et al. IEEE J. of QE, 28, 2619-2630 (1992)).

Ho:YLF – Calculated gain (π) vs inverted fraction



Q-Peak' Ho-laser development

2001

- Tunable Tm:YLF laser (>15 W)

2003

- Single Ho-crystal oscillator pumped with two Tm:YLF lasers (~50 W total power)

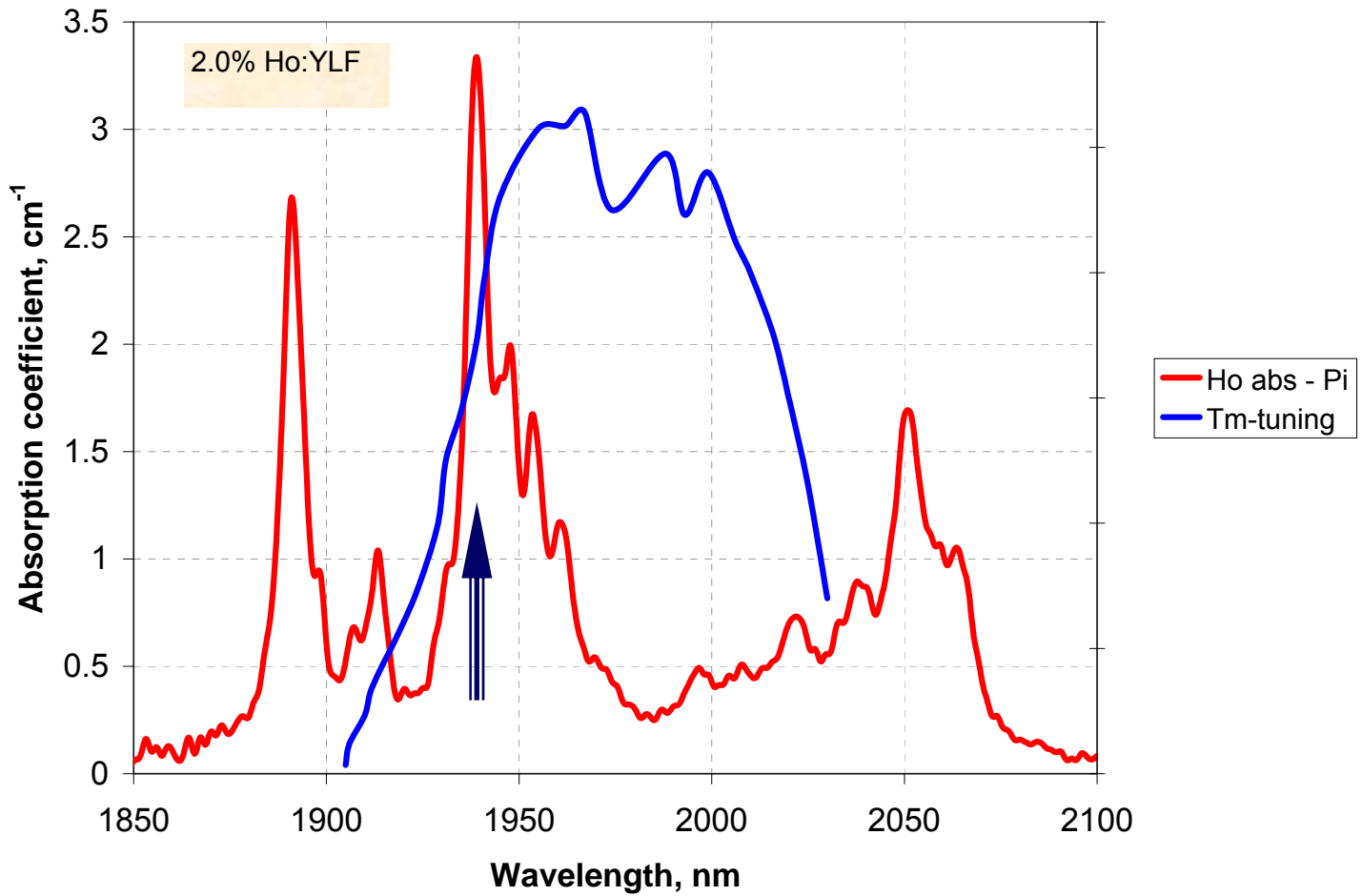
2005

- Double Ho-crystal oscillator pumped with one 100-W Tm:fiber laser

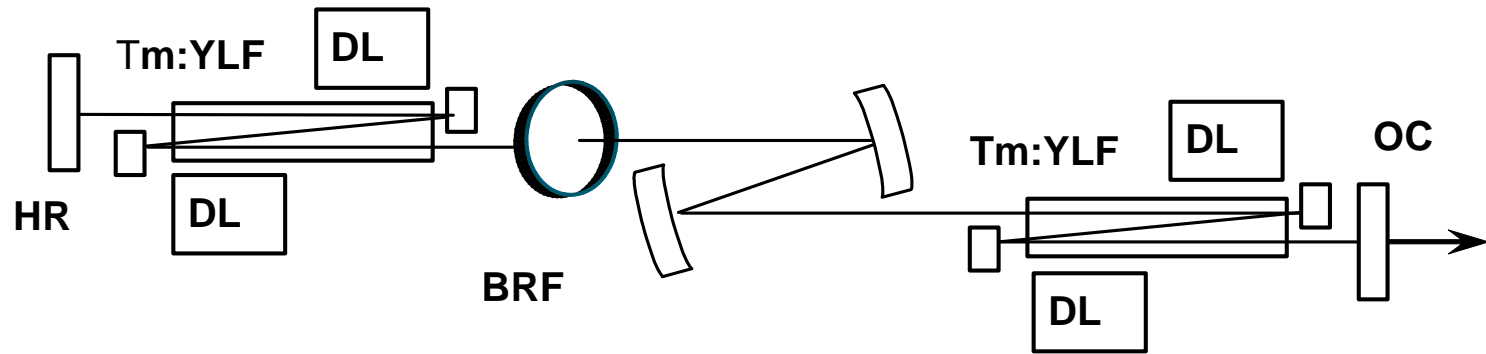
2006

- Single Ho-crystal oscillator followed by three amplifiers pumped with two Tm:fiber lasers (~230 W total power)

Q-Peak' prior results: Pumping Ho:YLF with Tm:YLF laser

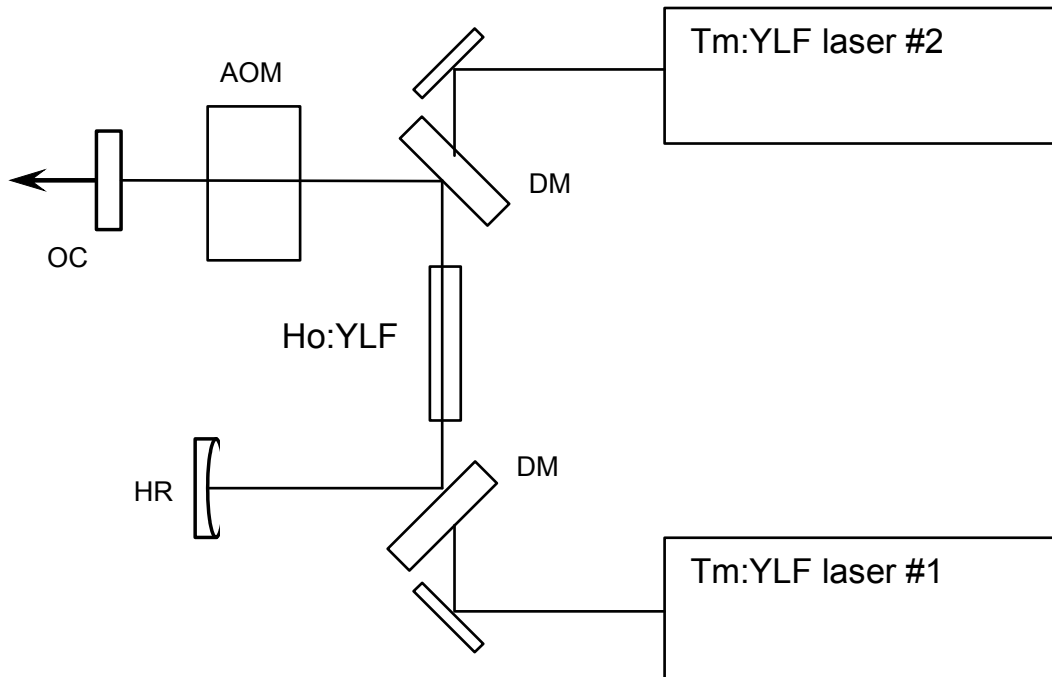


Q-Peak' prior results: Experimental Set-Up – Tm:YLF Laser



- ❑ Dual-Gain Module oscillator
- ❑ Beam quality: $M^2 \sim 1.05 \times 7$
- ❑ Wavelength tuning with BRF element
 - Alternative: Volume Bragg Grating reflector
- ❑ Average power (CW) > 30 W at 1940 nm

Q-Peak' Prior Results: End-pumped single-crystal Ho:YLF laser



CW output: (max)	21 W
Pulse energy (max):	
100 Hz	35 mJ
400 Hz	27 mJ
Pulsewidth:	
100 Hz	12 ns
400 Hz	15 ns

DM – Dichroic Mirror,
AOM – Acousto-Optic Modulator,
OC – Output Coupler,
HR – High Reflector

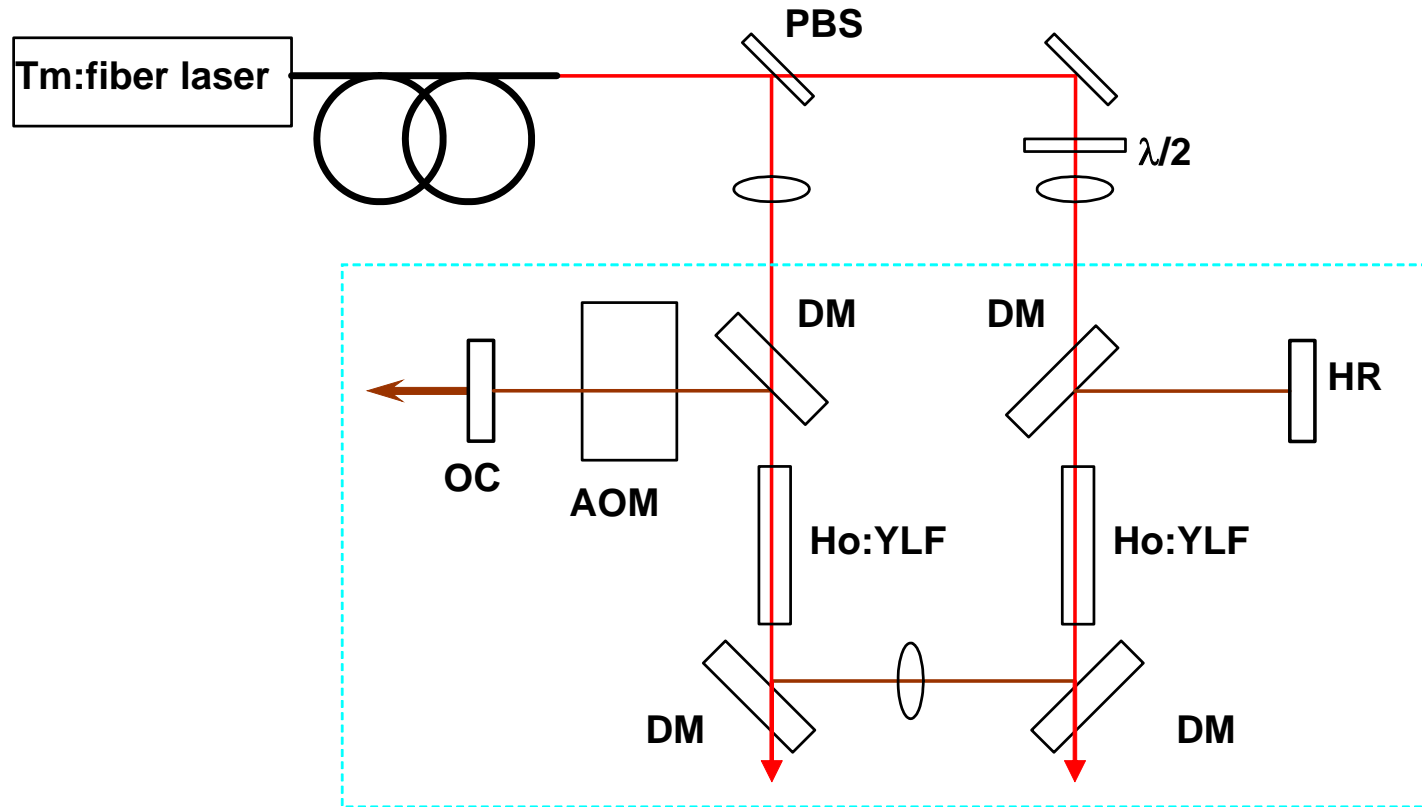
Scaling of Ho-laser: Tm-pump source

- ❑ Specific requirements for Tm-laser as a pump source for Ho:YLF:
 - Linear polarization (preferably)
 - Lasing wavelength at ~ 1940 nm
 - Linewidth < 6 nm

Tm-fiber laser TLR-100-1940
(IPG Photonics, www.ipgphotonics.com)

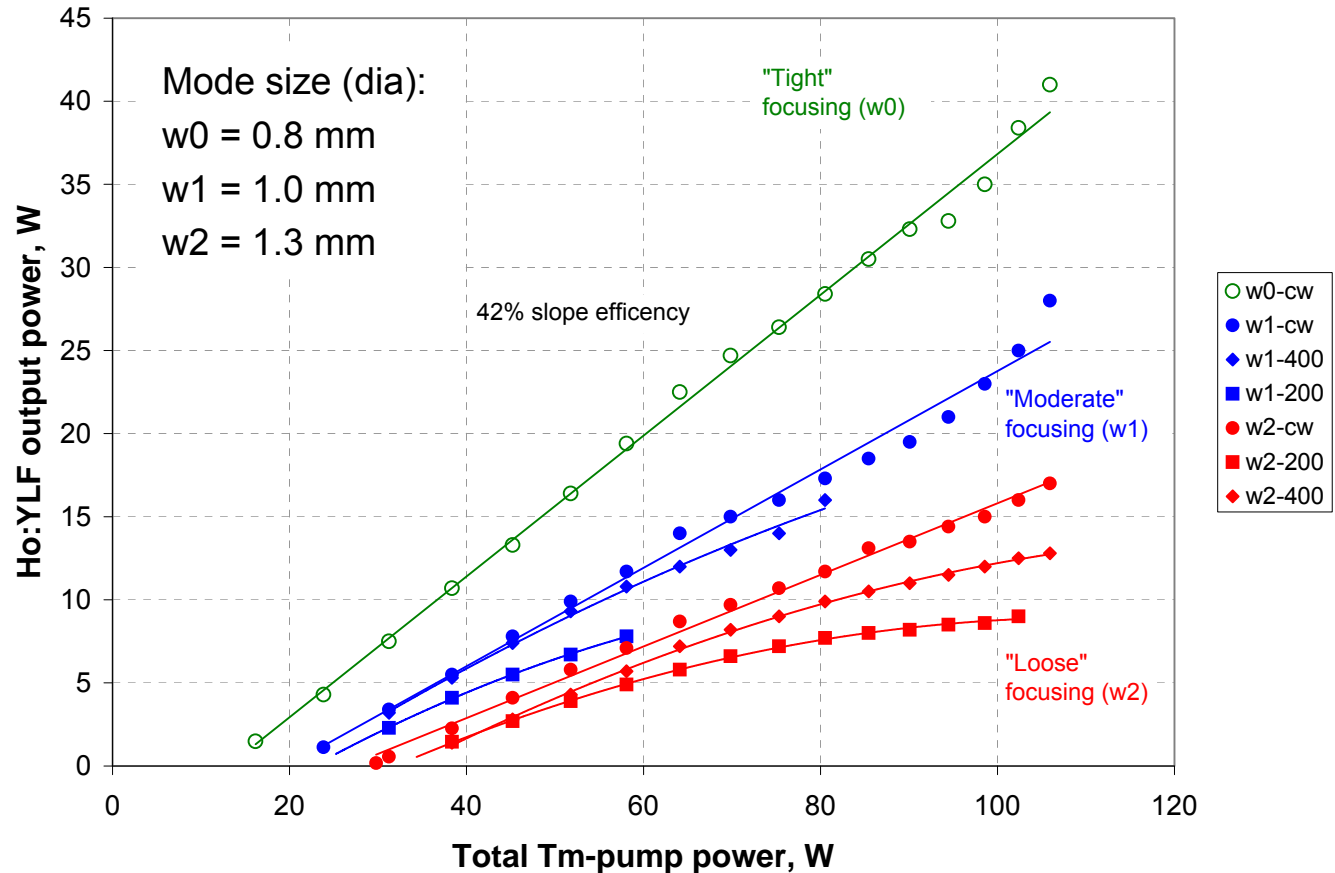
Operation regime	CW
Operational temperature	RT
Output power	≥ 100 W
Lasing wavelength range:	1750-2200 nm
Polarization:	Random
Linewidth	≤ 2 nm

Schematic layout of the double-crystal end-pumped Ho:YLF laser

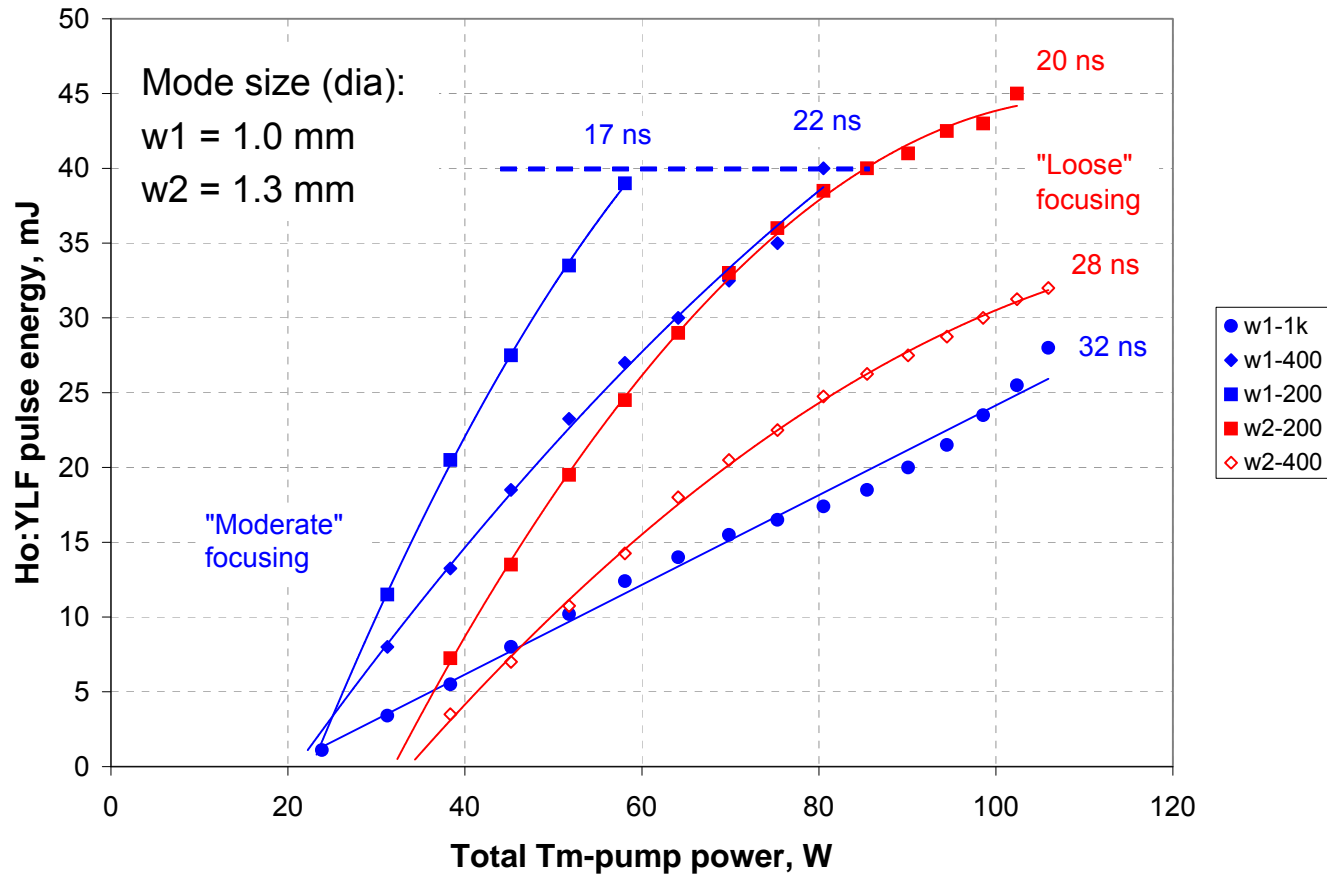


DM – Dichroic Mirror,
AOM – Acousto-Optic Modulator,
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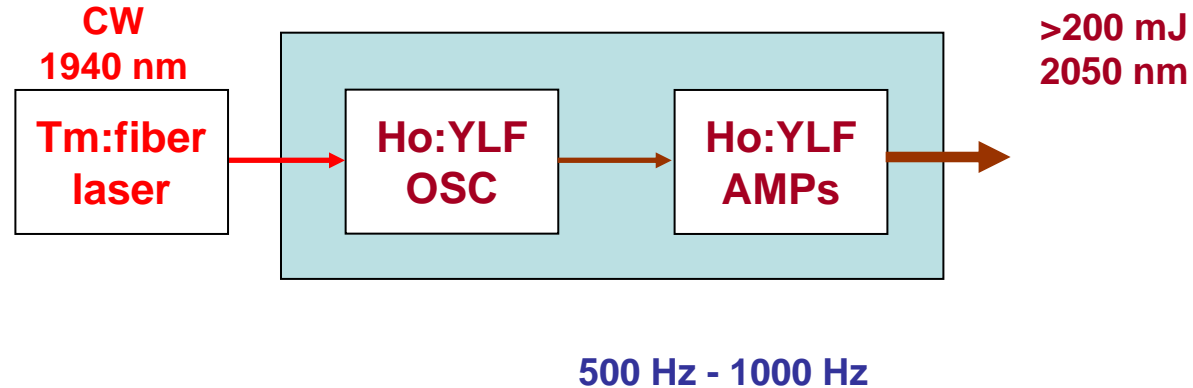
Ho:YLF Laser – Power output



Ho:YLF Laser – Pulse energy

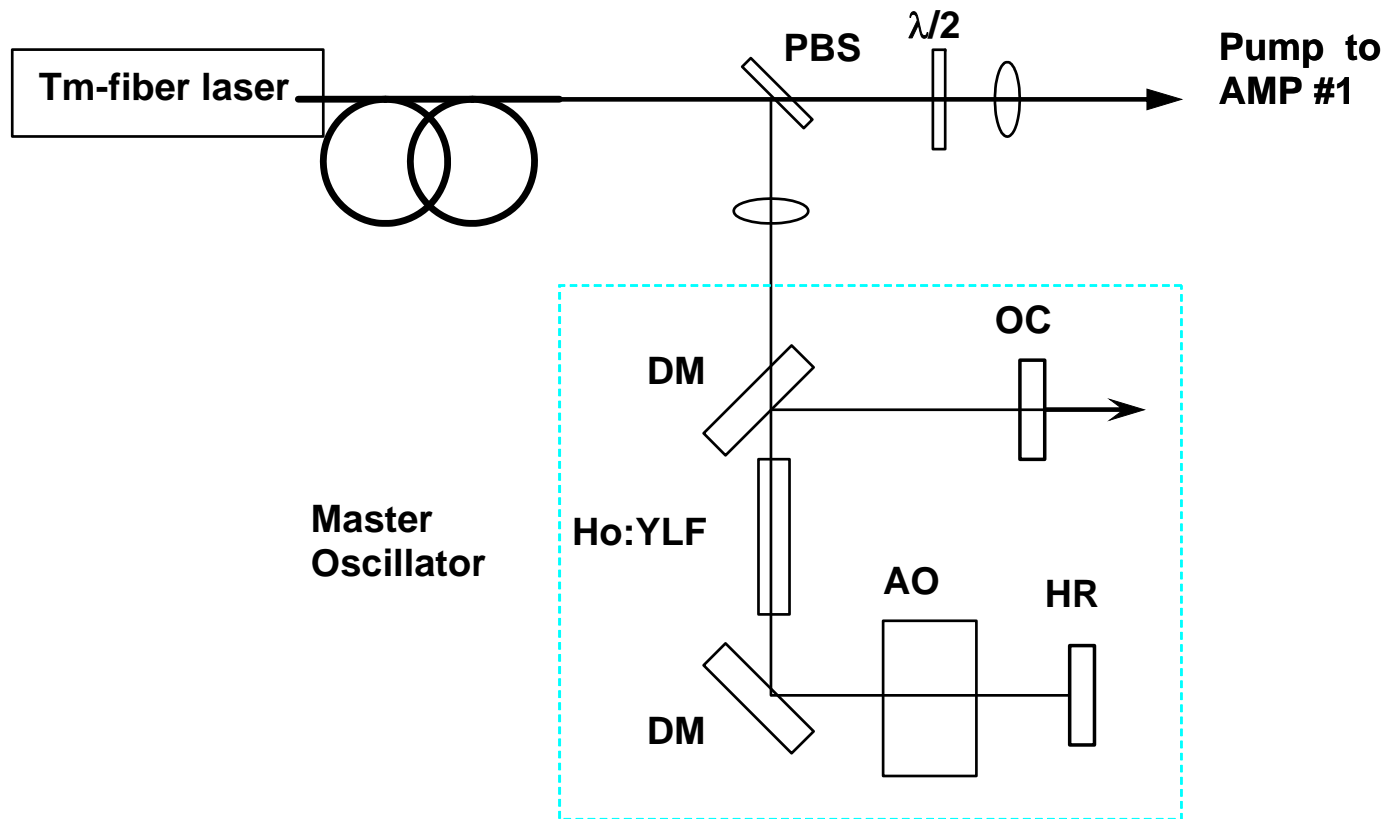


Current work: Specific objectives



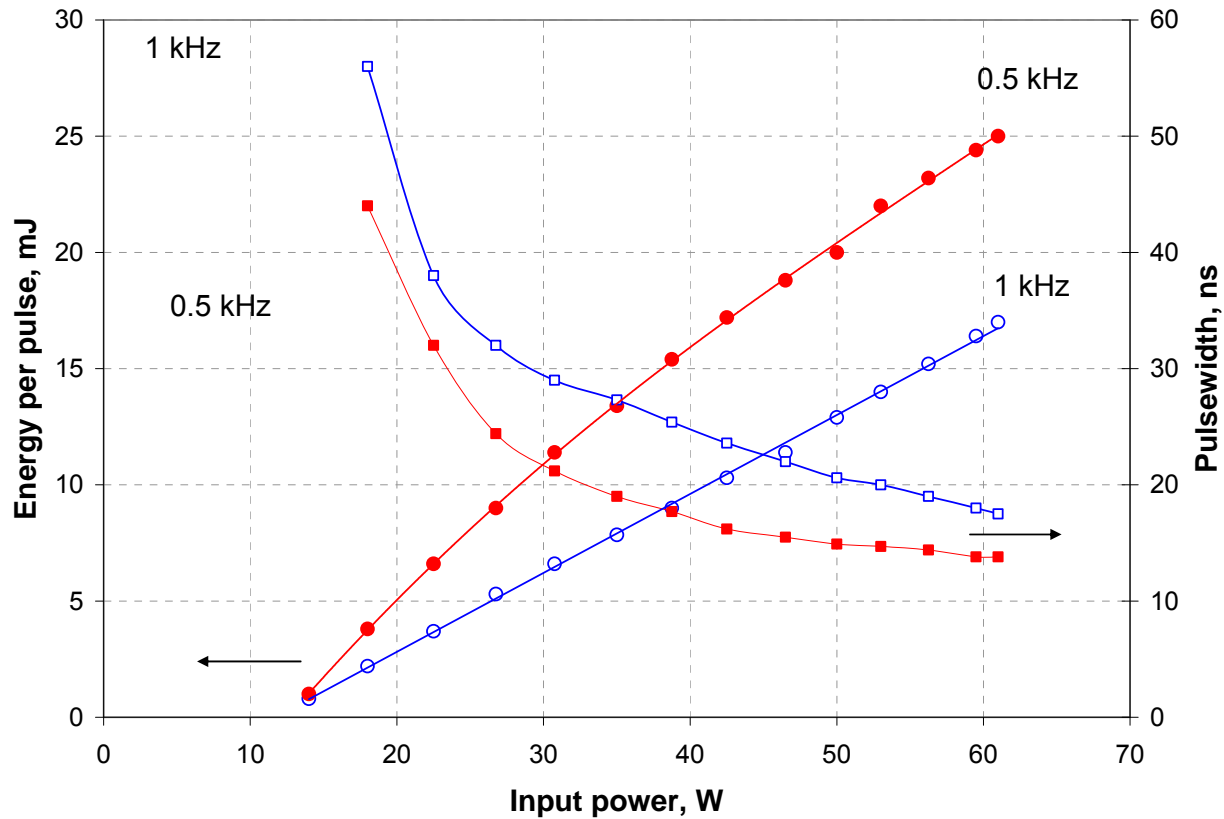
- Our approach for Tm-pumped Ho-laser:
 - Tm-pump CW Tm-fiber lasers
 - Ho-laser: Ho:YLF oscillator with AO Q-switching
 - Ho-Amplifiers Single-pass

Tm: fiber laser pumped single-crystal Ho:YLF laser

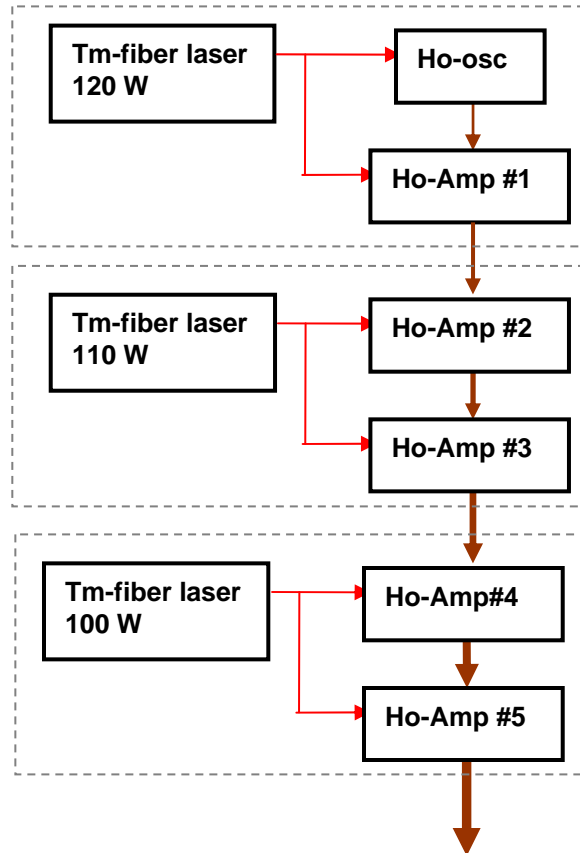


DM – Dichroic Mirror,
AOM – Acousto-Optic Modulator,
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Ho:YLF Master Oscillator



Ho:YLF MOPA



	CW	500 Hz	1000 Hz
Master osc	19 W	25 mJ	17 mJ
Amp 1	42 W	55 mJ	38 mJ
Amp 2	60W	90 mJ	58 mJ
Amp 3	78 W	115 mJ	73 mJ
Amp 4	97 W	***	***
Amp 5	113 W	***	***

*** work in progress

Ho-laser efficiency

- ❑ In order to achieve efficient Ho-operation
 - High optical density
 - Tight focusing to deplete (bleach) the ground state
- ❑ This works well in CW regime
- ❑ However, in Q-switched regime it is necessary to avoid the damage of all optical components
- ❑ A few examples:
 - We assumed generation of 10 mJ pulses with 15 ns pulsewidth
 - We took the values for the mode size and OC reflectivity from different Ho-papers and calculated intracavity energy/power density

	Roc	Beam Radius, um	Av. energy density, J/cm ²	Av. power density, MW/cm ²
Q-Peak	0.3	0.45	2.9	195
ORC	0.8	0.23	54	3600
BAE	0.85	0.28	50	3340

Conclusions

Development of an efficient 2-um Ho:YLF MOPA pumped with cw-Tm-fiber-lasers:

- ❑ Scalable (modular) Ho:YLF MOPA configuration
 - Highest (to the best of our knowledge) CW output of 113 W
 - Efficient Q-switched operation (> 115 mJ per pulse)
- ❑ Repetition rates in wide range (Hz to kHz), particularly, in 500-1000 Hz range
- ❑ High beam quality (TEM₀₀ beam)

Future work:

- ❑ Optimize Ho-amplifiers
- ❑ Test complete Ho-MOPA in QS regime
- ❑ Pump the OPO

Acknowledgements

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