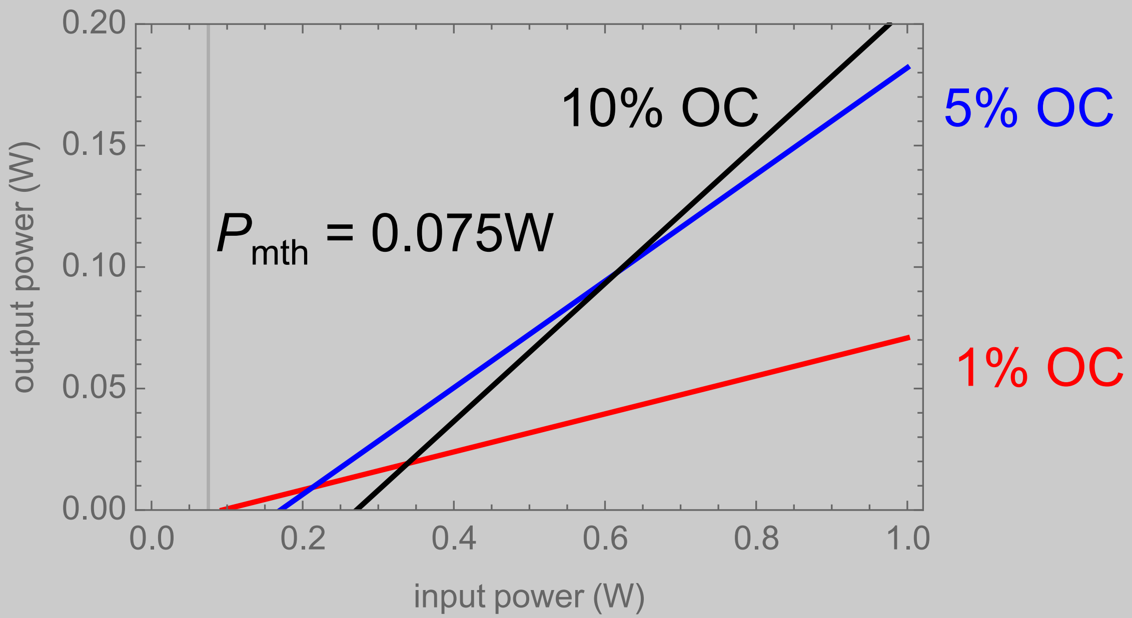
Optimizing output coupling

- As output coupling increases
  - pump threshold decreases
  - Fraction of intracavity power transmitted increases



  - P_{mth} = threshold for lasing when there is no output coupling

Minimum pump threshold

- The threshold power and slope efficiency both depend on the amount of output coupling loss

$$P_{out} = I_s A_b \frac{\gamma_2}{2}\left(\frac{P_p}{P_{th}} - 1\right) \qquad P_{th} = I_s A_p \frac{\gamma}{\eta_p}\frac{h\nu_p}{h\nu_{21}} \qquad \gamma = \gamma_i + \tfrac{1}{2}\gamma_1 + \tfrac{1}{2}\gamma_2$$

  - Lower output coupling leads to low threshold power, but less is let out of the cavity
  - Define P_{mth} = minimum threshold power, with ***no*** output coupling

$$P_{mth} = I_s A_p \frac{\gamma_i + \tfrac{1}{2}\gamma_1}{\eta_p}\frac{h\nu_p}{h\nu_{21}} \qquad \rightarrow P_{th} = P_{mth}\left(1 + \frac{\tfrac{1}{2}\gamma_2}{\gamma_i + \tfrac{1}{2}\gamma_1}\right)$$

  - Define ratio of pump power to minimum threshold pump power:

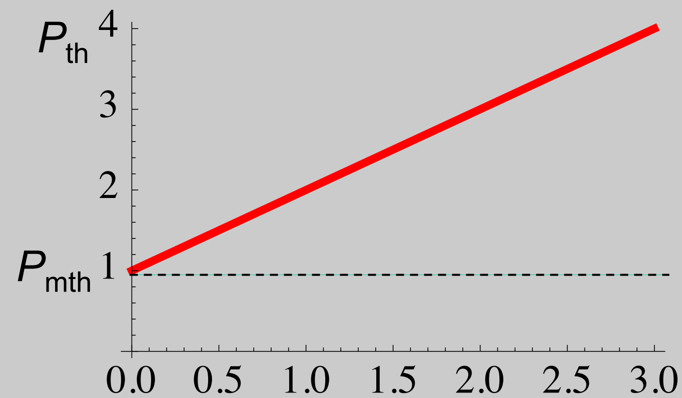
$$x_m = \frac{P}{P_{mth}}$$

Output power vs OC transmission

- Define a parameter S, which is the ratio of OC loss to other losses

$$P_{th} = P_{mth}\left(1 + \frac{\frac{1}{2}\gamma_2}{\gamma_i + \frac{1}{2}\gamma_1}\right) \equiv P_{mth}\left(1 + S\right)$$

  - Now look at output power vs S



$$S = \tfrac{1}{2}\gamma_2 / \left(\gamma_i + \tfrac{1}{2}\gamma_1\right)$$

$$\gamma_2 = 2S\left(\gamma_i + \tfrac{1}{2}\gamma_1\right)$$

$$x_m = \frac{P}{P_{mth}}$$

$$P_{out} = I_s A_b \frac{\gamma_2}{2}\left(\frac{P_p}{P_{th}} - 1\right)$$

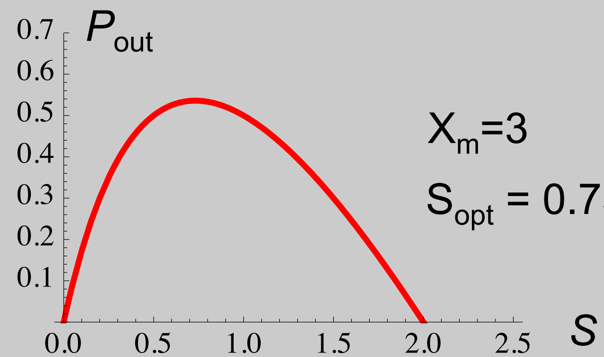
$$= I_s A_b \frac{\gamma_2}{2}\left(\frac{P_p}{P_{mth}(1+S)} - 1\right)$$

$$= I_s A_b \left(\gamma_i + \tfrac{1}{2}\gamma_1\right) S \left(\frac{x_m}{(1+S)} - 1\right)$$

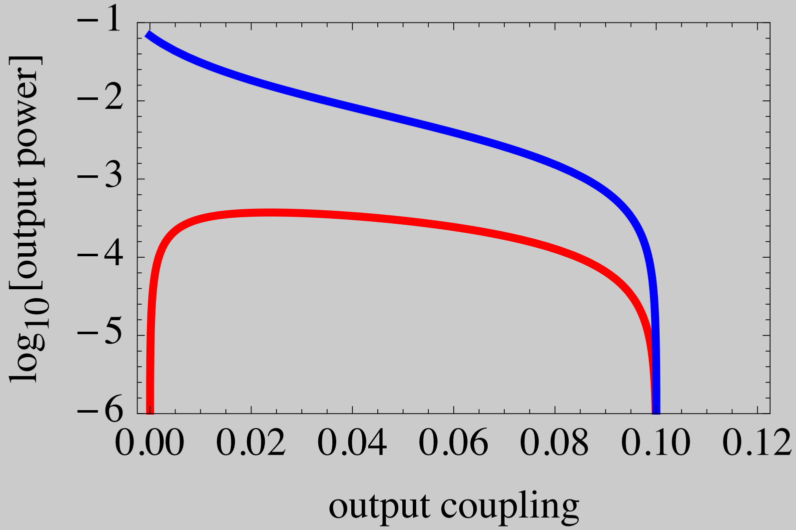
Optimized OC transmission

- Output power maximizes:
  - Low OC transmission, no output
  - High OC transmission, high P_{th}
- Find OC for maximum:
  - set $\partial_S P_{out}(S) = 0$

$$S_{opt} = \sqrt{x_m} - 1$$



- Intracavity power decreases with greater output coupling



$$P_{\text{int}} = P_{out} / \gamma_2$$

Intracavity power is always higher than output power

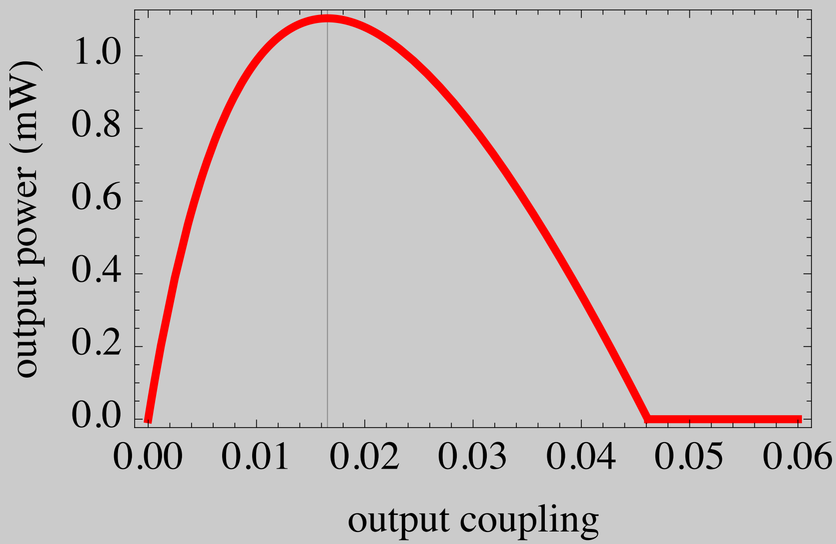
Example: HeNe laser

- Laser parameters

$$\lambda_L = 632.8nm \quad h\nu_{21} = 1.86\mathrm{eV}$$

$$\sigma_{21} = 3\times10^{-15}\,\mathrm{cm}^2 \quad \tau_{21} = 150\mathrm{ns}$$

$$\Gamma_{sat} = \frac{h\nu_{21}}{\sigma_{21}} = 1\mu\mathrm{J/cm}^2 \qquad I_{sat} = \frac{\Gamma_{sat}}{\tau_{21}} = \frac{h\nu_{21}}{\sigma_{21}\tau_{21}} = 6.6\mathrm{W/cm}^2$$



Assume uniform pump and laser mode

d_{pump}=2mm D_{mode}=1.75mm

γ_p=1% Min. threshold pump power: P_{mth}=2mW

L_{cavity}=40cm T_{RT}=2.7ns

Cavity photon lifetime at opt. OC: τ_c=72.5ns

Effective input pump power: P_p=7mW

Best slope efficiency, relative to effective input pump power: η_s=0.35

Lamp pumping

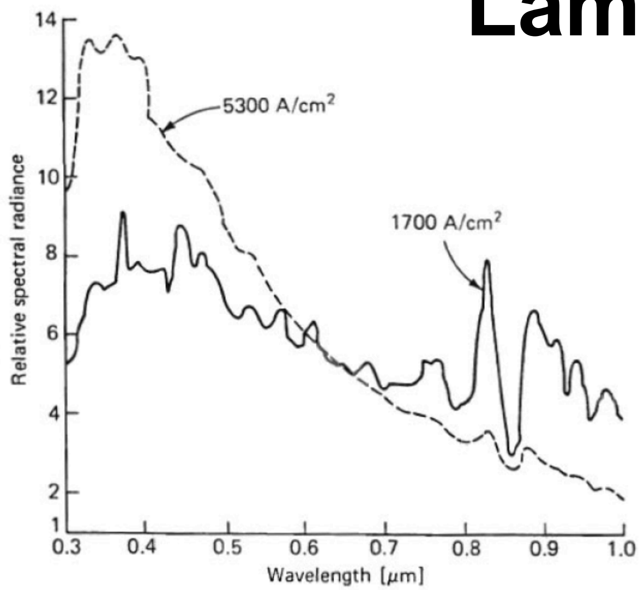
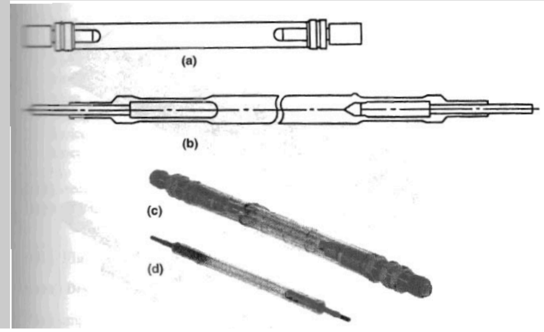


Fig. 6.3. Spectral emission of a xenon flash tube (EG&G, model FX-47A) operated at high current densities. Lamp fill pressure is 0.4 atm. The spectrum at the two current densities can be approximated by blackbodies at 7000 and 9400 K, respectively [6.1]



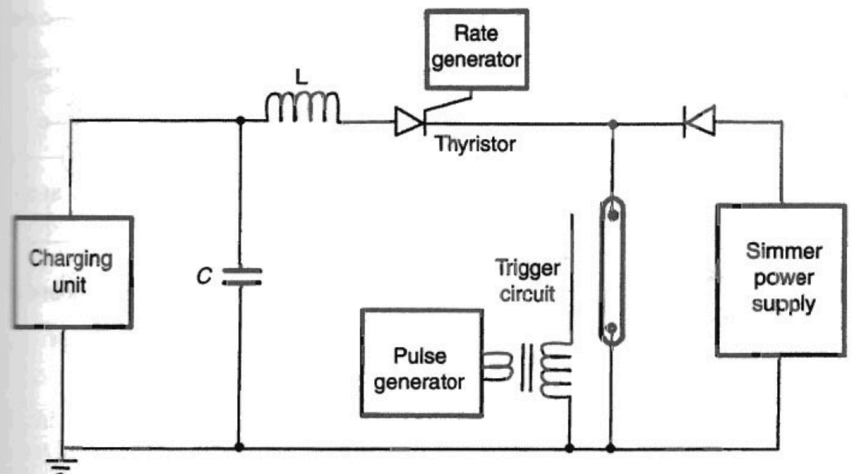
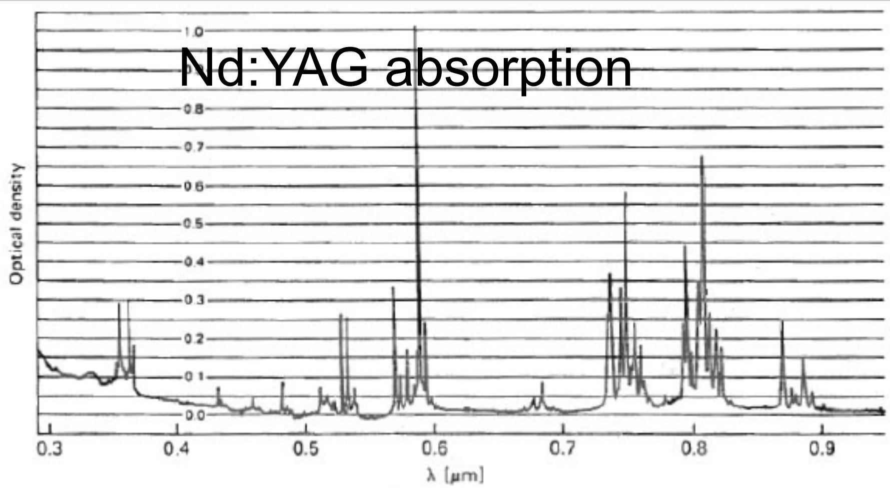


Fig. 6.10. Typical power supply employed for the operation of flashlamps

Nd:YAG absorption



(a)

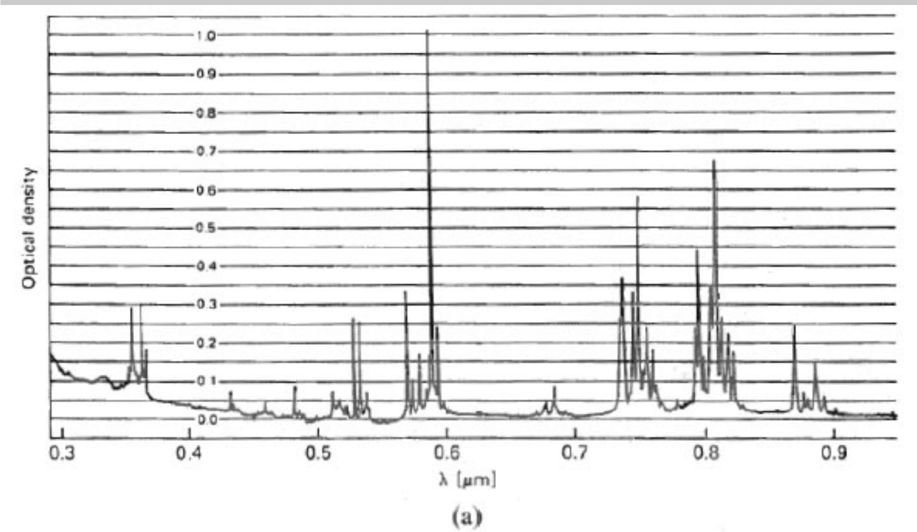
Account for:

- Efficiency of converting electrical to optical power
- spectral overlap efficiency

Improving spectral overlap

- Can sensitize material to absorb, then transfer to ions for better inversion density

Nd:YAG



Cr:Nd:GSGG

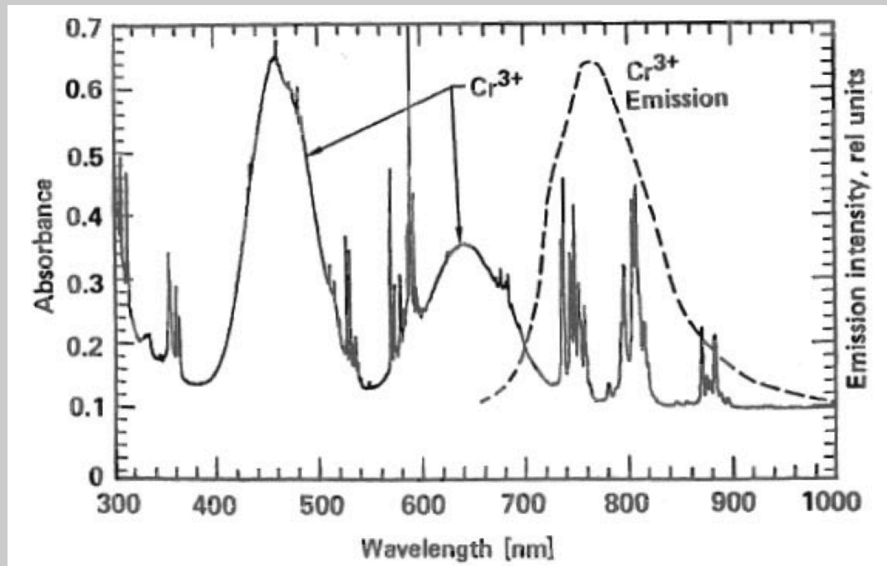
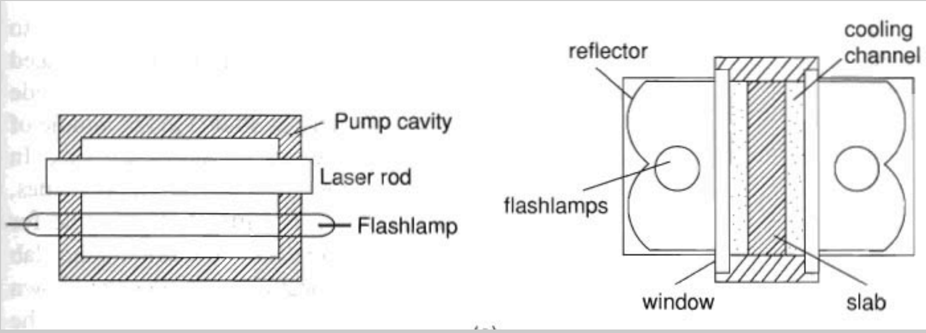
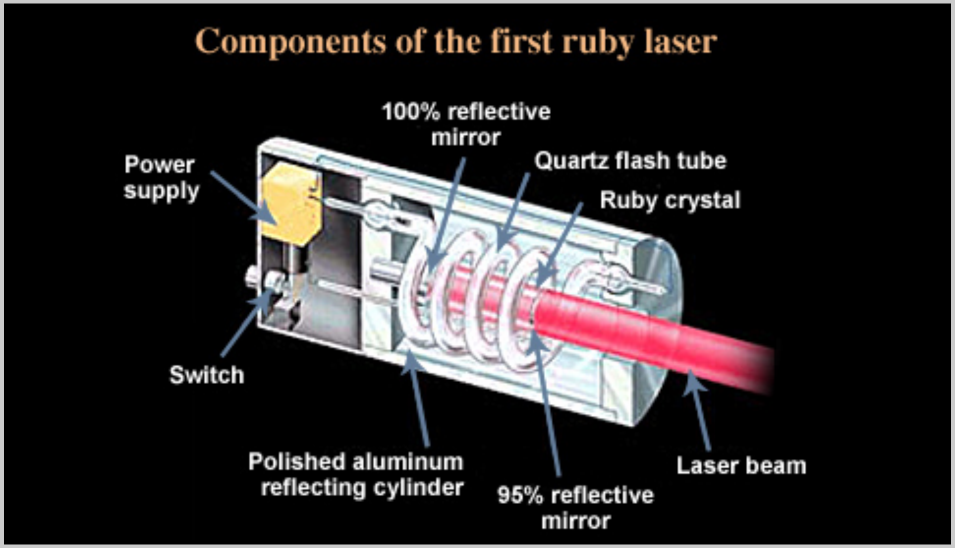


Fig. 2.8. Absorption spectra of Cr:Nd:GSGG [2.65]

Pump chambers



- Couple optical output from lamp into laser crystal



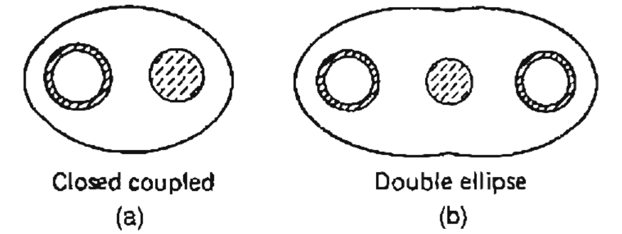


Fig. 6.48. (a) Single and (b) double elliptical pump cavity

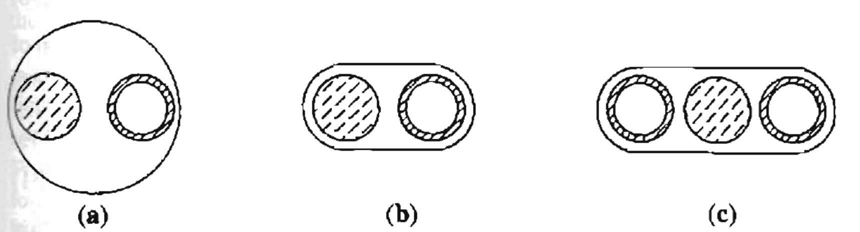
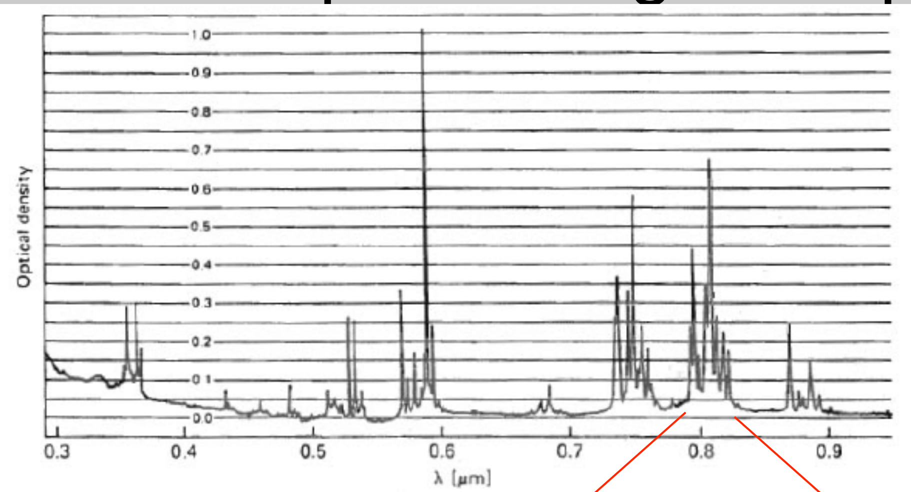


Fig. 6.49. Nonfocusing pump cavities; (a) circular cylinder, (b) single, and (c) double-lamp closed-coupled configuration

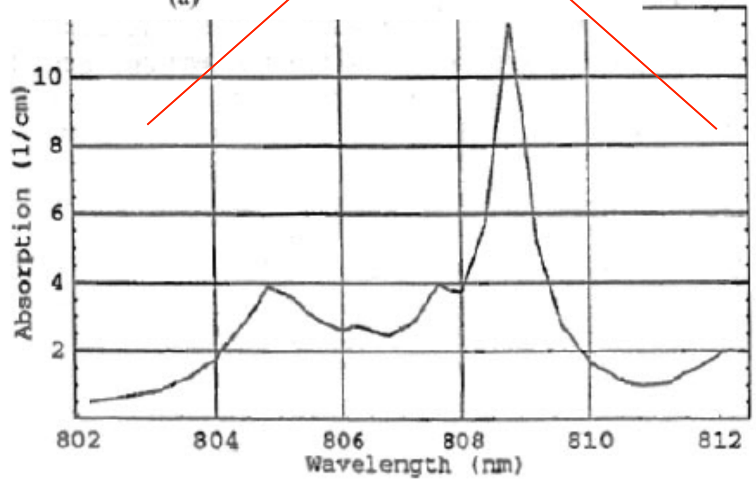
Account for pump transfer efficiency

Diode pumping

- Pump at strong absorption line near 808nm



(a)



(b)

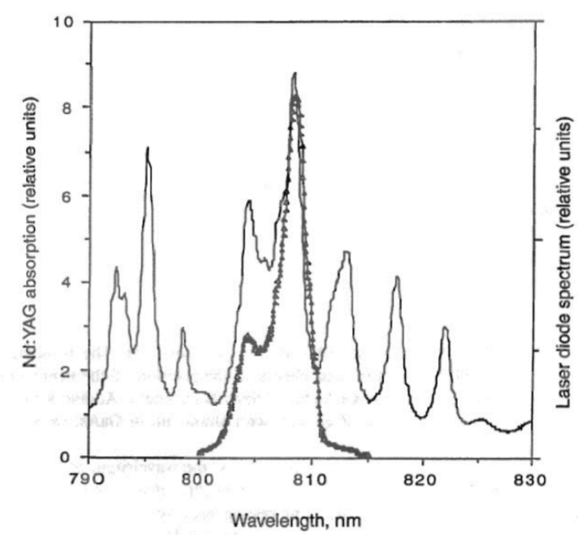
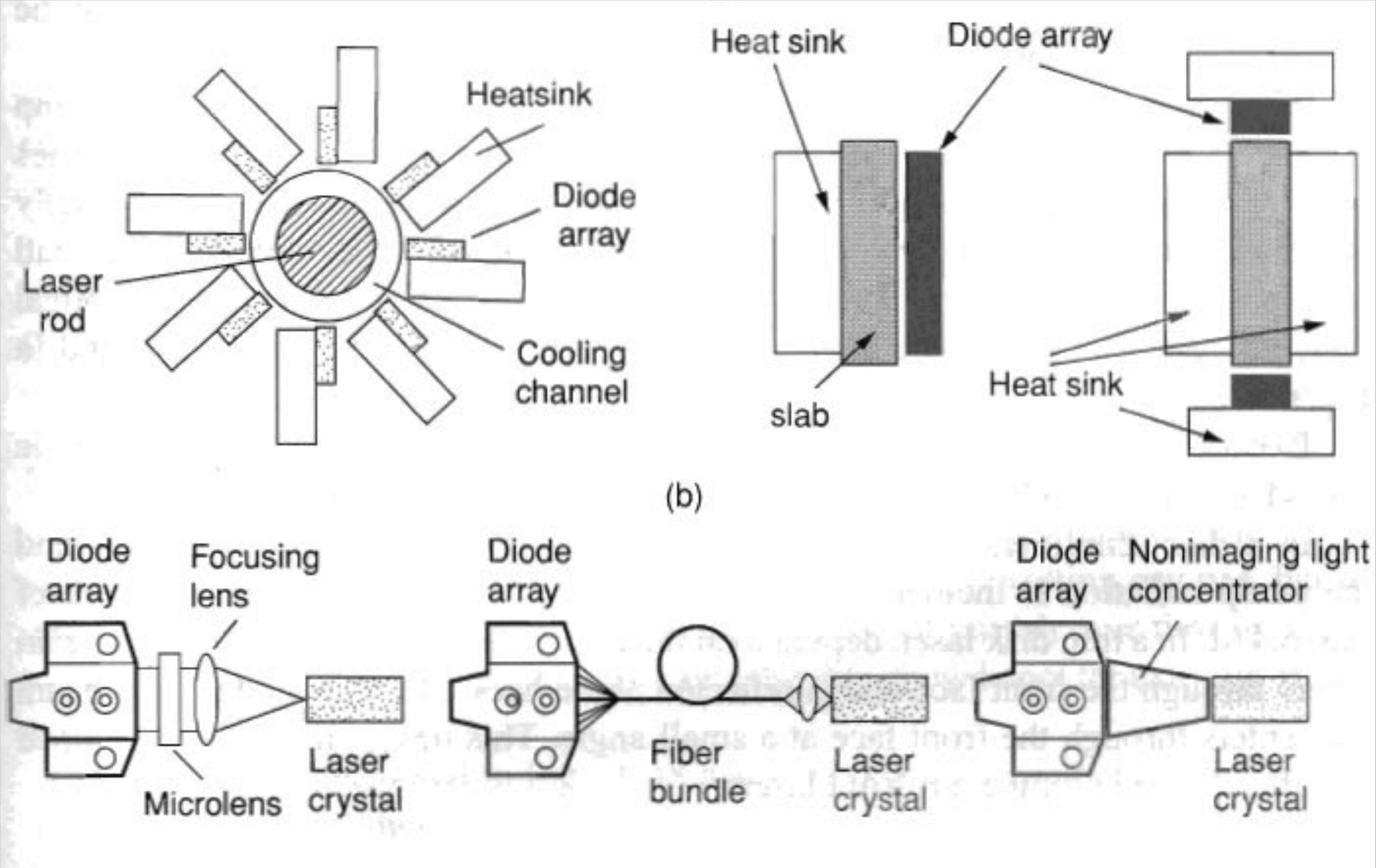


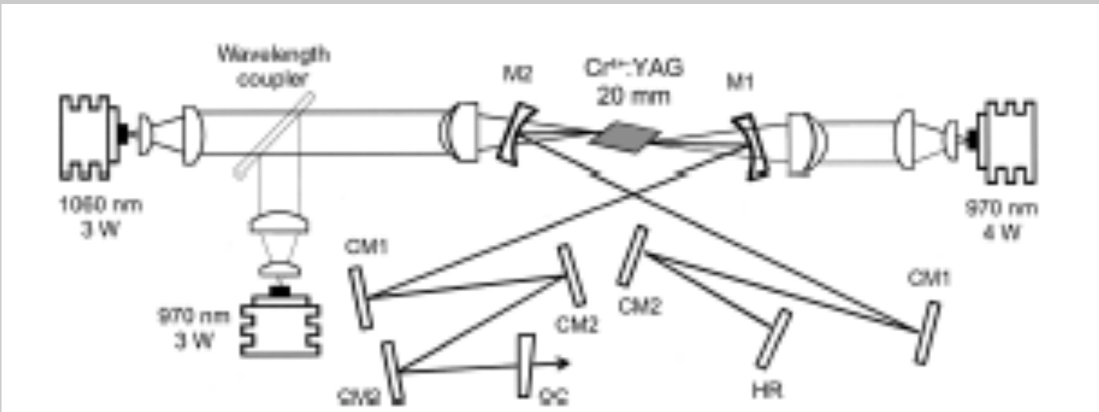
Fig. 6.40. Spectral overlap between Nd:YAG absorption and emission spectrum of a 10 bar array [6.56]

Diode pumping configurations

- Single emitters or arrays



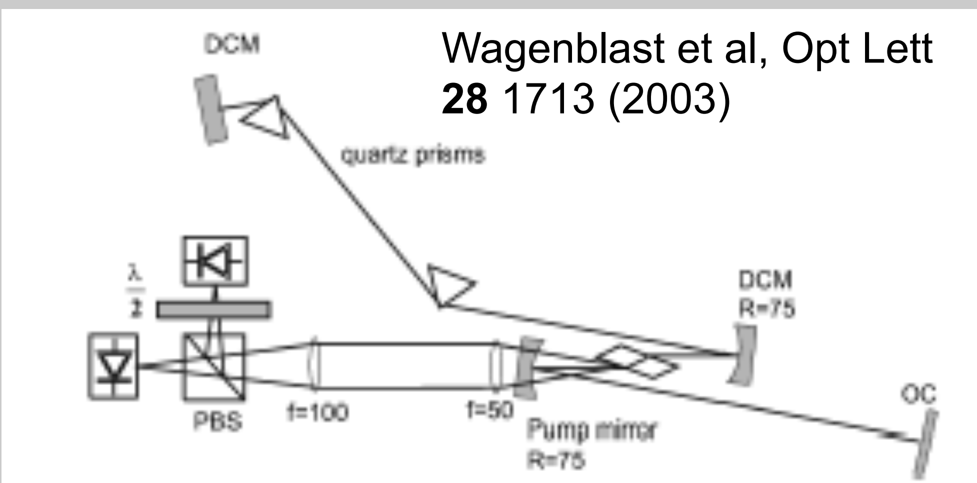
Direct-diode pumped KLM lasers



Naumov et al, Opt Lett v29 1276 (2004)

Cr^{4+}:YAG

8.3W pump, 10mW avg out
65fs pulse
Double-sided, 2 wavelength pumping



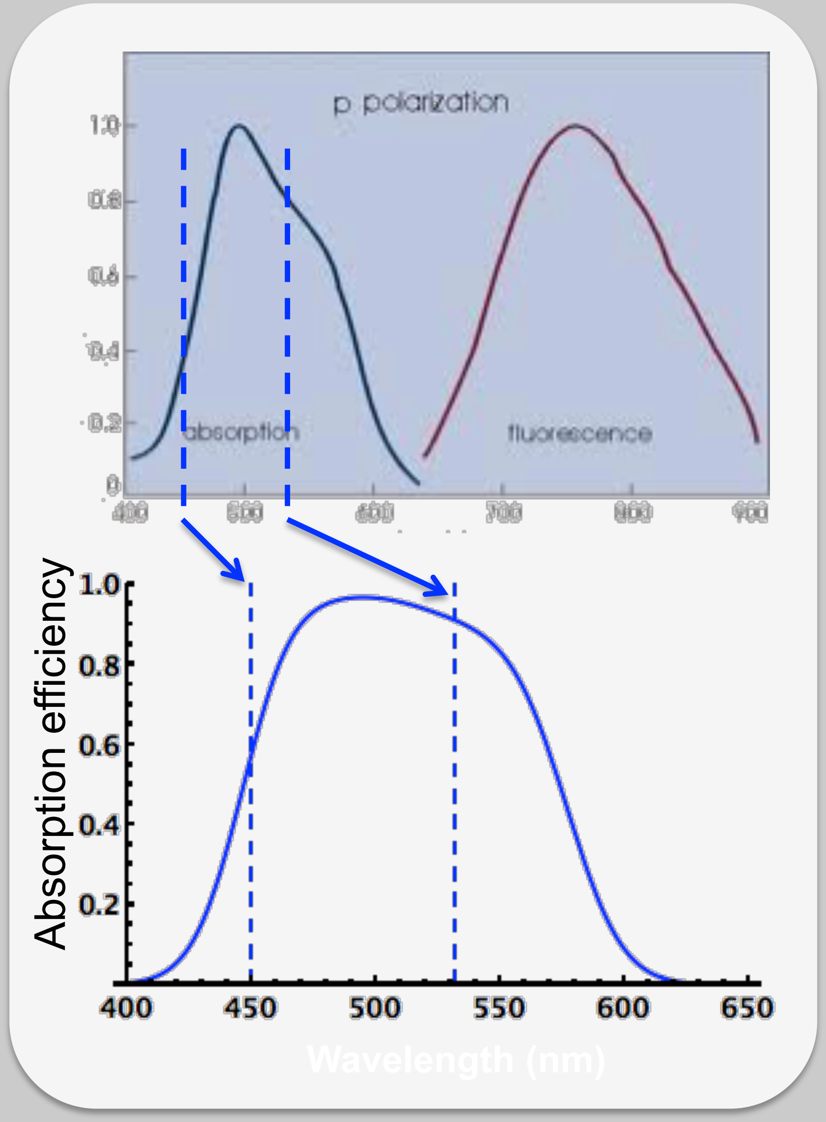
Wagenblast et al, Opt Lett **28** 1713 (2003)

Cr^{3+}:LiCAF

1.0W pump, 40mW avg out
10fs pulse
Polarization-multiplexed pumping

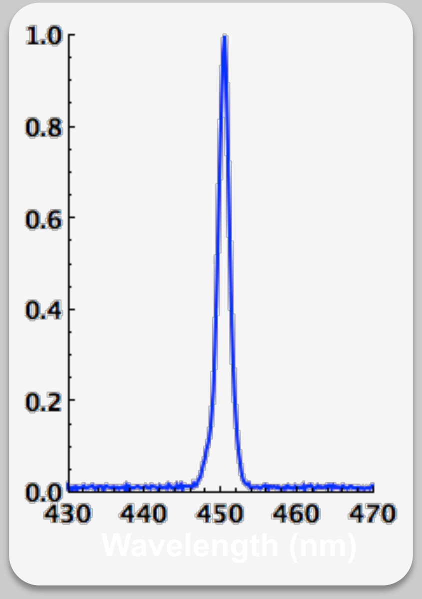
Challenges to diode-pumping Ti:sapphire

- Desire small pump mode volume
  - Efficiency
  - Soft-aperture for Kerr-lens modelocking
- Pump absorption efficiency
- Quantum defect

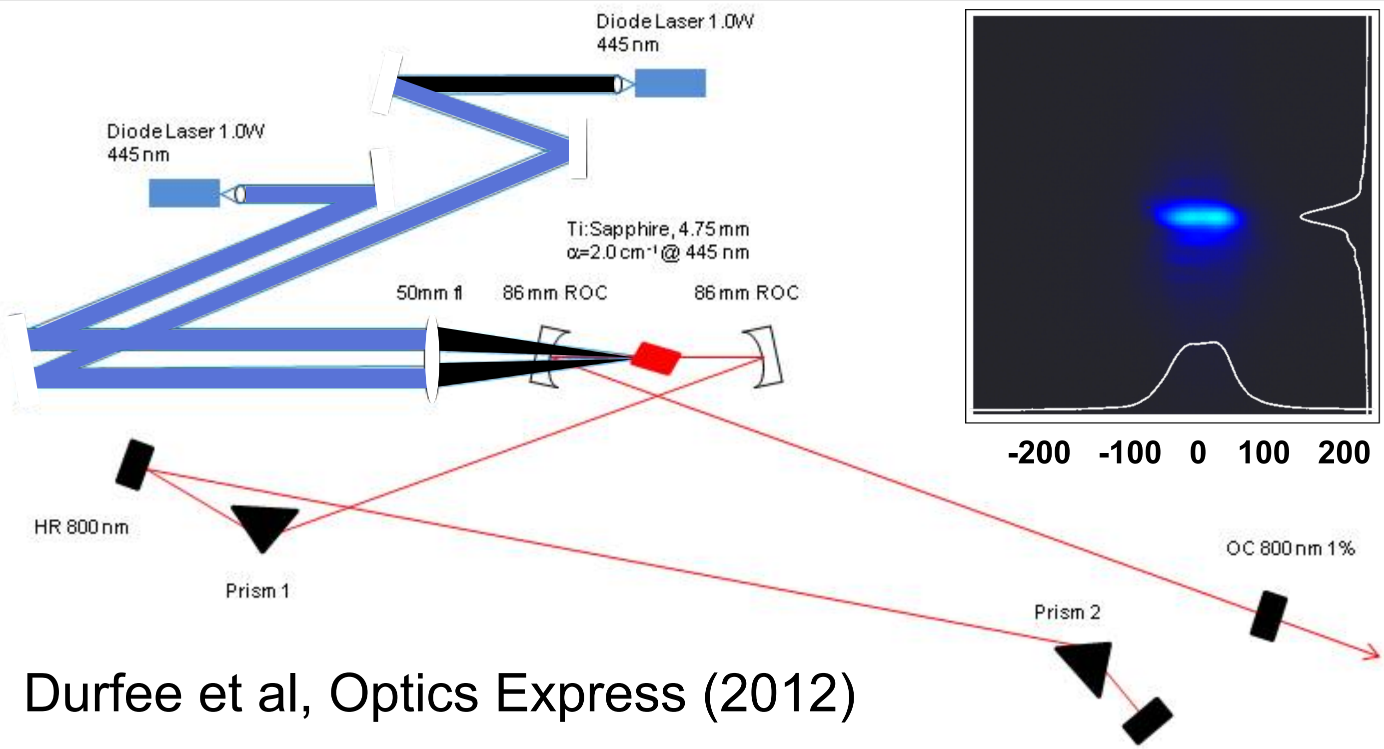


High-power blue laser diodes

- GaN based diodes
- Used commercially for projectors
- Facet: 15:1 aspect ratio
- Fast/slow axis divergence: ~3.5:1
- 1.2, 1.6, 2 watts/single emitter now available
- 445nm typical, some lot variation
- Small shift in output wavelength with temperature.



Cavity layout



Durfee et al, Optics Express (2012)

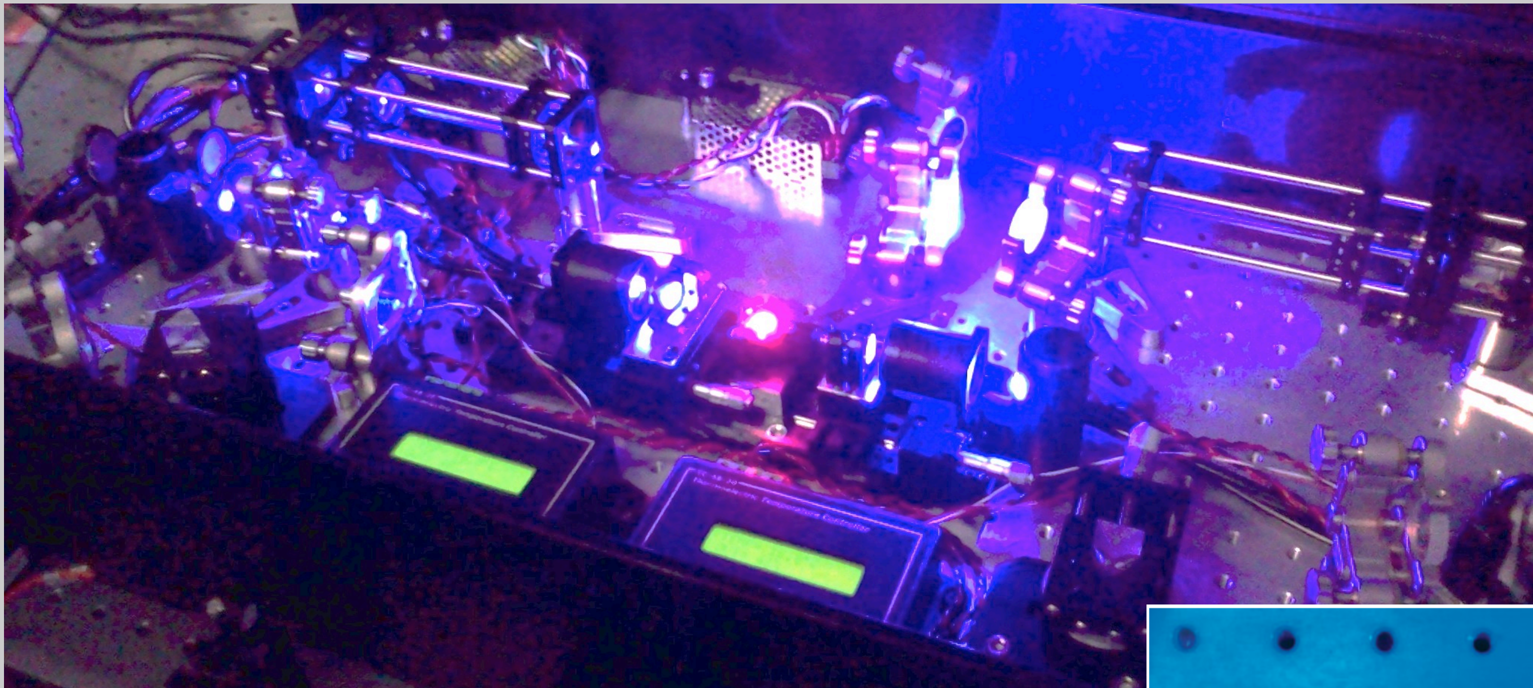
Pump optics:

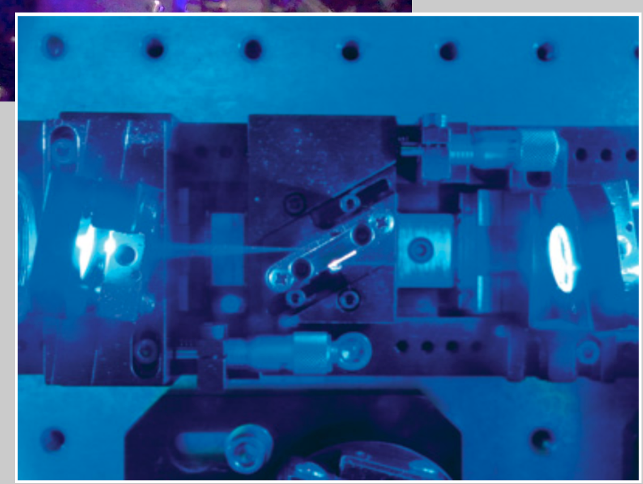
- Asphere + 3:1 cylindrical telescope
- Side-by-side beams

Laser cavity designed for low threshold

- 86mm ROC curved mirrors for smaller intracavity mode size
- 1% OC for higher intracavity power
- Green pump: 30mW mode-locked with 500mW pump power

Laser operation



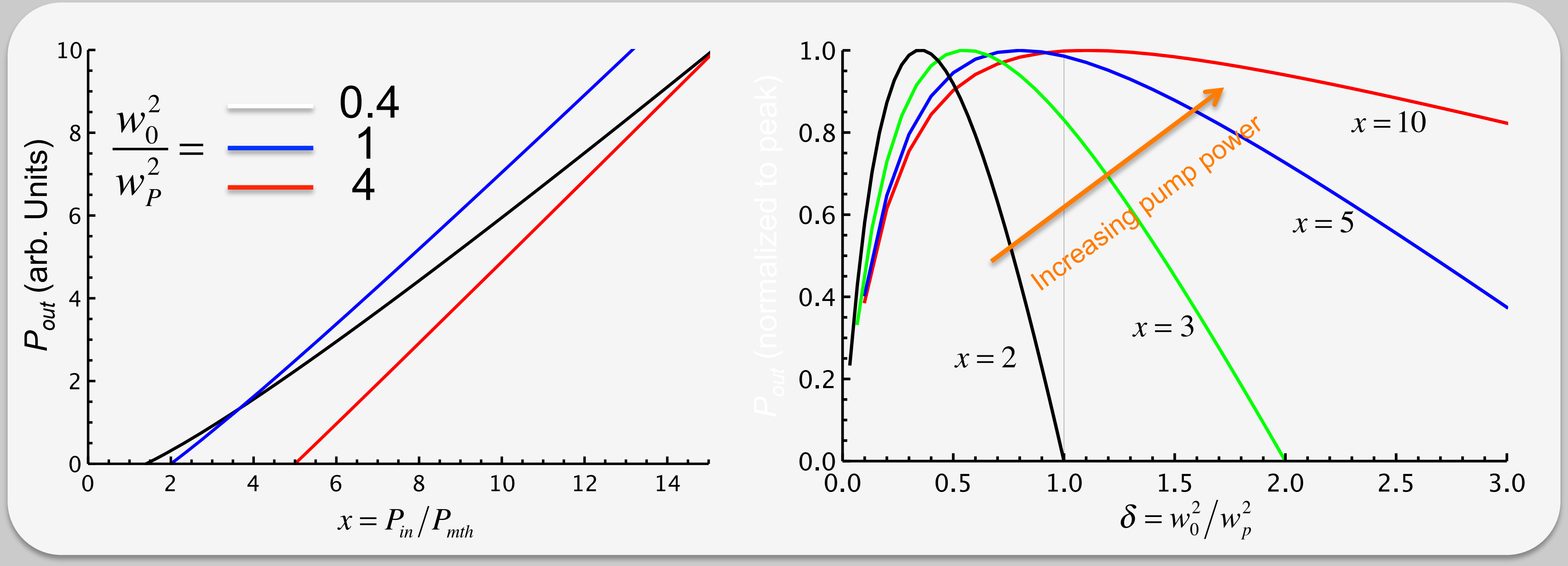


1.8W to crystal, 60% absorption
Average output power:

- 40mW optimized CW
- 32mW mode-locked

Contributions to KLM

- Soft aperture in vertical direction
- Uniform gain along optical axis (60% pump absorption)
- Re-imaging of CW and ML spots shows z-shift in waist location.
- Low-threshold operation for small mode size gives high discrimination



4-level system comparison: Nd:YAG

- Assume:
  - 1W pump available, aim for P_{th}=100mW
  - Thickness or concentration in gain medium enough to fully absorb pump
  - 5% OC
- Nd:YAG

$$\sigma_{21} = 2.8 \times 10^{-19} cm^2 \qquad \Gamma_{sat} = 0.63 J / cm^2$$

$$\lambda_L = 1064 nm \qquad I_{sat} = 2751 W / cm^2 \qquad w_P = 140 \mu m$$

$$\lambda_P = 808 nm \qquad \eta_S = 76\%$$

$$\tau_{21} = 230 \mu s$$