Intense lasers: high peak power
Part 2: Propagation

Bruno Le Garrec

Directeur des Technologies Lasers du LULI

LULI/Ecole Polytechnique, route de Saclay

91128 Palaiseau cedex, France

bruno.le-garrec@polytechnique.edu

Outline:

- We need high power lasers: high energy and high repetition rate = high average power

=> But the kW level looks like a barrier

- We need high quality beams for frequency conversion, for pumping Ti-Sapphire or for OPCPA
- It is said that diode pump lasers are highly efficient while flash lamp pumped lasers are not.
- What do we know about kW class diode-pumped solid state lasers (DPSSL)?
- Is there any "of the shelf" technology ?

Technical specification

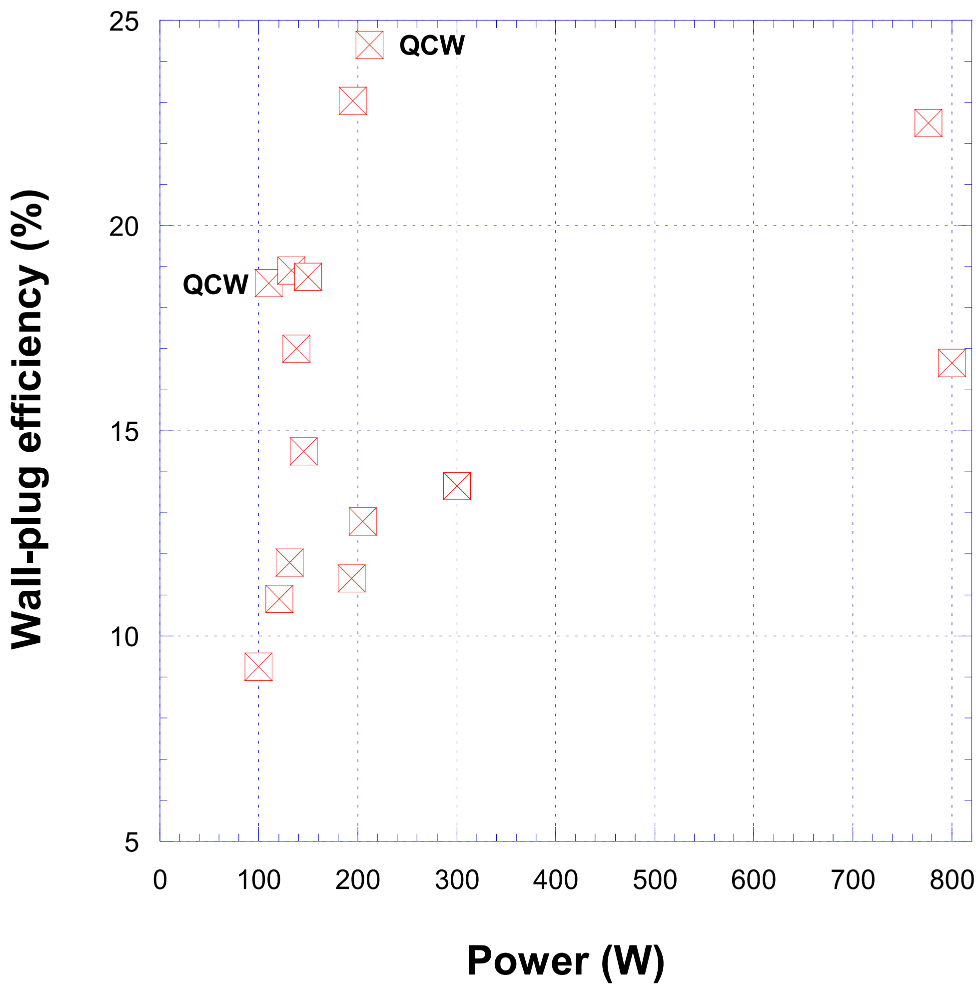
Create a laser beam that can be propagated and focussed:

- Low divergence (<< 0.1 mrad)
- High intensity (Power / beam area >> GW/cm^2)
- Focusability to few wavelengths
- Monochromatic ($\Delta\lambda/\lambda$ << 10^{-6})
- Large bandwidth ($\Delta\lambda/\lambda$ = ¼)

But getting these three parameters at the same time is highly challenging:

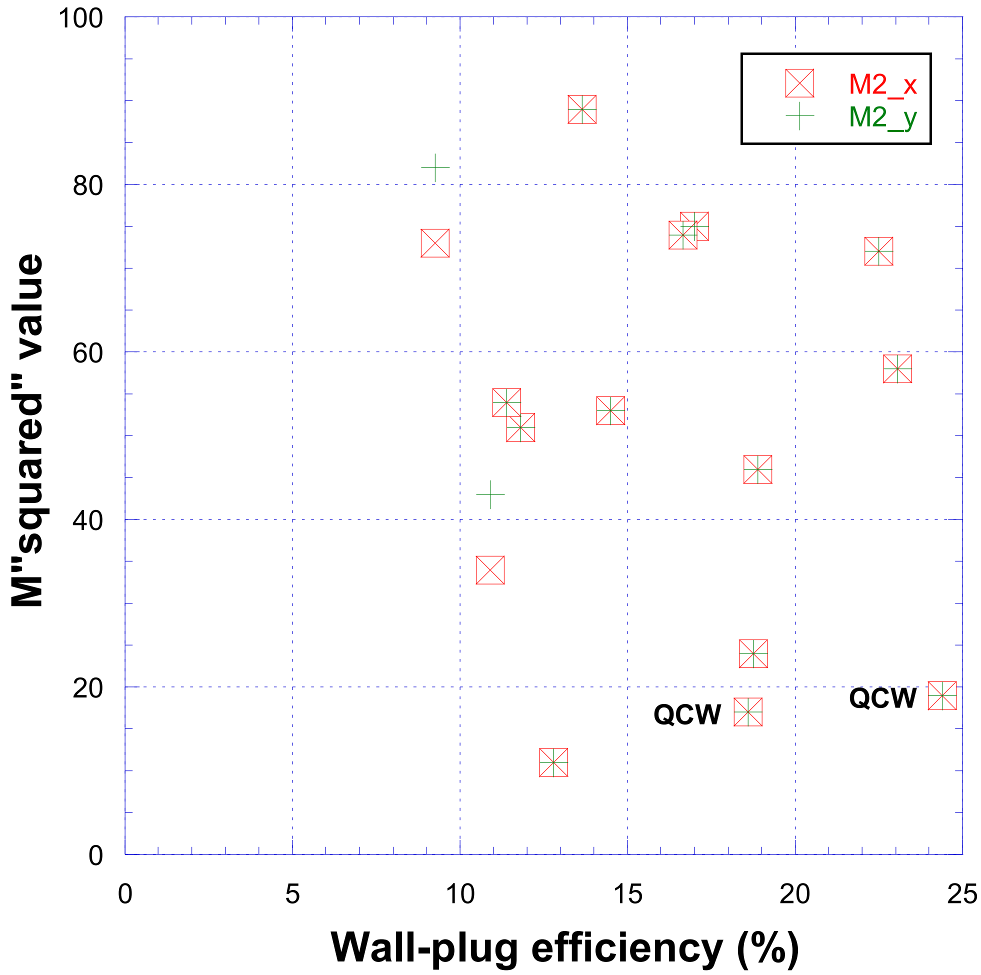
- Highest possible efficiency
- High beam quality (close to M^2=1)
- High energy/ high power (+ high repetition rate = high average power /kilowatt or multi kilowatt range)

Some data about high average power lasers



- Diode pumped lasers can be very efficient
- Examples can be found in *Quantum Electronics* **39** (1) 1-17 (2009) when power > 100 W and optical to electrical efficiency can reach 23-24% (cooling is not taken into account)
- Most of these examples concerns CW lasers
- Two examples are high rep-rate QCW lasers (rep-rate > kHz), efficiency looks very good too (17-24%)

Looking at both efficiency and beam quality



- None of these highly efficient lasers are suitable for frequency conversion because $M^2 > 10$

- As soon as $M^2 > 4$, it is quite impossible to have a good frequency conversion efficiency unless having intra-cavity frequency conversion

Why ?

If we discuss the possibility of extending solid-state laser technology to high-average-power and of improving the efficiency of such lasers, the critical elements of the laser design are:

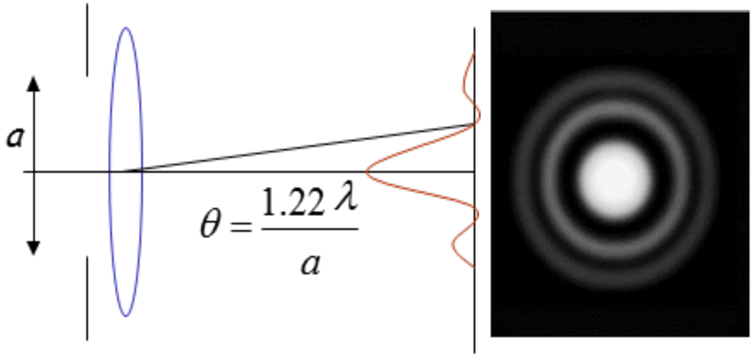
- the thermal management (removing heat from the center of the solid with a cooling system at the end surfaces),
- the thermal gradient control (minimizing optical wave front distortions),
- the pump energy utilization (overall efficiency including absorption, stored energy, gain etc),
- the efficient extraction (filling most of the pumped volume with extracting radiation and matching pump duration to the excited-state lifetime).

Does it make sense to optimize all these parameters? We can win a world record in laser extraction efficiency but can we achieve efficient second-harmonic-generation or how many times diffraction limited is the laser beam?

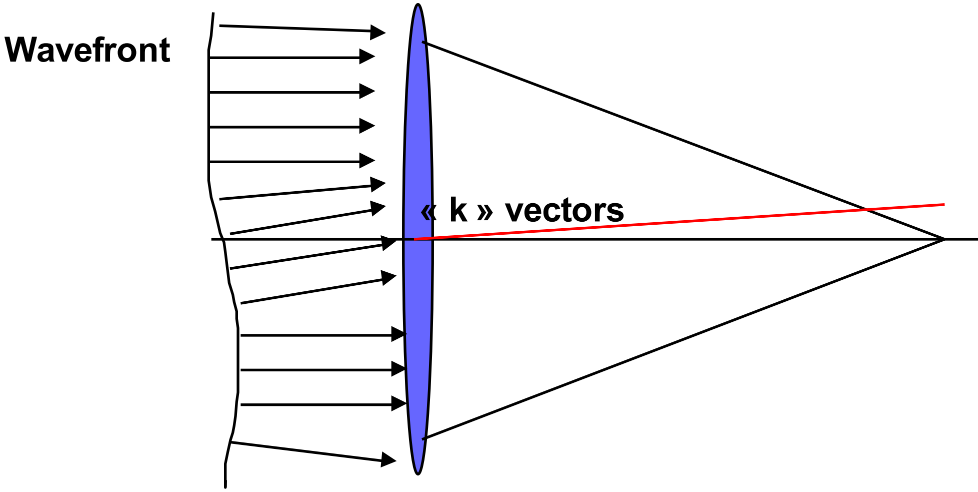
Wavefront and light rays

Flat intensity and phase beam:

- diffraction limited beam focused to the diffraction limit according to the Airy disk pattern.
- The larger the size of the beam “a”, the smaller the focal spot.
- The shape of the focal spot is the square of the 1st order Bessel function: $J_1(z)/z$.

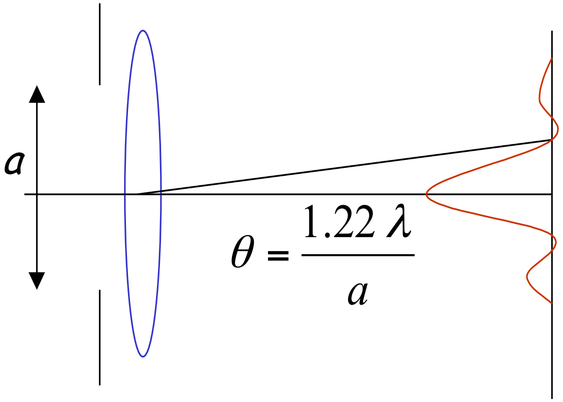


If the beam is suffering distortions, then the wavefront is no longer a plane. Rays are perpendicular to the plane. Rays are perpendicular to the wavefront. A “ray” has a direction given by its “k” vector

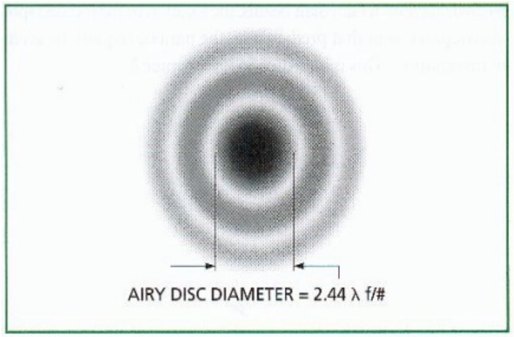


Back to basics = wave front distortion

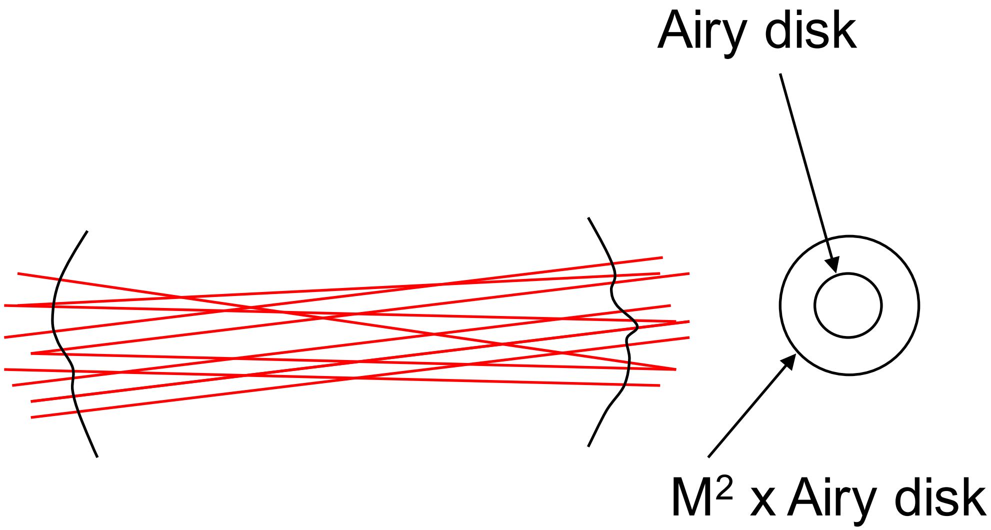
- A flat wave front beam should give a perfect Airy disk pattern when focused



$$\theta = \frac{1.22\,\lambda}{a}$$

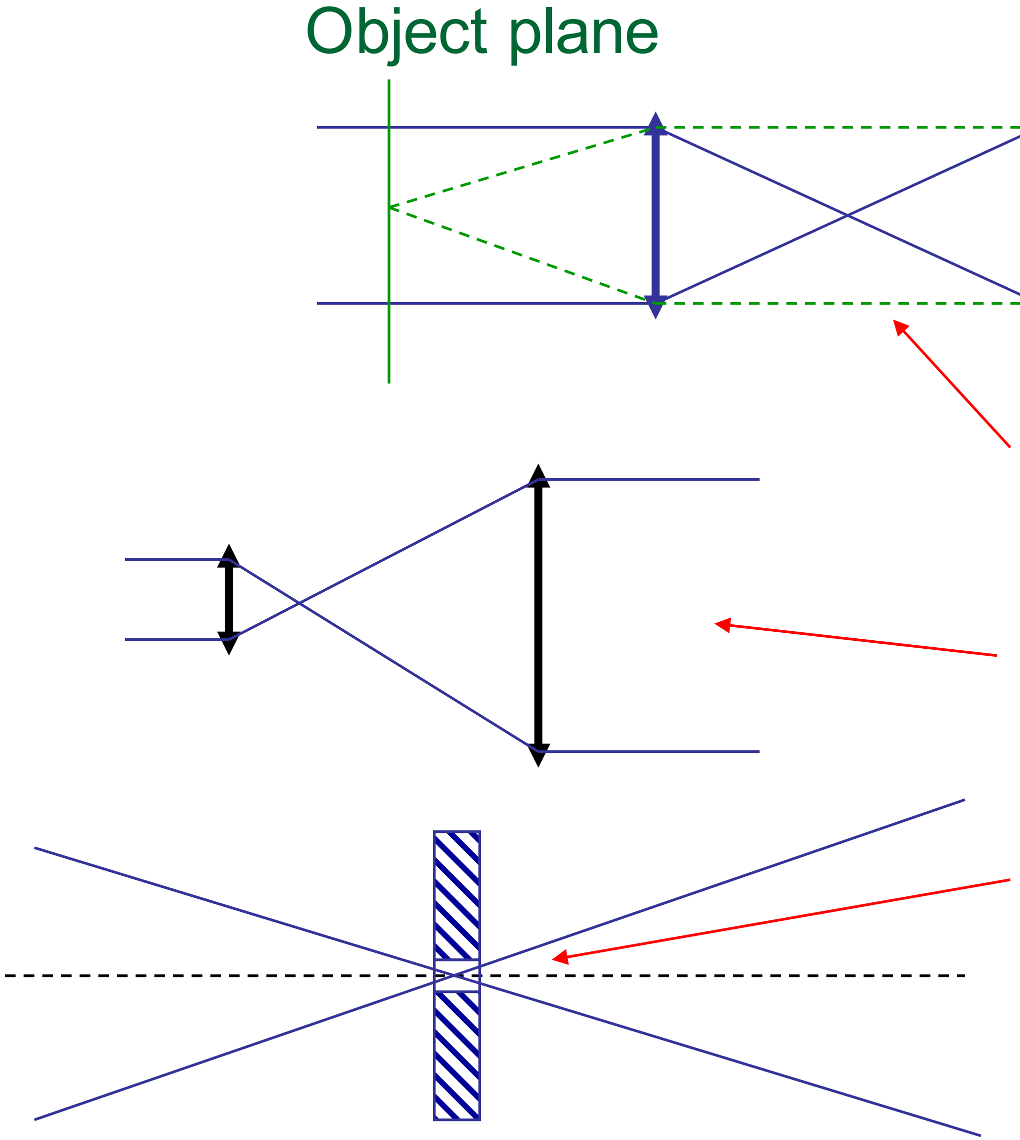


- A distorted wave front beam cannot be focused to that minimum size
- In other words the encircled energy is low or the M^2 is high
- M^2 means that the beam is M^2 x Diffraction Limit



A real beam propagates like a perfect beam whose intensity would be divided by M^4 !

Beam transport

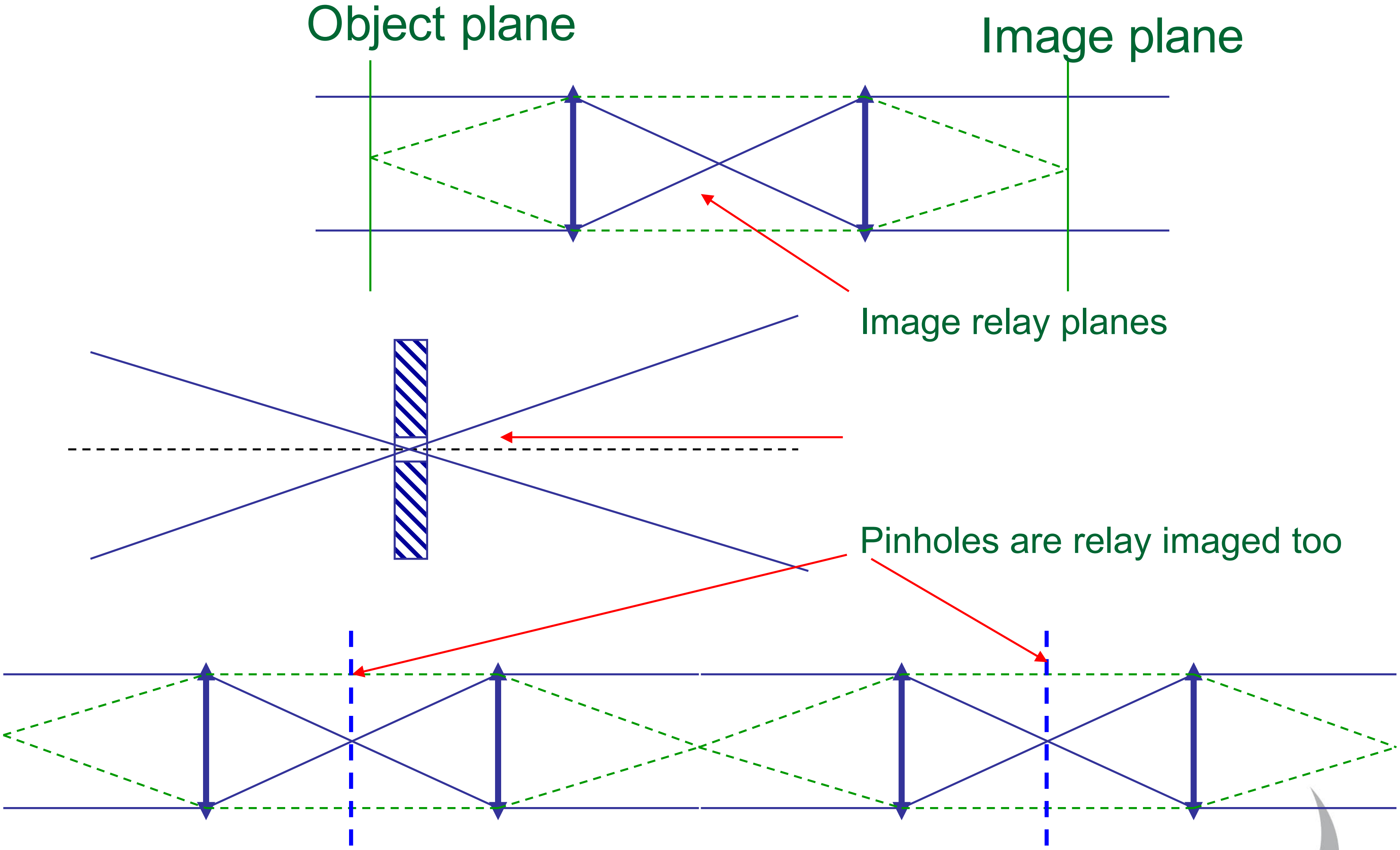


Beam transport is possible with afocal optical systems

A pinhole is located at the focal plane

Spatial frequencies can be seen at the focal plane

Beam transport



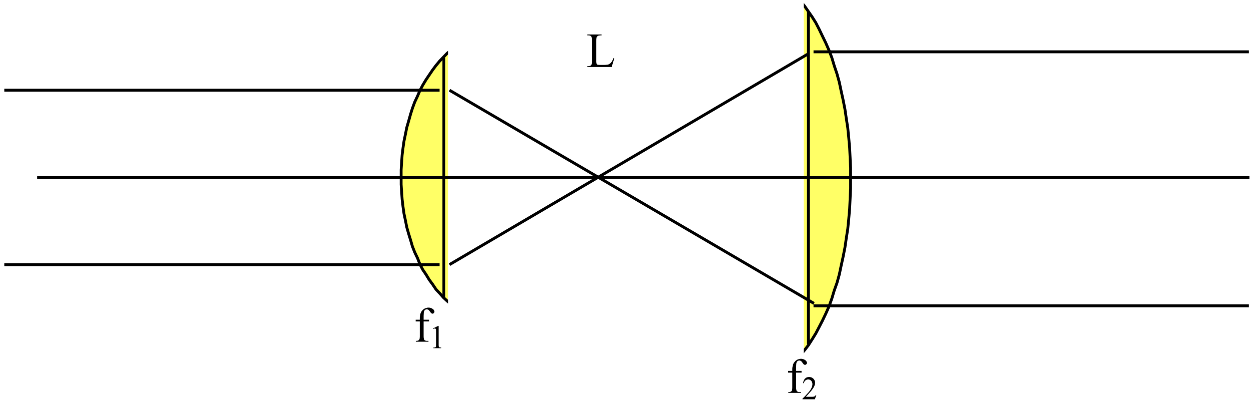
Object plane

Image plane

Image relay planes

Pinholes are relay imaged too

Spatial Filter



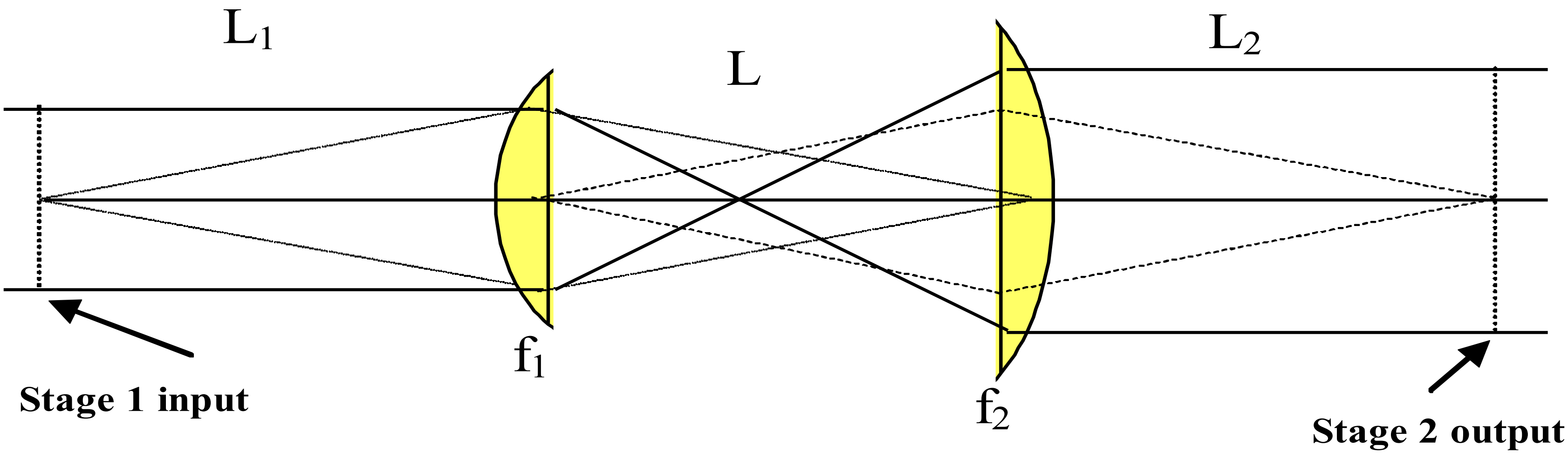
$$M=\begin{bmatrix}1 & 0\\ -1/f_2 & 1\end{bmatrix}\begin{bmatrix}1 & L\\ 0 & 1\end{bmatrix}\begin{bmatrix}1 & 0\\ -1/f_1 & 1\end{bmatrix}=\begin{bmatrix}1-L/f_1 & L\\ -(f_1+f_2-L)/f_1f_2 & 1-L/f_2\end{bmatrix}$$

Optical system is afocal when C=0 $L=f_1+f_2$

Beam size magnification=G $f_2=G\,f_1$

$$M=\begin{bmatrix}-G & L\\ 0 & -1/G\end{bmatrix}$$

Relay imaging



$$\begin{bmatrix}-G & L\\0 & -1/G\end{bmatrix}\begin{bmatrix}1 & L_1\\0 & 1\end{bmatrix}=\begin{bmatrix}-G & L-G\,L_1\\0 & -1/G\end{bmatrix}$$

$$L = G\,L_1$$

$$\begin{bmatrix}1 & L_2\\0 & 1\end{bmatrix}\begin{bmatrix}-G & L\\0 & -1/G\end{bmatrix}=\begin{bmatrix}-G & L-\;L_2/G\\0 & -1/G\end{bmatrix}$$

$$L = L_2/G$$

Filtering is possible in the Fourier plane

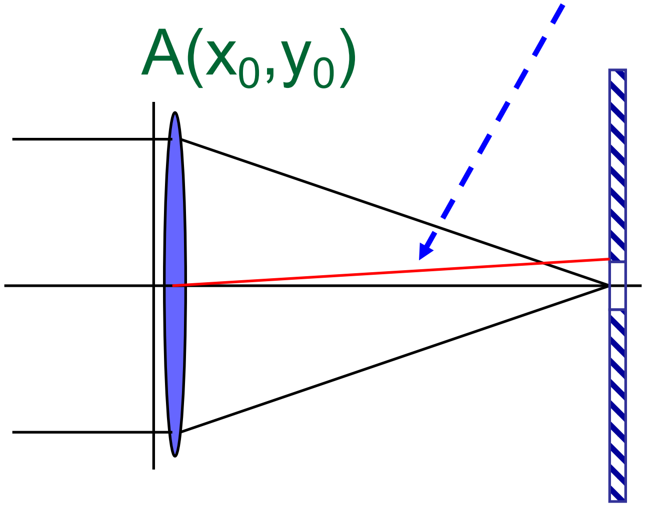
The electromagnetic field in the focal plane of a lens can be calculated in the framework of Fresnel diffraction.

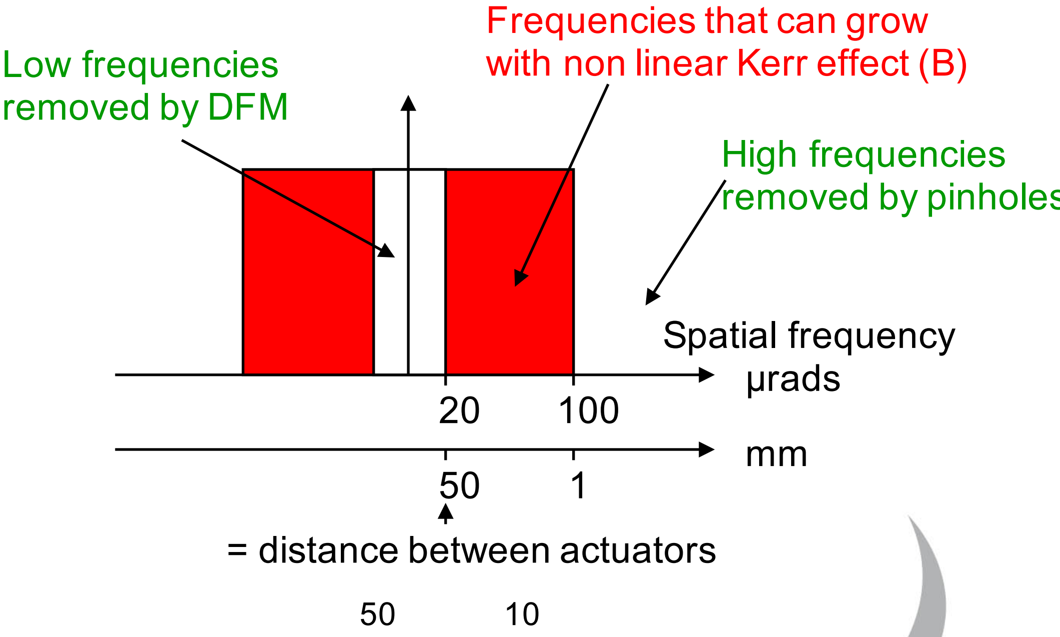
$$A(X,Y)=\frac{i}{\lambda f}Exp\frac{ik_0}{2k}(x^2+y^2)\iint A(x_0,y_0)Exp\frac{2\pi}{f}i(Xx_0,Yy_0)dx_0dy_0$$

Reduced variables are optical frequencies *(X, Y) = (x, y)/λf*

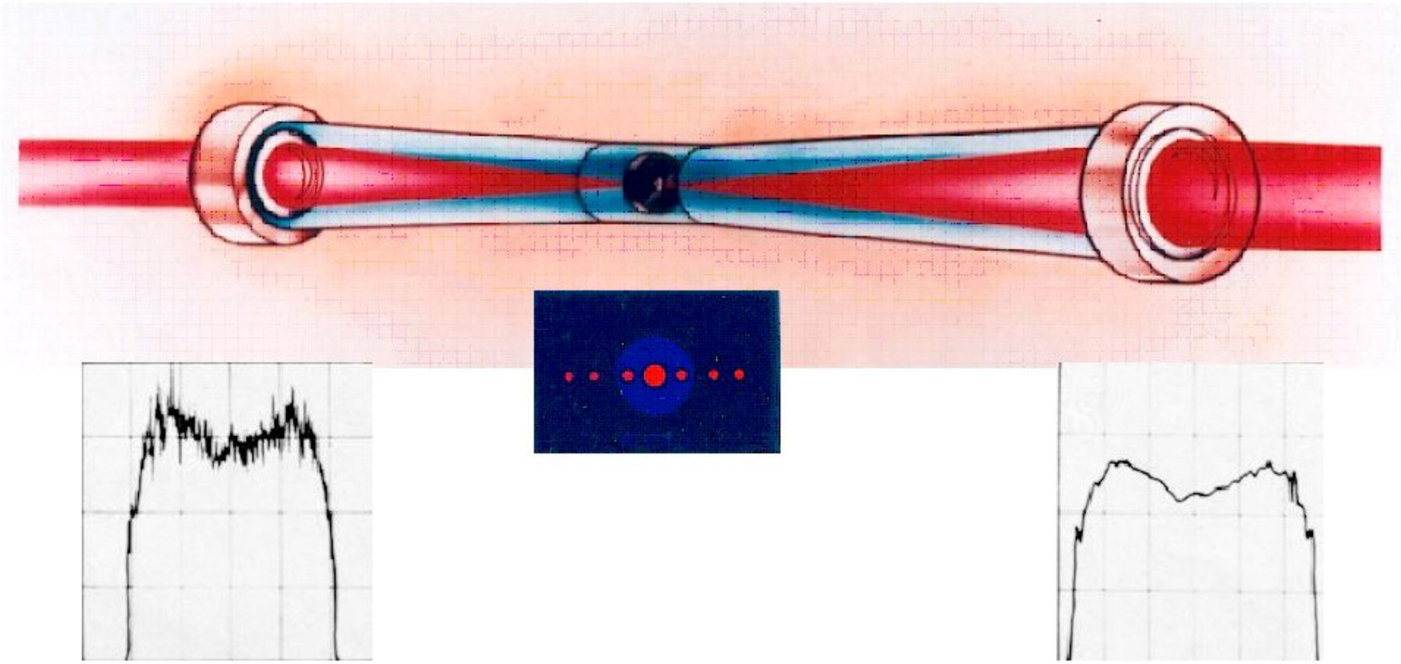
Pinhole size = half-angle of the pinhole as seen from the lens = optical frequency $\theta = \lambda/p$

À λ = 1µm, θ =1 mrad ⇔ p = 1 mm



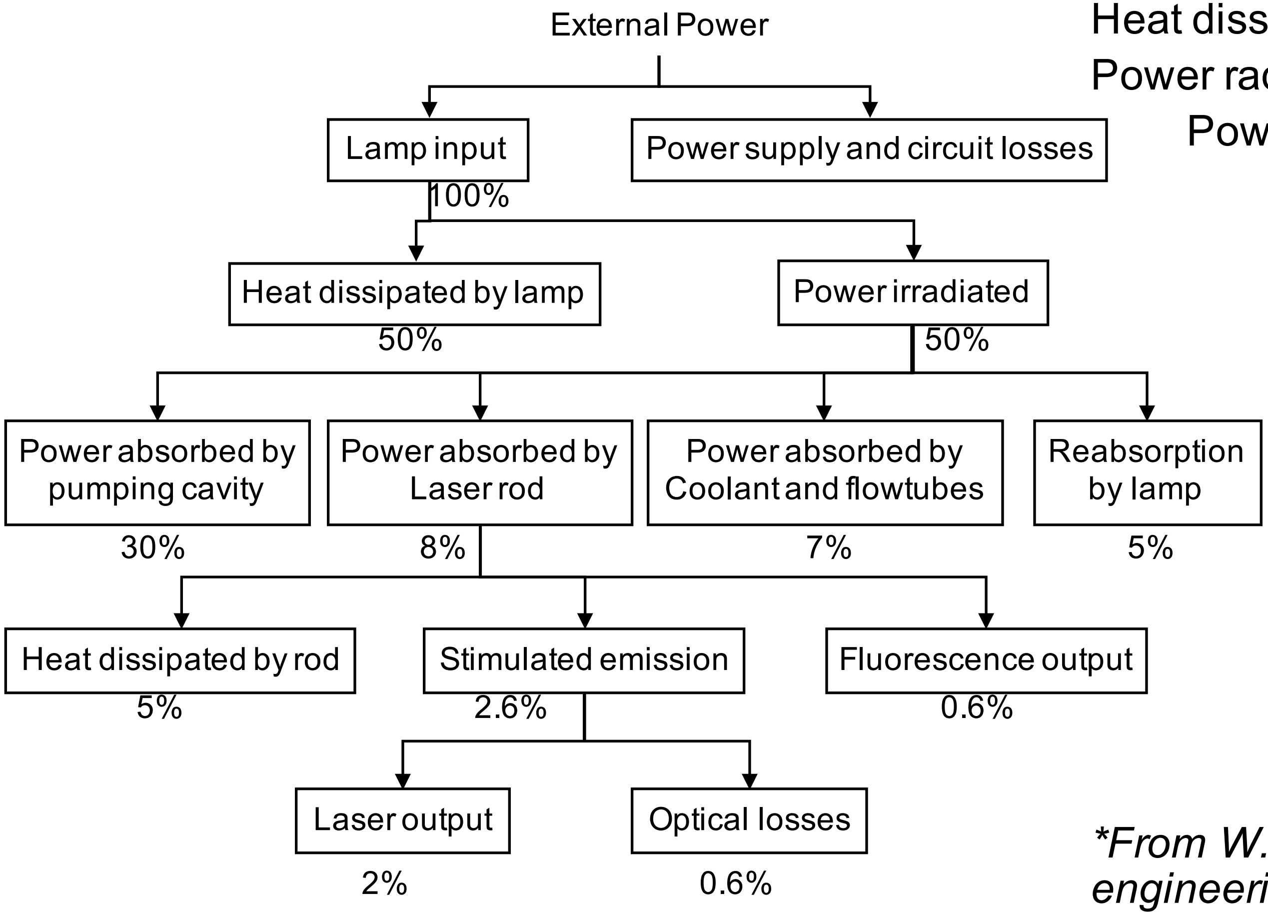


The Functions of Spatial Filtering



- *Suppressing high spatial frequency modulations with a single pinhole*
- *Reducing ASE solid angle*
- *Magnifying beam size*
- *Imaging relay planes*

Energy balance in an optically pumped SSL*


External Power

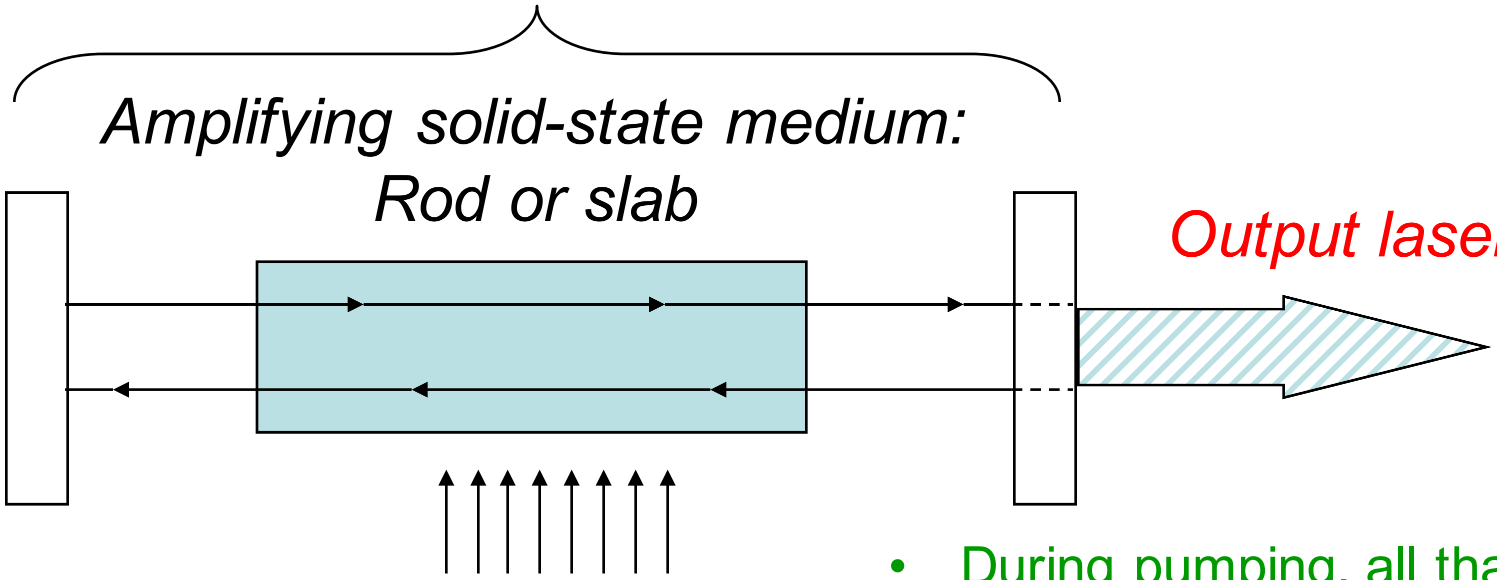
- Lamp input 100%
  - Heat dissipated by lamp 50%
  - Power irradiated 50%
    - Power absorbed by pumping cavity 30%
    - Power absorbed by Laser rod 8%
      - Heat dissipated by rod 5%
      - Stimulated emission 2.6%
        - Laser output 2%
        - Optical losses 0.6%
      - Fluorescence output 0.6%
    - Power absorbed by Coolant and flowtubes 7%
    - Reabsorption by lamp 5%
- Power supply and circuit losses

- Lamp input 100%
- Heat dissipated by lamp 50%
- Power radiated (0,3 to 1,5 µm) 50%
  - Power absorbed by
    - Pump cavity 30 %
    - Coolant and flowtubes 7%
    - Lamp 5 %
    - Laser rod 8%
      - Heat dissipated by rod 5%
      - Fluorescence 0.4%
      - Stimulated emission 2.6 %
        - Optical losses 0,6 %
        - Laser output 2%

**From W. Koechner “Solid state laser engineering”*

NIF/LMJ are in the range 0.5 to 1 %

Back to basics = laser physics



Optical resonator or cavity

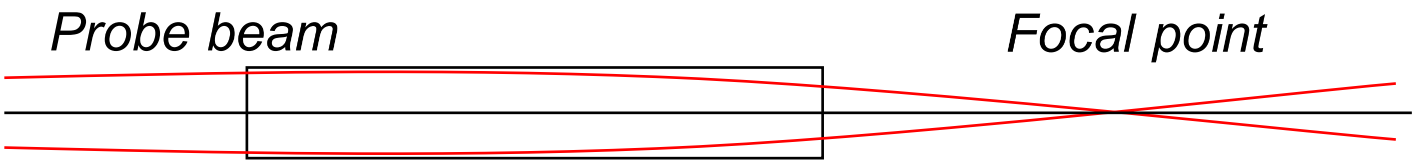
Amplifying solid-state medium:
Rod or slab

Output laser beam

Pump
(flash lamps,
laser diodes)

- During pumping, all that is not "in" the beam must be removed as heat otherwise it will induce wave front distortions of the output laser beam

Thermal gradient : thermal lensing



- Assumption : uniform internal heat generation and cooling along the cylindrical surface of an infinitely long rod leads to a quadratic variation of the refractive index with radius *r* : $n=n_0-\frac{1}{2}n_2r^2$

- This perturbation is equivalent to a spherical lens $f'=2\pi r^2K/(P_a dn/dT)$ with K the thermal conductivity, dn/dT the thermo-optic coefficient and P_a the absorbed power.

- Temperature- and stress-dependant variation of the refractive index + the distortion of the end-face curvature modifies the focal length about 25 %

Thermal management

- Thermo-optical distortions

$$\Delta T \propto \frac{P_{w/cm^3} d^2}{\kappa_{therm.cond}} \quad \text{with} \quad d = d, t, w$$

- *K* is the thermal conductivity and dn/dt the thermo-optic coefficient and α the thermal expansion coefficient
- *Figure of merit = K/(dn/dt)*
- \+ Thermally induced birefringence
- Stress fracture related to shock parameter

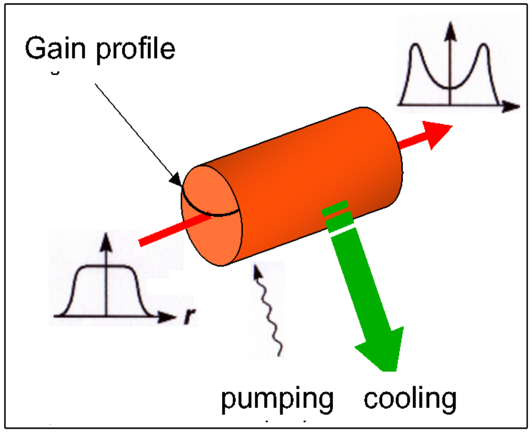
$$R_T = \frac{(1 - \nu_{poisson})\kappa_{therm.cond} S_T}{\alpha_{therm.ex} E_{young}}$$

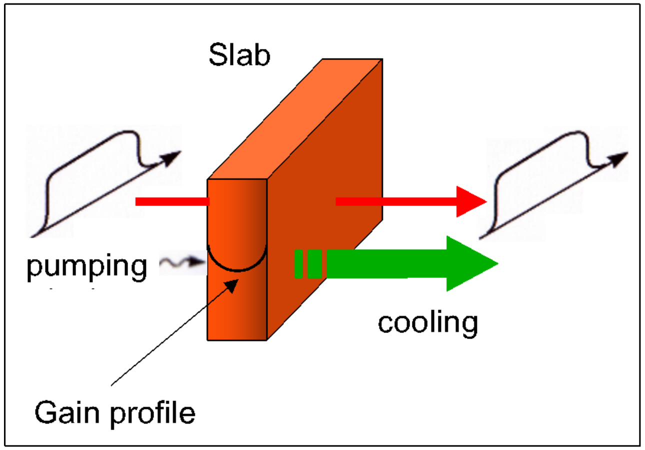
- *Figure of merit = K/α*
- We can compare the behaviour of different laser materials

Thermal management

$$P_{l,rod} = 8\pi R_T b$$

$$P_{V,disk} = 12\frac{R_T b}{t^2}$$





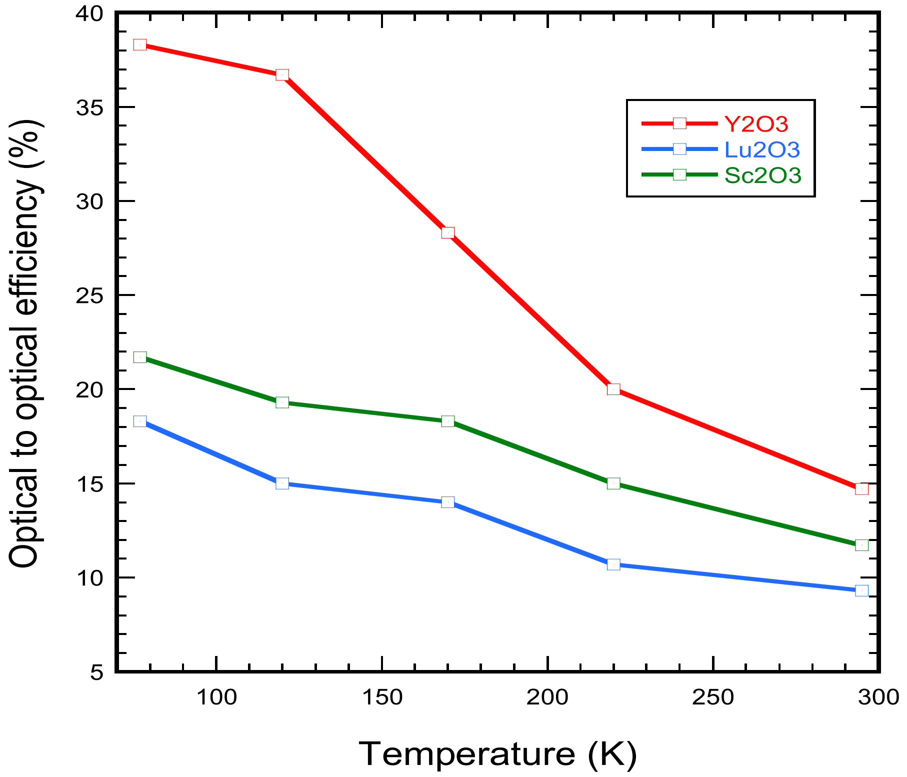
How much power ?

At 20% stress fracture : rod slab

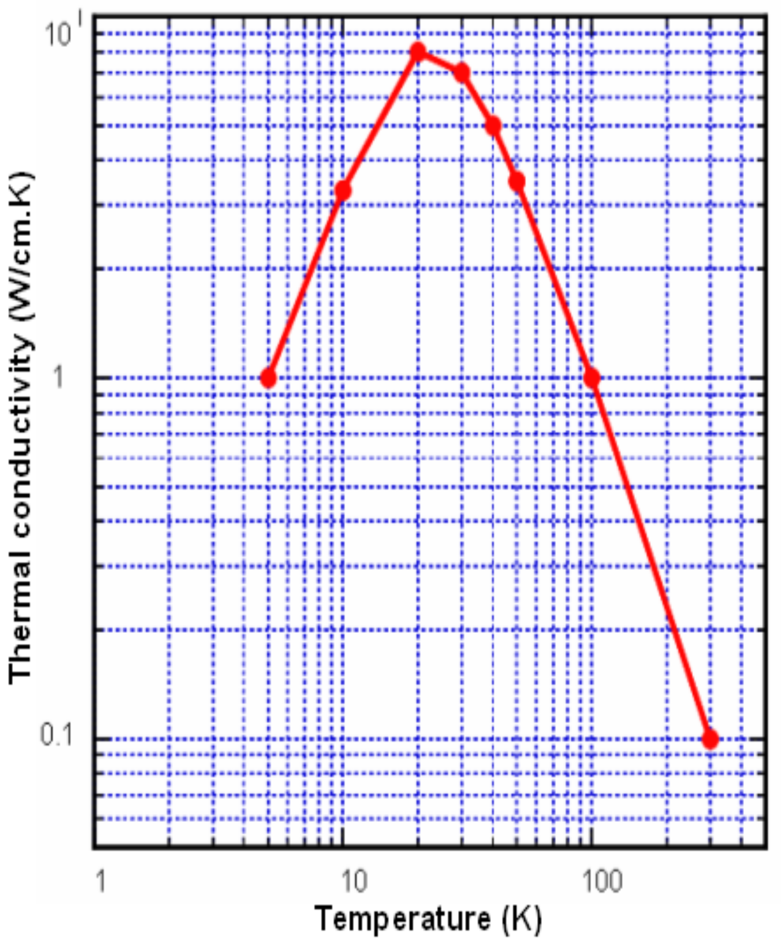
b=0.2	R_T (W/cm)	P_l (W/cm)	P_V (W/cm^3)	P (W) for 100 cm^3
glass LG750	0.43	2.2	1	100
SFAP $Sr_5(PO_4)_3F$	0.8	4	2.2	220
YLF L_iYF_4	1.8	9	4.3	430
YAG	8	40.2	19.2	1920
Al_2O_3	100	500	240	24000

Working at cryogenic temperature

Optical efficiency of diode-pumped 10% Yb-doped sesquioxides ceramics.
Efficiency = laser output/diode output



Thermal conductivity of YAG



- *G. Slack, D. Oliver, "Thermal conductivity of garnets and phonon scattering by rare-earth ions", Phys. Rev. B, **4**(2), p.592-609, 1971*

Thermal management

I know what I want to do:

Remove heat from the (center of the) solid with a cooling system (at the end surfaces) => *better cooling*

Minimize optical distortions (wave front distortion) = get a flat thermal gradient => *better “uniform” pumping*

Increase the pumping efficiency (absorption, stored energy, gain etc) => *diode pumping*

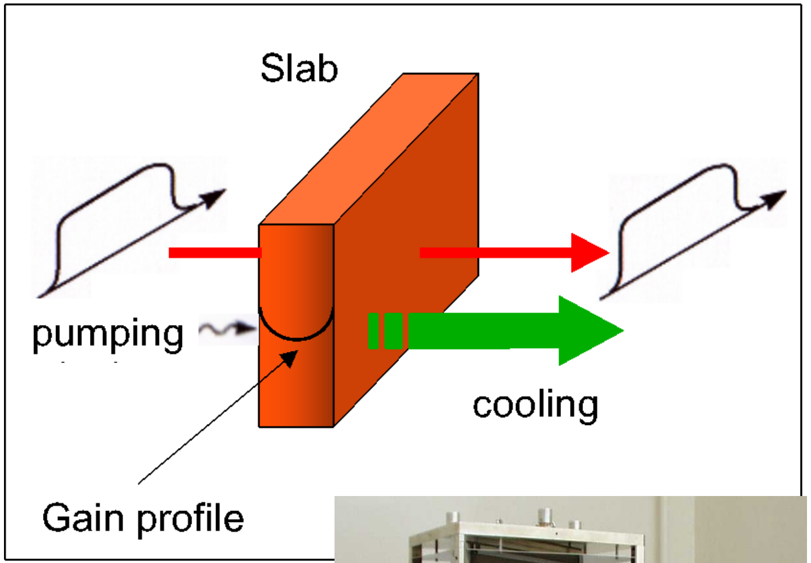
Increase the extraction efficiency, filling most of the pumped volume with extracting radiation and matching pump duration to the excited-state lifetime => *diode pumping*

Does it make sense to optimize all these elements ?

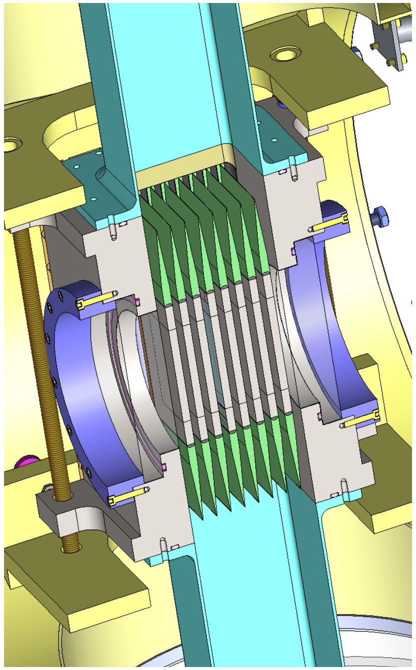
Can I achieve second harmonic generation or how many times diffraction limited is my laser beam ?

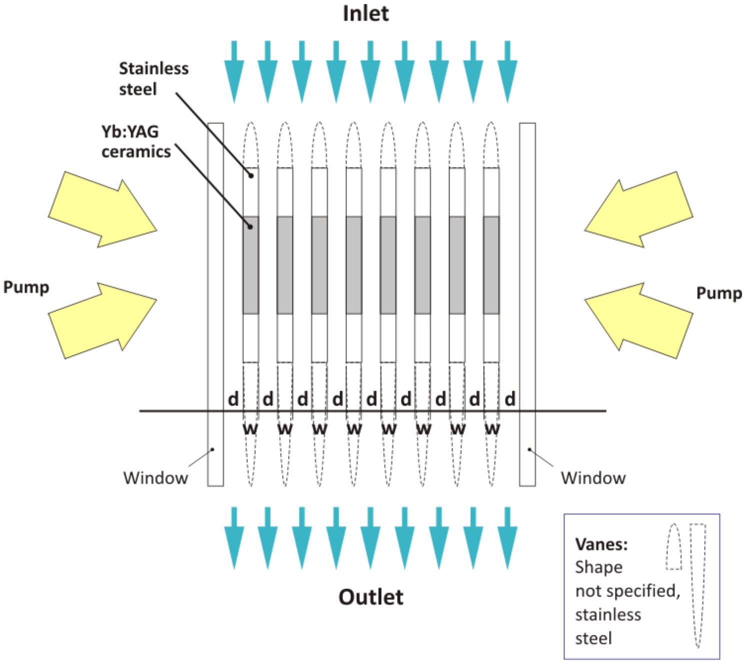
Thermal gradient control

- If the gain profile is flat (pump uniformity) then the thermal gradient will be flat too
- In fact I only care of the transverse gradient because the beam don't "see" the axial one
- Many thin slabs (at Brewster angle can be associated to design an amplifier)



Cryogenic gas cooled multi-slab amplifier





Kilowatt average power 100 J-level diode pumped solid state laser

Paul Mason,[1,*] Martin Divoký,[2] Klaus Ertel,[1] Jan Pilař,[2] Thomas Butcher,[1] Martin Hanuš,[2] Saumyabrata Banerjee,[1] Jonathan Phillips,[1] Jodie Smith,[1] Mariastefania De Vido,[1] Antonio Lucianetti,[2] Cristina Hernandez-Gomez,[1] Chris Edwards,[1] Tomas Mocek,[2] and John Collier[1]

[1] *Central Laser Facility, STFC Rutherford Appleton Laboratory, Didcot OX11 0QX, UK*
[2] *HiLASE, Institute of Physics, ASCR, Na Slovance 2, 182 21 Prague, Czech Republic*
**Corresponding author: paul.mason@stfc.ac.uk*

Optica Vol. 4, Issue 4, pp. 438-439 (2017) https://doi.org/10.1364/OPTICA.4.000438