Eye safe solid state lasers for remote sensing and coherent laser radar

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How to make a laser sensor “Eye-safe”

Keep energy/power low

- Low power laser, Large transmitted beam
- Low Duty Cycle
- Select wavelength for maximum allowed pulse energy

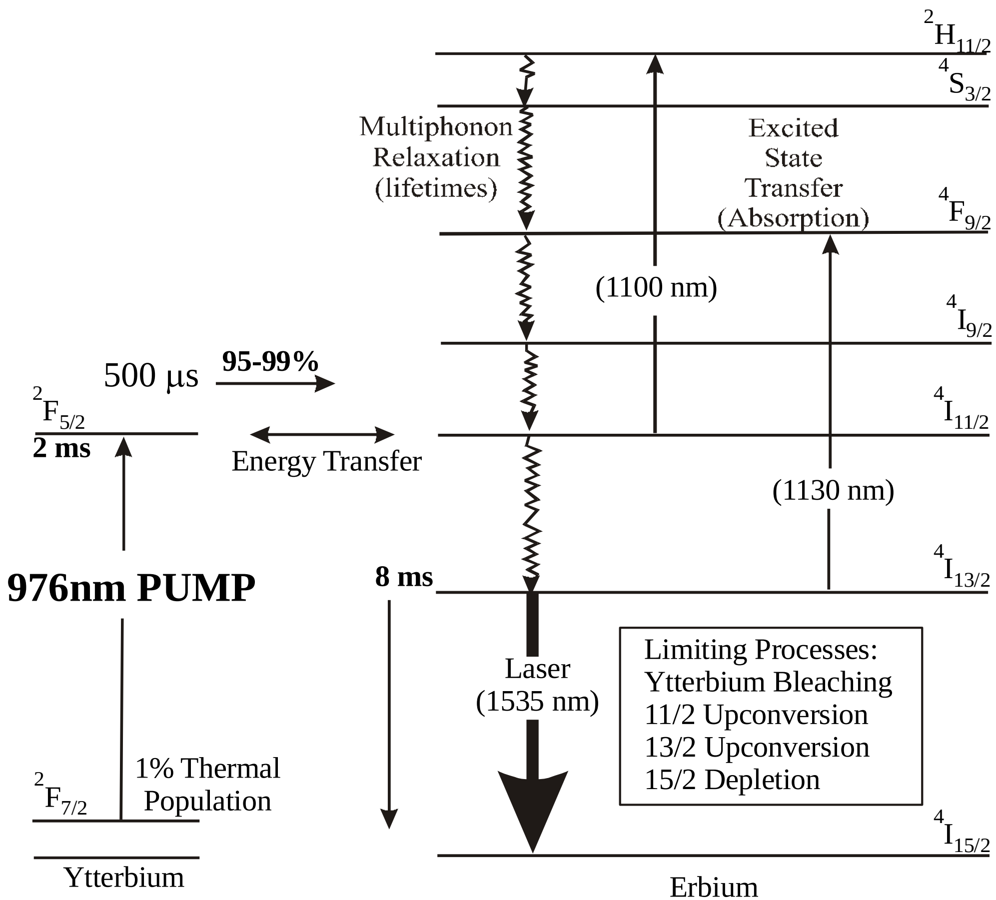
Content of talk

- Coherent eye-safe laser radar: Review of current work in Er:Yb:glass slab lasers
- Planned work in Er:Yb:YAG
- New composite slab laser design
- Eye-safe sensing at low power

Our chosen Eyesafe laser species is Erbium

- Erbium lases at 1.5 – 1.6 μm, where laser safety allows:
  - 10× the energy per pulse allowed at 2 μm
  - 100x the energy per pulse allowed at 10 μm
- Allows better spatial resolution (for otherwise similar conditions)
- Can make use of available telecommunications photonic components: eg Master fiber oscillator
- BUT: it is a 3-level laser, normally in a phosphate glass host

Er:Yb energy level diagram



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Summary of Early work in Adelaide*

- Demonstrated first injection seeding of single frequency Er:glass laser at 1.5μm

- Demonstrated successful transform limited coherent Doppler measurement at 1.5μm

- Initial wind sensing measurements

*A. McGrath, J. Munch, G. Smith, P. Veitch, Appl. Opt. **37** (29), 5706-5709 1998.

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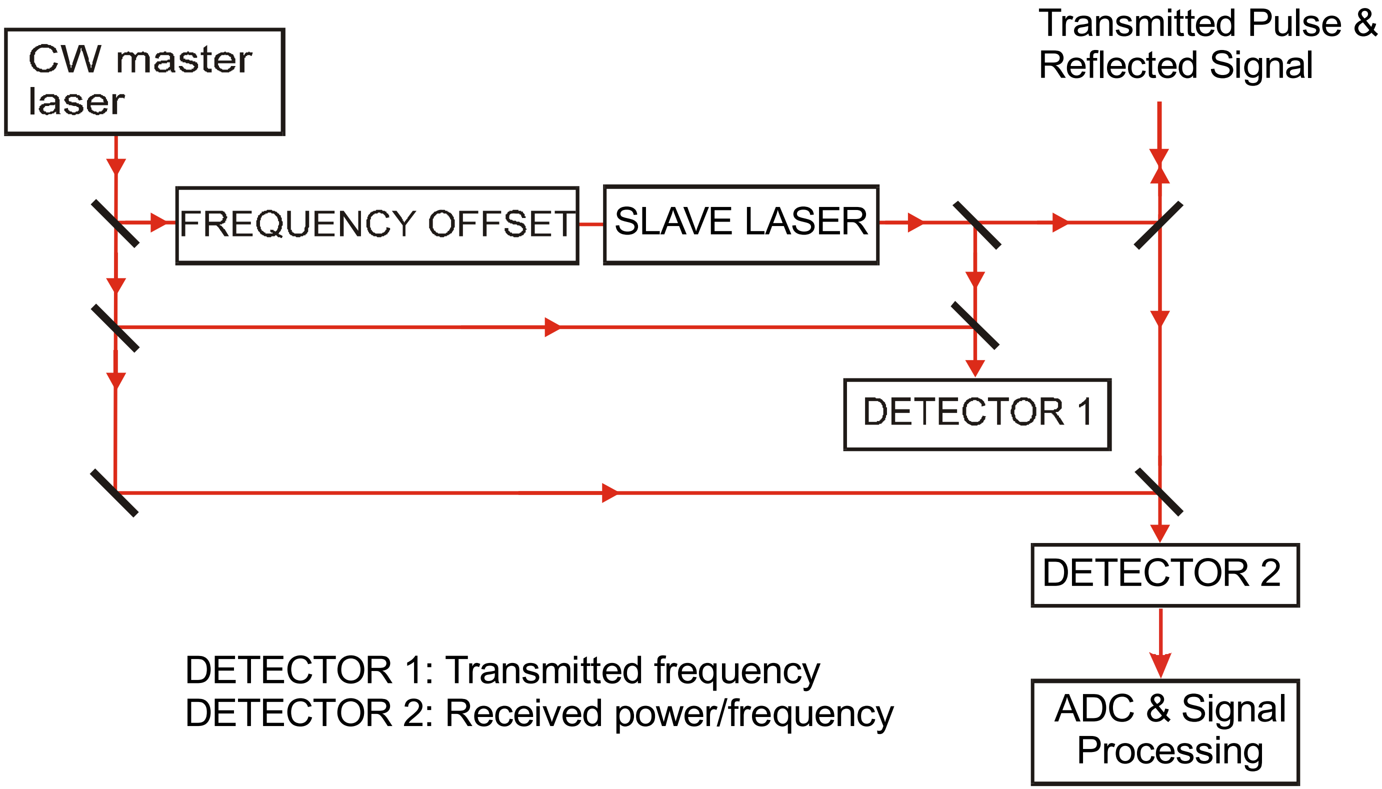
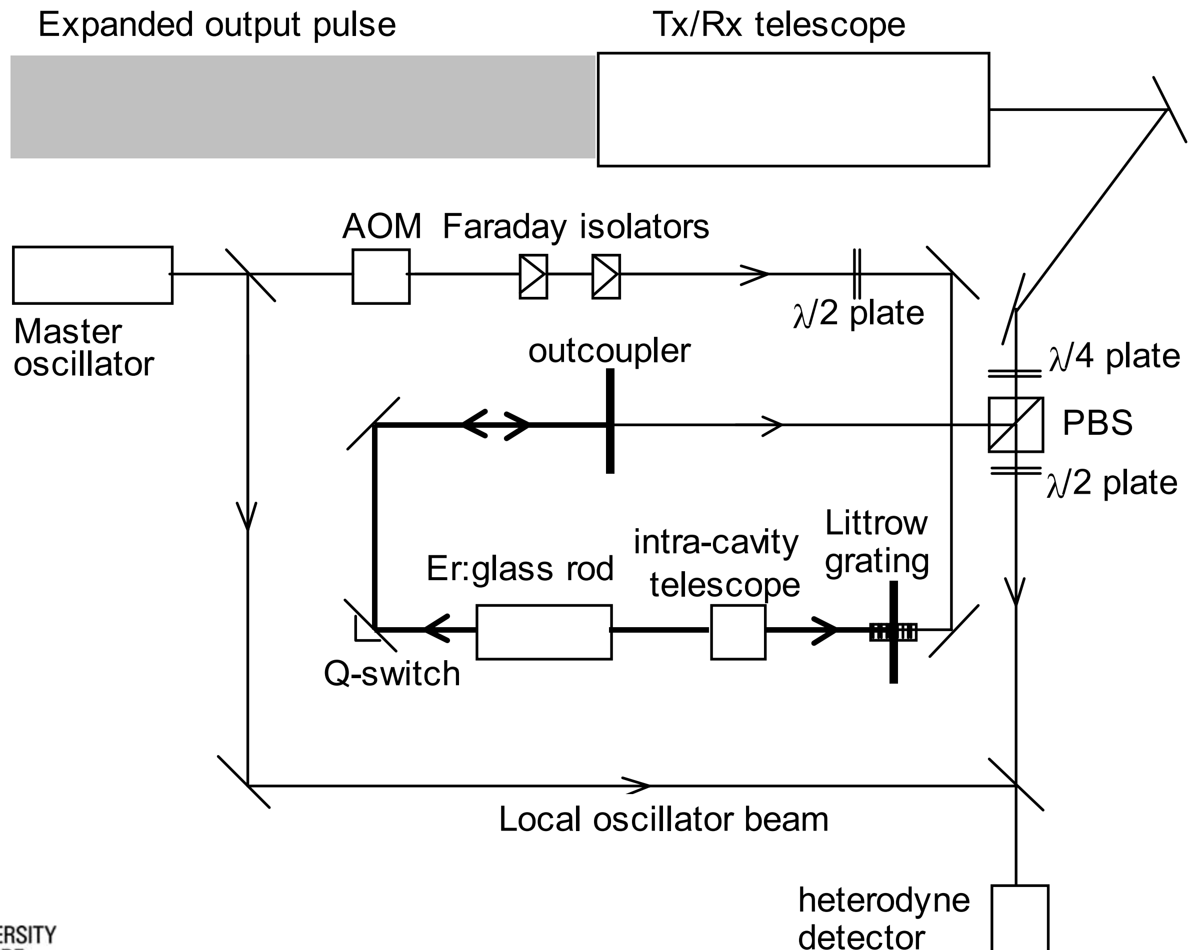
Coherent Laser Radar



DETECTOR 1: Transmitted frequency
DETECTOR 2: Received power/frequency

First injection seeded Er:glass at 1.5μm



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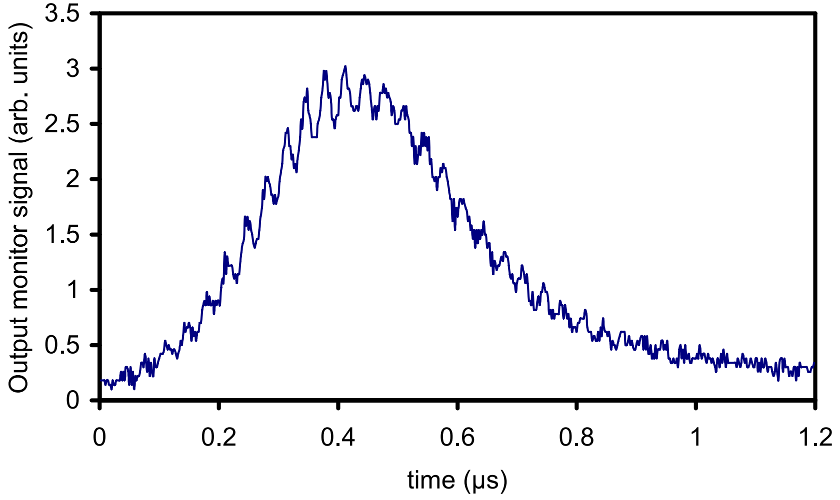
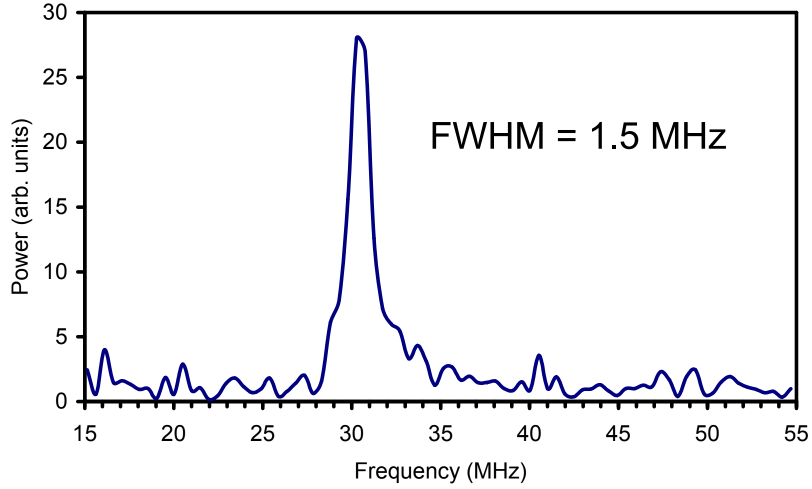
The injection seeded, Q-switched laser produced a transform limited linewidth





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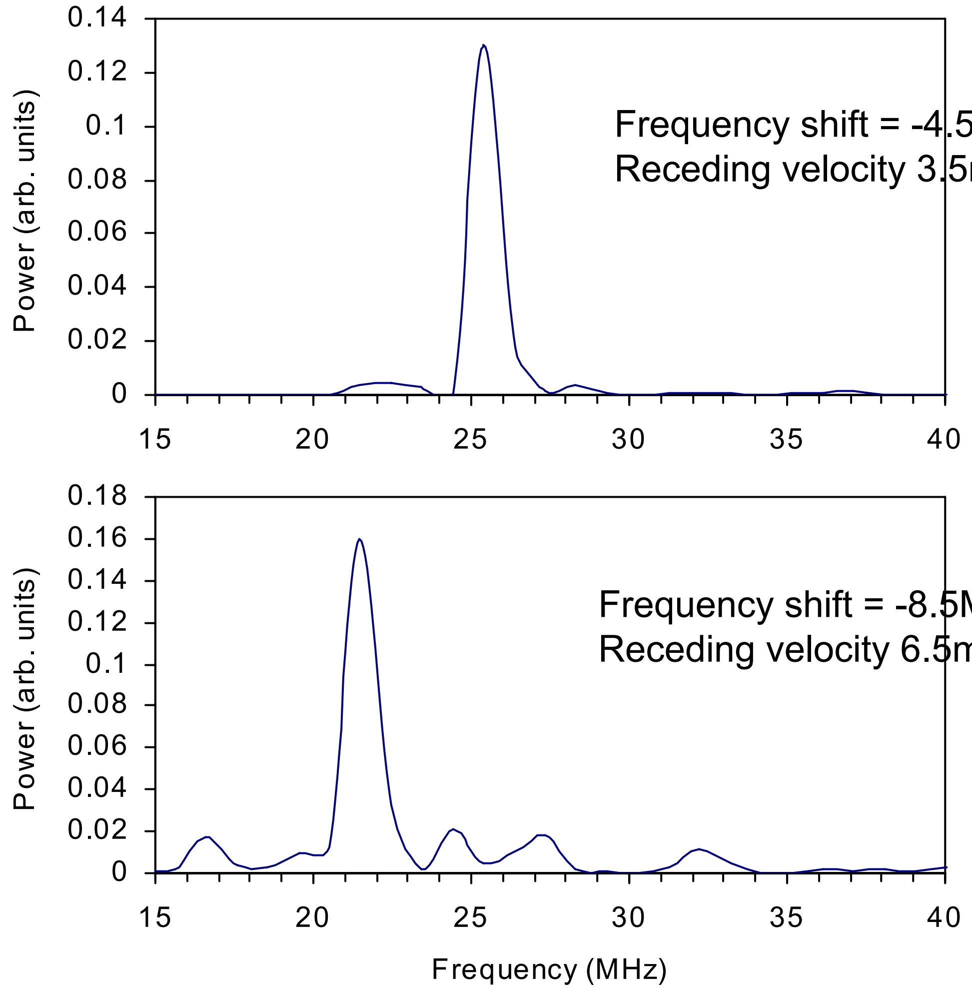
We used the Er:Glass laser to make a Doppler velocity measurement of moving hard-targets



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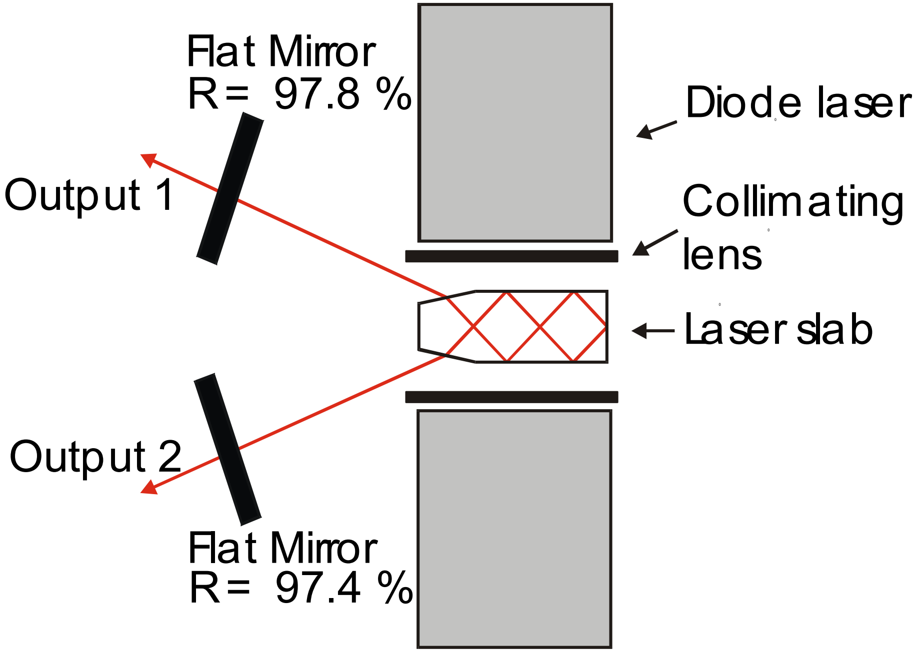
Second Generation Er:Yb:Glass Slab

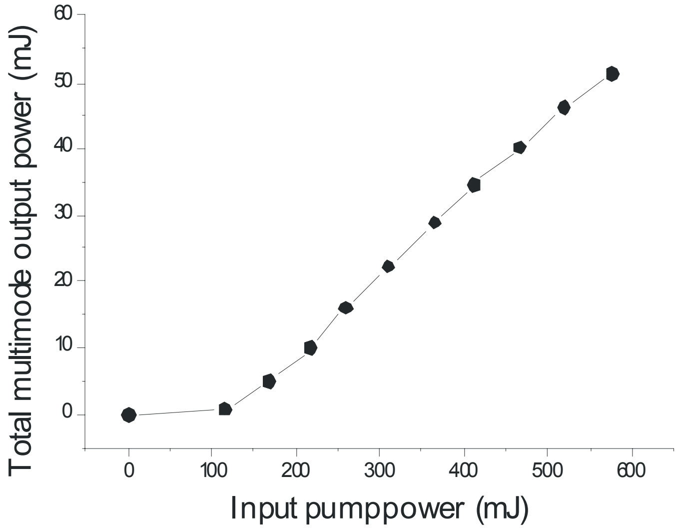
- Robust laser design
- Folded, total internal reflection, zig-zag slab
- Diode laser side-pumping (Q-CW)
- Injection seeded, Q-switched ring
- Long output pulse, using new resonator design with efficient out-coupling via throttled Q-switch

Standing-wave Er:Yb:Glass slab laser

Setup



Output power



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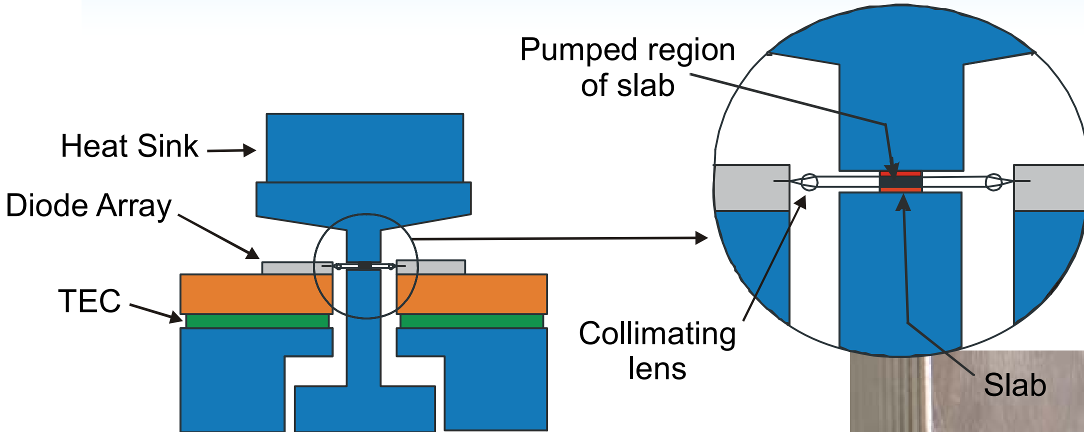
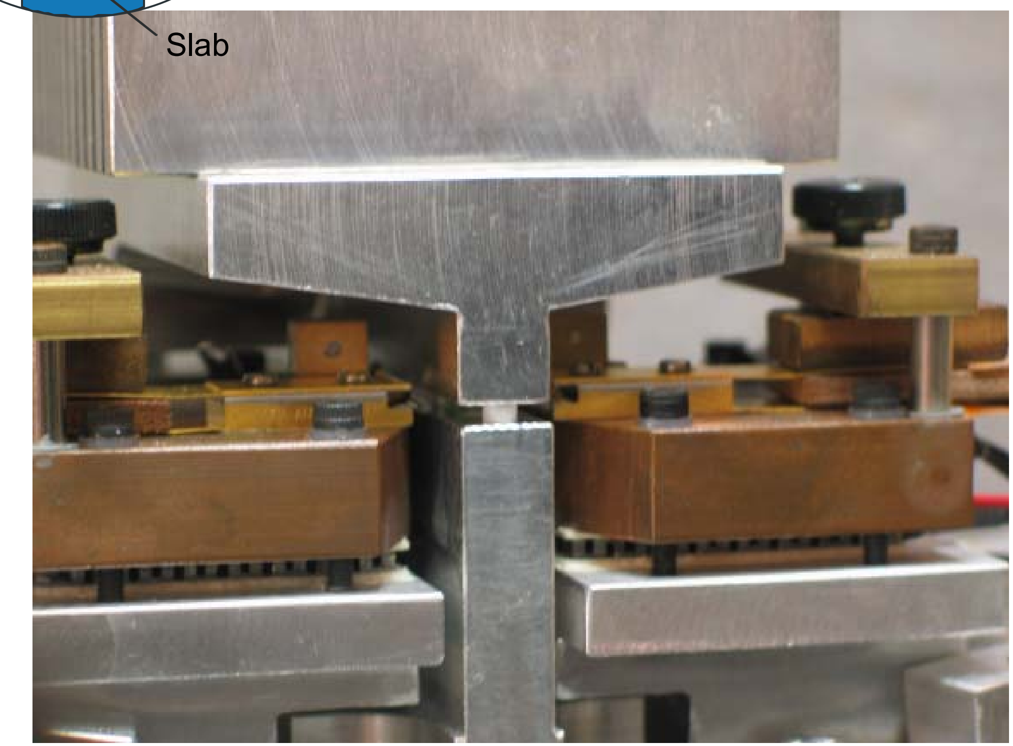
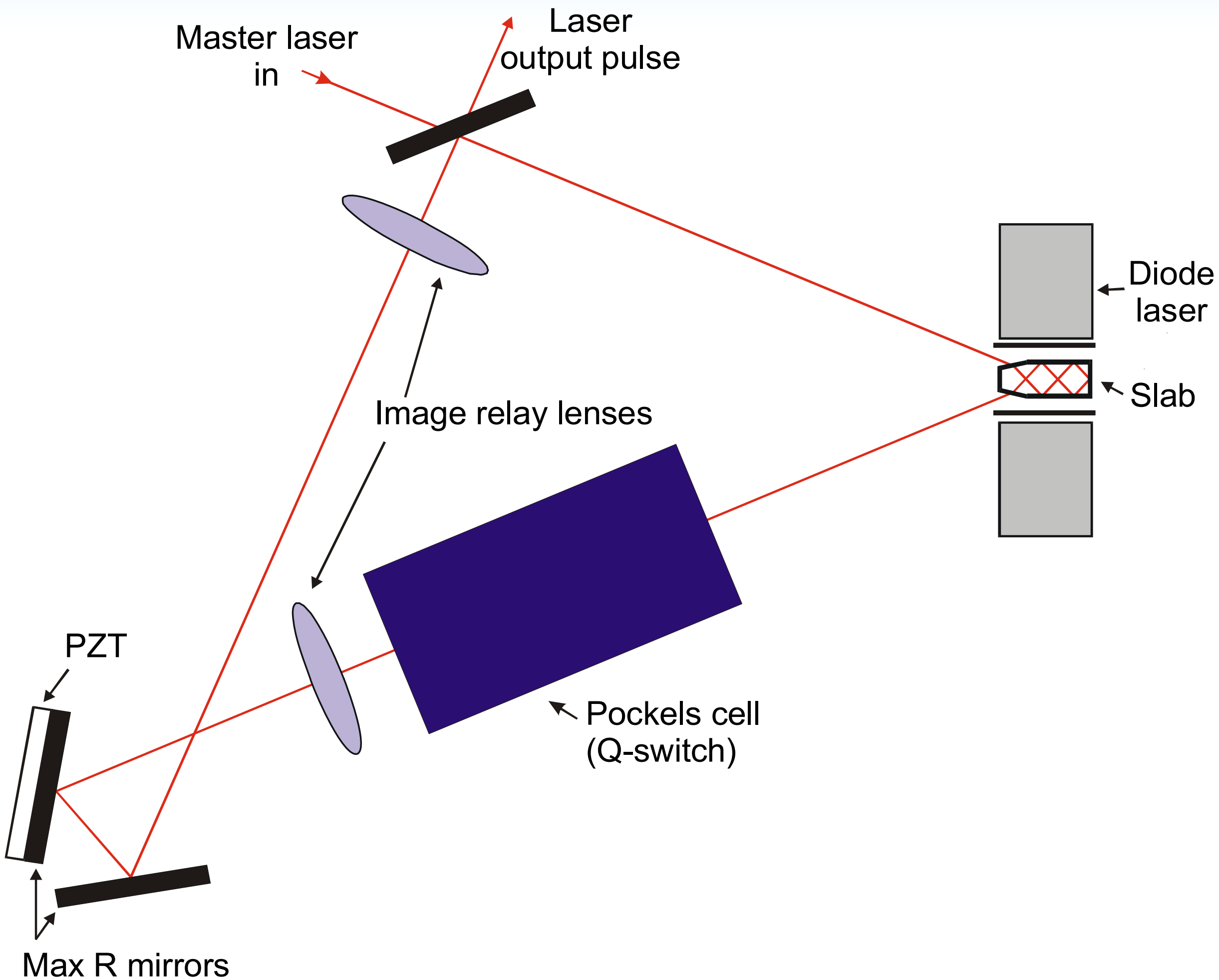
Side-pumped laser head





Injection seeded ring resonator



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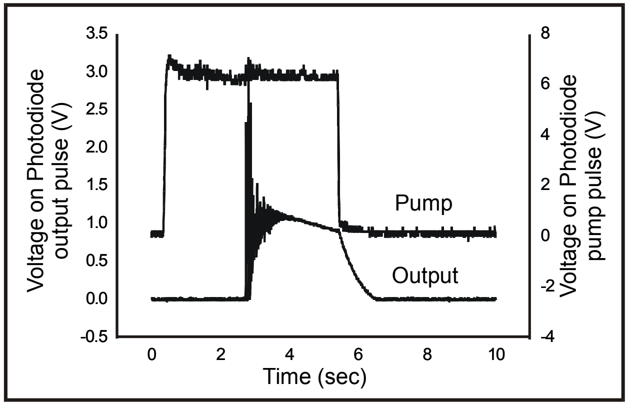
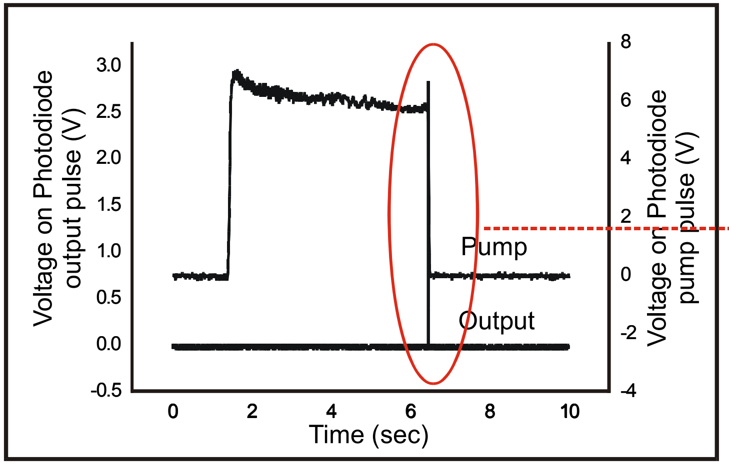
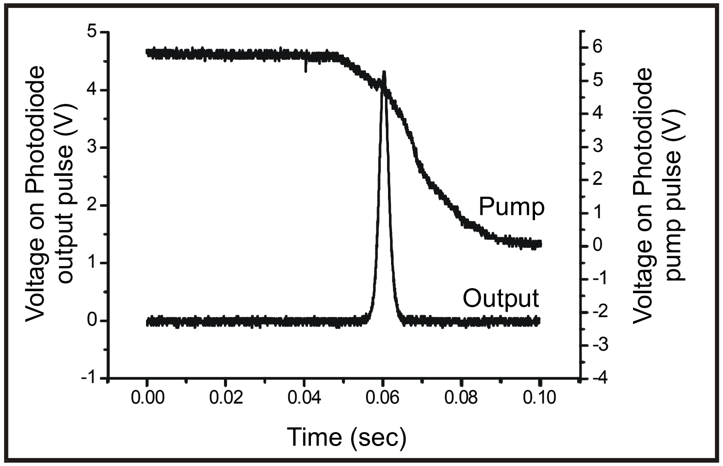
Ring Oscillator Q-switch results

Gain switched lasing
(E=8mJ/pulse)





Q-switched pulse (E=3mJ/pulse)



Q-switch pulse – expanded scale: ms

Current results with Er:Glass

- Good long pulse energy in standing-wave oscillator, near TEM_{oo} (50mJ)
- Q-switched ring oscillator demonstrated
- Injection seeding demonstrated

<u>However :</u>

Problems with current Er:Glass slab laser

- Energy output limited by Er bleaching (measured)
- High intra-cavity losses in ring oscillator (Pockels cell)
- Serious thermal lensing limitations
- Optical damage of glass host
- Currently max energy per pulse Q-switched is 10mJ/pulse,
  but need 20-50mJ/pulse raw laser output for scalable systems (eg: larger aperture, system losses)
- Pulse repetition rate will be limited by thermal effects
- Pumping limited by frequency chirp in diode-lasers used

Continuing effort in Erbium

Two parallel approaches:

1. Improve and optimize Er:Yb:glass subject to its inherent thermal limitations.
   - Experiments using different Er, Yb concentrations for optimum pumping
   - Reduce resonator losses
   - Complete injection seeding characterization as laser radar

2. Investigate third generation Er:Yb:YAG

Third generation: Er:Yb:YAG at 1.645μm

- Greatly improved thermal properties of YAG host
- Better control of thermal lens
- Better efficiency (lower level has 2% population)
- Scalable to higher power, rep. rate
- Manufacture as ceramic YAG material
- Permits use of our new end-pumped composite slab geometry
- Experience from our successful Nd:YAG designs directly relevant
- But requires a new, single frequency master oscillator
- Recently demonstrated in bulk Er:Yb:YAG*

* Georgiou & Kiriakidi, Opt. Eng., 44 Jun. 2005
  80mJ output, pumped by 4.7J

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Scaling to higher power slabs

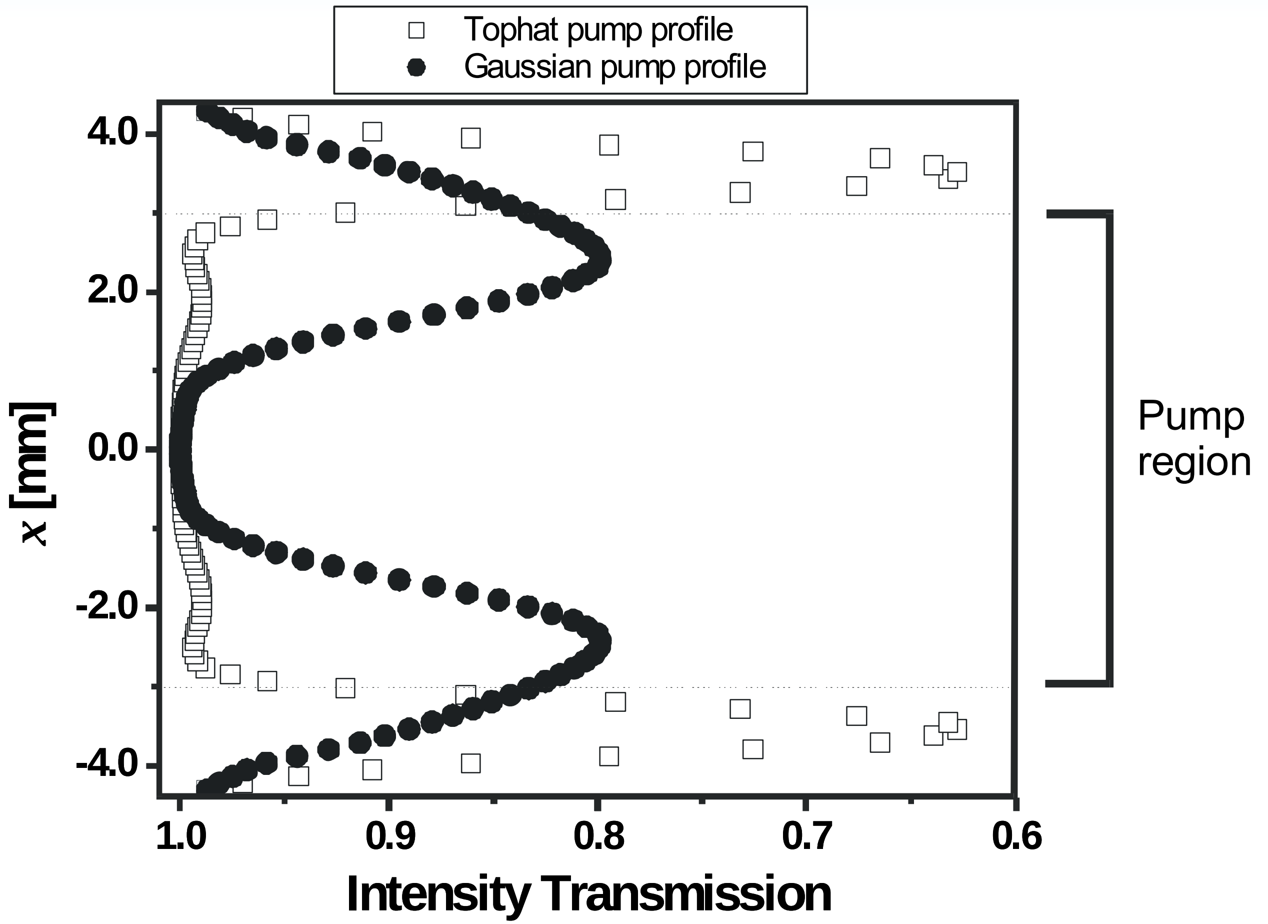
High pump intensities and necessary cooling of the gain medium leads to strong thermal gradients which cause undesirable effects.

Issues

- strong thermal lensing
  - change from top/bottom cooling to side cooling

- thermally induced birefringence
  - use specialized pump distribution

Effect of pump profile on depolarization loss in Nd:YAG



(Birefringence modeling: M. Ostermeyer)

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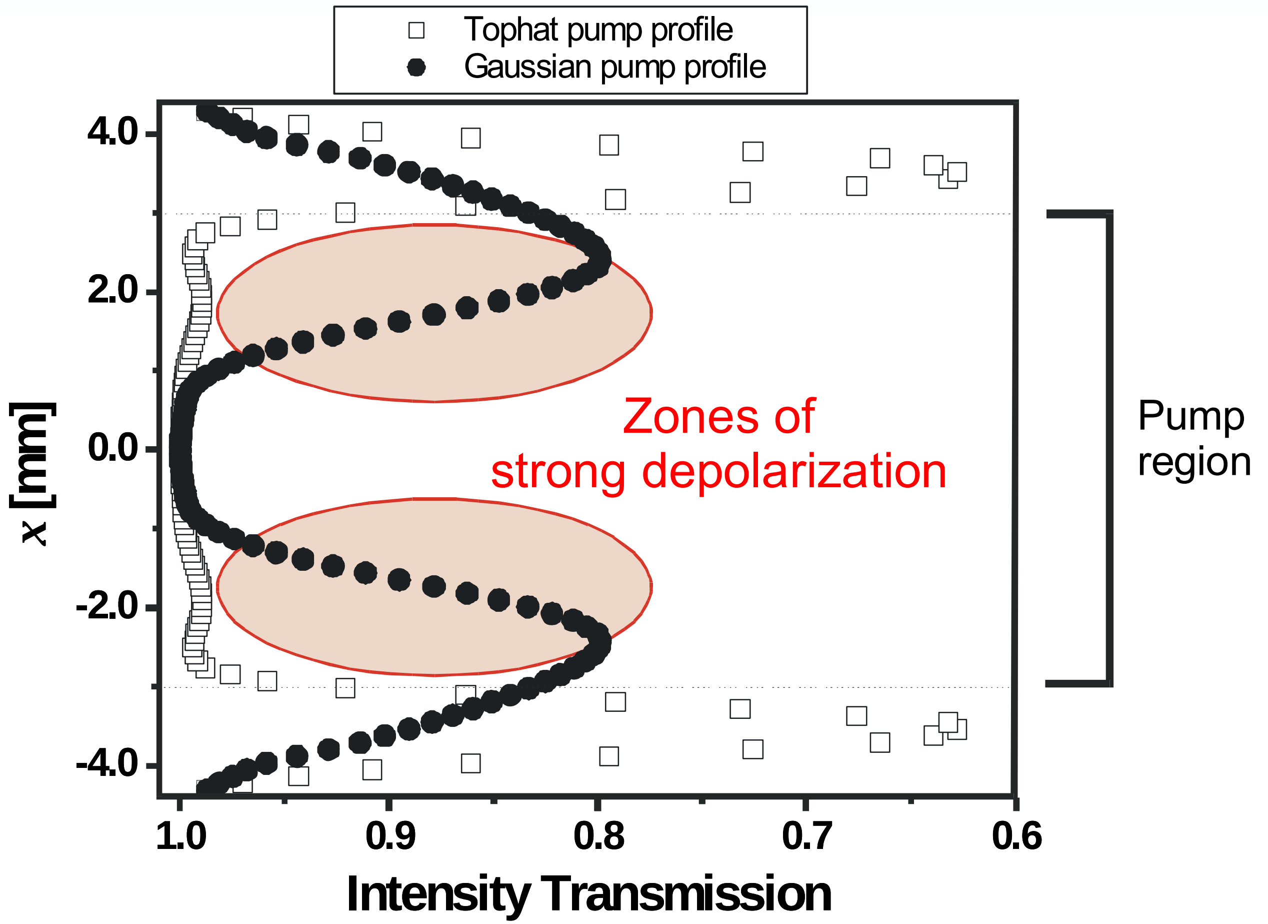
Effect of pump profile on depolarization loss in Nd:YAG



(Birefringence modeling: M. Ostermeyer)

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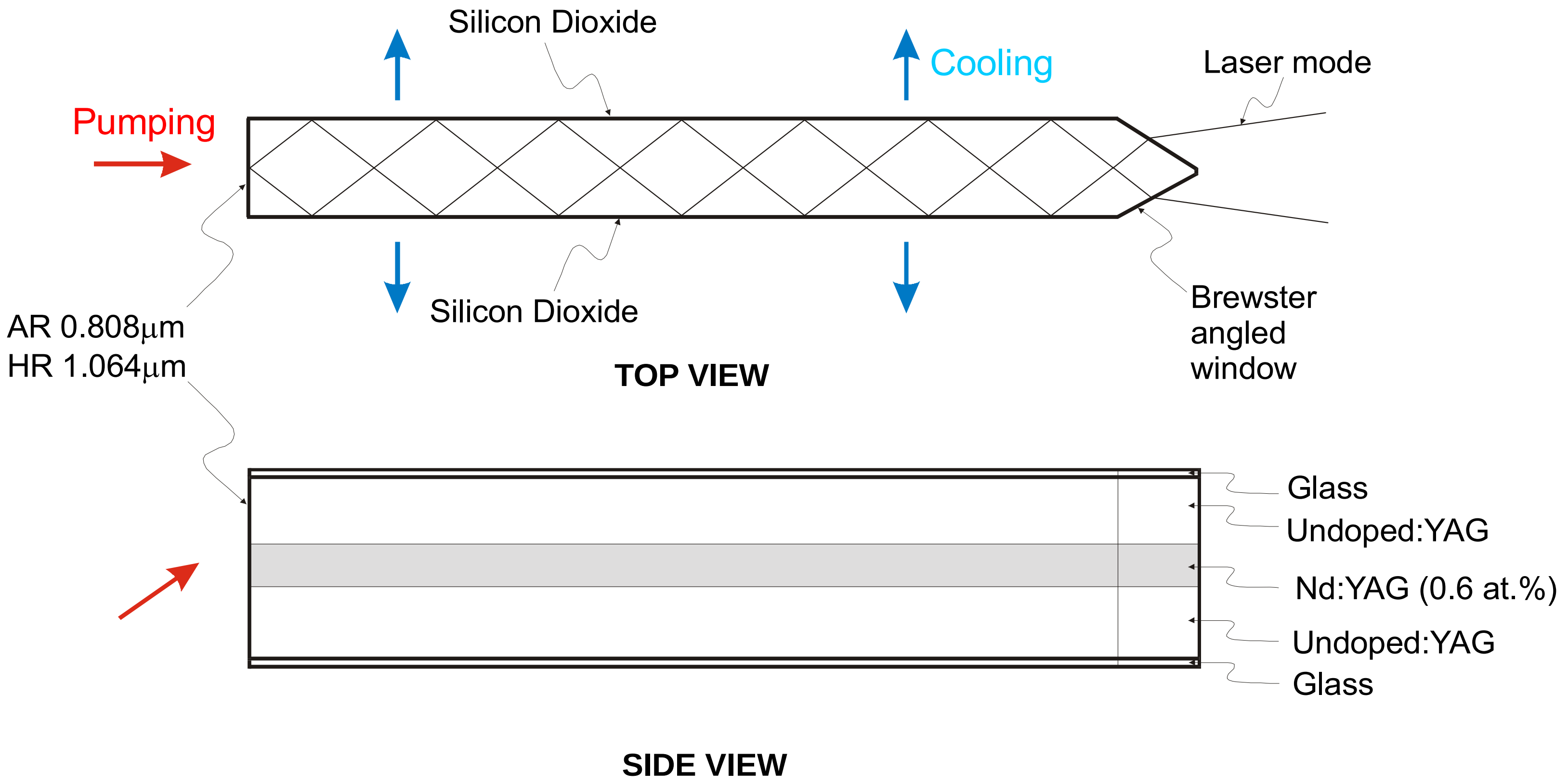
Composite end-pumped, side-cooled folded zigzag Nd:YAG slab



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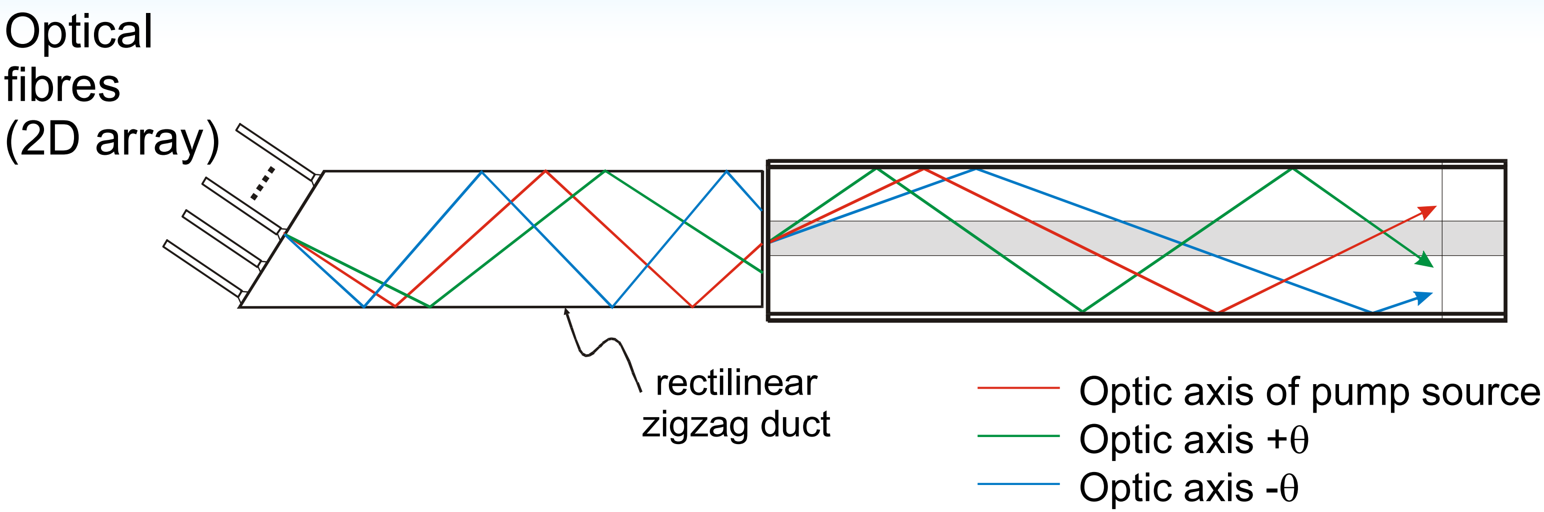
Off-axis zigzag pumping



- Rectilinear zigzag duct allows pumping at normal incidence and mixes pump light prior to slab entry
- Can pump using fibers by collimated bar-stack-array, and use non-imaging lens duct
- Scalable by increasing pump power, height of doped and undoped region (mode volume)

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Composite slab advantages

- **Tophat pump distribution** – minimum birefringence
- **Good absorption efficiency** due to quasi end-pumping
- **More uniform power loading** within slab due to double-clad structure transporting pump light along slab before absorption
- **No hard-edged apertures** in vertical direction
- **Large pump input aperture and acceptance angle** accommodates real divergent pump sources
- **Insensitive to pump beam-quality** due to mixing of pump light in slab
- Undoped YAG layers produce **reduced thermally induced stress**
- **Conduction-cooled**

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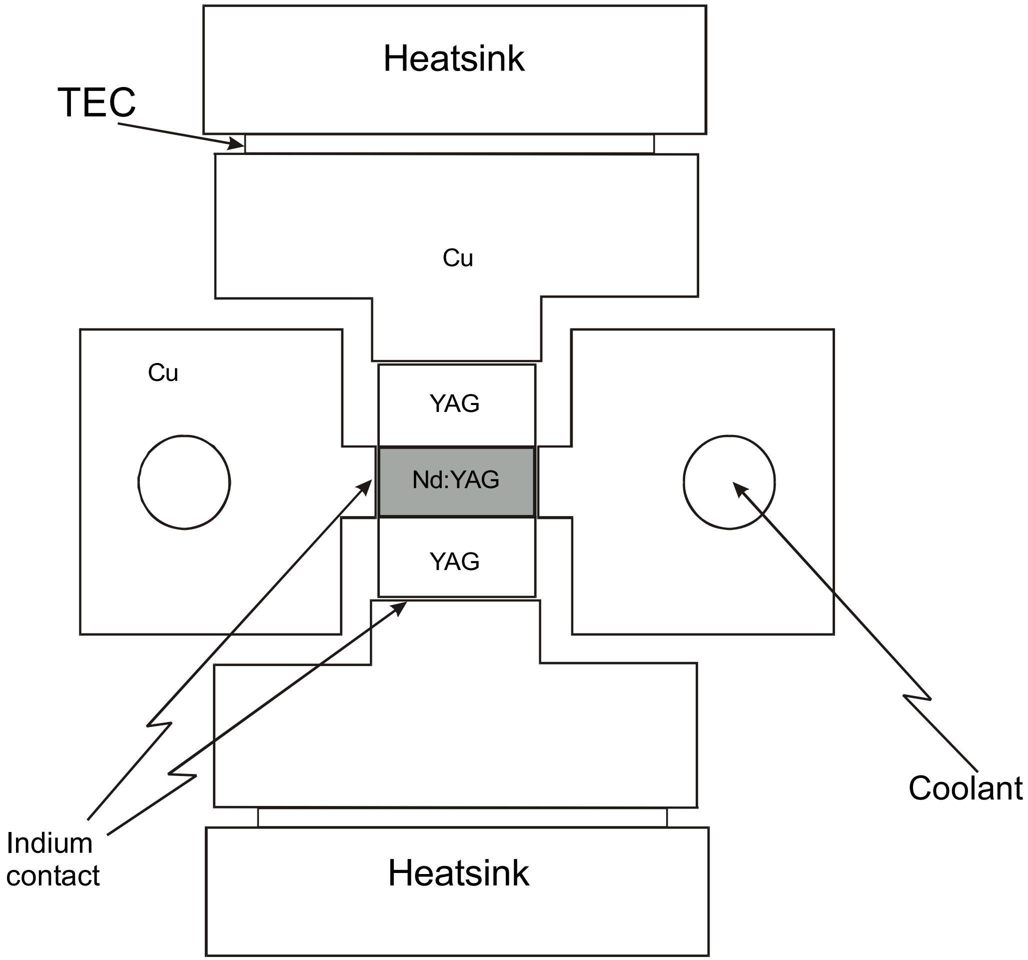
End view of conduction-cooled laser head



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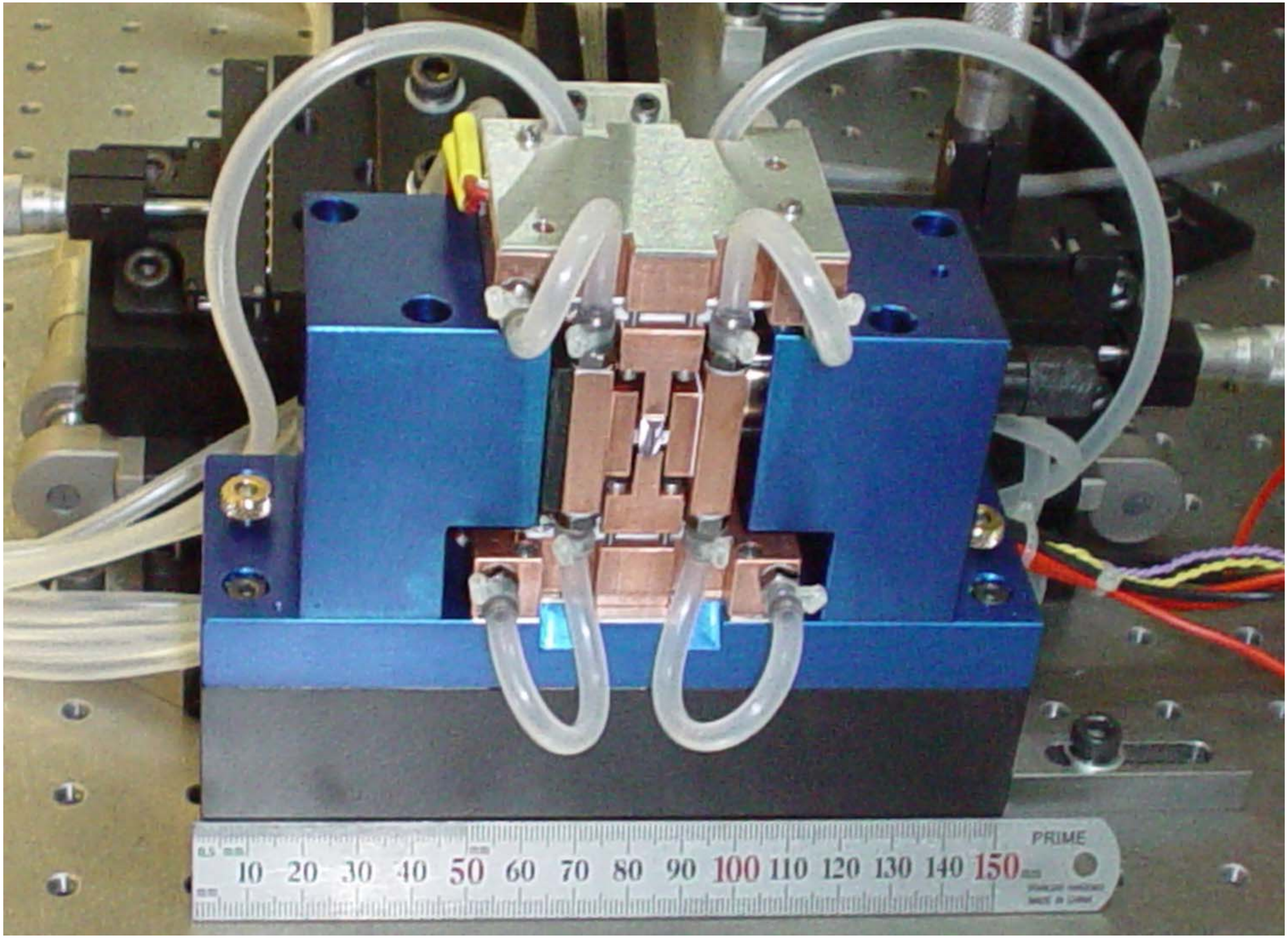

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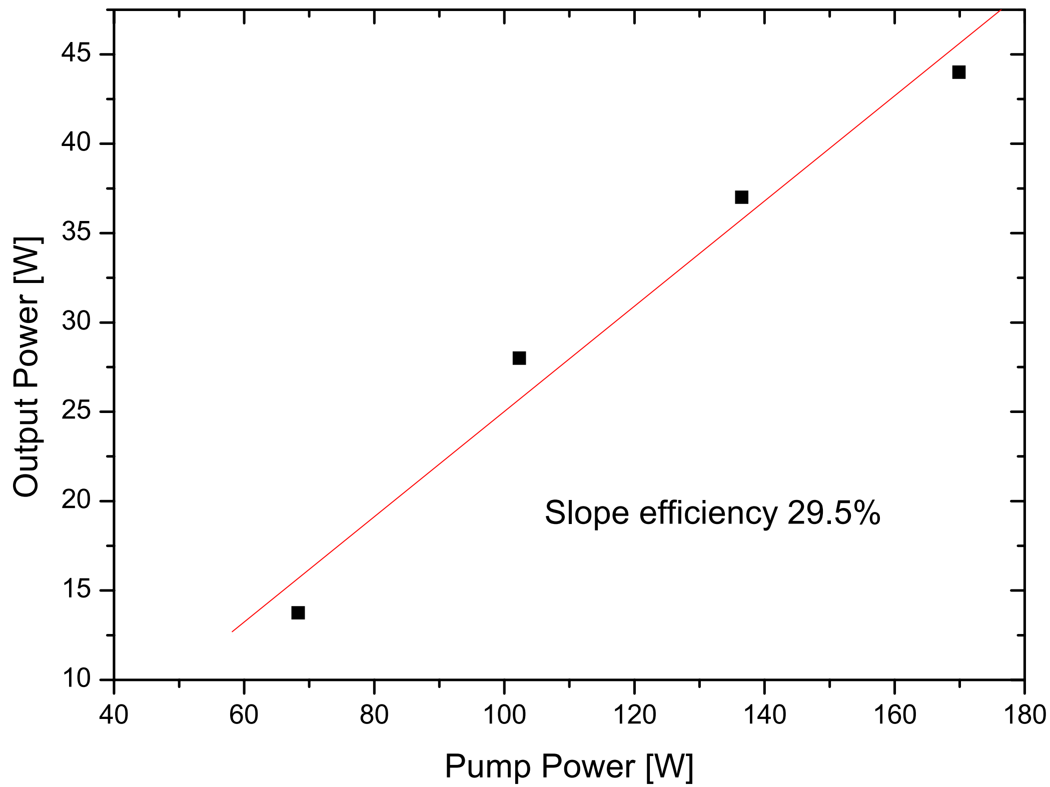
Initial Laser Performance in Nd:YAG



Approximately 90% pump light absorption in end-pumped slab

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Composite slab design for Er:Yb:YAG

- Ceramic
- Doped and undoped Er:Yb:YAG
- Doping concentrations easily changed
- Slab configuration based on success with Nd:YAG

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Er:Yb:YAG laser radar system

- New master oscillator under development
  - NPRO (non-planar monolithic ring oscillator)
  - Ceramic Er:Yb:YAG
  - To be developed in collaboration with Innolight

- Injection seeded slave ring oscillator

- Ceramic composite slab slave as described

The DIAL program

(DIAL = differential absorption lidar)

- Aim: **Low-Cost** profiling of water vapour up to top of boundary layer
- Provide water vapour concentrations for
  - Quantitative precipitation forecasting, Bushfire danger assessment, fog prediction
  - current technique - radiosondes, high recurrent cost, infrequent data
- 830nm GaAs diode lasers (mature technology)
  - Single mode limited to ca 0.5W (Average power ca 0.5mW - eyesafe!)
  - Detector technology well developed (low-noise single photon)
- Wavelength control
  - On-line laser (master oscillator) stabilised to peak of water resonance
  - Off-line/ On-line difference frequency stabilised to 15GHz
  - Water resonance ~ 6GHz width @ sea level ~ 1GHz width @ 4km altitude
  - Freq. stability of ~ 20MHz adequate

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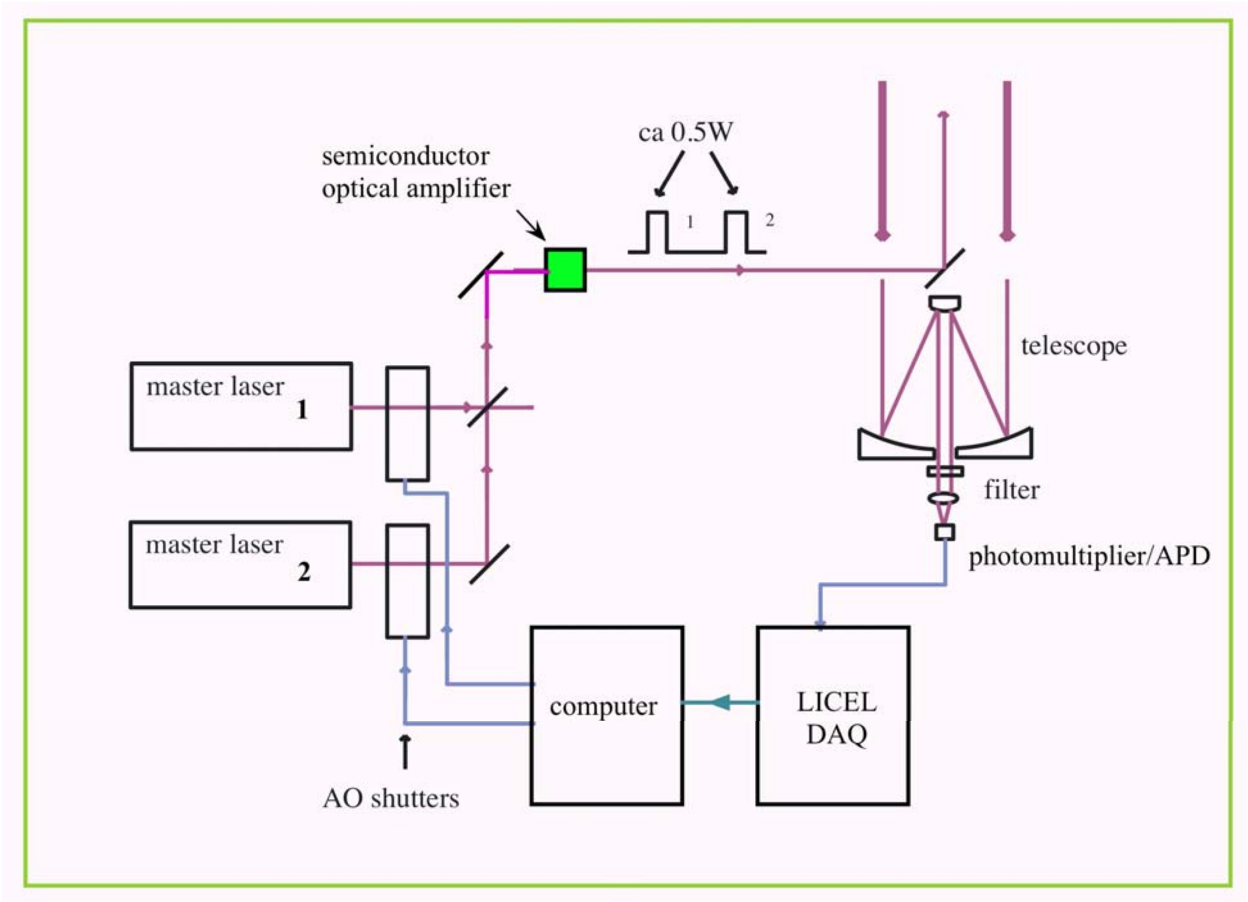
Setup for DIAL



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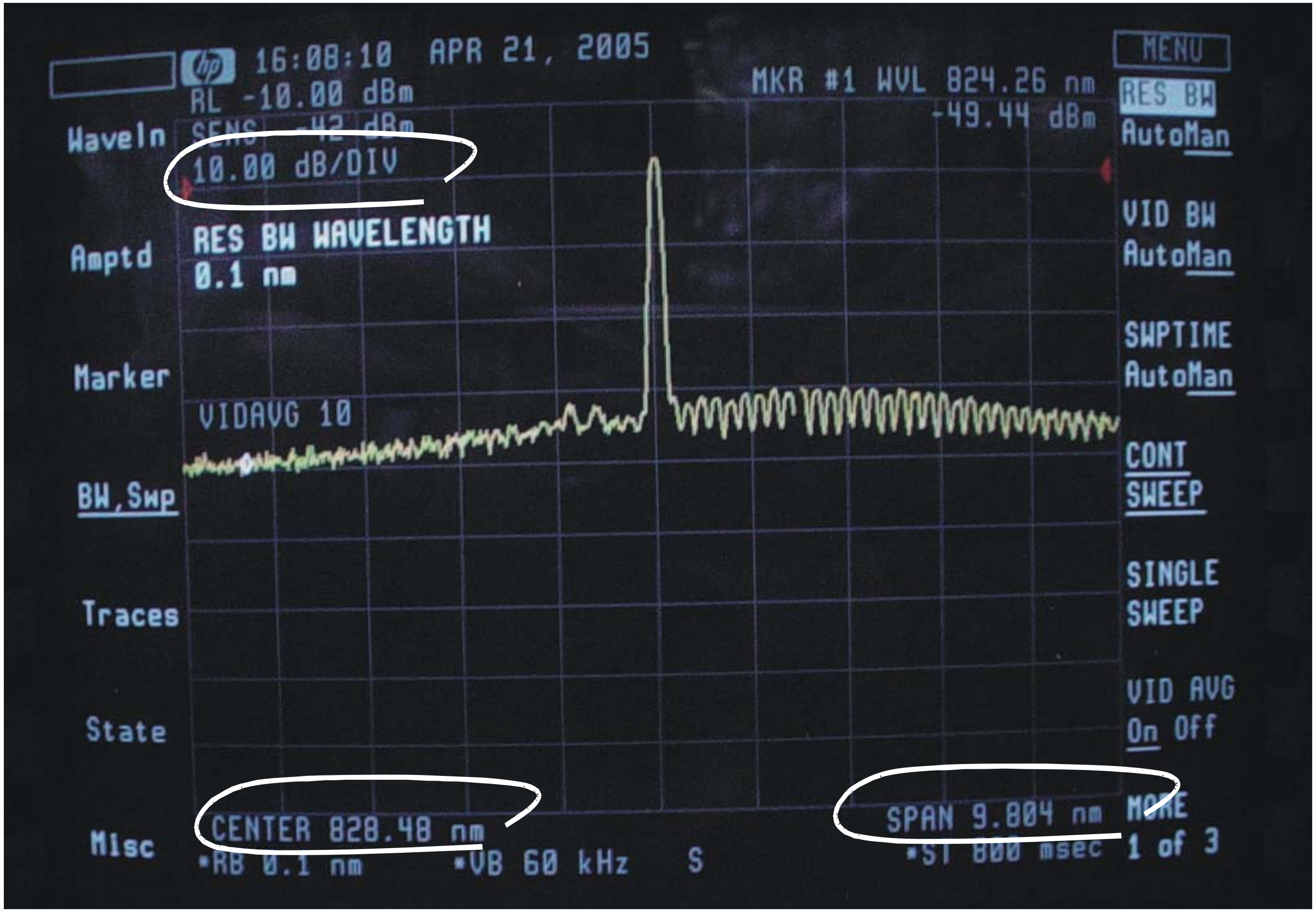
Spectral properties of amplifier



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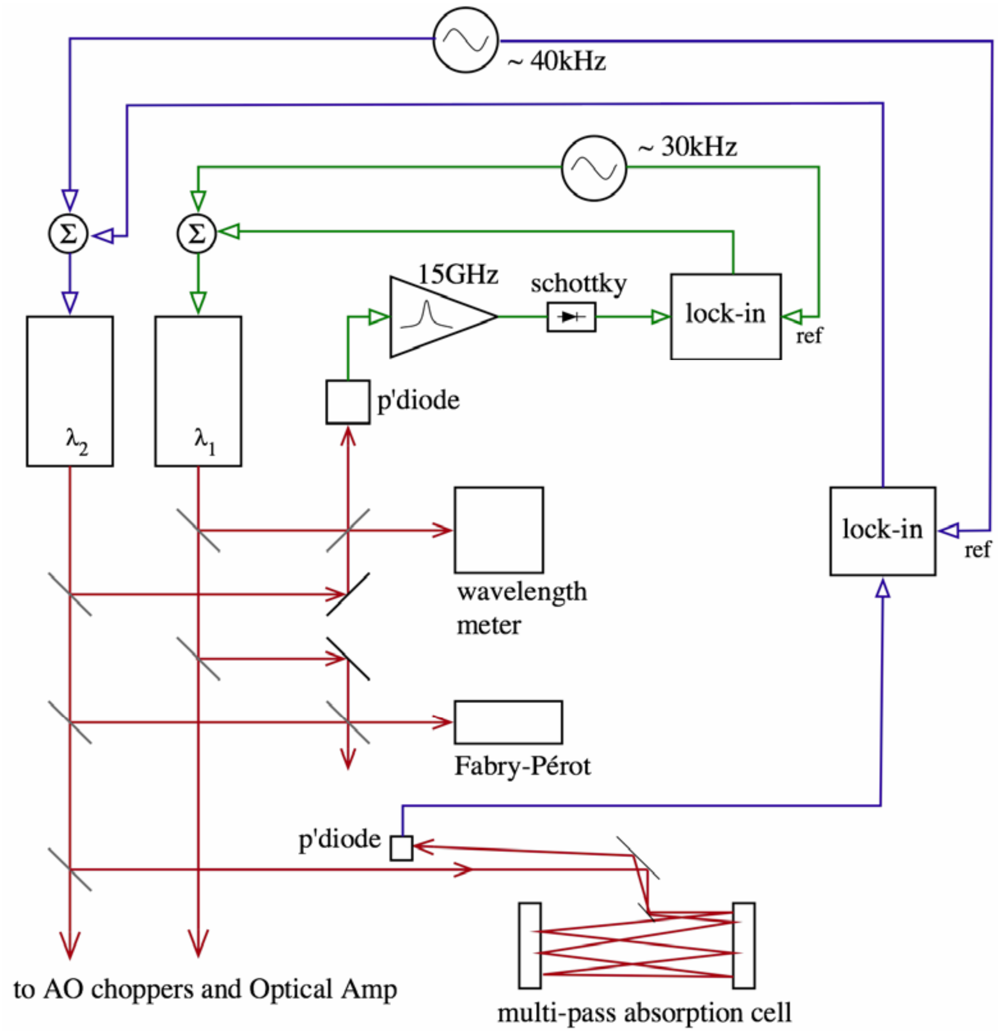
Wavelength control of master lasers

On-line laser stabilisation

– BLUE LOOP

Wavelength difference stabilisation

- GREEN LOOP



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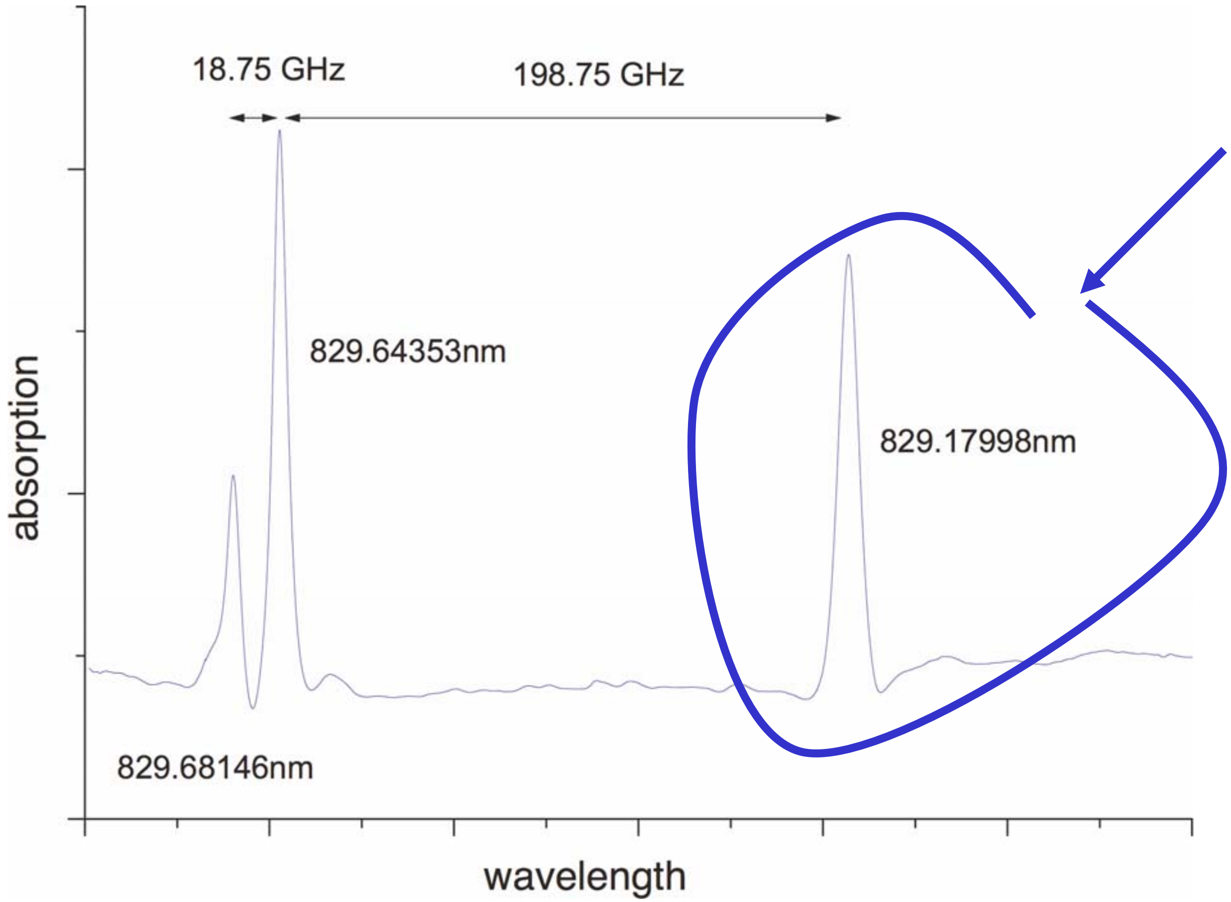
Water resonances near 829nm



- accessible for diode lasers
- appropriate line intensity ($10^{-23}cm^{-1}$)
- sufficiently isolated from other resonances
- other lines at 832nm

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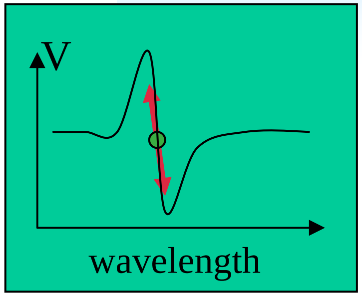
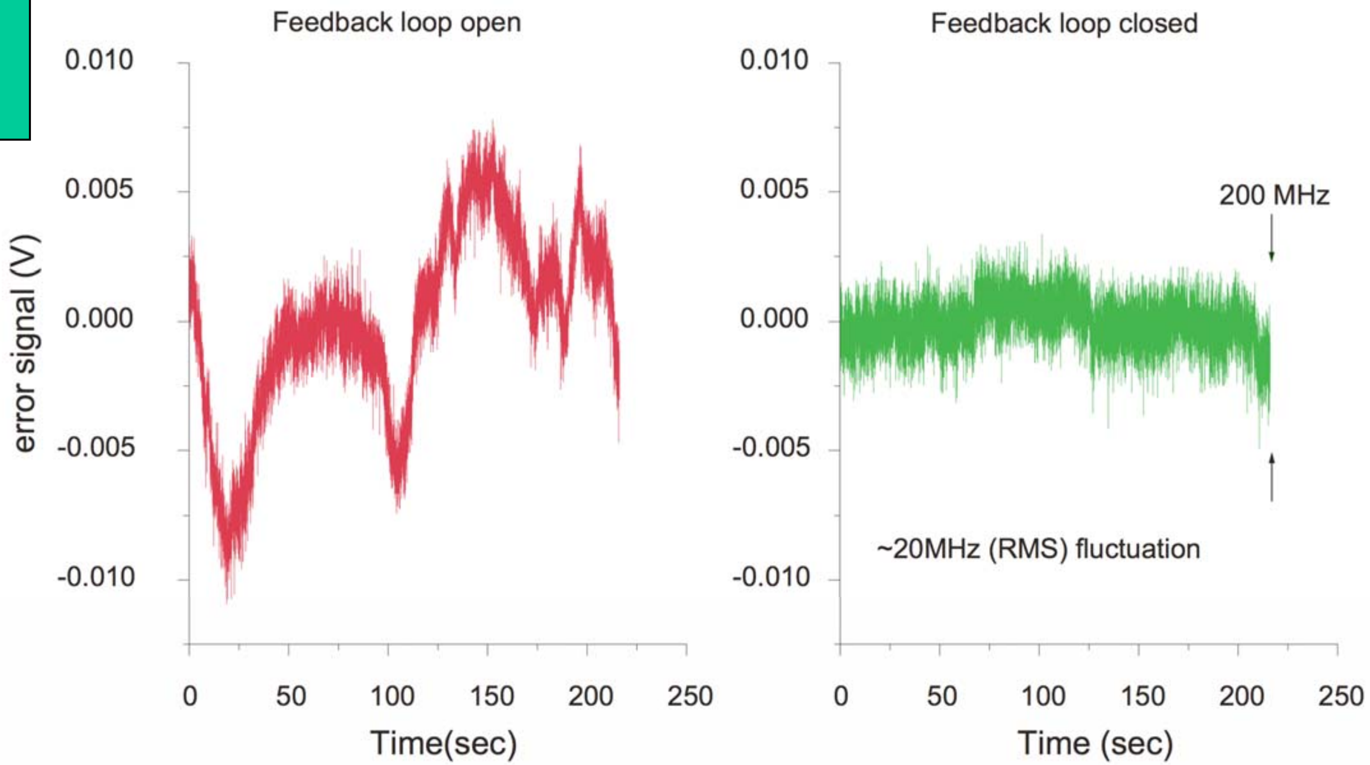
Stabilization to water resonance (832nm)

- error signal at lock-in output





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Conclusion

- Er:glass at 1.53 μm is a useful approach for a simple, low average power eye-safe coherent laser radar, but is limited by thermal effects and damage in glass.

- Er:Yb:YAG is a promising new, preferred option at 1.6μm

  Design experience form Nd:YAG directly transferable

- Low cost alternatives to eye-safe incoherent sensing for short range (<4km) applications using shorter wavelengths are feasible.

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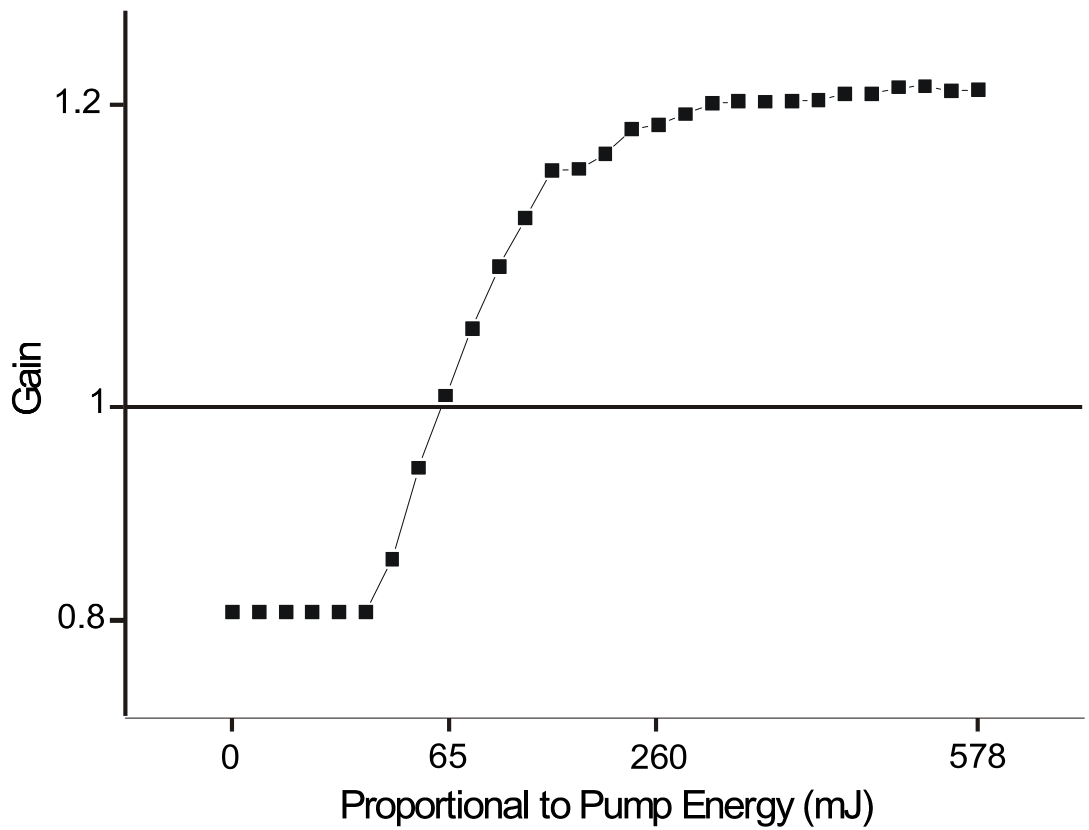
Producing a tophat pump distribution

- How?
  - Use a composite slab (doped & undoped YAG layers)
  - End-pumped for good efficiency
  - Side-cooled zigzag slab

→Pump absorption is a tophat profile, thus minimizing thermally induced birefringence loss (even though diode-laser pump profiles typically produce Gaussian transverse profiles)

→Thermal lensing minimized by using a zigzag mode-path in the plane of cooling, and by controlling the heat flow in the orthogonal plane

Small-signal gain measurement proves bleaching of Erbium



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