

High-power operation of Tm:YLF, Ho:YLF and Er:YLF lasers

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Solid State and Diode Laser Technology Review
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- **High-power Tm:YLF-pumped Ho:YLF laser**
- **ZGP OPO results**
- **High-power, cw Er:YLF laser**

High-power, high-energy diode-pumped Tm:YLF-Ho:YLF laser and ZGP OPO

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Acknowledgements:

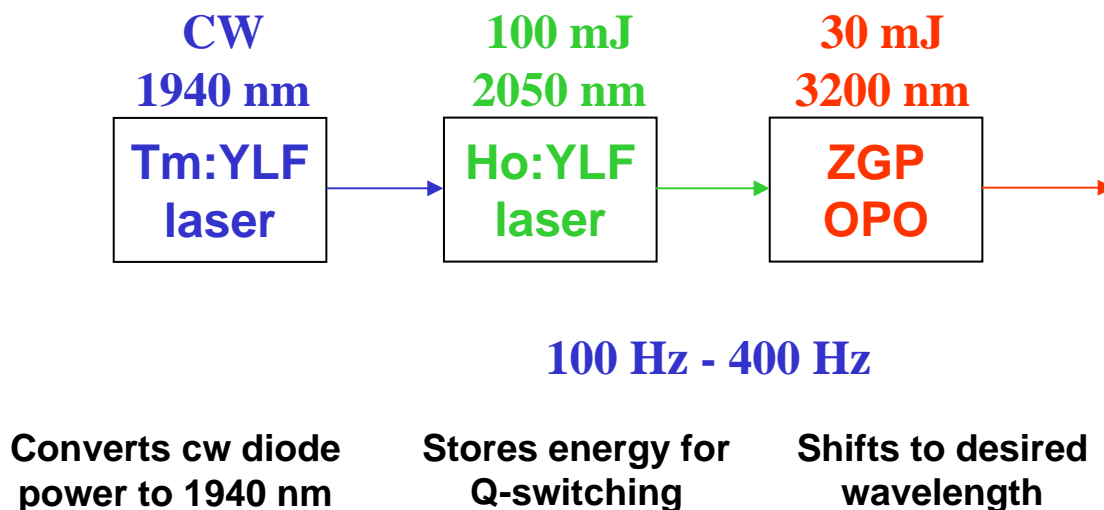
Lockheed Martin

Laser Ultrasonic Technology Center

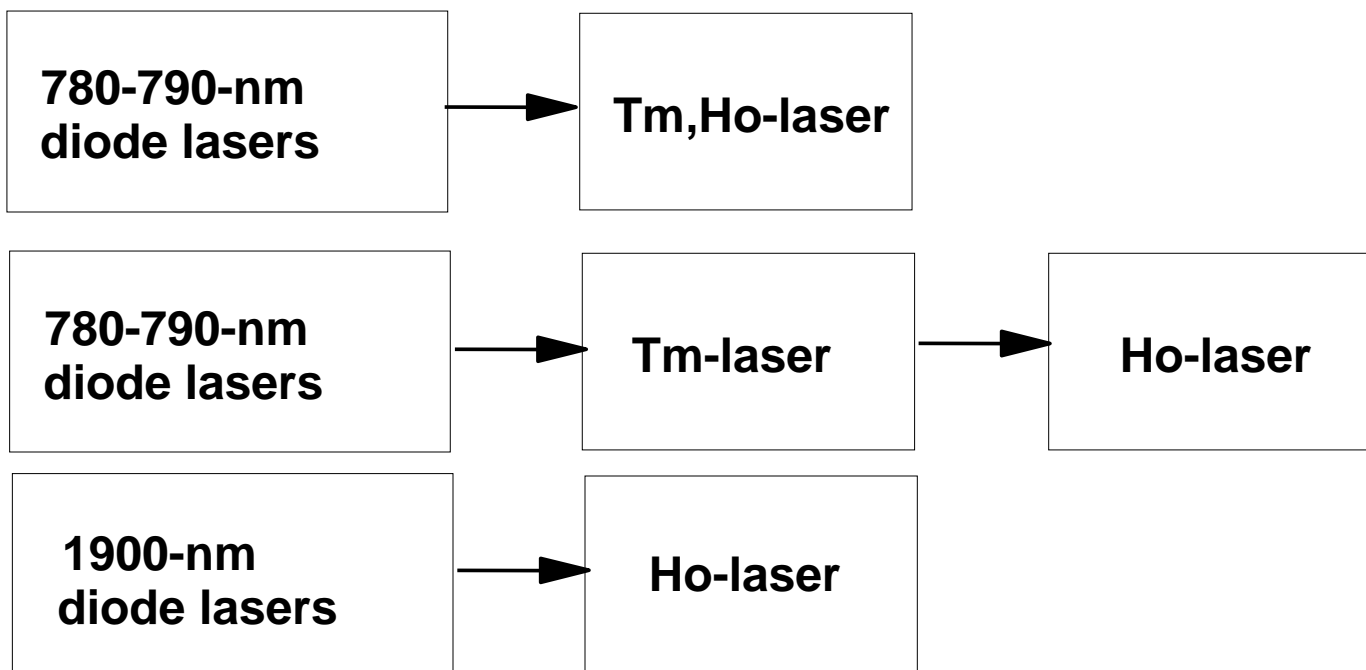


- Development of a 2-um laser source to pump an OPO:
 - High-energy (up to 100 mJ)
 - High repetition rate (100-400 Hz)
 - High beam quality (TEM₀₀)

*Also:
Eyesafe flash ladar*



Approaches to diode-pumping of Ho-doped lasers





References on resonantly pumped Ho lasers

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

R.C. Stoneman and L. Esterowitz, *Opt. Lett.* 17, 736 (1992).

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.

P.A. Budni, M.L. Lemons, J.R. Mosto, and E.P. Chicklis, *IEEE J. Sel. Topics in Quantum Electron.* 6, 629 (2000).

P.A. Budni, M.L. Lemons, C.A. Miller, P.A. Ketteridge, L.A. Pomeranz, T.M. Pollak, P.G. Schuneman, K.L. Lanier, J.R. Mosto, and E.P. Chicklis, "High power 1.9 micron pumped solid state holmium lasers," in *Conference on Lasers and Electro-Optics*, OSA Technical Digest (Optical Society of America, Washington, DC, 2000), p 564.

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).

- **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 1.907 μm (σ -line)
- Multimode, $M^2 \sim 2$

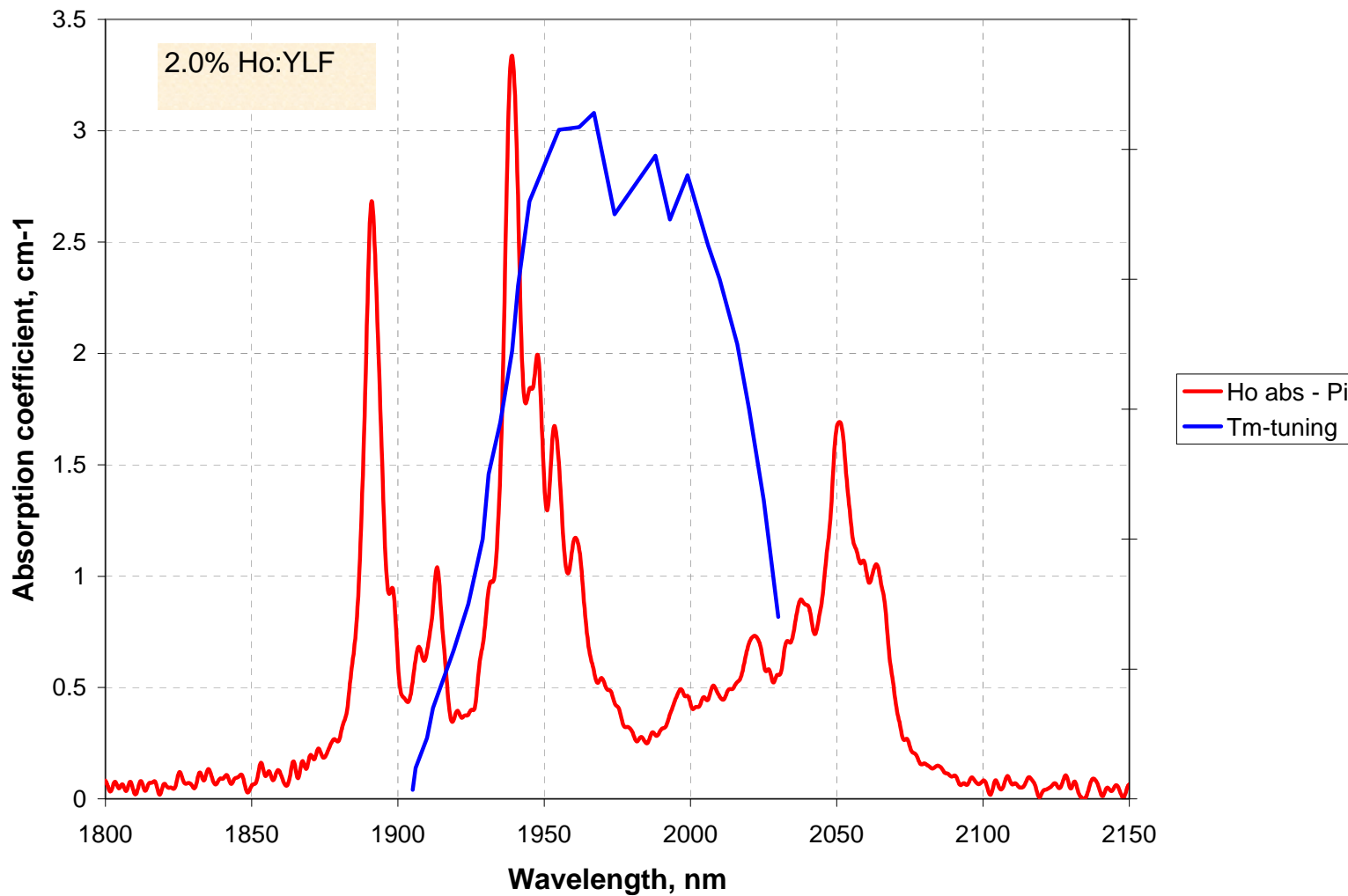
- **Ho:YAG**

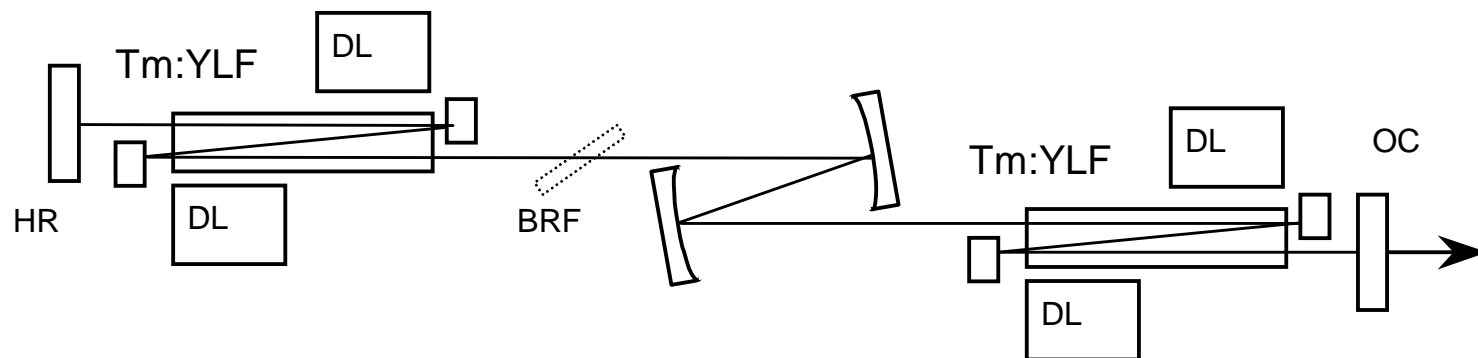
- CW: 19 W
- QCW: 16 W at 15 kHz

- **Why Ho:YLF?**
 - Long upper laser level lifetime ~ 15 ms
 - Higher emission cross-section
 - Naturally birefringent material
 - Low dn/dT → weak thermal lensing

- **Ho:YAG**
 - Isotropic
 - Lifetime (5I_7) 7 ms
 - Strong thermal lensing
 - Excellent thermo-mechanical properties

Pumping Ho:YLF with Tm:YLF laser



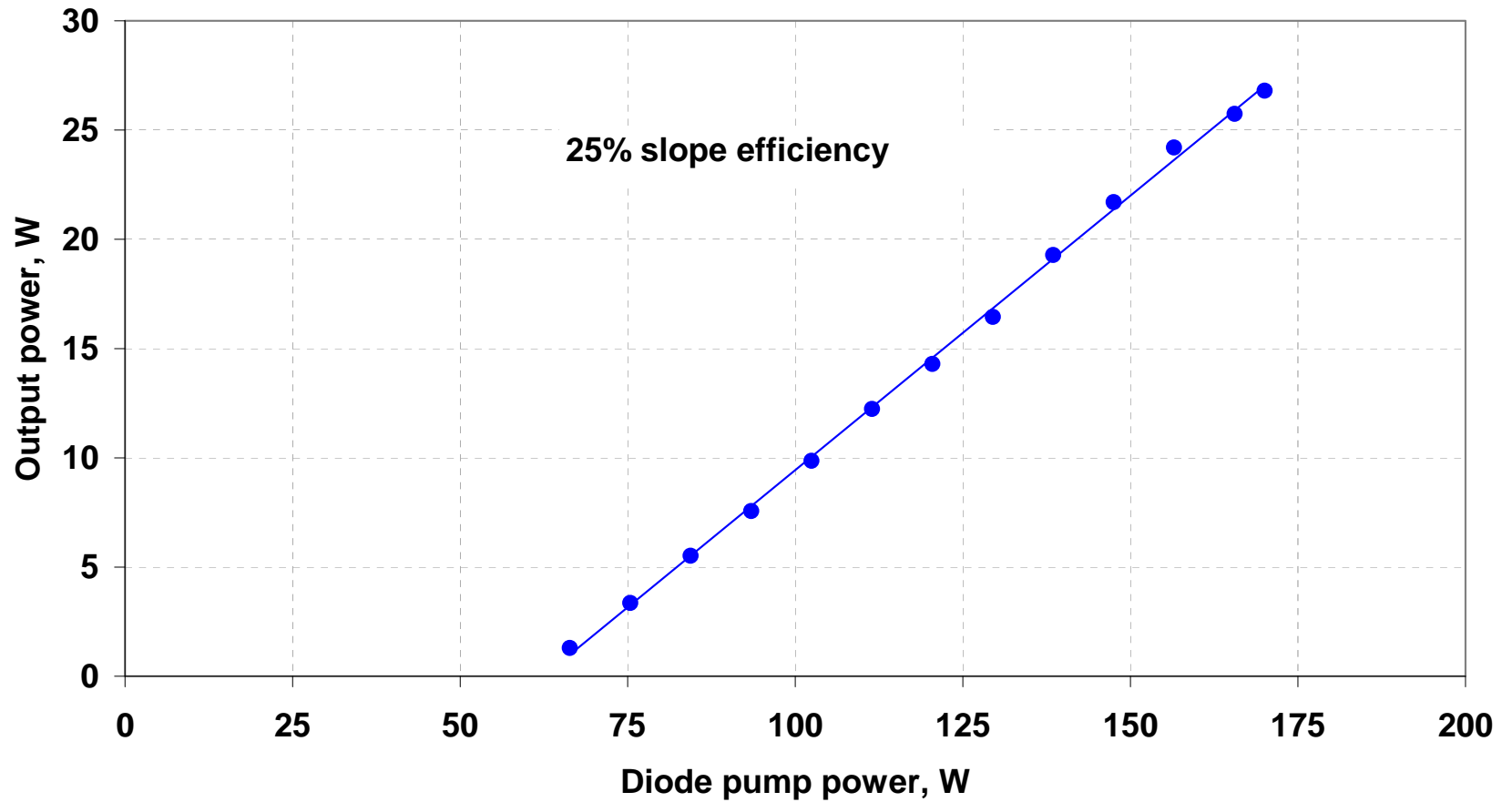


□ **Tm:YLF Active Element:**

Rectangular slab:

22-mm long

Clear aperture 2x6 mm.



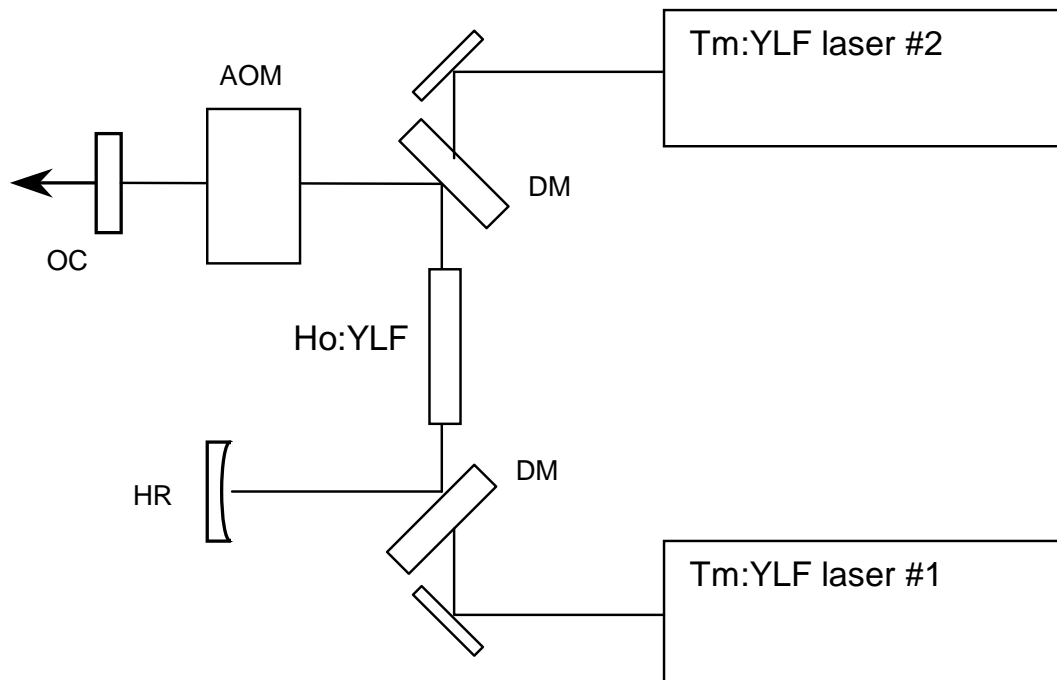


Calculations for Tm:YLF-pumped Ho:YLF laser at low pulse rates

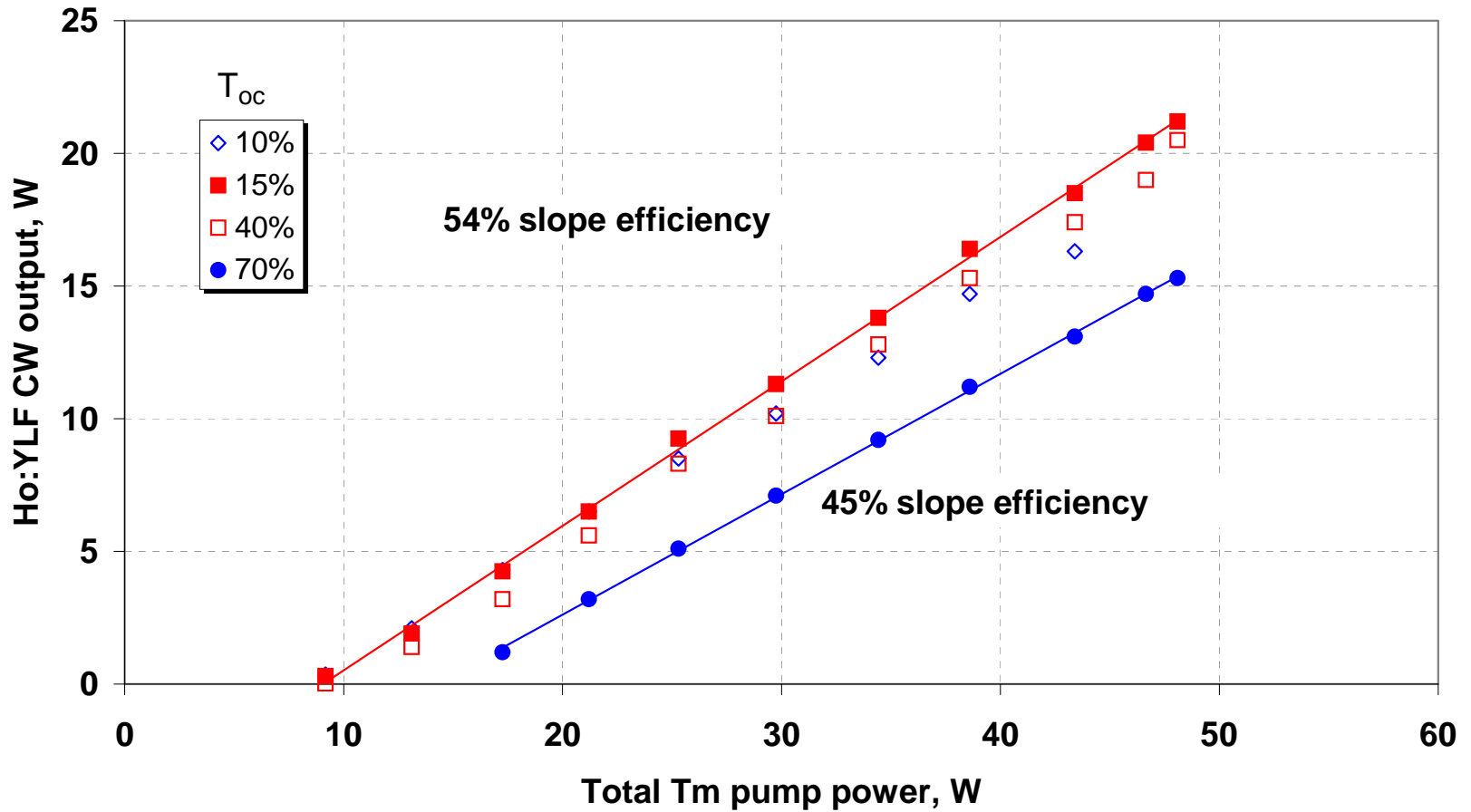
Crystal doping (%)	0.5
N_0 (cm ⁻³)	7×10^{19}
Crystal length (cm)	3.6
Scaled pump fluence	1.6
Pump pulsewidth (msec)	15
Pump power (W)	20
average inversion fraction	0.44
η_s pumping efficiency	0.52
F_p (J/cm ²)	21.1
Pump energy (J)	0.3
Pump-beam radius (cm)	0.048
Stored energy in crystal (J)	0.16
g_0 , Gain coefficient (cm ⁻¹)	0.36
G, Single-pass gain	3.7

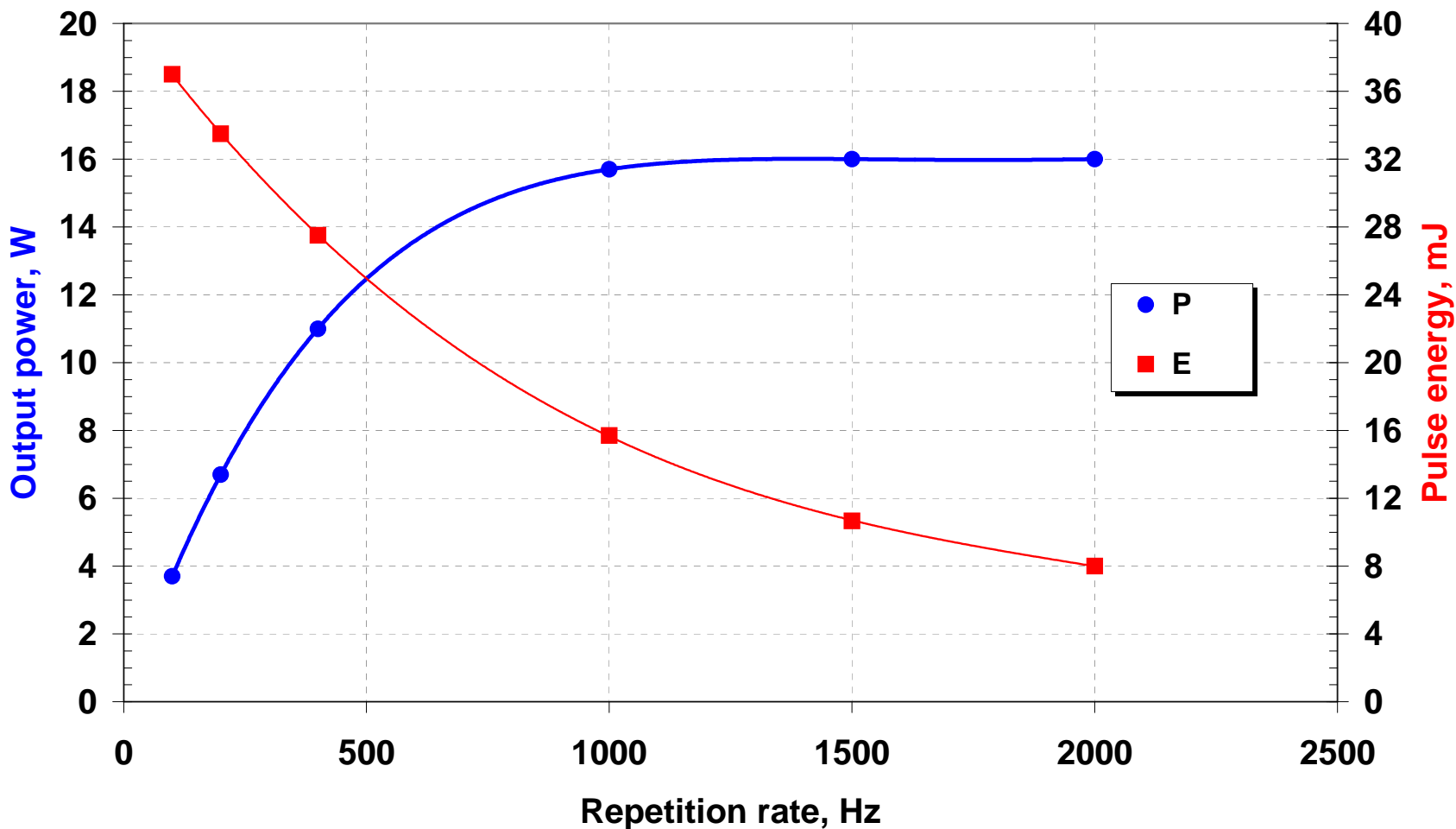
Calculations are based on work by W.F. Krupke and L.L. Chase,
Optical and Quantum Electron. 22, S1 (1989).

Schematic layout of the end-pumped Ho:YLF laser

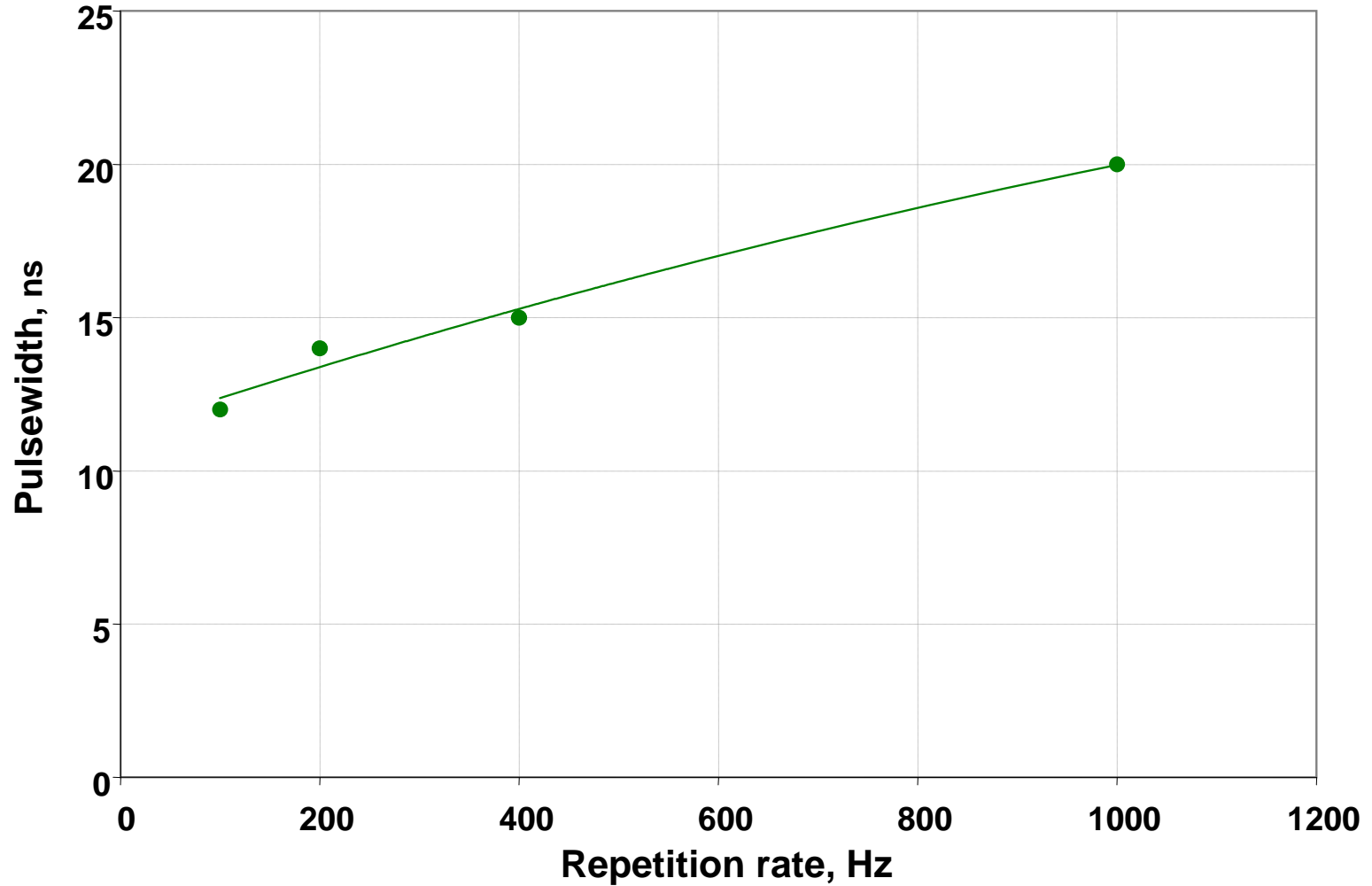


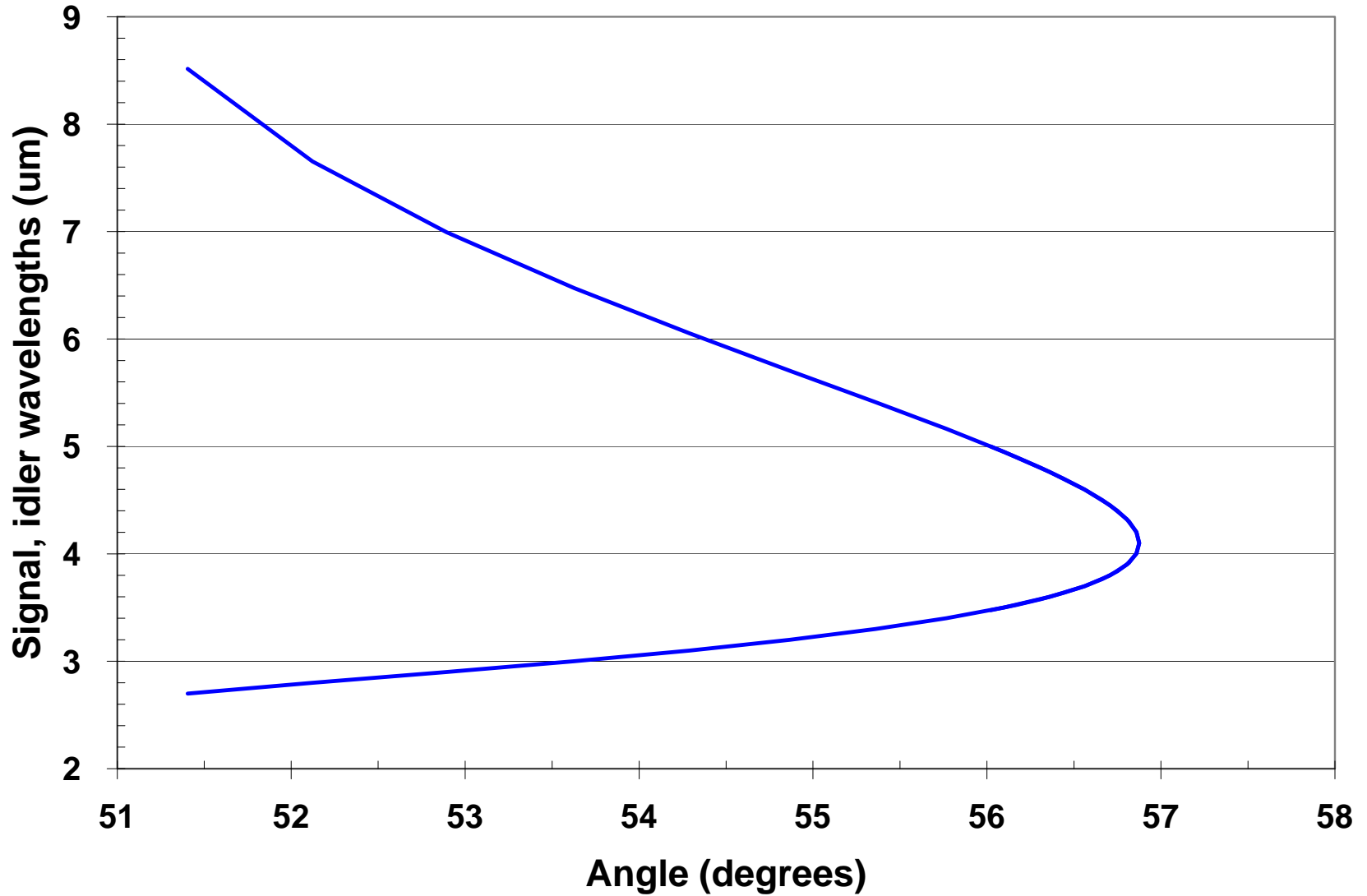
**DM – Dichroic Mirror,
AOM – Acousto-Optic Modulator,
OC – Output Coupler,
HR – High Reflector**

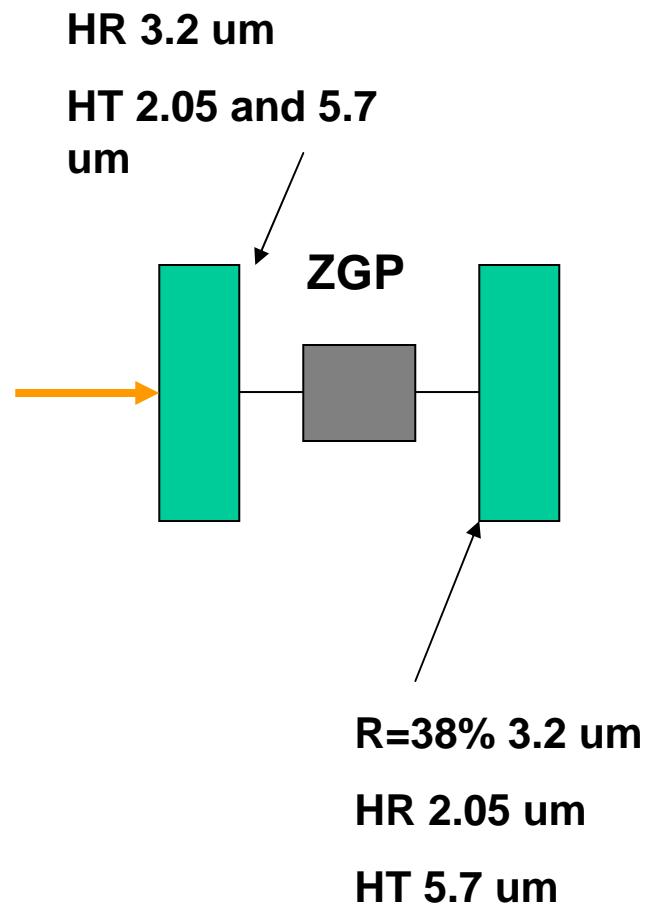




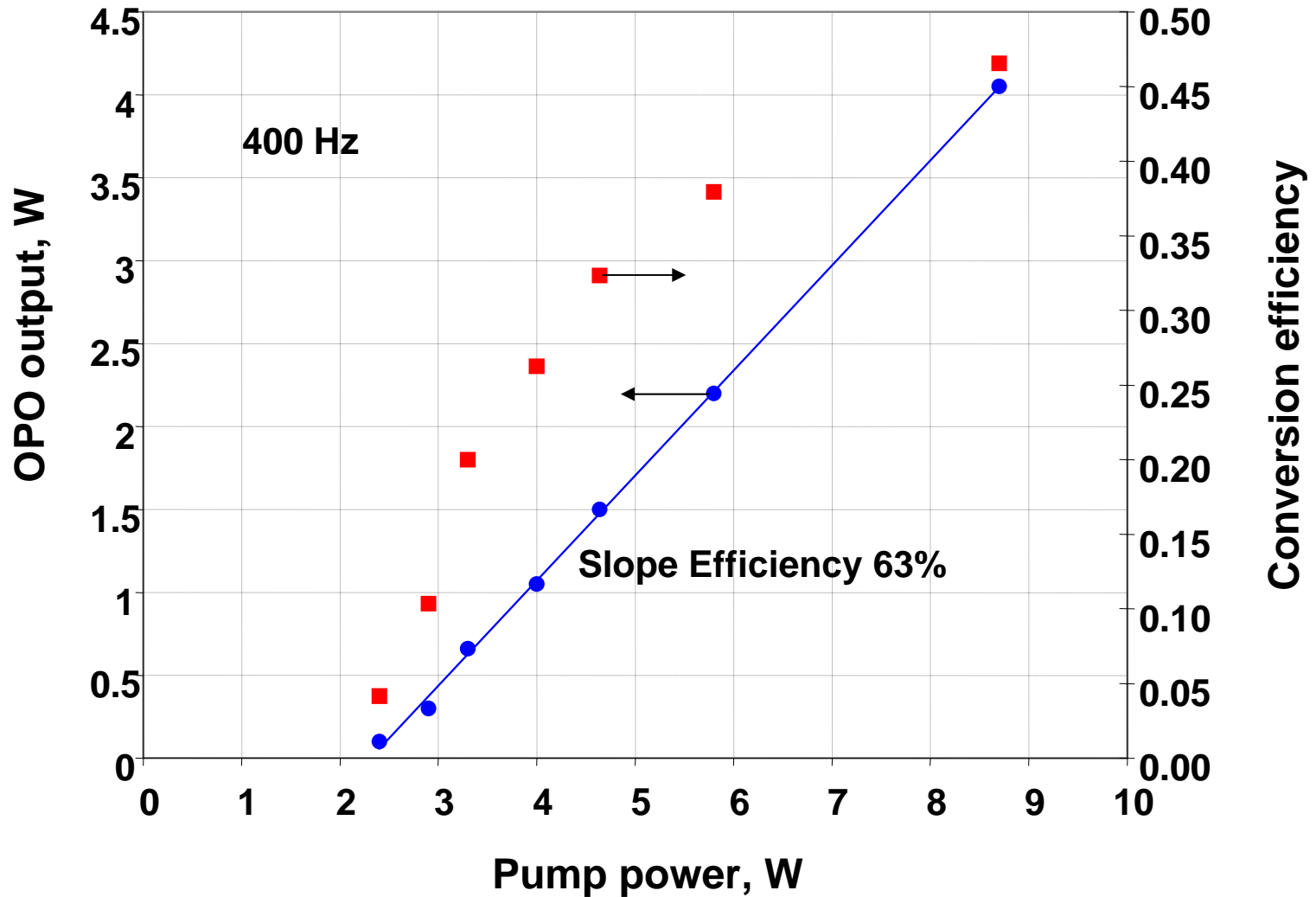
Ho:YLF – Pulsethwidth vs repetition rate

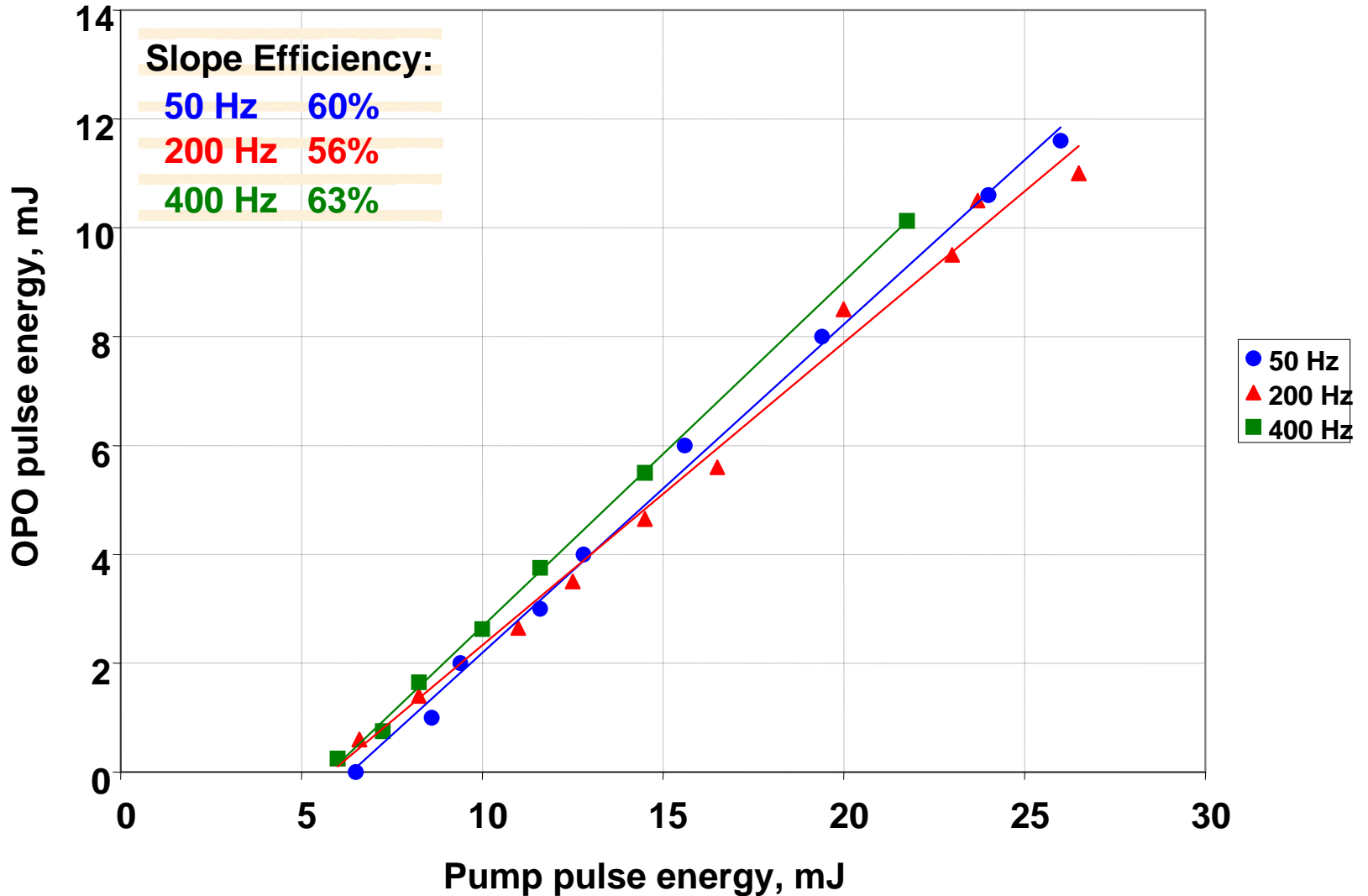






- **ZGP OPO:**
 - ZGP 1 cm-long
 - Type I, 53°-cut
 - Flat/flat resonator
 - Singly resonant cavity
 - Pump – double pass
 - ~6 cm-long resonator
 - OC 38% at 3.2 μm





Development of an efficient Tm:YLF - Ho:YLF – ZGP laser system:

- **Ho:YLF laser:**
 - Highest (to the best of our knowledge) cw output of 21 W for 2- μ m Ho:YLF laser
 - Efficient Q-switched operation (up to 37 mJ per pulse)
 - Repetition rates in wide range from Hz to kHz, particularly, in 100-400 Hz range
 - High beam quality (TEM₀₀) beam
- **ZGP OPO**
 - Demonstrated > 10 mJ (total) output at 50-400 Hz rep. rates

Tunable CW Er:YLF diode-pumped laser

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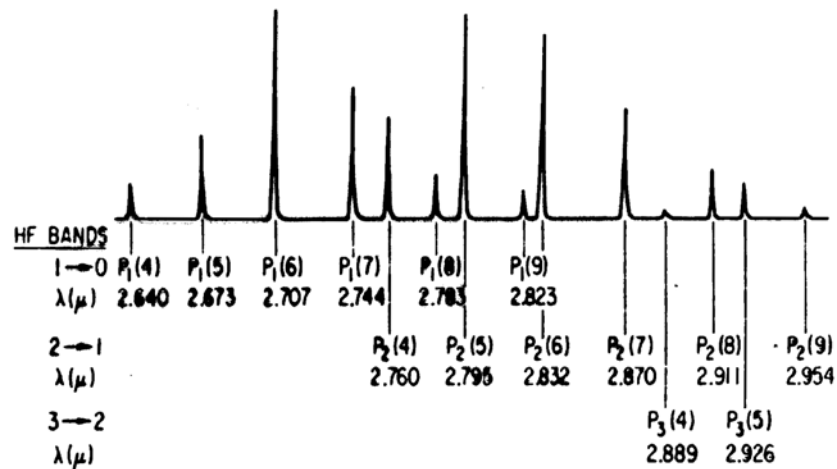
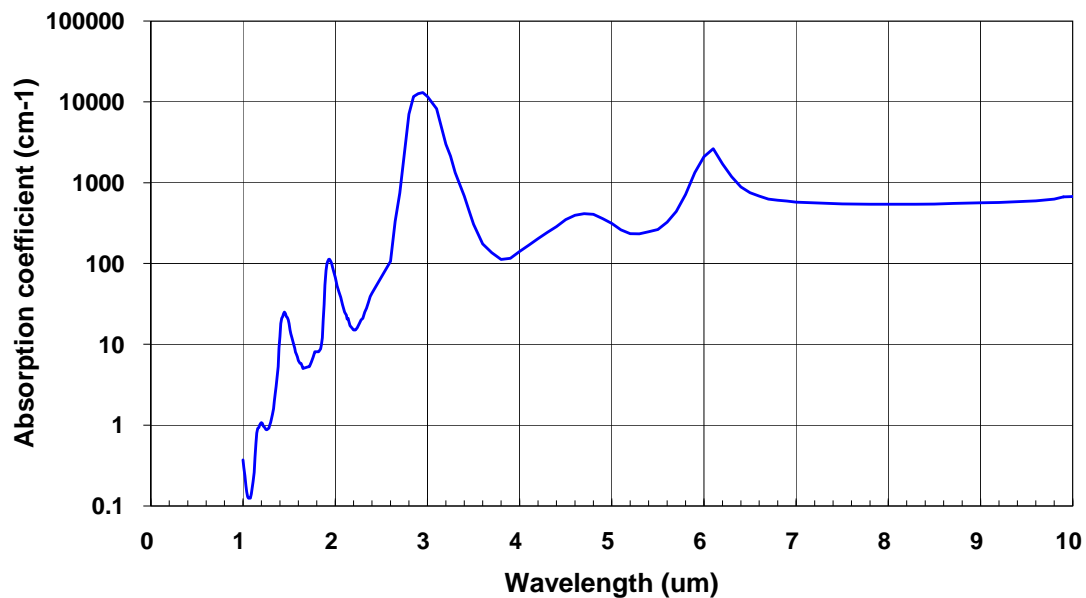
Acknowledgements:

US Air Force, Contract # F29601-02-C-0128



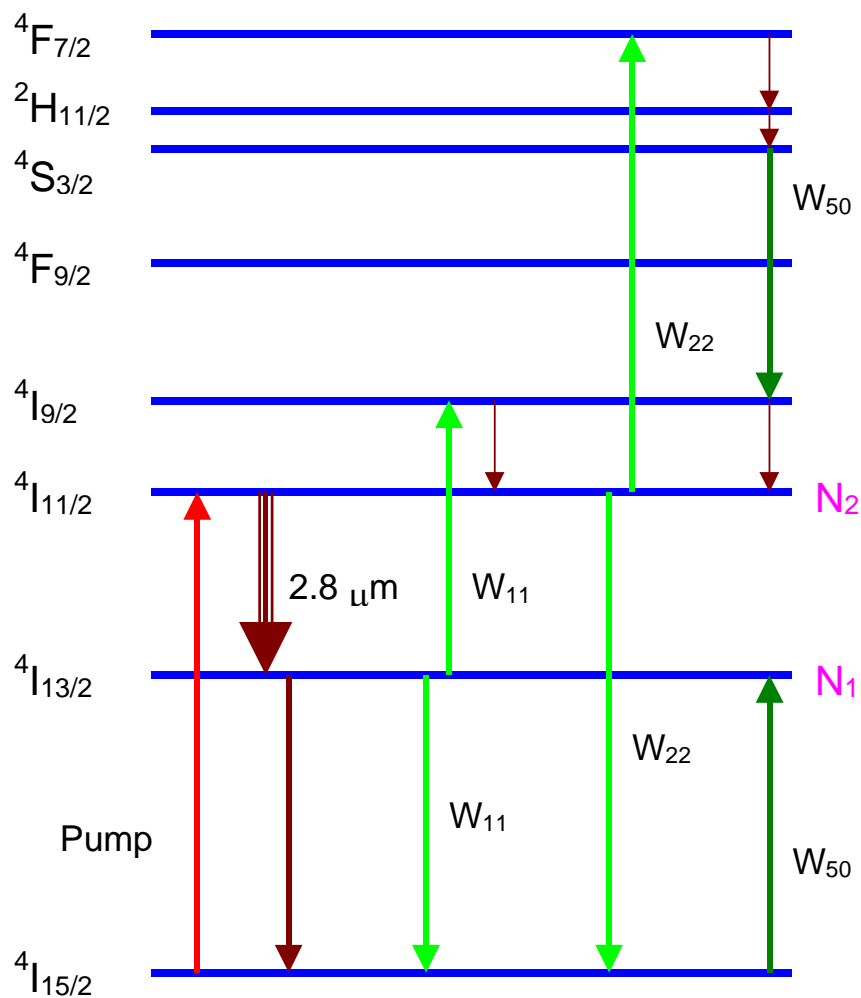
- Development of a directly diode-pumped tunable CW high-power (> 1 W) 3- μ m laser
- Possible applications
 - Medical
 - HF laser diagnostics

Absorption coefficient of liquid water and emission lines of HF laser

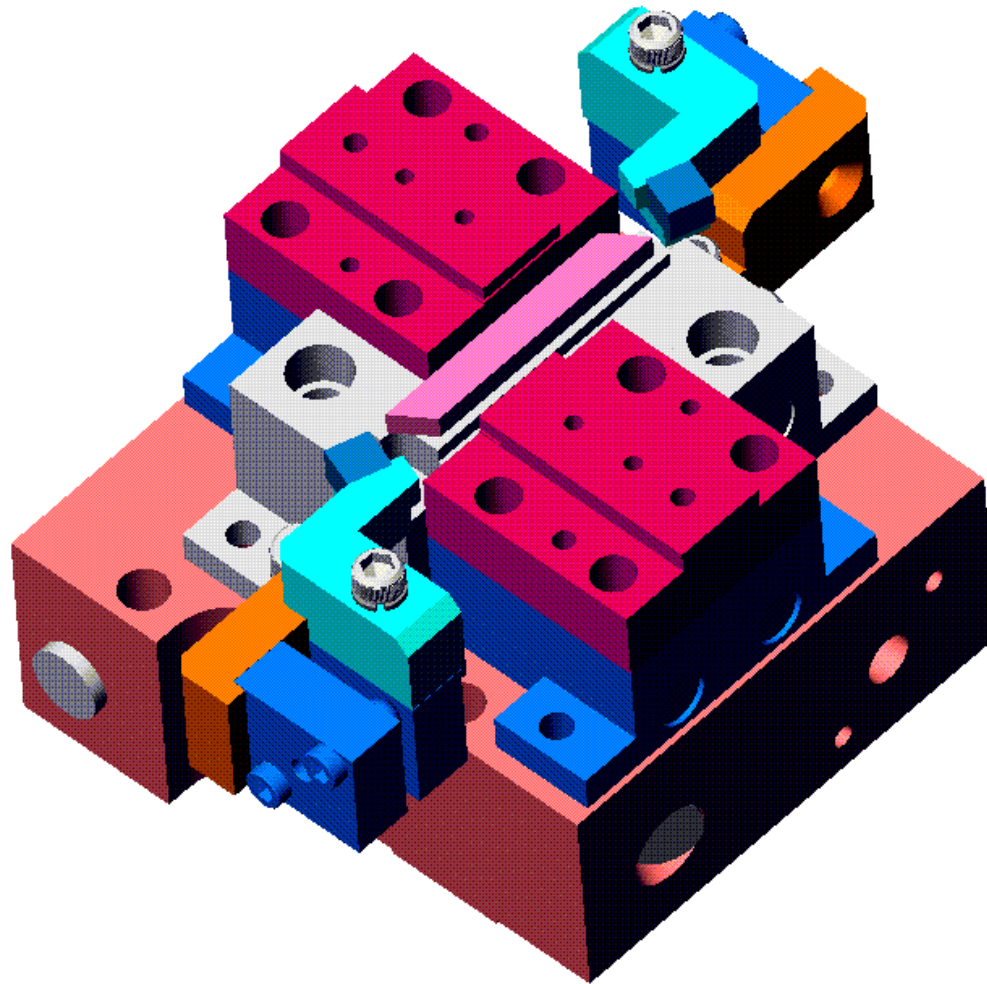


Er³⁺ Energy Level Diagram

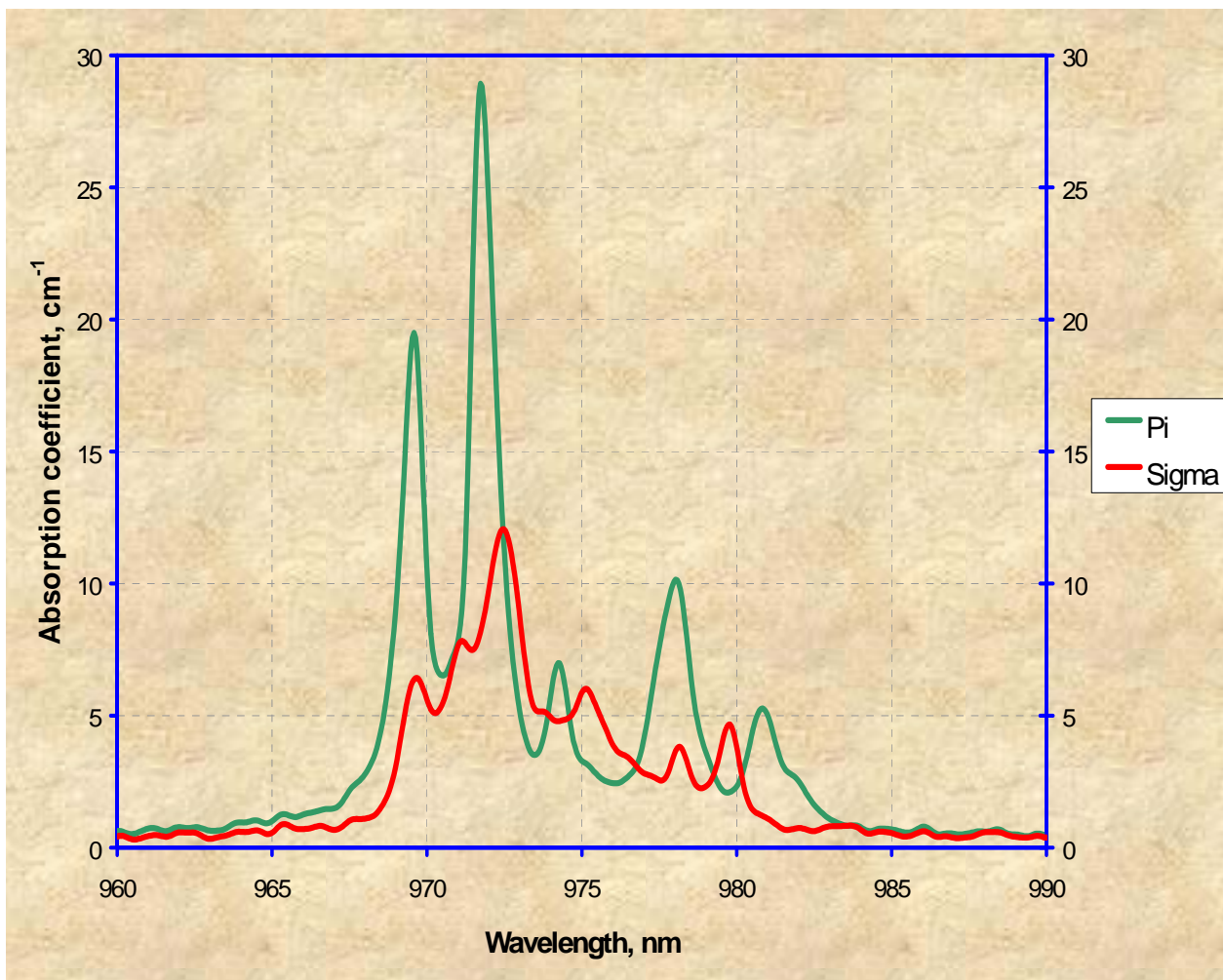
- high Er concentration
- 980-nm pump
- strong up-conversion
- high heat generation



- **Maximum slope efficiency :**
 - ~ 40% - Ti:Sapphire excitation (970 nm, longitudinal)
M.Pollnau et al., “Efficiency of Erbium 3-mm crystal and fiber lasers” IEEE J. of Quantum Electronics, 32, 657-663 (1996)
 - ~ 35% - Diode-Pumped (970 nm, longitudinal)
T. Jensen, A. Dening, G. Huber, and B.H.T. Chai, “Investigation of diode-pumped 2.8- μm Er:LiYF₄ lasers with various doping levels, Opt. Lett., 21, 585-587 (1996).
- **Maximum CW output:**
 - ~ 1.1 W Diode-pumped (970 nm, longitudinal, fiber-coupled diode laser)
T. Jensen et al. (see above)
- **Drawbacks:**
 - difficult to scale to higher powers
 - fracture of the laser elements at 4-6 W pump power (0.3-0.5 mm spot)

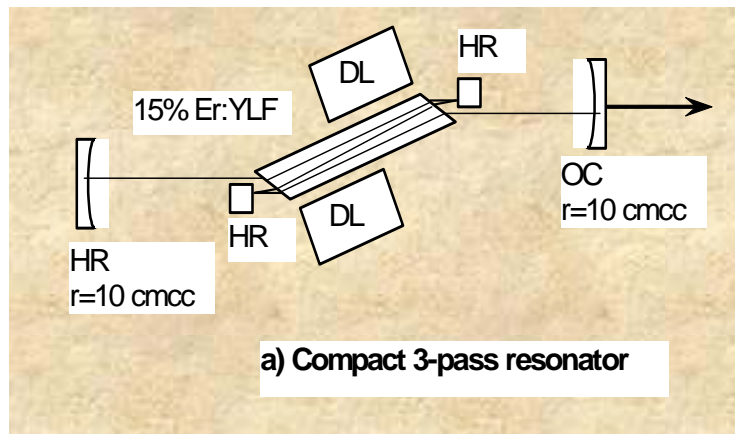


Absorption Properties of Er:YLF Laser Crystals

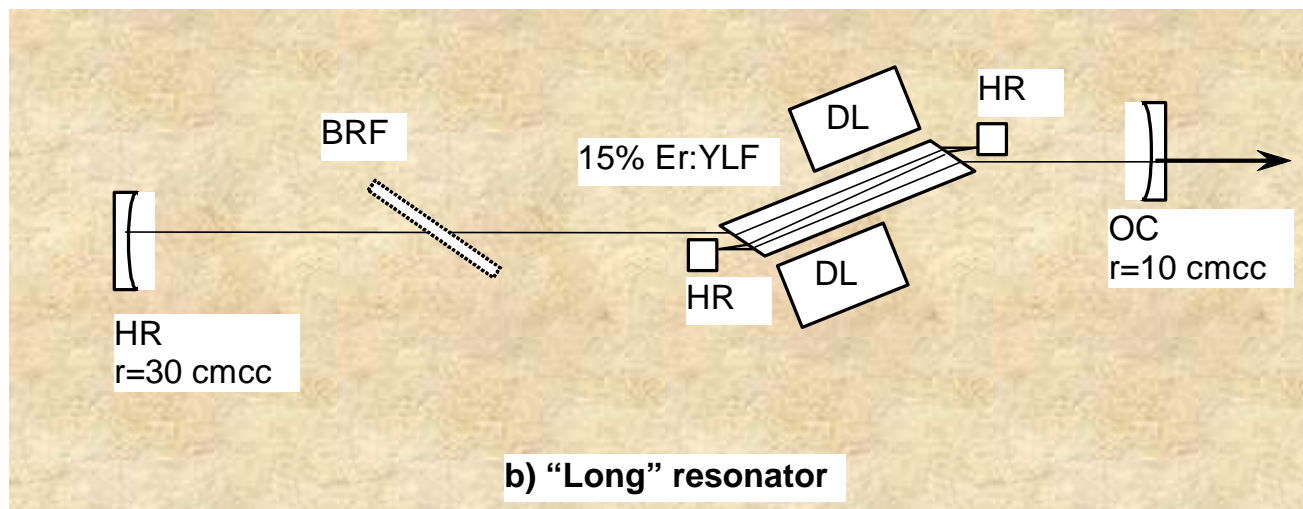


Polarized absorption spectra for 15% Er:YLF crystal at 300 K.

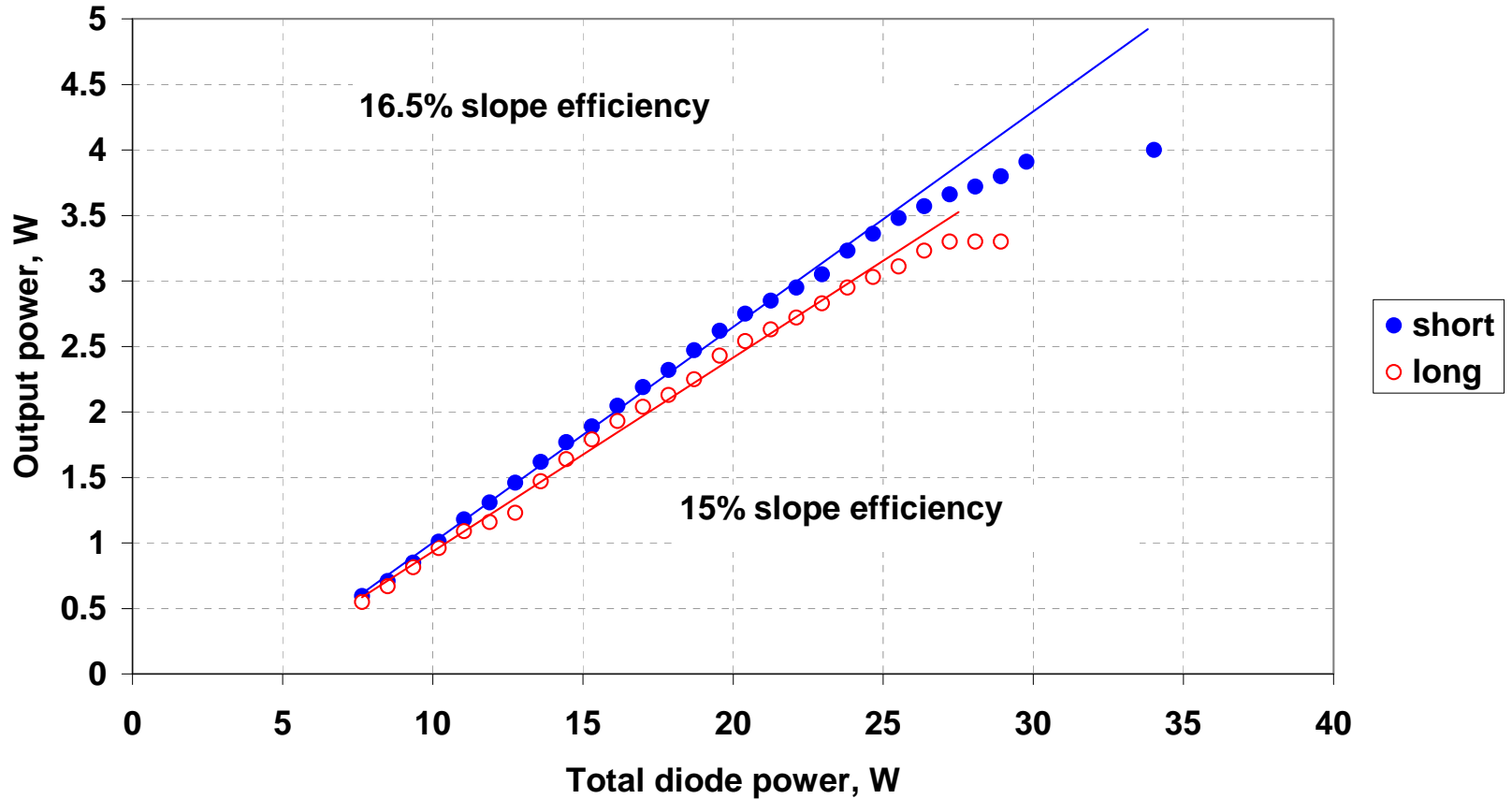
Experimental Set-Up



- Er:YLF Active Element:
Brewster/Brewster-cut slab:
28-mm long
Clear aperture 1.25 x 6 mm.

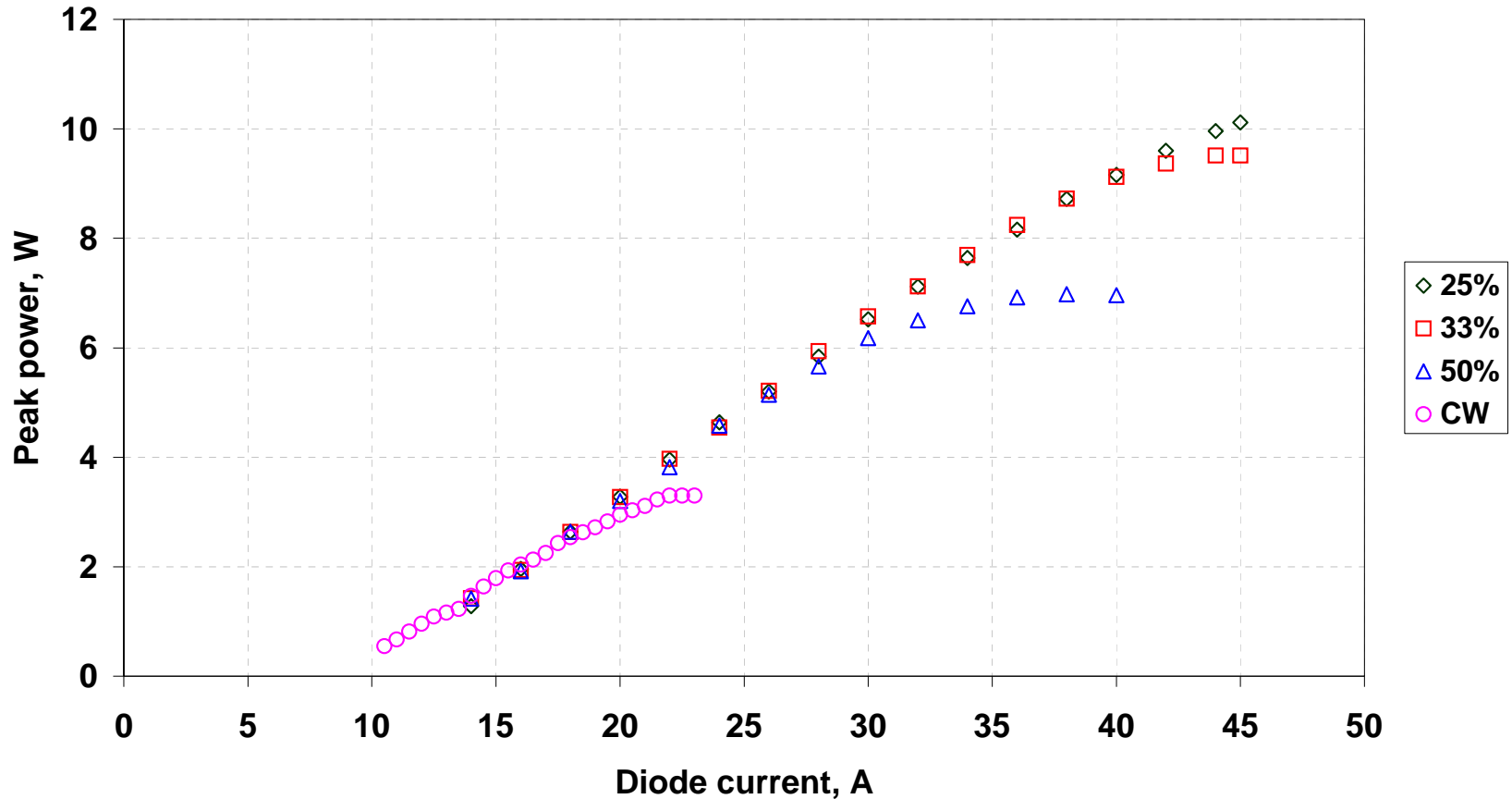


Er:YLF CW Laser Operation Three-Pass Geometry



	short	long
HR mirror	2600-3000 nm	
Output coupling	T ~ 4% at ~ 2600-2900 nm	T ~ 4% at 2600-2900 nm
Resonator length	~ 20 cm	~ 40 cm

Er:YLF quasi-CW Laser Operation Three-Pass Geometry



HR mirror	2600-3000 nm
Output coupling	T ~ 4% at 2600-2900 nm
Resonator length	~ 40 cm

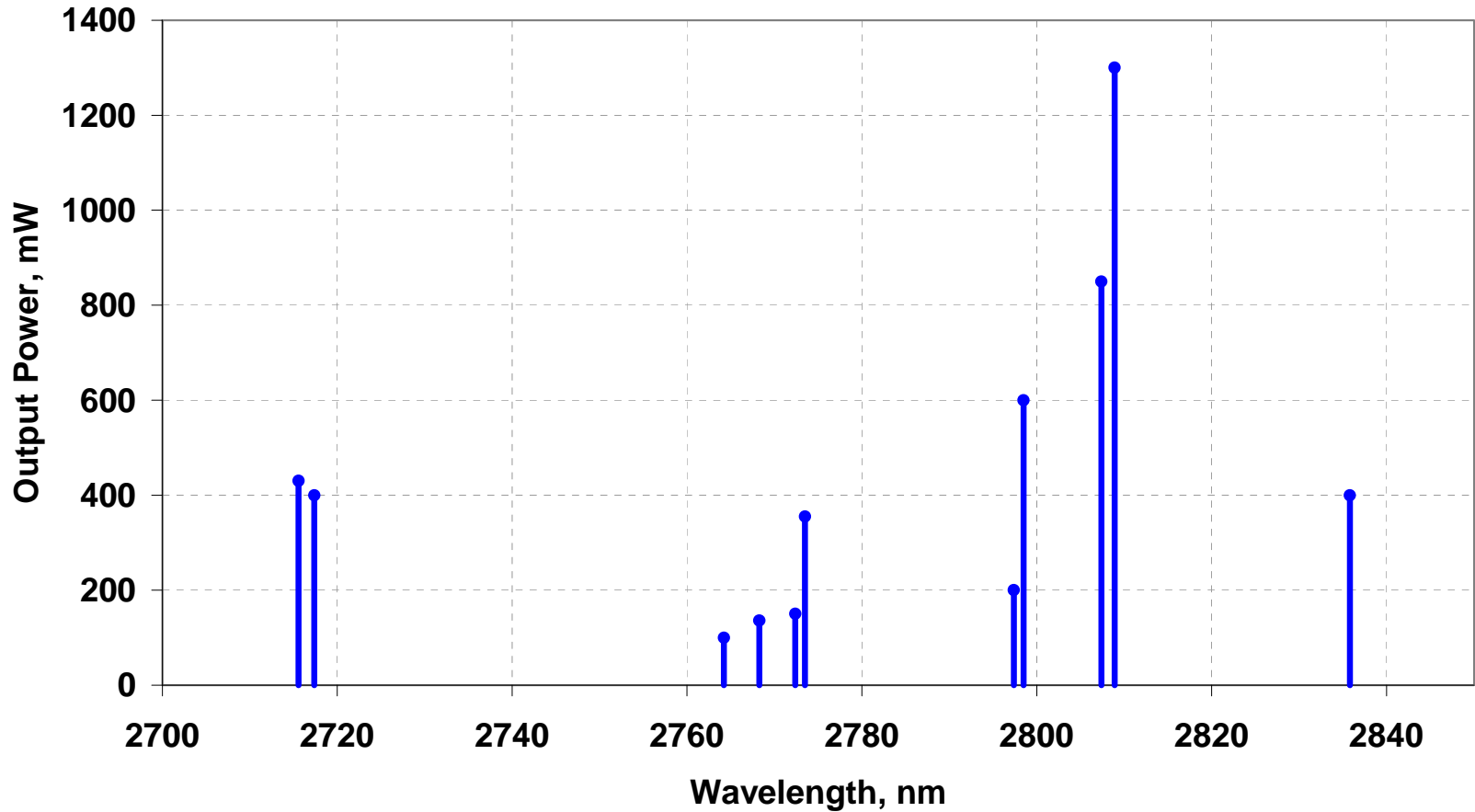


Calculated Wavelengths for Transitions Between $4I_{11/2}$ and $4I_{13/2}$ Manifolds in Er:YLF

Manifold	Level	Energy, cm-1	4I/11/2				
			1	2	3	4	5
			10222	10235	10283	10289	10315
			nm	nm	nm	nm	nm
4I13/2	7	6738	2870.3	2859.6	2820.9	2816.1	2795.6
	6	6724	2858.8	2848.2	2809.8	2805.0	2784.7
	5	6697	2836.9	2826.5	2788.6	2784.0	2764.0
	4	6674	2818.5	2808.2	2770.9	2766.3	2746.5
	3	6579	2745.0	2735.2	2699.8	2695.4	2676.7
	2	6539	2715.2	2705.6	2670.9	2666.7	2648.3
	1	6535	2712.2	2702.7	2668.1	2663.8	2645.5

Note: Bold numbers indicate wavelengths for which lasing has been obtained in prior work.

Er:YLF CW laser operation wavelength tuning



Wavelength tuning of Er:YLF laser with a 1-plate birefringent filter

Development of an efficient side-pumped CW Er:YLF laser:

- **First demonstration (to the best of our knowledge) of a tunable CW side-pumped 3- μ m Er:YLF laser**
- **Wide tuning range: 2716-2836 nm**
- **Record output CW power for a diode-pumped Er- laser
~ 4 W**