High-power, high-energy, high-repetition-rate 2050-nm Ho:YLF laser

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Outline

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- Previous Results
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- Q-Peak’ Previous Results
- Tm:fiber Laser - Details
- Ho:YLF Laser – Details
- Conclusions

Motivation

- Development of a 2-um laser source:
  - High-energy (> 200 mJ)
  - High repetition rate (200-1000 Hz)
  - High beam quality (TEM_{00})
- Immediate applications:
  - Pump source for OPOs
  - Lidar
  - Medical, industrial, military

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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 or Ho:YLF, have a large enough gain cross-section for effective high-energy operation.
  - Ho:YAG σ_{em}~$1x10^{-20}$ cm^2
  - Ho:YLF σ_{em}~$2x10^{-20}$ cm^2

References on resonantly pumped Ho lasers

P.F. Moulton, "Industry R&D related to 2-μm lidars," Second Review of 2-μm Solid State Laser Technology, NASA Headquarters, Washington, DC, May 18-19, 1992.

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D.W Hart, M. Jani and N.P. Barnes, Opt. Lett. 21, 728 (1996).

M. Petros, J. Yu, U. N. Singh and N.P. Barnes, "High energy directly pumped Ho:YLF laser," in *Advanced Solid State Lasers*, OSA Technical Digest (Optical Society of America, Washington, DC, 2000), pp. 79-81.

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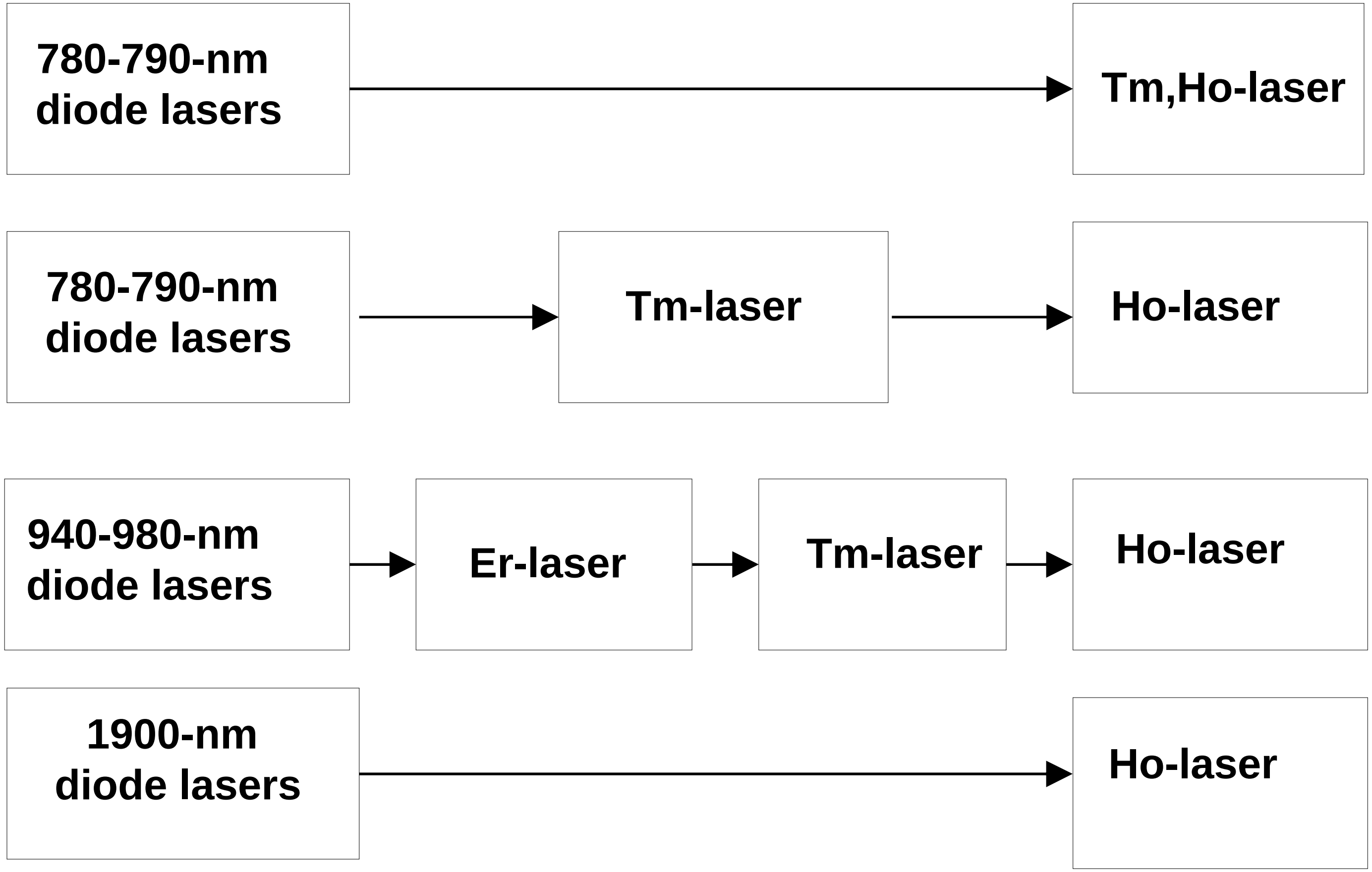
L.D. DeLoach, S.A. Payne, L.L. Chase, L.K. Smith, W.L. Kway and W.F. Krupke, IEEE J. Quantum Electron. 29, 1179 (1993).

W.F. Krupke and L.L. Chase, Optical and Quantum Electron. 22, S1 (1989).

Approaches to diode-pumping of Ho-doped lasers



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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 the availability of high-power Tm-lasers**

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**

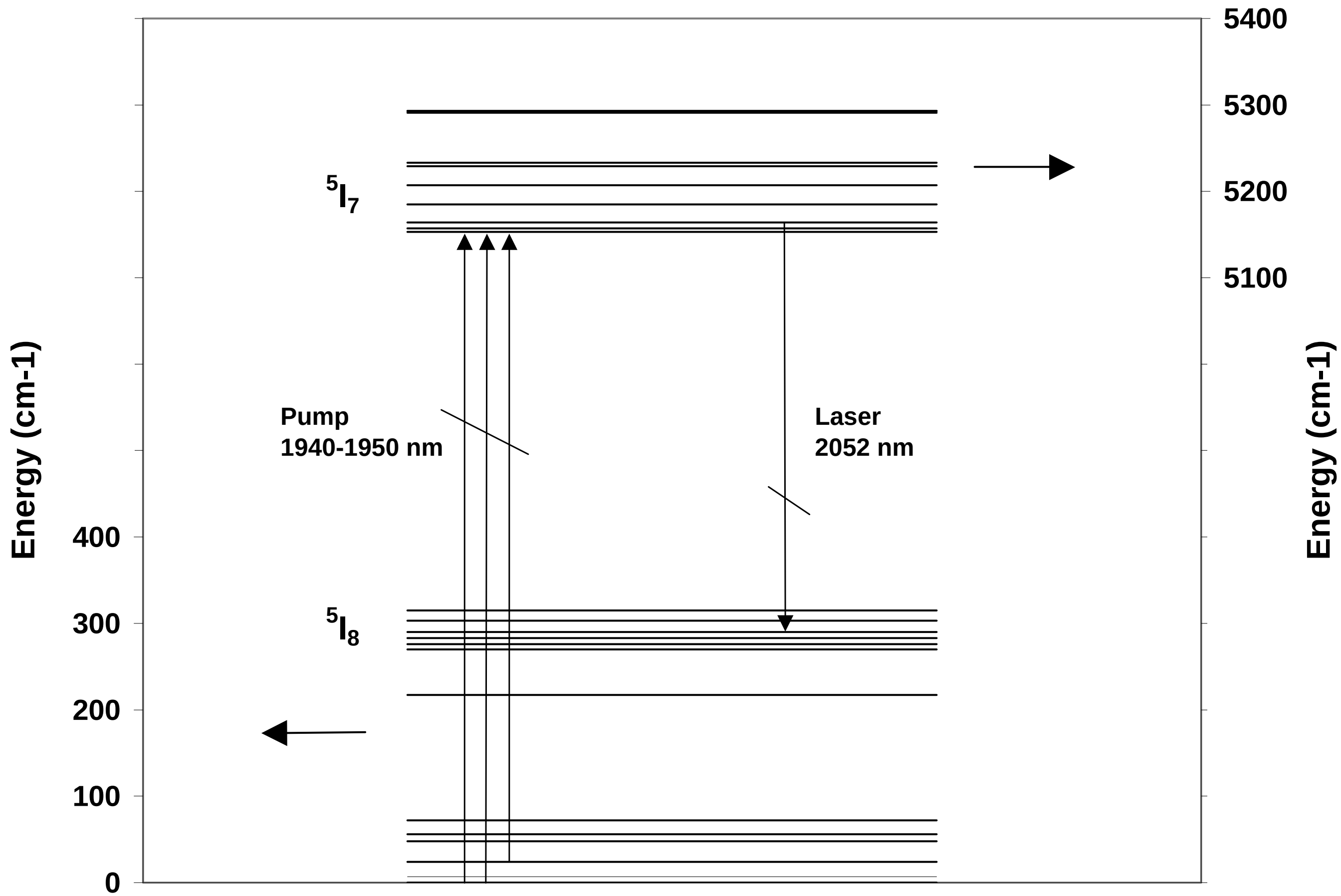
  A. Dergachev, P.F.Moulton, "High-power, high-energy diode-pumped Tm:YLF-Ho:YLF-ZGP laser system", OSA TOPS Vol. 83, ASSP, (OSA, 2003), pp. 137-141
  - Tm:YLF pump
    - 2 x ~25 W CW output at 1940 nm (σ-line)
    - $M^2 \sim 1.05 \times 7$
  - Ho:YLF
    - CW: 21 W
    - QS: 16 W at 1 kHz
- **Ho-lasers pumped with Tm:fiber lasers:**
  - ORC, Univ. of Southampton, UK (Ho:YAG)
  - FFI (Forsvarets forskningsinstitutt), Norway (Ho:YAG)
  - NASA (Ho:YLF)
  - BAE Systems (Ho:YAG)

Ho:YLF vs Ho:YAG

- Why 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 - Energy level diagram



Theoretical model

Cross-section determination - reciprocity method:

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

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

The net gain coefficient:

$$g(\nu) = N [p \, \sigma_{em}(\nu) - (1-p) \, \sigma_{abs}(\nu)]$$

Definitions:

Z_l, Z_u – partition functions for upper (u) and lower (l) states,
E_{ZL} – zero-"phonon" line.
p – inversion fraction,
N – Ho^{3+} concentration

Table. *Values for 0.5% Ho:YLF used in the calculations*

Z_l / Z_u	0.81
E_{ZL}	5153 cm^{-1}
N	7×10^{19} cm^{-3}

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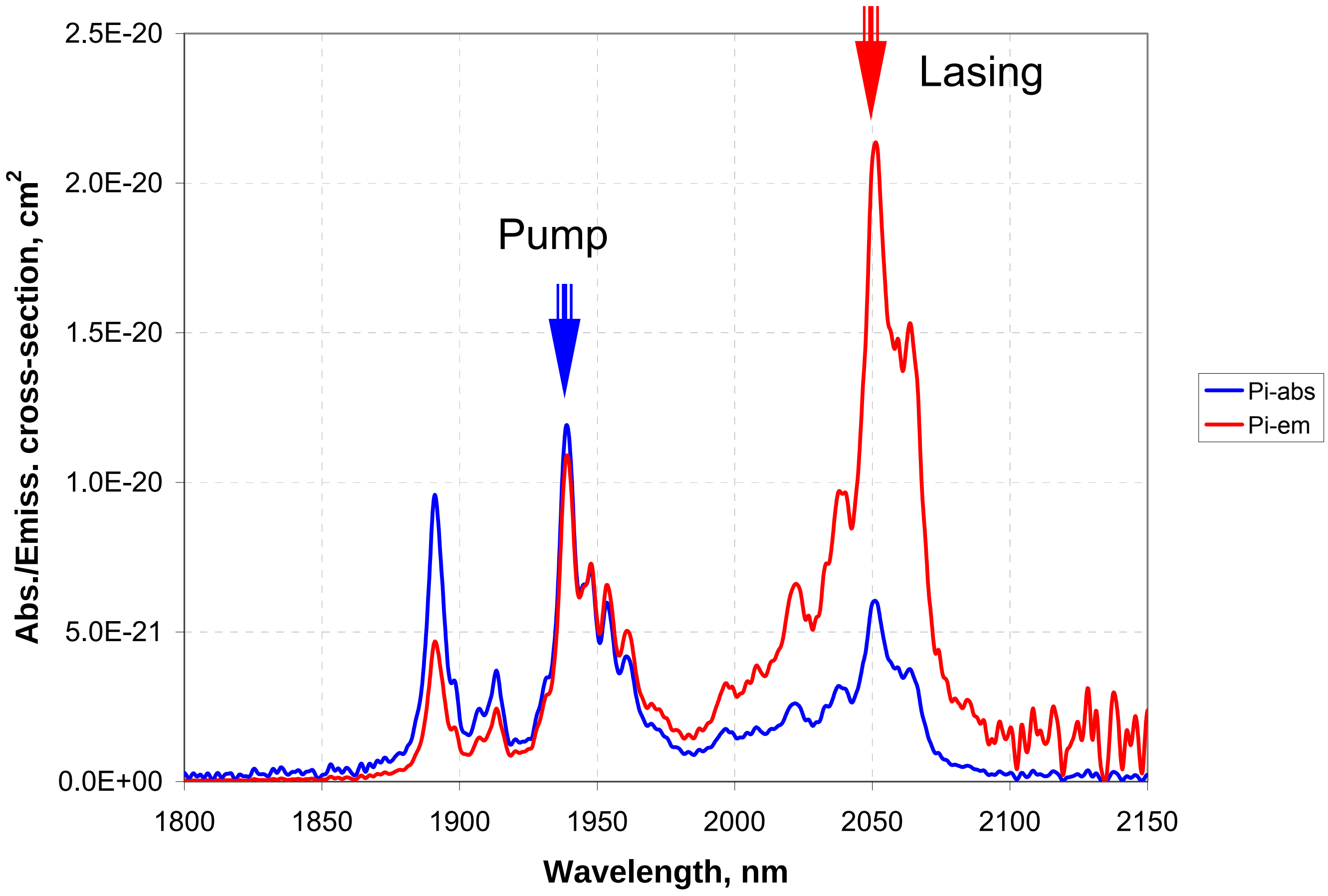
Ho:YLF – Absorption/ Emission



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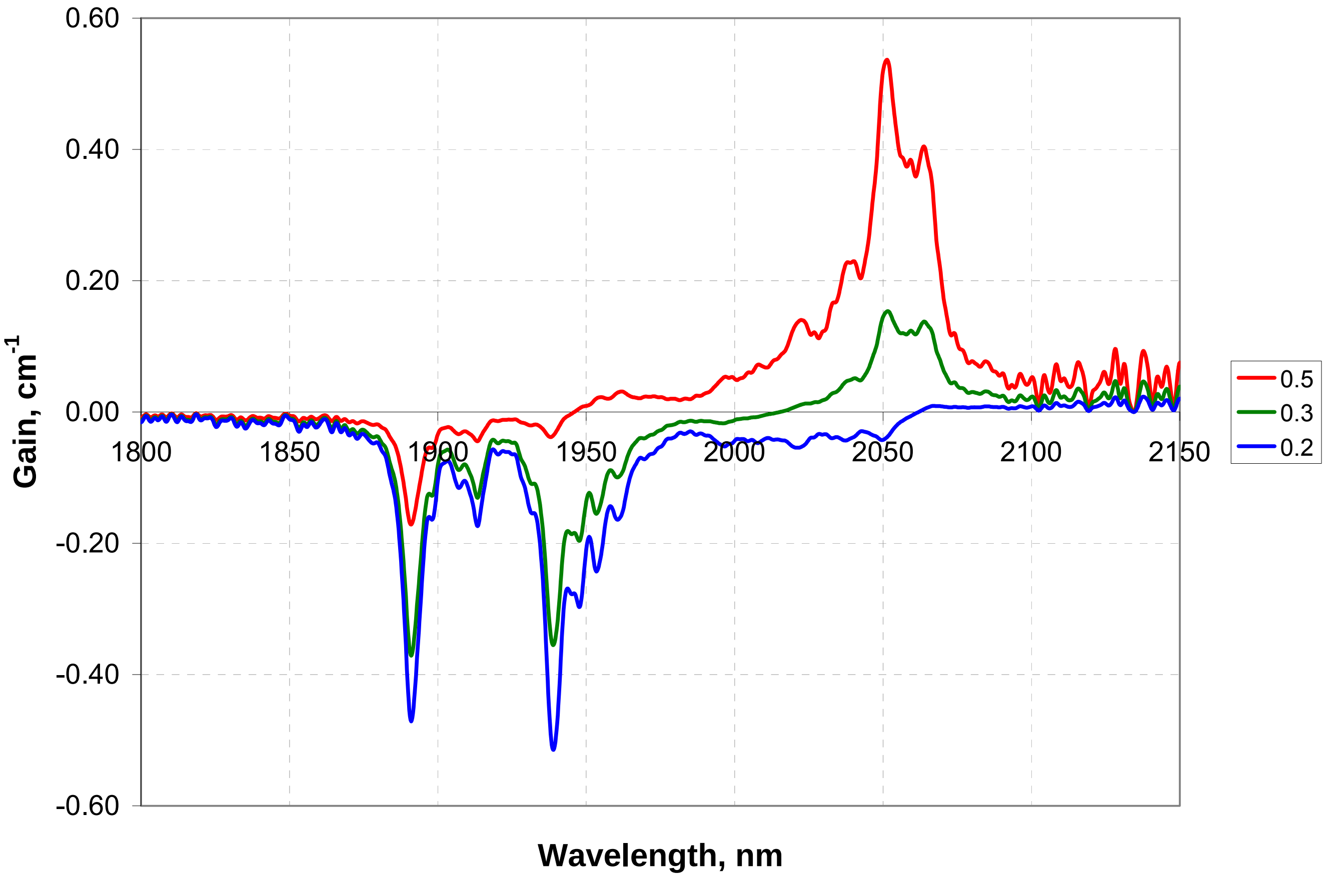
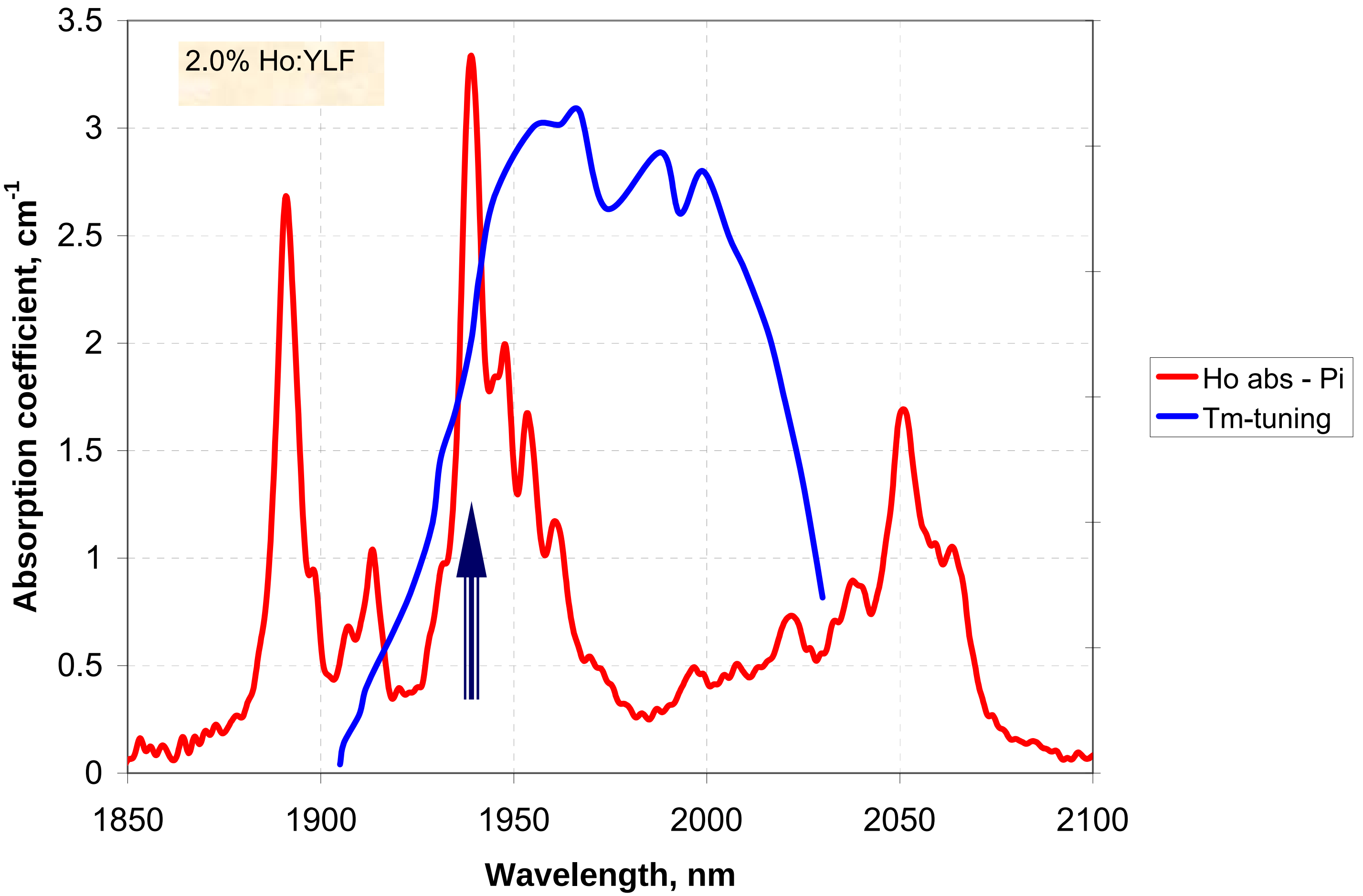
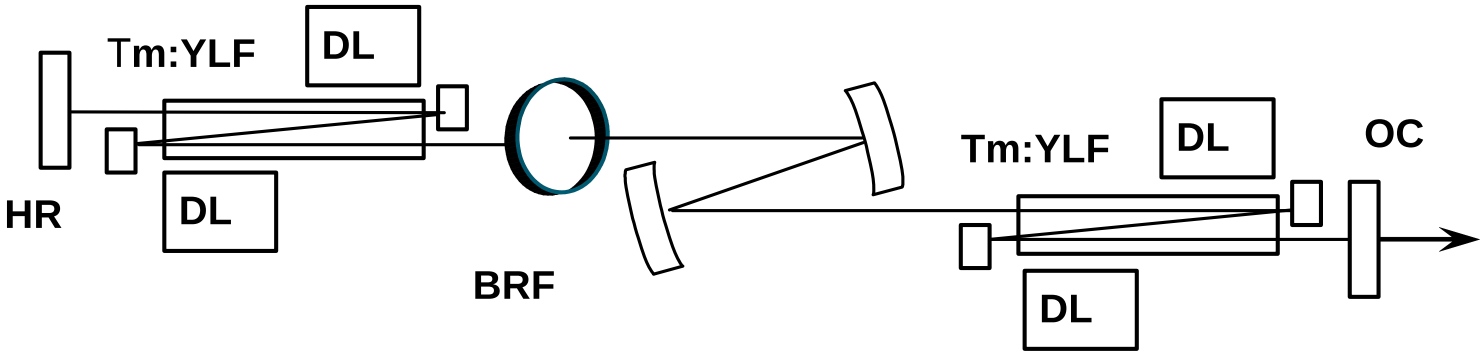
Ho:YLF – Calculated gain (π) vs inverted fraction



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

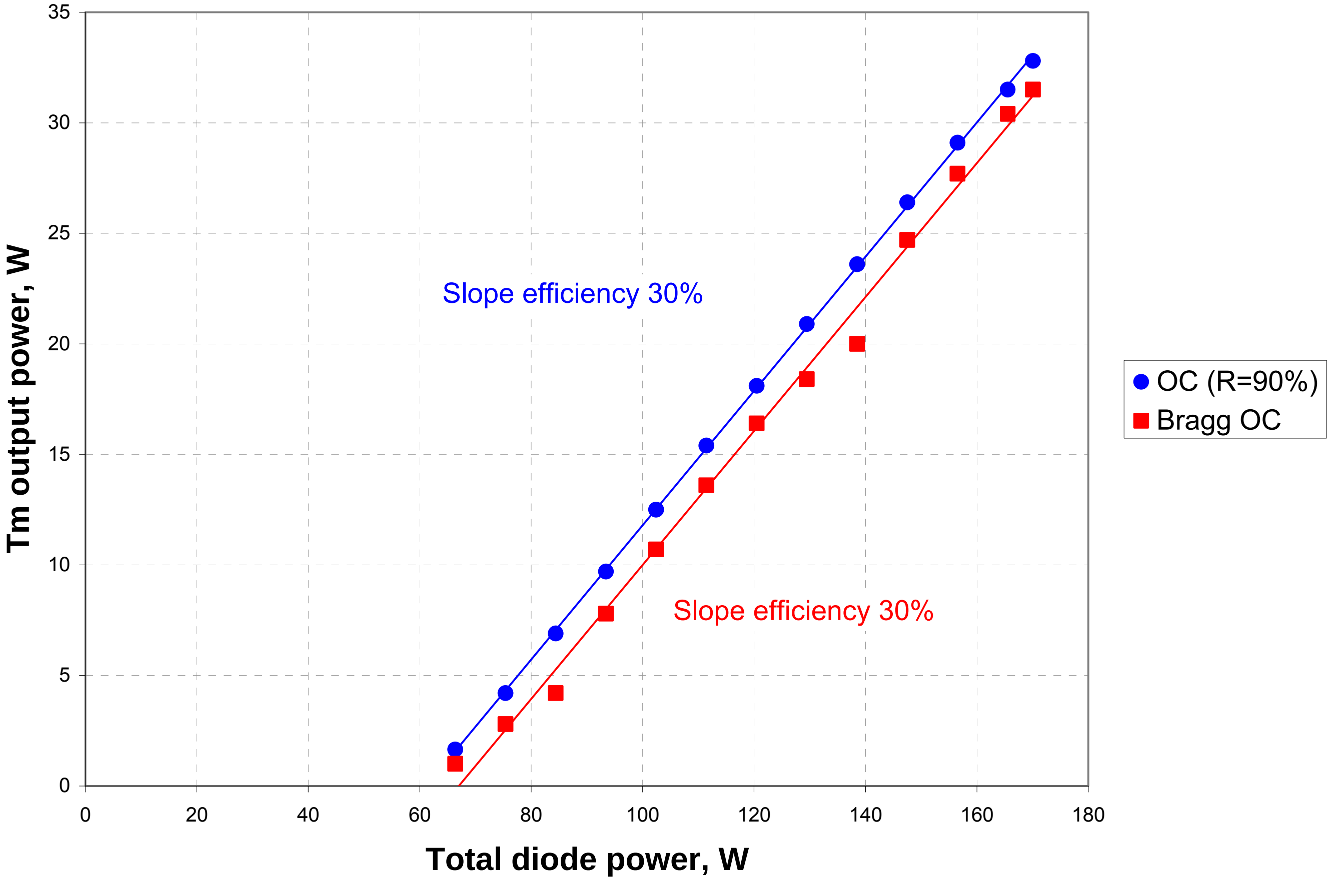


Q-Peak' prior results:
Experimental Set-Up – Tm:YLF Laser

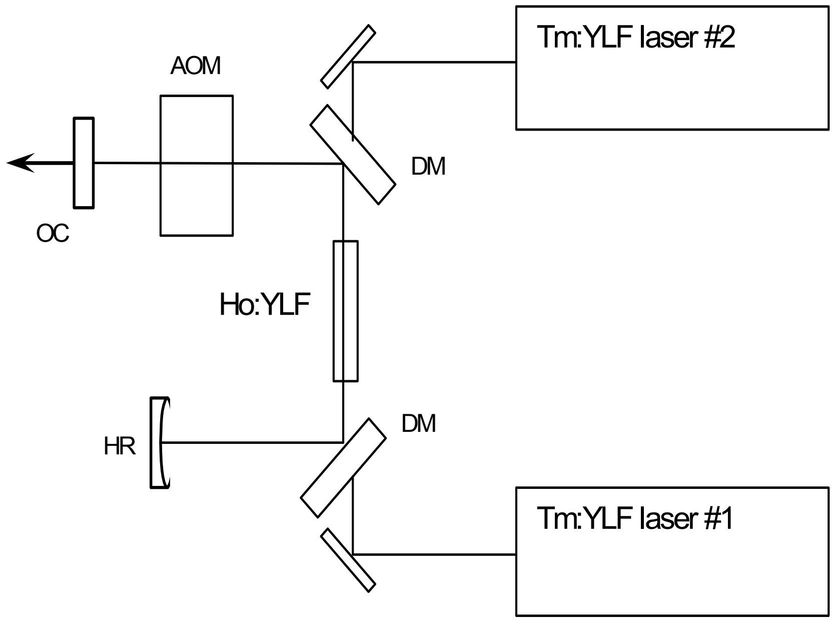


- Dual-Gain Module oscillator
- Beam quality: $M^2 \sim 1.05 \times 7$
- Wavelength tuning with BRF element
  - Alternative: Volume Bragg Grating reflector
- Average power (CW) > 30 W at 1940 nm

Q-Peak' prior results:
Tm:YLF–Laser with a Bragg reflector



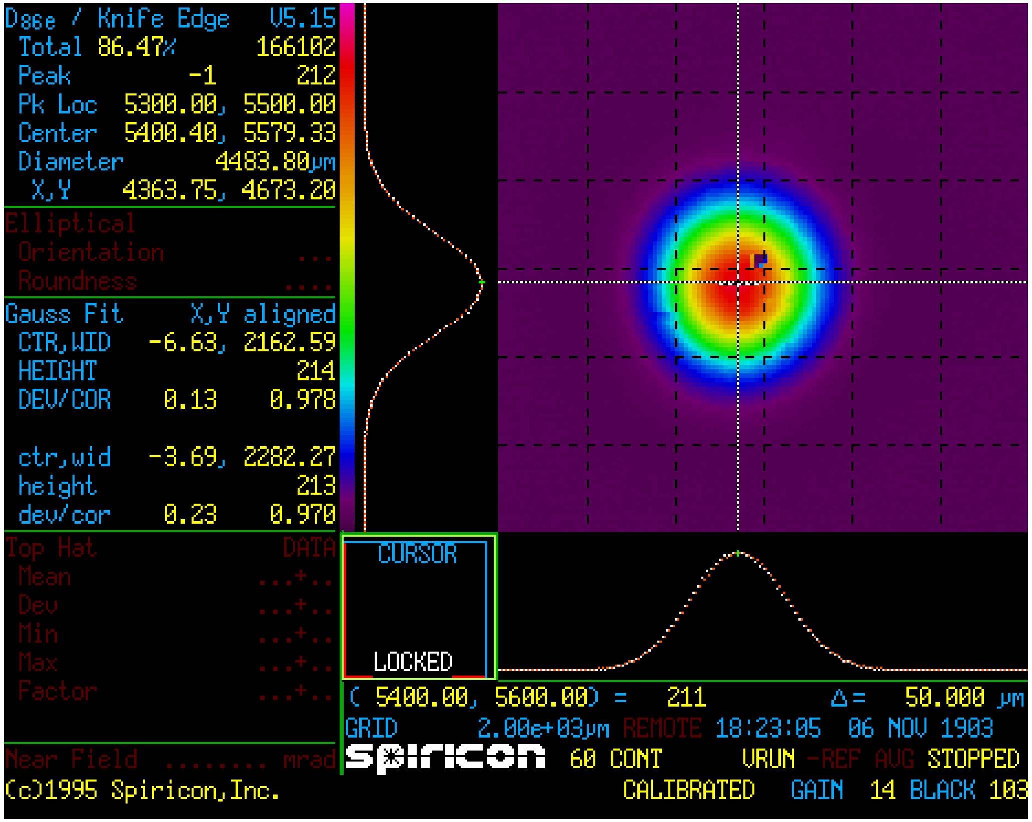
Q-Peak' Prior Results:
End-pumped Ho:YLF laser



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

Q-Peak' prior results: Ho:YLF laser operation (TEM_{oo})

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



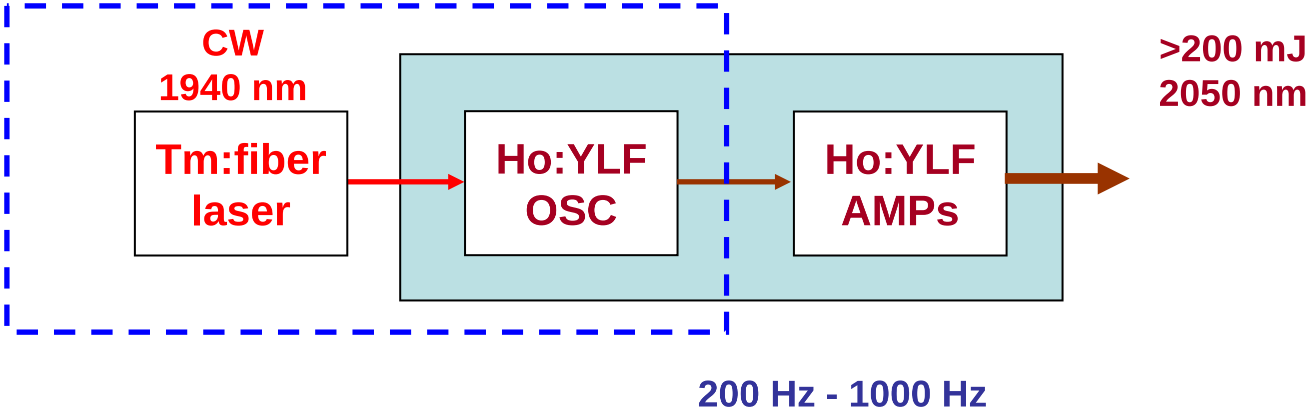
Current work: Specific objectives

Our approach for Tm-pumped Ho-laser:

- Tm-pump: CW Tm-fiber laser
- Ho-laser: Ho:YLF with AO Q-switching

❑ First thing to do:

- Define a Tm-fiber laser pump source



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

Tm-laser requirements and characteristics

Specific requirements for Tm-laser as a pump source for Ho:YLF:

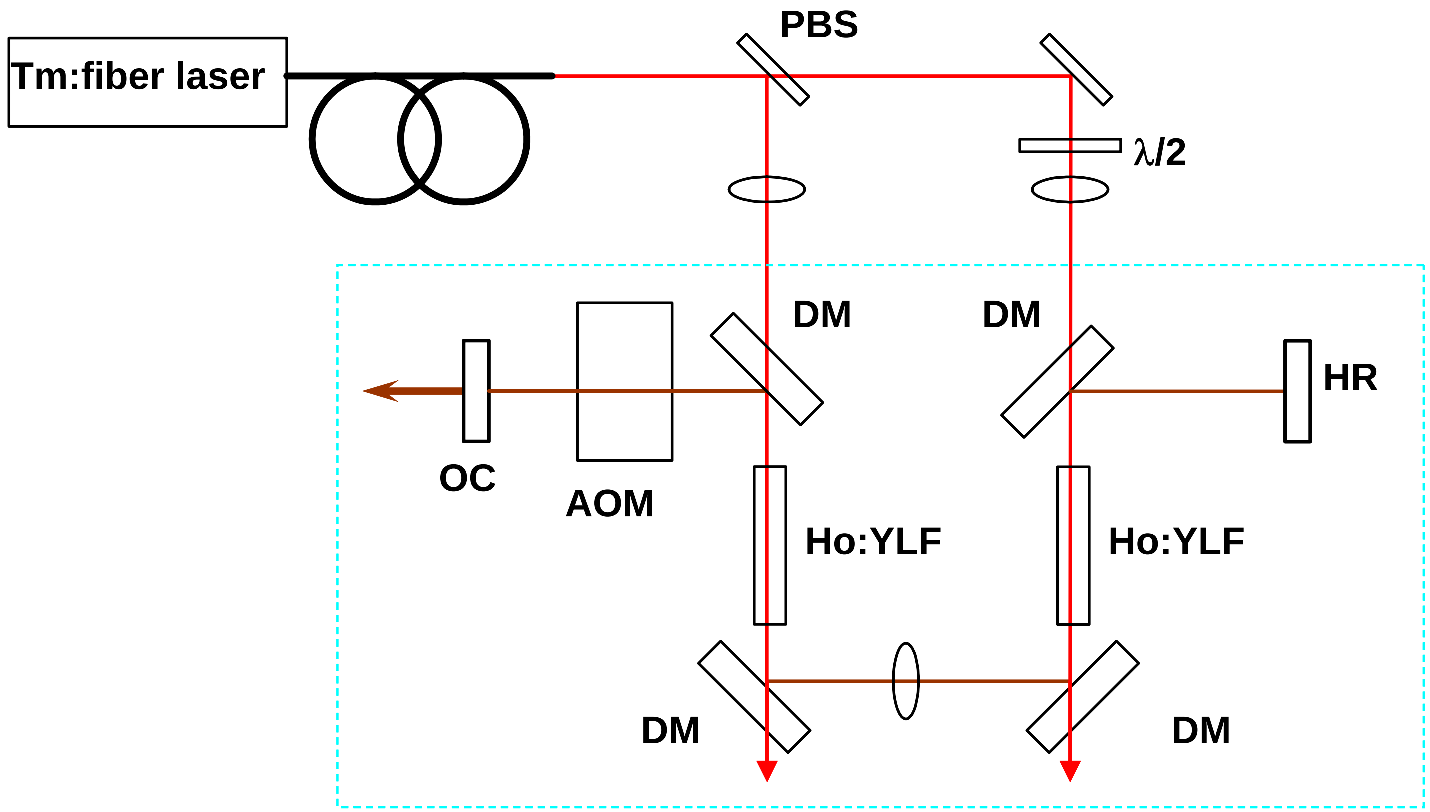
- Linear polarization (preferably)
- Lasing wavelength at ~ 1940 nm
- Linewidth < 6 nm

Tm-fiber laser TLR-100-1940

(IPG Photonics, www.ipgphotonics.com)

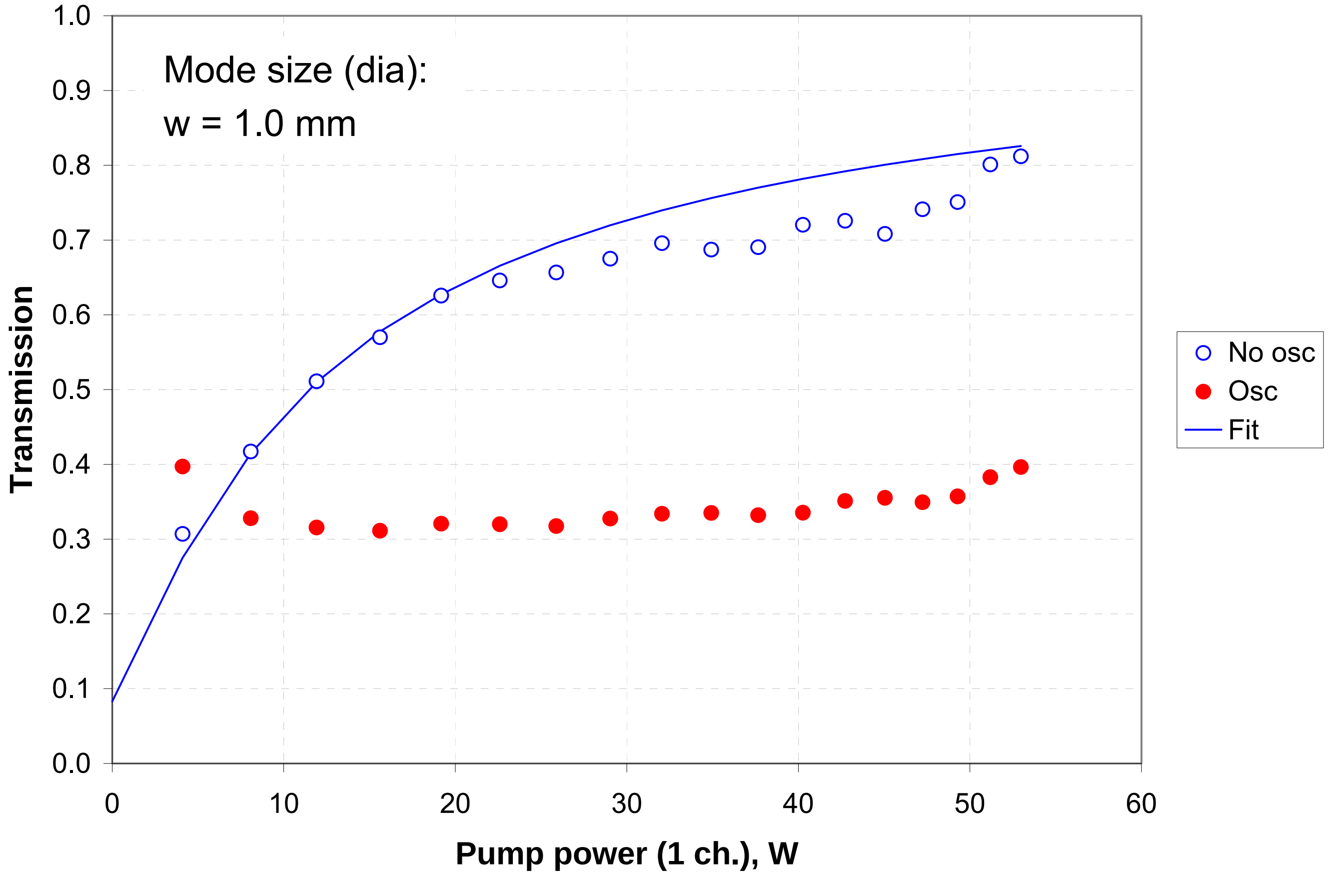
Operation regime	CW
Operational temperature	RT
Output power	≥ 100 W
Lasing wavelength range:	1750-2200 nm
Polarization:	Random
Linewidth	≤ 2 nm

Schematic layout of the end-pumped Ho:YLF laser

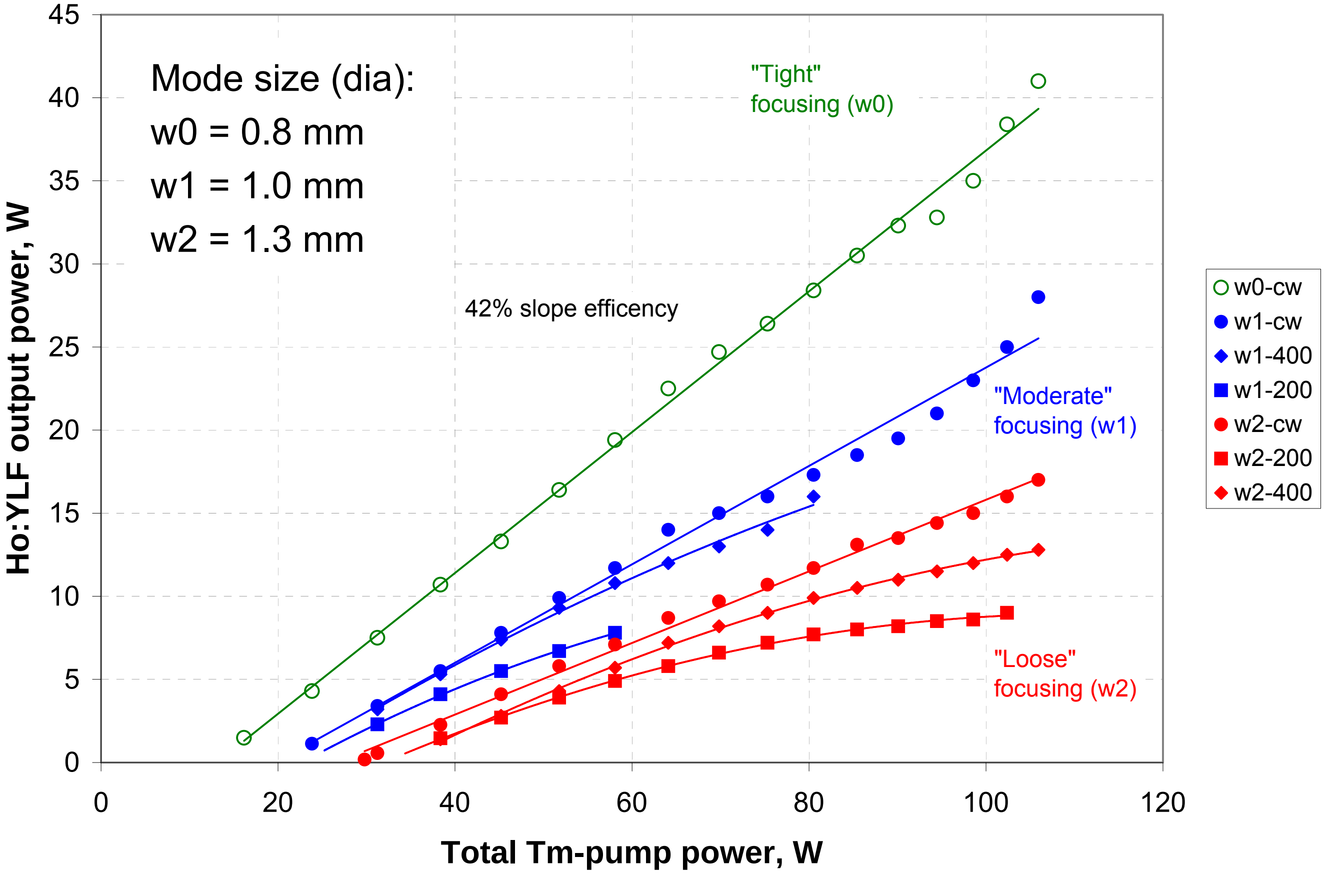


DM – Dichroic Mirror,
AOM – Acousto-Optic Modulator,
OC – Output Coupler,
HR – High Reflector

Ho:YLF pump transmission



Ho:YLF Laser – Power output



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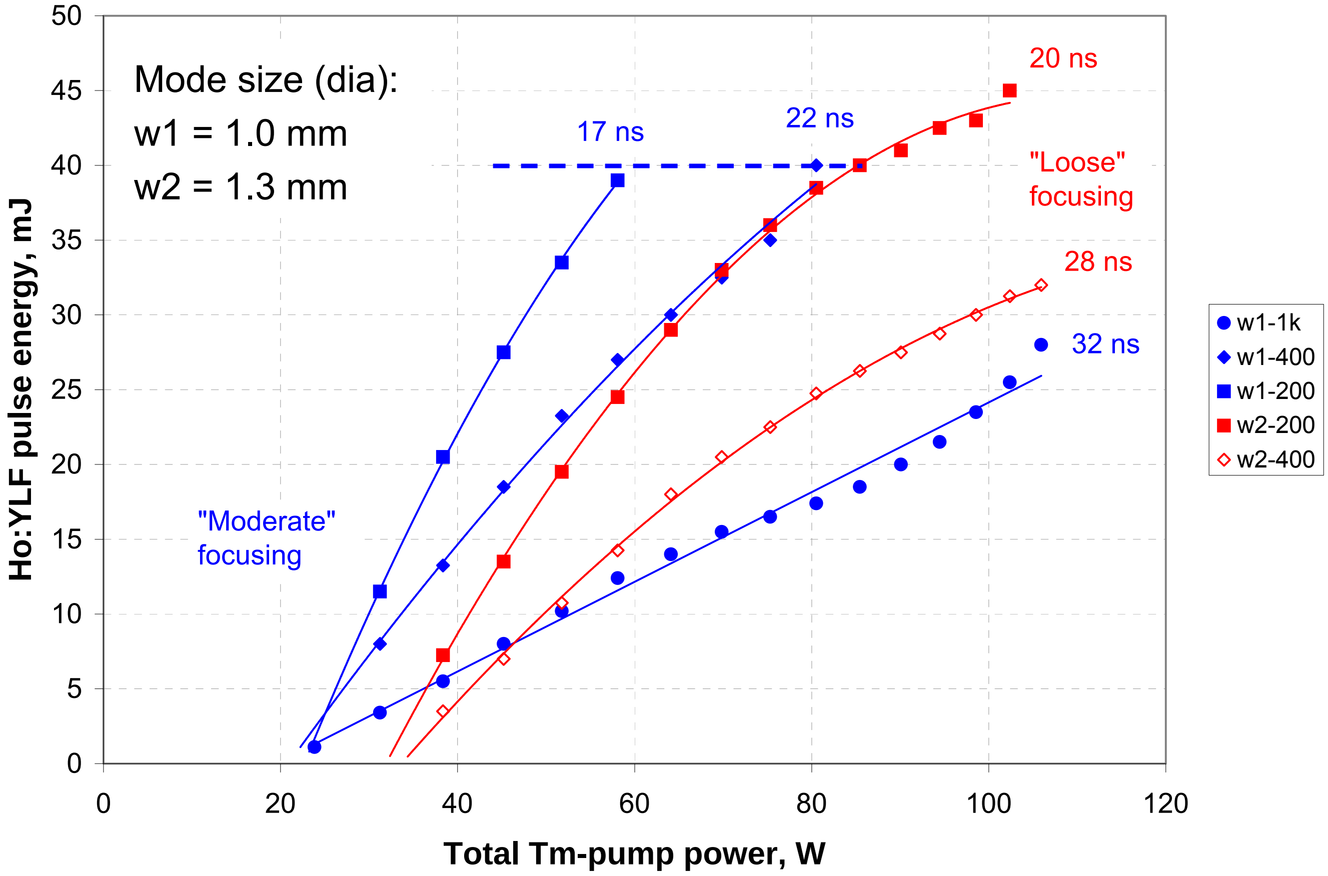
Ho:YLF Laser – Pulse energy



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Conclusions

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

- Highest (to the best of our knowledge) CW output of 43 W
- Efficient Q-switched operation (up to 45 mJ per pulse)
- Repetition rates in wide range (Hz to kHz), particularly, in 100-1000 Hz
- High beam quality (TEM_{00} beam)

Future work:

- Optimize Ho-oscillator
- Add Ho-amplifier modules

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