CLEO '92
R.V. POLE MEMORIAL LECTURE

SOLID STATE LASERS:
THE RENAISSANCE CONTINUES

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What's all this about a renaissance?

Origin of word - to be born again

Websters: "The transitional movement in Europe between medieval and modern times .. marked by a humanistic revival of classical influence expressed in a flowering of the arts and literature and by the beginnings of modern science *or*

a movement or period of vigorous artistic and intellectual activity

Renaissance in solid state lasers - who said it?

"A renaissance in solid state lasers has thus begun" Emmett, Krupke and Trenholme, "Future development of high-power solid-state laser systems, " Sov. J. Quantum Electron. **13**, 1 (1983)

"Renaissance in solid-state lasers" OSA Lasers Technical Group Meeting, OSA Annual Meeting, October, 1983

"The renaissance in solid state lasers," R.L. Byer, R.V. Pole Memorial Lecture, CLEO '87

1960's - the "classical" period

- Transition-metal ions
  - Cr, Ni, Co, V
- Rare-earth ions
  - Nd, Ho, Tm, Er, Yb
- Sensitized lasers
- Upconversion lasers
- Laser-pumped lasers
- Diode-pumped lasers
- The "ings"
- Monolithic lasers
  - ruby!
- Unidirectional rings
- Efficient harmonics
  - External, internal
- Parametric oscillators
- "Slab" geometry?

What caused the dark ages?

- Bell Labs stopped working on the problem
- Realities of materials caught up with promises
- Other technologies became fashionable

Lesson: improvements in science and technology are not inevitable

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What started the Renaissance?

Practical tunable lasers
- Alexandrite, Ti:sapphire

Sensitized lasers that worked well
- Cr,Nd:GSGG
- Promise of higher energies, more average power, better beam quality

Better semiconductor lasers

Why is the renaissance continuing?

Continuing improvements in diode lasers

- more power, energy, efficiency, lower cost,new wavelengths

Continuing improvements in diode-pumped lasers

- higher efficiency, power, energy, better beam quality, new modes of operation

Advances in tunable systems

Nonlinear optics that work

The essence of advances

- Materials
  - Semiconductors
- Materials
  - Linear crystals
  - Materials
  - Nonlinear crystals

Now, the technologies

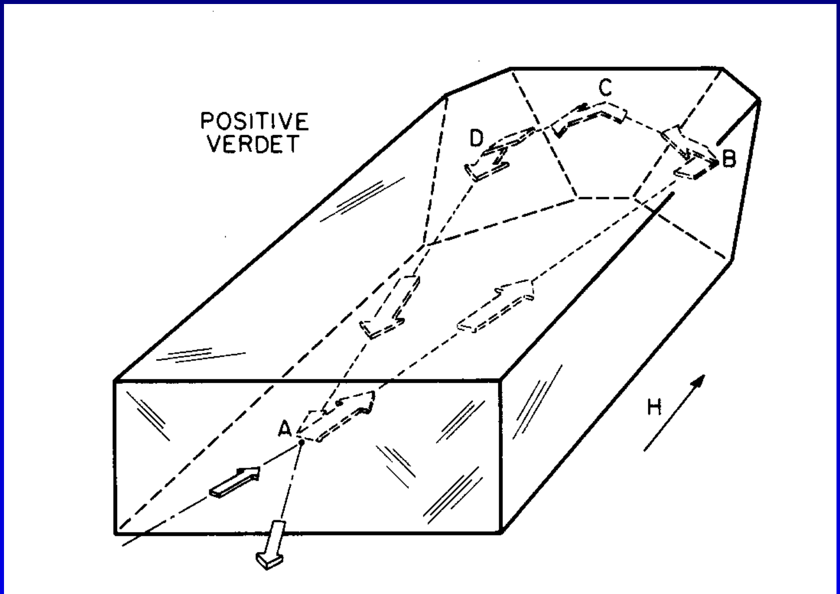
Diode pumping
Upconversion
Chromium-doping
Ti:sapphire

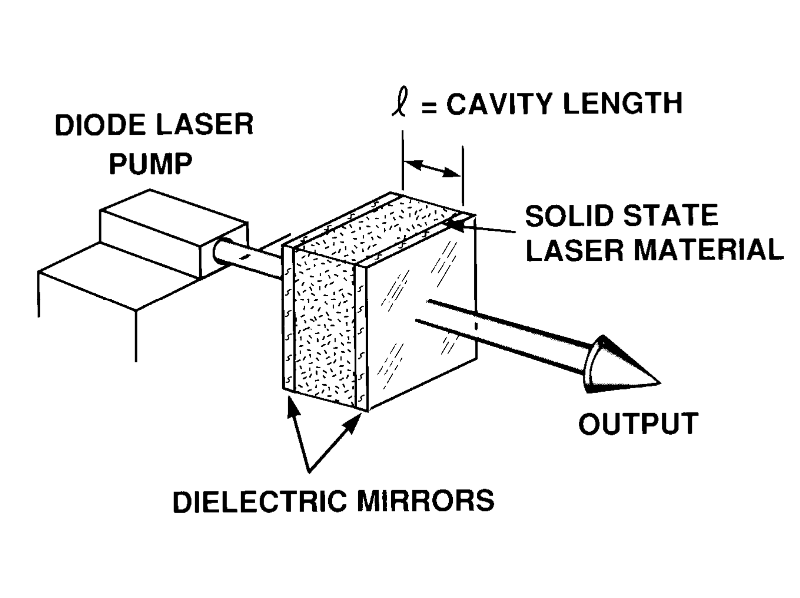
Ultrafast systems
Mid infrared
Frequency conversion

Diode-pumped lasers

- CW pumping, Nd-doped lasers
- Transition from single diodes to bars
- New CW diode wavelengths
  - 785 nm -> Tm, Ho
  - 680 nm -> Cr
  - 940 nm -> Yb, Er
- Pulsed pumping, Nd-doped lasers
- Scaling to 1 J, 275 W (not together)
- Pulsed pumping, other systems
  - Just beginning

Single-frequency sources





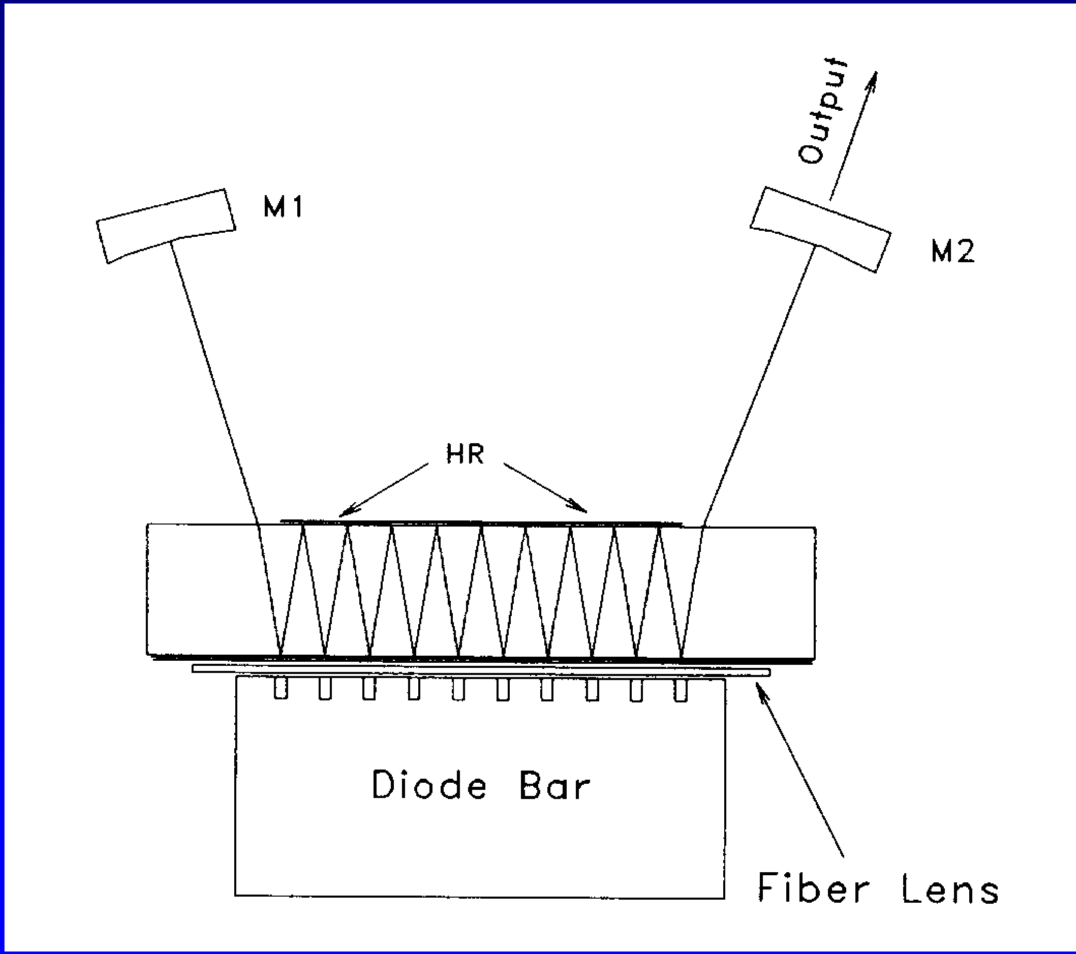
"MISER"

Kane and Byer
(Stanford)

"Microchip laser"

Mooradian and Zayhowski
(MIT Lincoln Lab)

Tightly folded resonator (Baer, Spectra-Physics)



High-power bar-pumped design (Tidwell, *et al*, STI Optrontics)

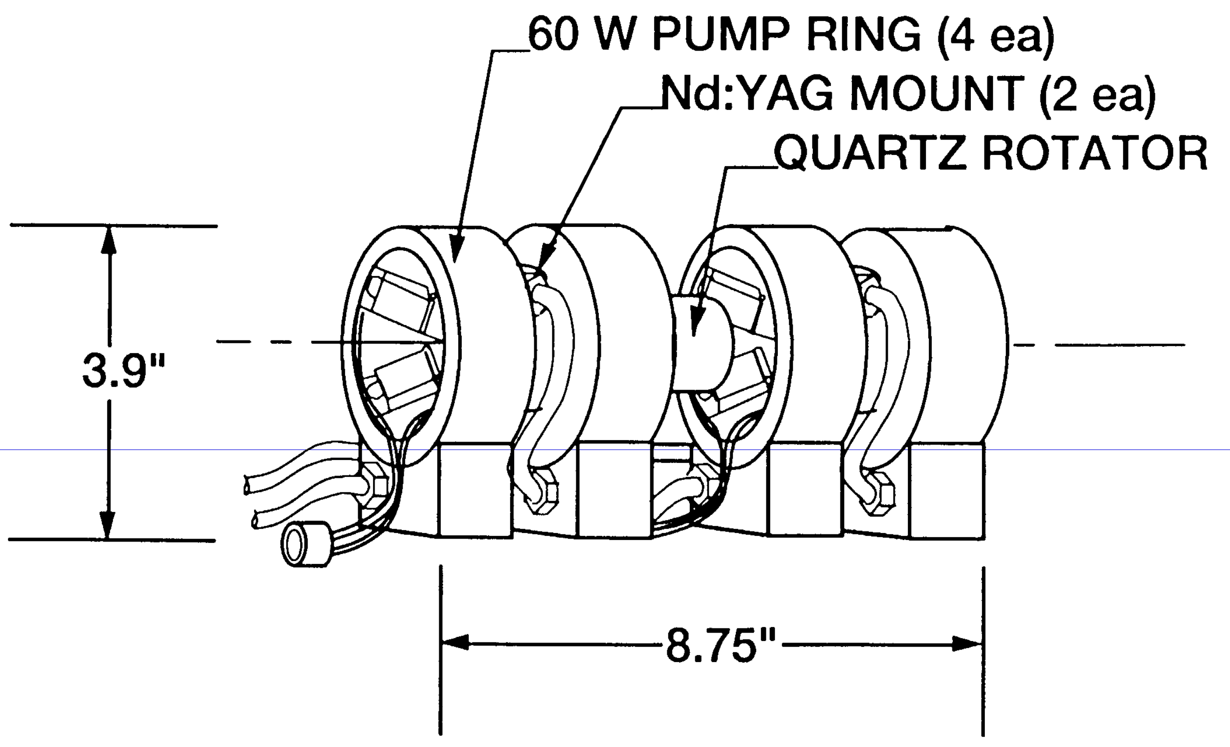
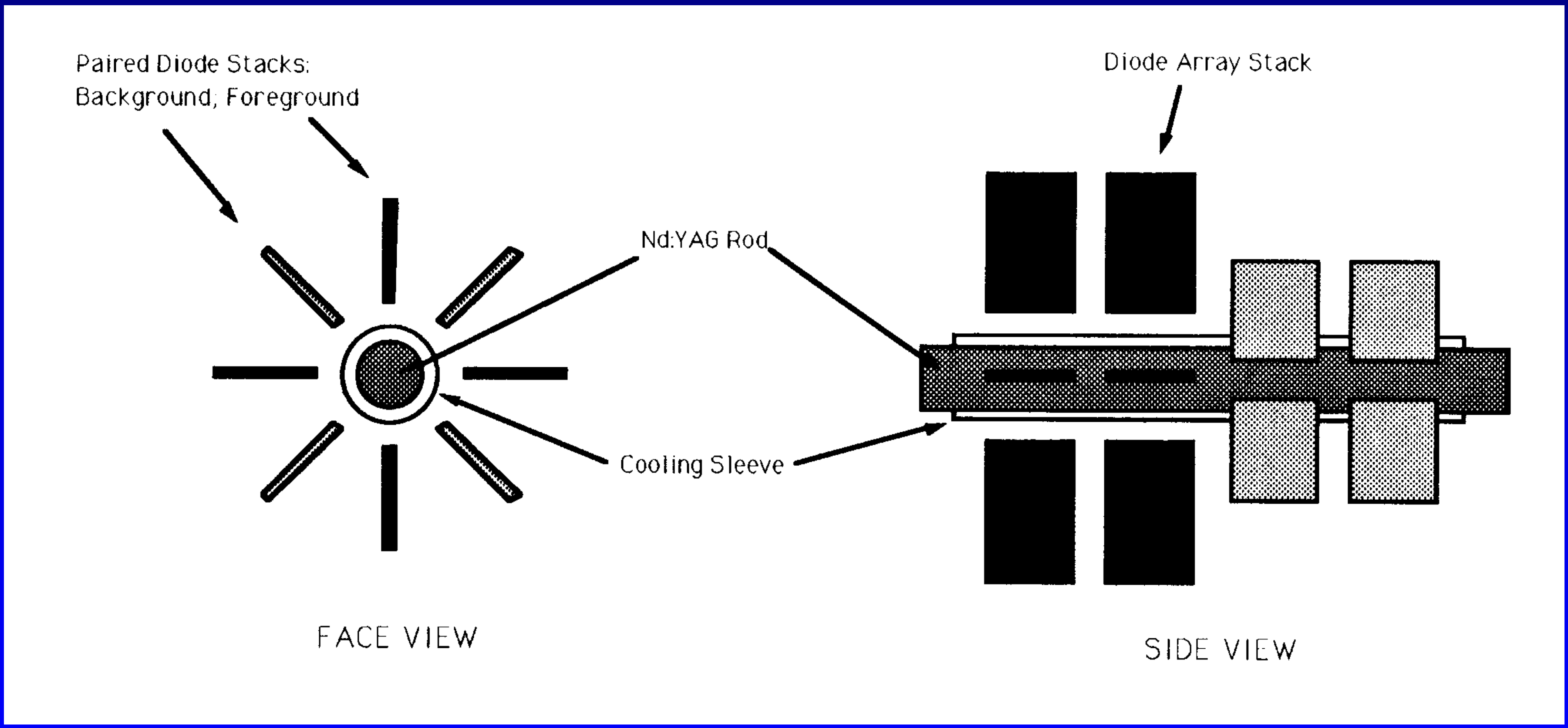


Fig. 1. Compact, modular, dual-rod, diode-end-pumped Nd:YAG laser head capable of producing 80-100 W cw.

Array-pumped rod design (Fibertek)



Array-pumped slab design (MDESC)

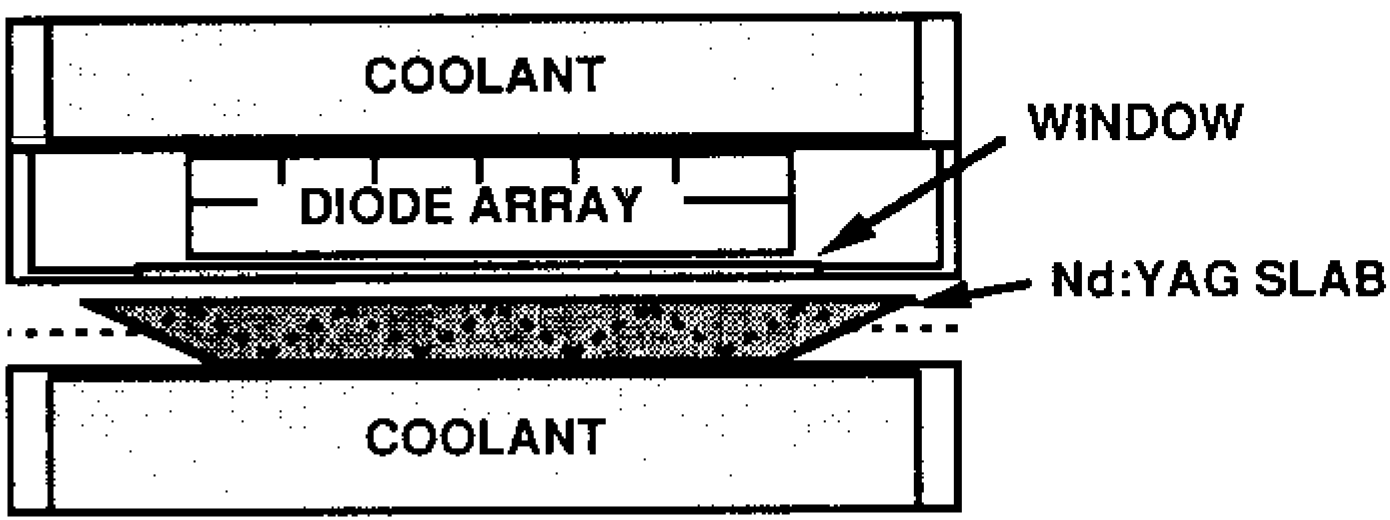
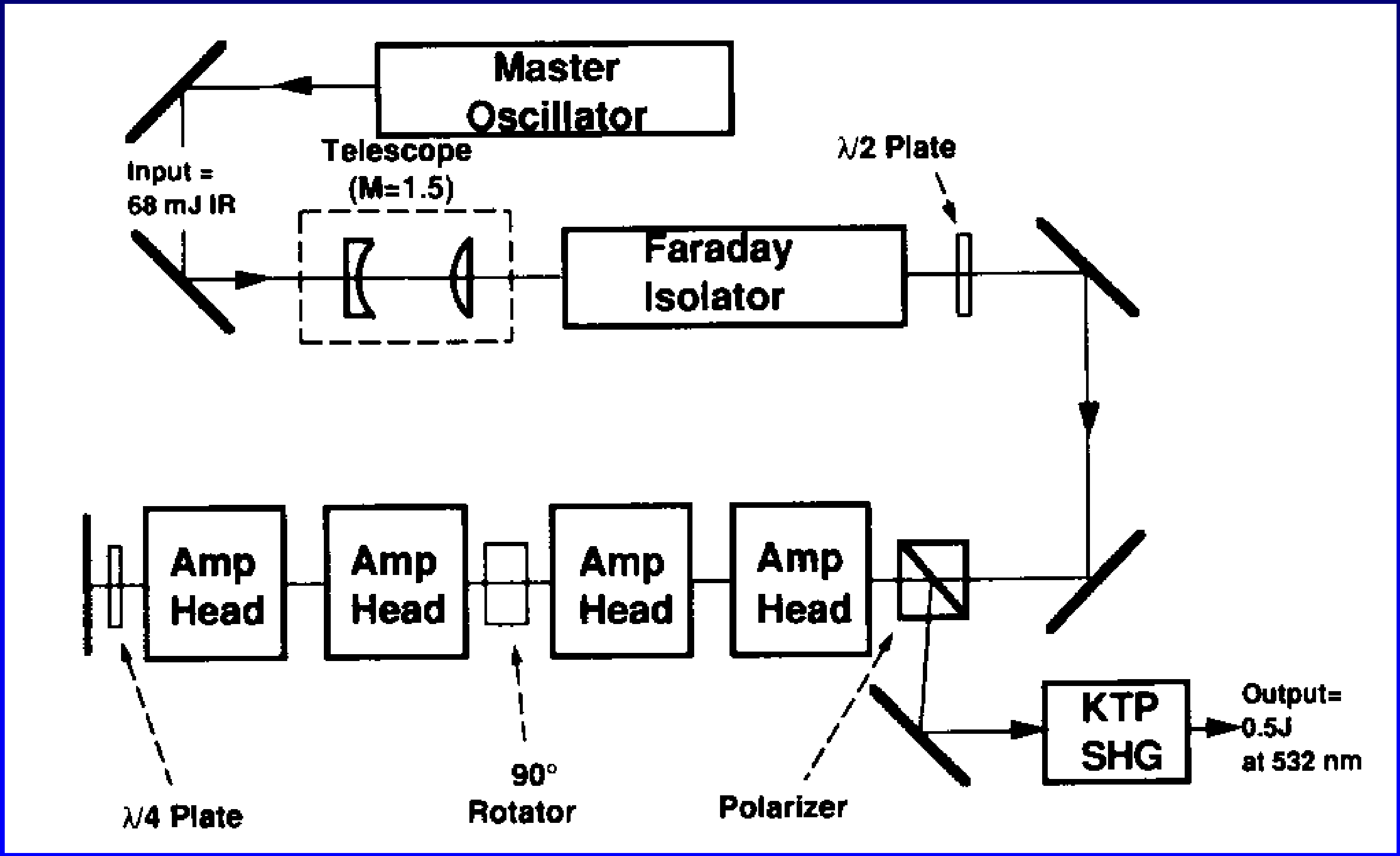
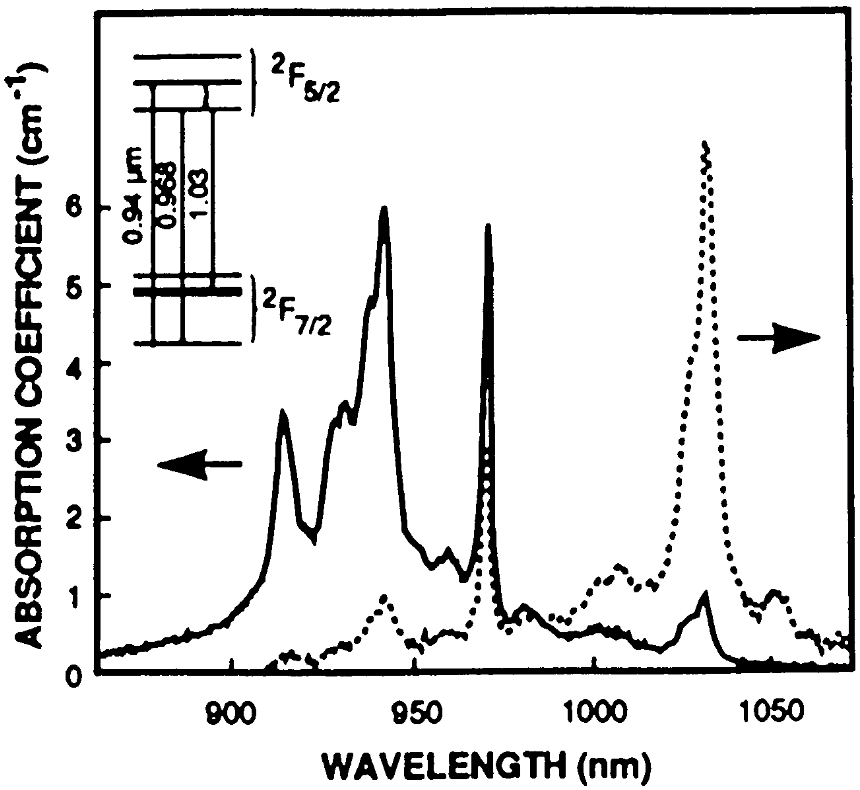


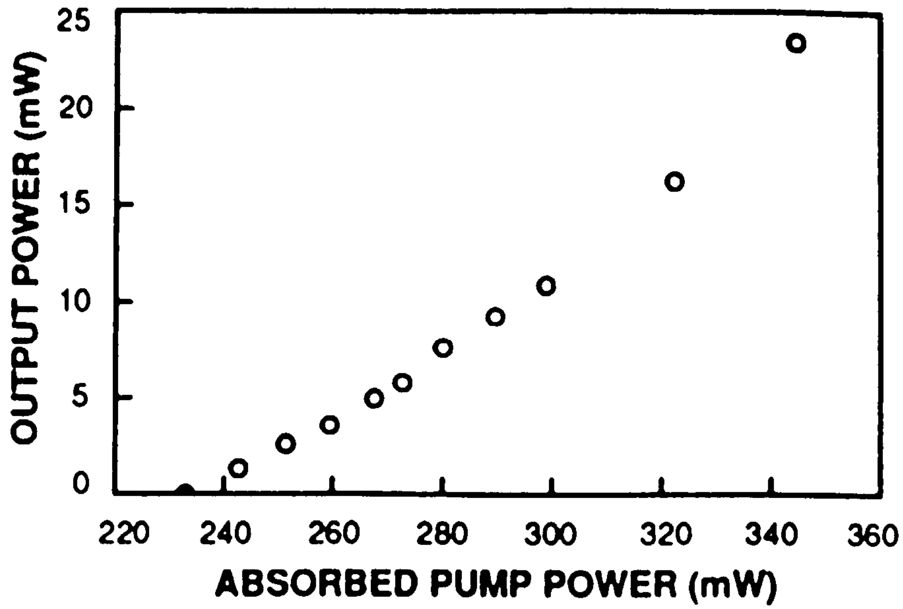
Fig. 2. Diagram of diode-pumped zig-zag slab laser head.

System layout - One-Joule laser (Fibertek)



Diode-pumped Yb:YAG laser
(Fan, Lacovara *et al*, MIT Lincoln)





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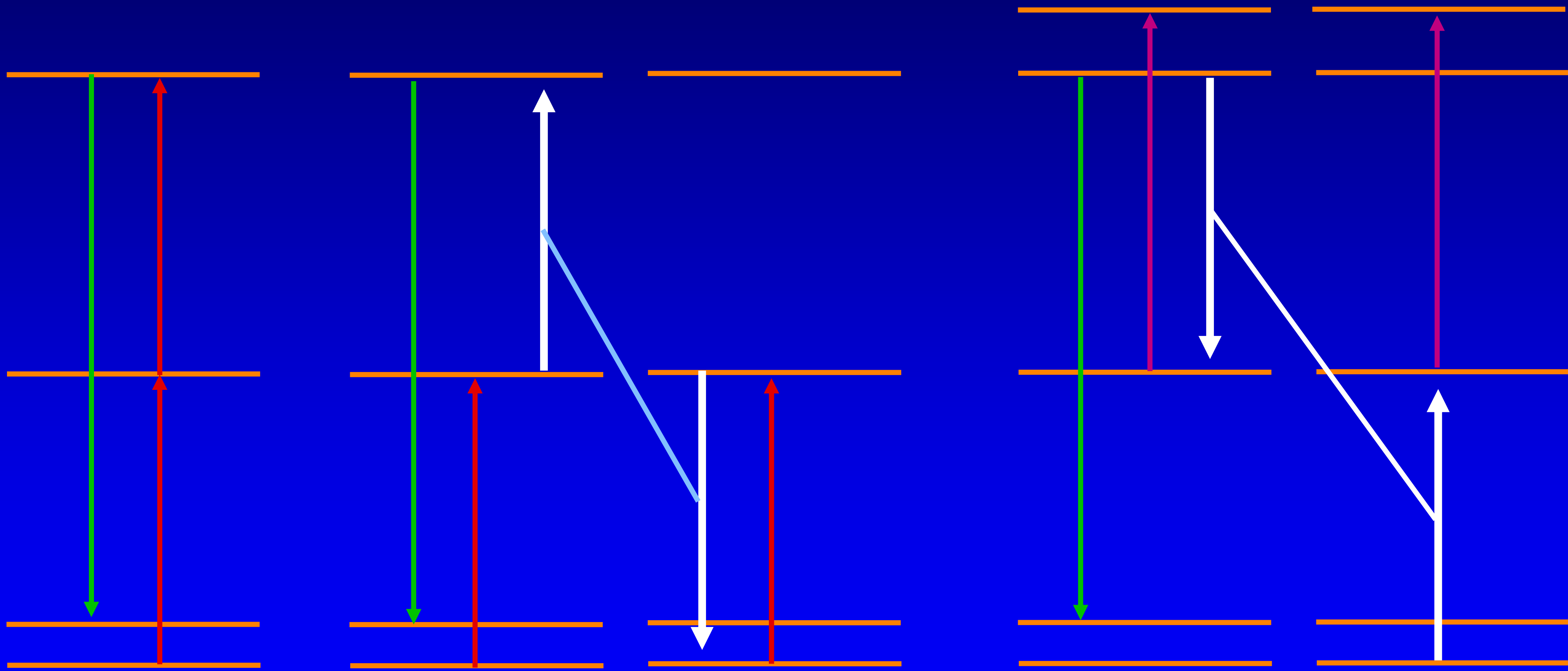
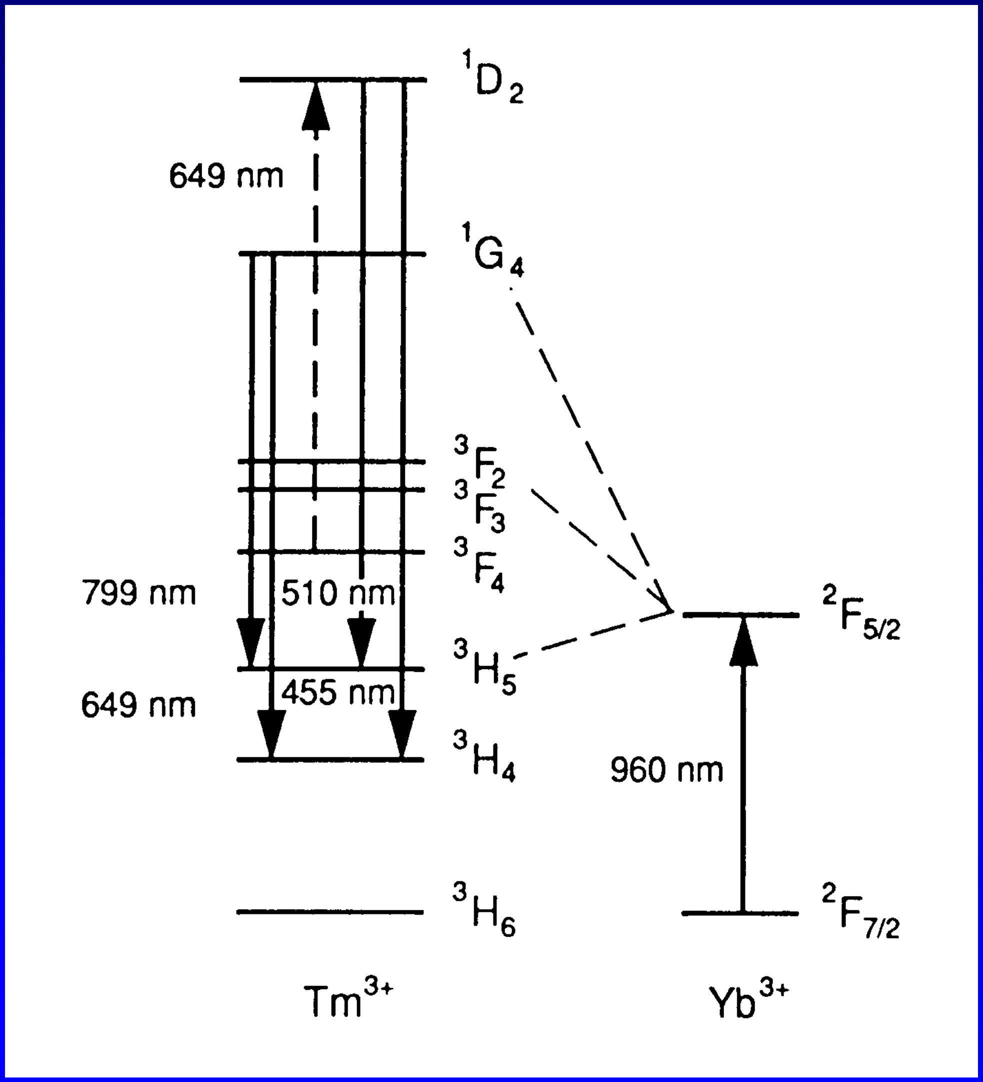
Upconversion processes



Two-step Cross relaxation Avalanche

Room-temperature upconversion (Thrash and Johnson, Amoco)

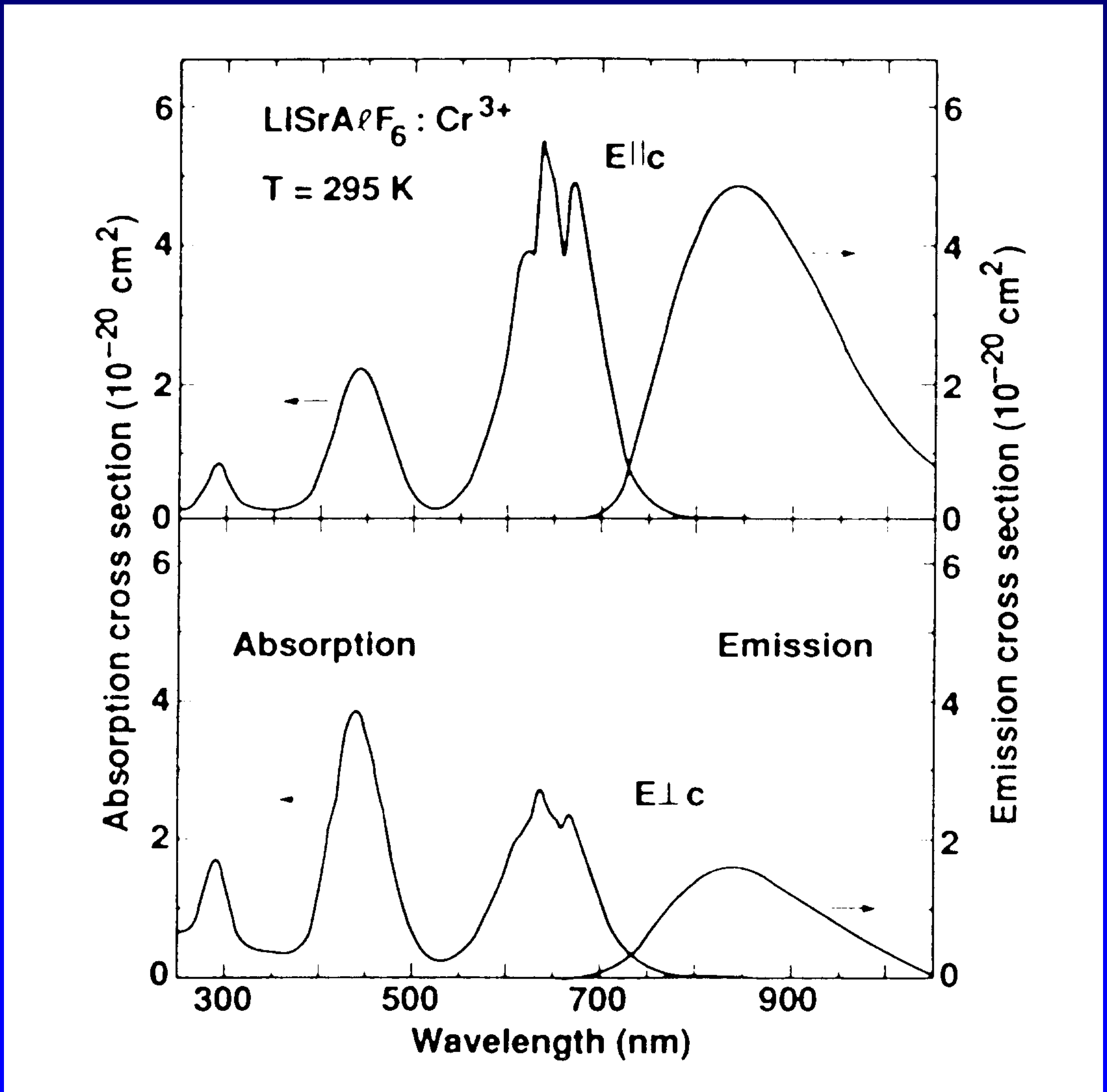
Crystal:
Yb,Tm:BYF



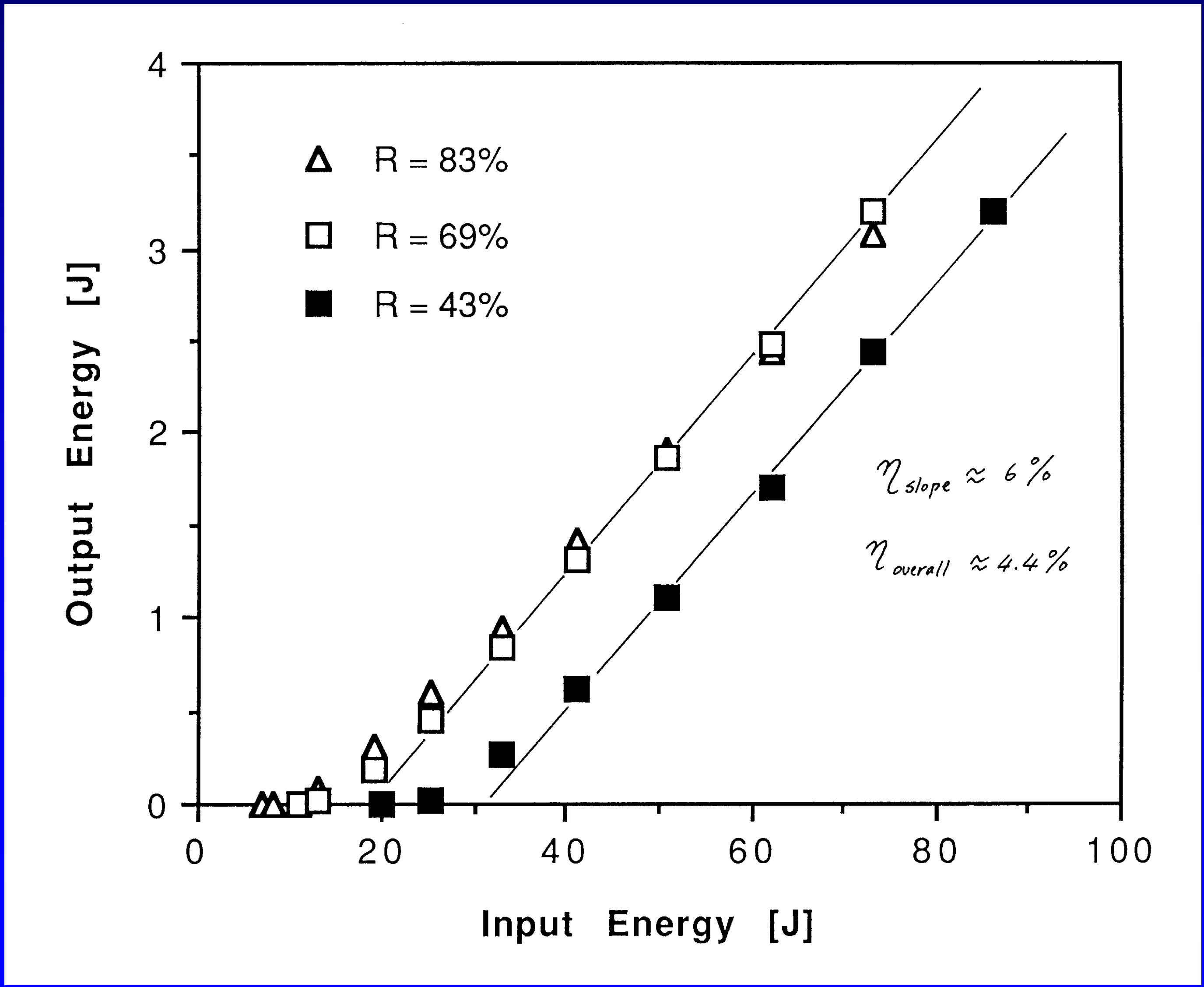
Chromium-doped systems

- Trivalent chromium
  - Alexandrite system has reached maturity
  - Practically all other hosts have significant problems
  - New fluoride hosts LiCAF, LiSAF and variations show considerable promise
- Quadrivalent chromium
  - First identifed in forsterite host
  - Still questions about exact nature of center
  - Other hosts being examined

Cr:LiSAF - Spectroscopy (Payne *et al*, LLNL)



Cr:LiSAF Lamp-pumped data (Bass, Chai *et al*, CREOL)



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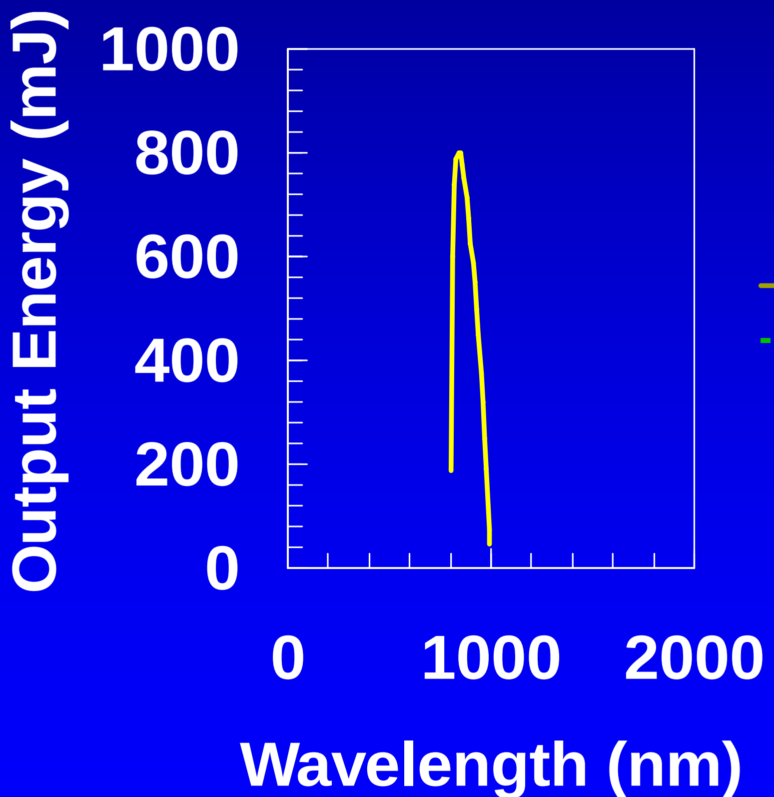
Cr:LiSAF Tuning and Q-switching



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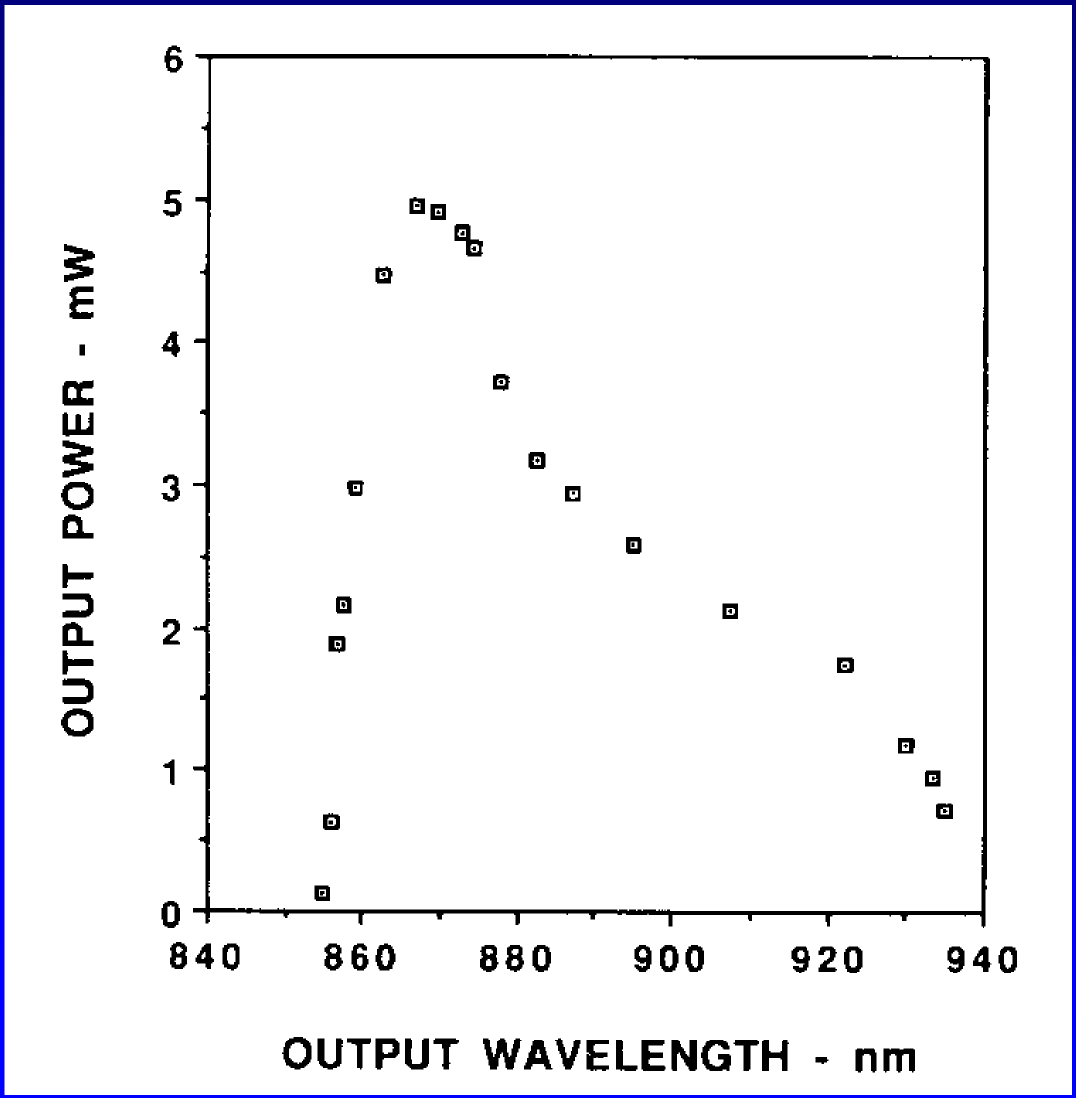
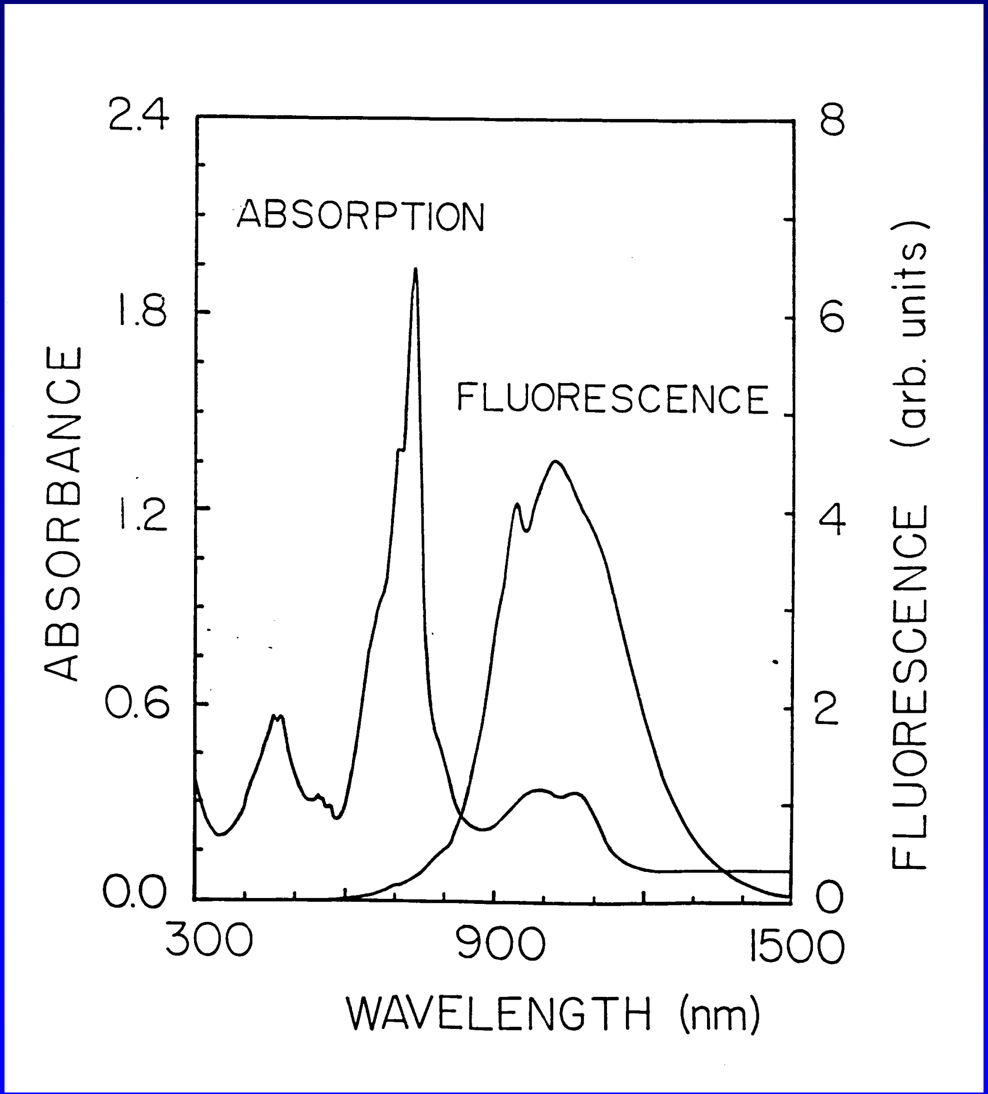
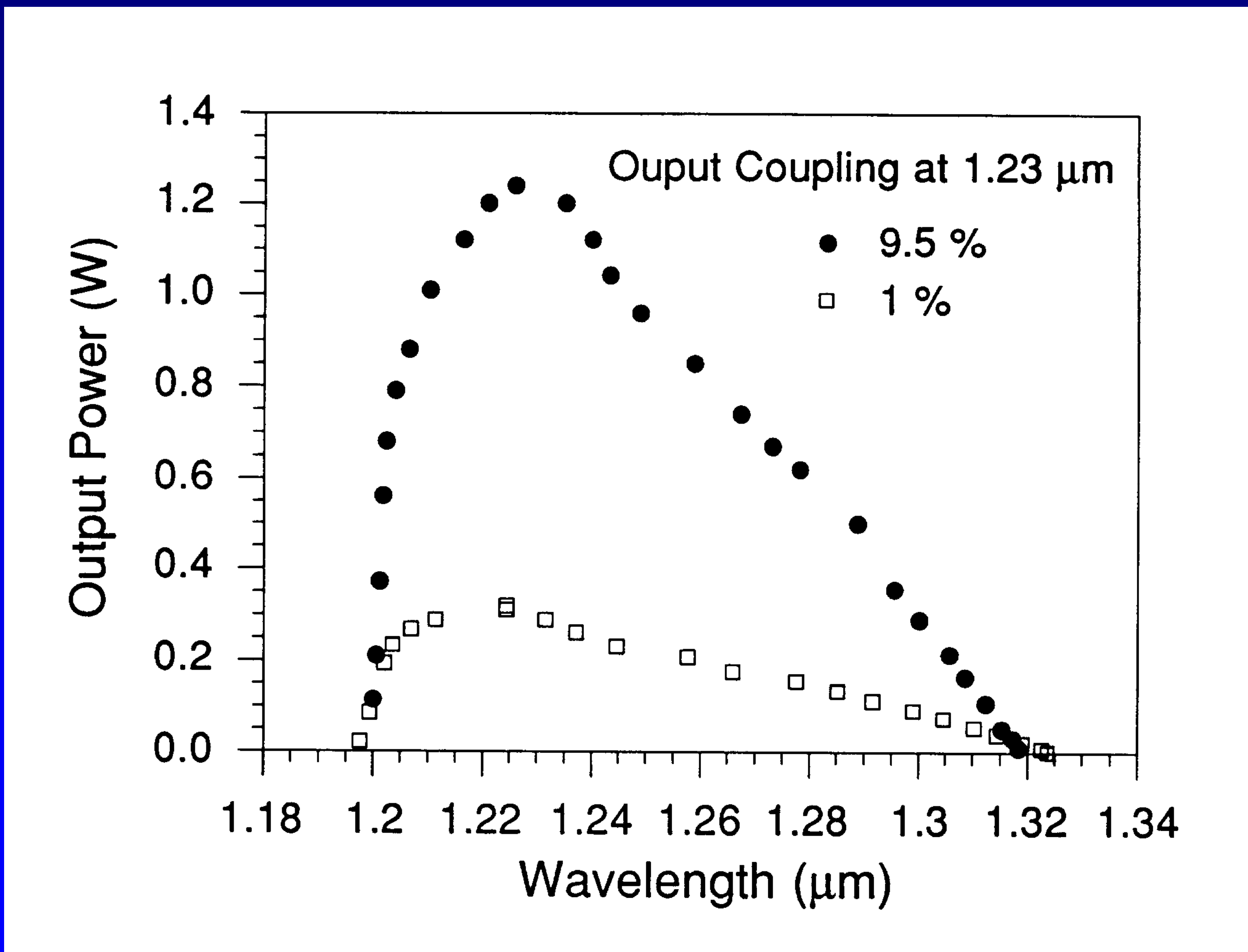
Diode-pumped, tunable Cr:LiSAF (Zhang, Dixon, Chai, Kean, CREOL)



Chromium- doped forsterite (Petricevic *et al*, CCNY, Mitsui)



CW forsterite laser - tuning curve (Carrig and Pollock, Cornell)



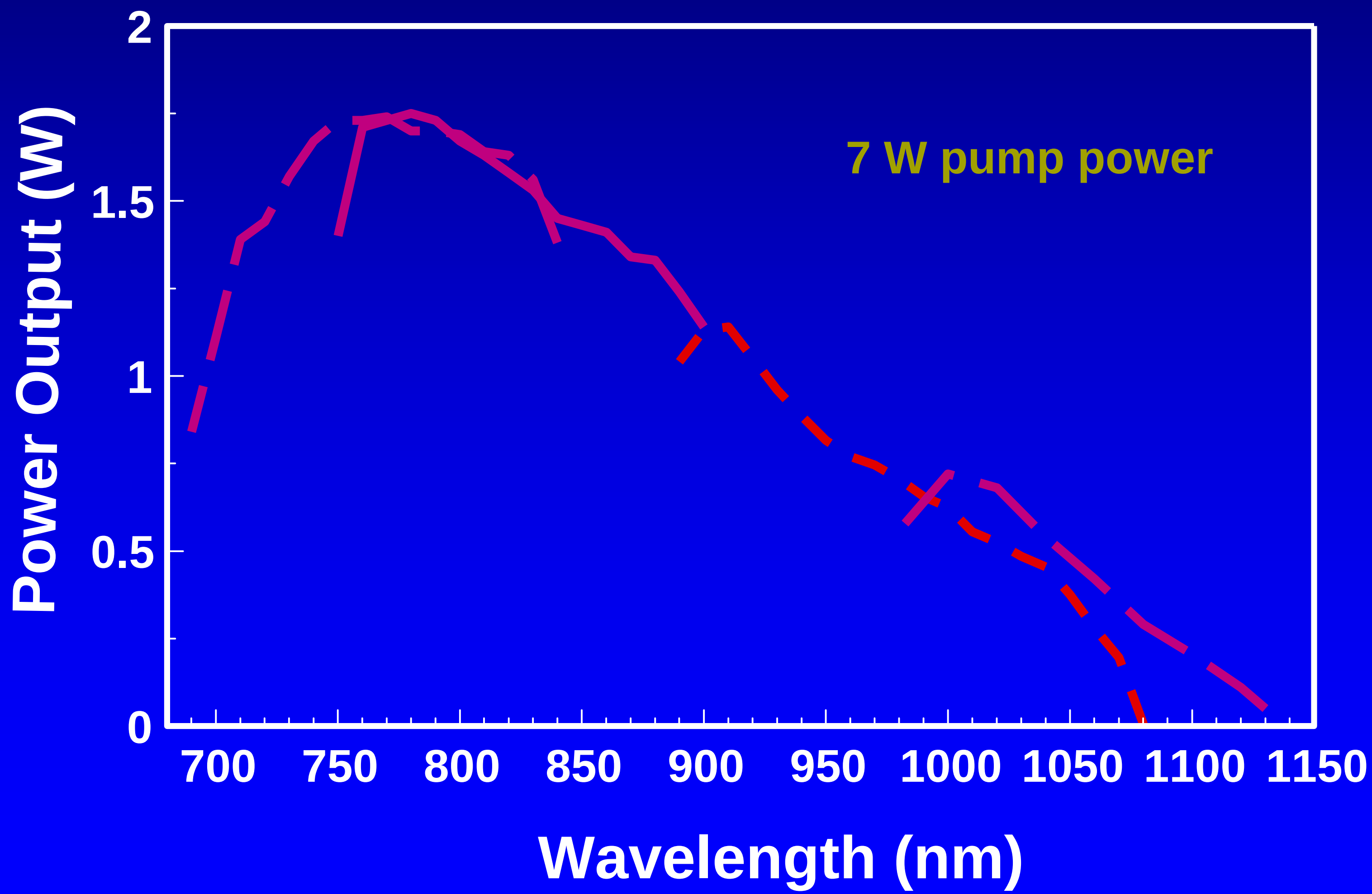
Crystal Temp. = 95 K

Nd:YAG pump power = 6 W

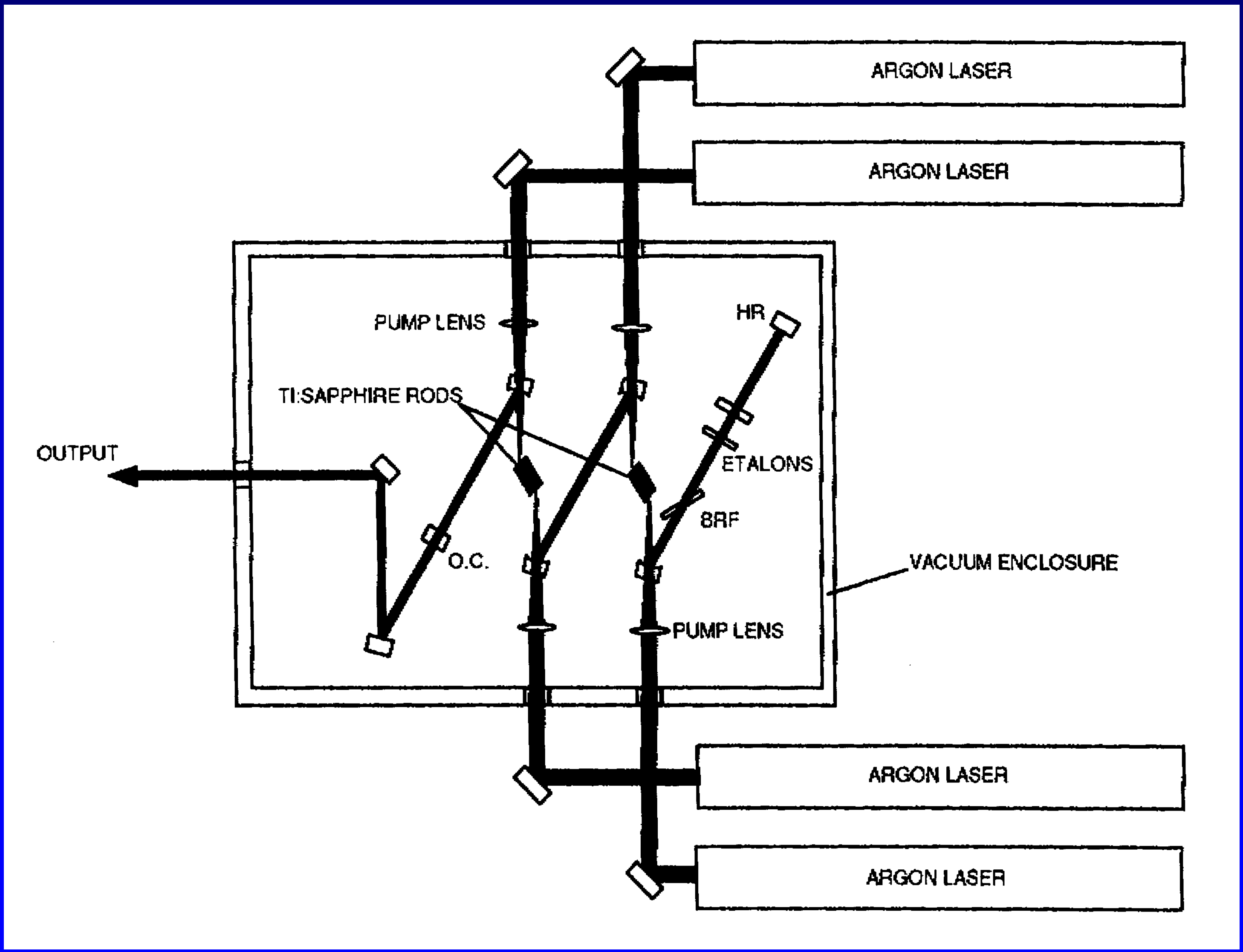
Ti:sapphire lasers

- Tenth-year anniversary
- CW systems
  - 43 W of output power with ion pumping
  - All-solid-state configuration
- CW mode-locked systems
  - Low-pump-power KLM
- Pulse-pumped systems
  - High energies at longer wavelengths
- Application to ultrahigh-power systems

Tuning curve of cw Ti:sapphire laser

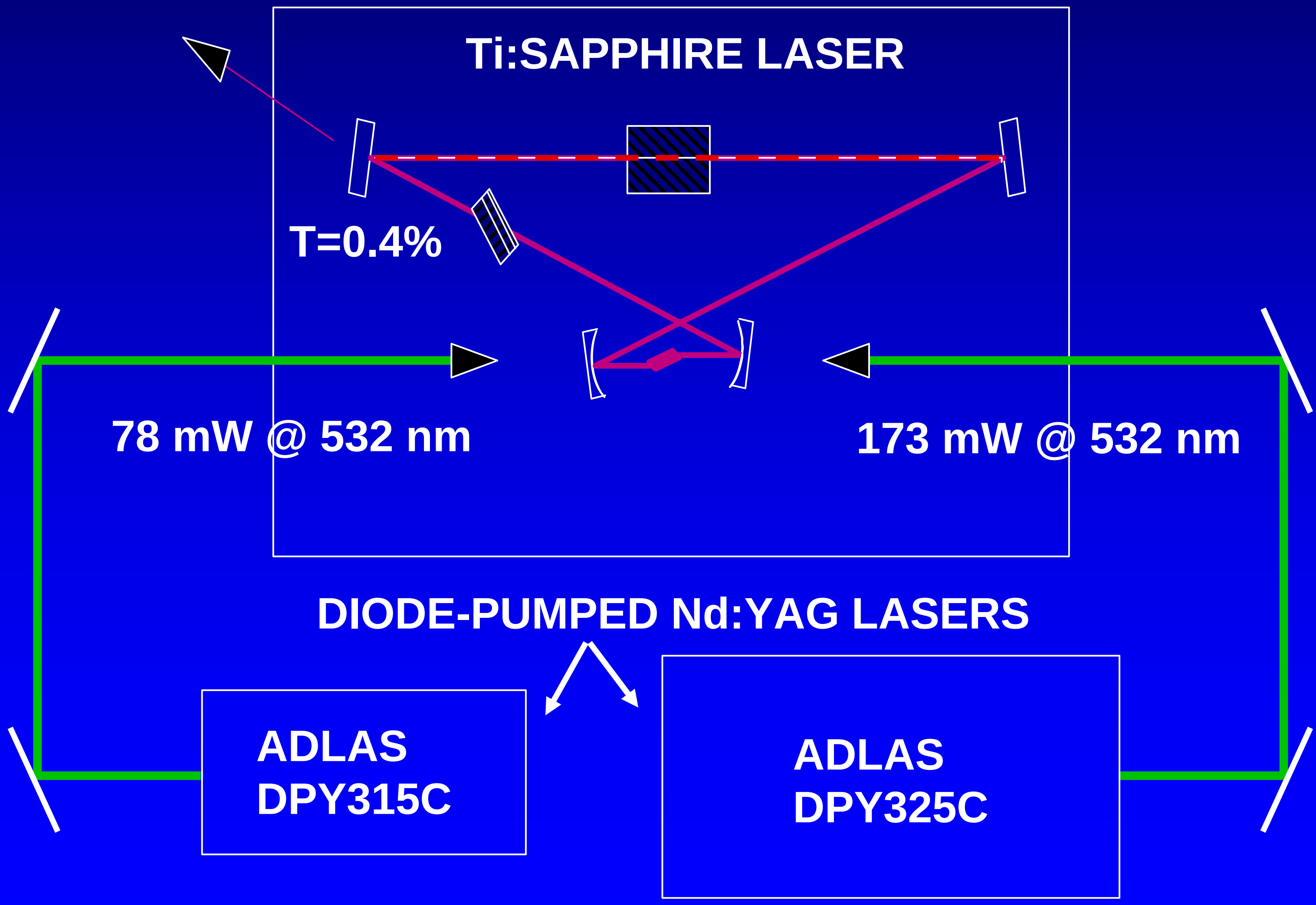


High-power cw Ti:sapphire laser (Erbert *et al*, LLNL)

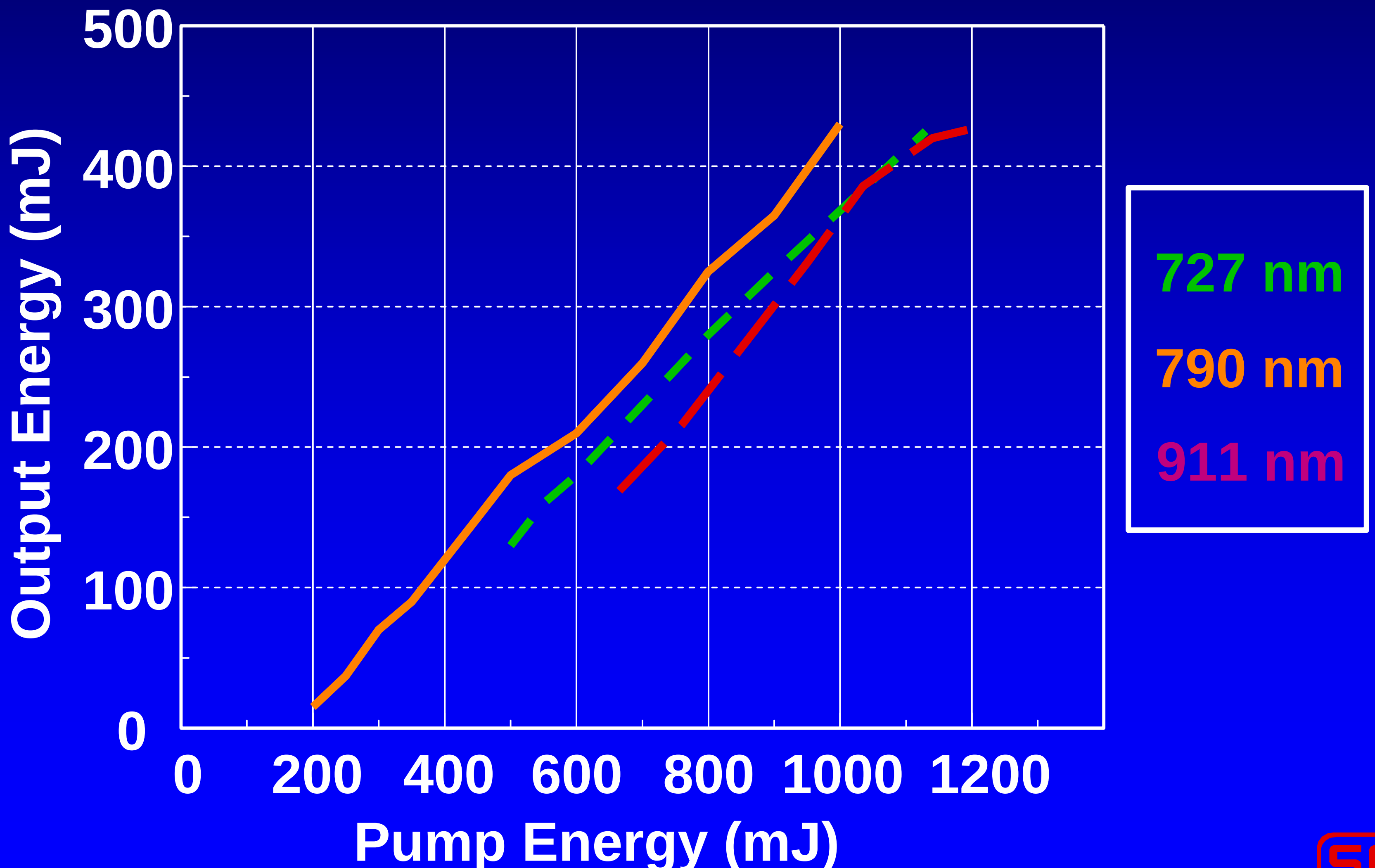


100 W pump
43 W output
TEMoo mode

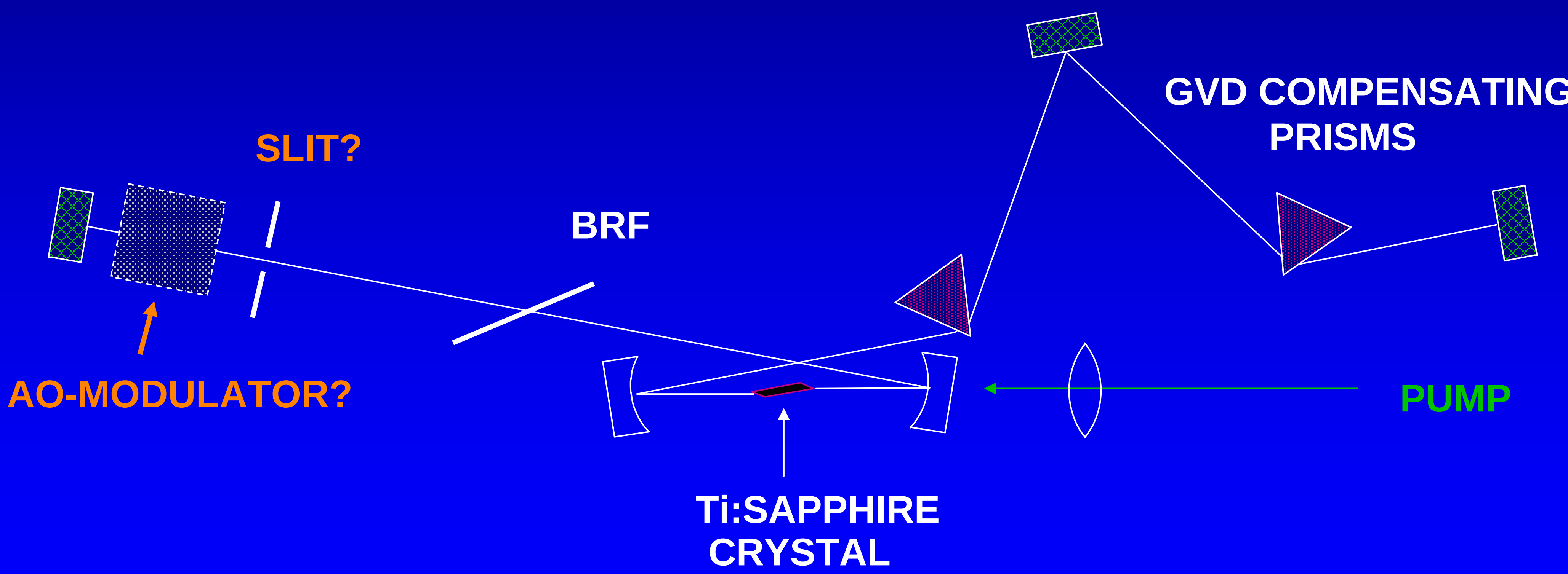
All-solid-state cw Ti:sapphire laser



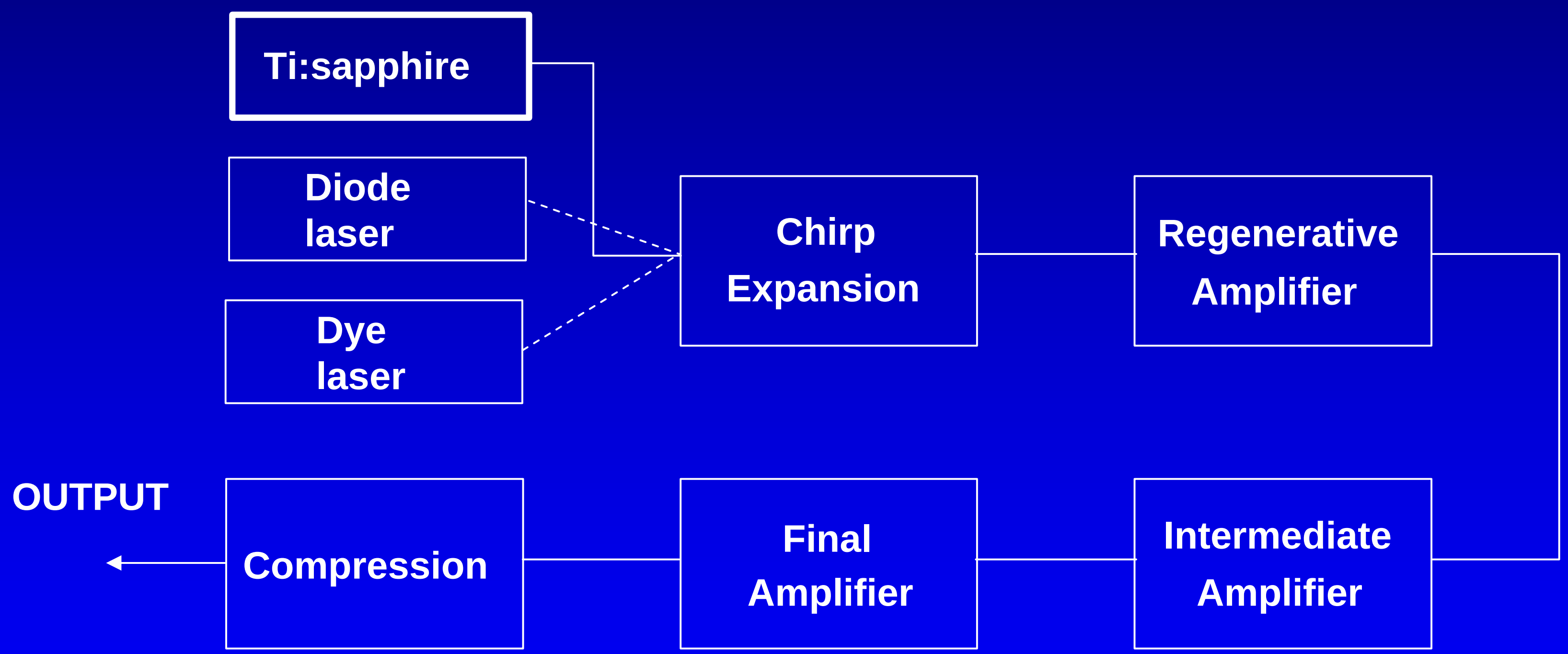
High-energy pulsed Ti:sapphire Doubled Nd:YAG-pumped



Mode - locked Ti:sapphire laser



Ultra-high-power generator - generic chirped- pulse system



Alexandrite?
Ti:sapphire?
Nd:glass?
Cr:LiSAF?

Mid - infrared lasers

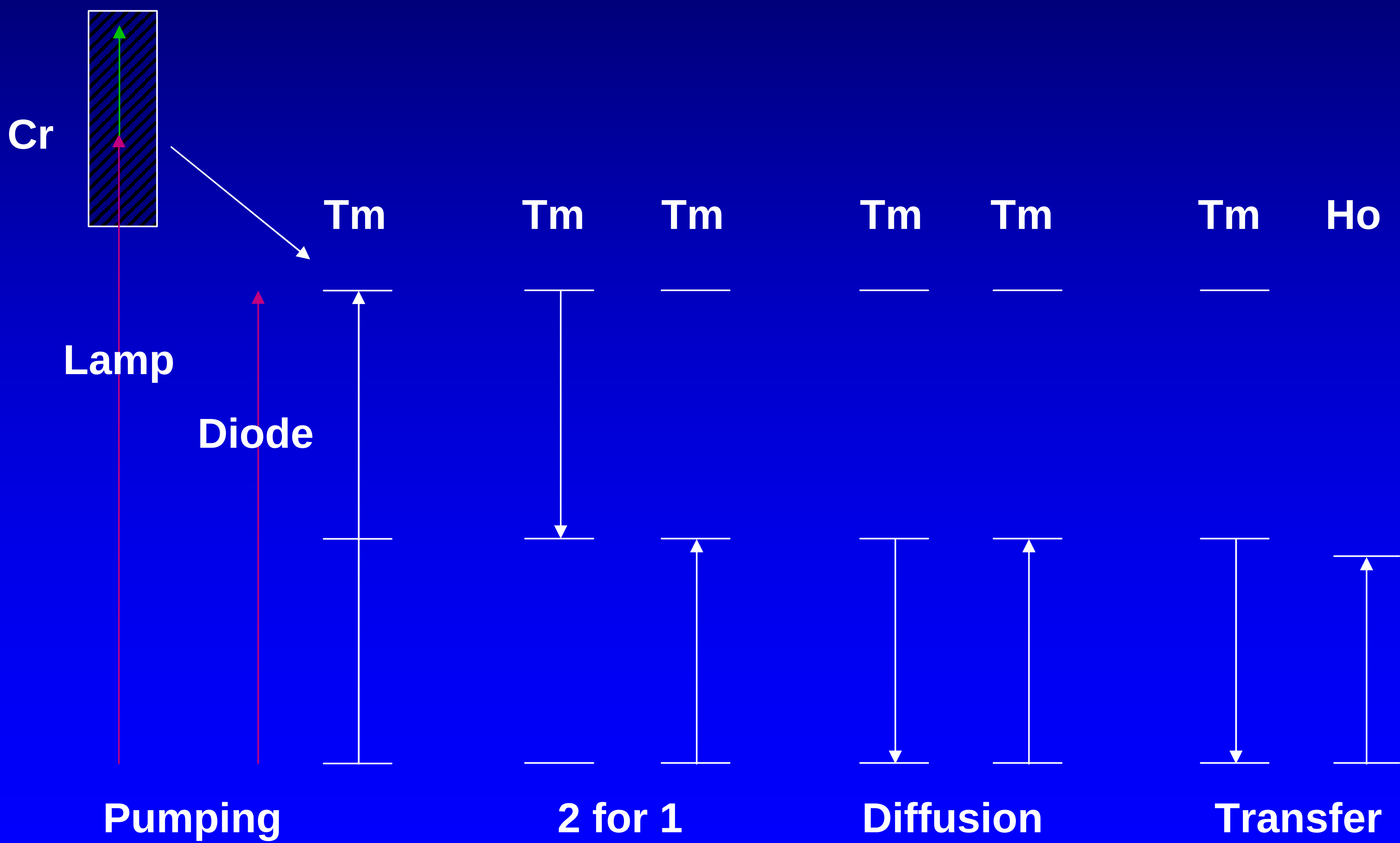
Holmium
- 40 W ave. powers at high, low pulse rates

Thulium
- Watt-level powers from diode pumping

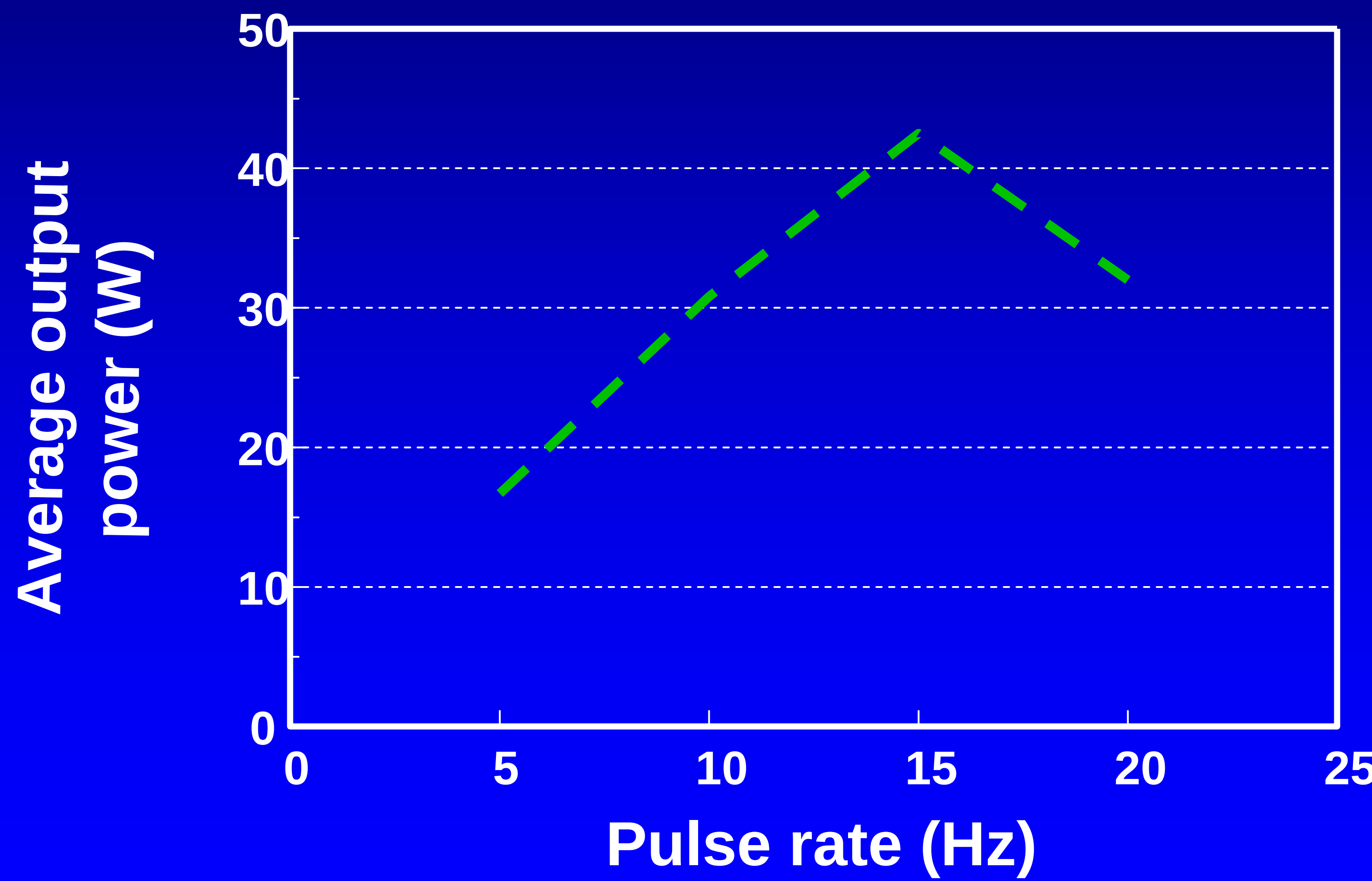
Erbium
- Efficient CW operation in 3-μm region
- CW operation from Er:glass at 1.54 μm

Cobalt
- 0.9 J output at room temperature

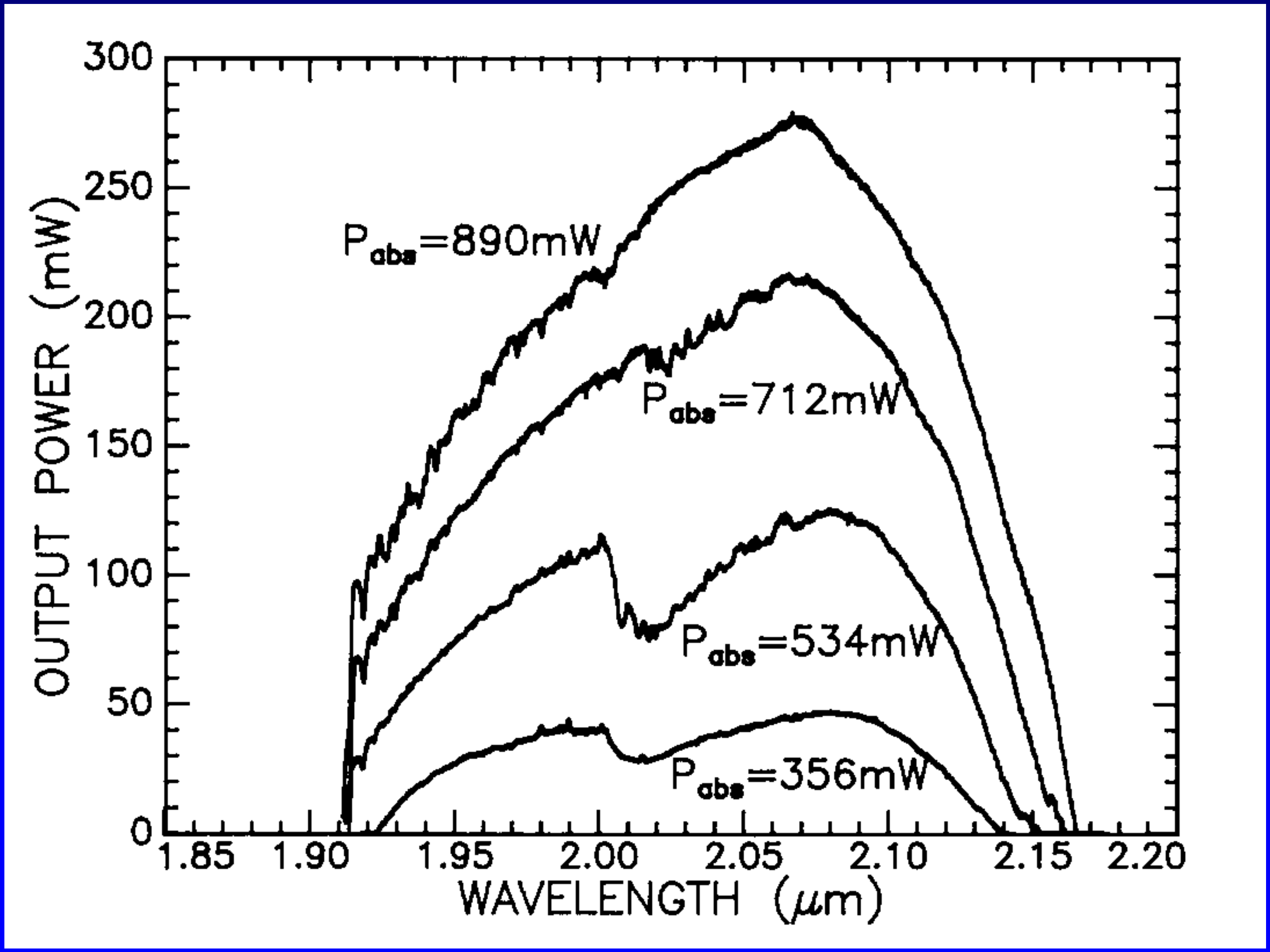
Tm-Ho pumping process



High-power CTH:YAG



Tm:YAG tuning curve (Stoneman and Esterowitz, NRL)



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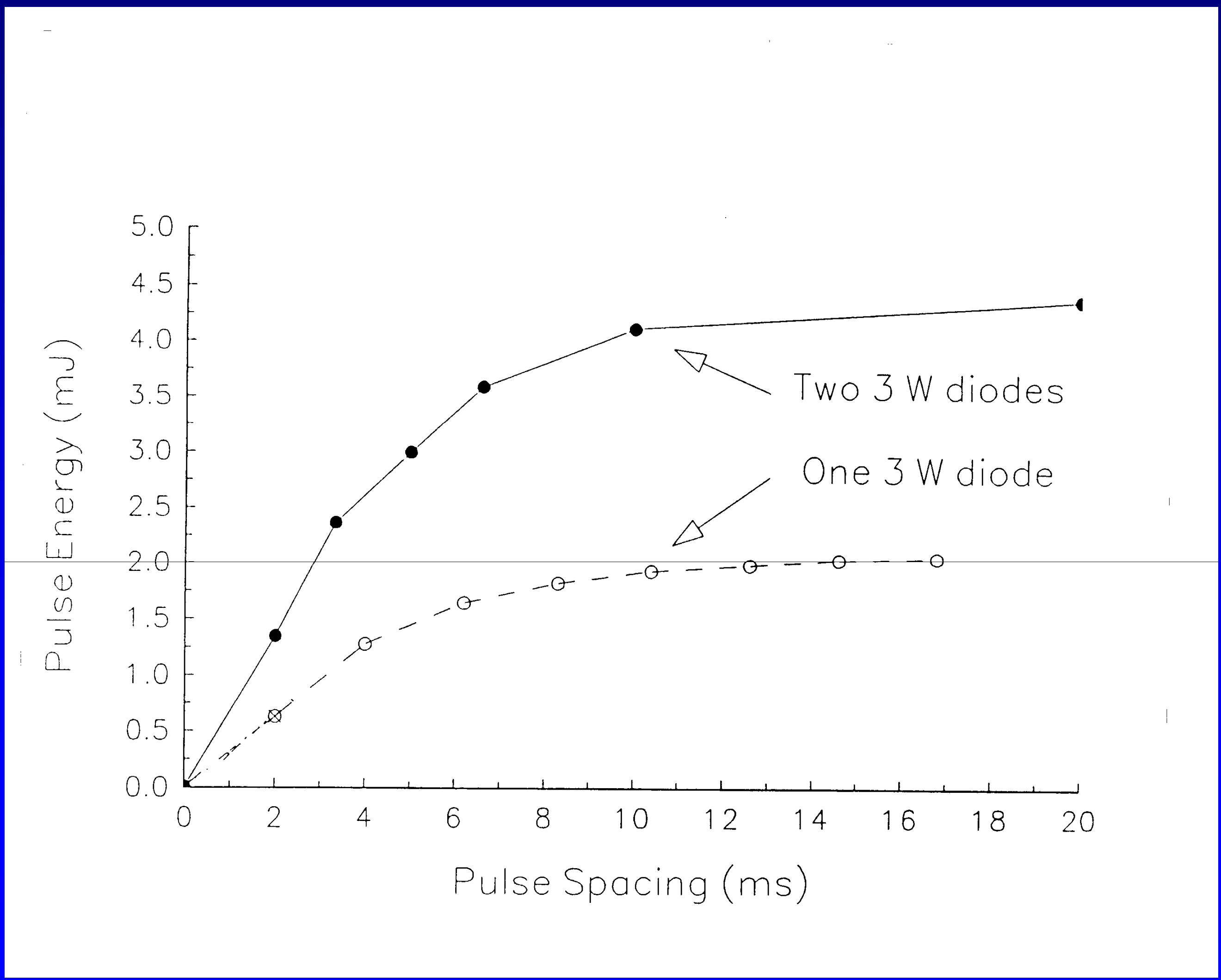
Diode-pumped, Q-switched Tm:YAG (Suni and Gates, CTI)



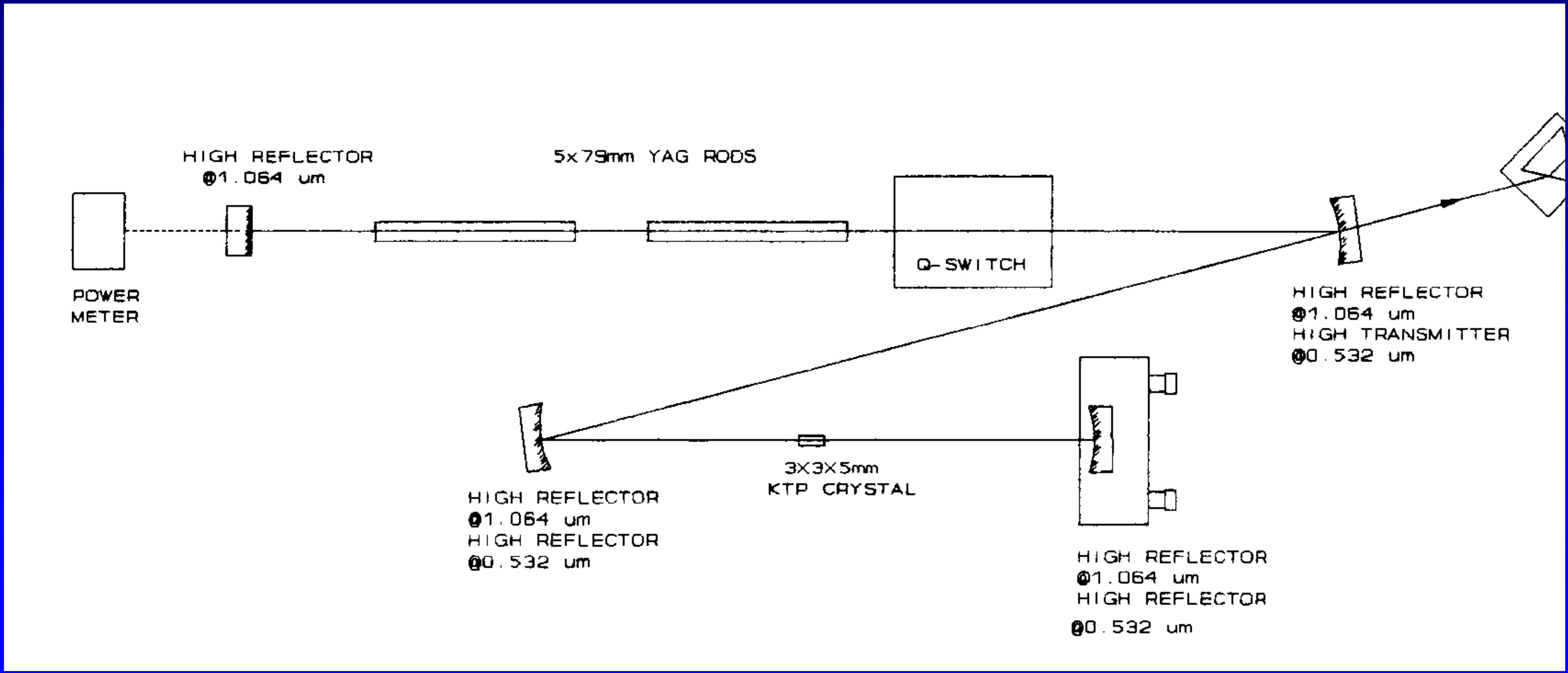
Also:
Session CMD,
6 W output
(Shannon *et al*,
Lightwave)

Nonlinear conversion

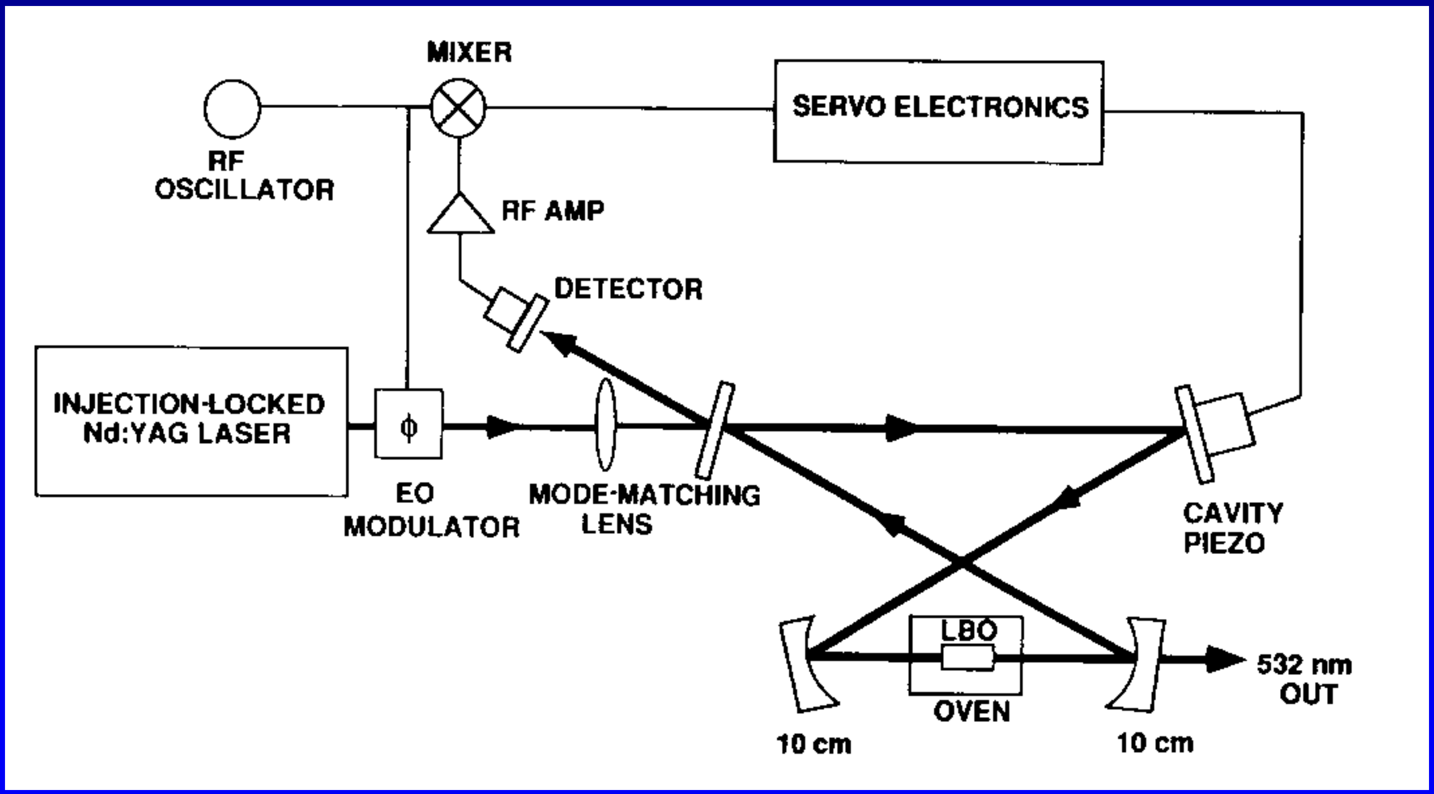
Harmonic generation
- Record levels of SHG average power
- Resonant-cavity SHG, FHG
- High-energy tunable SHG, SFG, THG and FHG from Ti:sapphire

Parametric conversion
- BBO, LBO - broadly tunable visible, IR
- KTP - near, mid-IR
- Semiconductors - mid, far-IR

>100 W Pave Doubled Nd:YAG (Ortiz, Kuizenga, Fair, Laserscope)

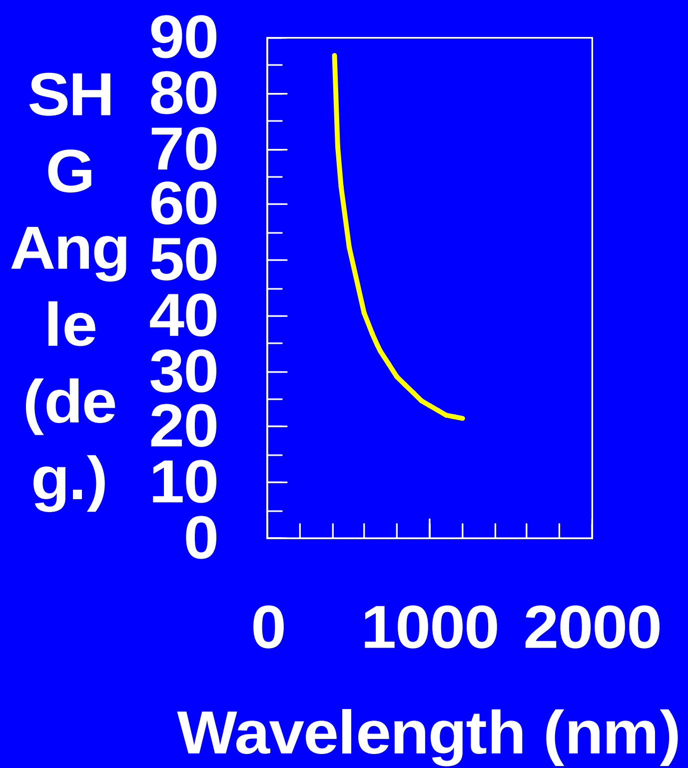


6.5 W CW Doubled Nd:YAG laser (Yang *et al*, Stanford)



Other sources:
Ti:sapphire
Nd SH

Ti:sapphire - harmonic generation in BBO



SHG
- 340-525 nm
- 60% conversion

THG
- 227-350 nm

FHG
- 205-263
- 10 mJ at 220 nm

Emerging applications (besides science)

- Diode-pumped
  - "Crystal oscillator"
  - Lasers in flight
  - Materials processing
- Upconversion
  - Optical storage, display
- Chromium
  - "Desktop" high-power
- Ti:sapphire
  - Remote sensing
  - Ultrafast, medical diagnostics
- Mid-infrared
  - Laser surgery
  - Coherent lidar
- Nonlinear
  - Materials processing
  - Remote sensing

The future

- Higher-power, higher-brightness, new-wavelength diode lasers
  - Improved pumping capability
  - New systems
  - Replacement of cw solid state lasers
- New and/or improved materials
  - More wavelengths
  - Enhanced performance

How to avoid a new dark ages

- Maintain commitment to fundamental, vaguely specific materials research
  - Government
  - Industry
- Reduce uncertainty about industrial, national goals
- Get out of the laboratory!