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

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Solid State Lasers
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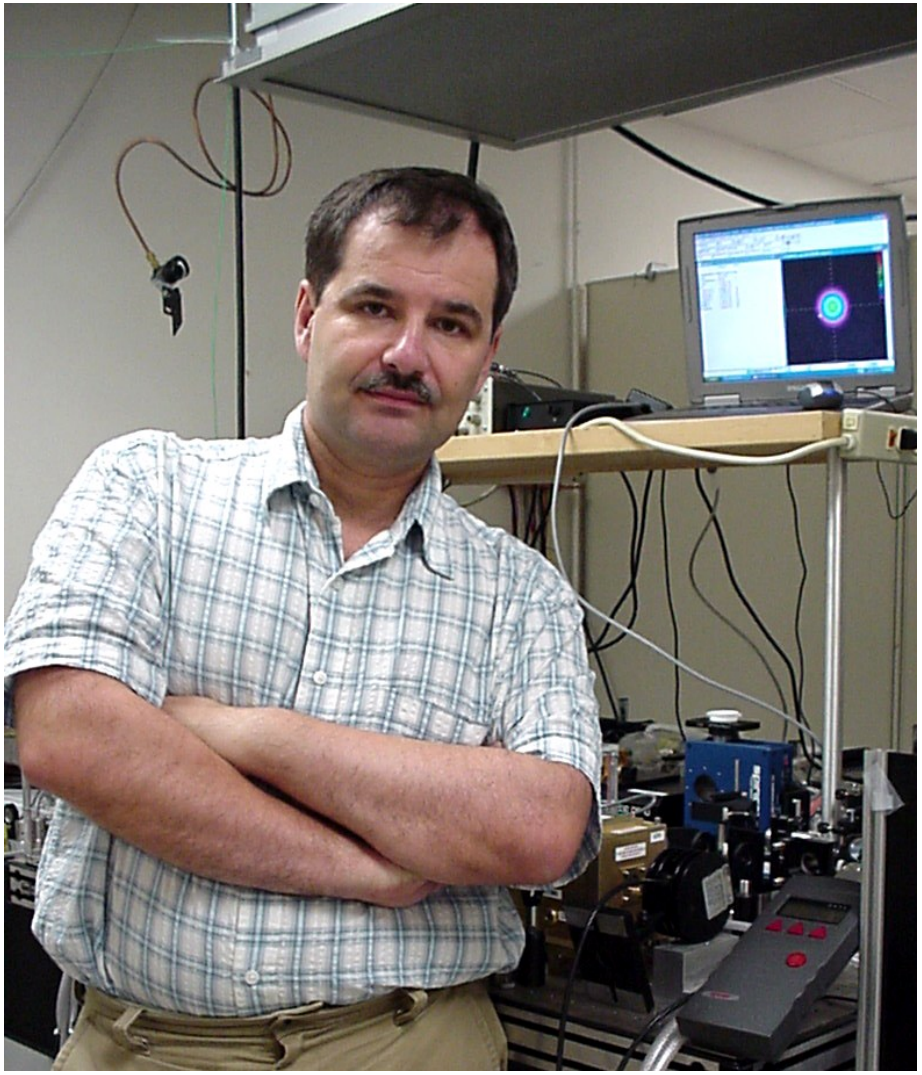
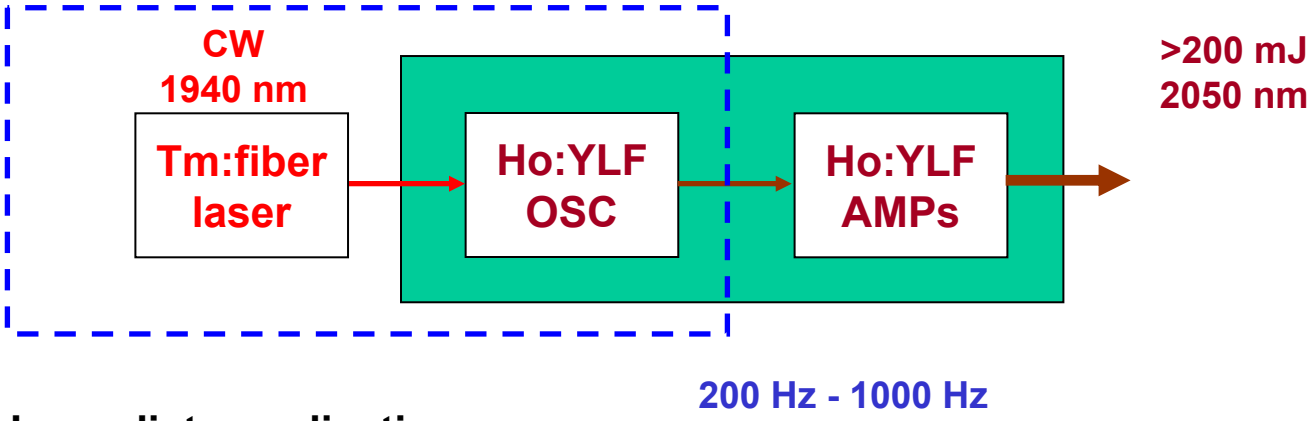
Qpeak APPLIED PHOTONIC SYSTEMS

I just talk, Alex does the work



Motivation

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



- Immediate applications:
  - Industrial (laser materials processing)
  - Military (eye-safe, long-range 2D and 3D imaging, coherent systems for Doppler and vibrometry sensing)
  - Pump source for OPOs (laser acoustics, IRCM, chem-bio standoff detection)

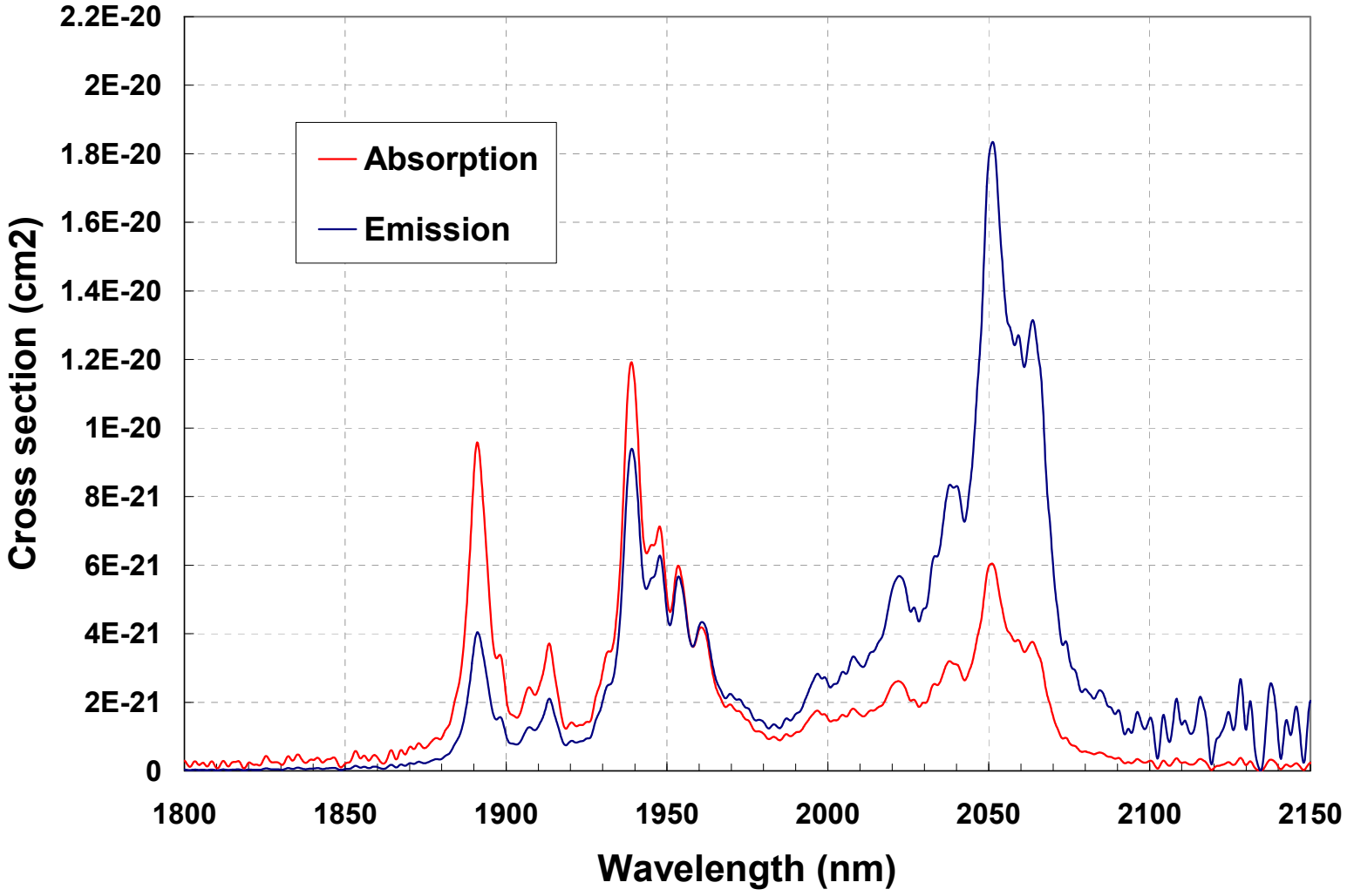
Why a laser pumping a laser pumping a laser?

- **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

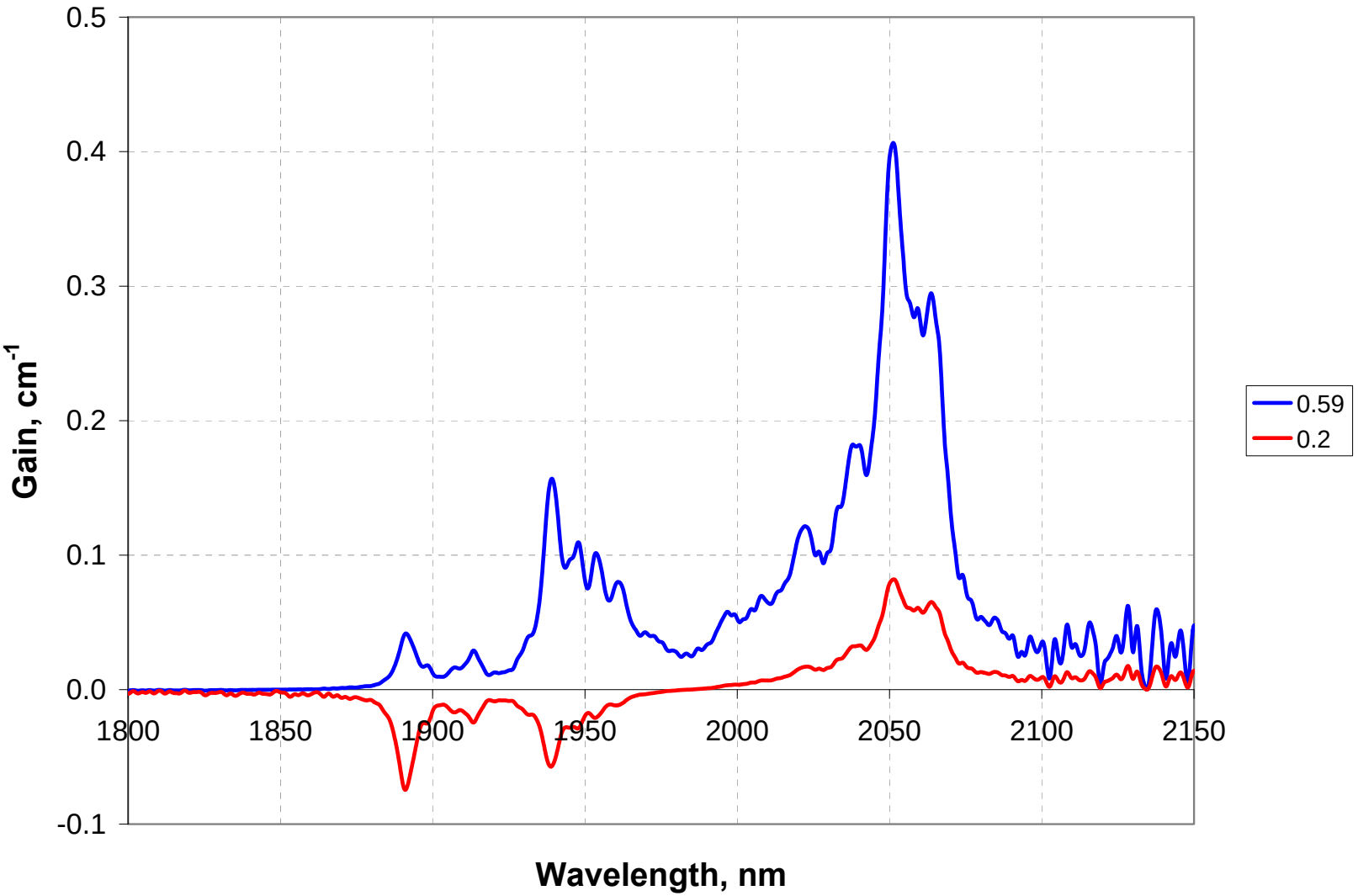
Ho:YLF *vs.* Ho:YAG

- **Why Ho:YLF (Q-Peak, NASA) ?**
  - **Long upper laser level lifetime ~ 15 ms (in theory)**
  - **Highest emission cross-section known for Ho-doped crystals**
    σ = 1.84 x 10^{-20} cm^2
  - **E_{sat} = 5.3 J/cm^2**
  - **Naturally birefringent material**
  - **Low dn/dT –> weak thermal lensing**
  - **~5% quantum defect**
- **Compared to Ho:YAG (BAE, SORC)**
  - **Upper state lifetime 7 ms**
  - **Emission cross section 0.98 x 10^{-20} cm^2**
  - **E_{sat} = 9.6 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



Ho:YLF laser development at Q-Peak

2001

- Tunable Tm:YLF laser (>15 W)

2003

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

2005

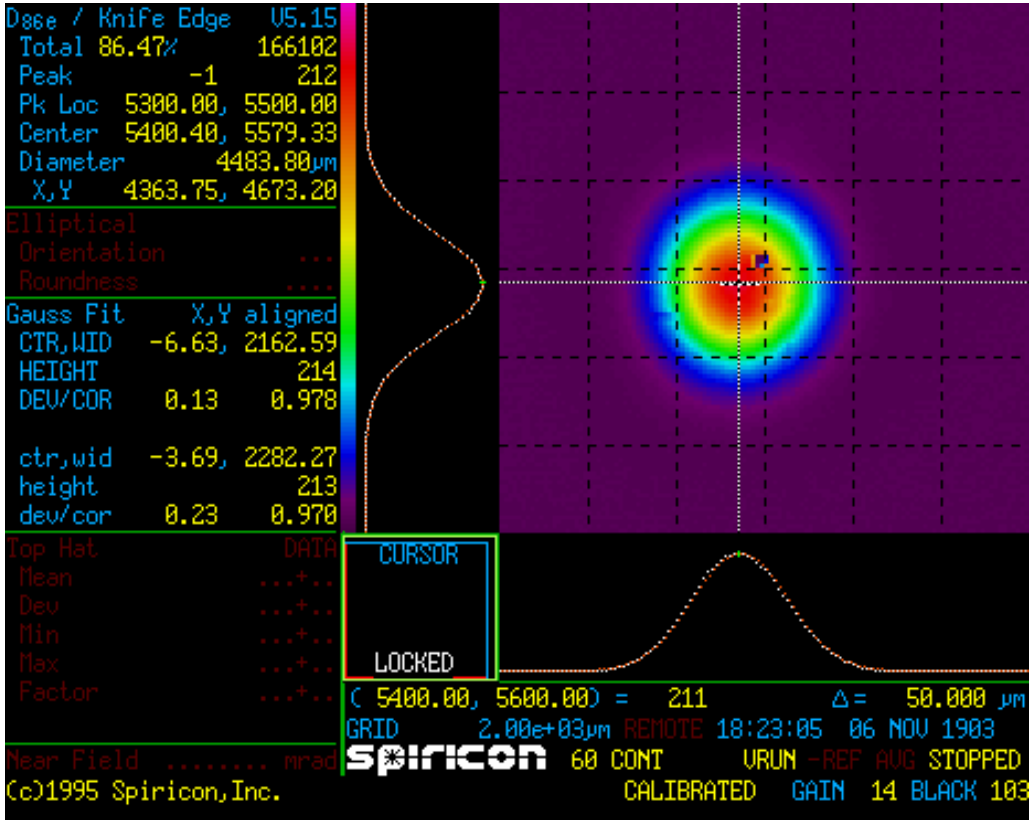
- Double Ho:YLF-crystal oscillator pumped with one 100-W Tm:fiber laser

2006

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

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

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**



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

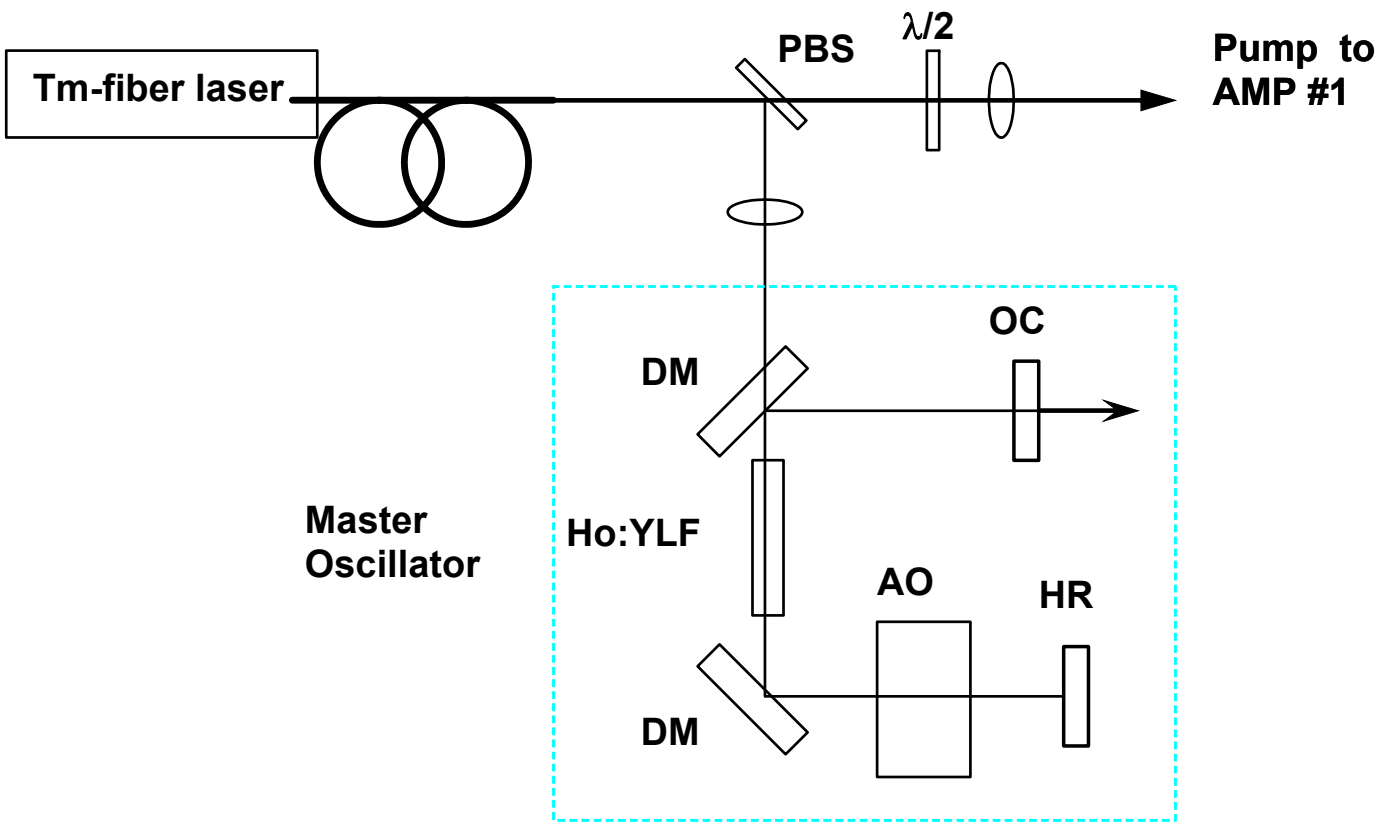
Specific requirements for Tm-laser as a pump source for Ho:YLF:

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

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

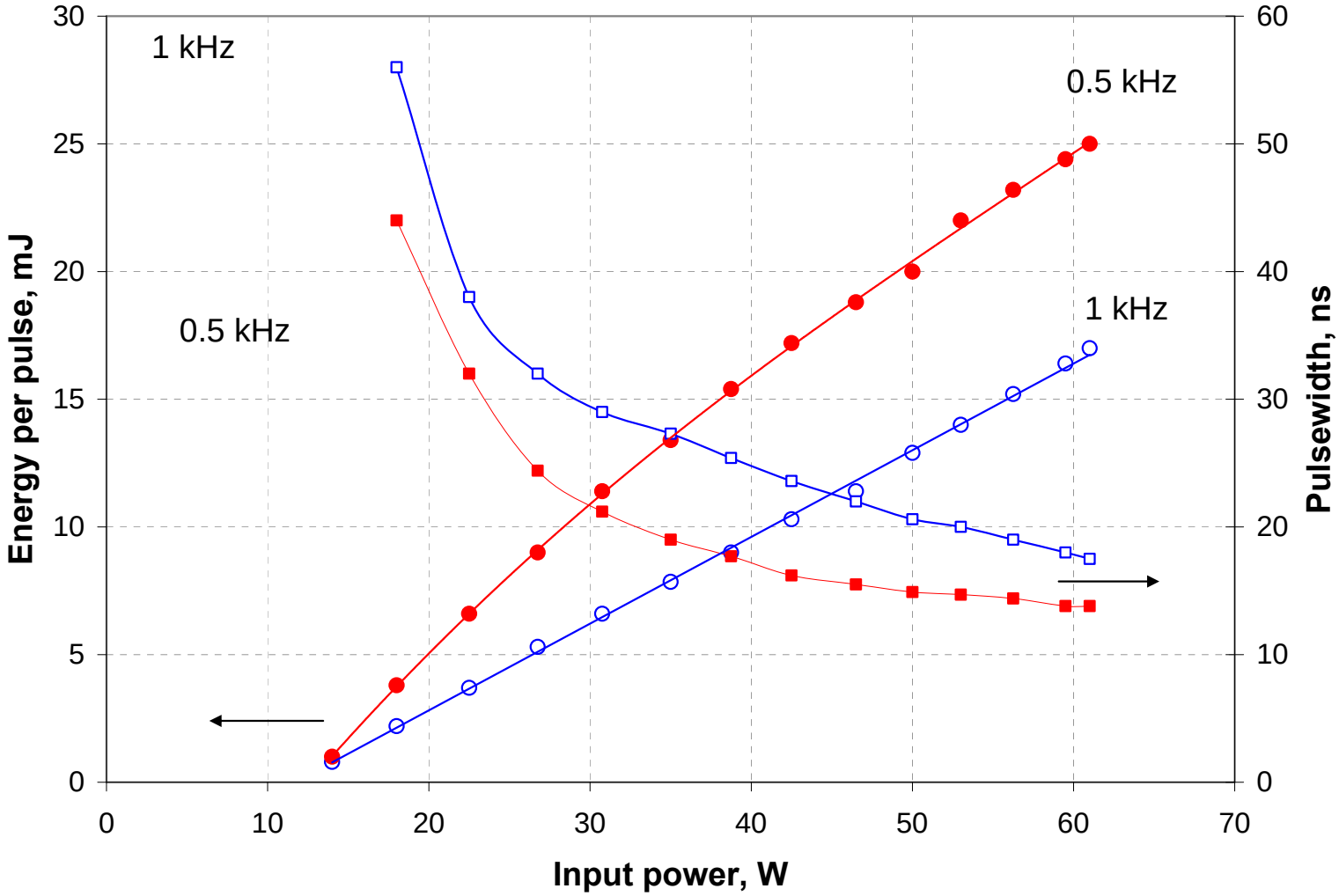
Operation regime	CW
Operational temperature	RT
Output power	≥ 100 W
Lasing wavelength range:	1750-2200 nm
Polarization:	Random
Linewidth	≤ 2 nm

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

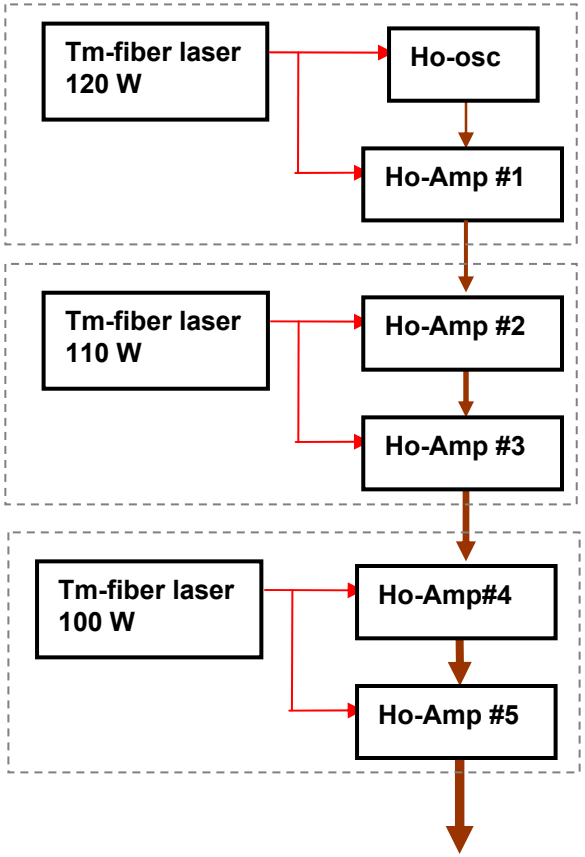


DM – Dichroic Mirror,
AOM – Acousto-Optic Modulator,
OC – Output Coupler,
HR – High Reflector

Ho:YLF Master Oscillator



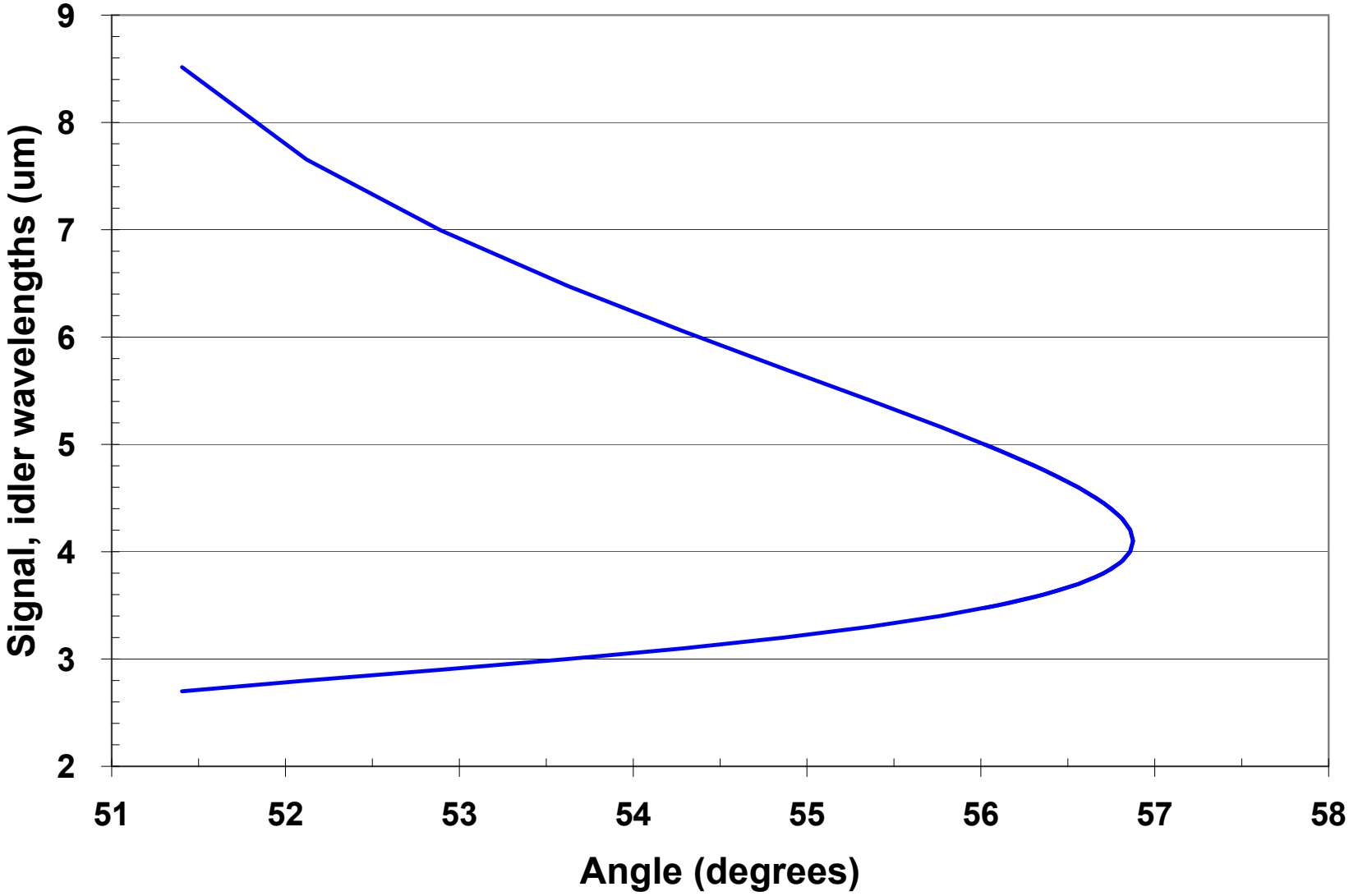
Ho:YLF MOPA chain



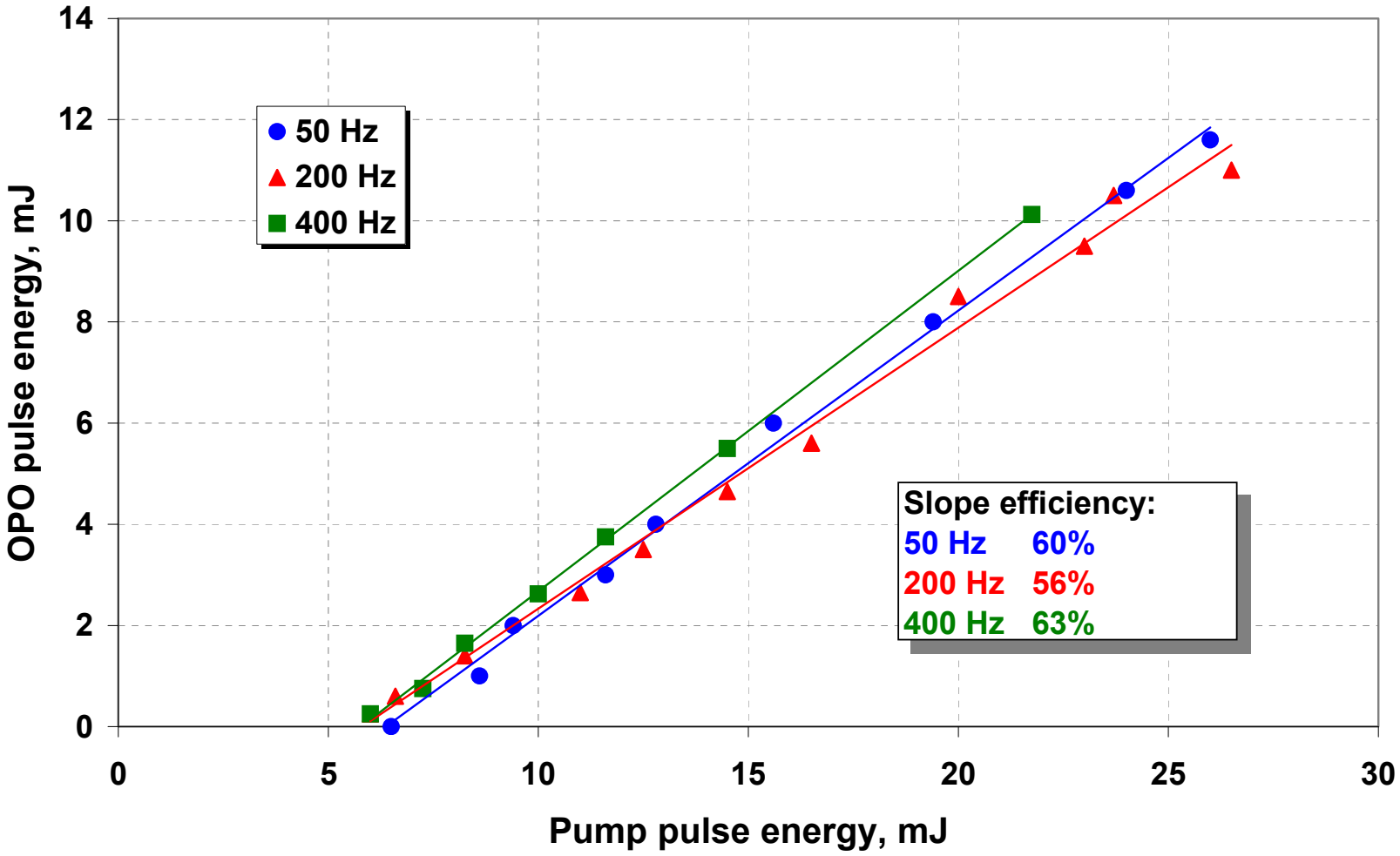
	CW	500 Hz	1000 Hz
Master osc	19 W	25 mJ	17 mJ
Amp 1	42 W	55 mJ	38 mJ
Amp 2	60W	90 mJ	58 mJ
Amp 3	78 W	115 mJ	73 mJ
Amp 4	97 W	***	***
Amp 5	113 W	***	***

*** work in progress

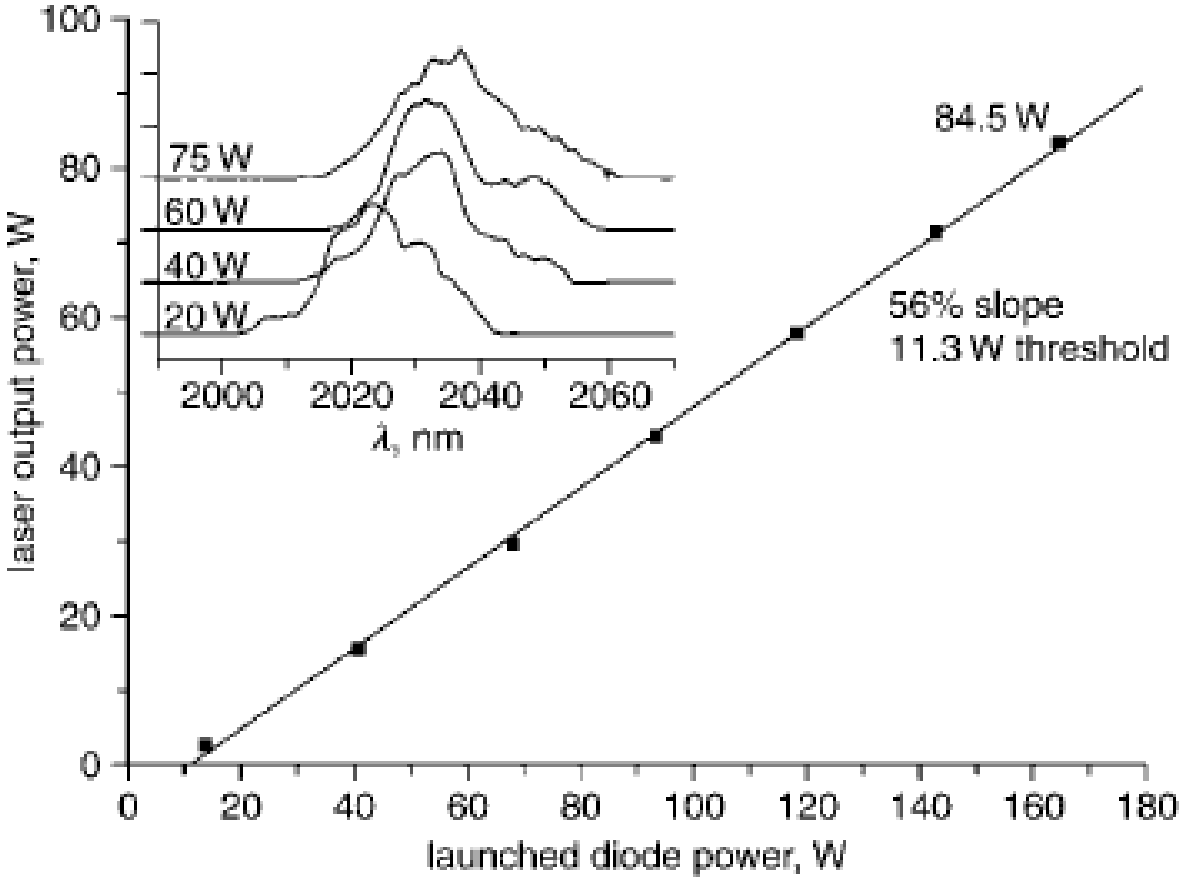
Tuning curve for Ho:YLF-pumped ZGP OPO shows broad mid-IR coverage



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



Highly doped Tm fiber lasers demonstrate high efficiency



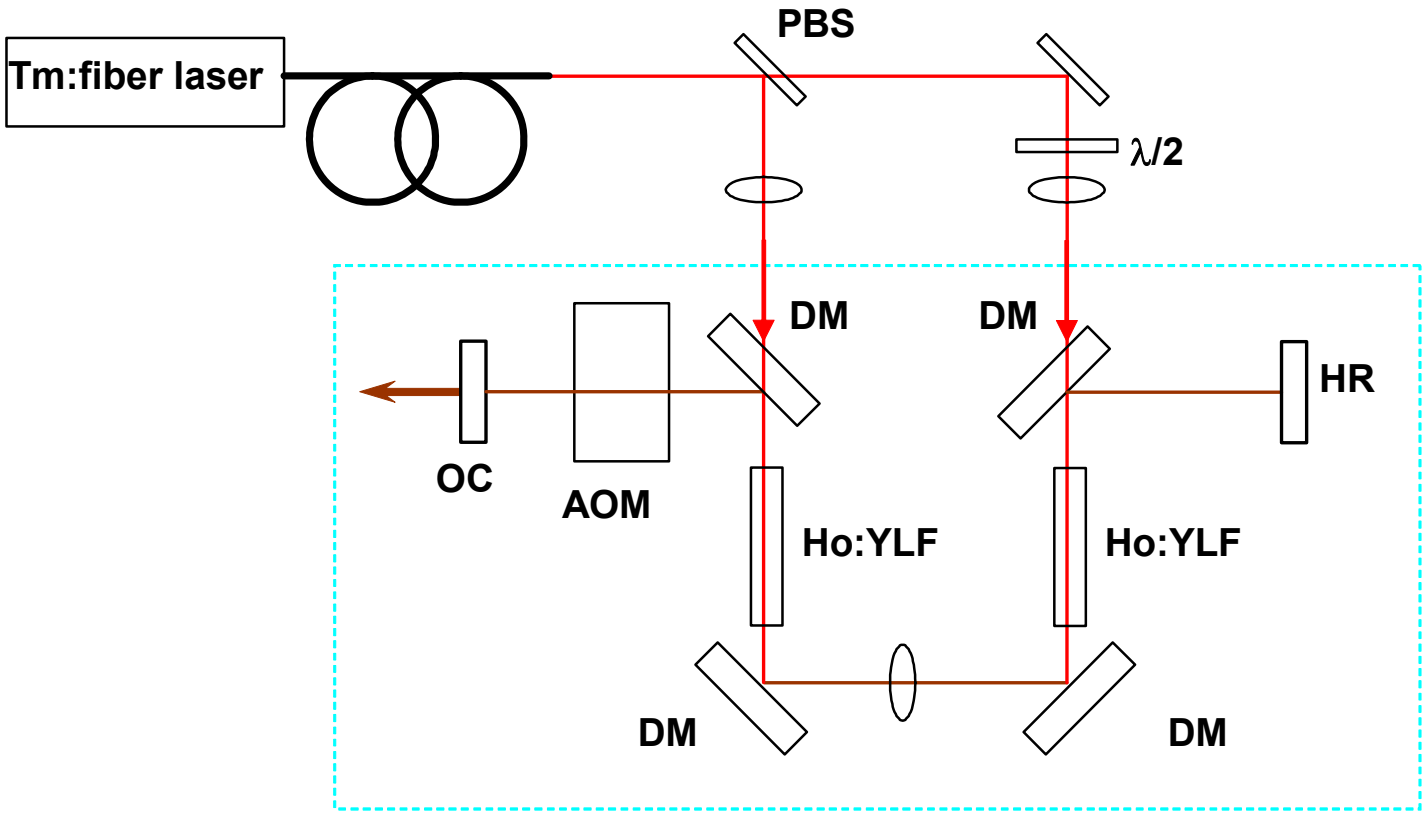
G. Frith, D.G. Lancaster and S.D. Jackson, Electron. Lett. 41, 1207 (2005).

Conclusions

- Fiber-laser pumped Ho:YLF crystals (and similar materials) combines best features of fiber and bulk solid state lasers
  - High beam quality and powers of fiber lasers
  - Energy storage capability of bulk lasers
- Recent advances in commercial (IPG) Tm:fiber lasers have made 100-W devices available.
- 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
- The results reported are, to the best of our knowledge the highest powers and energies yet achieved with Ho:YLF lasers
- High-efficiency Tm:fiber pump lasers are on the horizon

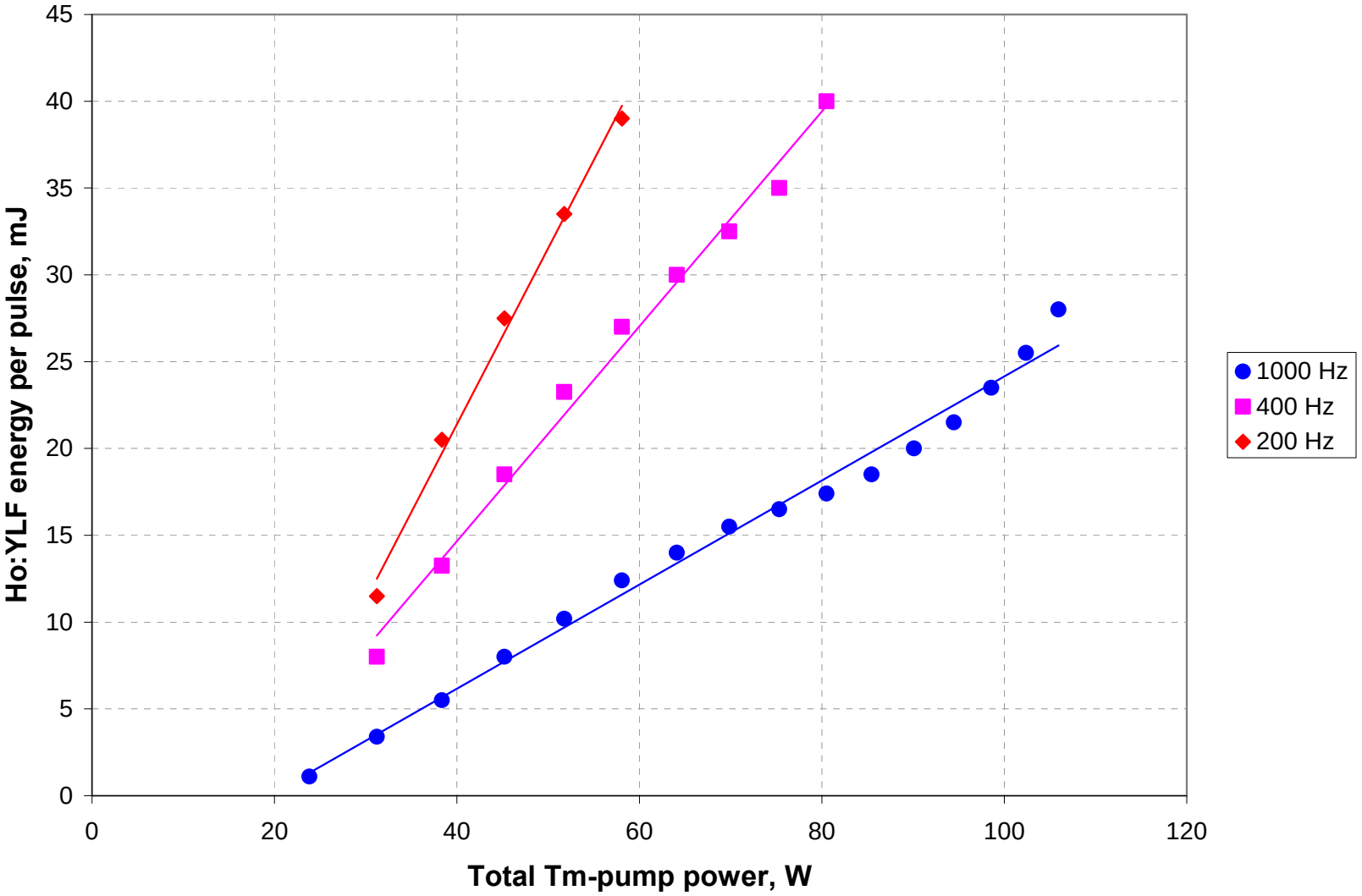
Backup

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



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

Double oscillator: 40 W of cw power
40 mJ of Q-switched energy in 17-ns pulse

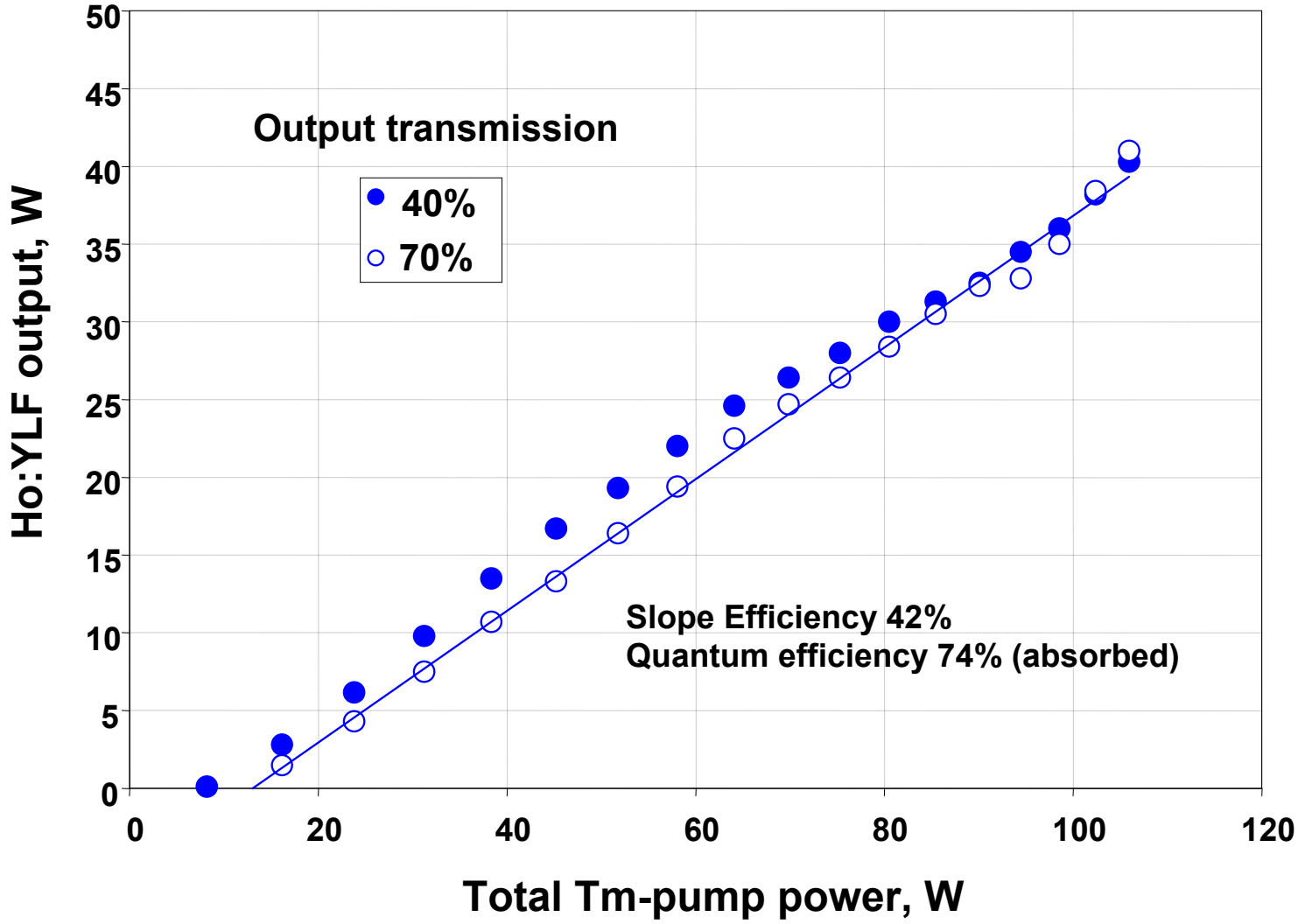


Ho-laser efficiency

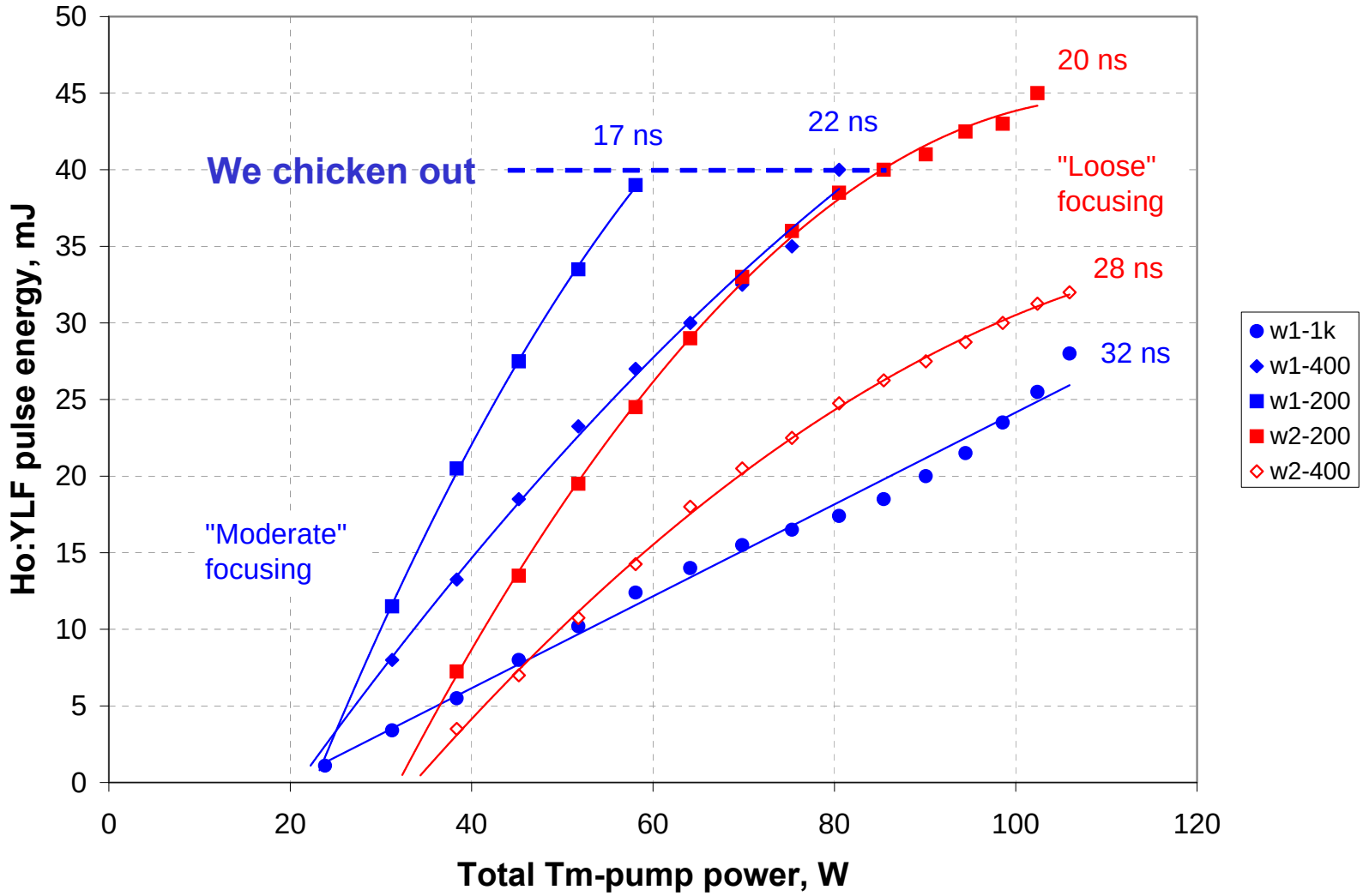
- In order to achieve efficient Ho-operation
  - High optical density
  - Tight focusing to deplete (bleach) the ground state
- This works well in CW regime
- However, in Q-switched regime it is necessary to avoid the damage of all optical components
- A few examples:
  - We assumed generation of 10 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

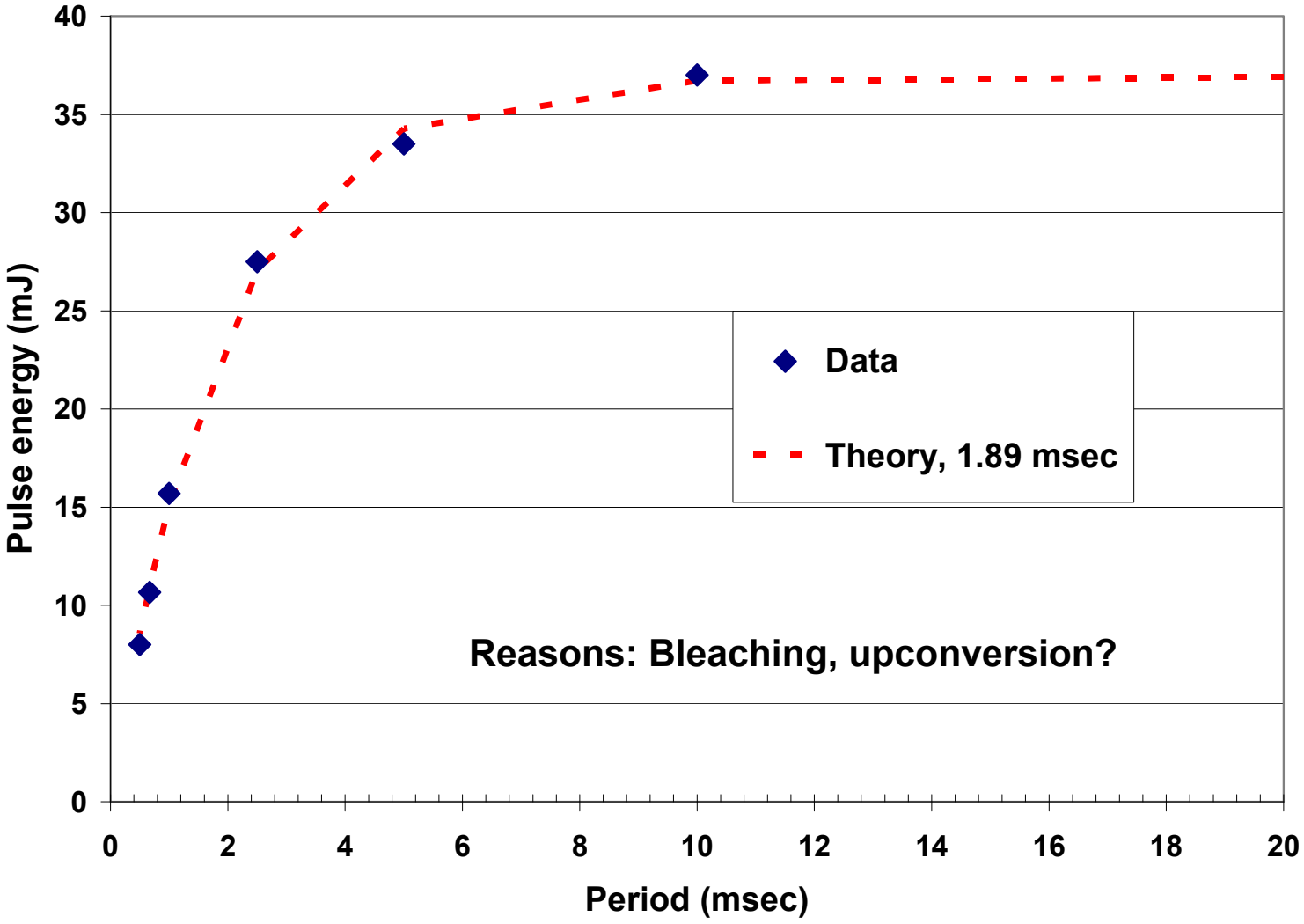
CW laser operation provides 40-W of output power



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