



Empa

Materials Science and Technology



ÉCOLE POLYTECHNIQUE
FÉDÉRALE DE LAUSANNE

Laser Processing of Materials **Beam Delivery & Beam Quality**

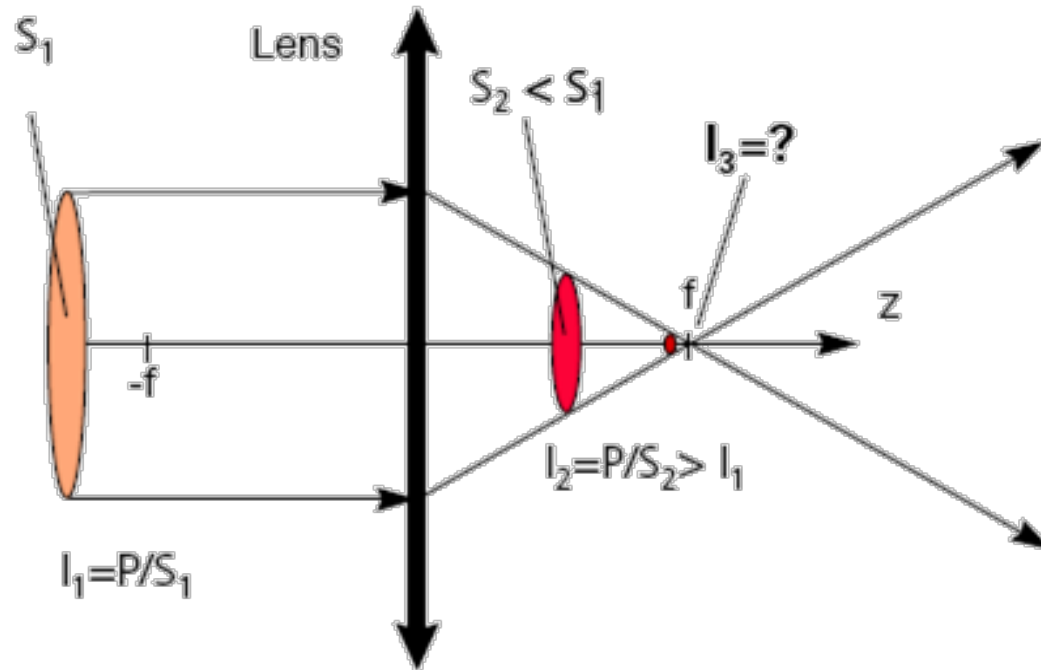
Patrik Hoffmann

Content

- Gaussian beams
- Focusing
- Mask imaging
- Laser diode beam forming
- Optical fibers
- Interferometric methods

Imaging and Gaussian beams

Geometrical "focusing"

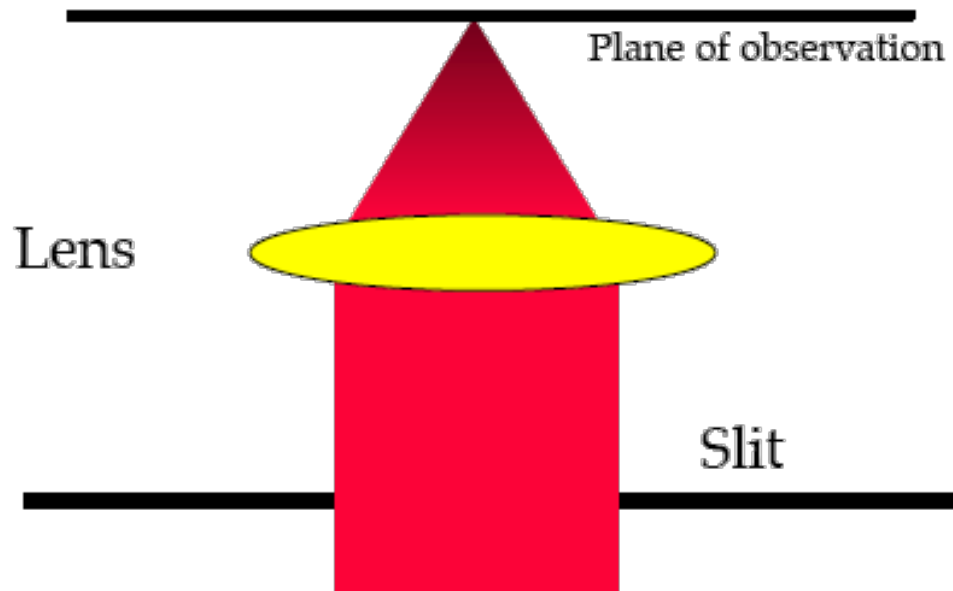
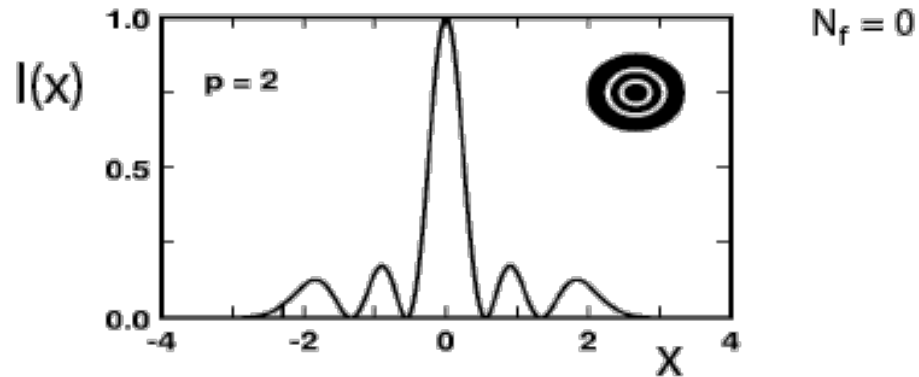


The surface of the beam vanishes
at the exact focus location

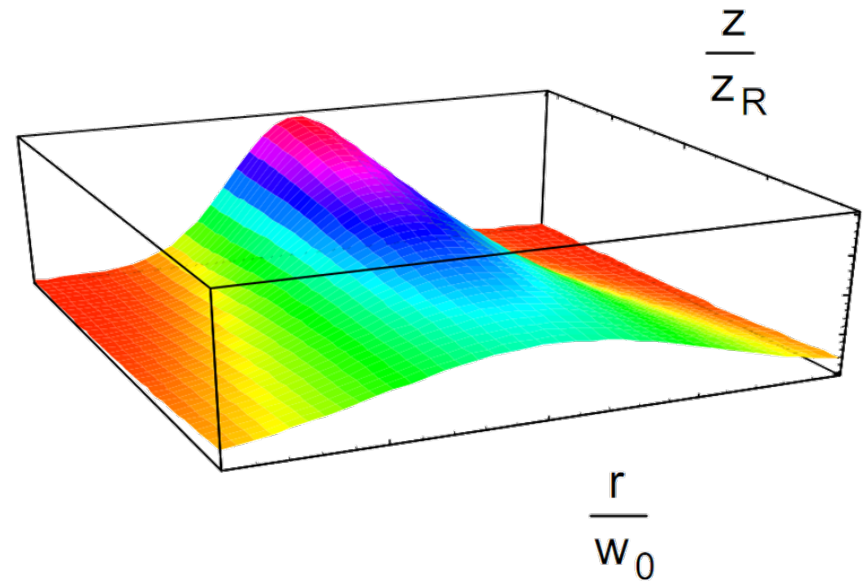
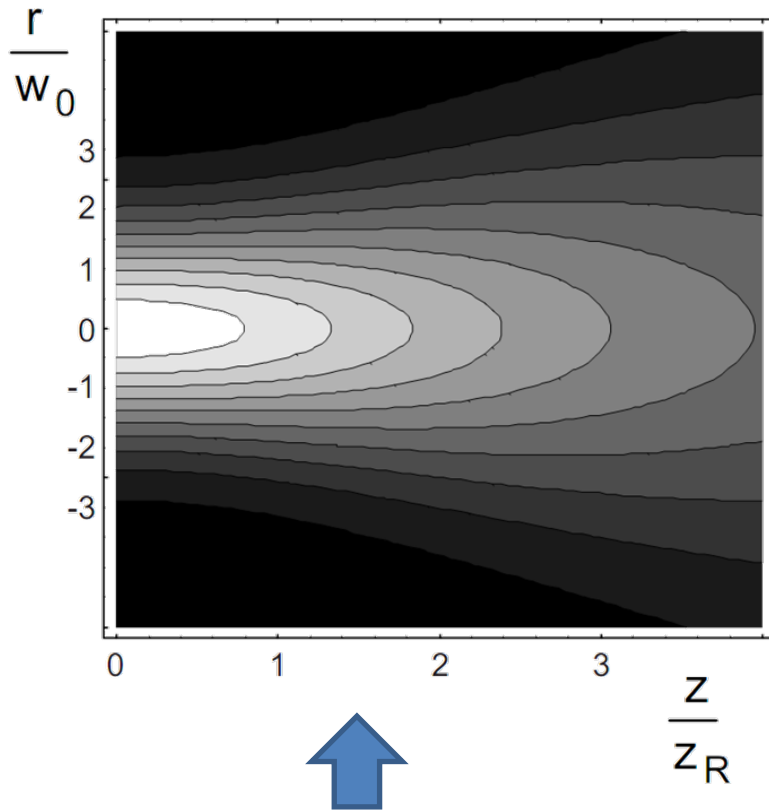
“Real World” Focusing

Diffraction with a slit aperture

$$I(x) \propto \left(\frac{\sin(kx)}{kx} \right)^2$$



Intensity Distribution in Gaussian Beam

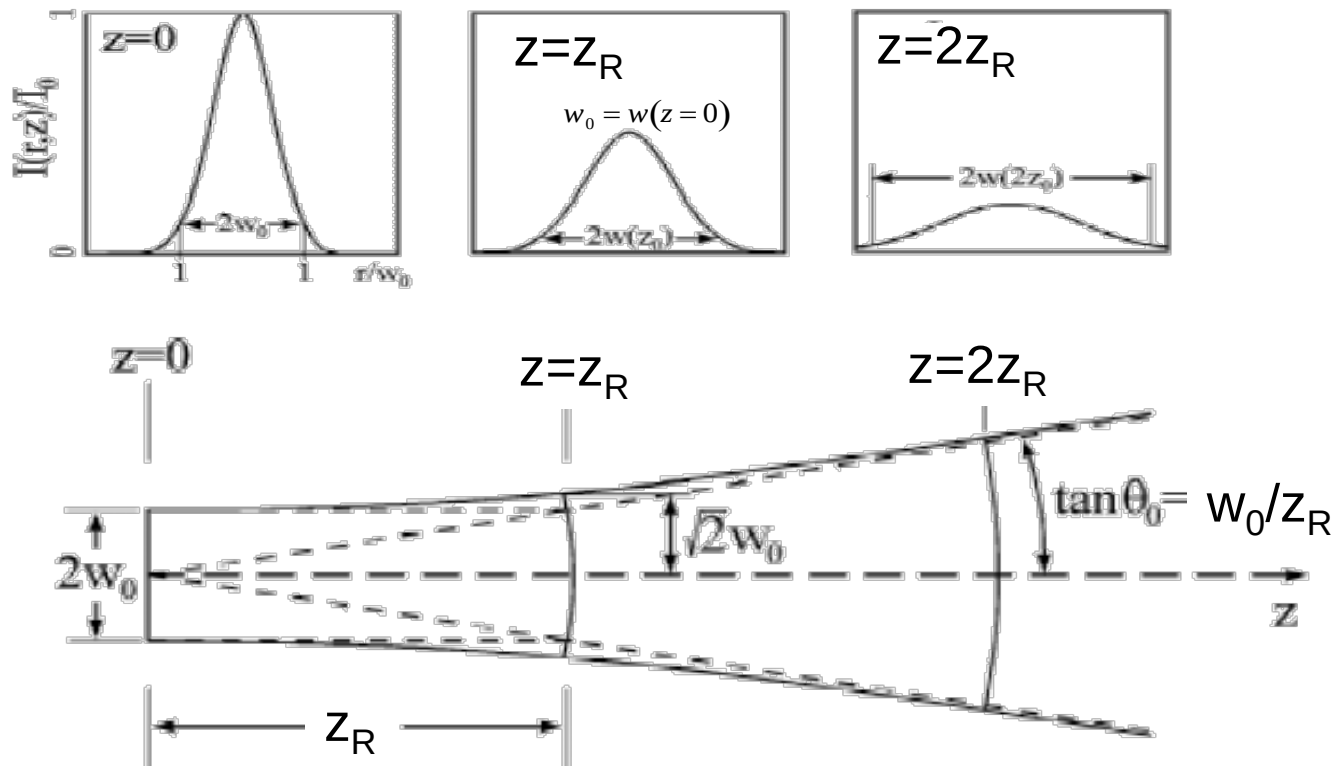


at each z -position, radial intensity distribution is Gaussian

Definition of Gaussian Beam

Fundamental mode intensity

$$I(r, z) = I_0 e^{-2\left(r/w(z)\right)^2}$$



Definitions of the Beam Size

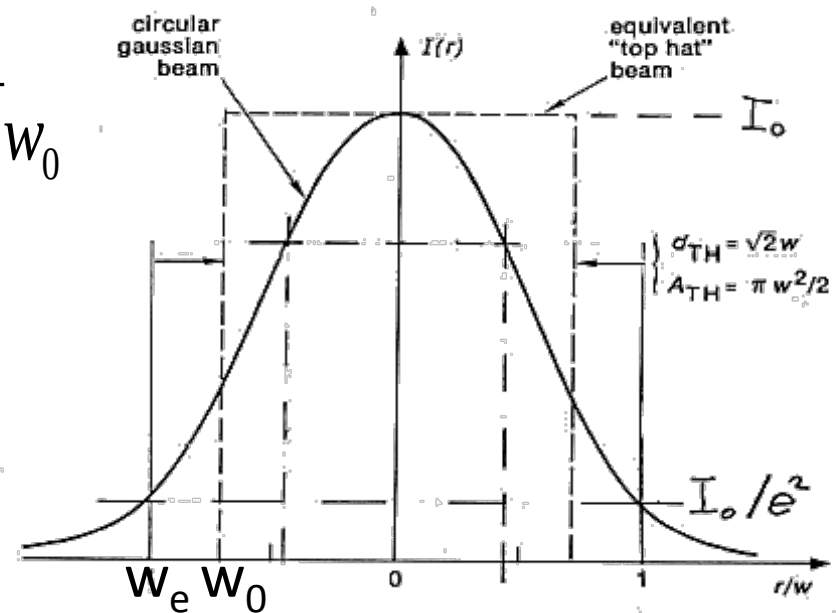
Definitions of the beam size (waist):

$$I(w_0, 0) = I_0/e$$

$$I(w_e, z_e) = I_0 / e^2, \quad w_e = w(z_e) = \sqrt{2}w_0$$

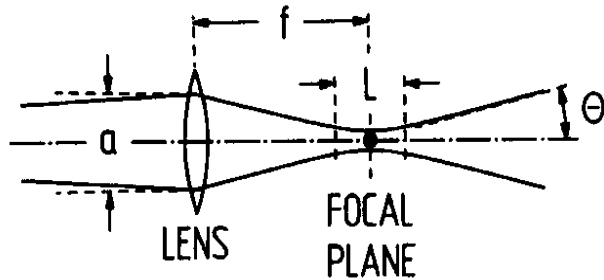
Total intensity of the beam:

$$P_0 = 2\pi \int_0^\infty r I(r) dr = \pi w_0^2 I_0$$



Normalised Gaussian beam profile,
with different approximations

Rayleigh Range and Depth of Focus

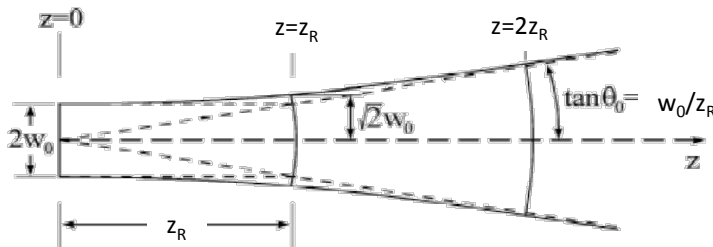


Waist

$$w_0 \approx \frac{2f\lambda}{\pi a} \approx \frac{\lambda}{\theta \cdot \pi}$$

Divergence

$$\theta = \frac{w_0}{z_R} = \frac{a}{2f}$$



Rayleigh range definition: $I(r=0, z=z_R) = I_0/2$

Rayleigh range value
$$z_R = \frac{\pi}{\lambda} w_0^2$$

Depth of focus

$$L = 2z_R = \frac{2\pi w_0^2}{\lambda} = \frac{4f^2\lambda}{\pi a^2}$$

Beam radius at the distance

$$w(z) = w_0 \sqrt{1 + \left(\frac{z}{z_0}\right)^2}$$

Cross-section of Gaussian Beam

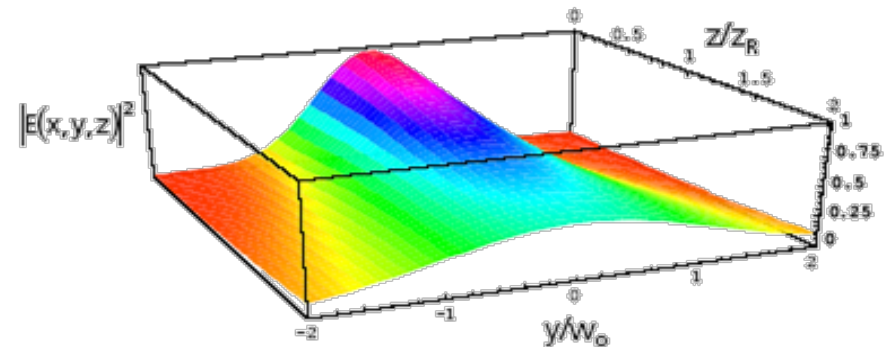
a Gaussian Beam is completely defined by the parameters:

w_0 - waist at focal point

z_R – Rayleigh range

$$w_0 \approx \frac{2f\lambda}{\pi a} \approx \frac{\lambda}{\theta \cdot \pi}$$

$$z_R = \frac{\pi}{\lambda} w_0^2$$



$$I(r,z) = I_0 \left(\frac{w_0}{w(z)} \right)^2 \exp \left[-2 \left(\frac{r}{w(z)} \right)^2 \right]$$

$$w(z) = w_0 \sqrt{1 + \left(\frac{z}{z_R} \right)^2}$$

Cross-section of Gaussian Beam

$$I(r,z) = I_0 \left(\frac{w_0}{w(z)} \right)^2 \exp \left[-2 \left(\frac{r}{w(z)} \right)^2 \right] \quad w(z) = w_0 \sqrt{1 + \left(\frac{z}{z_R} \right)^2}$$

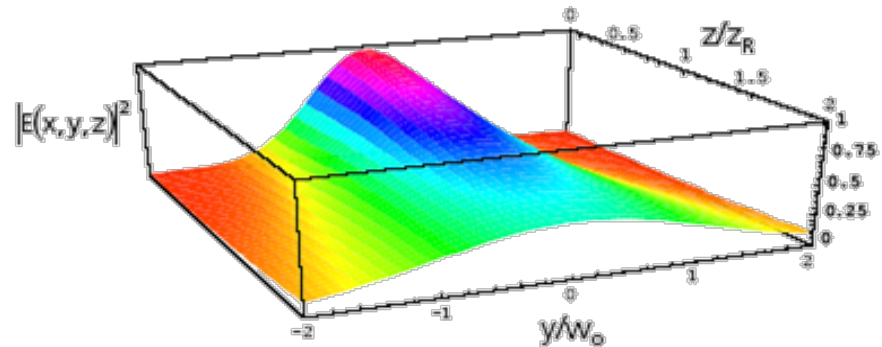
Some examples of properties:

$$I(r=0,z) = I_0 \left(\frac{w_0}{w(z)} \right)^2 = \frac{I_0}{1 + \left(\frac{z}{z_R} \right)^2}$$

$$I(r=0, z=z_R) = I_0/2$$

After one Rayleigh length

$$I(r=0, z \gg z_R) = I_0 (z_R/z)^2 \quad \text{In the far field}$$



Beam Parameter Product (BBP)

As $\theta = w_0/z_R$ et $z_R = \pi w_0^2/\lambda$

BBP

$$\theta \cdot w_0 = \frac{\lambda}{\pi} = \text{const.}$$

The product of the radius times the divergence is
minimal for the Gaussian beam
and contains only the parameter wavelength λ .

This product is invariant during propagation and also focusing.

For a real laser beam:

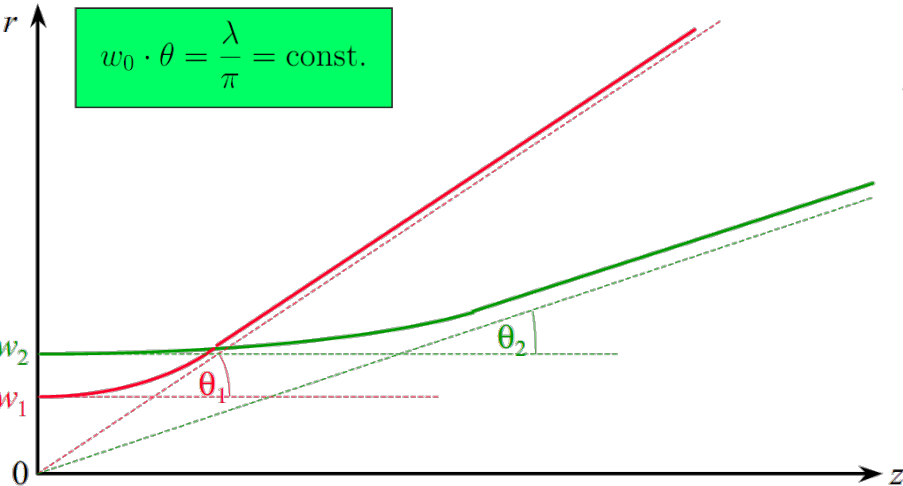
3 mm x mrad for a CO2 laser $\lambda = 10,6 \mu\text{m}$

0,3 mm x mrad for a Nd-YAG laser $\lambda = 1,06 \mu\text{m}$

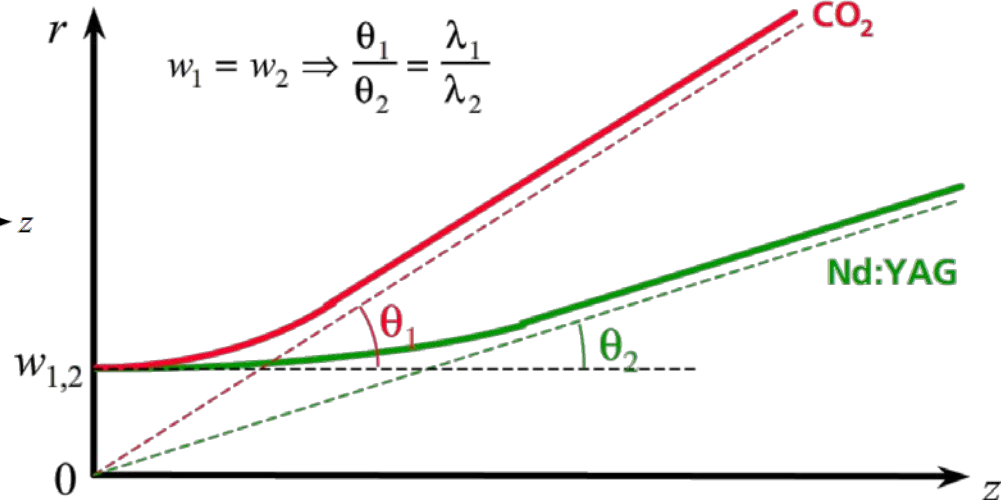
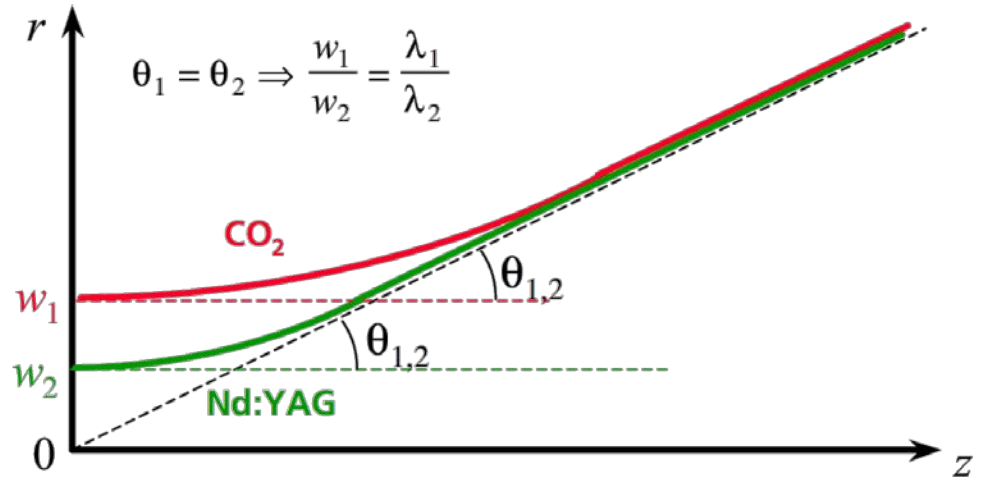
Focusing of a Gaussian Beam

BBP stays constant for the same beam

$$w_0 \cdot \theta = \frac{\lambda}{\pi} = \text{const.}$$

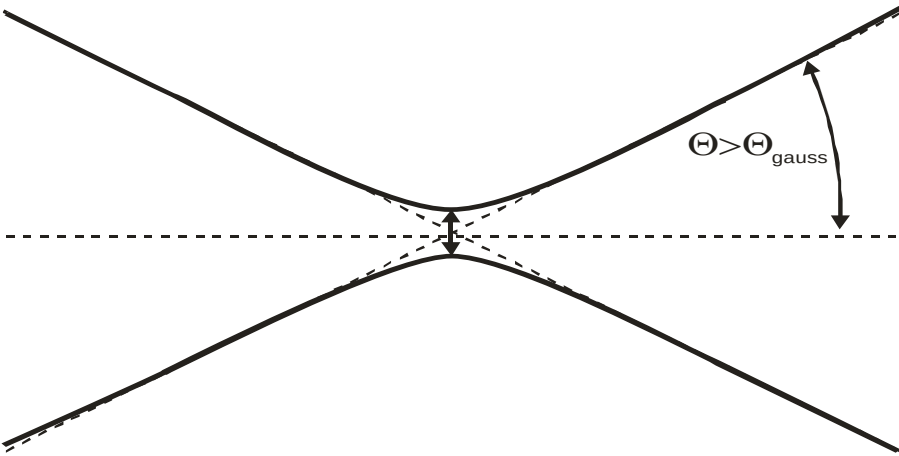


Nd:YAG and CO₂ laser



M² Factor

gaussian beam ($M^2=1$, $BPP = \lambda / \pi$)



for Gaussian ('ideal') beam

$$\theta = \frac{\lambda}{w_0 \pi}$$

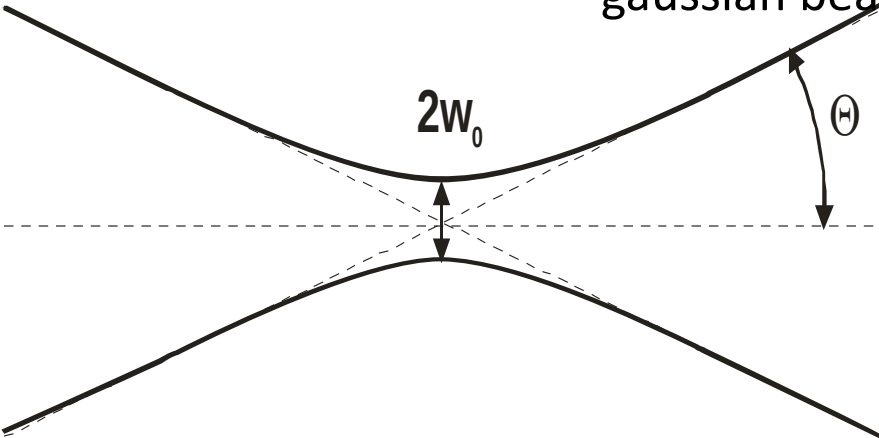
for non-ideal beam an M2 factor introduced
BPP (beam parameter product)

$$BPP = \theta \cdot w_0 = M^2 \frac{\lambda}{\pi}$$

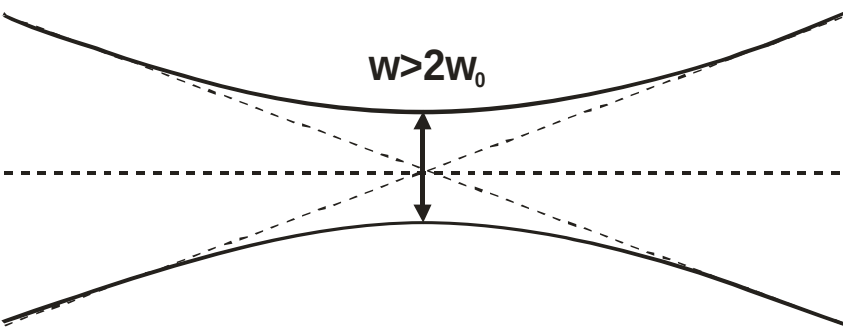
**M2 is a wavelength-independent measure of beam quality
(comparison with Gaussian beam)**

M² Factor

gaussian beam ($M^2=1$, $\text{BBP} = \lambda / \pi$)

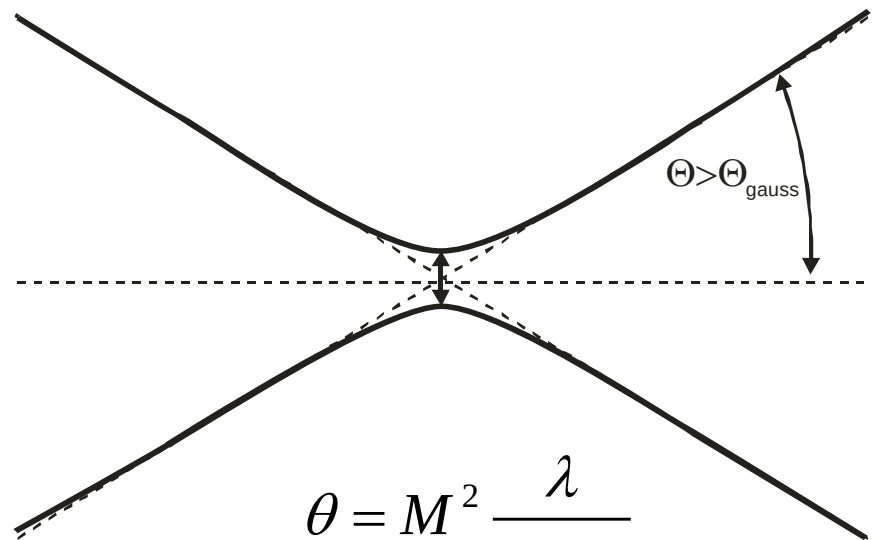


worse quality beam:
same focusing, larger spot



$$w_0 = M^2 \frac{\lambda}{\theta \cdot \pi}$$

worse quality beam:
stronger focusing to get same spot



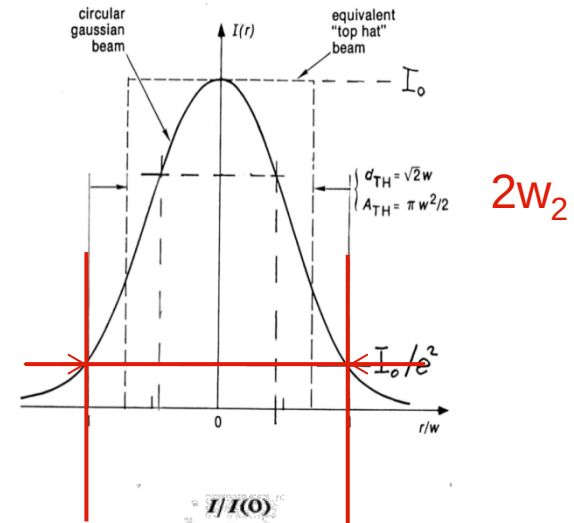
$$\theta = M^2 \frac{\lambda}{w_0 \cdot \pi}$$

Comparison of Gaussian Beam and Plane Wave

Gaussian Beam

$$2w_2 \cong \frac{1}{2w_1} \frac{4\lambda f}{\pi} = \frac{1}{2w_1} 1.27 \lambda f$$

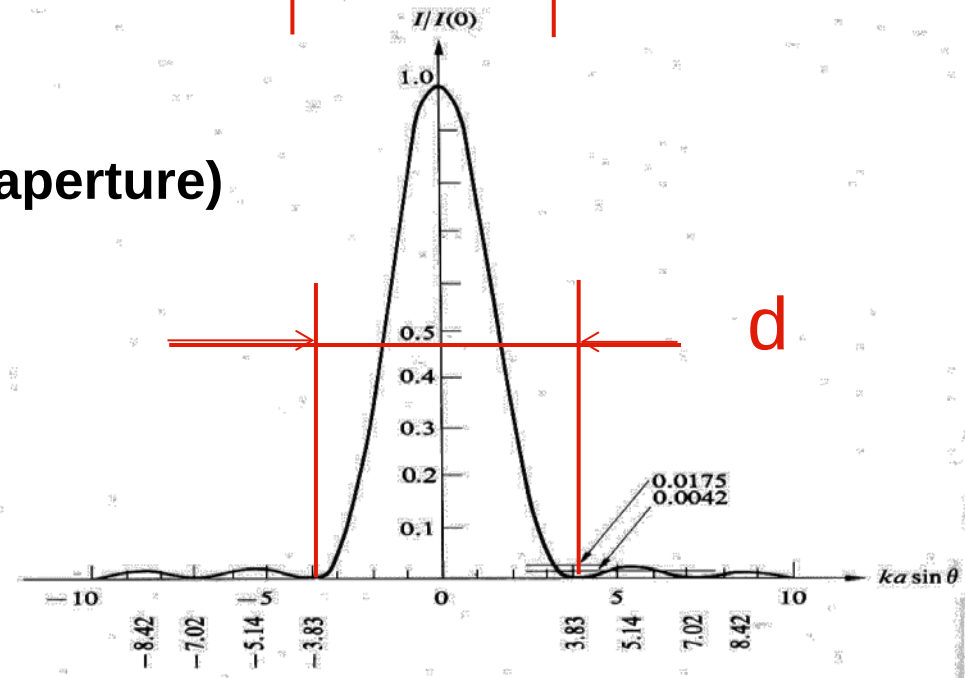
$$d_{G,FWHM} = \frac{1}{2w_1} 1.18 \lambda f \quad \text{smaller spot!}$$



Airy (plane wave with circular aperture)

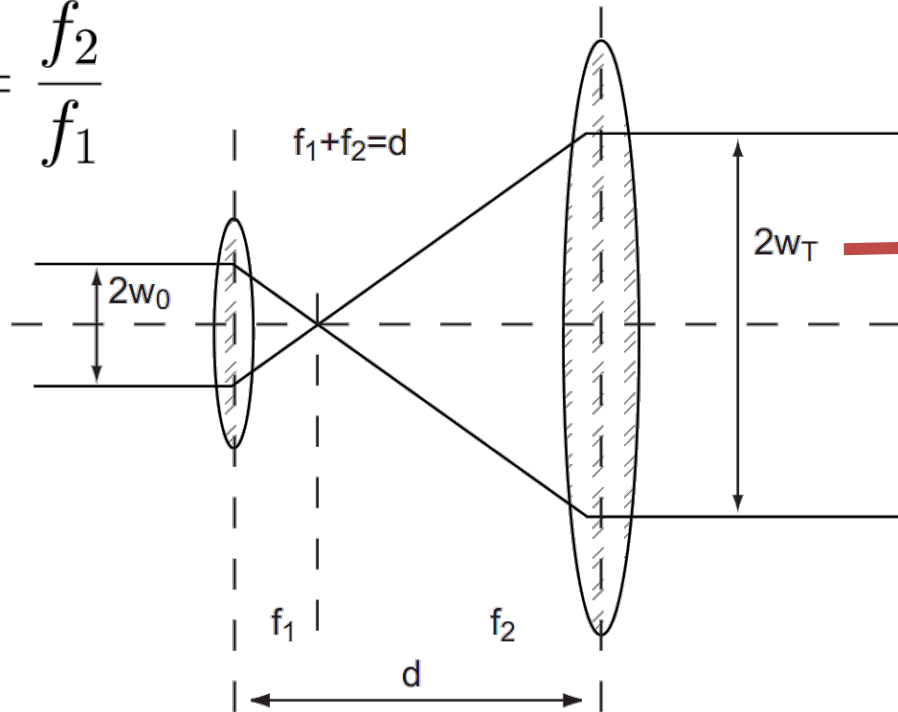
$$d \cong \frac{1}{D} 2.44 \lambda f$$

$$d_{Airy,FWHM} = \frac{1}{D} 2.0 \lambda f \quad \text{larger spot!}$$



Focusing

$$\frac{w_T}{w_0} = \frac{f_2}{f_1}$$



$$w_0 \approx \frac{2 f \lambda}{\pi a}$$

Telescope can be used to increase beam diameter
 $\Rightarrow$ and reduce the minimal spot size

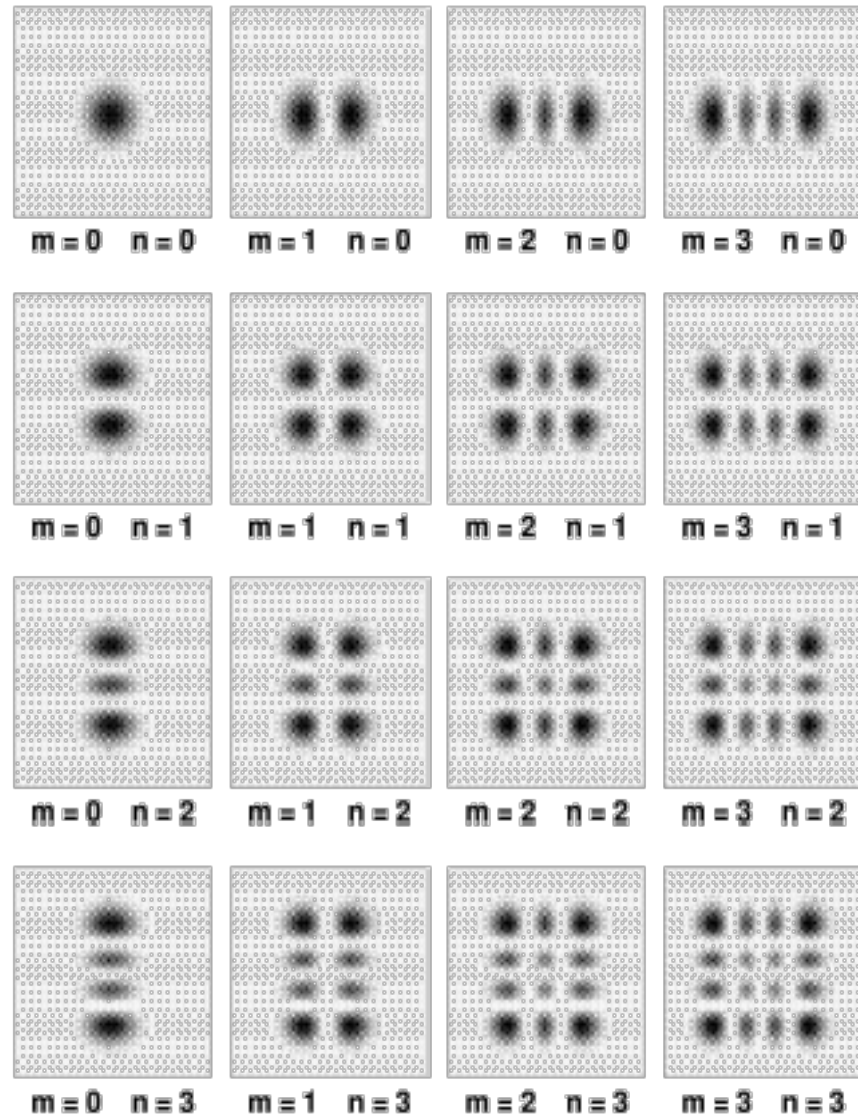
Why Beam is not always Gaussian?

Modes TEM_{m,n}

Beam quality, M^2 :
The ratio of the laser beam's multimode diameter-divergence product to the ideal diffraction limited (TEM_{00}) beam diameter-divergence product

$M^2=1 \rightarrow$ Gaussian beam

$$q^*=M^2 \cdot \lambda/\pi$$



Gauss-Laguerre modes

(Helmholtz equation solutions in cylindrical coordinates)

$$U_{p,l}(r, \varphi, z) = U_0 \left(\sqrt{2} \frac{r}{w(z)} \right)^l \cdot L_p^{(l)} \left(2 \left(\frac{r}{w(z)} \right)^2 \right) \cdot \begin{pmatrix} \cos(l \varphi) \\ \sin(l \varphi) \end{pmatrix} \cdot \exp \left(-\frac{r^2}{w^2(z)} \right) \cdot \exp(-i(2p+l) \cdot \arctan \left(\frac{z}{z_0} \right))$$

C D

Termes:

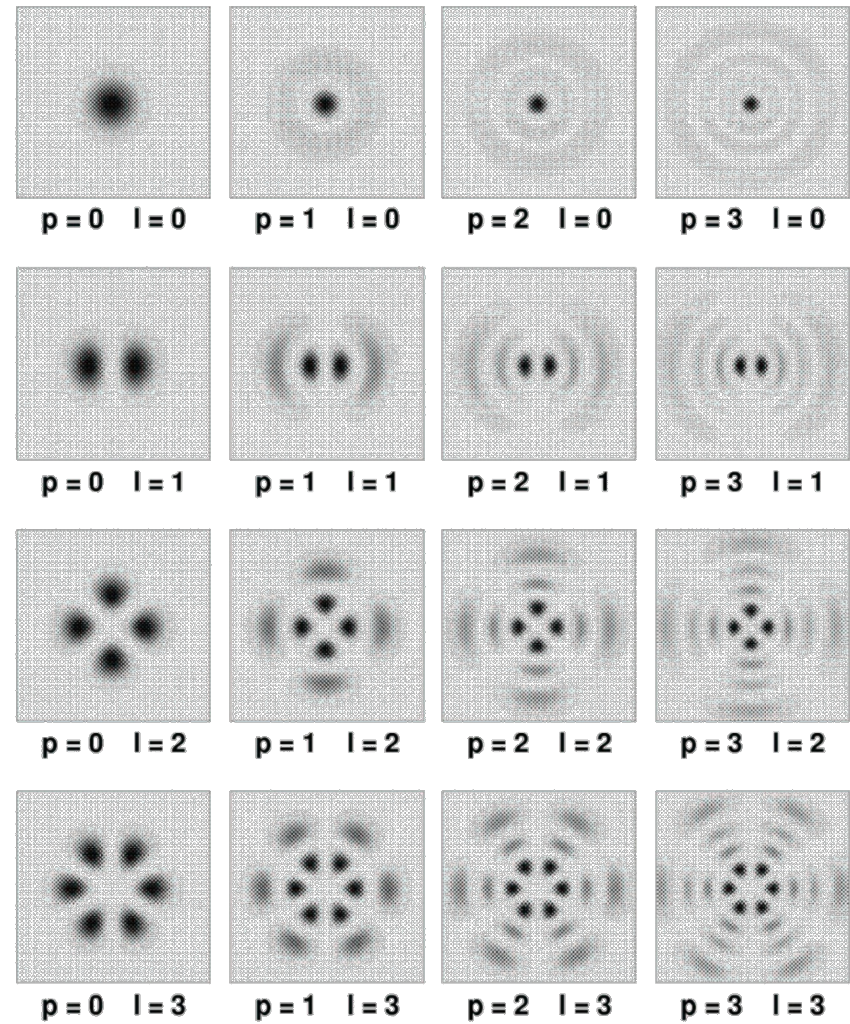
A: Amplitude; B: Hermite functions;

C: Gauss functions; D: Phase

Polynôme de Laguerre:

$$L_0^{(0)}(\rho) = 1; \quad L_1^{(0)}(\rho) = 1 - \rho;$$

$$L_2^{(0)}(\rho) = 1 - \frac{\rho^2}{2}; \quad \rho = \frac{\sqrt{2}r}{w(z)}$$

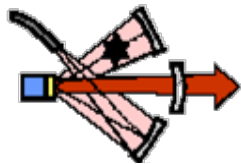


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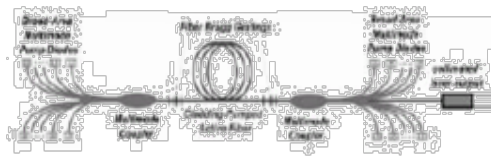
Comparison of BBP for Different Laser Designs



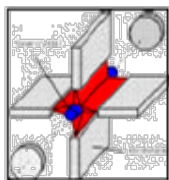
INNOSLAB



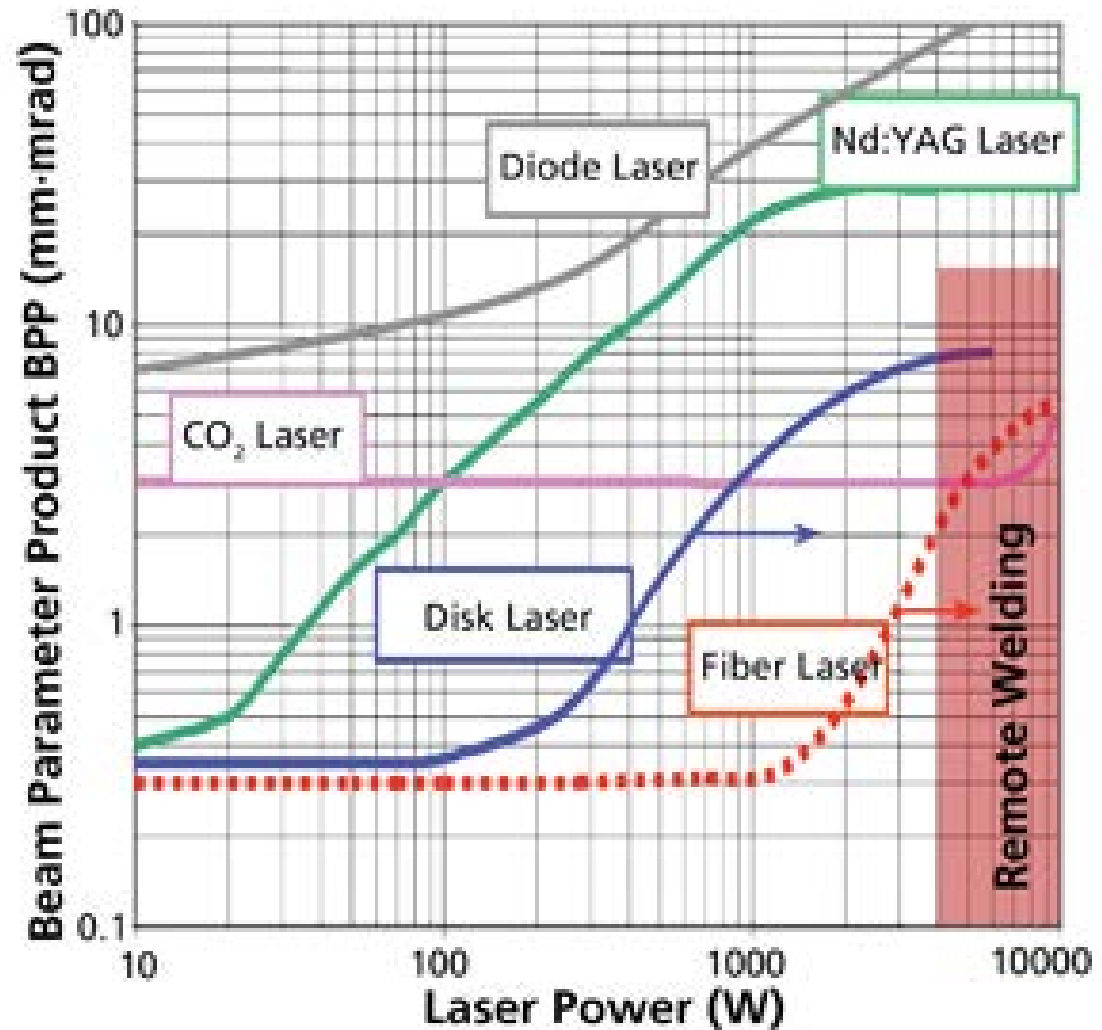
✗ Thin Disk Laser



Fiber Laser

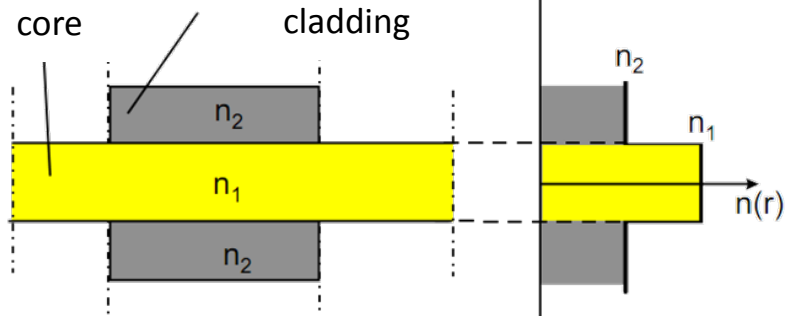


Rod Laser

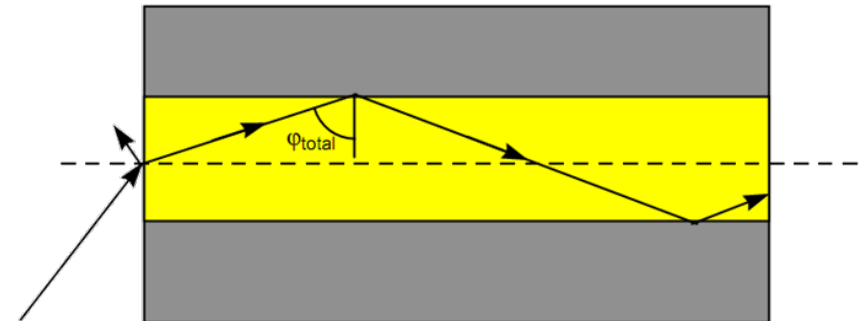


Principle of Waveguiding

step index fiber

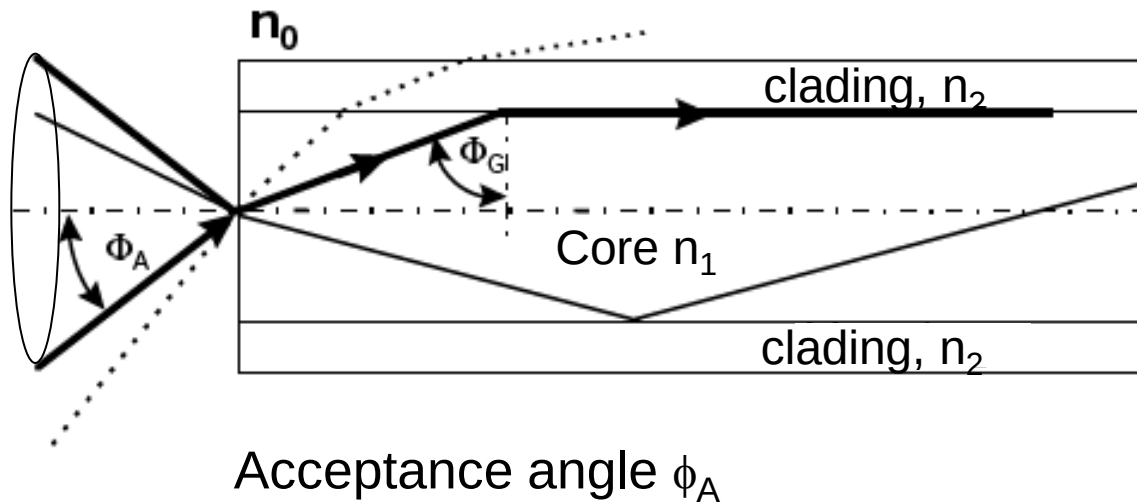


total internal reflection



Optical Fibers

Optical fiber, acceptance angle Φ_A , numerical aperture NA

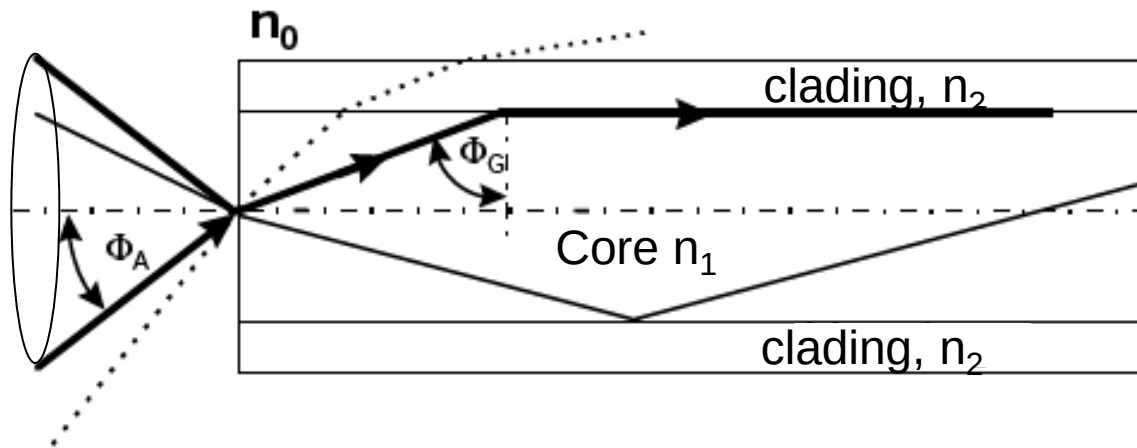


At injection, the refraction law gives

$$\begin{aligned} n_0 \cdot \sin(\Phi_A) &= n_1 \cdot \sin(90^\circ - \Phi_G) = n_0 \cdot \sin(\Phi_A) \\ &= n_1 \cdot \cos(\Phi_G) = n_0 \cdot \sin(\Phi_A) = n_1 \sqrt{1 - \sin^2(\Phi_G)} \end{aligned}$$

Optical Fibers

Optical fiber, acceptance angle Φ_A , numerical aperture NA



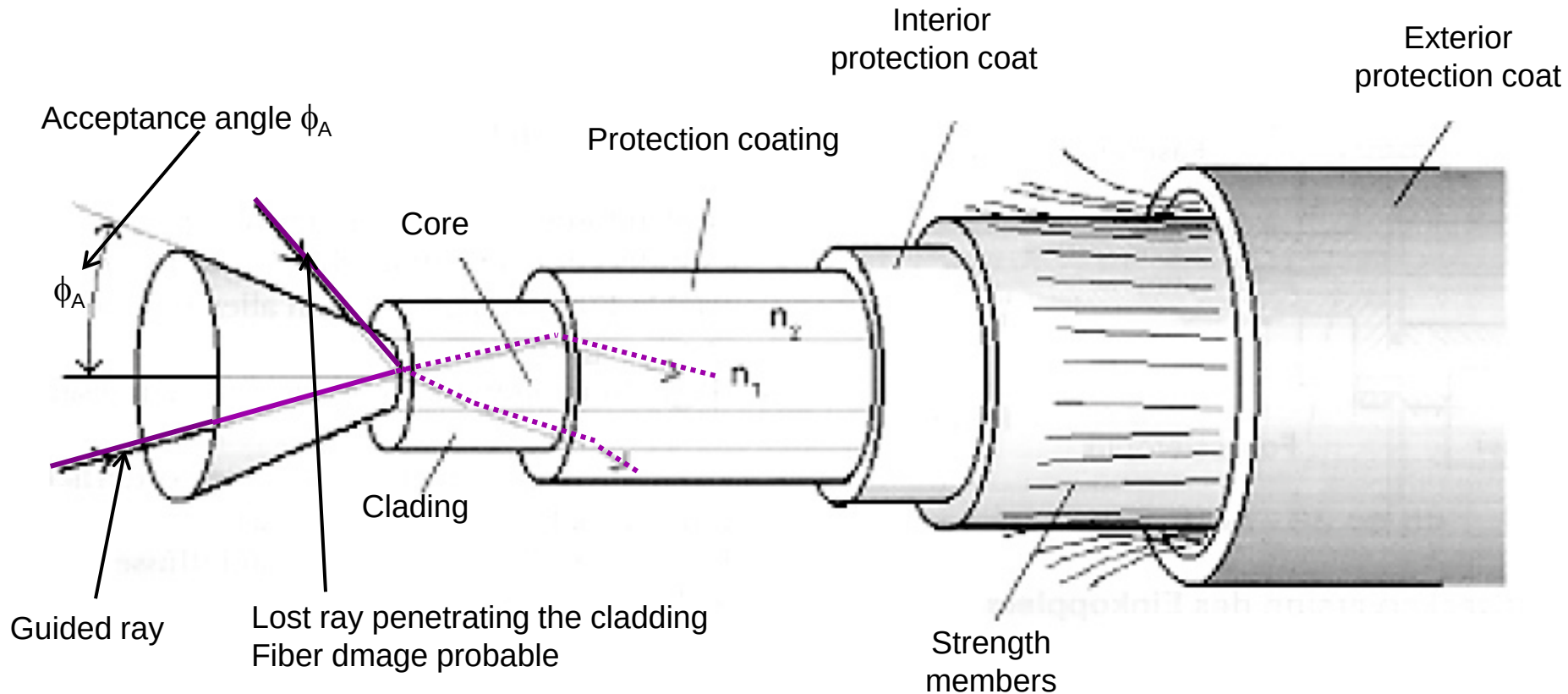
Numerical aperture NA for straight fiber

$$NA = n_0 \cdot \sin(\Phi_A) = n_1 \sqrt{1 - \frac{n_2^2}{n_1^2}} = \sqrt{n_1^2 - n_2^2}$$

Numerical aperture NA

Acceptance angle ϕ_A

Fiber cable for high power laser



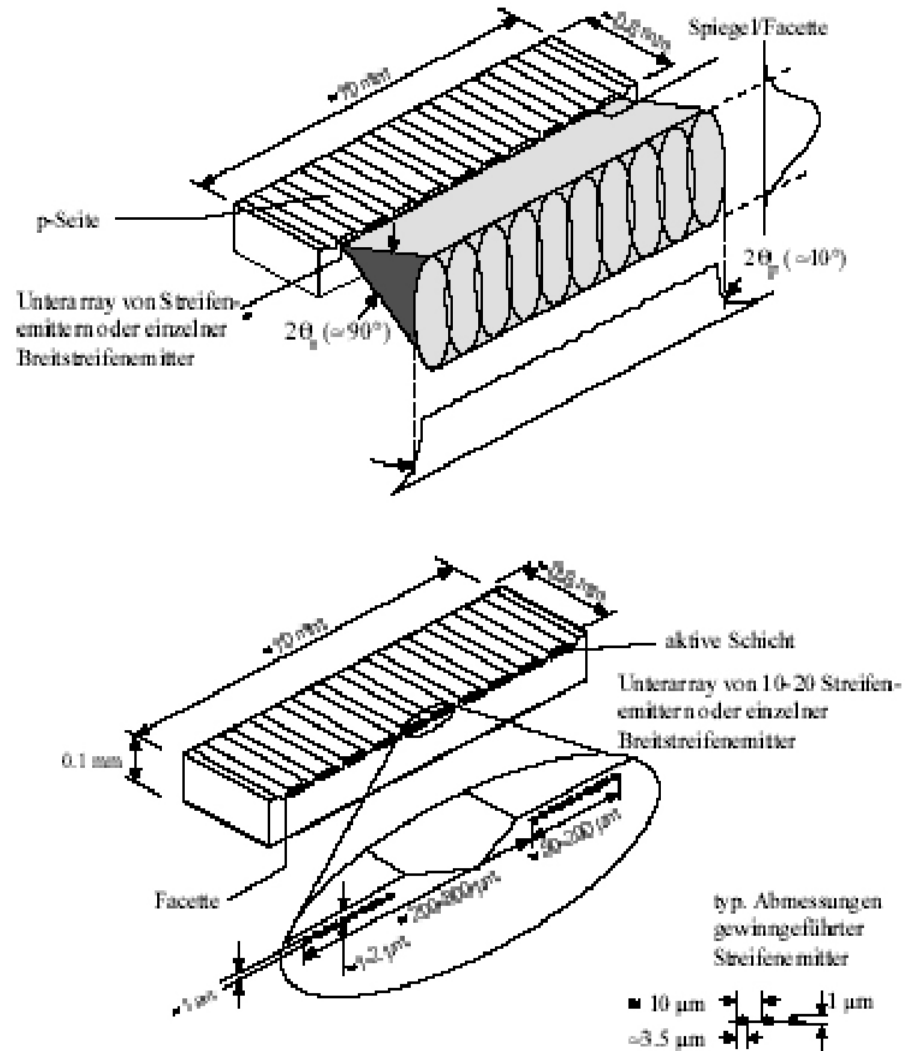
Fiber-coupled Industrial Laser

High power Nd-YAG welding laser with fiber beam delivery

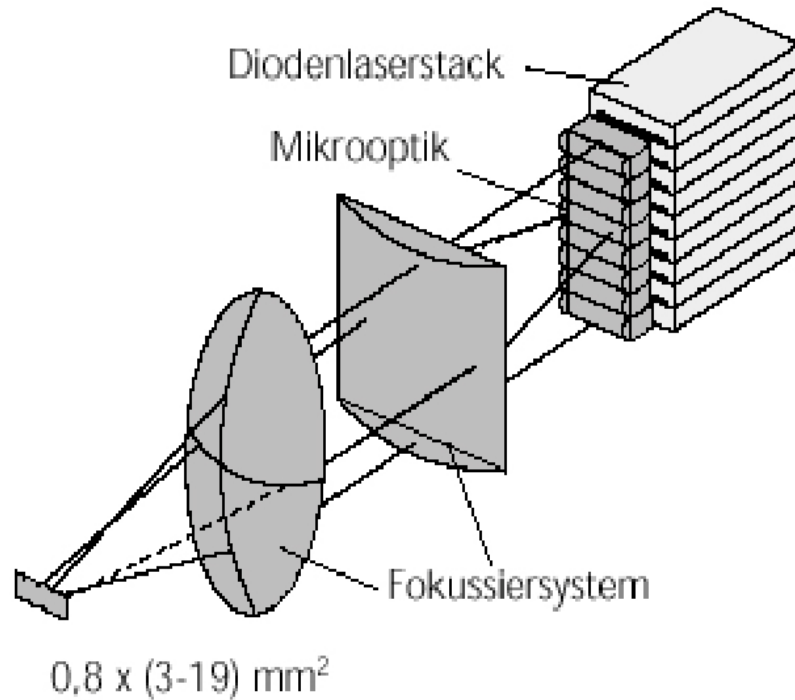


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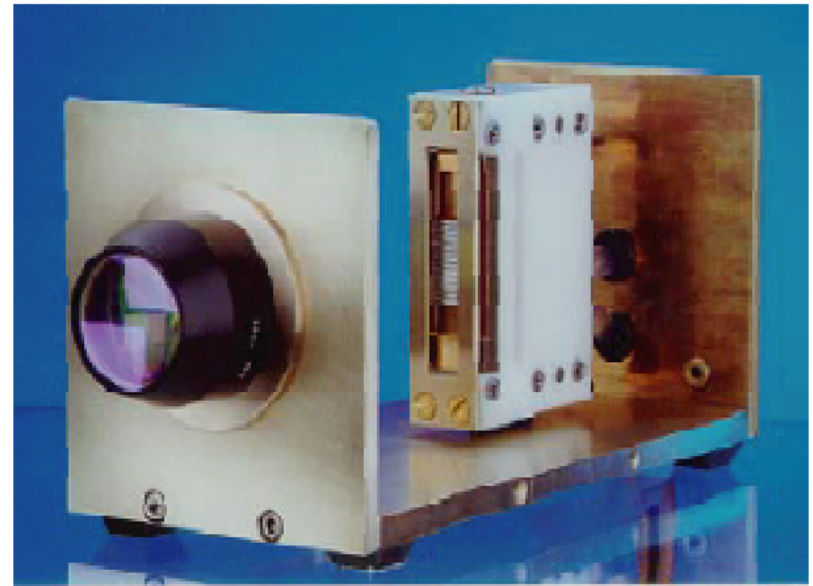
Laser Diode Bar



Laser Diode Stack

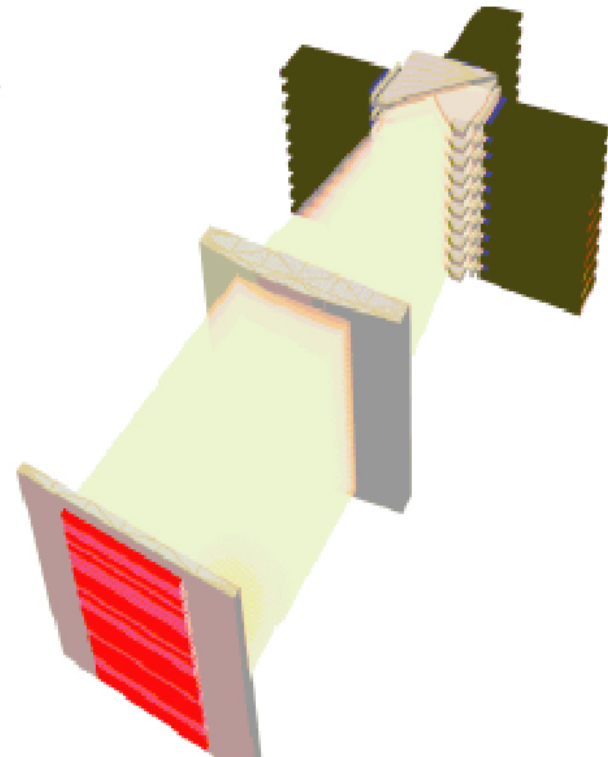


- bis zu 40 Diodenlaser (mit Polarisations/Wellenlängenmultiplexing)
- bis zu 1 kW
- bis zu $2 \times 10^4 \text{ W/cm}^2$



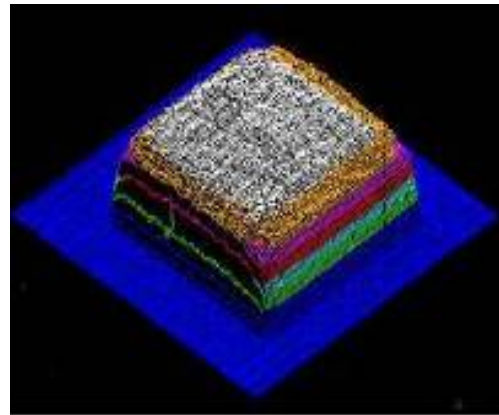
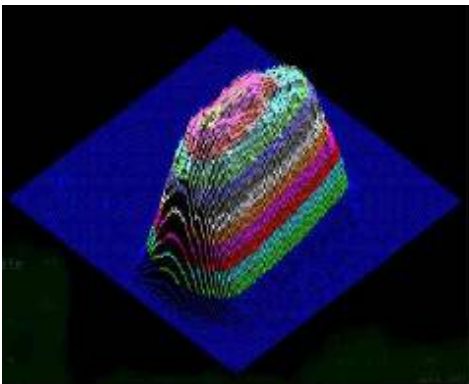
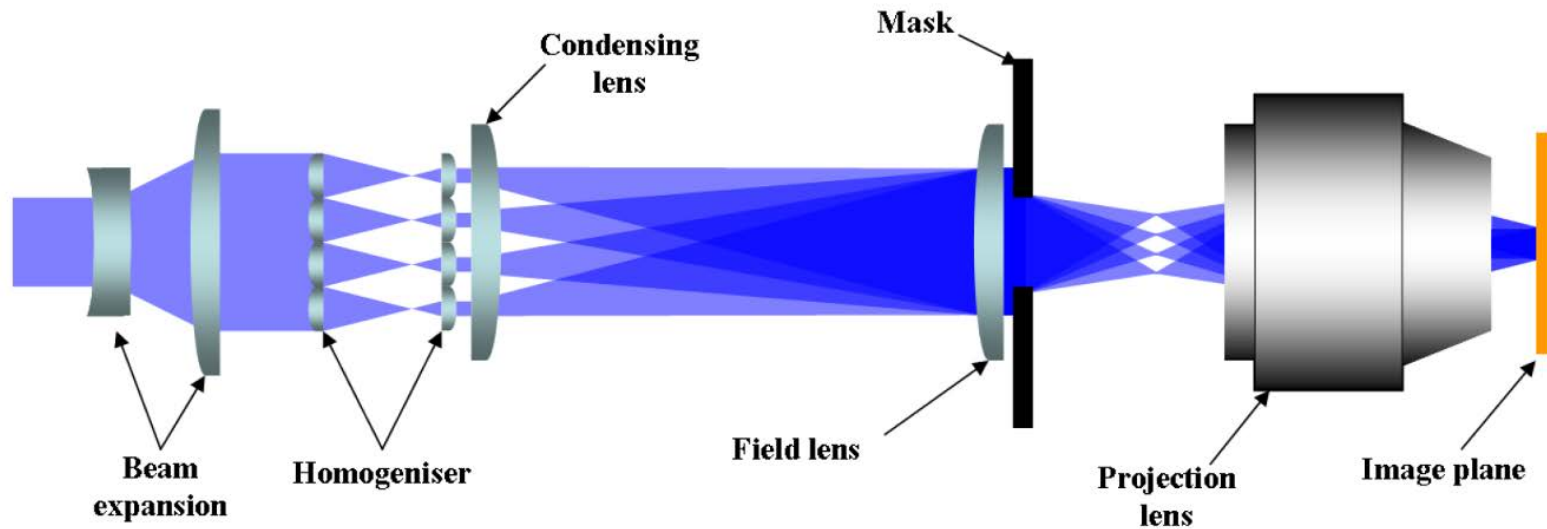
Laser Diode T-Stack

- 3 x 2 Diodenlaser (805 nm) aufgebaut
- bis zu 3 x 10 möglich
- 3,6 mm Strahlabstand im Stack
- 1,2 mm Strahlabstand (T-Stack)
- Füllfaktor $A_f = 0,92$

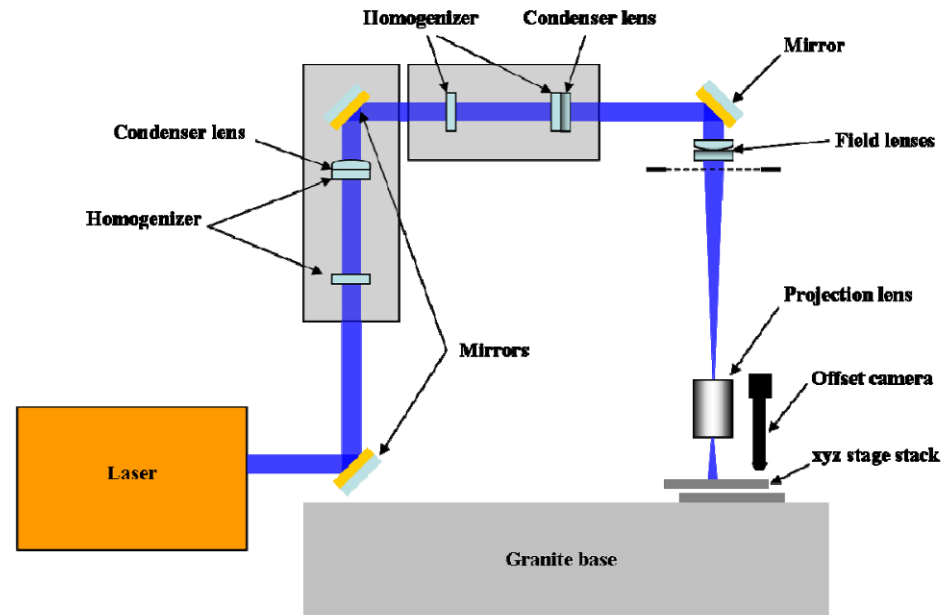


ILT Patent Appl. Nr. DE 196 48 789.7

Mask projection system

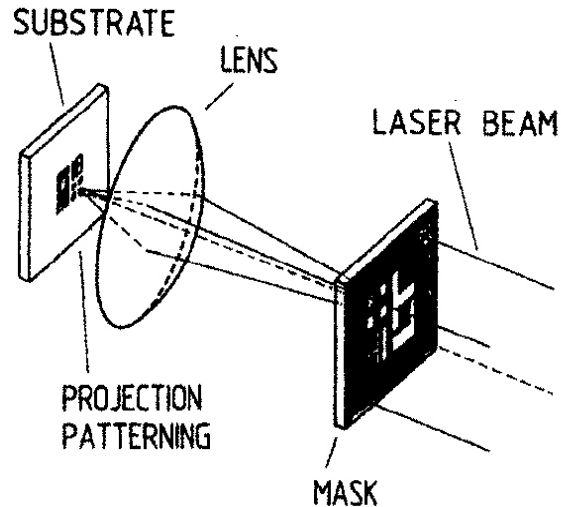


Exitech M8000 Micromachining System



Travel	400 mm
Accuracy	$\pm 0.50 \mu\text{m}$
Repeatability	$\pm 0.20 \mu\text{m}$
Straightness	$\pm 0.40 \mu\text{m}$
Flatness	$\pm 0.40 \mu\text{m}$

Mask material



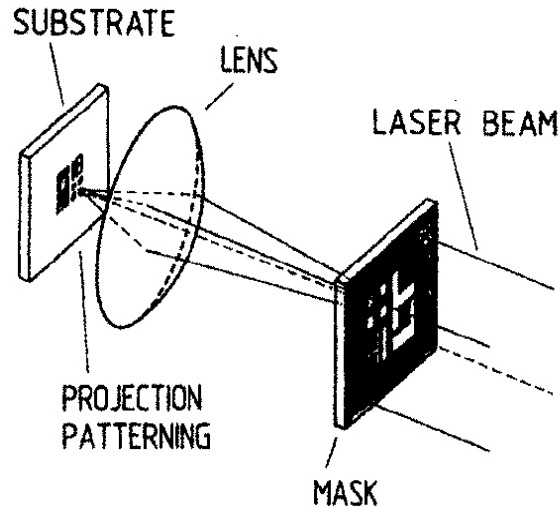
Industrially applied for 193 nm lithography:

- 75 nm Cr layer on fused silica
- with AR Cr_2O_3

Materials for excimer laser ablation masks

?

Mask material



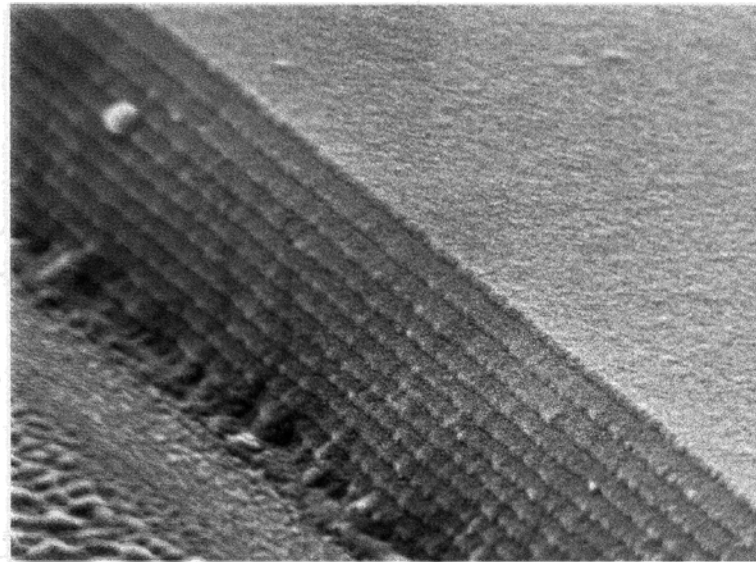
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Materials for excimer laser ablation masks

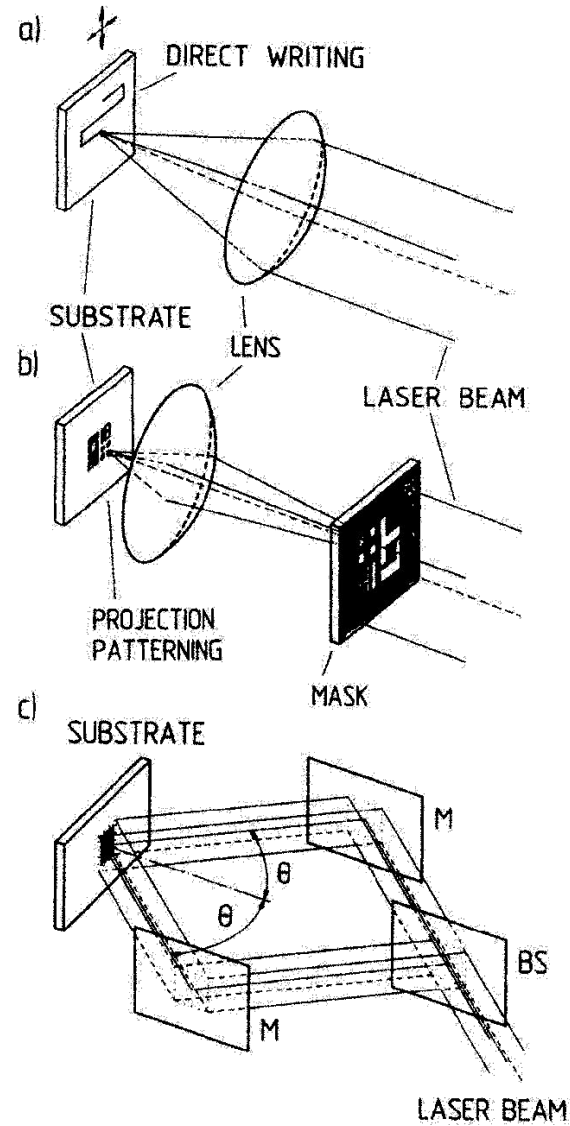
Material	Mo – Molybdenum sheets	Cr on SiO_2	Dielectric multilayer coating
Reflectivity [%]	58	65	>99
Damage Threshold [J/cm^2]	0.5	0.3	>2

Dielectric Mask



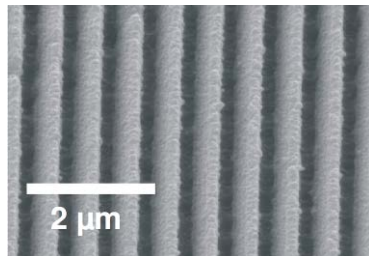
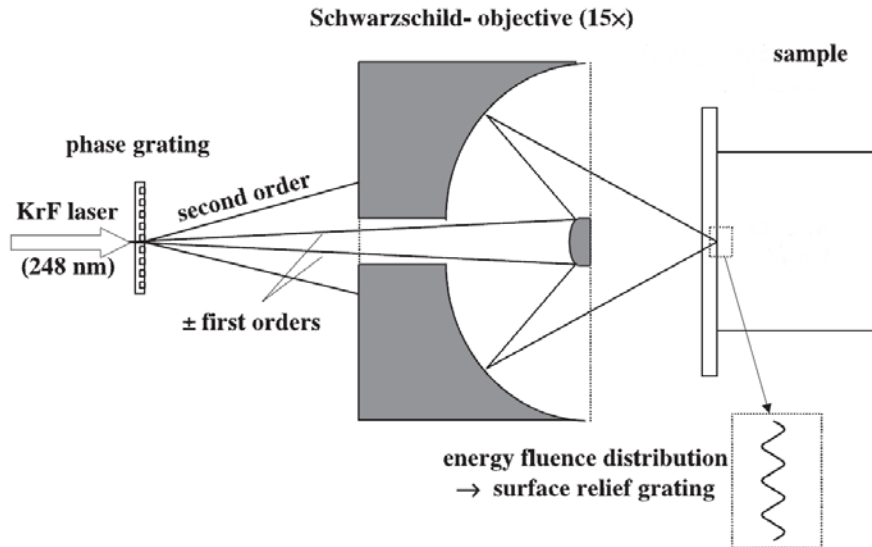
1 μm

Method Based on Interference



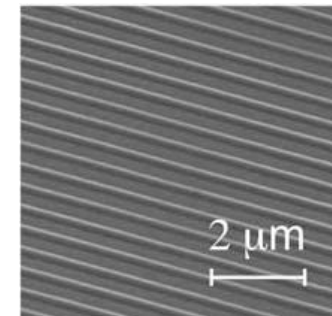
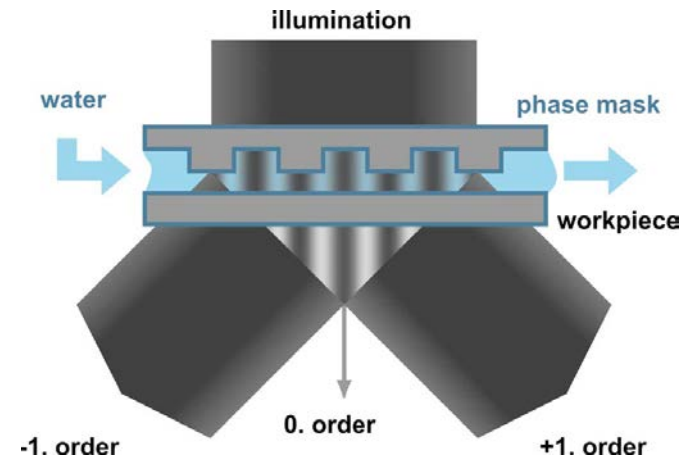
Submicron Structures

- Phase mask setup for submicron structures



Experimental set-up for the generation of submicron gratings by laser-ablation

K. Zimmer et al, Appl. Phys. A 74, 453–456 (2002)



Principle of the proximity phase mask setup with water immersion

B. Borchers et al, Appl. Phys. 107, 2010