Heat-Fraction-Limited CW Yb:YAG Cryogenic Solid-State Laser With 100 % Photon-Photon Efficiency

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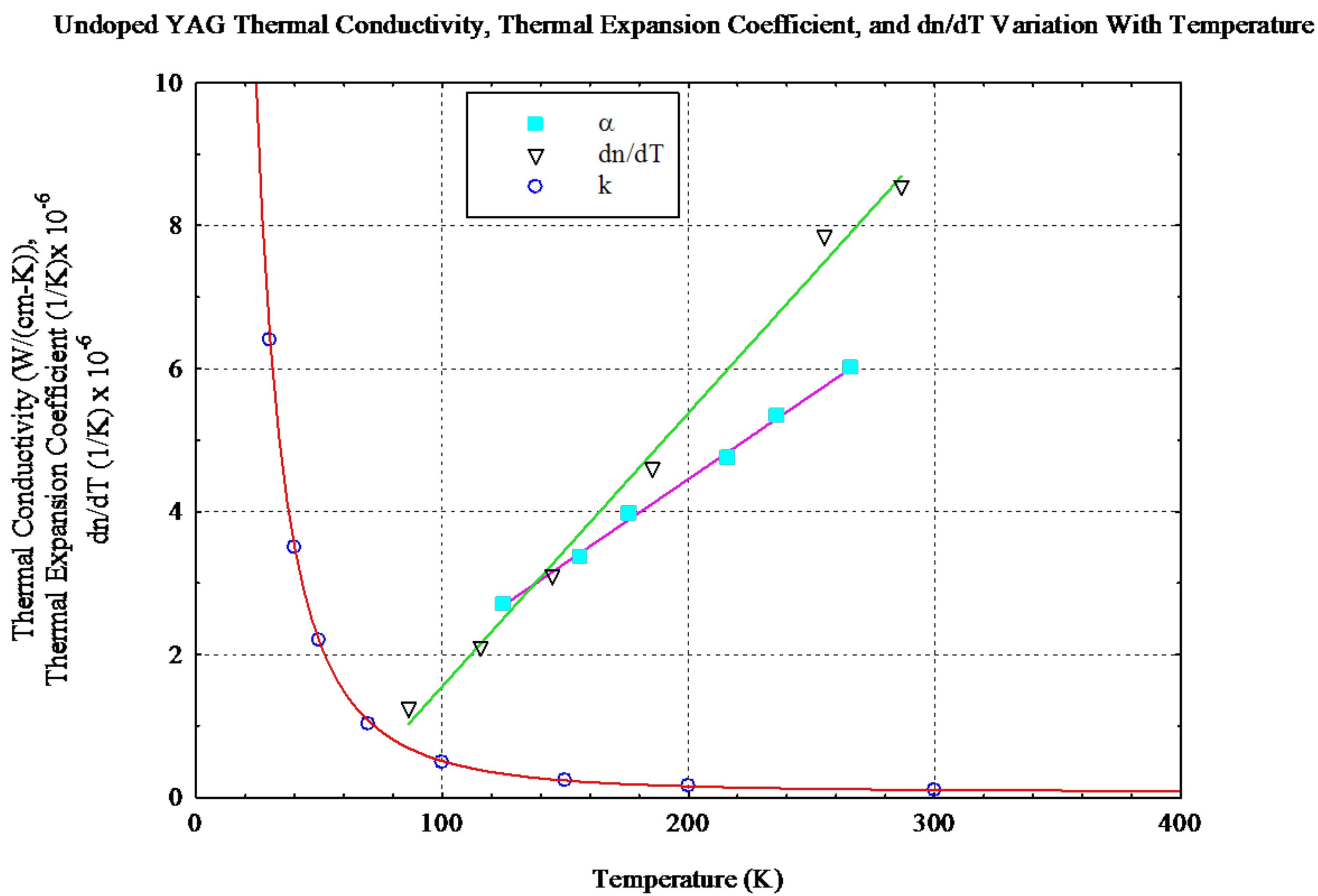

Optical Distortion, Stress, and Birefringence Negligible Around 100K

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Cryogenic Yb:YAG Spectroscopic and Laser Properties

- Peak Absorption Cross-Section at 940 nm ~ 2X Room Temperature Value

- Absorption Bandwidth at 940 nm Reduced:
  - 18.3 nm at 300K
  - 12.6 nm at 75K
  - Diode-Pumping Still Efficient at 75K

- Peak Emission Cross-Section at 1029 nm ~ 5X Room Temperature Value

- Saturation Intensity and Fluence Reduced by ~ 6X From Room Temperature Value

- Terminal Level Population Density Inconsequential Below ~ 110K

- Threshold Power Density Approaches Zero Below ~ 110K

- Increased Slope and Optical-Optical Efficiencies

Experimental Approach

- Cryogenically Cool Yb:YAG Crystal for Low Saturation Intensity, High Gain, and Eliminate Ground-State Absorption
- Cryogenically Cool Yb:YAG Crystal to Eliminate Thermal Effects
- Utilize Diffraction-Limited Pump Laser For Good Mode Matching (Overlap Efficiency)
- Utilize Pump Laser Transition With Close Wavelength Match (946 nm) to Laser Transition (1029 nm)
- Optimize Outcoupler Transmission For Maximum Output Power
- Utilize Near-Confocal X-Resonator to Produce Small Spot Sizes in Yb:YAG Crystal
    - Large Ratio of Laser Intensity/Saturation Intensity to Maximize Gaussian Extraction
- Experimentally Vary Resonator Parameters to Maximize Laser Efficiency

Advantages of Pumping at Nd:YAG Wavelength of 946 nm

- **Close Wavelength Match Between Pump and Resonator Laser Mode Insures Good Overlap Efficiency**
- **Use Diffraction-Limited Laser to Pump Diffraction-Limited Laser**
- **Absorption Still Sufficiently Strong**
- **Measured M^2 Value of 946 nm Pump Laser = 1.1**
- **Ready Availability of SCL 946 nm Lasers**

Yb:YAG Heat Fraction and Maximum Slope Efficiency

Summary of Heat Fraction Results For Pumping at 940 and 946 nm

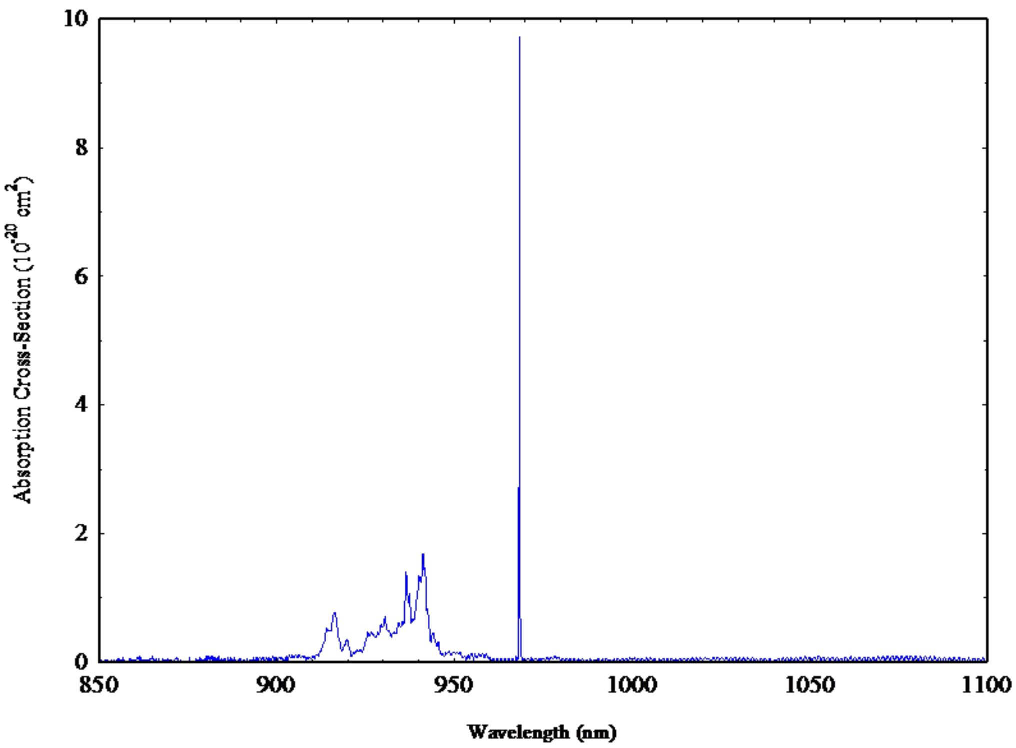
Source	295 K,	295 K,	77 K,	77 K,
Extraction Efficiency Value	0	1	0	1
Brown, Vitali [1]	0.04605	0.06532	0.05874	0.08522
Fan [2]	0.066	0.085	-	-
Quantum Defect	0.086	0.086	0.086	0.086
Pumping at 946 nm				0.085

Maximum Slope Efficiency is 91.53 %
With Pumping at 946 nm
Assuming 100 % Overlap and Extraction Efficiencies

[1] D. C. Brown and V. Vitali, "Yb:YAG Kinetics Model Including Saturation and Power Conservation", Paper Submitted to IEEE Journal of Quantum Electronics May 2010

[2] T. Y. Fan, "Heat Generation in Nd:YAG and Yb:YAG", IEEE J. Quant. Electron. 29, 1457-1459 (1993)

Yb:YAG Absorption Cross-Sections at 75 K



Calculated and Measured Diode Absorption at 941 nm > 99 % (3 nm Bandwidth)
Calculated Absorption at 946 nm = 66.7 %
Measured Absorption at 946 nm = 65.2 %

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Yb:YAG-Sapphire Crystal Assembly

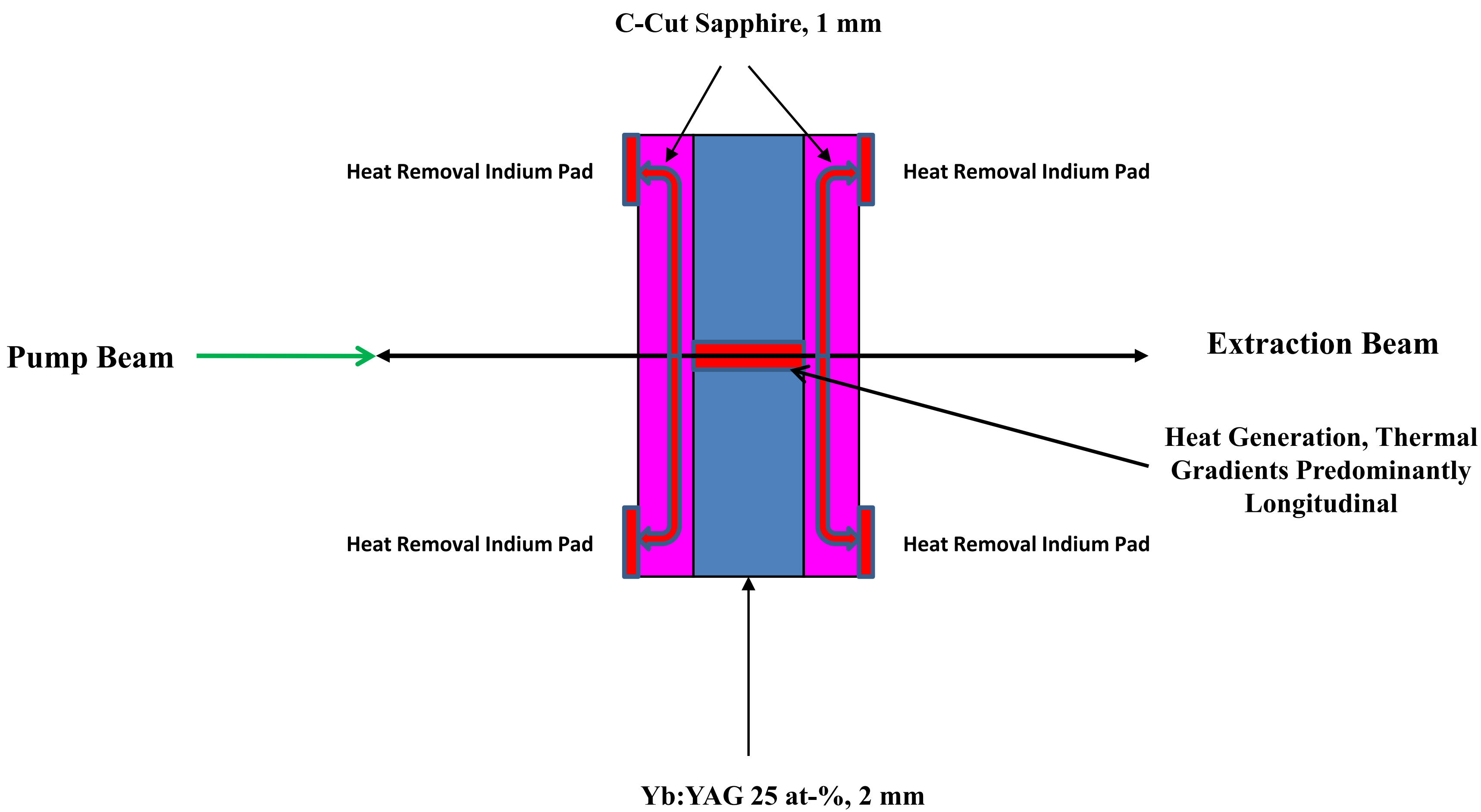

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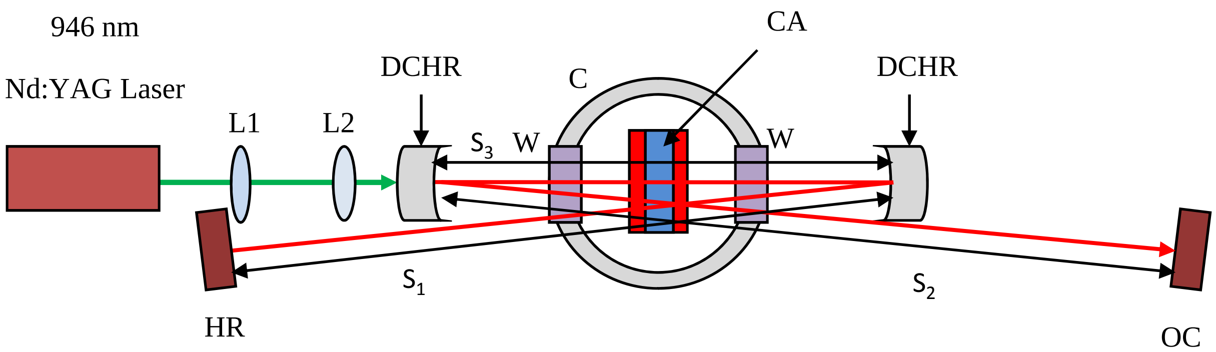
Table: Comparison of Recent Cryogenic Yb:YAG Laser Results

Reference	Coolant Temperature (K)	Slope Efficiency (With Respect to Absorbed Pump Power)	Optical-Optical Efficiency	Output Power (W)
[1]	77	67	62	0.073
[2]	77	85	76	165.000
[3]	77	90	74	0.425
[4]	77	80	70	75.000
[5]	77	66	61	264.000
[6]	77	59	53	550.000

[1] P. Lacovara, H. K. Choi, C. A. Wang, R. L. Aggarwal, and T. Y. Fan, "Room-Temperature Diode-Pumped Yb:YAG Laser", Opt. Lett. 16, 1089-1091 (1991).
[2] D. J. Ripin, J. R. Ochoa, R. L. Aggarwal, and T. Y. Fan, "165-W Cryogenically Cooled Yb:YAG Laser", Opt. Lett. 29, 2154-2156 (2004).
[3] T. Shoji, S. Tokita, J. Kawanaka, M. Fujita, and Y. Izawa, "Quantum-Defect-Limited Operation of Diode-Pumped Yb:YAG Laser at Low Temperature", J. Jour. Appl. Phys. 43, L496-L498 (2004).
[4] S. Tokita, J. Kawanaka, M. Fujita, T. Kawashima, and Y. Izawa, "Sapphire-Conductive End-Cooling of High Power Cryogenic Yb:YAG Lasers", Appl. Phys. B 80, 635-638 (2005).
[5] D. C. Brown, J. M. Singley, E. Yager, J. W. Kuper, B. J. Lotito, and L. L. Bennett, "Innovative High-Power CW Yb:YAG Cryogenic Laser", Proc. of SPIE, Laser Source Technology for Defense and Security IV, Ed. by M. Dubinskii and G. L. Wood, Volume 6552, Orlando, FL (2007).
[6] D. C. Brown, J. M. Singley, E. Yager, K. Kowalewski, J. Guelzow, and J. W. Kuper, "Kilowatt Class High-Power CW Yb:YAG Cryogenic Laser", Proc. of SPIE, Laser Source Technology for Defense and Security IV, Ed. by G. L. Wood and M. Dubinskii, Volume 6952, Orlando, FL (2008).

Cryogenic CW Yb:YAG Oscillator Experimental Set Up



Legend

C-Cryogenic liquid nitrogen vacuum dewar
HR- Flat high reflector at 1029 nm
OC- Curved outcoupler with 50 % reflectivity at 1029 nm and 1250 cm radius
W- Anti-reflection coated at 1029 nm fused silica windows
DCHR- 10 cm radius of curvature, high reflector
at 1029 nm,
L1- 50 cm collimating lens
L2- 7.5 cm or 10 cm AR coated 946 nm focusing lens
CA- Sapphire-Yb:YAG crystal assembly.

Experimental Procedures

- **Obtain 5 Sets of Data Over Three Week Time Period**
- **Complete Re-Alignment For Each Data Set**
- **Iterate Resonator Parameters to Maximize Performance**
- **Data Sets 1-3**
    - **S_1 = 64 cm, S_2 = 65 cm, $S_3 \approx$ 10 cm, f_{L2} = 7.5 cm**
- **Data Sets 4-5**
    - **S_1 = 65 cm, S_2 = 64 cm, $S_3 \approx$ 10 cm, f_{L2} = 10 cm**
- **Paraxia simulations determined that the pump spot $1/e^2$ diameter at the center of the Yb:YAG crystal was about 28 μm using the 7.5 cm focal length lens, and about 39 μm using the 10 cm focal length lens. TEM_{00} resonator mode size varied from 28-39 μm.**
- **In order to match the pump diameter to the resonator TEM_{00} mode diameter, the resonator was iterated experimentally to maximize the obtained slope efficiency by iterating the distance S_3**

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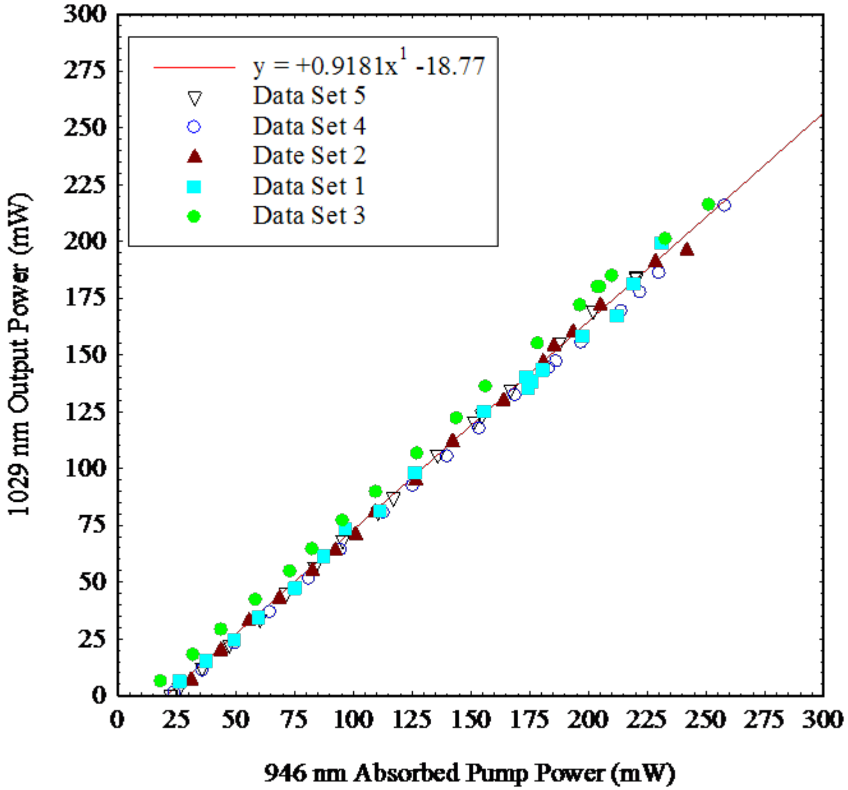
Cryogenic Yb:YAG Oscillator CW Experimental Results



CW output power at 1029 nm as a function of absorbed 946 nm pump power for five different data sets, using an outcoupler transmission of 50%. Average fit slope efficiency is 91.81 %.

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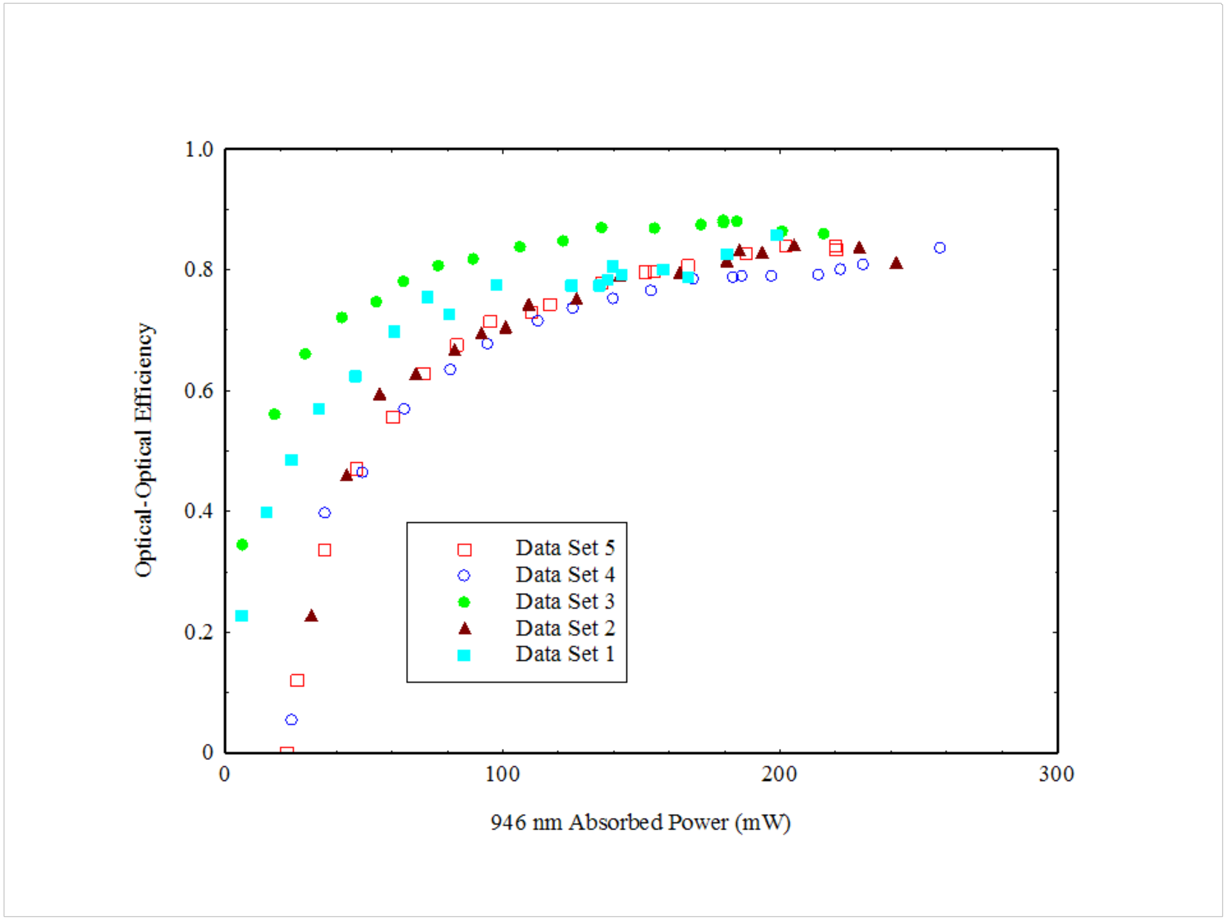
Cryogenic Yb:YAG Oscillator Optical-Optical Efficiency



Optical to optical efficiency as a function of absorbed 946 nm pump power for five different data sets, using an outcoupler transmission of 50 %.

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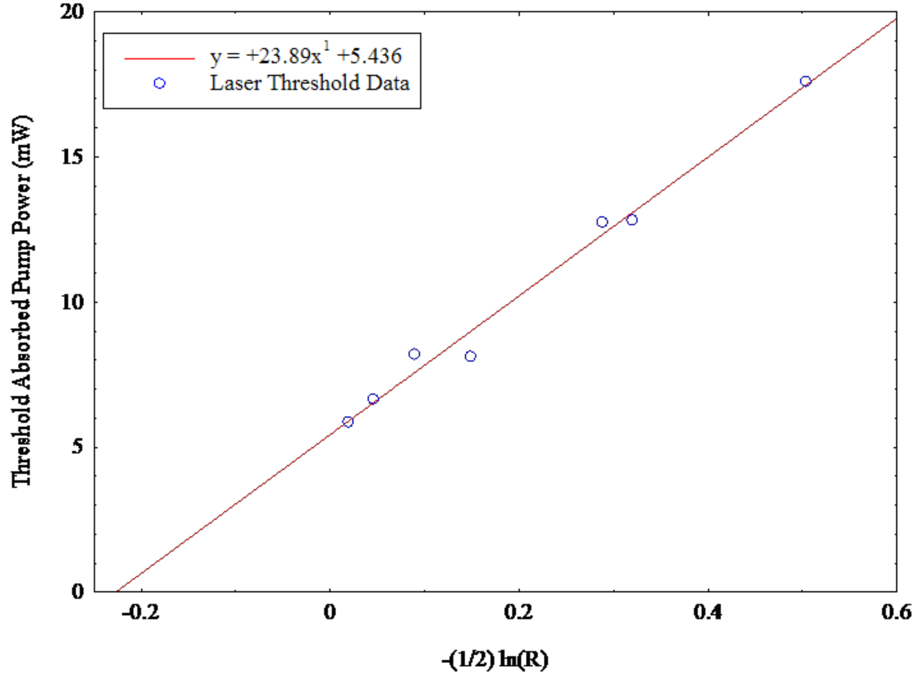
CW Experimental Data Summary

Data Set	Threshold Absorbed Pump Power (mW)	Slope Efficiency (%)	Photon-Photon Efficiency (%)	Optical-Optical Efficiency (%)
1	19.36	90.80	98.77	85.6
2	20.27	92.17	100.26	81.0
3	11.21	92.35	100.45	85.9
4	21.45	90.38	98.31	83.6
5	21.87	93.87	102.11	83.9
Average Value	18.83	91.91	99.98	84.0
Standard Deviation	4.37	1.39	1.51	1.96

Threshold absorbed pump power, slope efficiency, photon-photon efficiency, and optical-optical efficiency for all five data sets, with average values and standard deviation.

Cryogenic Yb:YAG Oscillator Findlay-Clay Analysis



Findlay-Clay Plot showing threshold absorbed 946 nm pump power as a function of the parameter – (1/2) ln(R), where R is the measured outcoupler reflectivity.

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Findlay-Clay Analysis Conclusions

- **F-C Analysis Shows One-Way Loss of 22.8 % at Threshold**
- **Separate Calculated Estimate of Resonator One-Way Loss of 0.56 %**
- **Such a Large F-C Loss Would Significantly Reduce Slope Efficiency at Full Power**
- **Loss Must be Absent at Full Power to Achieve Average 91.8 % Slope Efficiency**
- **We Conclude That F-C Loss Must be Saturable**
- **Further Investigation Underway But Suspect Impurity Ion Sinks**

Summary of Experimental Results Achieved

Threshold Pump Power (mW):

Average 18.83, Maximum 21.87, Minimum 11.21

Slope Efficiency:

Average 91.90 %, Maximum Value 93.87 %, Minimum Value 90.38 %

Optical-Optical Efficiency:

Average 84.00 %, Maximum Value 85.90 %, Minimum Value 81.00 %

Photon-Photon Efficiency:

Average 99.98 %, Maximum 102.11 %, Minimum 98.31 %

M^2 Measurements Using Spiricon M^2 Measurement System:

$M^2 = 1.1$

Spectral Bandwidth Measurements (FWHM) Using Ando Spectrum Analyzer:

0.341 nm for 33 mW Out, 0.338 nm for 96 mW Out, 0.295 nm for 173 mW Out

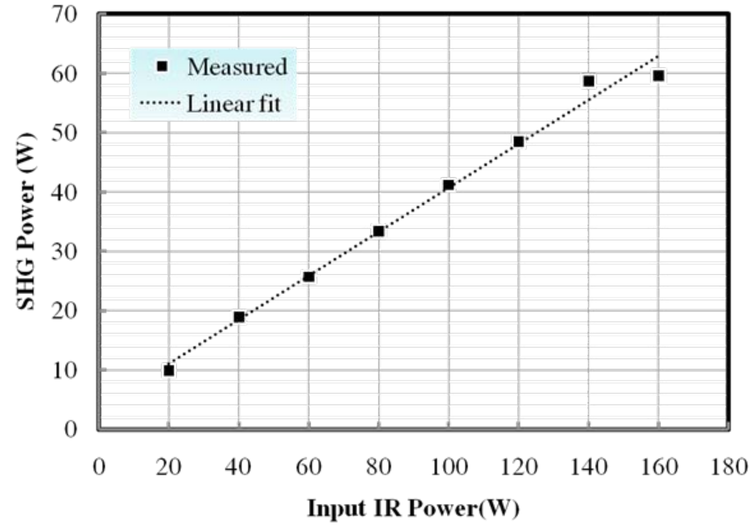
SCL Has Also Recently Achieved New Levels of Performance For High Average Power Cryogenic Solid-State Lasers

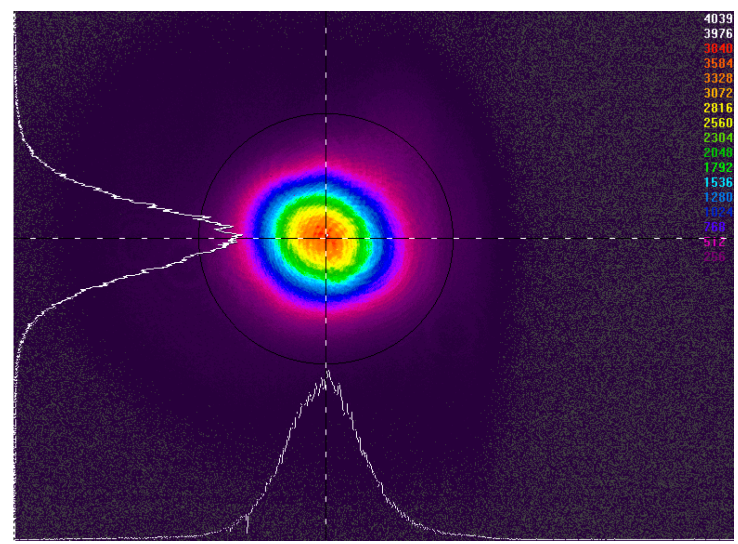
- **Near-Diffraction-Limited CW Oscillator-Amplifier**
  - > 1 kW of Output Average Power
  - $M^2 < 1.30$
- **Near-Diffraction-Limited Ultrafast Oscillator-Amplifier**
  - > 700 W of Output Average Power
  - $M^2 < 1.28$
  - 50 MHz Fiber-Laser Driver
  - 13.1 μJ/Pulse
  - 11 ps FWHM Pulses
  - 1.2 MW Peak Power

These results will be presented in a future paper.

Preliminary Second Harmonic Generation Experiment*

- > 60 W average power at 515 nm was achieved
- > 42% conversion efficiency
- Analysis/calculation are being performed, much higher efficiency (~70%) is expected for future experiment





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