CW and Passively Q-switched Double-Clad Planar Waveguide Lasers

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Outline

- Results overview
- What is a planar-waveguide laser?
- Advantages and issues
- Experimental set-up and results
- Energetics modelling
- Technology summary

Side-Pumped Results Overview

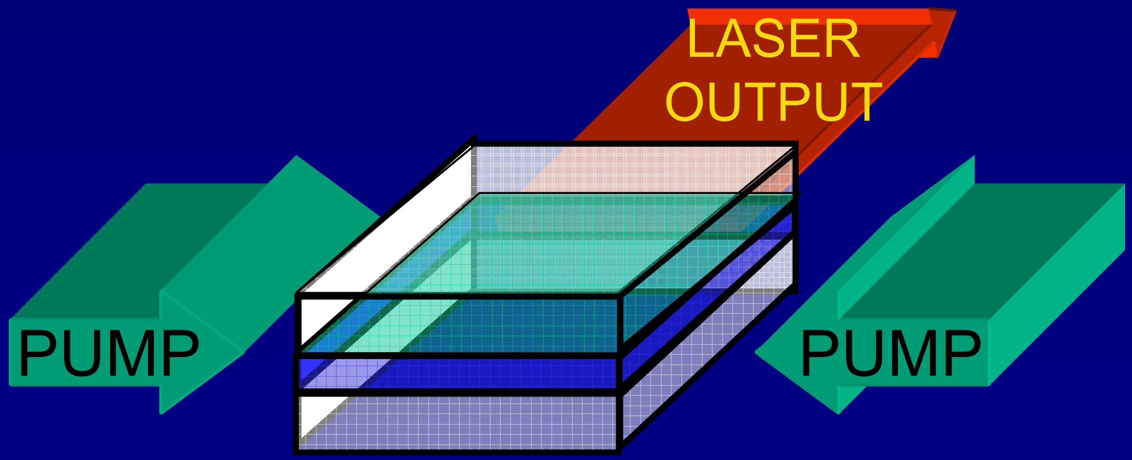
- YAG host medium
- CW lasing
  - Wavelengths 1μm (Nd, Yb), 2μm (Tm)
  - P_{max} 12W @ 1μm, 15W @2μm
  - Efficiency
    - Peak opt-opt 0.34W/W @2μm
    - Slope 0.5W/W @ 1μm
- Passive Q-switched
  - Wavelength 1μm (Nd)
  - P_{max} 8.1W @ 1μm, τ_p= 2.5-3.5ns, PRF_{max}= 80kHz
  - Efficiency
    - Peak opt-opt 0.21W/W
    - Slope 0.28W/W

End-Pumped Results Overview

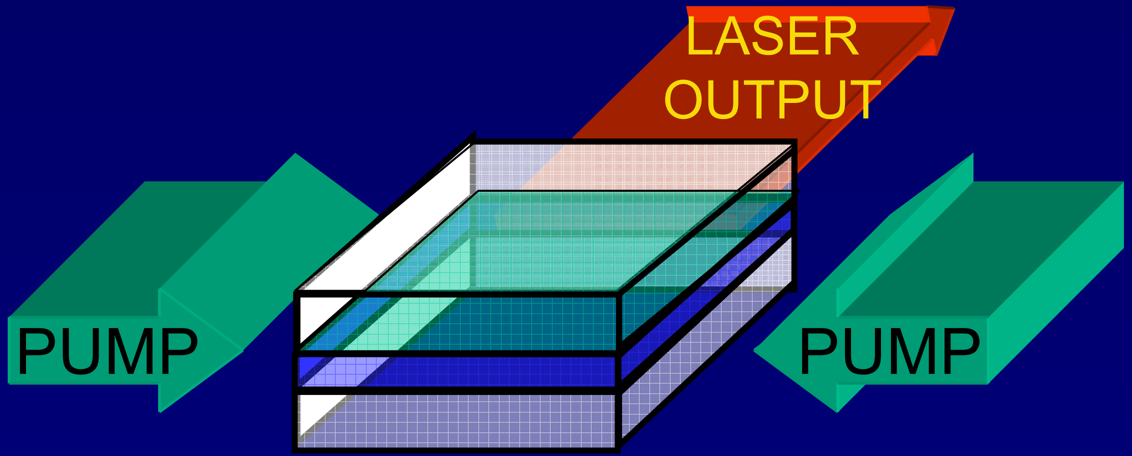
- CW lasing
  - 946nm, 1.06μm, and 1.32μm Nd:YAG
  - P_{max} 4.3W @1.06μm
  - Efficiency
    - Peak opt-opt 0.44W/W
    - Slope 0.45W/W (vs available diode power)
  - Good beam quality
    - $M^2_{x,y} \approx 1.8 \times 1.0$
    - Latest experiment indicates diffraction-limited

Planar Waveguide Lasers (PWL)

- Thin laminated structures
- Optical confinement of both pump and developed laser radiation



Planar Waveguide Lasers (PWL)

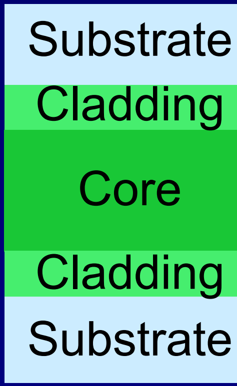


- Original concept - Yb:YAG slab sandwiched between sapphire blocks
  - Numerical Aperture (NA) of the waveguide:
    - $n_{YAG} = 1.82$, $n_{Sapphire} = 1.76$
    - $NA = 0.46 \Rightarrow \sin^{-1}(0.46) = 27.6^\circ$

$$NA = \sqrt{n_Y^2 - n_S^2}$$

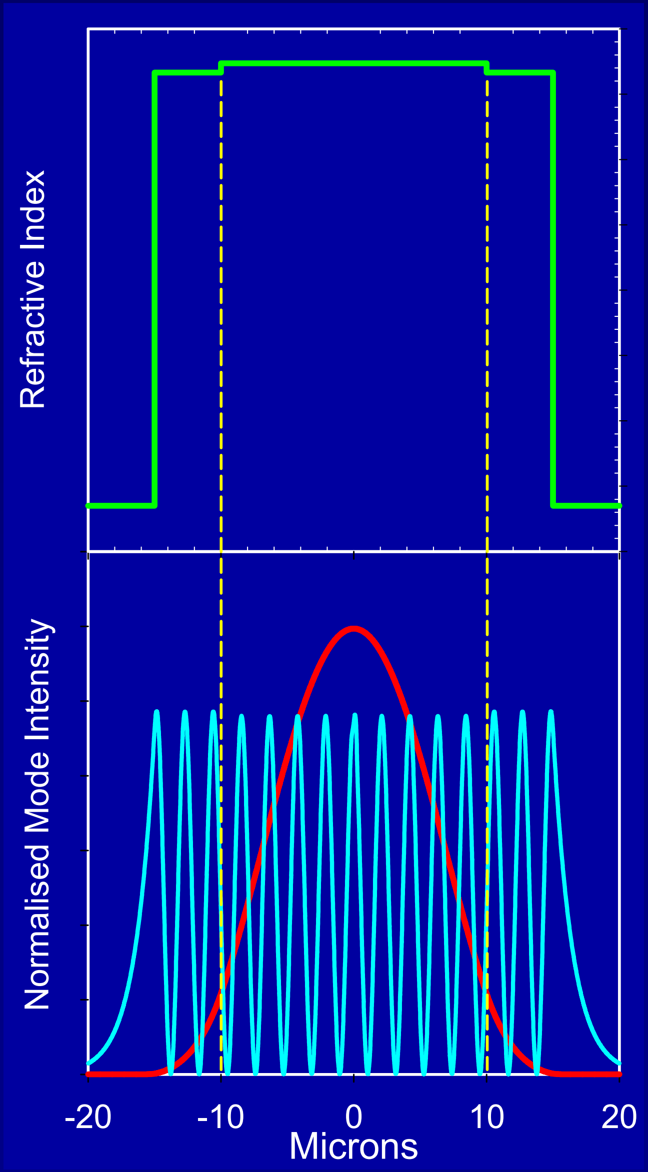
Double-Clad Waveguide Laser

- 5 layer structure: $n_{core} > n_{cladding} > n_{substrate}$
  - Large-Mode Area (LMA) waveguide
  - High numerical aperture, multi-mode structure
  - Doped core ⇒ weak index change

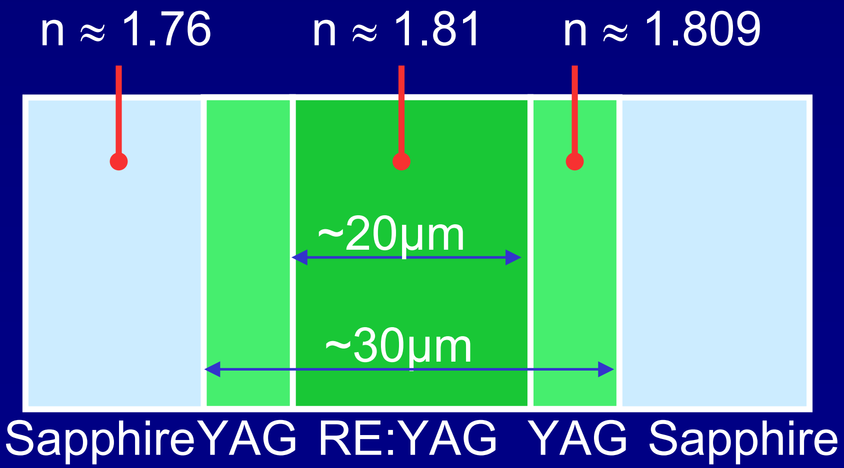


- LMA waveguides provide:
  - High efficiency
    - Good overlap between pump and signal fields
    - Reasonable pump absorption length, in comparison to cladding-pumped fibres
  - Diffraction-limited beam quality
    - Fundamental waveguide mode selection

5 Layer Waveguide Structure



- 5 layer structure defines modes
  - Core waveguide - **small NA <0.05** – interacts with cladding waveguide



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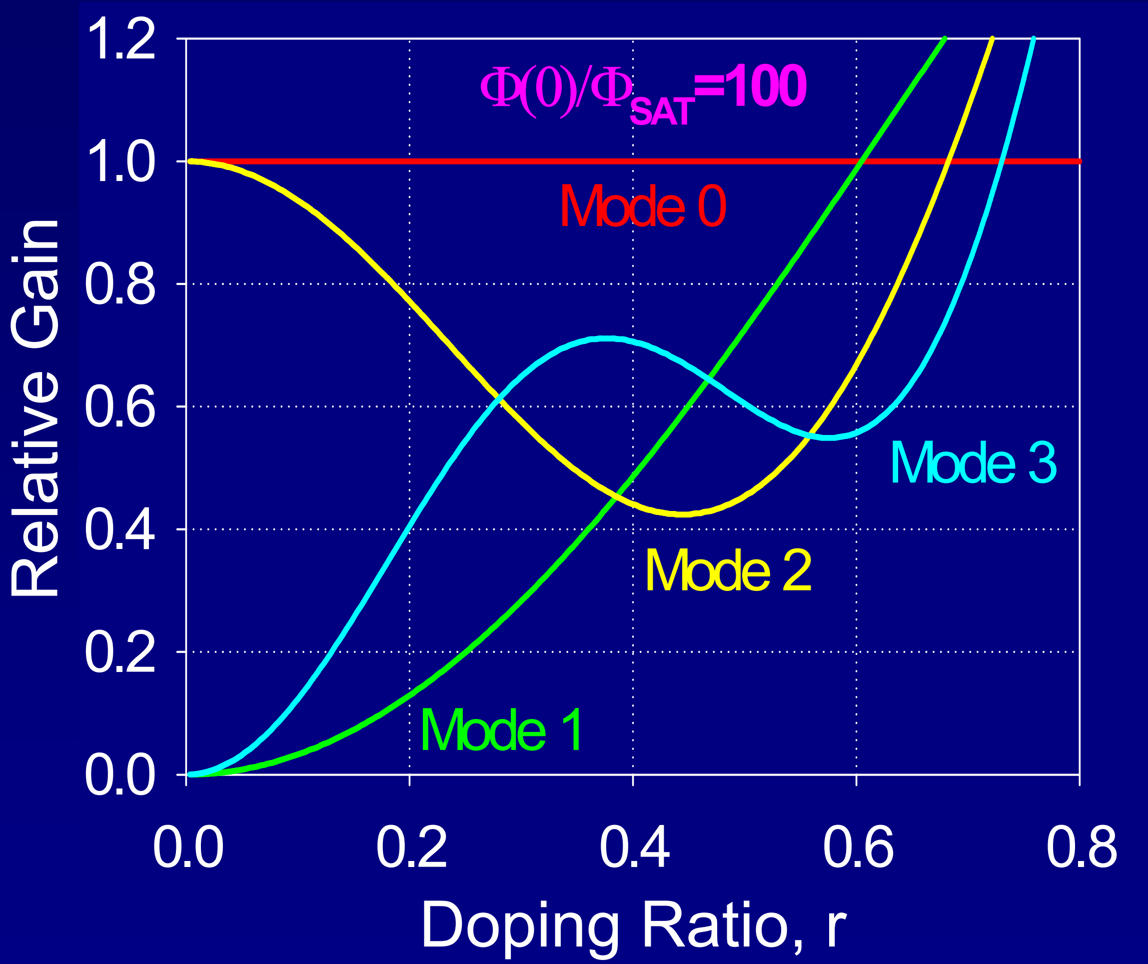
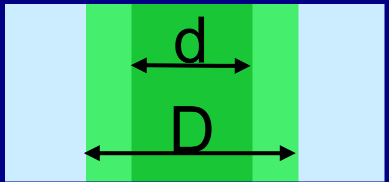
Gain-Mode Selection



- Fundamental mode behaviour achieved by gain-mode-selection
- Gain-saturation limits the maximum doping ratio
- Doping ratio, r< 0.6 will always select fundamental mode

r = d/D



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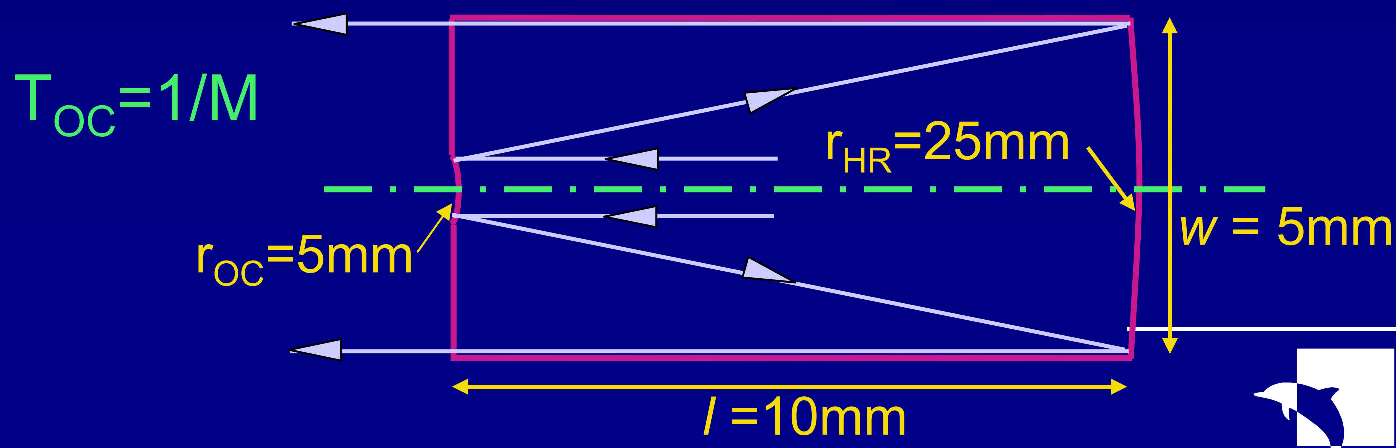
Beam Quality Unguided Dimension

- In plane axis – resonator modes develop
- High gains associated with waveguides ideally suit Unstable Strip Resonators (USR)
- USR ⇒ good beam quality from high Fresnel Number laser resonators
  - e.g. confocal resonator, Mag = 5, r_{HR} - r_{OC} = 2*l*



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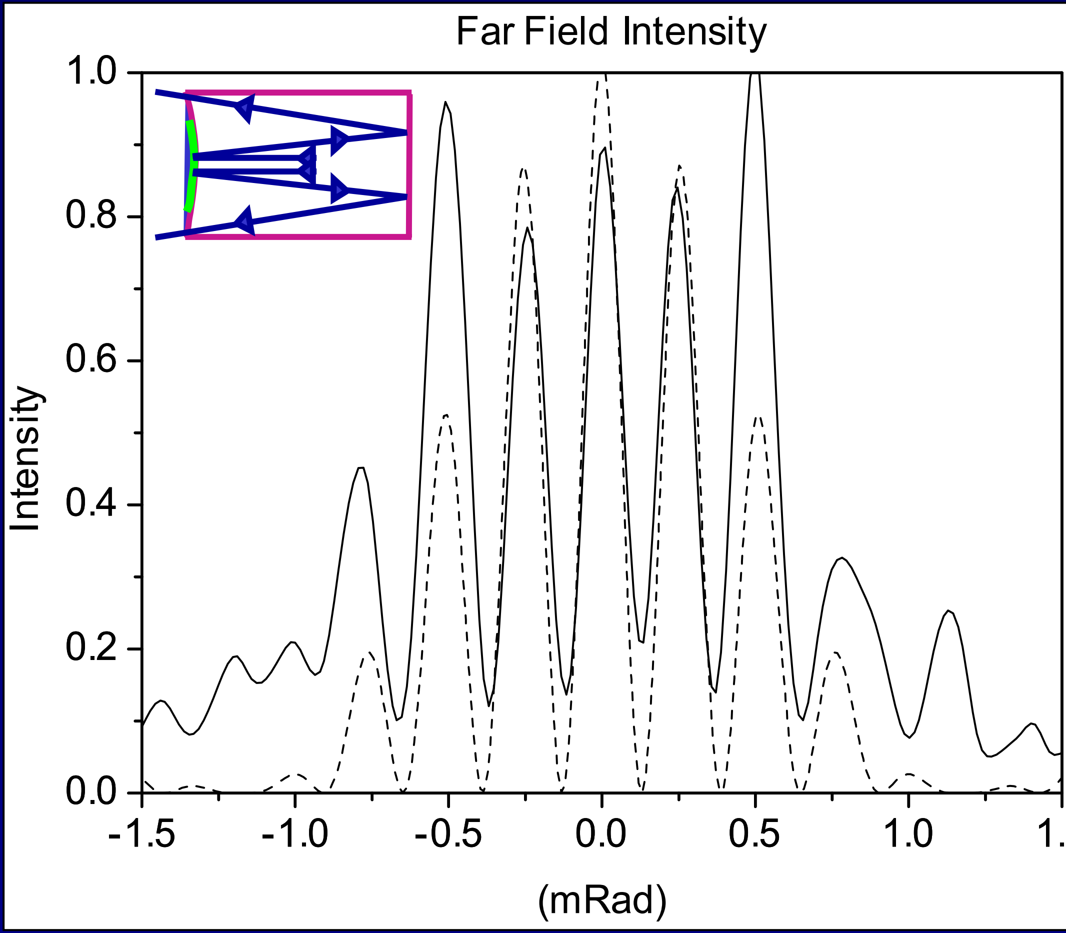
Prototype Unstable Strip Resonator

- Mag = 1.56 USR
- Output coupler central area R_{OC}=70%
- Solid line measured far-field intensity
- Dashed line uniformly filled USR with central obscuration



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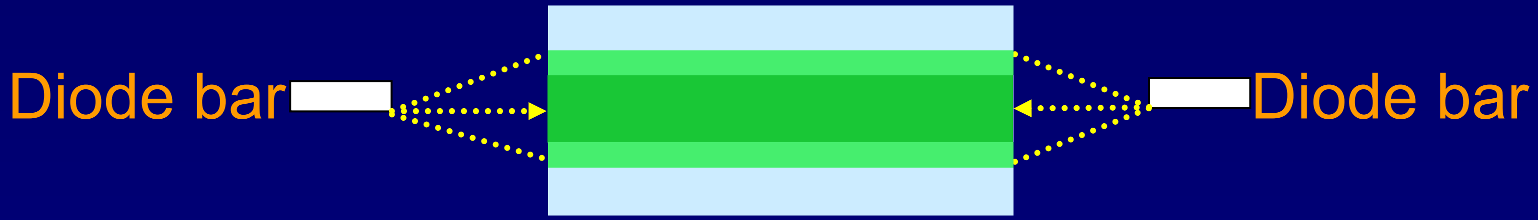
Side-Pumped Proximity Coupling

- Simple, robust, and efficient coupling



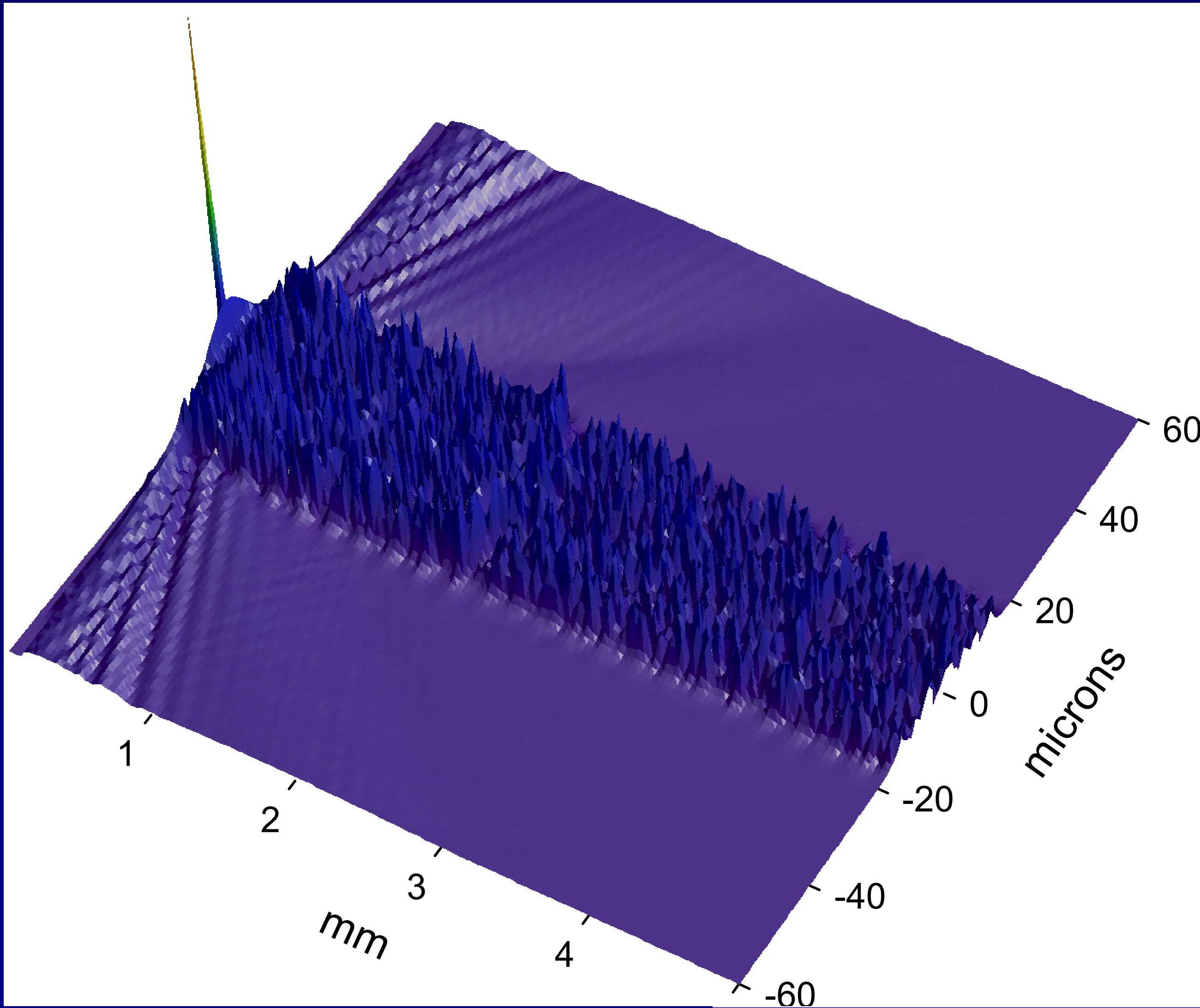
- Diode bar positioning precision

$$W^2 = W_0^2 + \theta_0^2 (z - z_0)^2$$

  - 18μm cladding structure implies ~18μm diode stand-off position

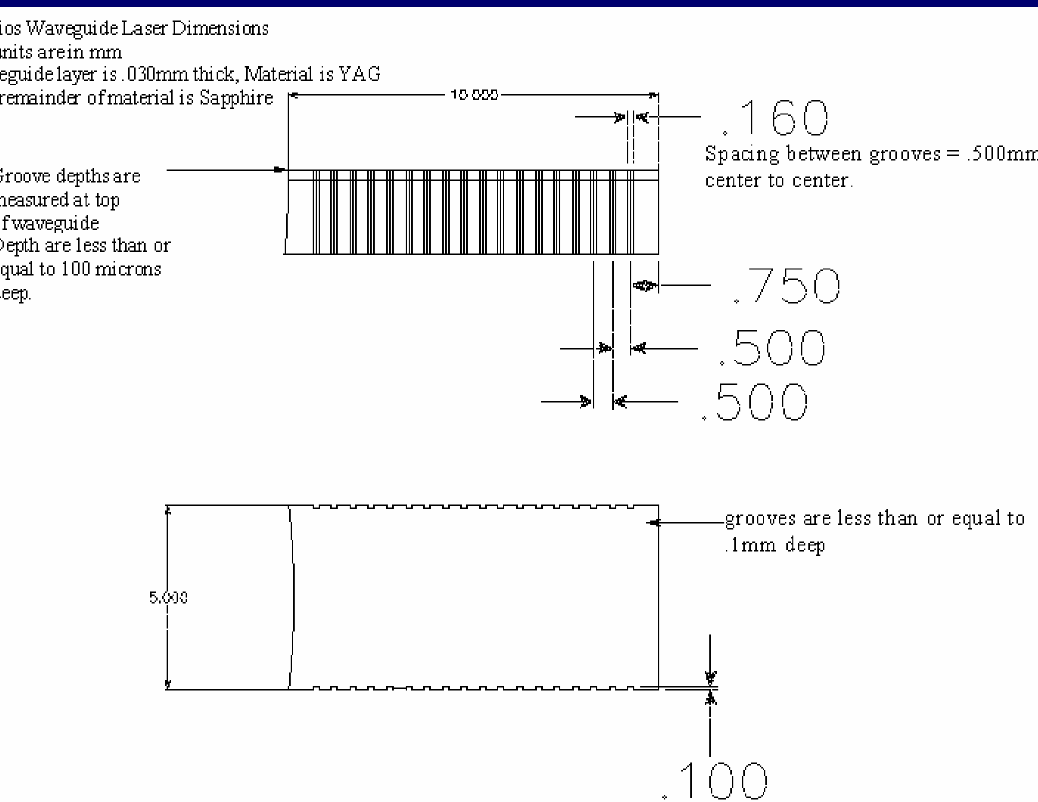
Proximity Coupling - BPM Model

- Launch eff. η_l~95%
- Structure width ~1/e absorption length

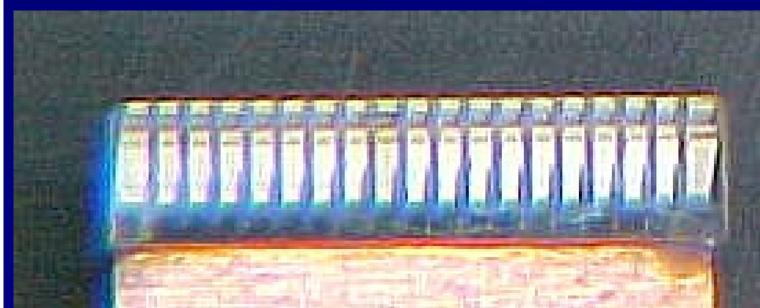


Parasitics Suppression

- Grooved pump faces prevent parasitic lasing and ASE build-up

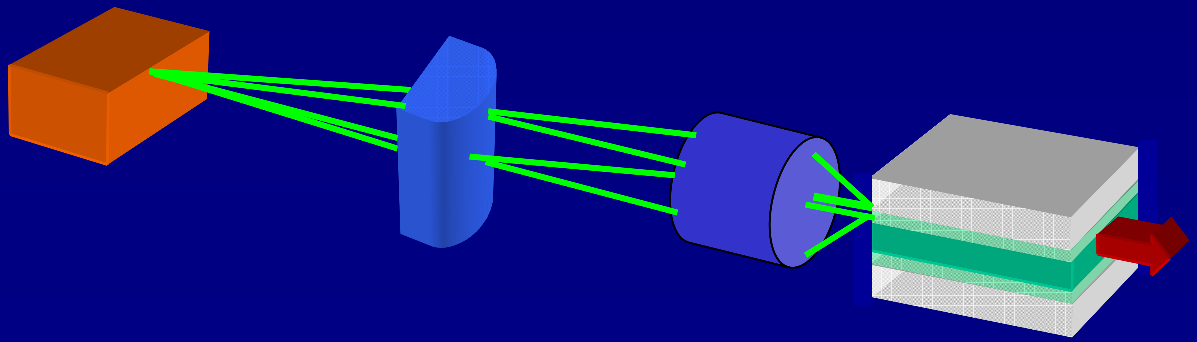


Side view of waveguide



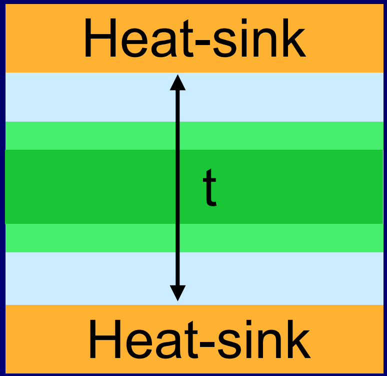
End Pumping Scheme

- Polaroid single broad-stripe diode ~4W
  - $M^2_{x,y} \approx 40 \times 3$
- Unique Mode 10W source
  - $M^2_{x,y} \approx 17 \times 17$

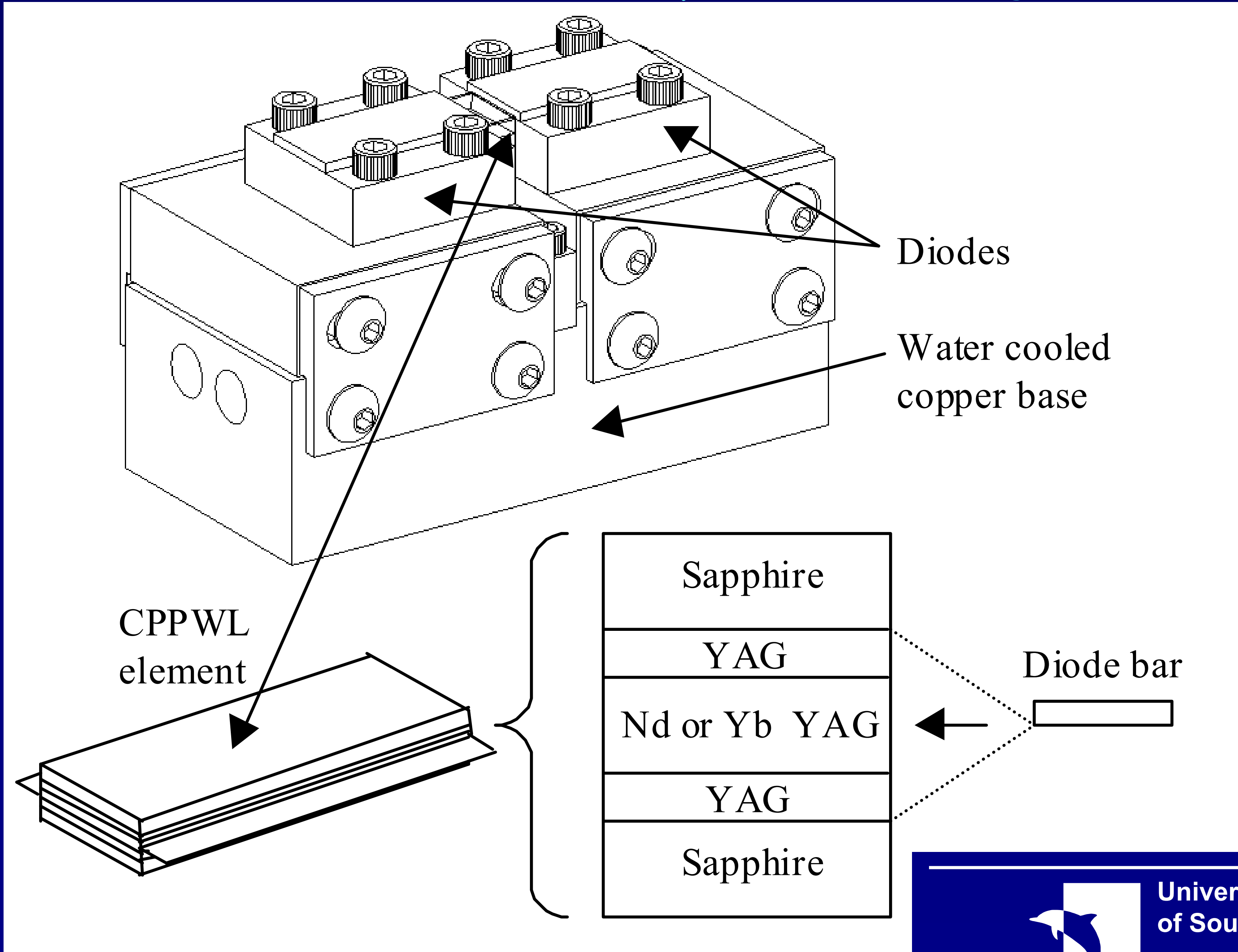


Waveguide Thermal Management

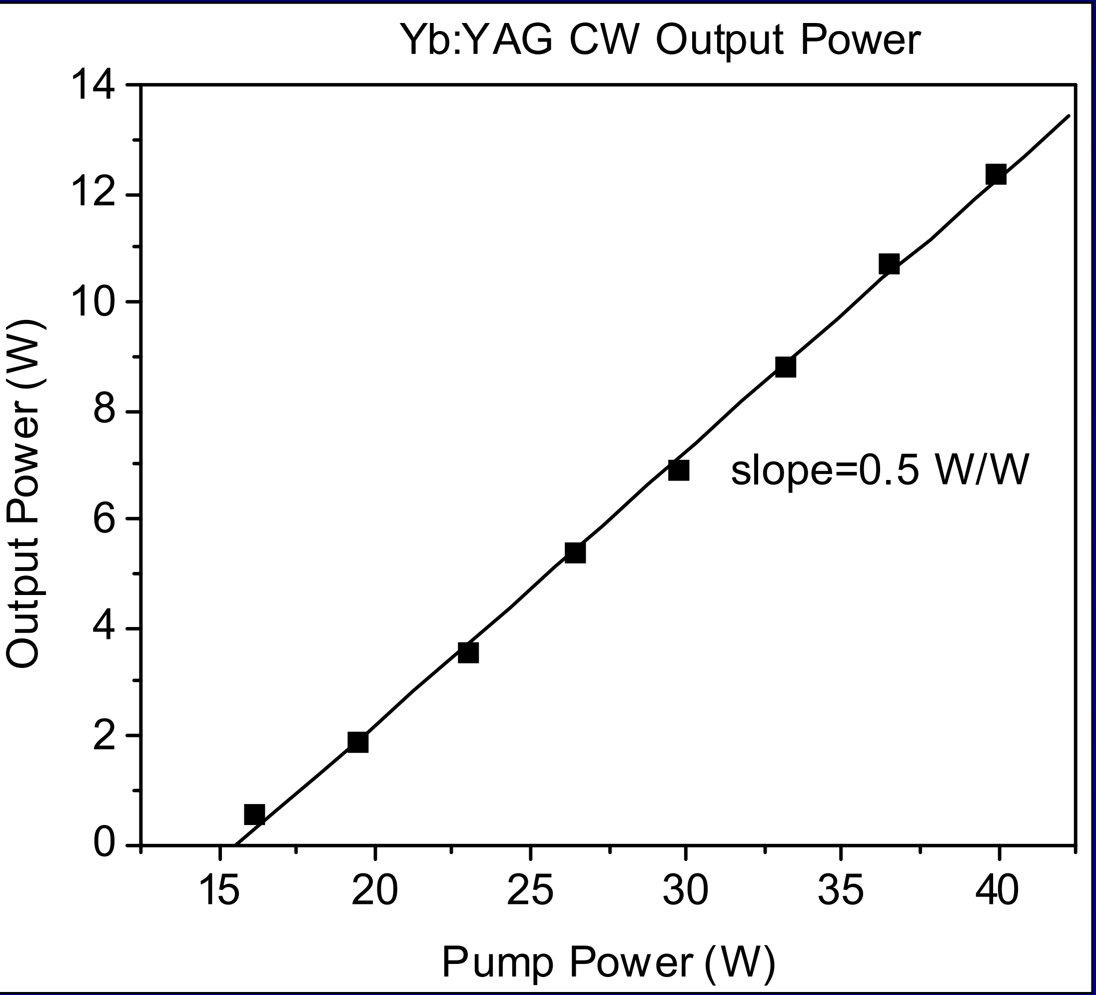
- PWL⇒ limiting case of slab laser
  - 1D heat flow
  - Large surface area to extract heat
  - Stress fracture limit α $1/t^2$
- Smaller ΔT in comparison to bulk crystals
  - Ideal for quasi-three level laser systems
    - e.g. Yb^{3+} at 1μm, Tm^{3+} at 2μm, Er^{3+} at 1.5μm
- Thermally induced lens overcome by waveguide



Characterisation of 1μm laser systems



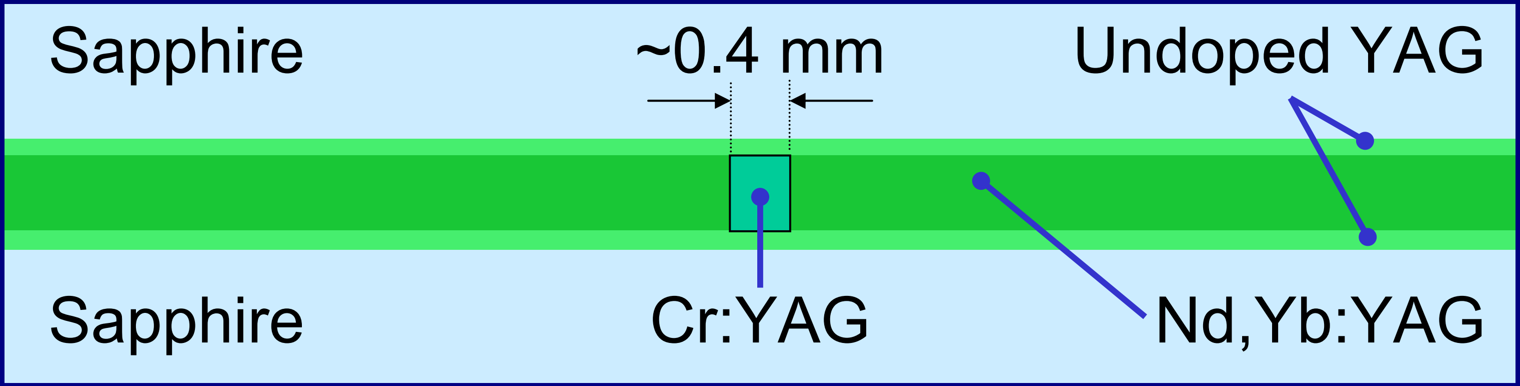
Yb:YAG CW Results



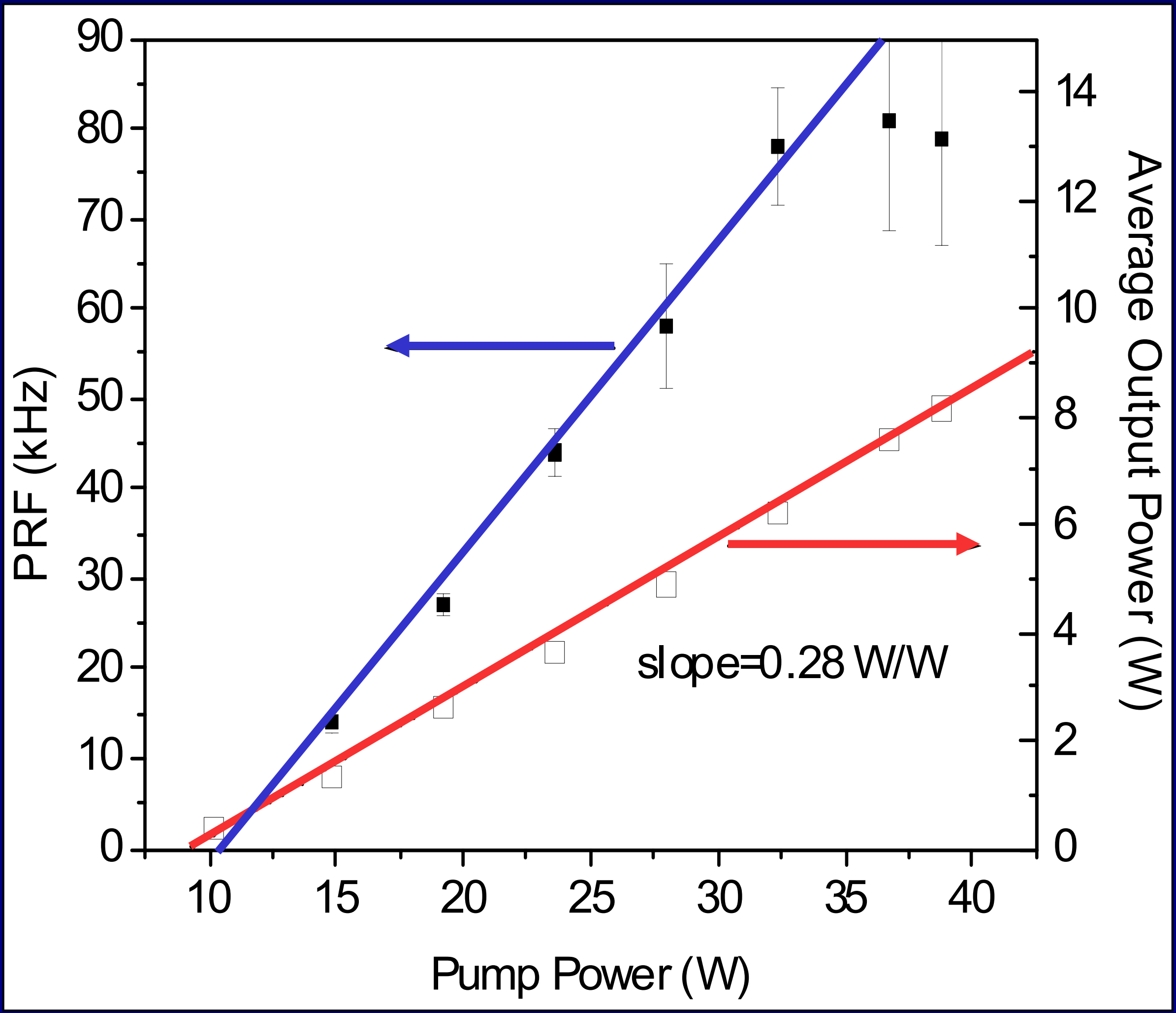
- Peak optical to optical efficiency 31%
- Output beam diffraction-limited in guided axis

1μm Passive Q-Switching - Cr^{4+}:YAG

- Compact, robust, and monolithic passively Q - switched resonator
- Cr^{4+}:YAG saturable absorber integrated into doped region of waveguide

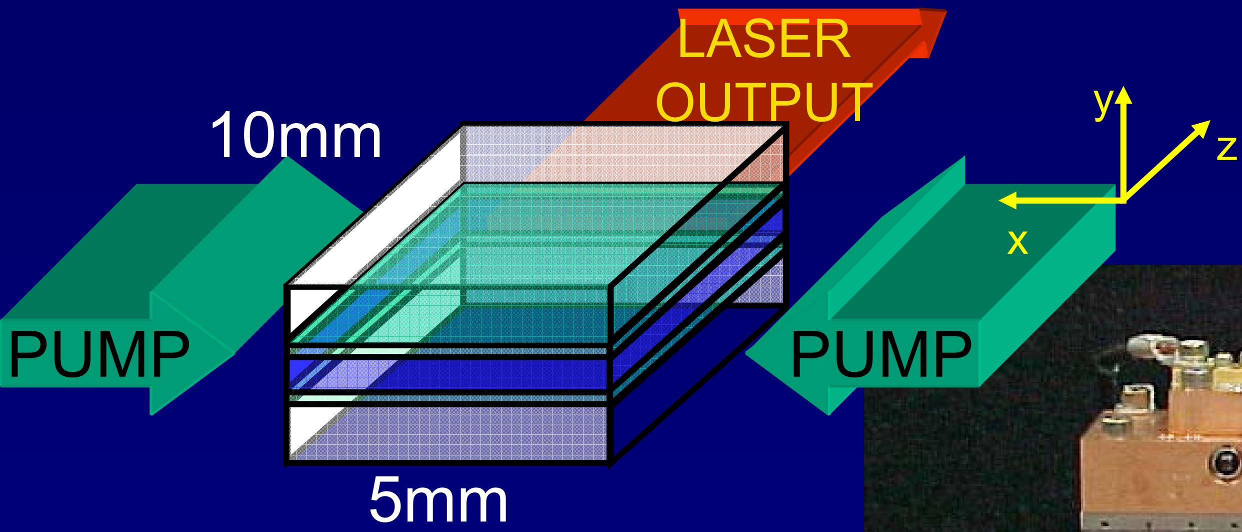


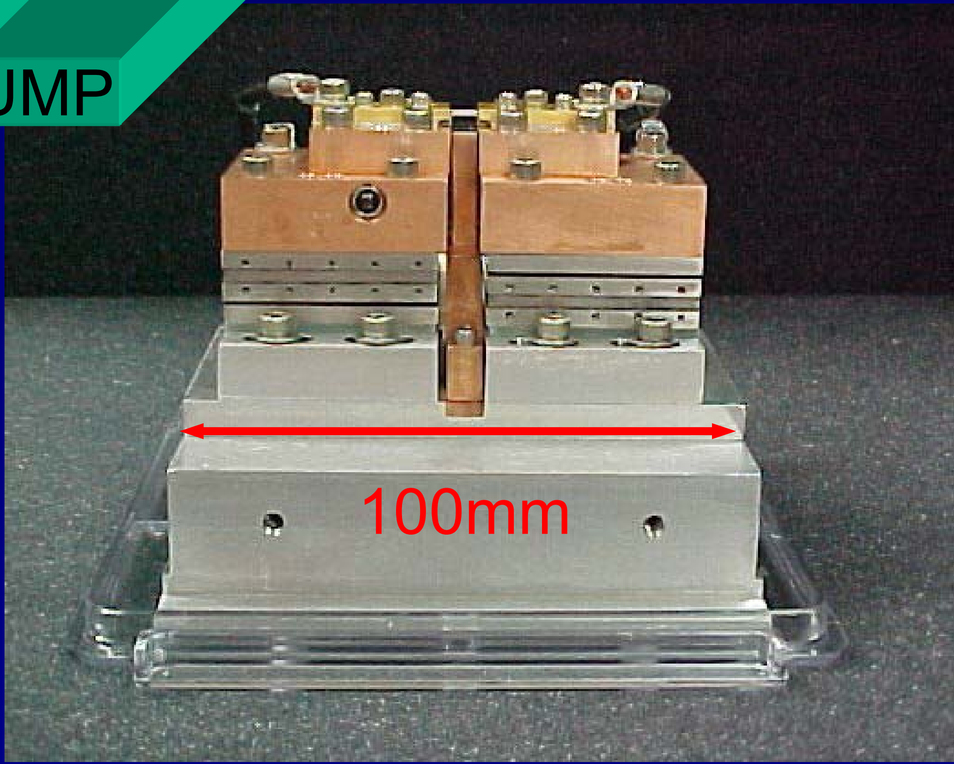
Nd:YAG Passive Q-Switched Results



- 21% peak to peak optical efficiency
- $\tau_p \approx 3$ns
- PRF roll-off attributed to Cr^{4+} lifetime

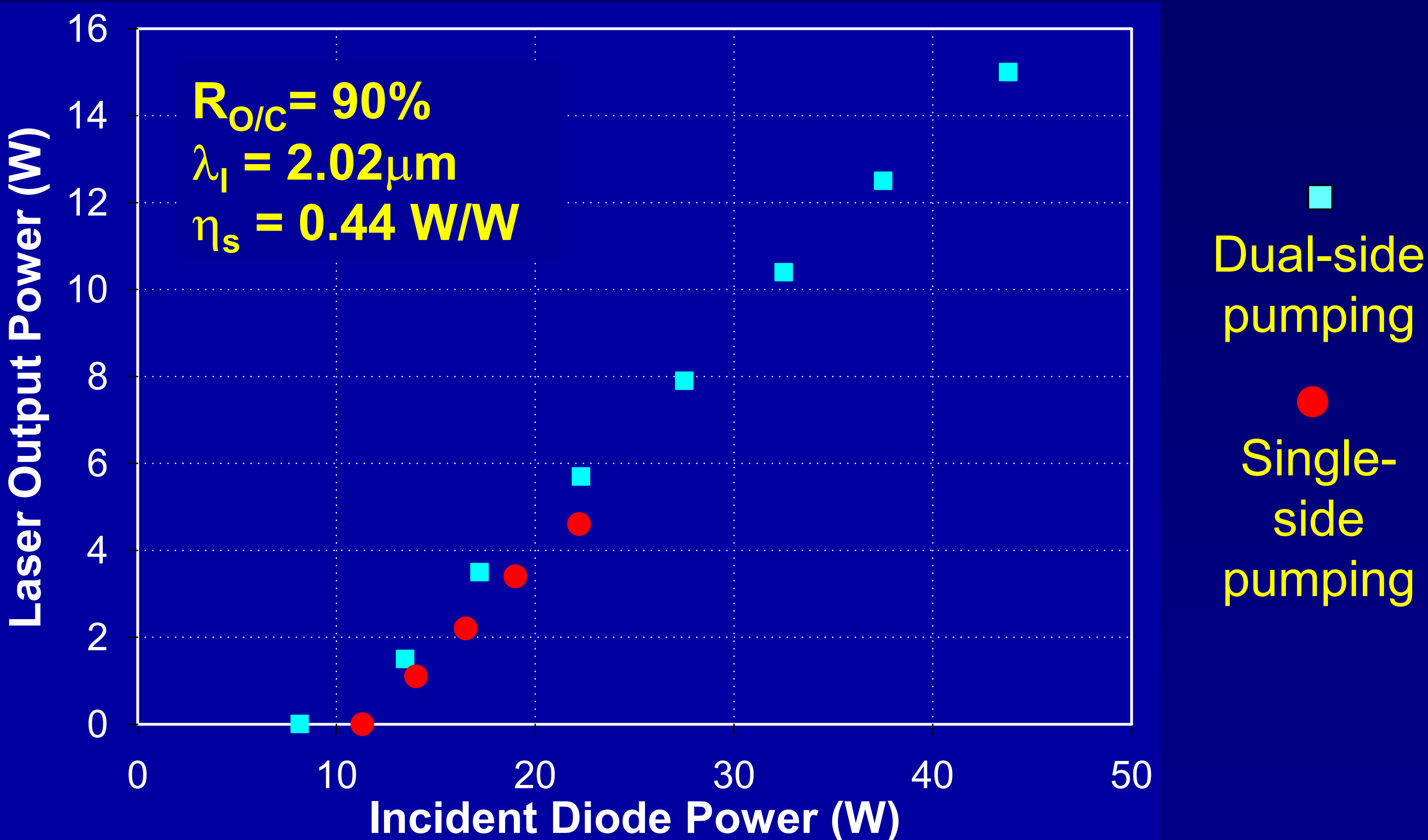
Characterisation of 2μm laser





- Compact Maxios flexure laser head
- 5-layer $Tm_{10\%}$:YAG waveguide structure
- Mirrors coated onto end faces

Tm:YAG CW Results



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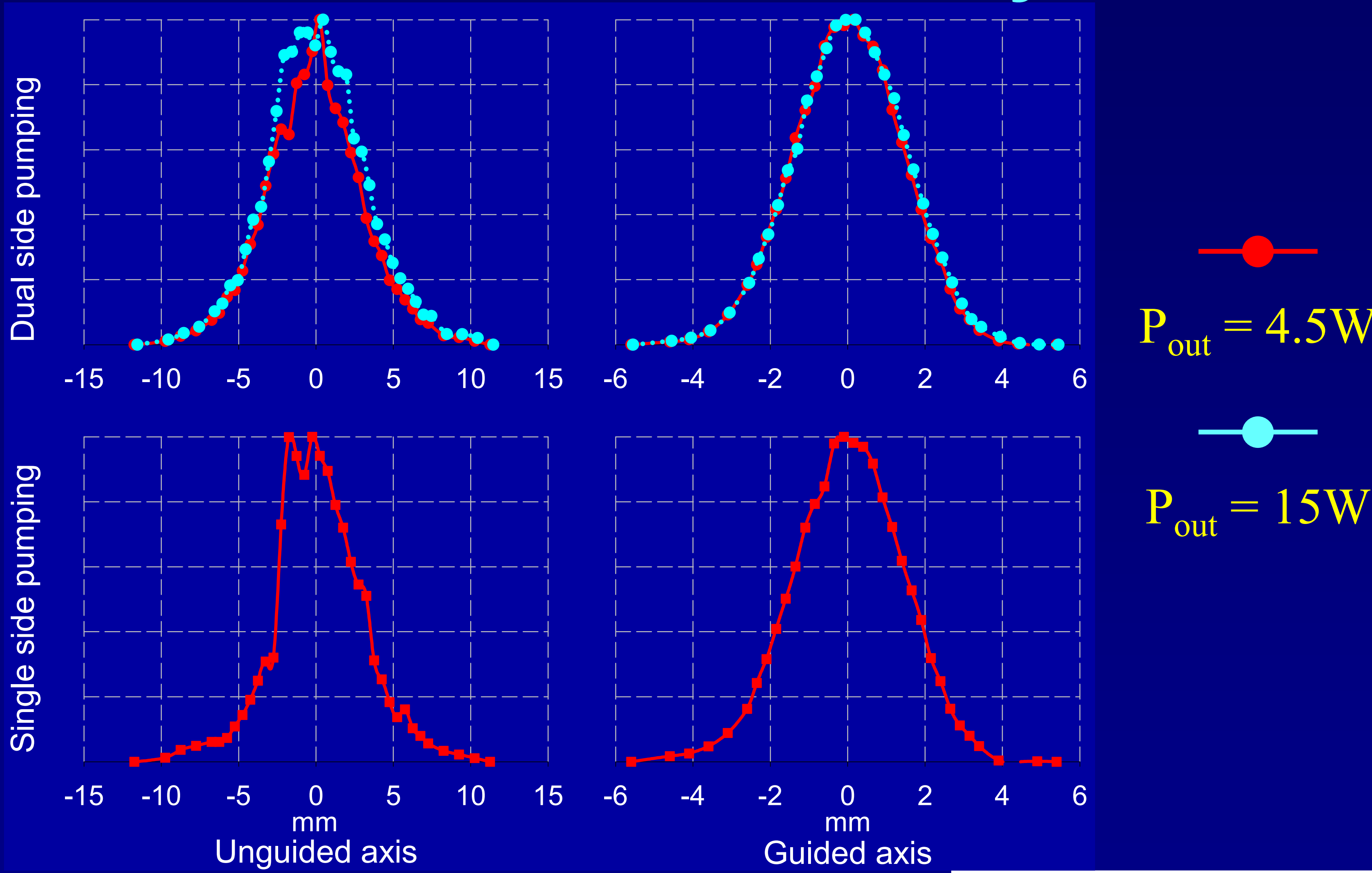
Tm:YAG Beam Quality



$M_x^2 \approx 300$

$M_y^2 = 1.1$

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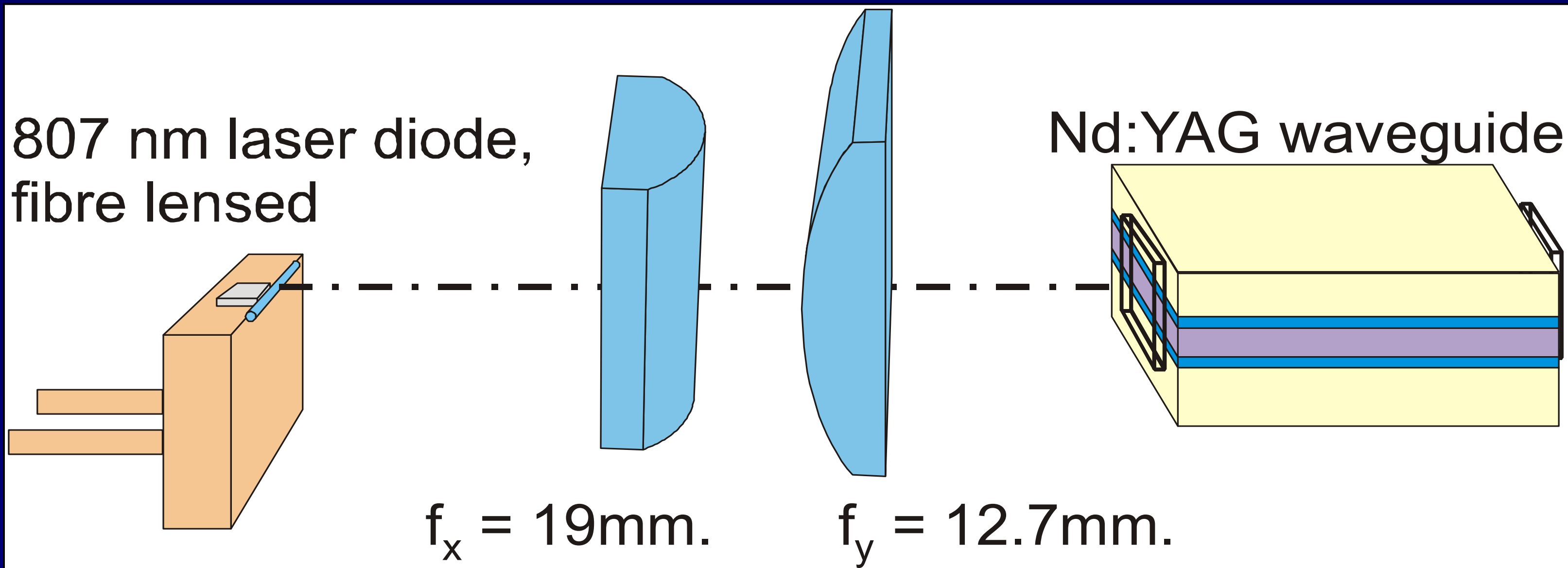
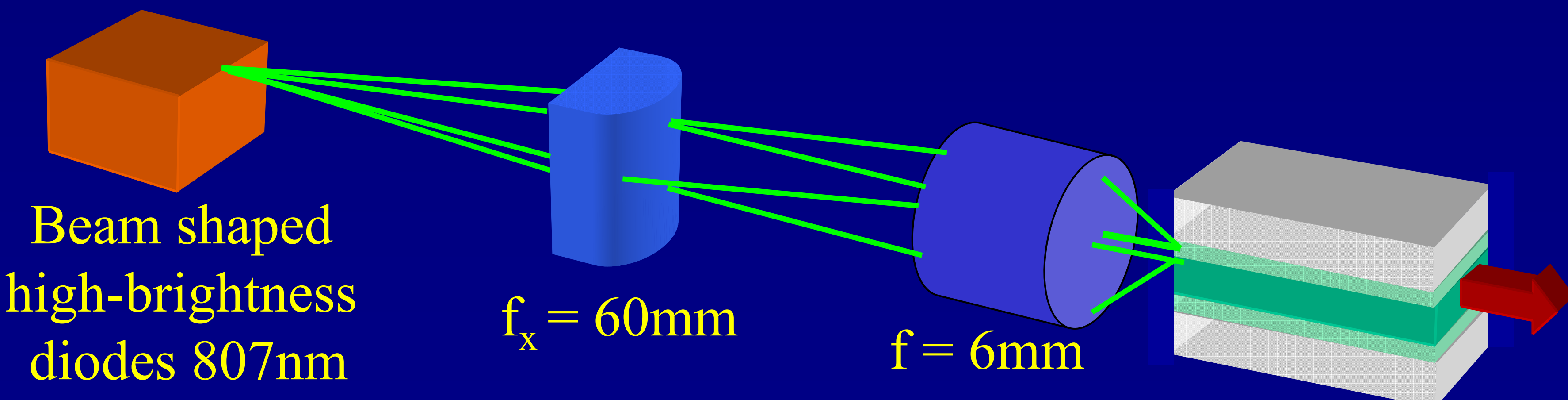
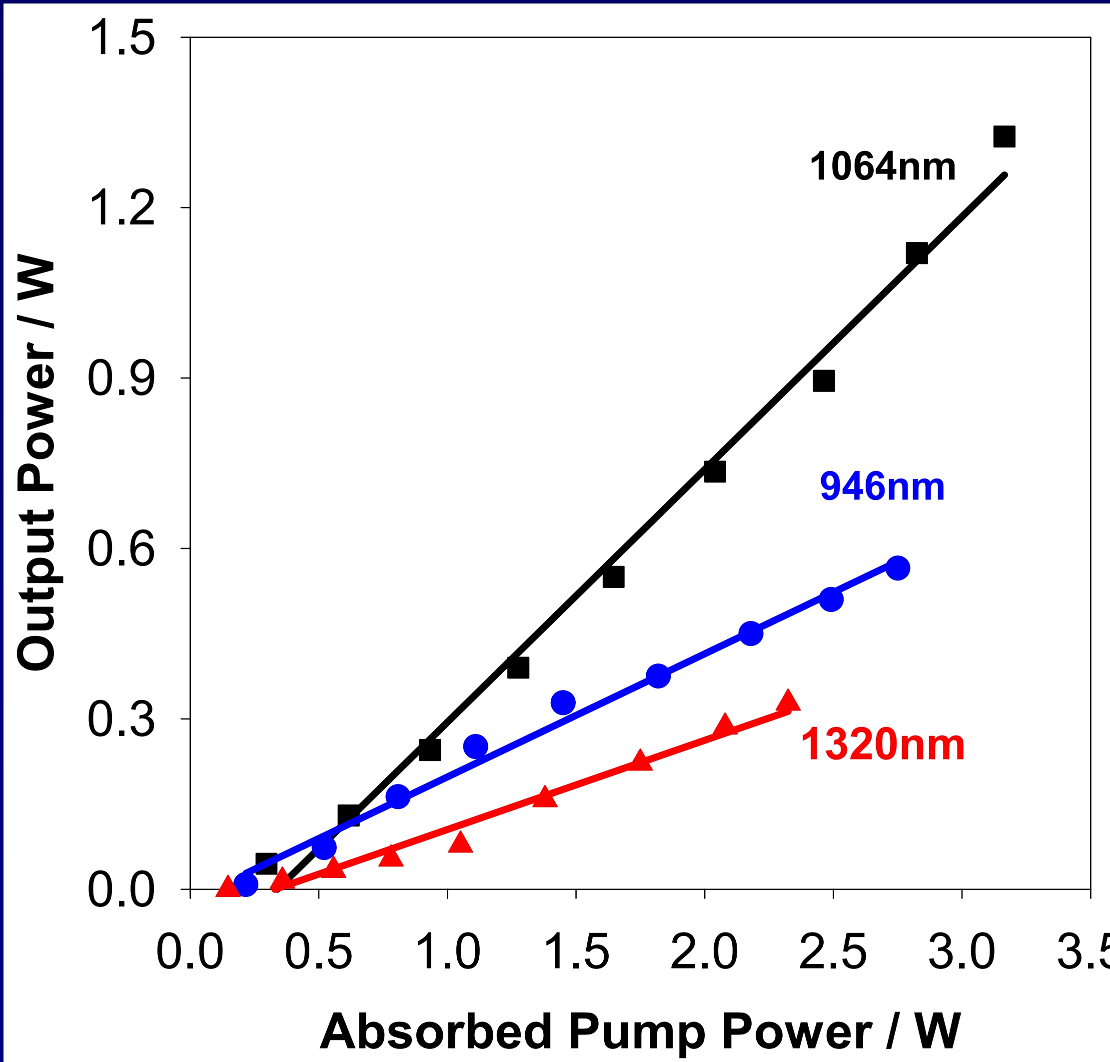
End-Pumping Results



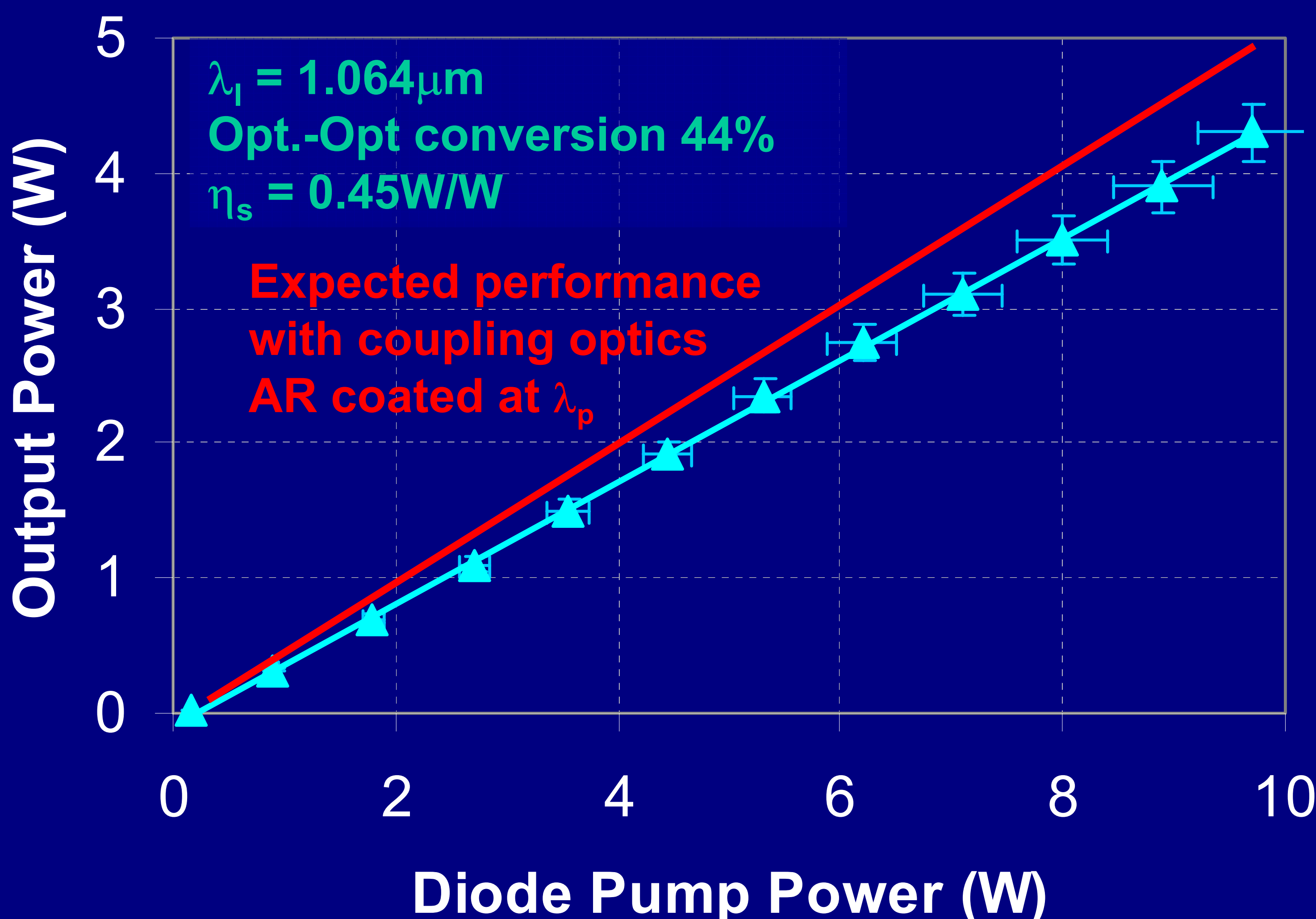


4W End-Pumping Results

- λ_l=1064nm
  - $T_{o/c}$=32%, η_s=45%
- λ_l= 946nm
  - $T_{o/c}$=3%, η_s=22%
- λ_l= 1320nm
  - $T_{o/c}$=7%, η_s=17%



10W End-Pumping Results



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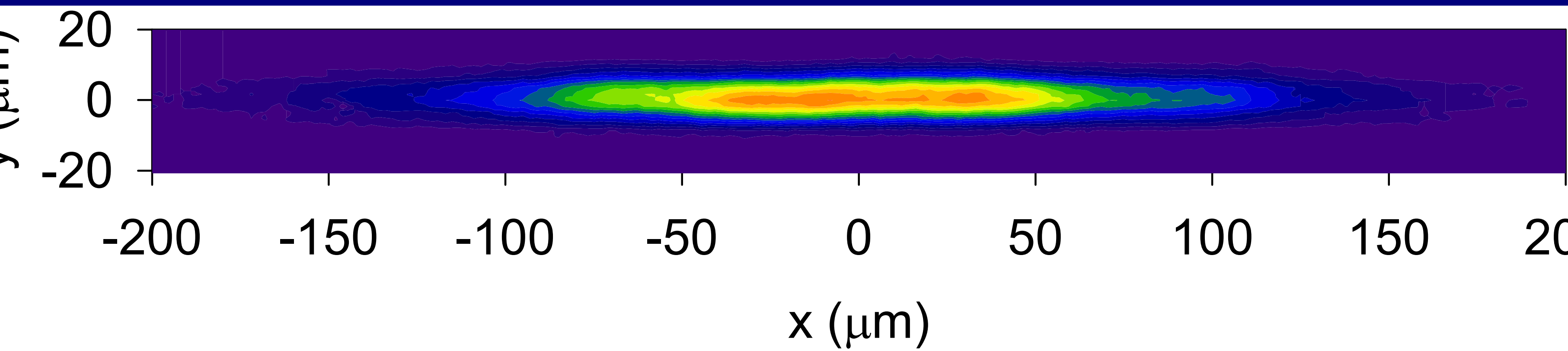
Beam Quality

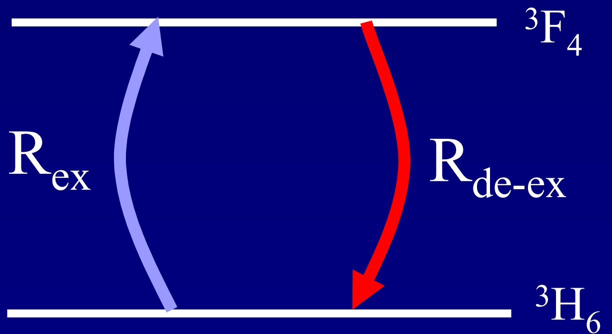
Pump source	$W_{0\,(x,y)}$*	$M_{x,y}^2$
4W	10 ± 0.1 x 165 ± 5 μm	1.8 x 1.1 ± 0.1
10W	10 ± 0.1 x ~135 μm	1 ? Hopefully!

* Second moments $1/e^2$ radius, at output coupler.



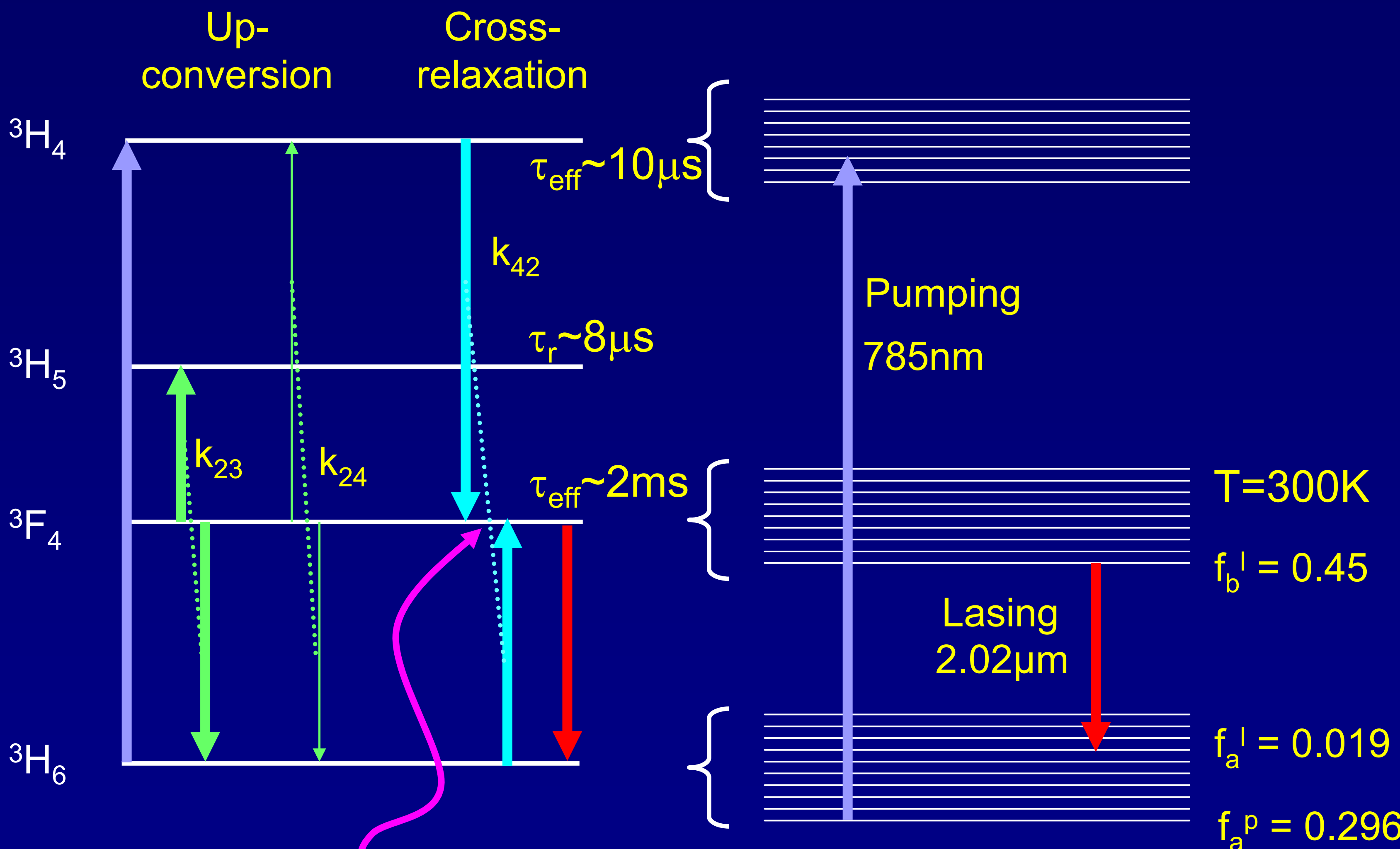
Energetics modelling

- Simply match the excitation and de-excitation rates between upper and lower laser levels



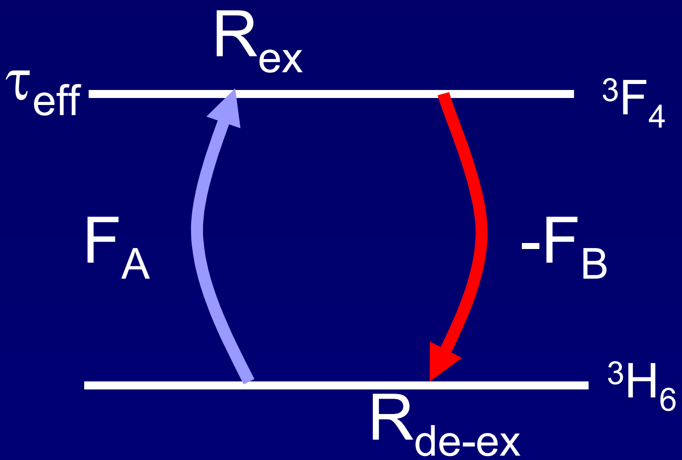
- Assumptions:
  - Plane waves
  - Uniform gain
  - Loss collected at HR mirror
  - Unity overlap in non-guided plane

Tm:YAG Energy Levels



Quantum yield → 2, Tm^{3+} > 2 At.%

Energetics Modelling



Fractional absorption per pass

$$F_A = 1 - \exp(\eta^{p}_{ovlp} \cdot \sigma_a \cdot N_{2p})$$

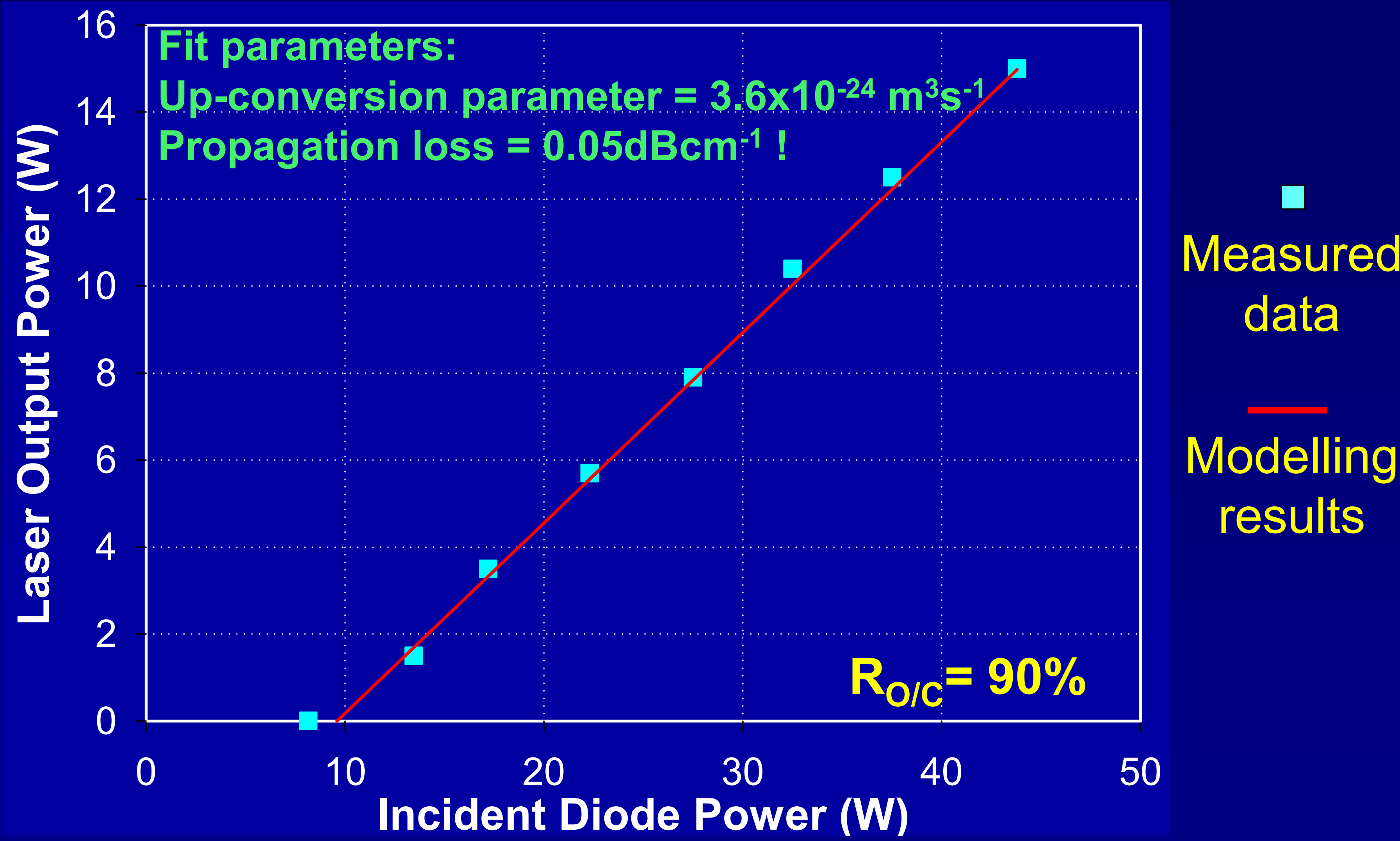
$$F_B = 1 - \exp(\eta^{l}_{ovlp} \cdot \sigma_e \cdot N_{2l})$$

$$P_{out} = \eta_s \left(P_p - P_{th}\right)$$

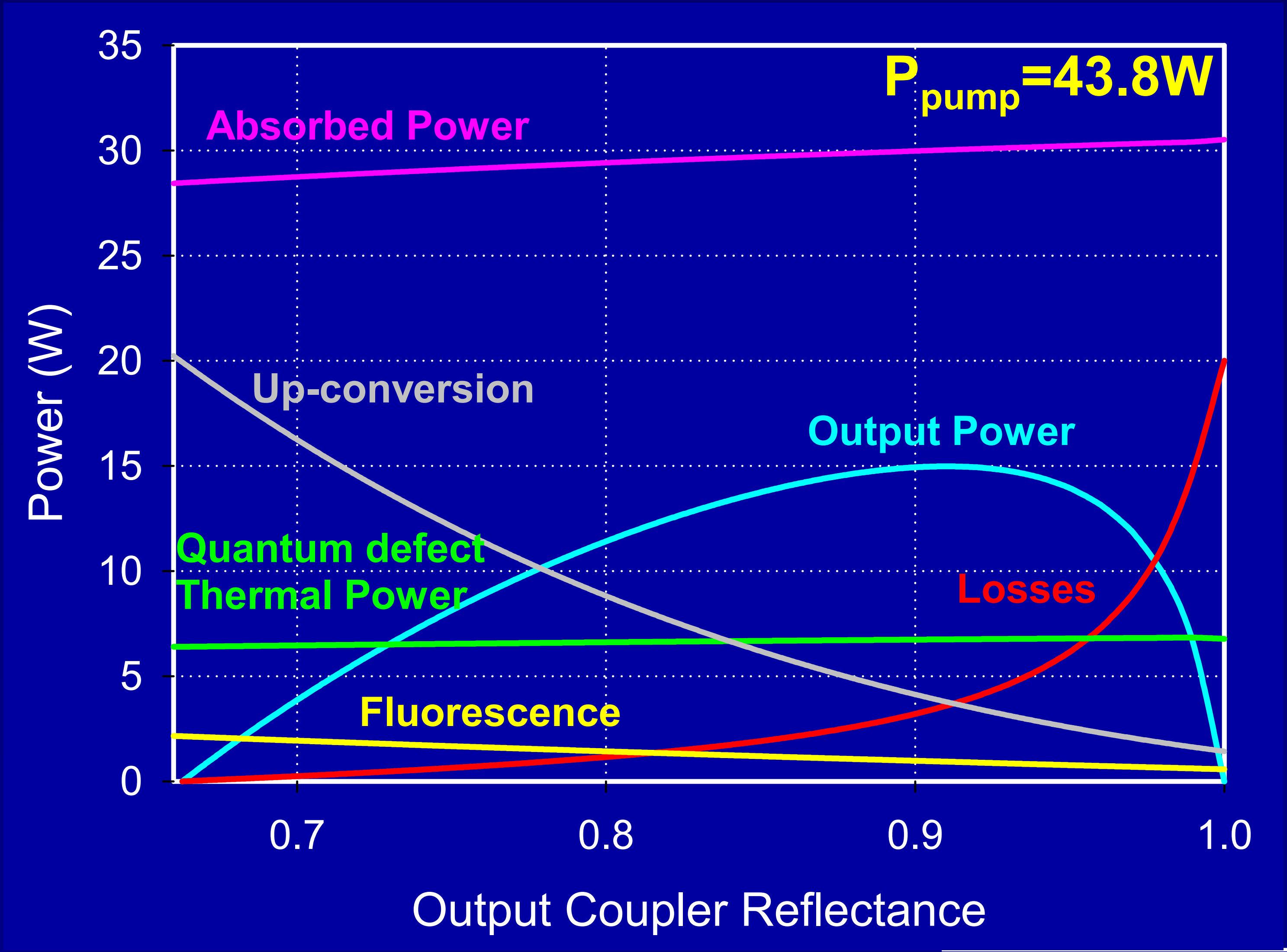
$$P_{th}(R_{oc}, UC) := \frac{h \cdot \nu_p}{\eta_{del} \cdot \eta_{QY}} \cdot \frac{n_2(R_{oc}) \cdot l \cdot w \cdot t_{core}}{\tau_{eff}(R_{oc}, UC)} \cdot \frac{1}{F_A(R_{oc})}$$

$$\eta_s(R_{oc}) := \eta_{del} \cdot \eta_{QY} \cdot \frac{\nu_l}{\nu_p} \cdot \frac{(1 - R_{oc})}{R_{oc}} \cdot \frac{F_A(R_{oc})}{-F_B(R_{oc}) \cdot \left[1 + T_{sp}^{2} \cdot (1 - F_B(R_{oc}))\right]}$$

Model Results



De-excitation channels



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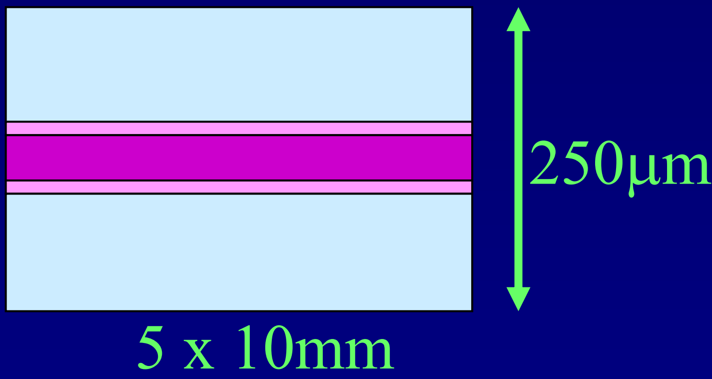
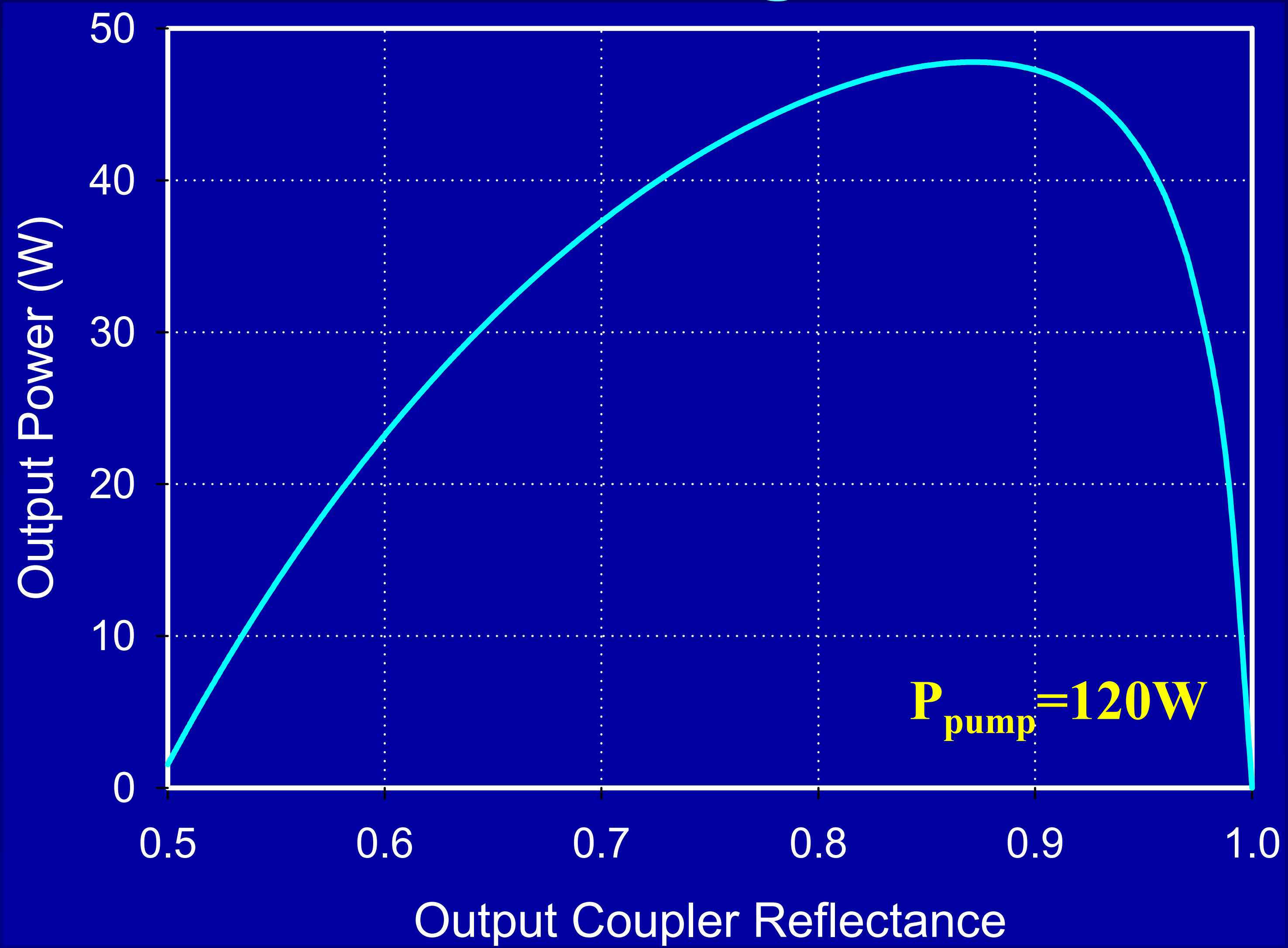
Power Scaling Implications

- Current technology $\Rightarrow$120W pump
- Performance degradation dominated by temperature rise
  - Single face cooling, $\Delta T \approx 60°$
  - Dual face cooling, $\Delta T \approx 30°$
  - Across core itself, $\Delta T < 0.25°$



- Guiding overcomes thermal lens
- Sapphire surface stress fracture - $P_p/P_{max} \approx 2x10^{-3}$

Power Scaling Model



Technology Summary

- PWL's emerging technology ⇒ compact, efficient
  - Diffraction-limited performance in guided axis
  - Ongoing work on unstable resonators, tapers, etc., to obtain fully diffraction-limited output
- Thin planar geometry ideal for thermal management
- Ideal for quasi-three level systems: (Nd^{3+}, Yb^{3+}, Tm^{3+}, Er^{3+})
- Proximity coupling ⇒ simple and robust
  - No coupling optics
  - Compatible with cheap high power diode lasers
- High power, high rep-rate Q-switched lasers
  - Non-linear and commercial applications

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