

# High-Power, Tm-Fiber-Laser-Pumped, Ho:YLF Laser

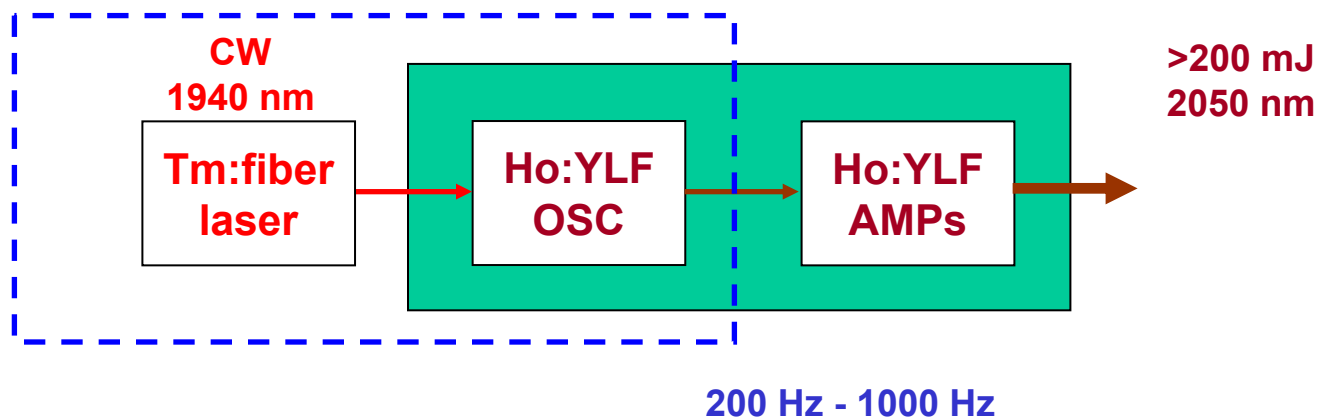
Alex Dergachev, Peter F. Moulton  
*Q-Peak, Inc.*

Thomas E. Drake  
*Lockheed Martin Aeronautics Company*

Solid State Lasers Session #1  
June 8, 2005  
SSDLTR 2005  
Los Angeles, CA



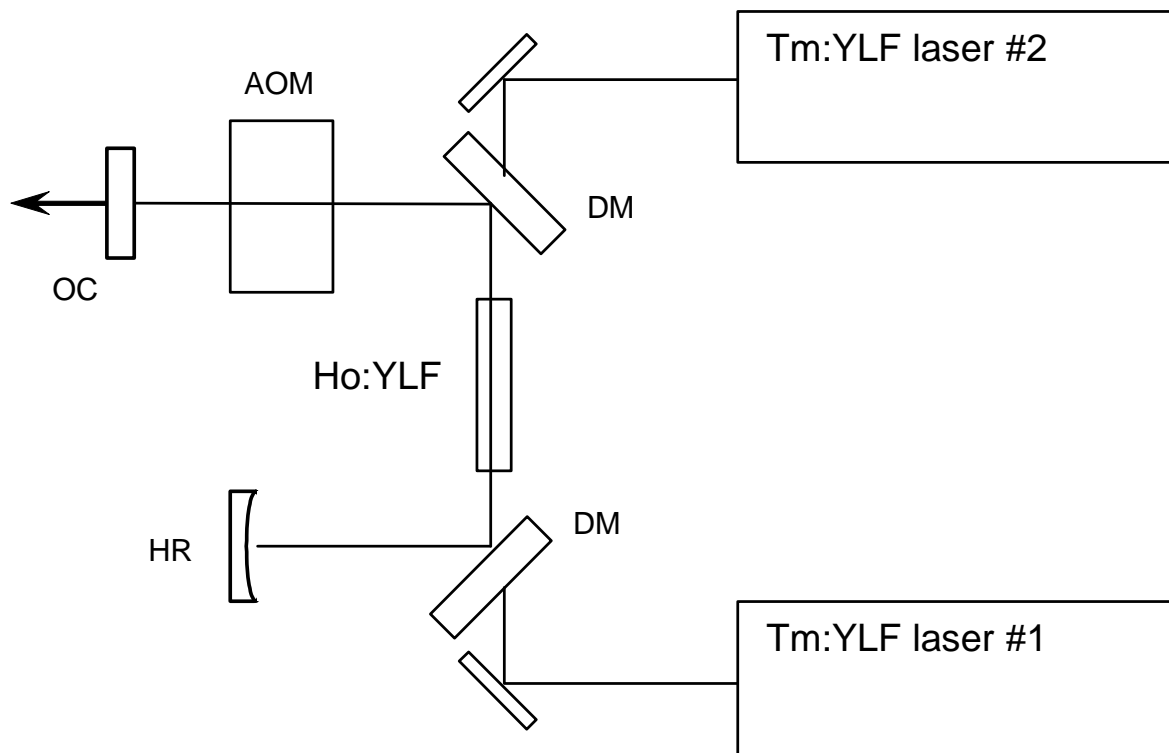
- Development of a 2050-nm laser source:
  - High-energy (> 200 mJ)
  - High repetition rate (200-1000 Hz)
  - High beam quality ( $TEM_{00}$ )



- Immediate applications:
  - Pump source for OPOs
  - Industrial
  - Military

- **Semiconductor diode laser**
  - high electrical-optical efficiency *but*
  - only cw-like output, poor beam quality at high powers
- **Fiber solid state laser**
  - good (in theory) conversion of poor quality beam from diode lasers into diffraction-limited beam *but*
  - limitations in stored energy and nonlinear/damage issues prevent generation of high pulse energies
- **Bulk solid state laser**
  - good conversion of pump power to output power
  - high energy storage and extraction capability allows generation of high-peak-power pulses

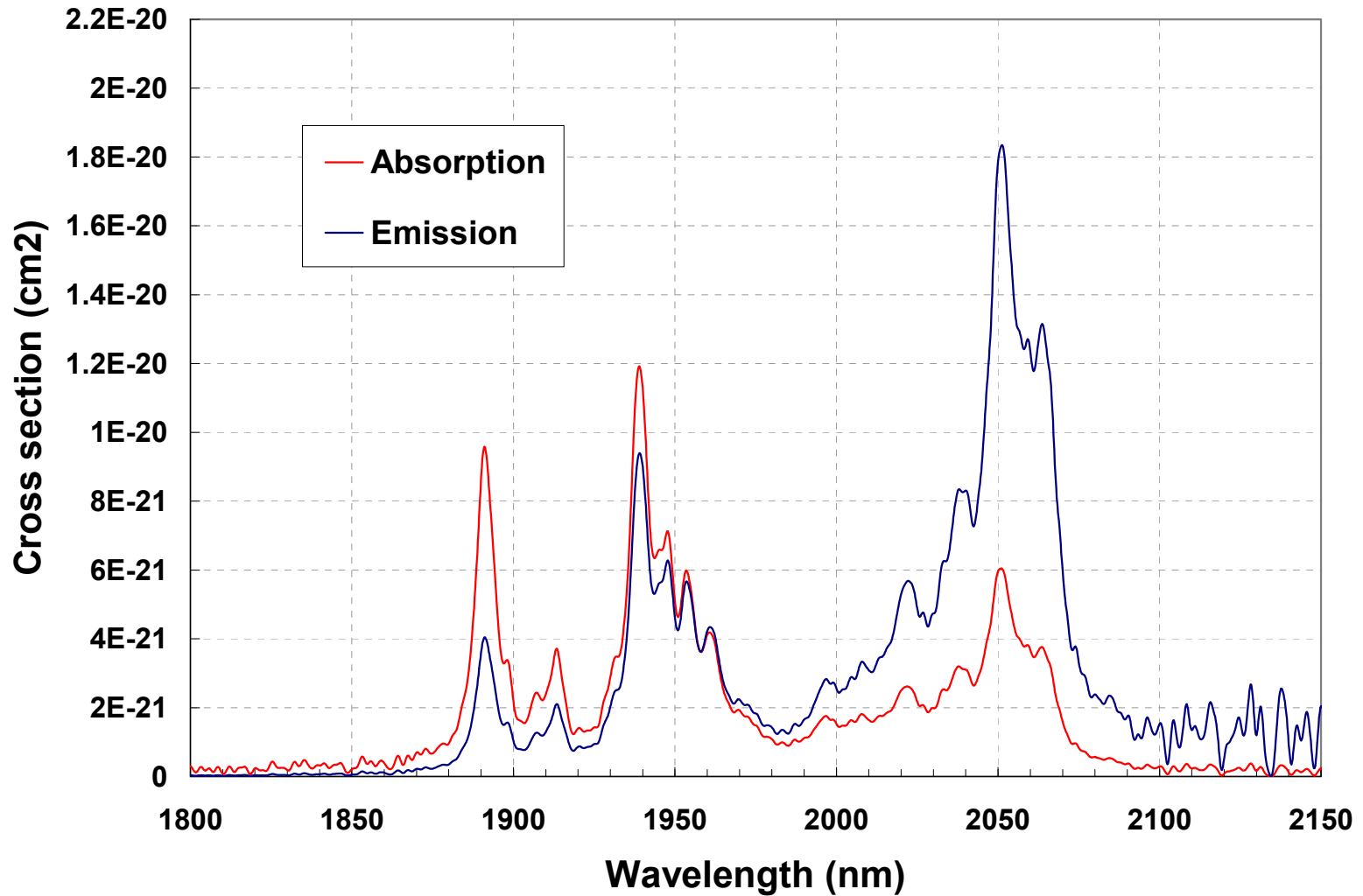
## Q-Peak prior design employed two Tm:YLF pump lasers



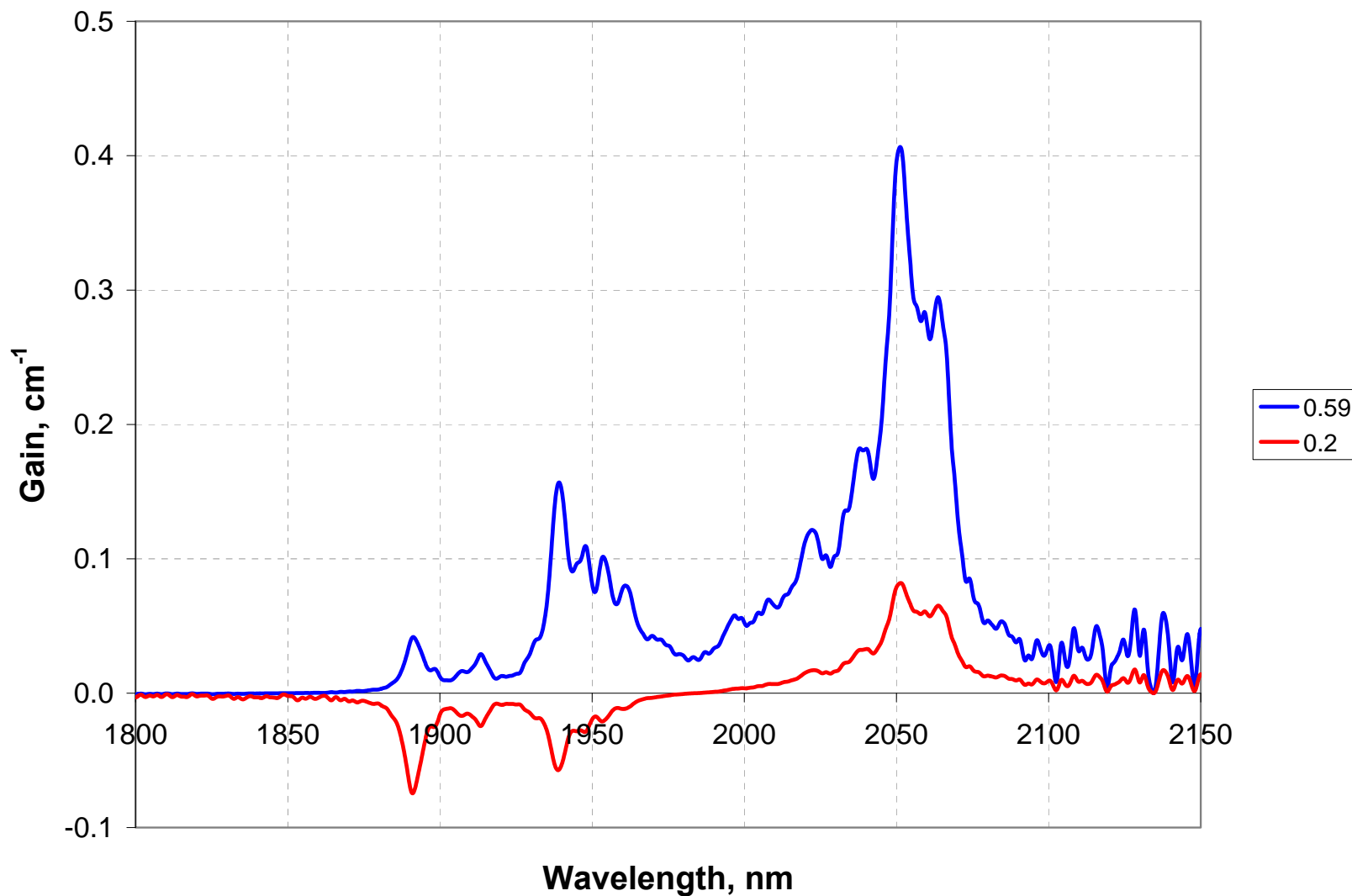
**DM – Dichroic Mirror,  
AOM – Acousto-Optic Modulator,  
OC – Output Coupler,  
HR – High Reflector**

- **Why Ho:YLF (Q-Peak, NASA) ?**
  - Long upper laser level lifetime ~ 15 ms (in theory)
  - Highest emission cross-section known for Ho-doped crystals  
 $\sigma = 1.84 \times 10^{-20} \text{ cm}^2$
  - $E_{\text{sat}} = 5.3 \text{ J/cm}^2$
  - Naturally birefringent material
  - Low  $dn/dT \rightarrow$  weak thermal lensing
  - ~5% quantum defect
- **Compared to Ho:YAG (BAE, SORC)**
  - Upper state lifetime 7 ms
  - Emission cross section  $0.98 \times 10^{-20} \text{ cm}^2$
  - $E_{\text{sat}} = 9.6 \text{ J/cm}^2$
  - 10% quantum defect
  - Isotropic, higher thermal lensing, stress birefringence
  - Superior thermo-mechanical properties

# Ho:YLF absorption data yields prediction of emission cross section



# Ho:YLF gain is predicted to be high for a 59% inversion fraction





# Prior Ho:YLF laser operation demonstrated high pulse energies with excellent mode quality

**CW output:** 21 W  
(max)

**Pulse energy (max):**

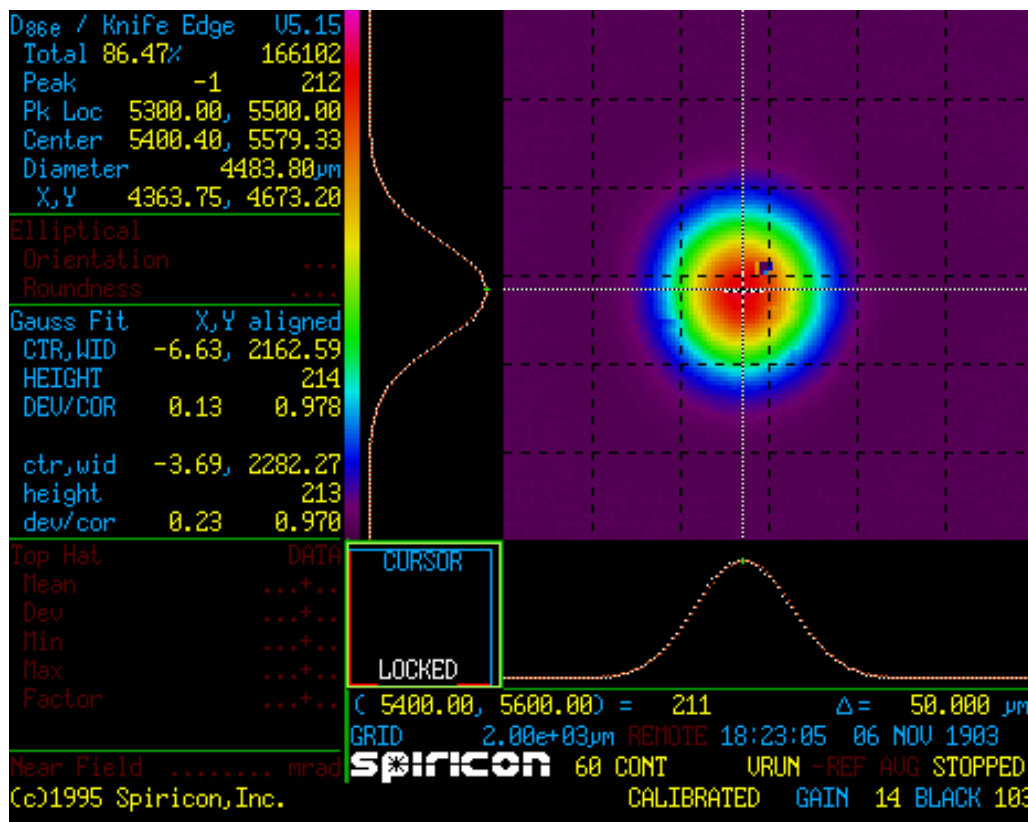
100 Hz 35 mJ

400 Hz 27 mJ

**Pulsewidth:**

100 Hz 12 ns

400 Hz 15 ns





## Ho-laser power scaling is possible with Tm: fiber-laser pumps

---

- **CW Tm: fiber commercial lasers with output >100 W have emerged as alternative to bulk Tm-laser:**
  - **Turn key operation based on industrial designs developed for Yb: fiber lasers**
  - **Cost-effective in terms of \$/W**
  - **Maintenance-free (we hope)**
  - **Fiber delivery (no surprise!)**



**Tm-pump laser requirements are satisfied  
(mostly) by commercial IPG laser**

---

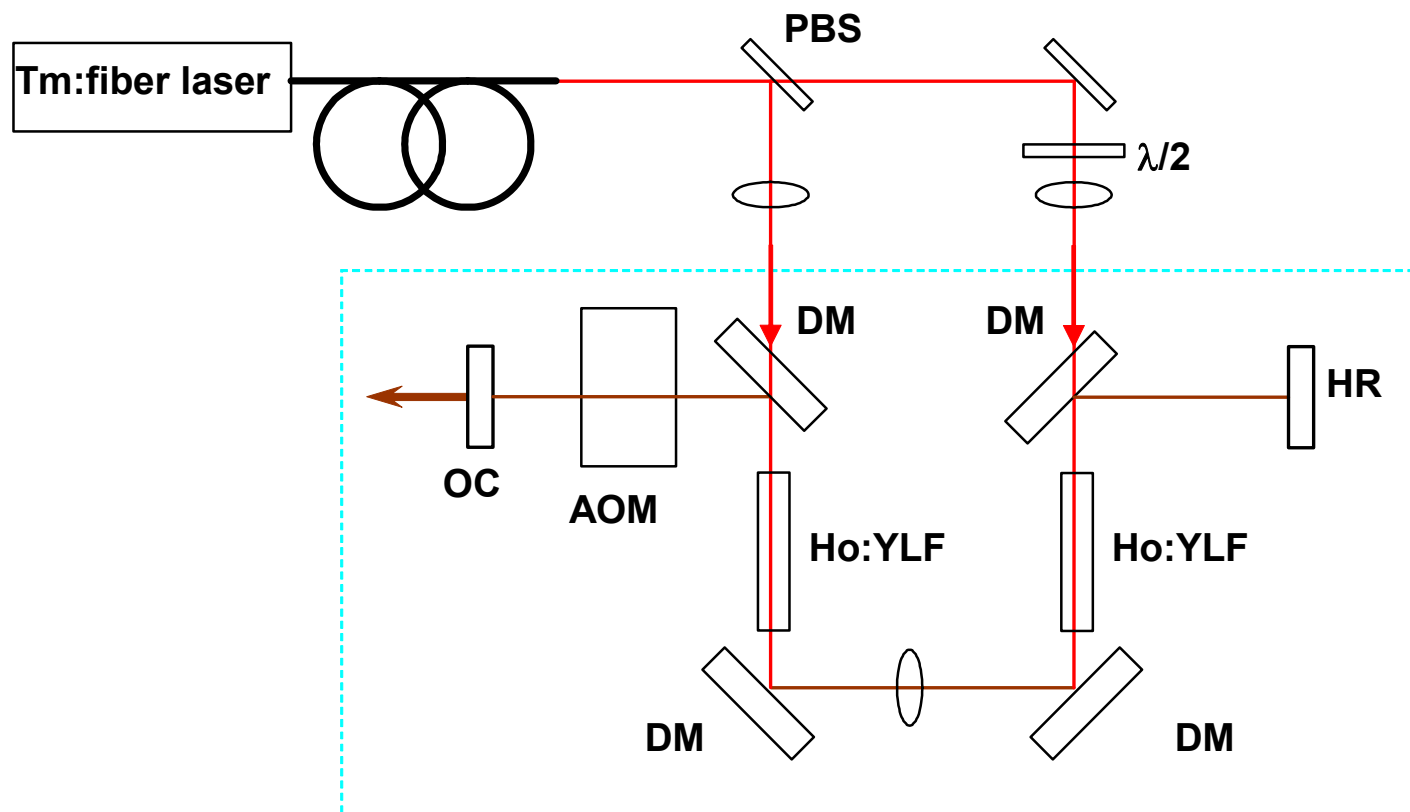
**Specific requirements for Tm-laser as a pump source for Ho:YLF:**

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

**Tm-fiber laser TLR-100-1940  
(IPG Photonics, [www.ipgphotonics.com](http://www.ipgphotonics.com) )**

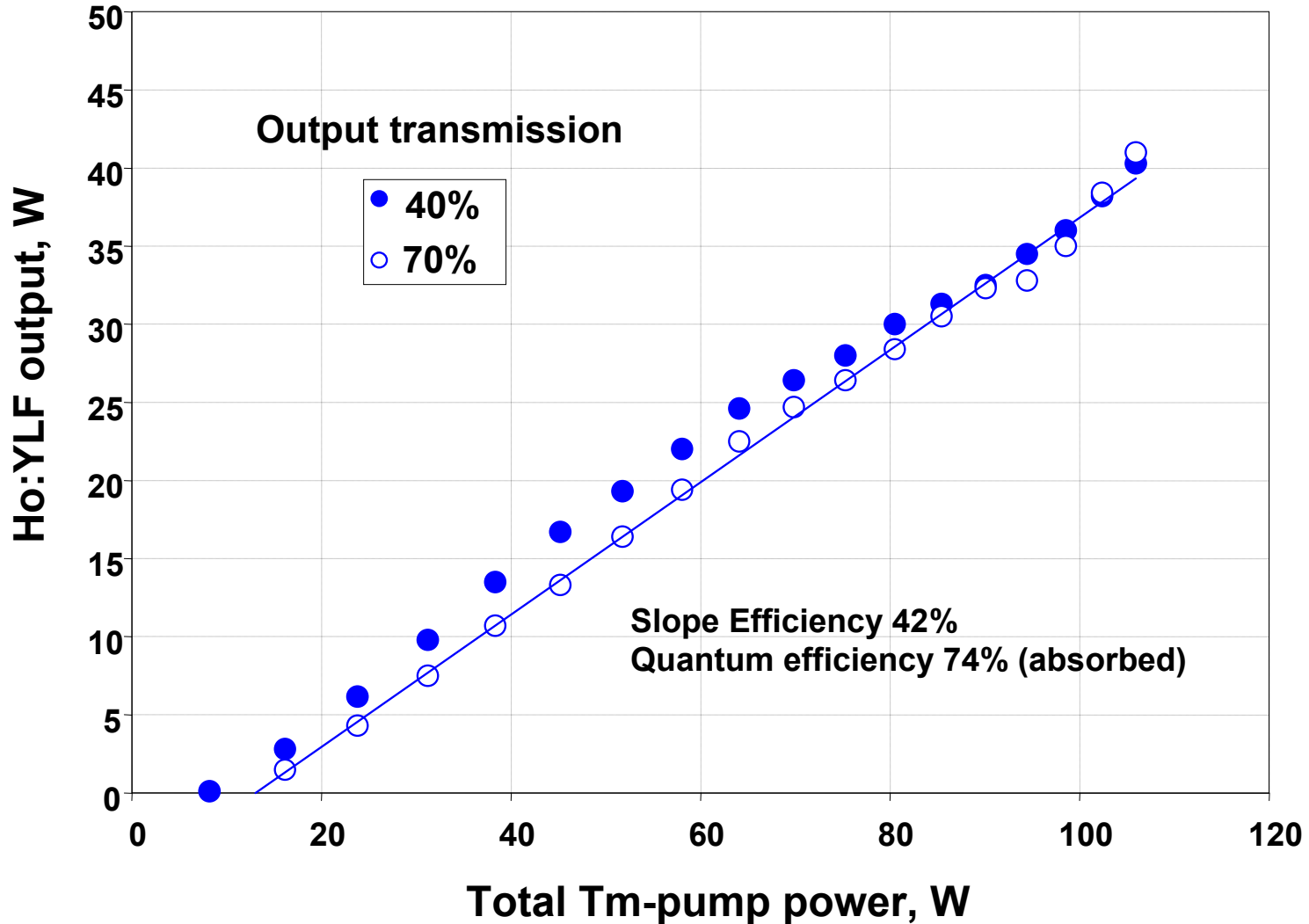
|                                 |                     |
|---------------------------------|---------------------|
| <b>Operation regime</b>         | <b>CW</b>           |
| <b>Operational temperature</b>  | <b>RT</b>           |
| <b>Output power</b>             | <b>≥ 100 W</b>      |
| <b>Lasing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

## Schematic layout of the end-pumped Ho:YLF laser shows two-crystal design

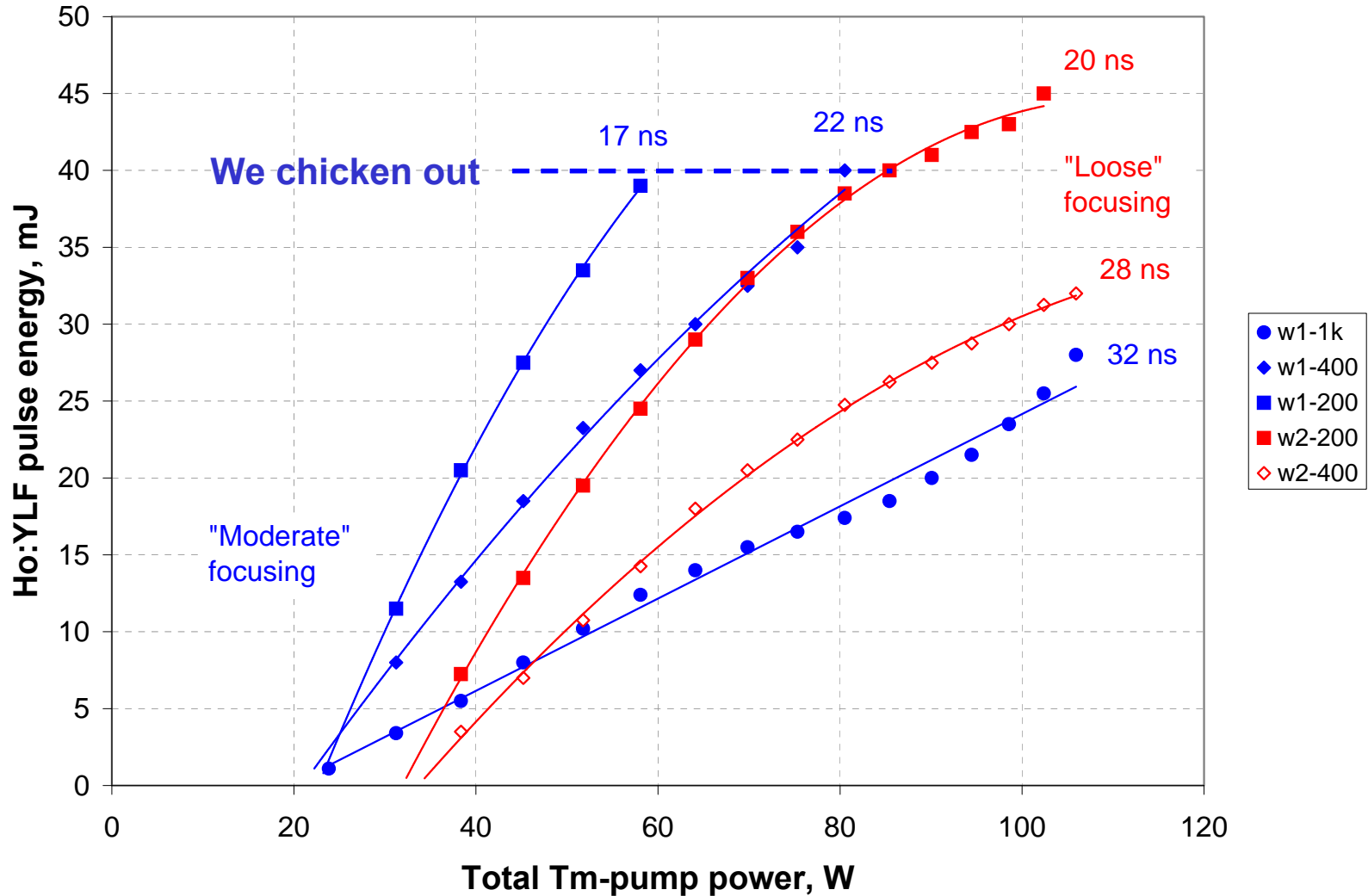


DM – Dichroic Mirror,  
AOM – Acousto-Optic Modulator,  
OC – Output Coupler,  
HR – High Reflector

# CW laser operation provides 40-W of output power

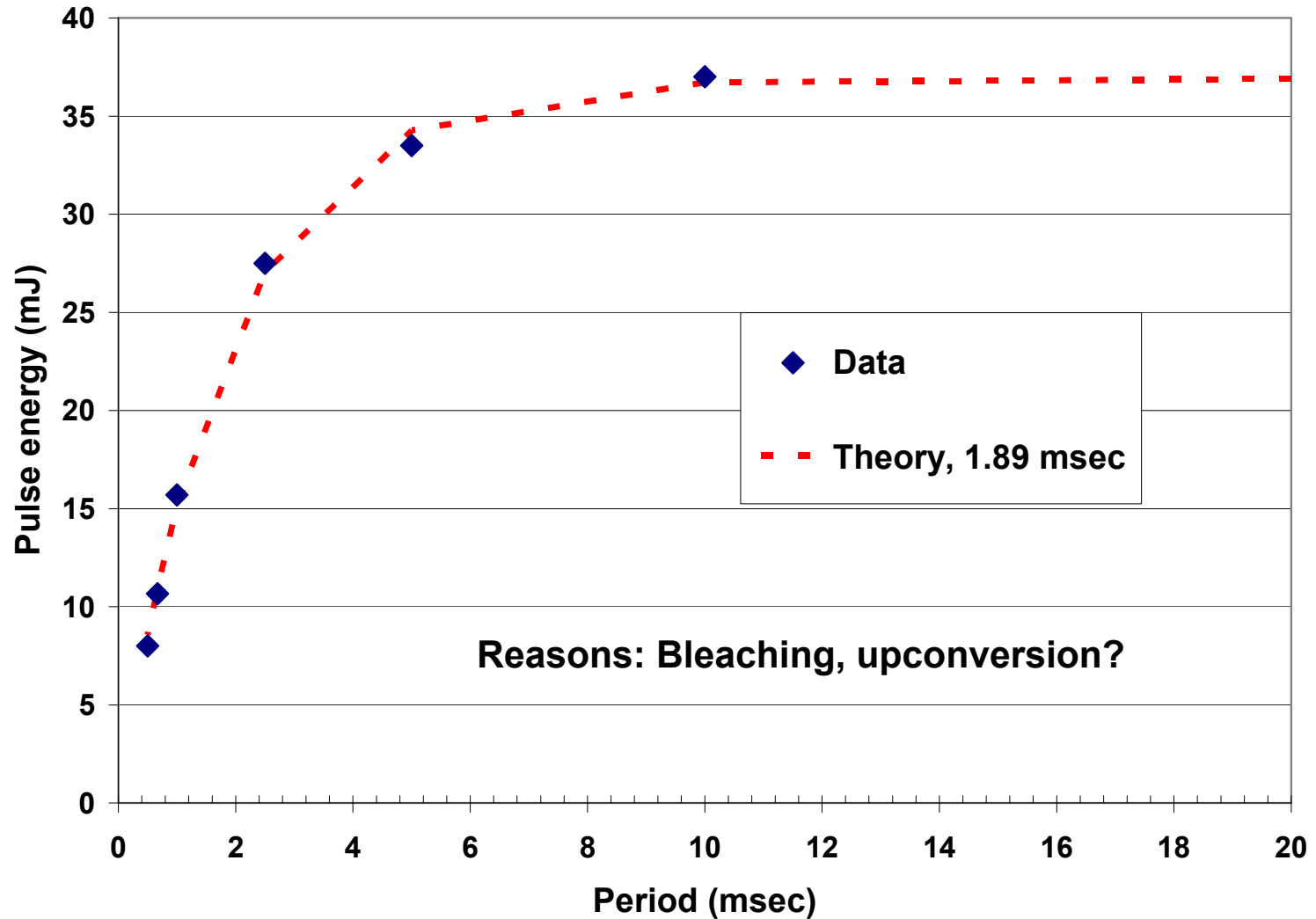


# Ho:YLF Q-switched laser operation observed at pulse rates from 200-1000 Hz

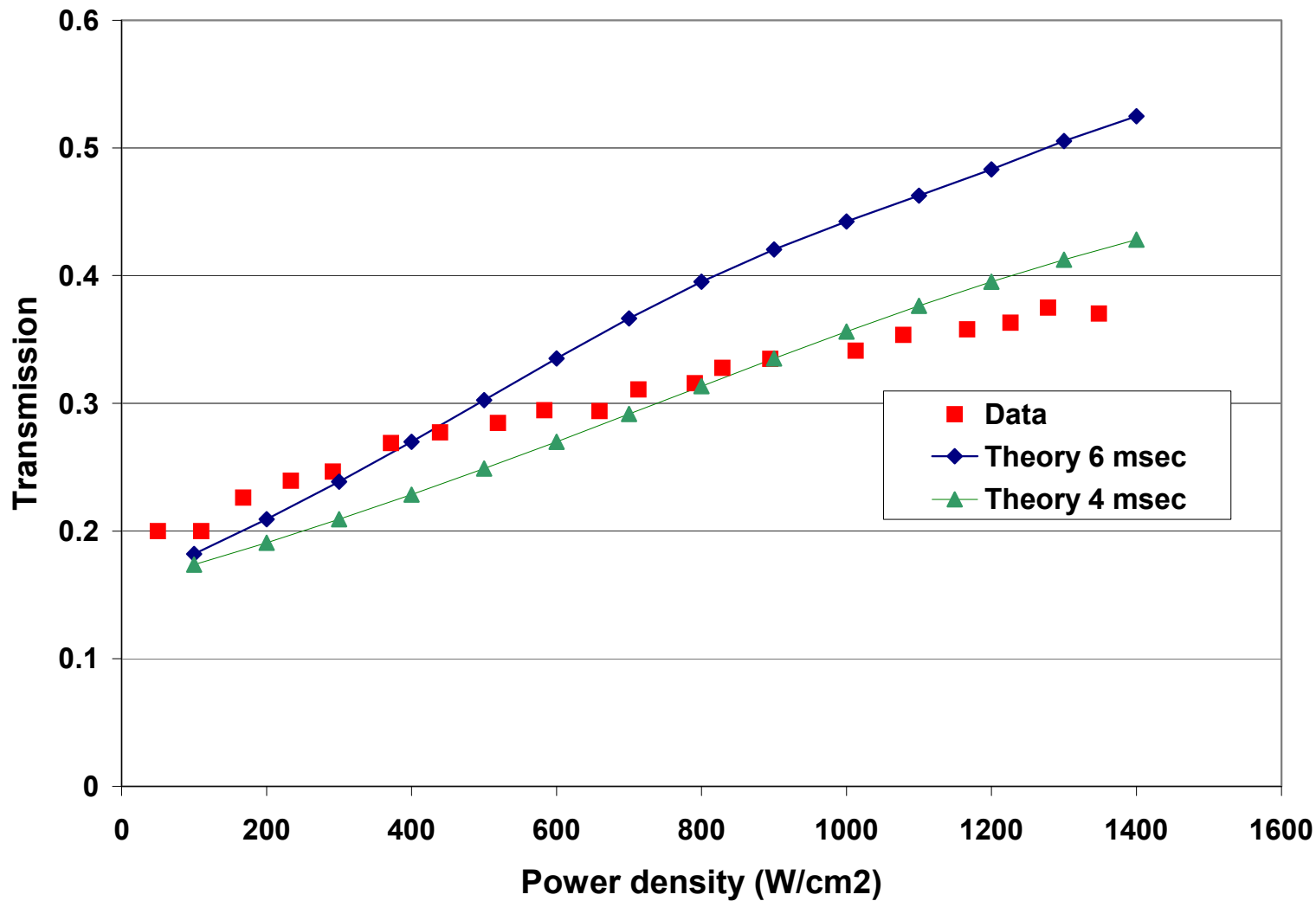




# Ho:YLF effective storage time is around 2 msec based on energy vs. pulse rate data

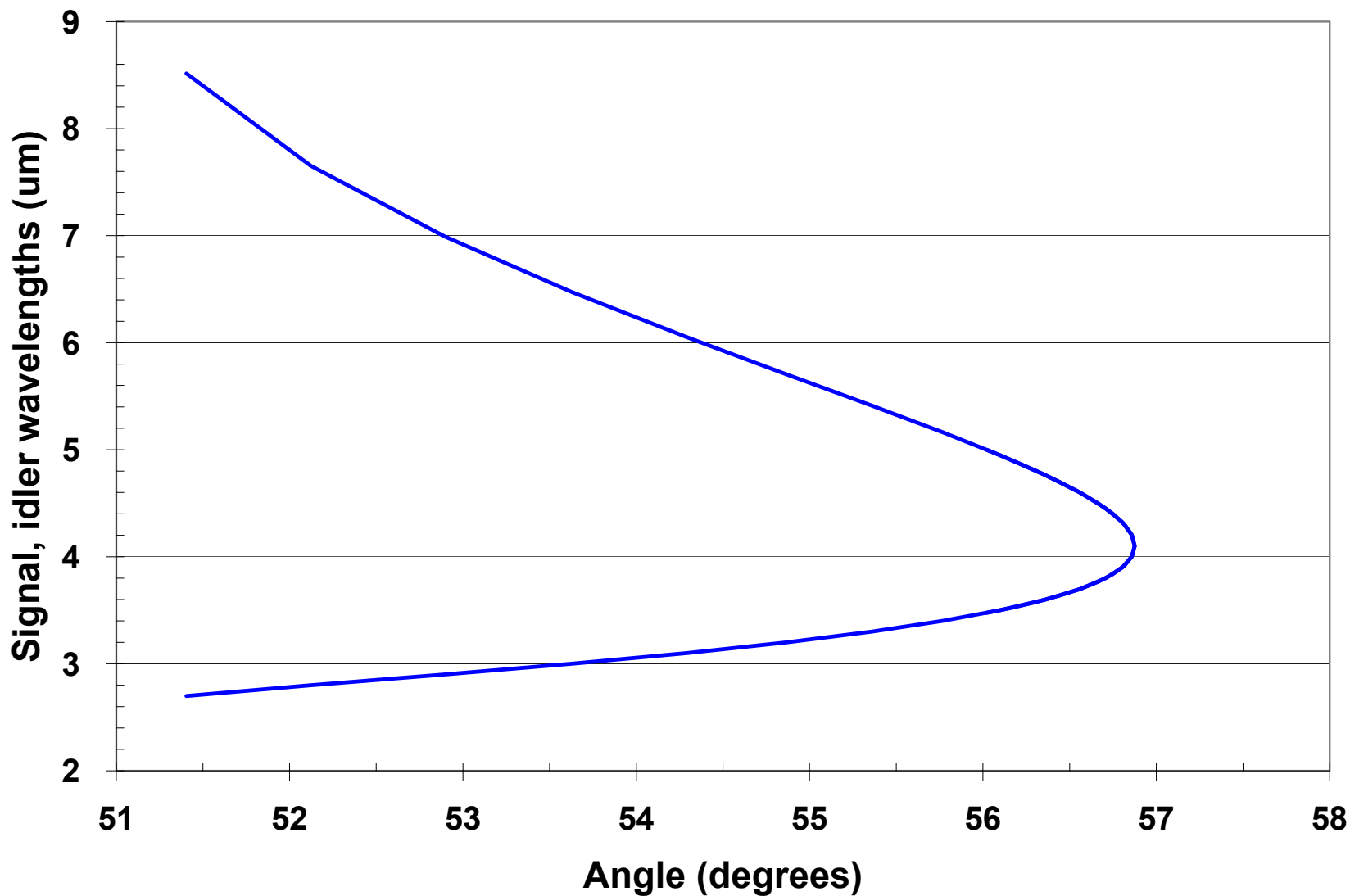


## Absorption saturation in 2% Ho-doped YLF at 1940 nm shows reduced lifetime



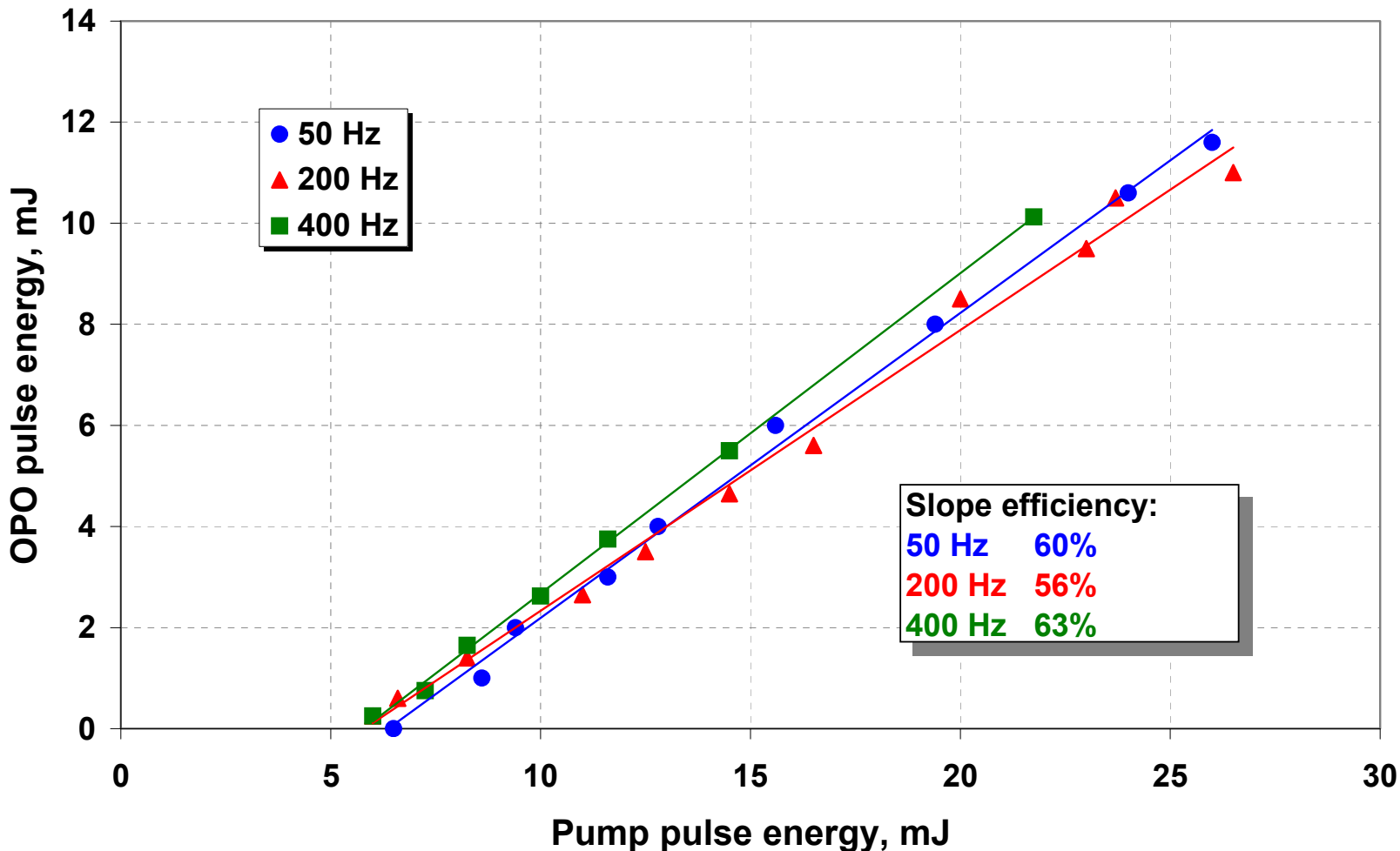


# Tuning curve for Ho:YLF-pumped ZGP OPO shows broad mid-IR coverage





# ZGP OPO data on pulse energy at 3200 nm shows no significant average-power limitations



- **Fiber-laser pumped Ho:YLF crystal (and similar materials) combines best features of fiber and bulk solid state lasers**
  - High beam quality and efficiency of fiber lasers
  - Energy storage capability of bulk lasers
- **Recent advances in commercial (IPG) Tm:fiber lasers have made 100-W devices available. Future powers even higher?**
- **Ho:YLF laser has a favorable combination of energy storage and high gain cross section, suitable for high-energy, short-pulse Q-switched oscillators and amplifiers at 2050 nm**
- **2050-nm wavelength is eyesafe, transmits well through the atmosphere and is a good pump wavelength for ZGP OPOs providing coverage of entire mid-IR wavelength region**
- **Scaling to 40 W average power, 45 mJ pulses at 20 ns to date**
- **Stayed tuned, another 200 W of pump power yet to go!**



**Backup**

---



## Tm-pumped Ho-laser has advantages over other designs

---

- ❑ **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, high-beam-quality Tm-lasers**

- **Tm:YLF pumped Ho:YAG**

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

  - Tm:YLF pump
    - 36 W CW output at 1907 nm ( $\sigma$ -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 ( $\sigma$ -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:**
  - NASA (Ho:YLF)
  - BAE Systems (Ho:YAG)
  - ORC, Univ. of Southampton (Ho:YAG)

## 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 JQE, 28, 2619-2630 (1992)).

## The net gain coefficient:

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

## Definitions:

- $Z_l, Z_u$  – partition functions for upper (u) and lower (l) states,
- $E_{ZL}$  – zero-“phonon” line.
- $\rho$  – inversion fraction,
- $N$  – Ho<sup>3+</sup> concentration

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

|           |                                     |
|-----------|-------------------------------------|
| $Z_l/Z_u$ | 0.81                                |
| $E_{ZL}$  | 5153 cm <sup>-1</sup>               |
| $N$       | 7x10 <sup>19</sup> cm <sup>-3</sup> |

**Results to date: 40 W of cw power  
40 mJ of Q-switched energy in 17-ns pulse**

