A CW side-pumped Yb:S-FAP laser

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Motivation

- Develop a QCW diode-pumped MOPA system
  - compact, Q-switched Nd:YLF laser
  - side-pumped multi-pass Yb:S-FAP power amplifier
  - Gaussian beam quality
  - Goal: 30 to 40 mJ energy-per-pulse capability

Previous Results

- Yb-doped materials
  - Yb^{3+} has two electronic states $^2F_{7/2}$ and $^2F_{5/2}$
  - Absorption band ~ 900 nm
  - No excited state absorption
  - Quasi-four-level operation
  - Not good material for lamp pumping
  - Renewed interest due to availability of high-power diode lasers at ~ 900 nm

- Ti:Sapphire pumping
  - Longitudinal pumping
  - High-brightness
    - High-slope efficiency
    - High beam quality
  - Low pump power -> low output

- Diode pumping
  - Longitudinal or side-pumping
  - Lower brightness
    - Lower slope efficiency
    - Worse beam quality
  - High pump power -> higher output

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Yb:S-FAP

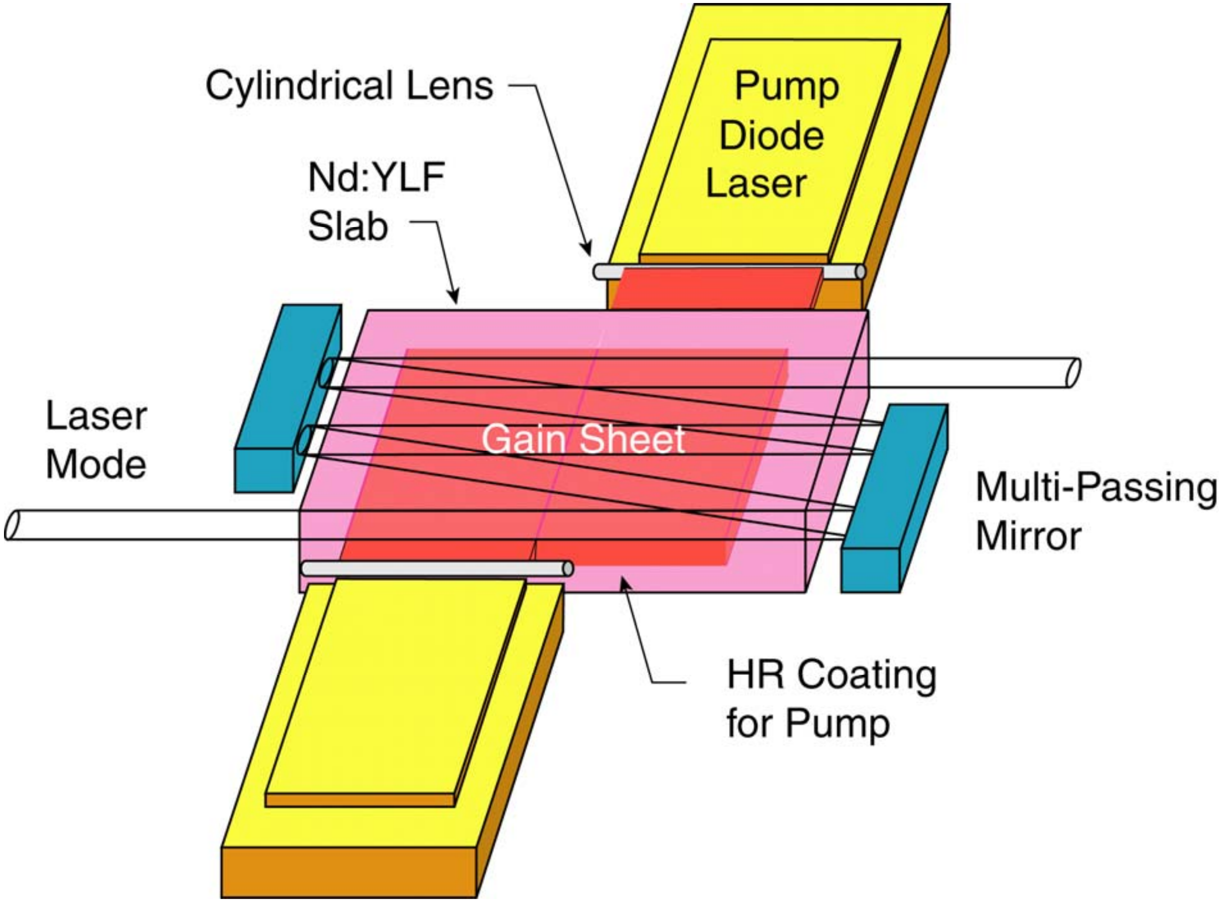
- Advantages
  - Birefringent material
  - Simple two-level structure
    - No ESA, upconversion
  - Low quantum defect
    - Low heat generation (~14%)
  - Long upper laser level lifetime ~ 1.26 ms
- Drawbacks
  - Quasi-four level operation
  - Narrow absorption bandwidth ~ 3-4 nm
    - Stringent requirements on the pump diode linewidth and wavelength

Previous Results – Yb:S-FAP Experiments

- **CW Ti:sapphire pumping (longitudinal) [1]**
  - Slope efficiency (actual) ~60%
  - Output power ~ 0.5 -0.6 W (~ 1 W pump power)
  - Pump density ~ 14 kW/cm^2
- **Diode-pumping (longitudinal)**
  - QCW [2]
    - Slope efficiency ~ 43% (low rep. rate of 1 Hz)
    - Output power ~13 W at 70 Hz (~100 W pump power)
    - Pump density ~23 kW/cm^2
  - CW [3]
    - Slope efficiency ~ 53%
    - Output power ~0.15 W (1.5 W pump power)
    - Pump density ~ 11 kW/cm^2

1. L.D. DeLoach et al. "Laser and spectroscopic properties of $Sr_5(PO_4)_3F$:Yb" JOSA B, 11, 269-276 (1994)
2. C.D.Marshall et al. "Diode-pumped Ytterbium-doped $Sr_5(PO_4)_3F$ laser performance" IEEE J. of Q.E., 32, 650-656 (1996)
3. L.A.W. Gloster et al. "Diode-pumped Q-switched Yb:S-FAP laser" Opt.Commun. 146 177-180 (1998)

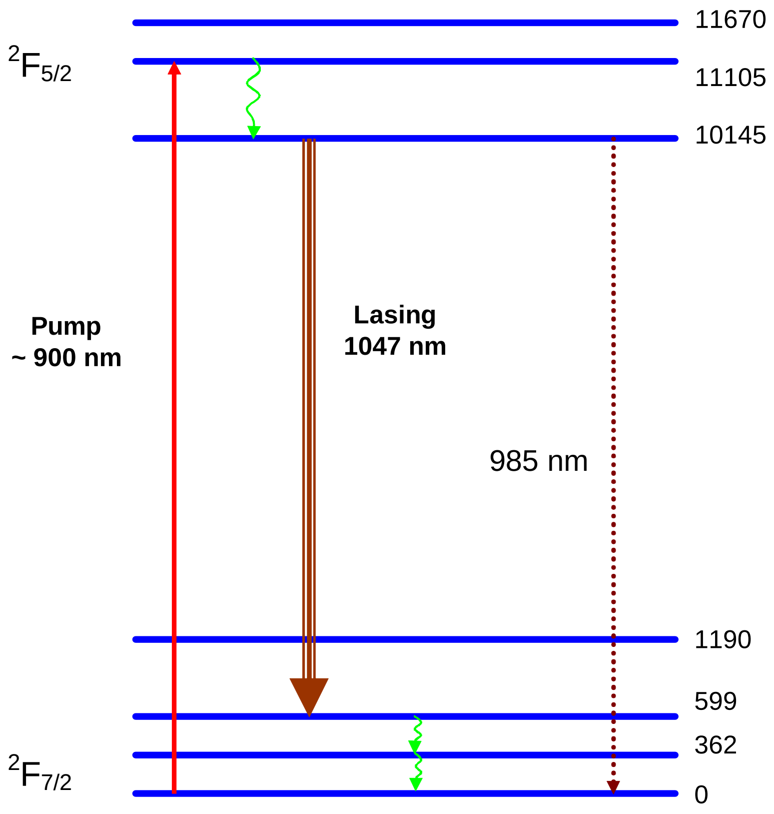
Q-Peak' Gain Module Technology



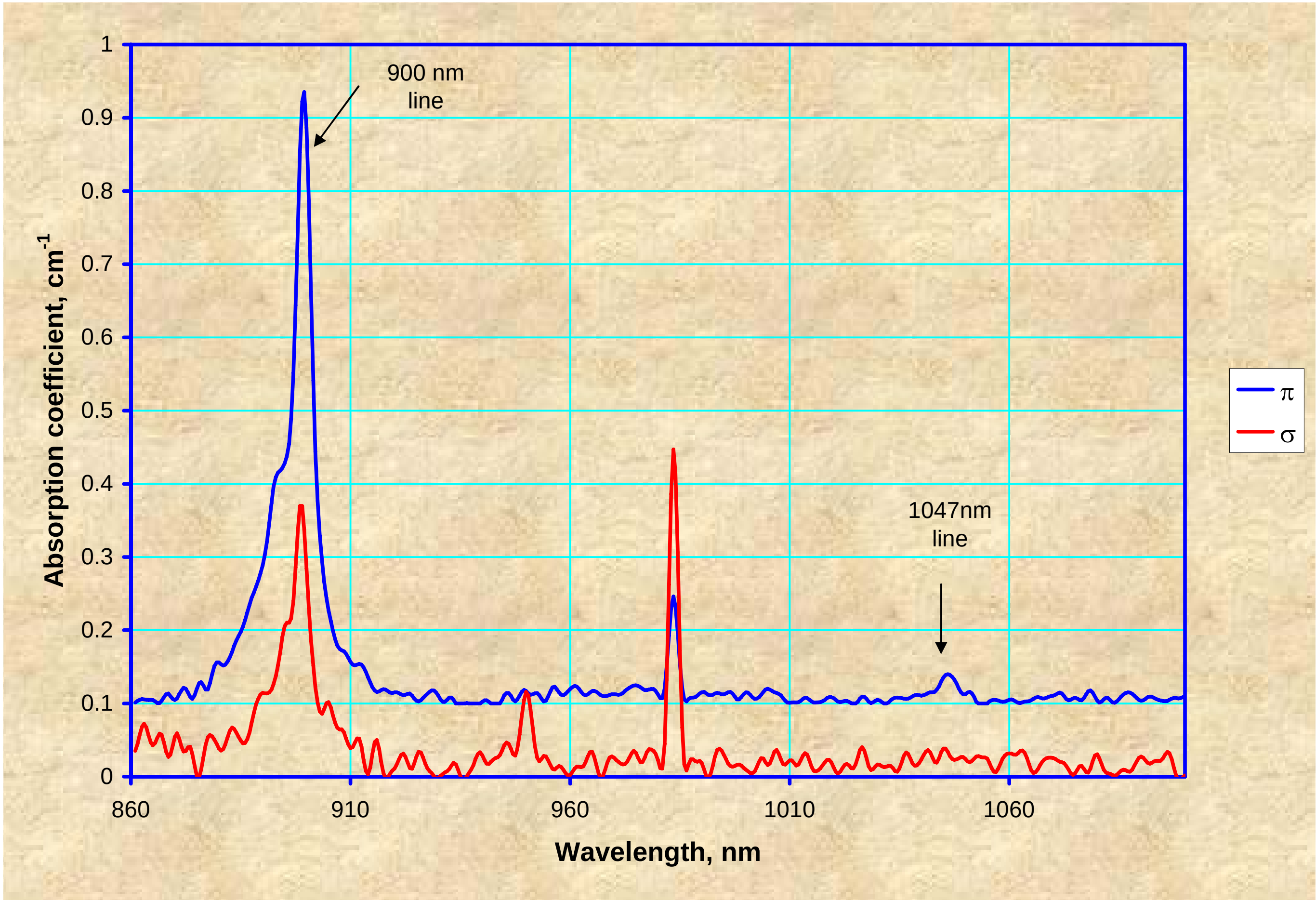
Yb:S-FAP Properties

- Yb:$Sr_5(PO_4)_3F$ Strontium fluorapatite

	Yb:S-FAP	Yb:YAG	Nd:YLF
λ_{abs}, nm	***900***	942	792-797
σ_{abs}, cm^2	***$8.6 \cdot 10^{-20}$***	$0.8 \cdot 10^{-20}$	$(2.5\text{-}7.7) \cdot 10^{-20}$
$\Delta\lambda_{abs}$, nm	***3.7***	~18	~2 (~15)
λ_{em}, nm	***1047***	1031	1047
σ_{em}, cm^2	***$7.3 \cdot 10^{-20}$***	$2 \cdot 10^{-20}$	$1.8 \cdot 10^{-19}$
τ_{em}, ms	***1.26***	1.08	0.485
I_{sat}, kW/cm^2	***2.0***	28	10

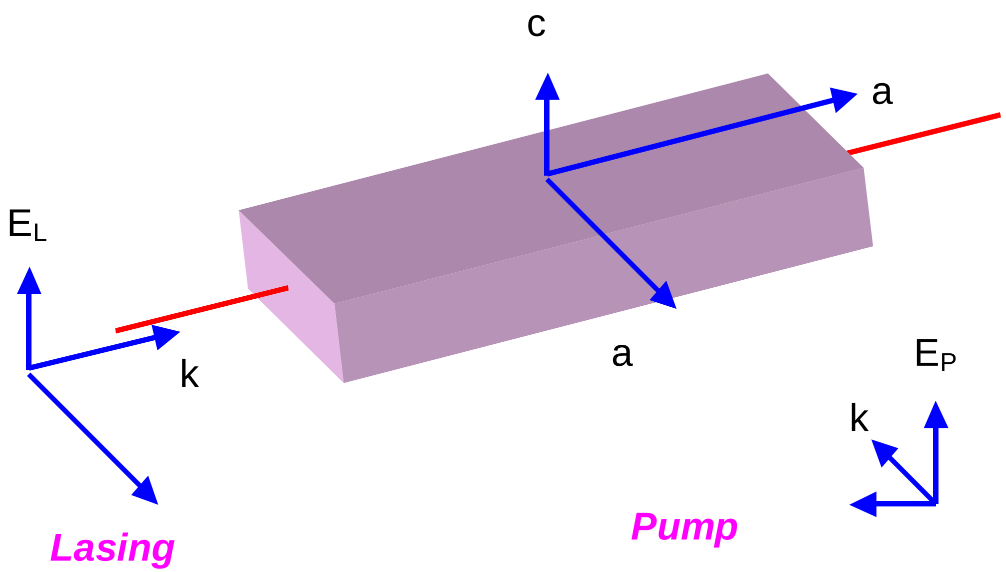


Yb:S-FAP Absorption



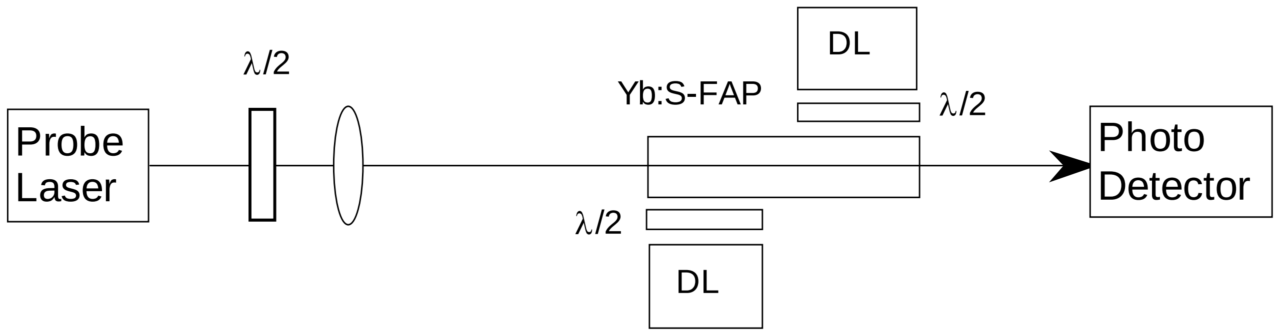
Wavelength, nm	Absorption coefficient, cm^{-1}	
	σ	π
900	0.37	**0.835**
1047	~0	**0. 032**

Laser Element Design



- Laser element: 2.5 x 8 x 22 mm
- Max pump power:
  - CW ~ 55 W
  - QCW ~ 100 W (25% duty)
- Pump intensity:
  - CW 0.8 kW/cm2
  - QCW 1.45 kW/cm2

Gain Measurement – Experimental set-up



- *Probe laser*
  - *1047-nm CW Nd:YLF laser, linearly polarized*
- *Yb:S-FAP crystal*
  - *22 mm (L) x 8 mm (W) x 2.5 (H)*
- *Pump source*
  - *Two 30-W diode bars at ~900 nm.*

Gain Measurements

- Single pass 1047-nm transmission

	Transmission, %
σ	96
π	89

- CW gain measurements

	Actual gain	Absolute gain (corrected for losses)
π	1.06	1.11

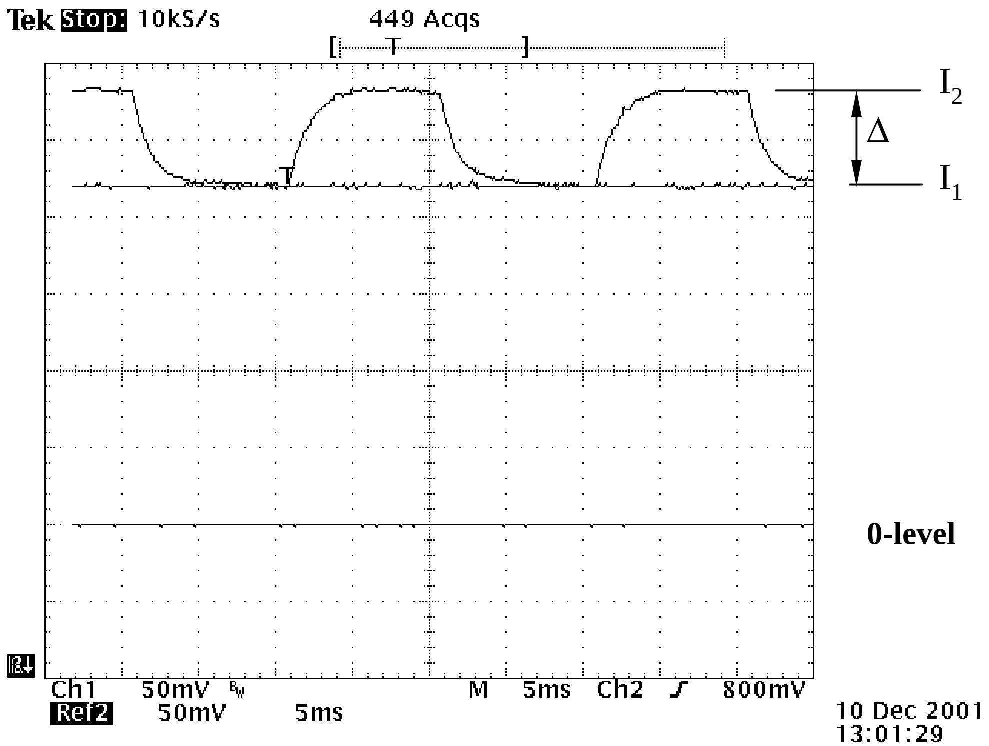
Actual gain /loss $G_{act} = P_{out}/P_{in}$

Absolute gain $G_{abs} = k*P_{out}/P_{in}, = k*G_{act}$

where $k = 1/(1-L)$,

L – single-pass reflection/scatter losses equal to 0.04 (4%).

QCW Gain Measurements

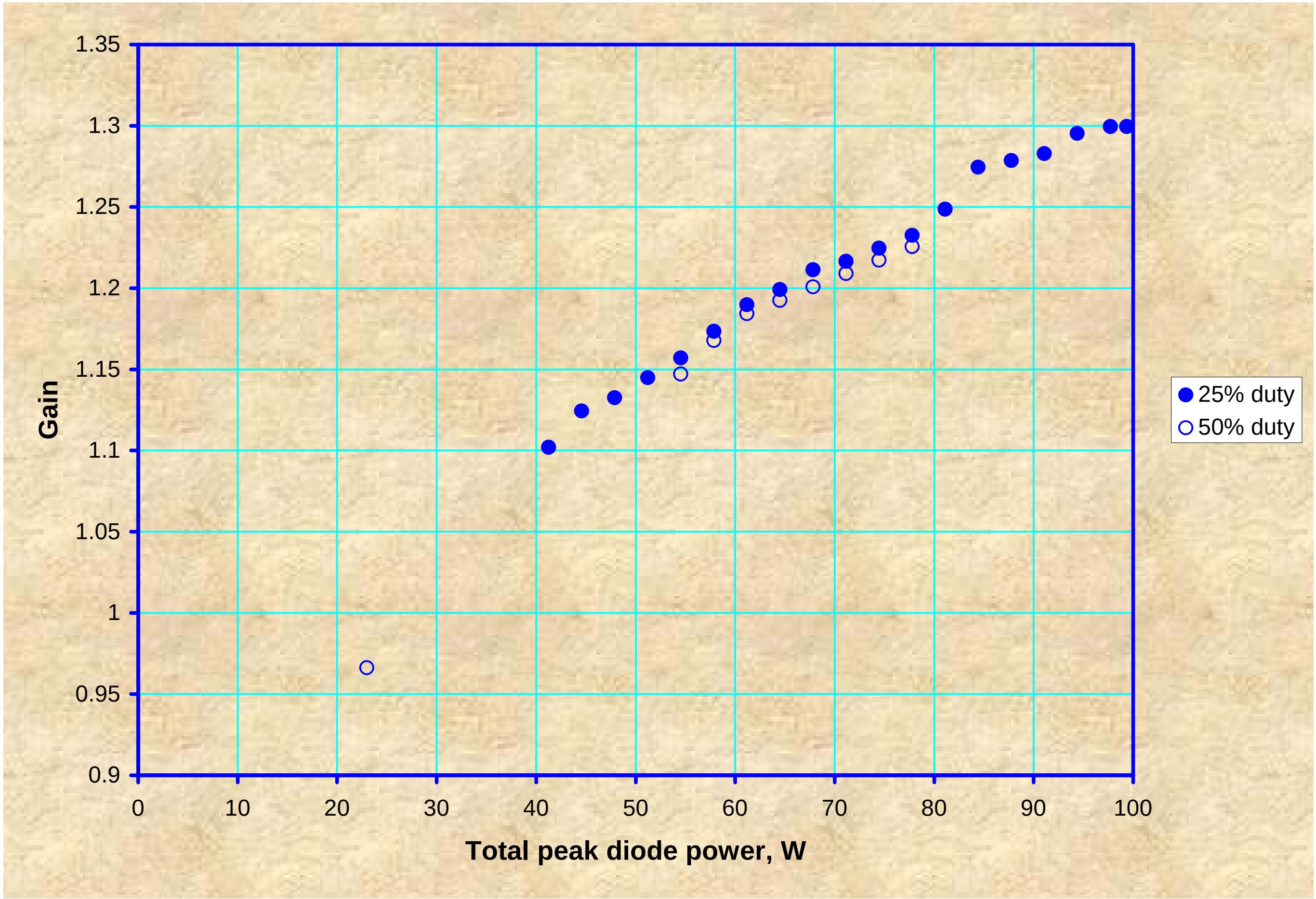


Measured gain $G_{meas} = I_2/I_1 = (I_1+\Delta)/I_1$,

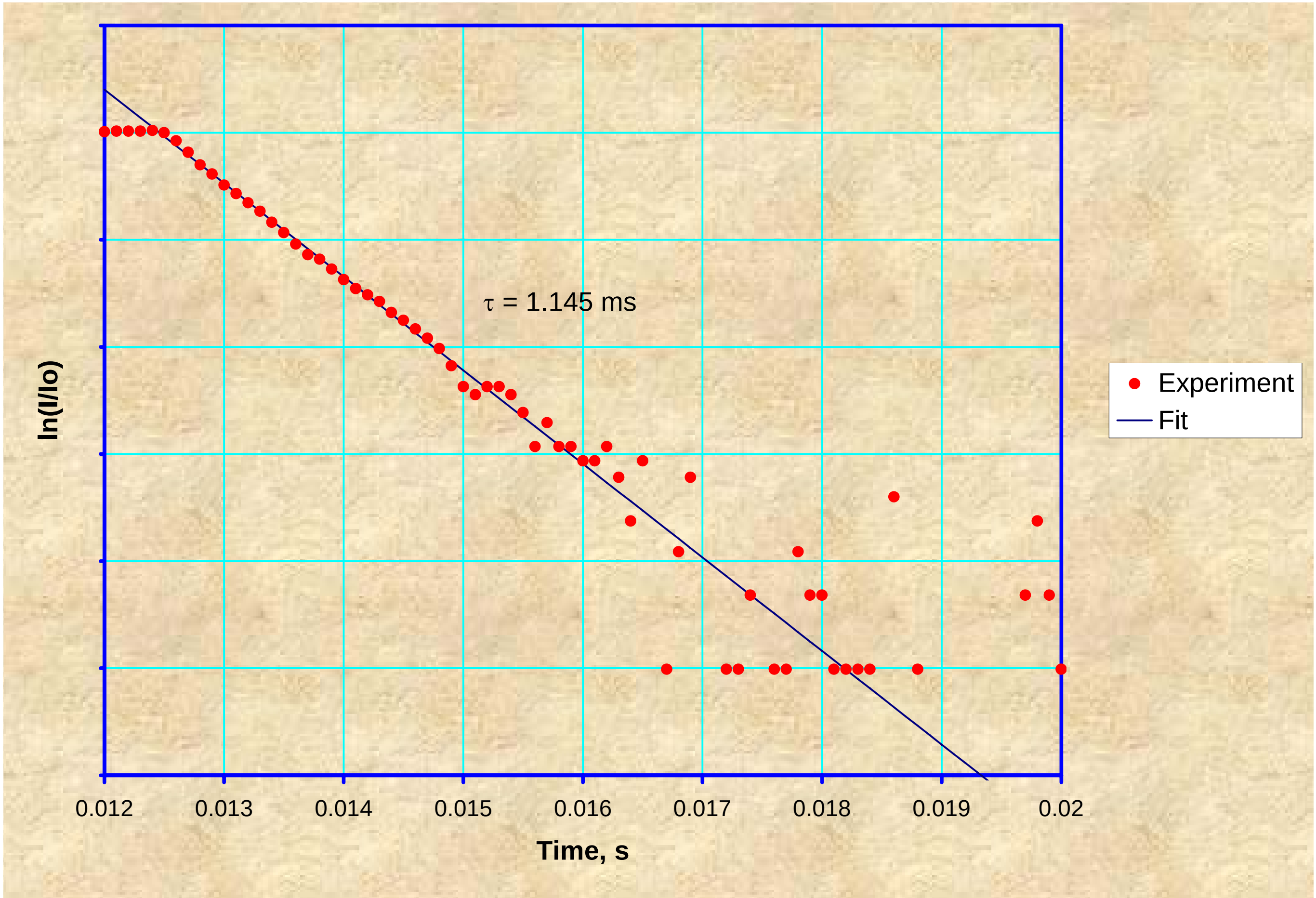
Actual gain $G_{act} = T^*G_{meas}$

where T - single-pass transmission with bars off.

QCW Gain Measurements

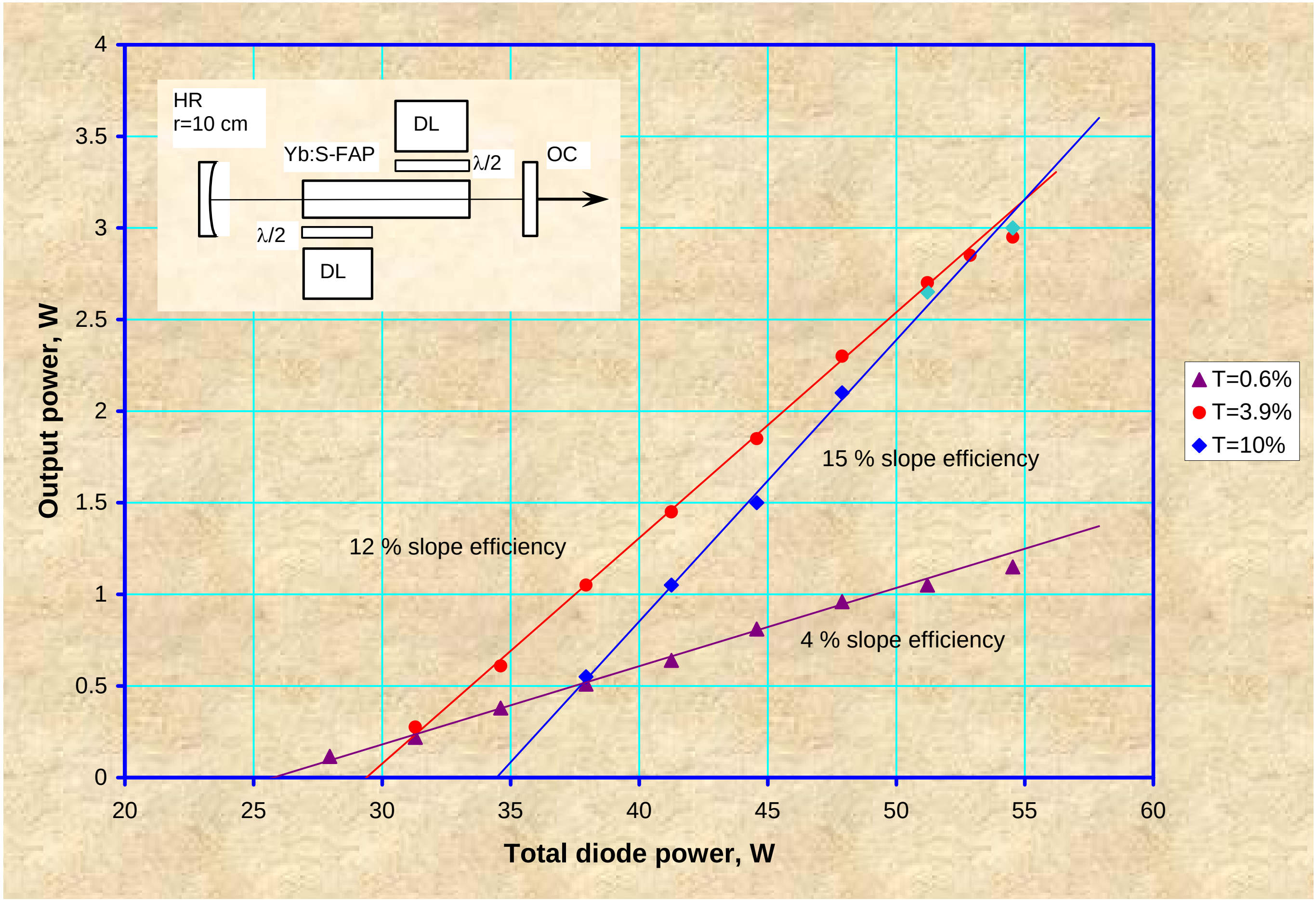


Gain Decay

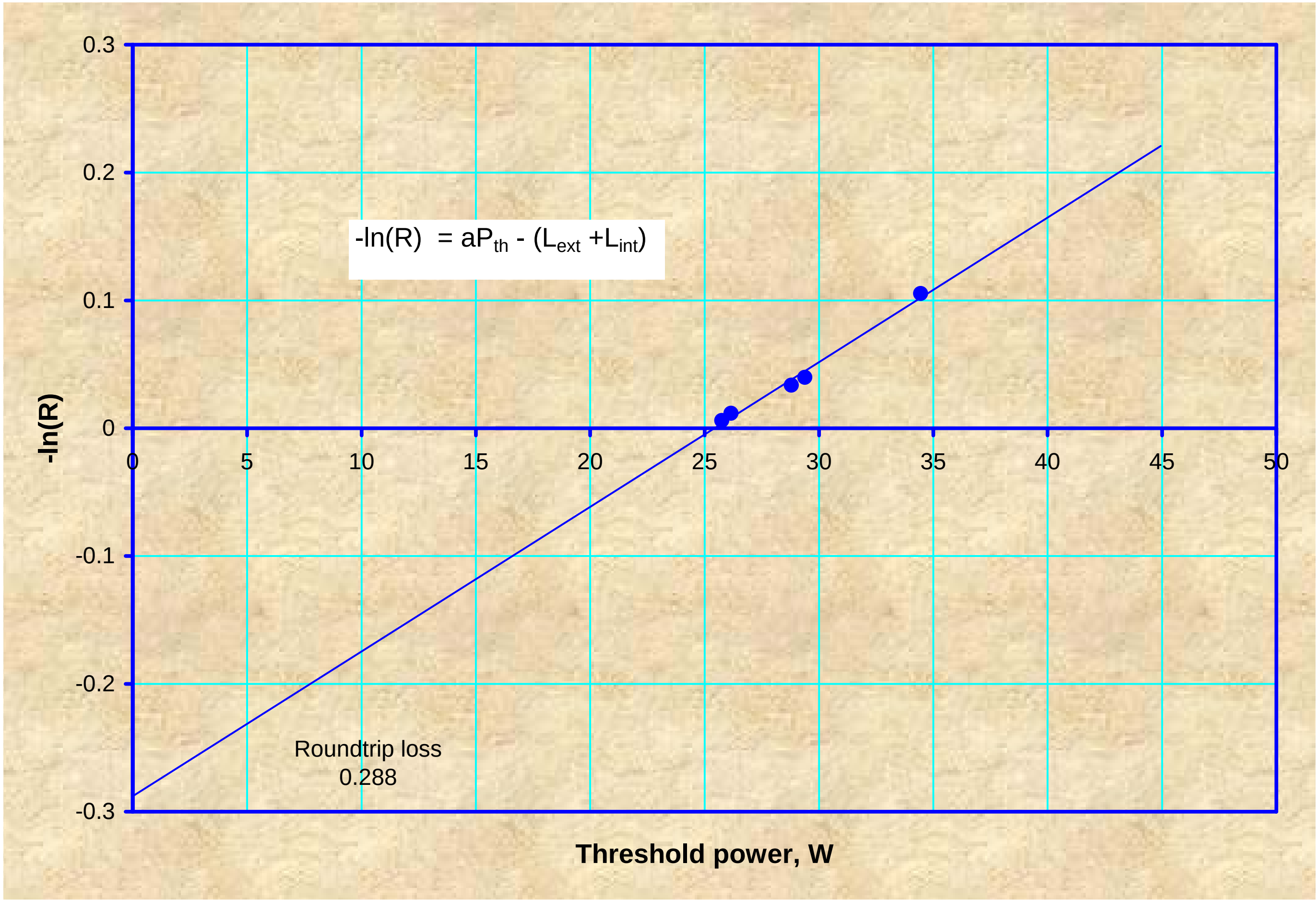


τ = 1.145 ms
ln(I/Io)
0.012
0.013
0.014
0.015
0.016
0.017
0.018
0.019
0.02
Time, s
Experiment
Fit

Laser Operation - CW

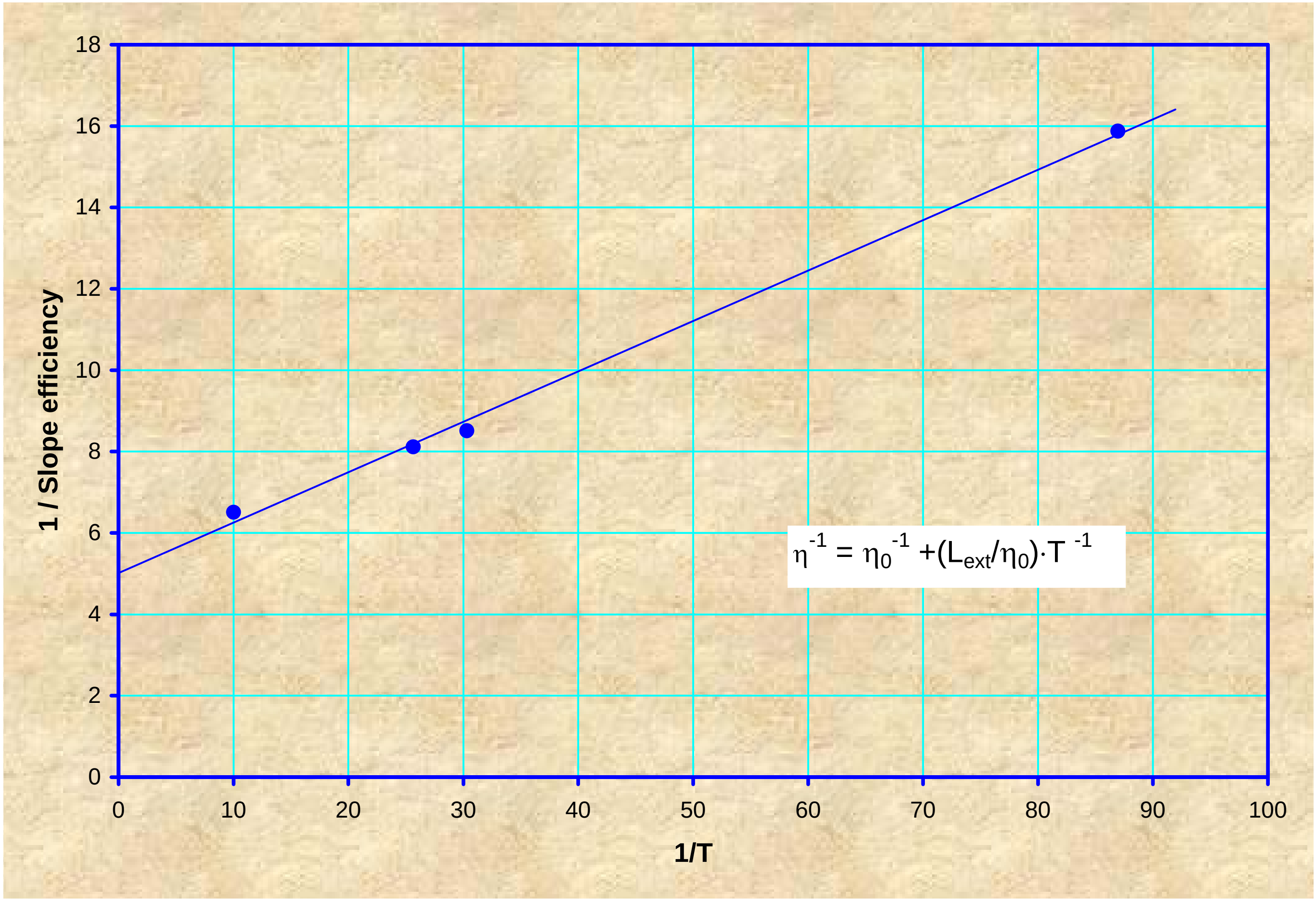


CW Laser Operation – Analysis



- Total roundtrip loss ($L_{ext}+L_{int}$) ~ 0.288
- Quasi-4-level loss L_{int} ~0.141
  (0.032 cm^{-1} x 2.2 cm x 2)
- Roundtrip L_{ext} = ~0.147

CW Laser Operation – Analysis



- Intrinsic slope efficiency ~ 20%
- Extrinsic loss ~ 0. 025

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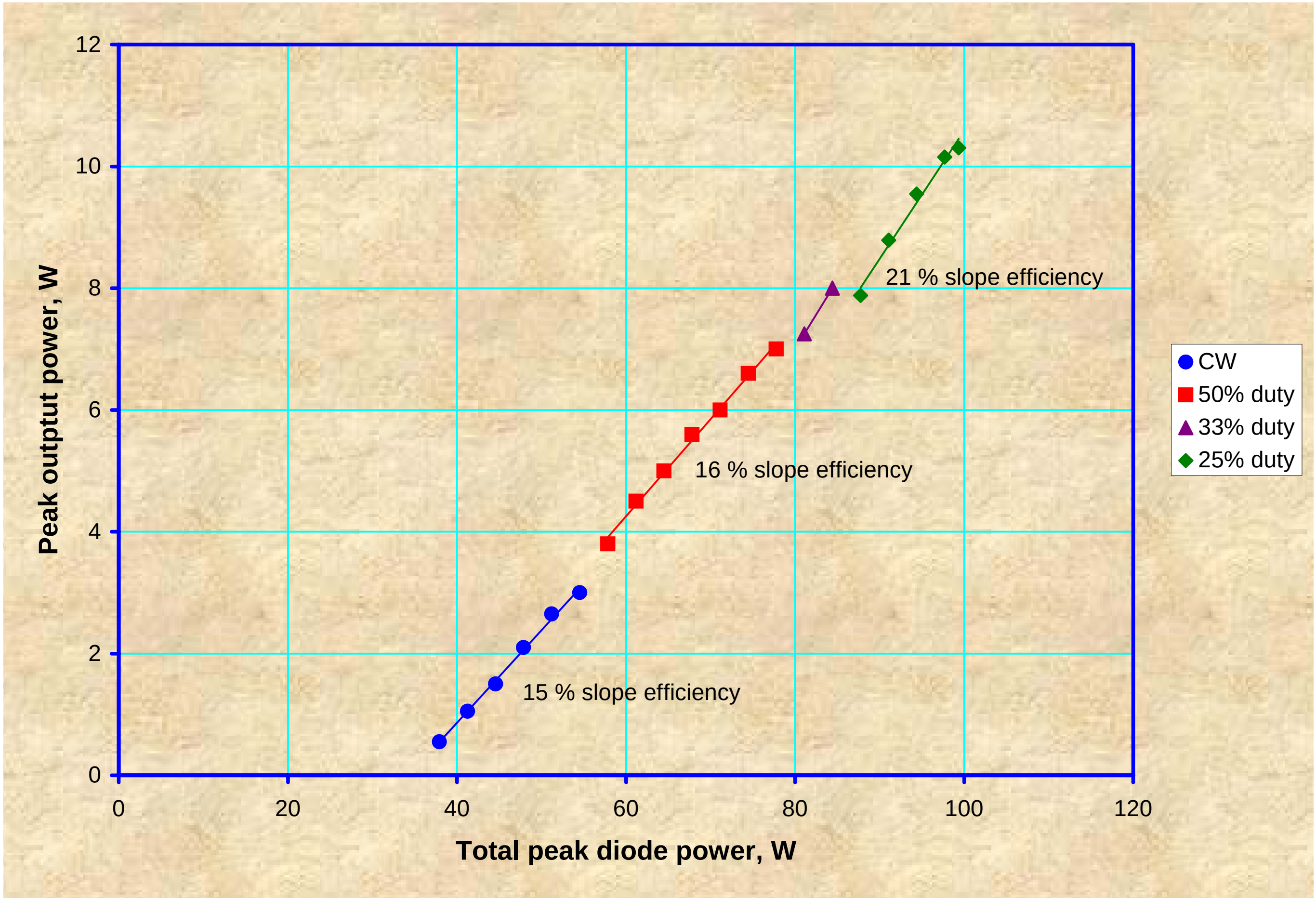
Laser Operation - QCW



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Conclusions

- First demonstration of a CW side-diode-pumped Yb:S-FAP laser
  - CW output ~ 3 W
  - QCW output ~ 10 W (peak)
- Future work:
  - output optimization
    - better matching of the laser mode and the pumped volume
    - better matching of diode laser wavelength and spectral width
    - higher pump power
  - MOPA development
    - QCW pumping at rep.rates < 2 kHz
    - QCW diode bars with high peak power output