Empa
Materials Science and Technology

ÉCOLE POLYTECHNIQUE FÉDÉRALE DE LAUSANNE

Laser Processing of Materials

Beam Delivery & Beam Quality

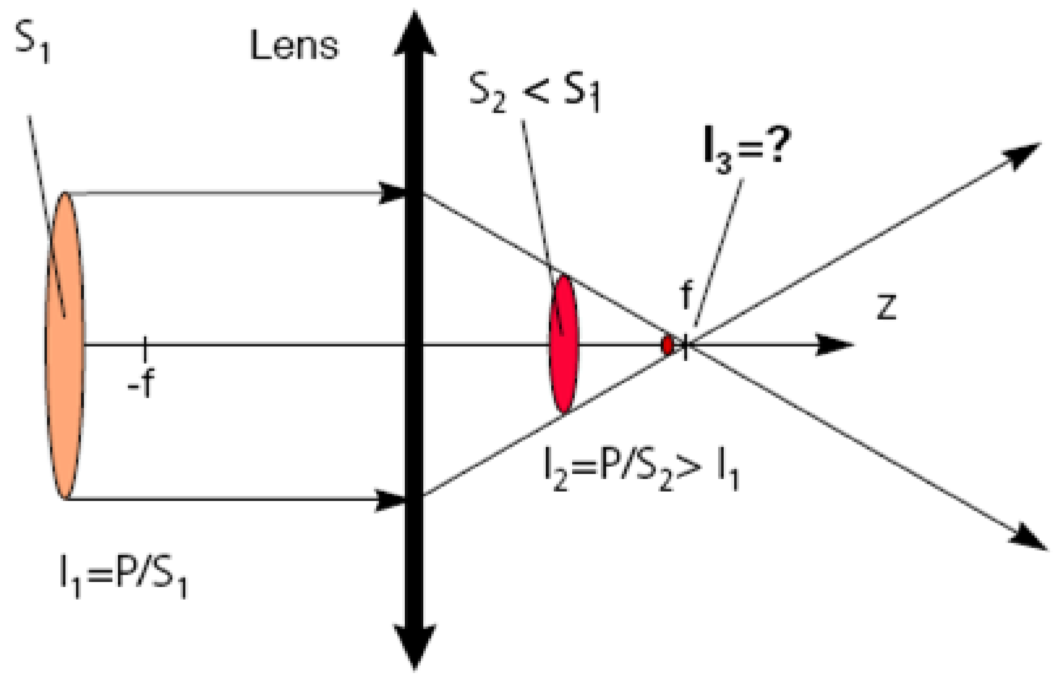
Patrik Hoffmann

Content

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

Imaging and Gaussian beams

Geometrical "focusing"

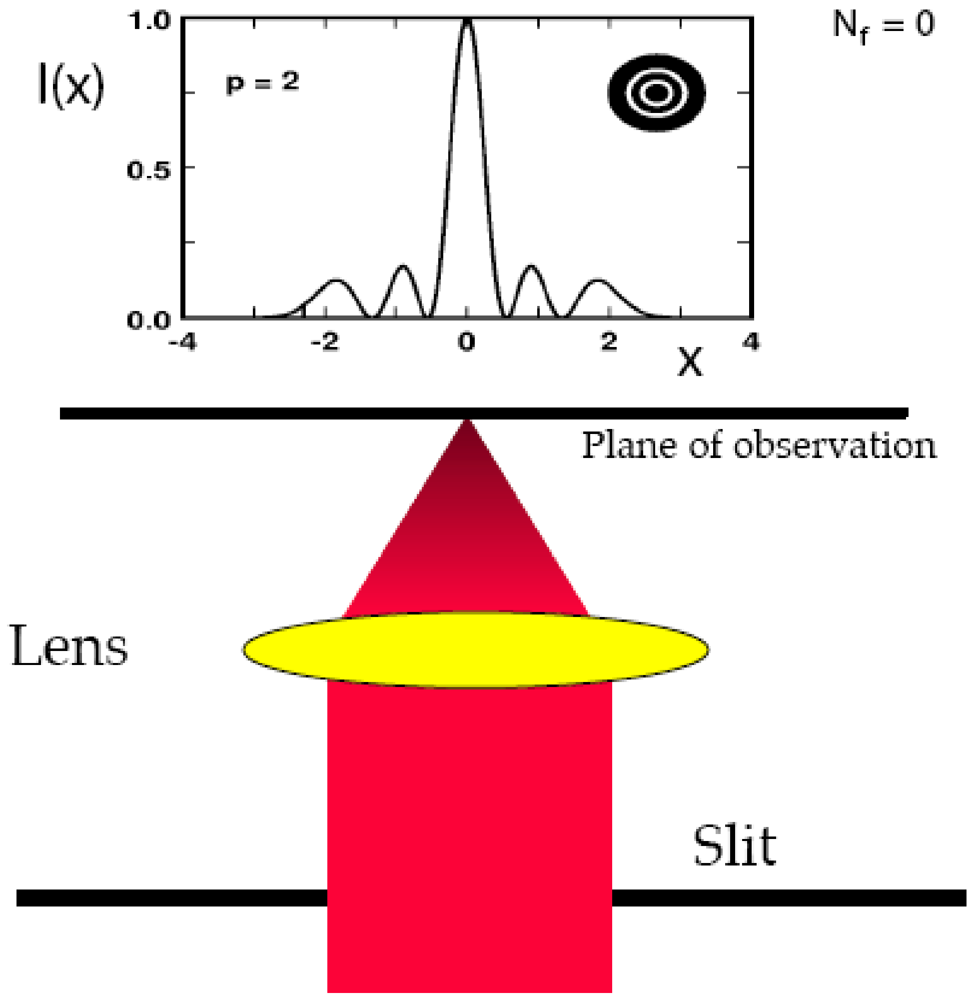


The surface of the beam vanishes at the exact focus location

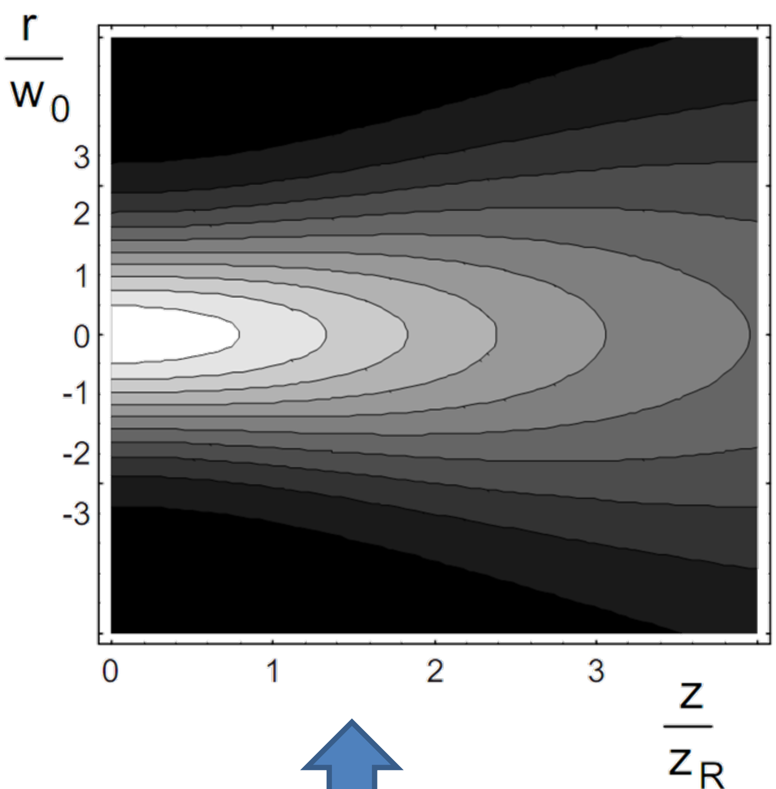
"Real World" Focusing

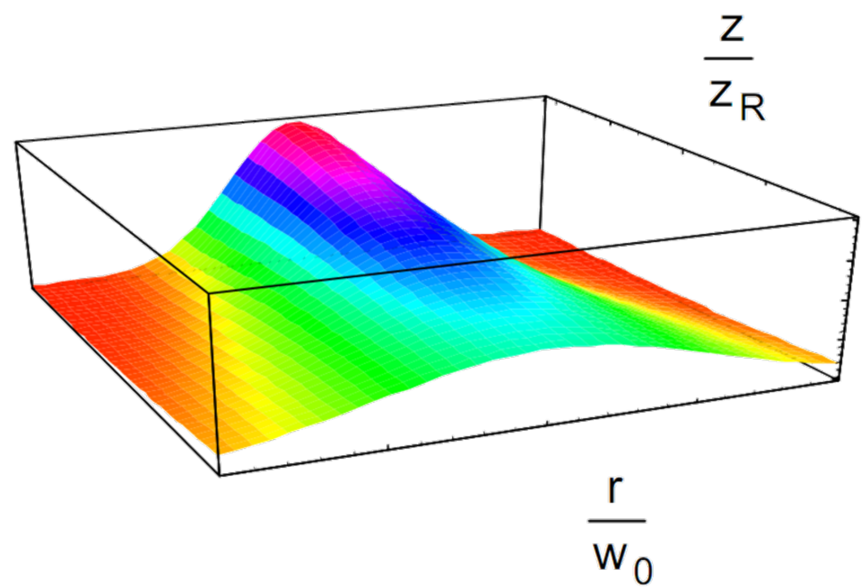
Diffraction with a slit aperture

$$I(x) \quad \mu \left(\frac{\mathrm{Sin}(kx)}{kx}\right)^2$$



Intensity Distribution in Gaussian Beam

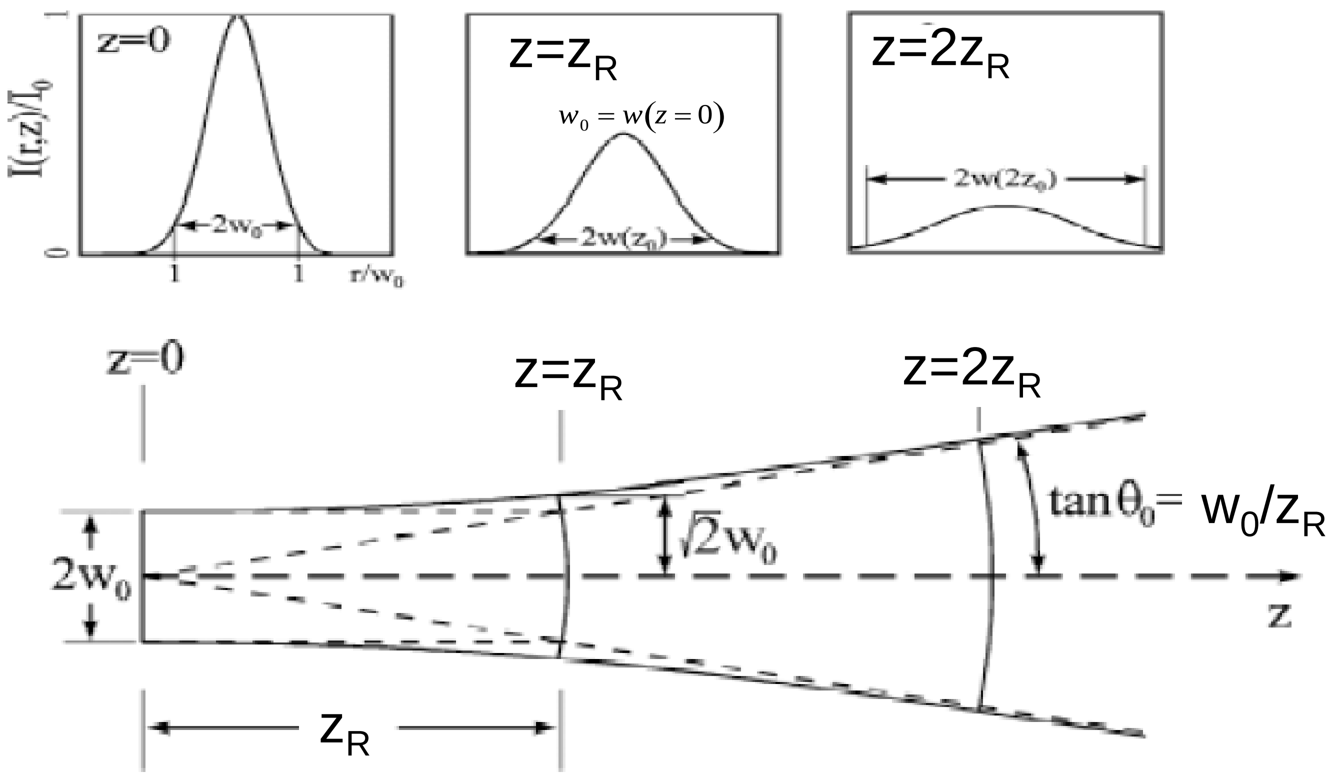




at each z-position, radial intensity distribution is Gaussian

Definition of Gaussian Beam

Fundumental mode intensity $$I(r,z) = I_0 e^{-2\left(\frac{r}{w(z)}\right)^2}$$



Definitions of the Beam Size

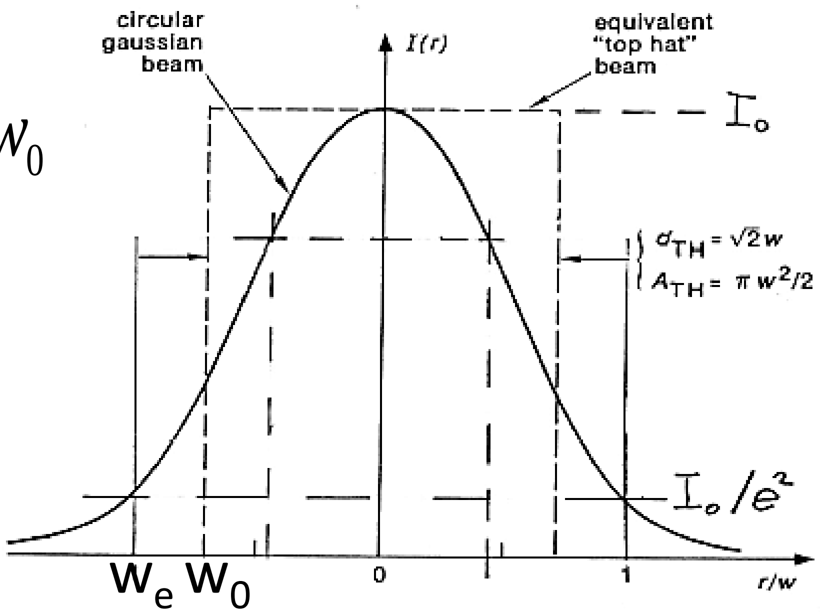
Definitions of the beam size (waist):

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

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

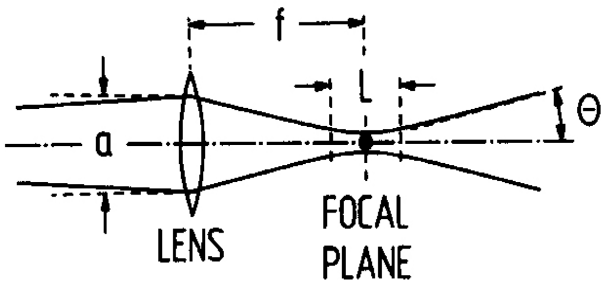
Total intensity of the beam:

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



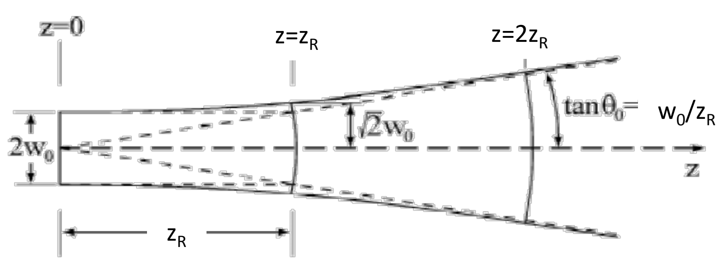
Normalised Gaussian beam profile, with different approximations

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

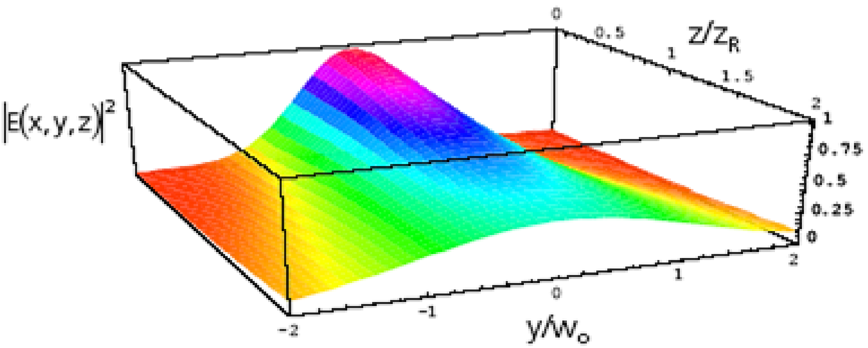
a Gaussian Beam is completely defined by the parameters:

w_0 - waist at focal point

z_R – Rayleigh range

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

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

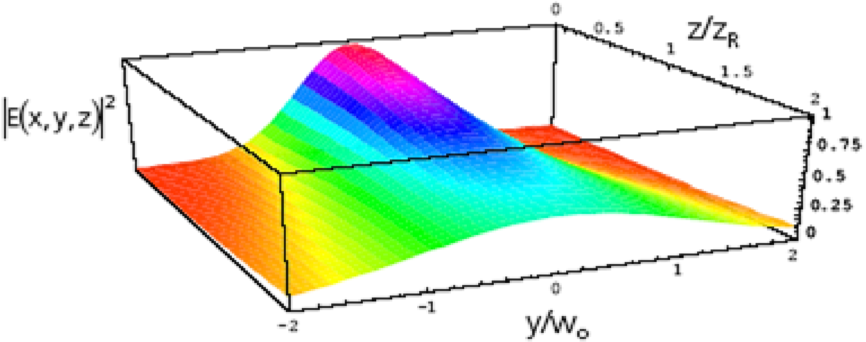


$$I(r,z) = I_0 \left(\frac{w_0}{w(z)} \right)^2 \exp\left[-2 \left(\frac{r}{w(z)} \right)^2 \right]$$

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

Cross-section of Gaussian Beam

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



Some examples of properties:

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

$I(r{=}0,\ z{=}z_R) = I_0/2$ After one Rayleigh length

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

Beam Parameter Product (BBP)

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

BBP

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

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.

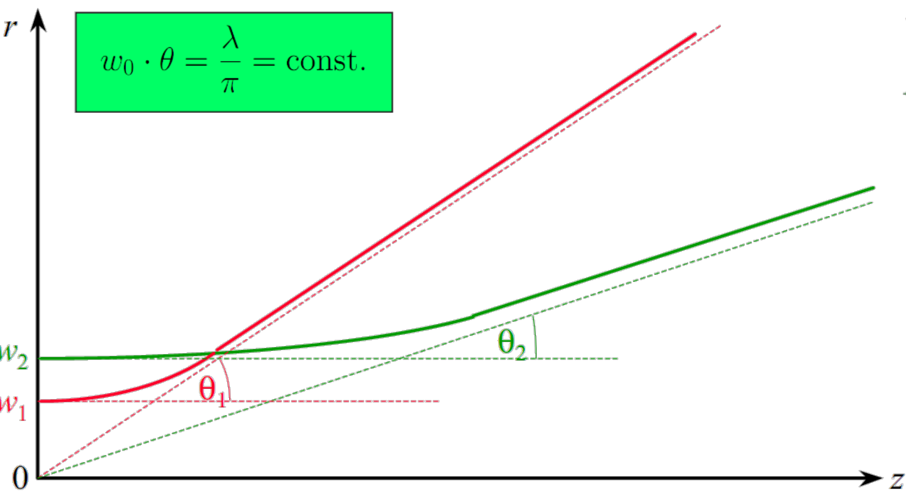
For a real laser beam:

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

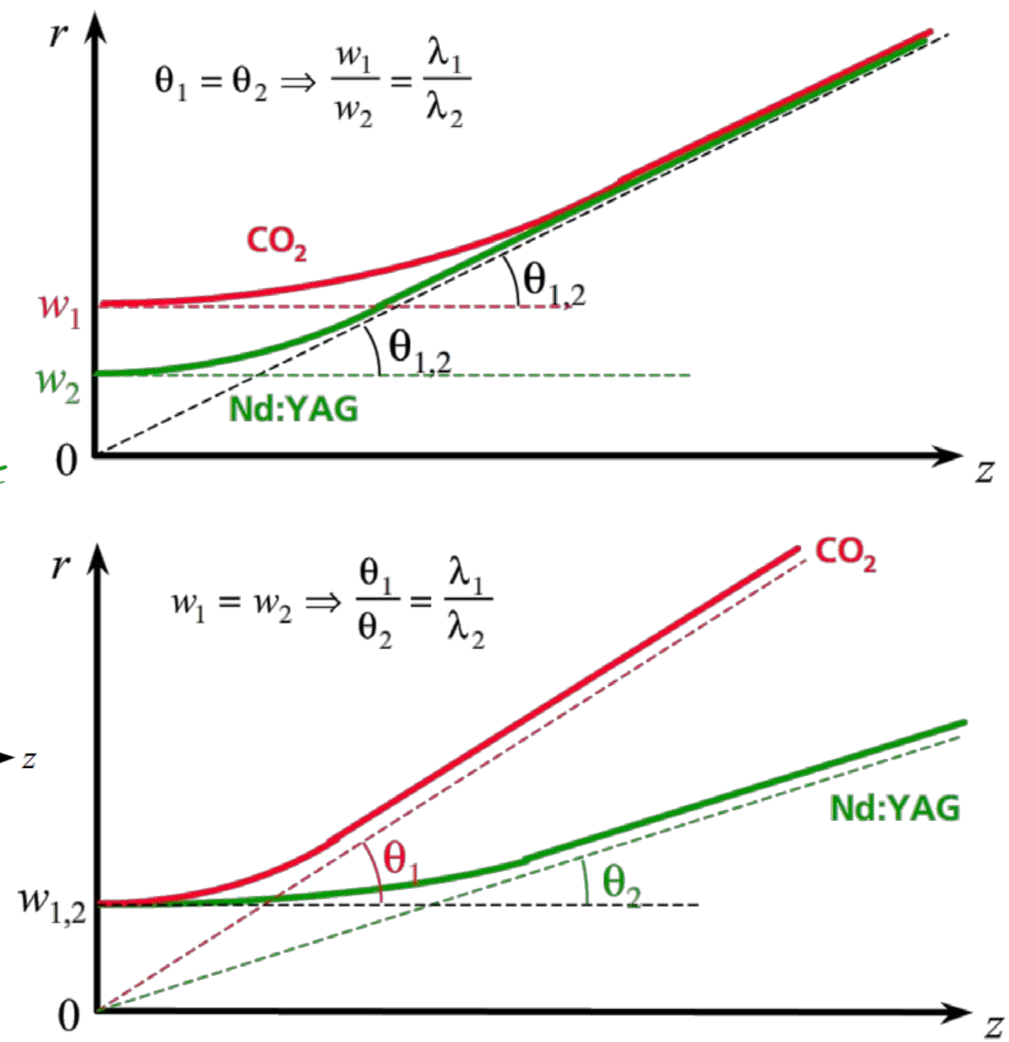
0,3 mm x mrad for a Nd-YAG laser $\lambda = 1{,}06\ \mu m$

Focusing of a Gaussian Beam

BBP stays constant for the same beam

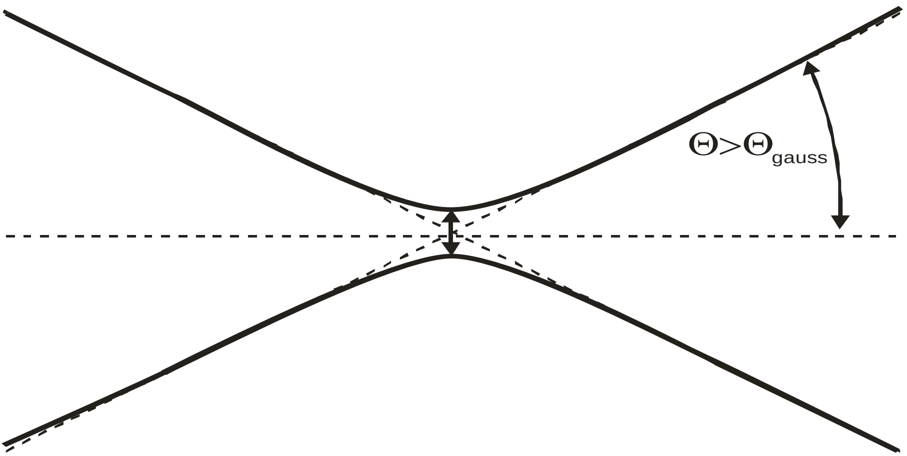


Nd:YAG and CO_2 laser



M^2 Factor

gaussian beam (M^2=1, BBP = λ / π)



for Gaussian ('ideal') beam

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

for non-ideal beam an M2 factor introduced

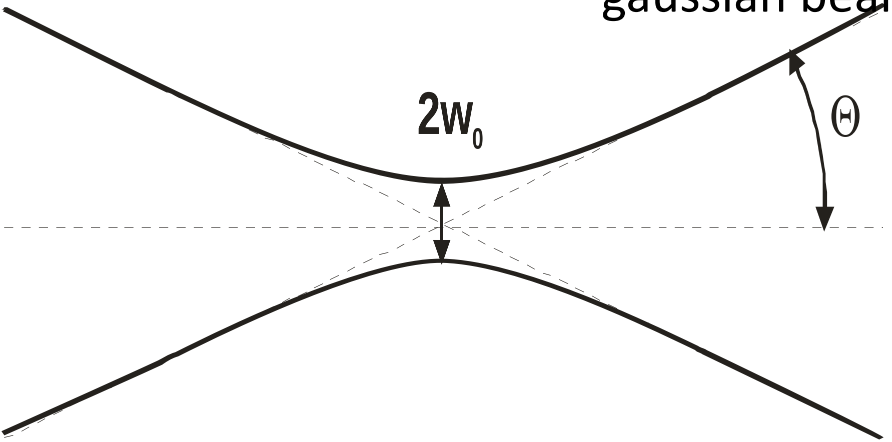
BPP (beam parameter product)

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

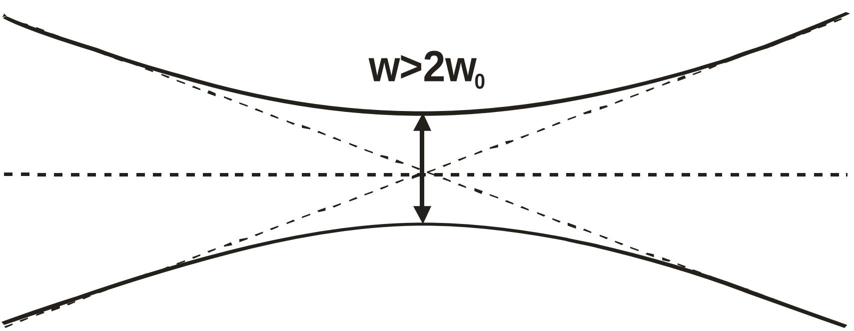
M2 is a wavelength-independent measure of beam quality (comparison with Gaussian beam)

M^2 Factor

gaussian beam (M^2=1, BBP = λ / π)

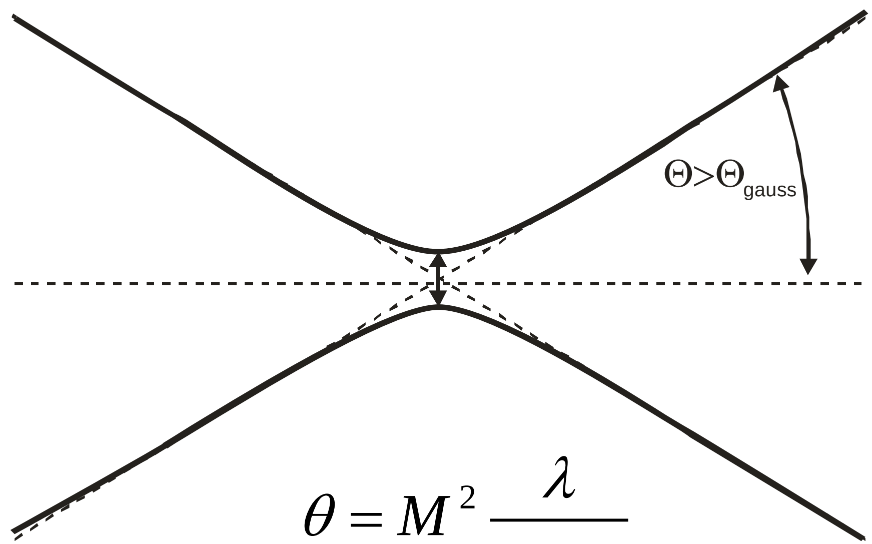


worse quality beam:
same focusing, larger spot



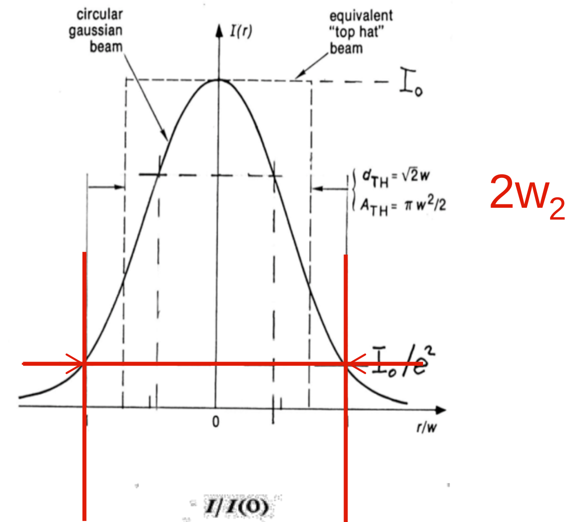
$$w_0 = M^2 \frac{\lambda}{\theta \cdot \pi}$$

worse quality beam:
stronger focusing to get same spot



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

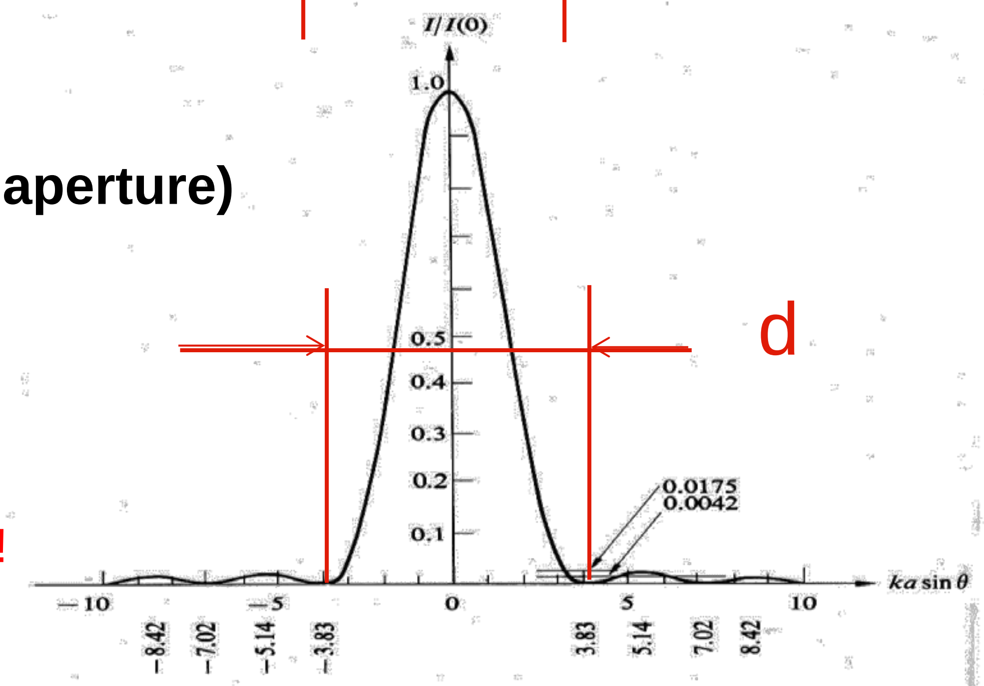
Comparison of Gaussian Beam and Plane Wave



Gaussian Beam

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

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



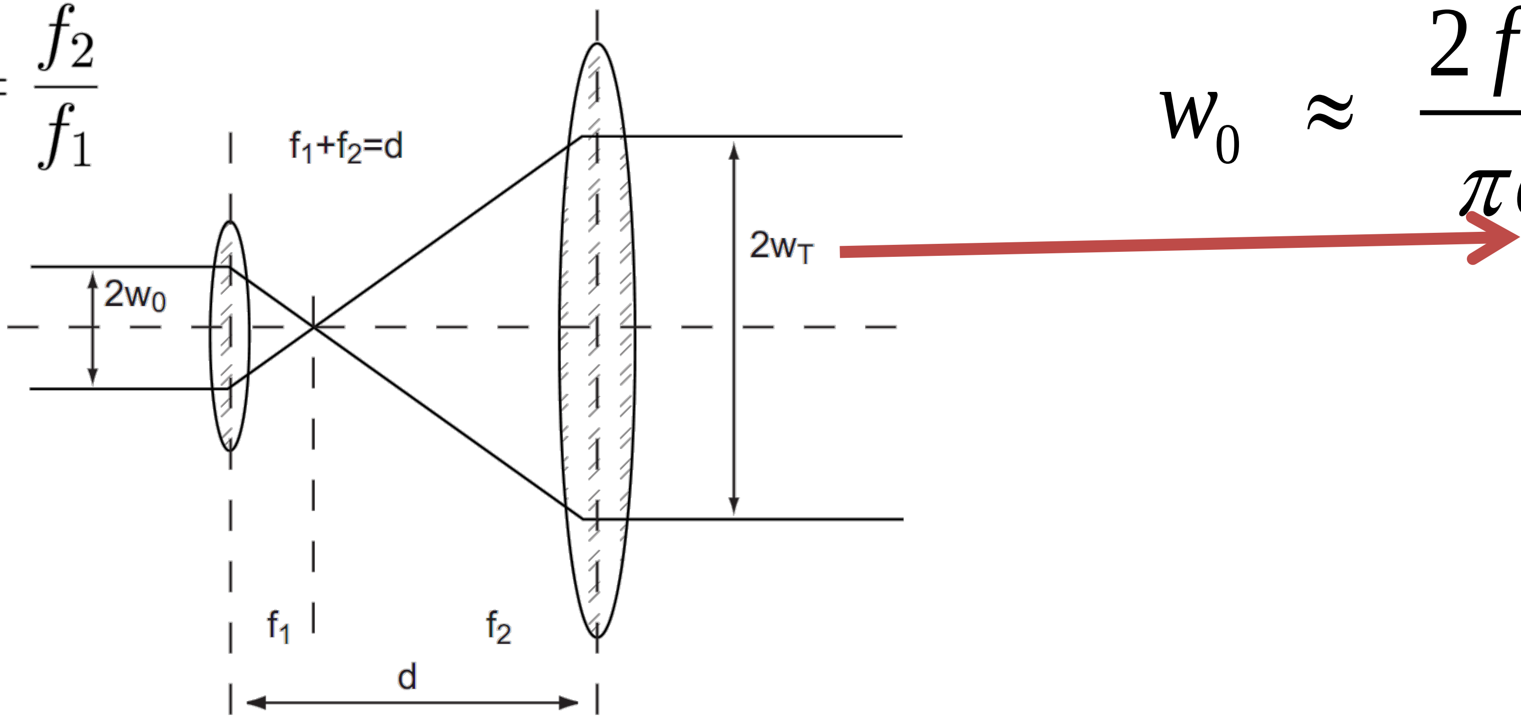
Airy (plain wave with circular aperture)

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

$$d_{Airy,FWHM} = \frac{1}{D}2.0\lambda f$$ 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

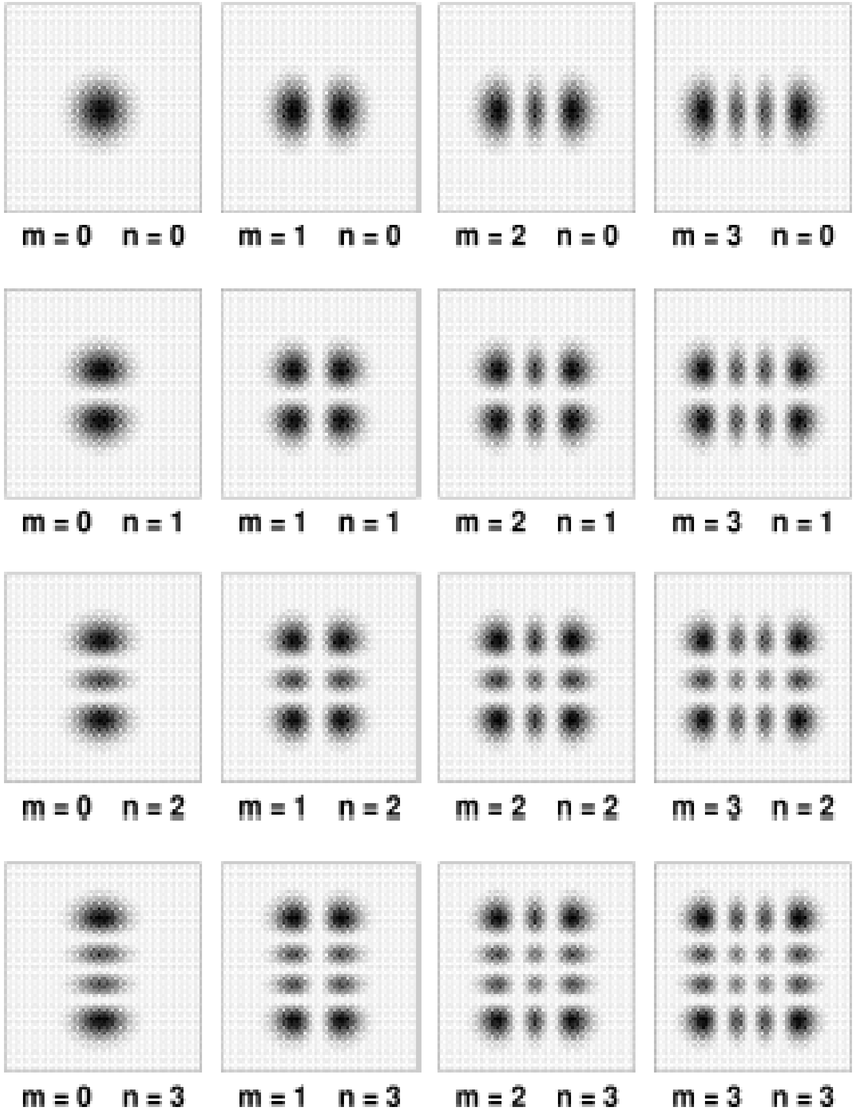
Why Beam is not always Gaussian?

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 coordinnates)

$$U_{p,\ell}(r,\varphi,z) = \overbrace{U_0\left(\sqrt{2}\,\frac{r}{w(z)}\right)^{\ell}}^{A}$$

$$\cdot \overbrace{L_p^{(\ell)}\left(2\left(\frac{r}{w(z)}\right)^2\right)\cdot\begin{pmatrix}\cos(\ell\varphi)\\ \sin(\ell\varphi)\end{pmatrix}}^{B}$$

$$\cdot\underbrace{\exp\left(-\frac{r^2}{w^2(z)}\right)}_{C}\cdot\underbrace{\exp\left(-i(2p+\ell)\cdot \arctan\left(\frac{z}{z_0}\right)\right)}_{D}$$

__Termes:__

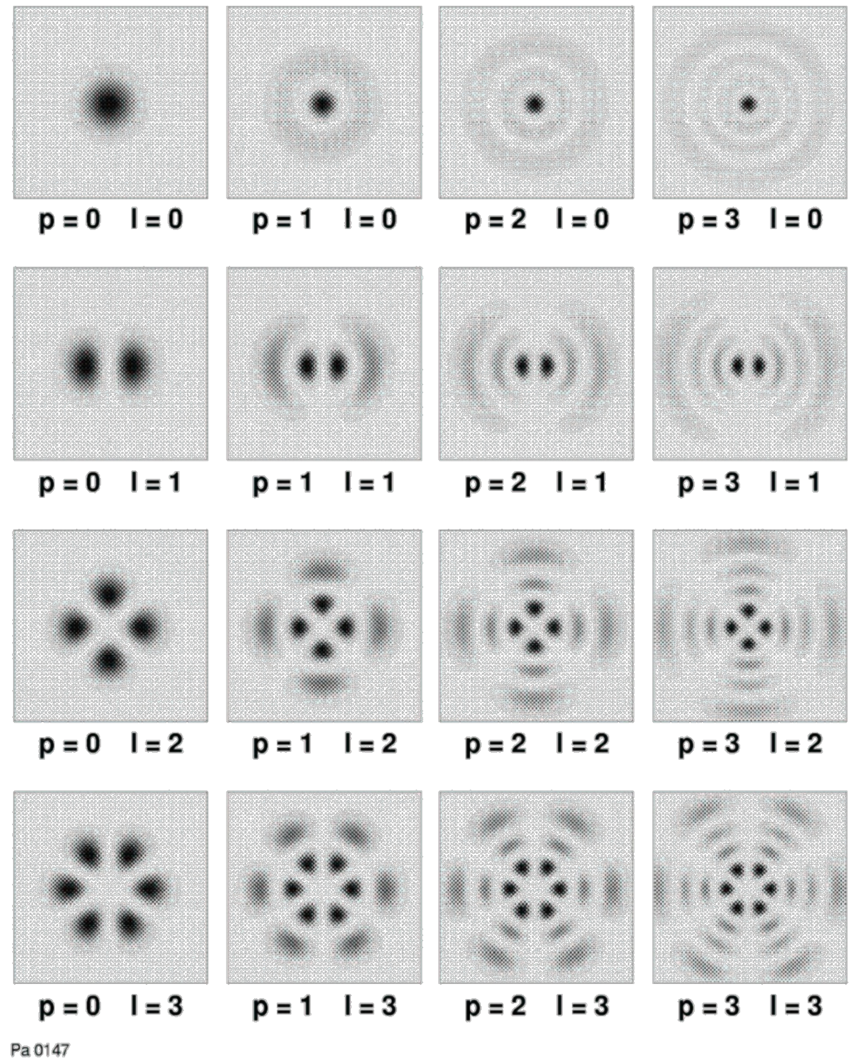
A: Amplitude; B: Hermite functions;

C: Gauss functions ; D: Phase

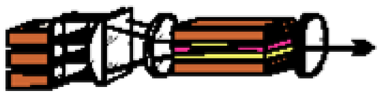
Polynôme de Laguerre:

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

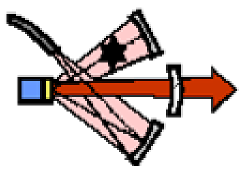
$$L_2^{(0)}(\rho)=1-\frac{\rho 2}{2};\qquad \rho=\frac{\sqrt{2}r}{w(z)}$$



Comparison of BBP for Different Laser Designs

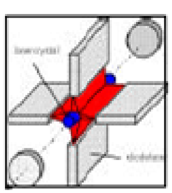


INNOSLAB

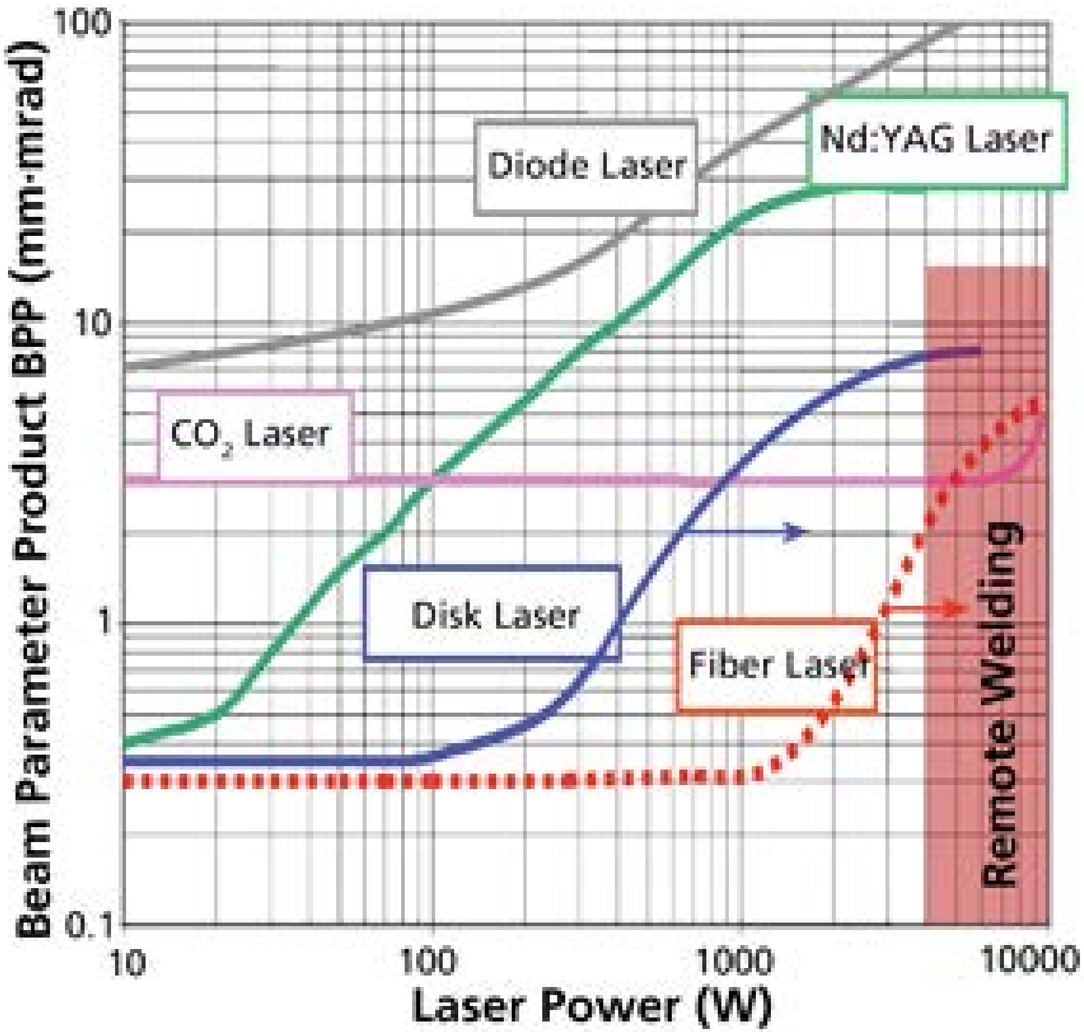


Thin Disk Laser

Fiber Laser

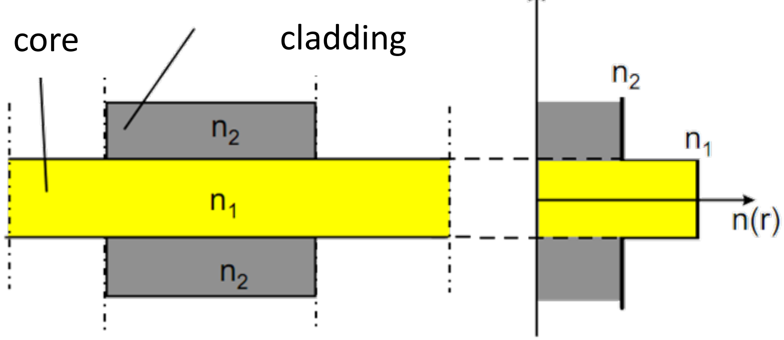


Rod Laser

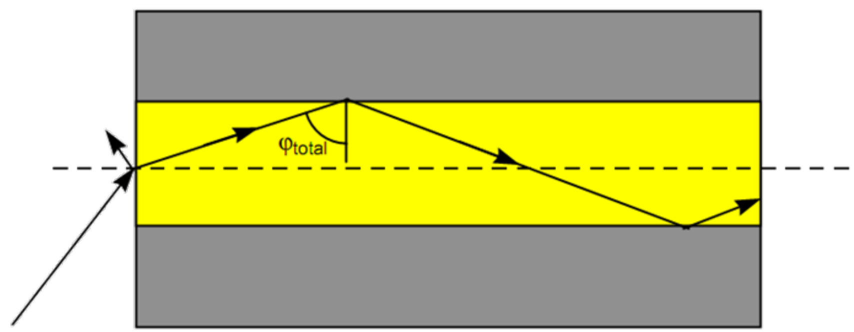


Principle of Waveguiding

step index fiber

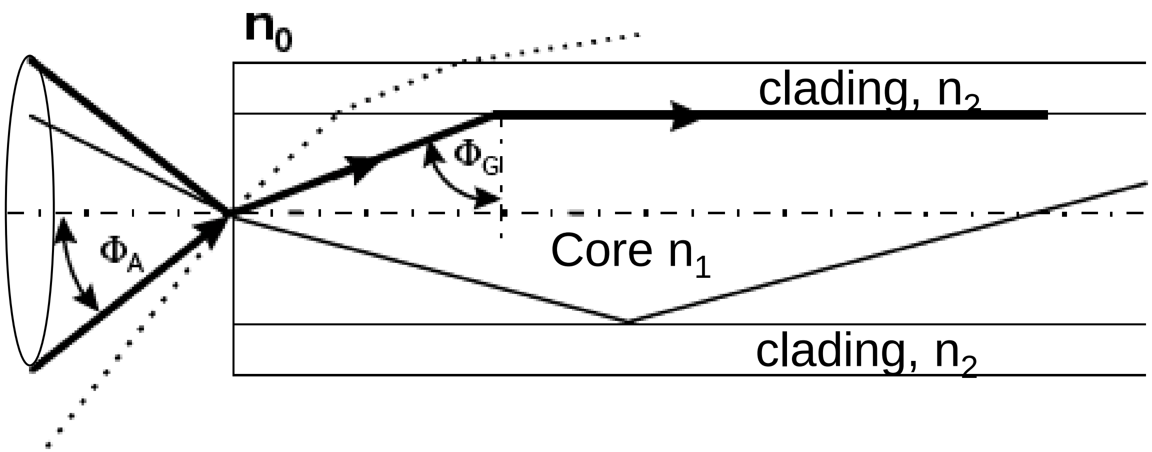


total internal
reflection



Optical Fibers

Optical fiber, acceptance angle Φ_A , numerical aperture NA



Acceptance angle ϕ_A

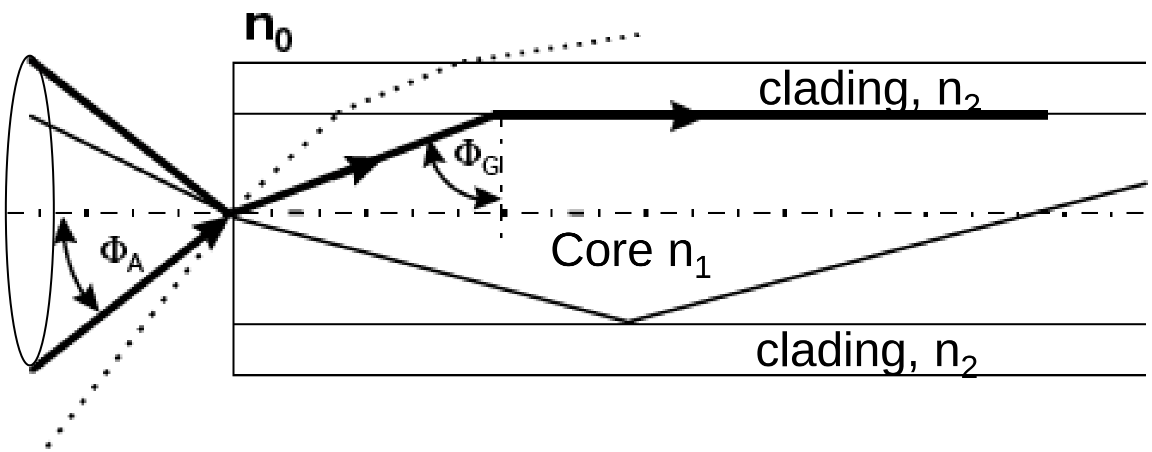
At injection, the refraction law gives

$$n_0 \cdot \sin(\Phi_A) = n_1 \cdot \sin(90° - \Phi_G) = n_0 \cdot \sin(\Phi_A)$$

$$= n_1 \cdot \cos(\Phi_G) = n_0 \cdot \sin(\Phi_A) = n_1 \sqrt{1 - \sin^2(\Phi_G)}$$

Optical Fibers

Optical fiber, acceptance angle Φ_A , numerical aperture NA



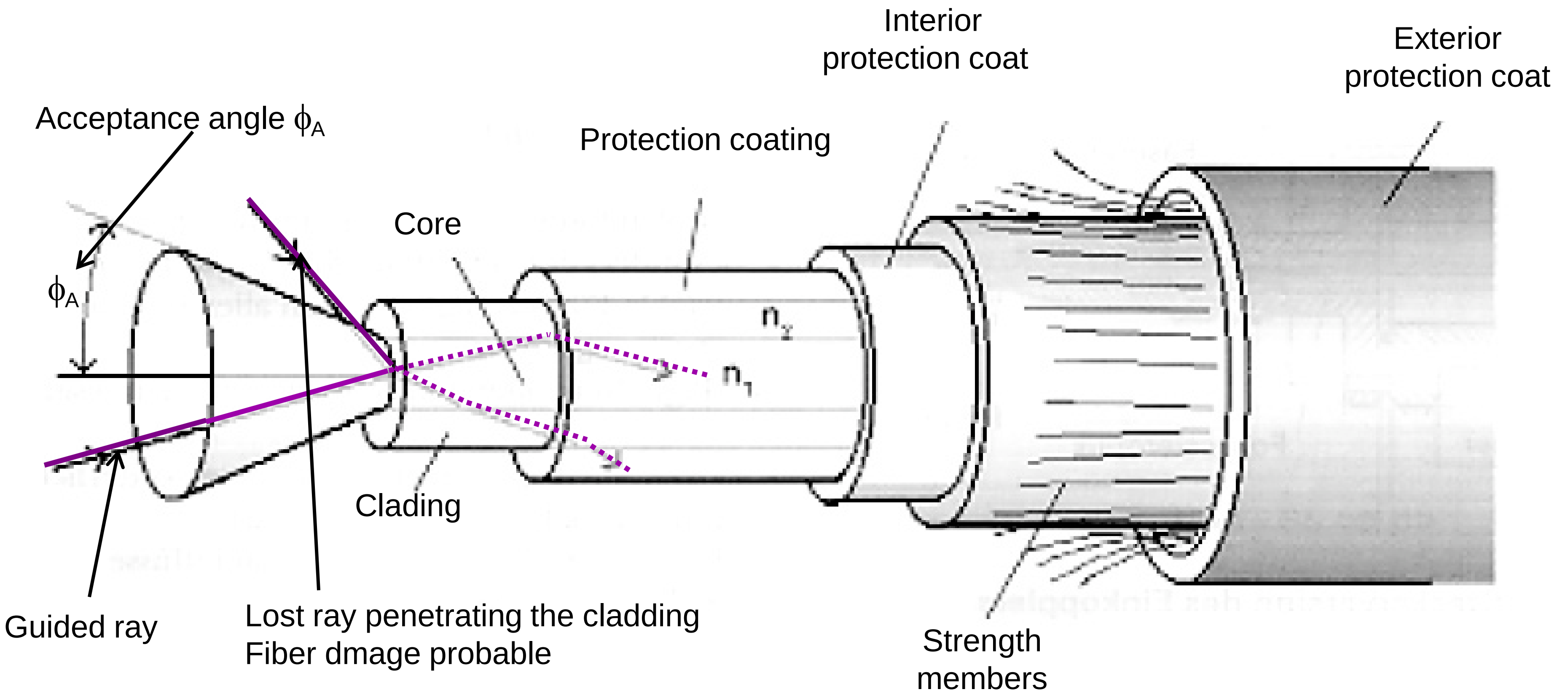
Numerical aperture NA for straight fiber

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

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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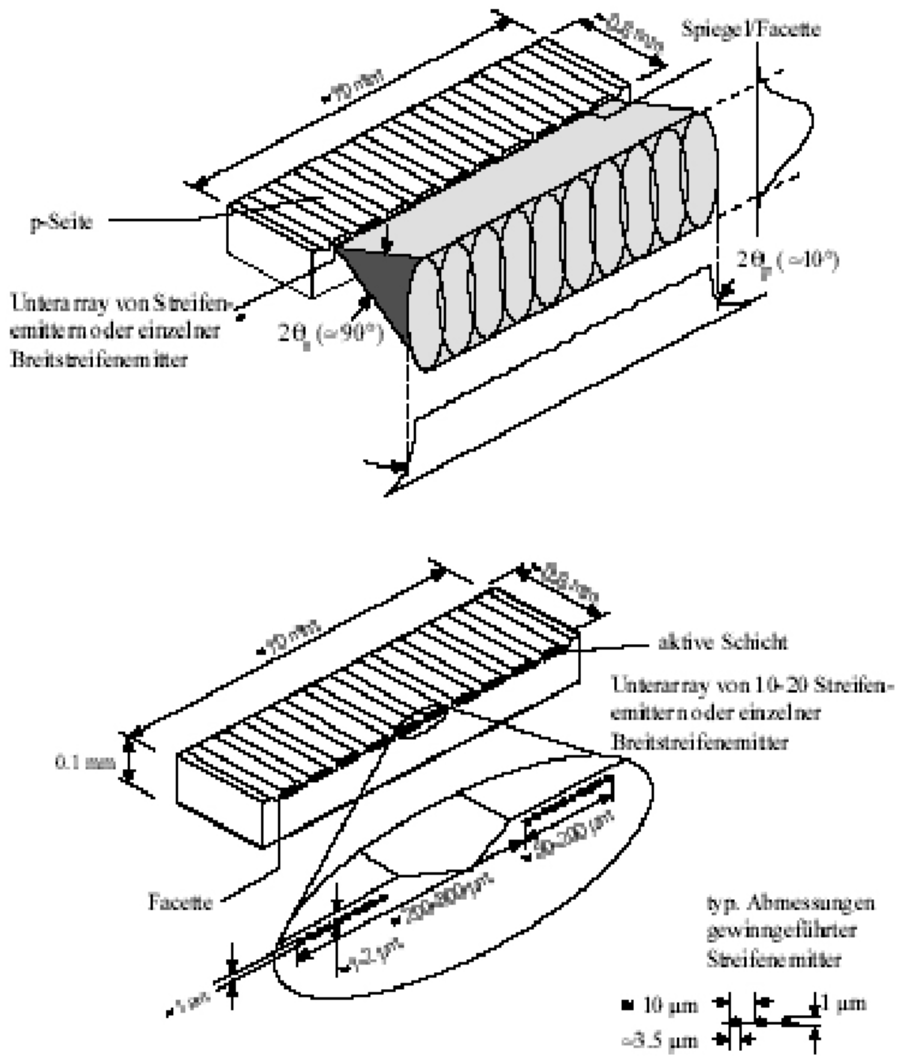
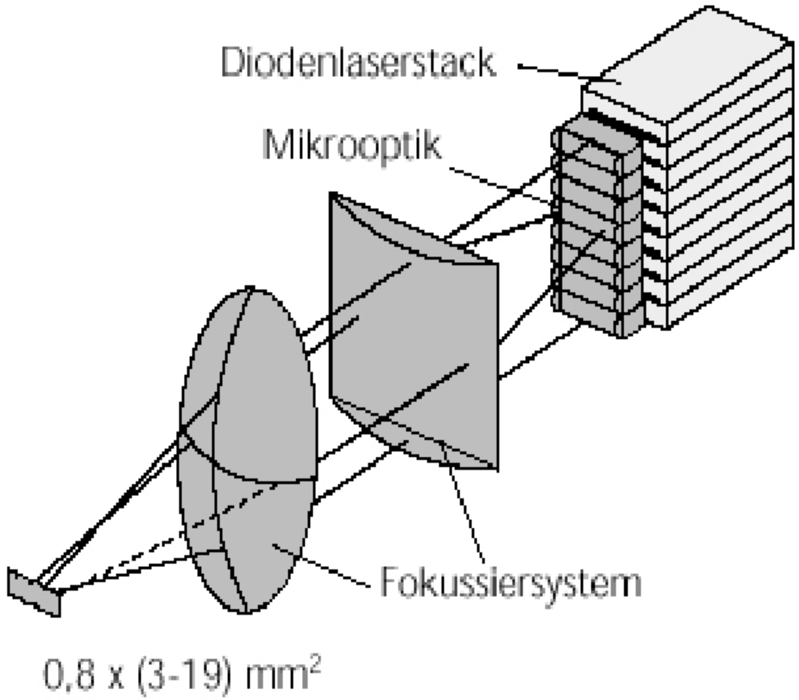
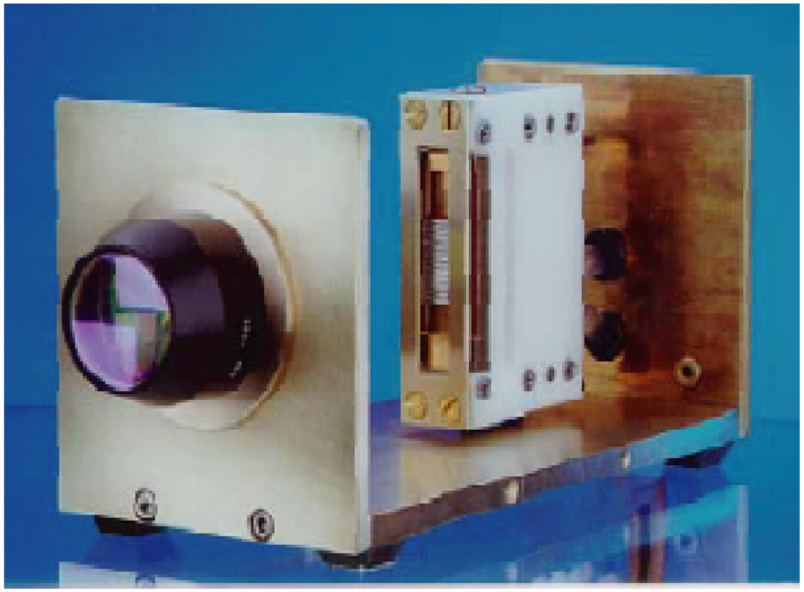
Laser Diode Bar



Laser Diode Stack



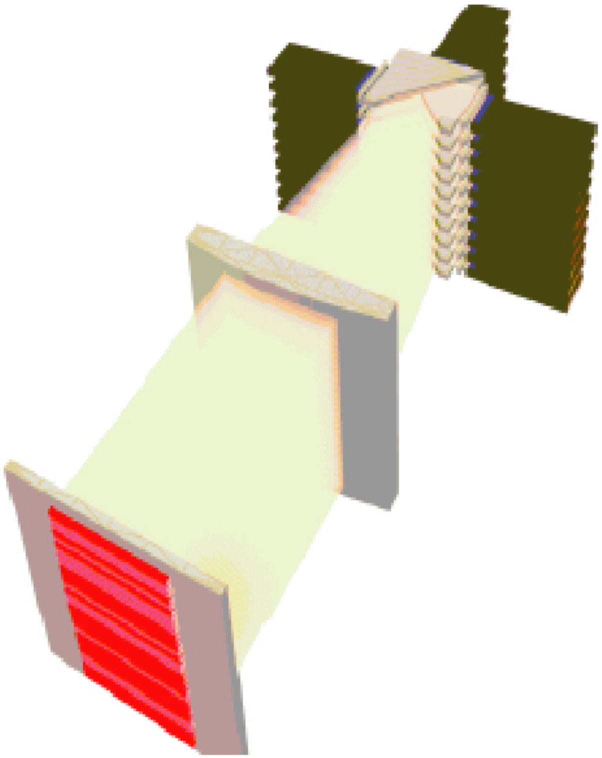
- bis zu 40 Diodenlaser (mit Polarisations/Wellenlängenmultiplexing)
- bis zu 1 kW
- bis zu 2×10^4 W/cm²



LLT RWTH
LEHRSTUHL FÜR LASERTECHNIK

Laser Diode T-Stack

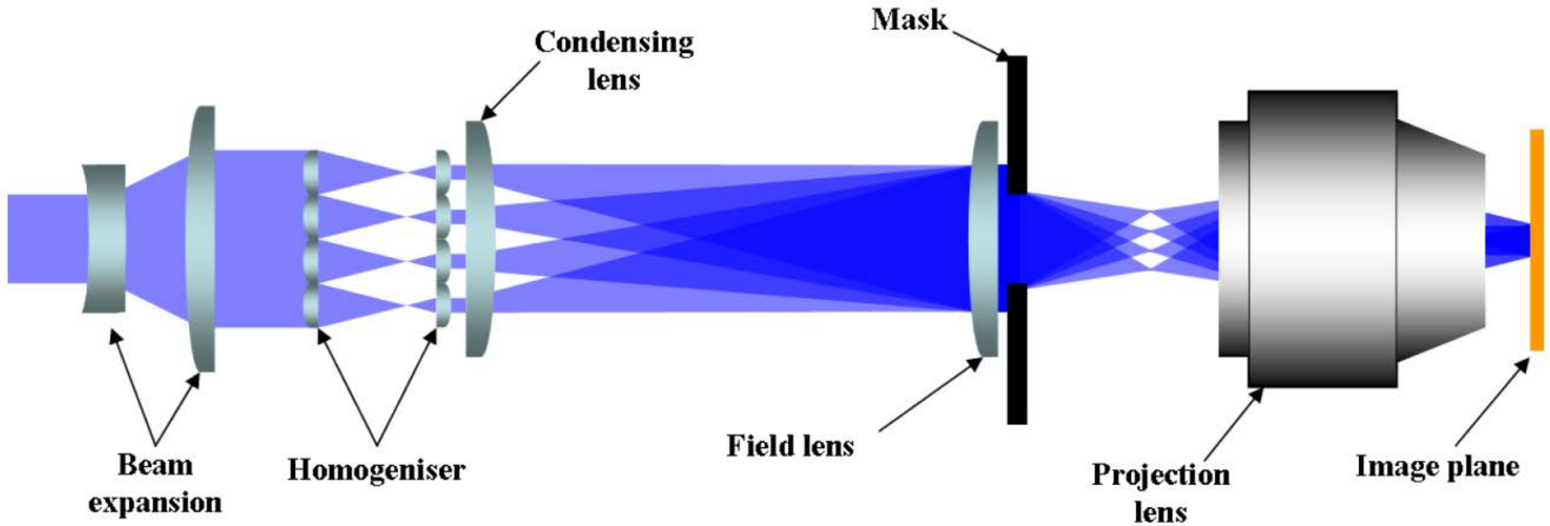
- 3 x 2 Diodenlaser (805 nm) aufgebaut
- bis zu 3 x 10 möglich
- 3,6 mm Strahlabstand im Stack
- 1,2 mm Strahlabstand (T-Stack)
- Füllfaktor A_F = 0,92

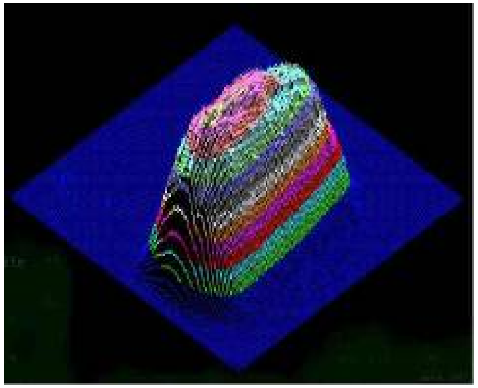


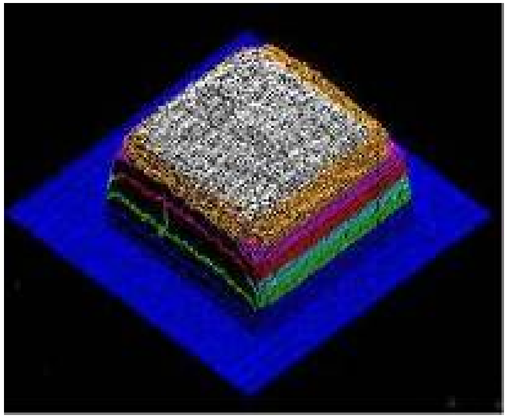
ILT Patent Appl. Nr. DE 196 48 789.7

LEHRSTUHL FÜR LASERTECHNIK

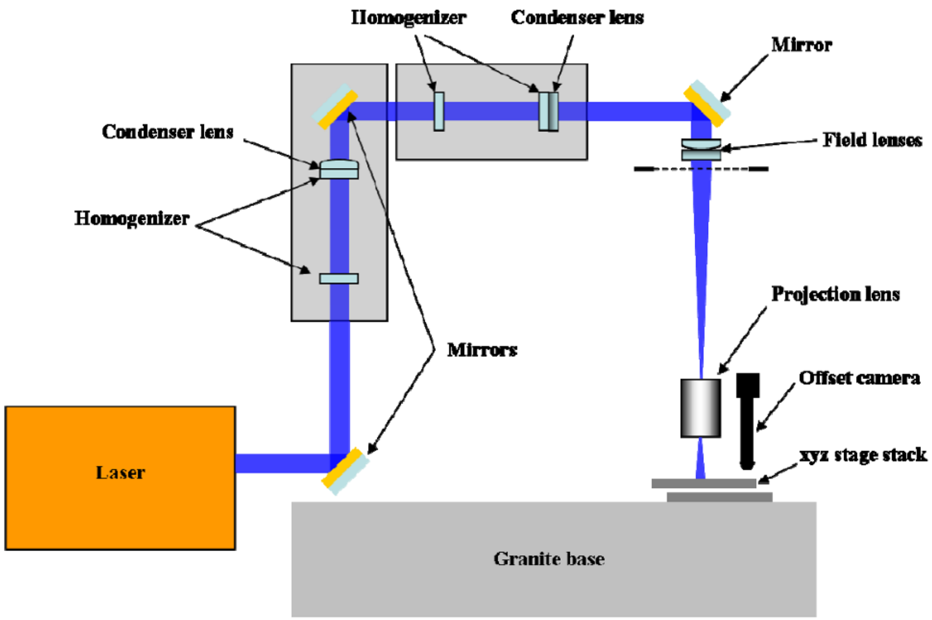
Mask projection system







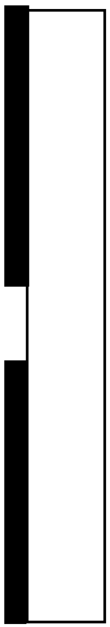
Exitech M8000 Micromachining System

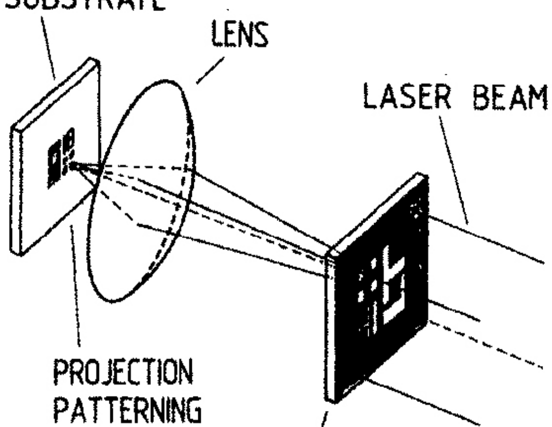


Travel	400 mm
Accuracy	±0.50 µm
Repeatability	±0.20 µm
Straightness	±0.40µm
Flatness	±0.40µm

CREALAS Smart Micromachining

Mask material





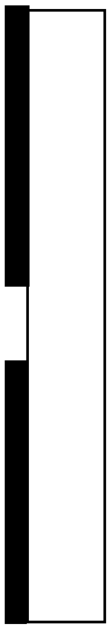
Industrially applied for 193 nm lithography:

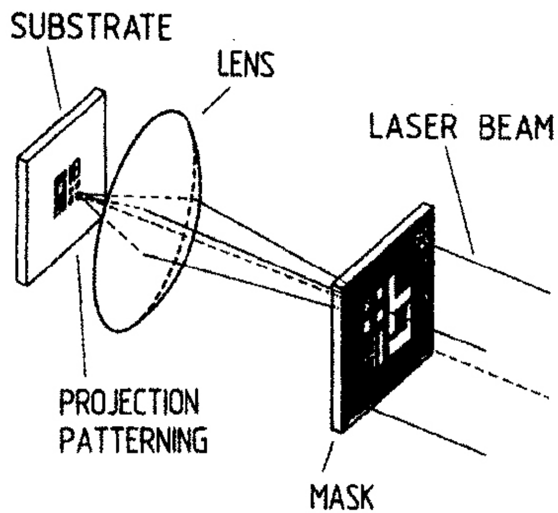
- 75 nm Cr layer on fused silica
- with AR Cr_2O_3

Materials for excimer laser ablation masks

?

Mask material





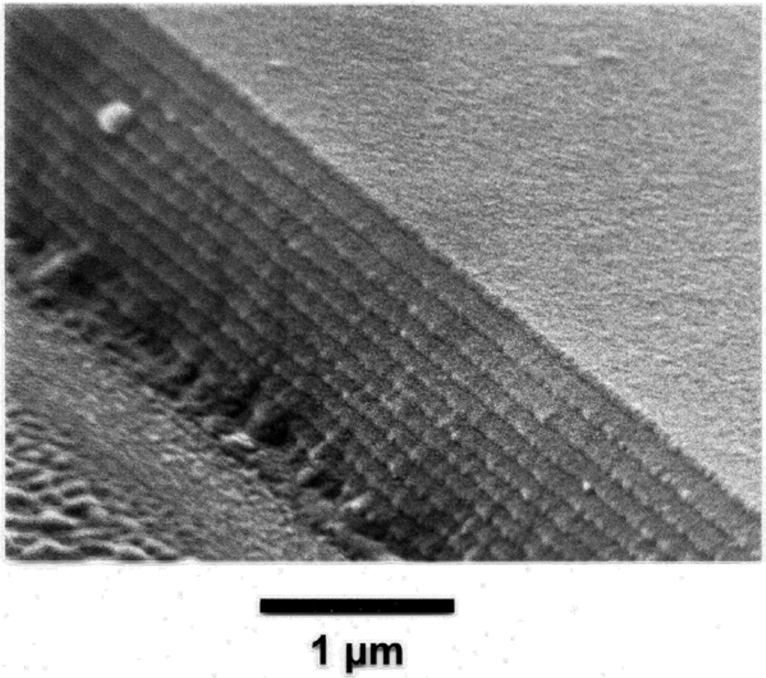
Industrially applied for 193 nm lithography:

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

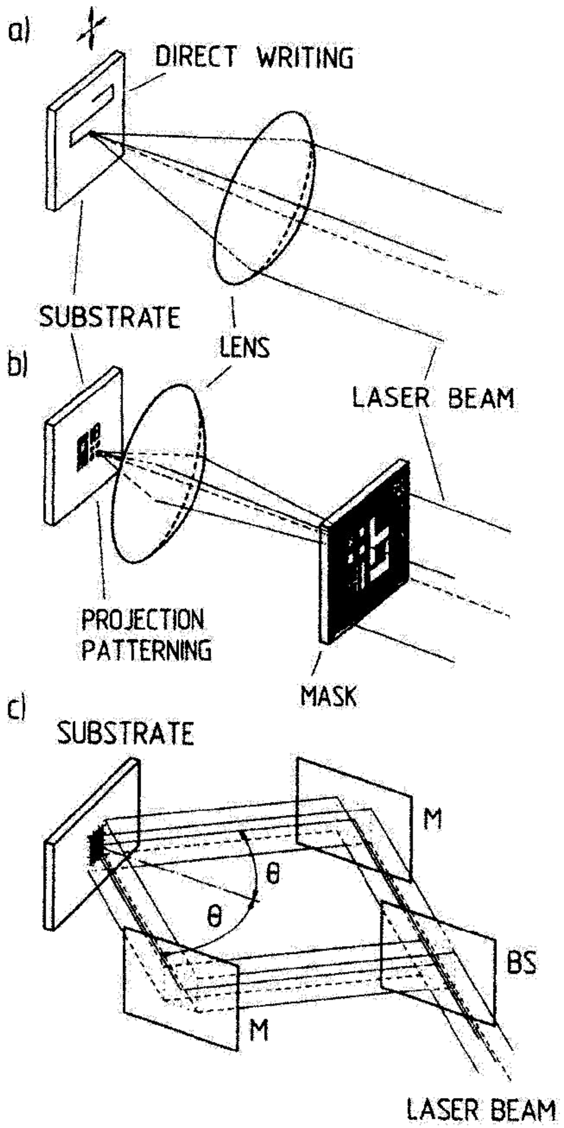
Materials for excimer laser ablation masks

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

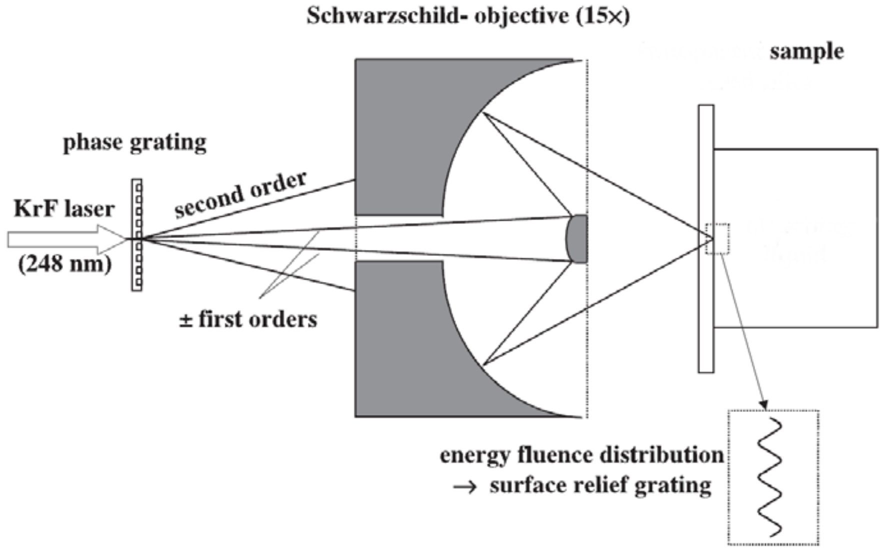


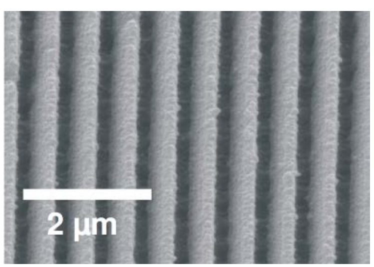
Method Based on Interference



Submicron Structures

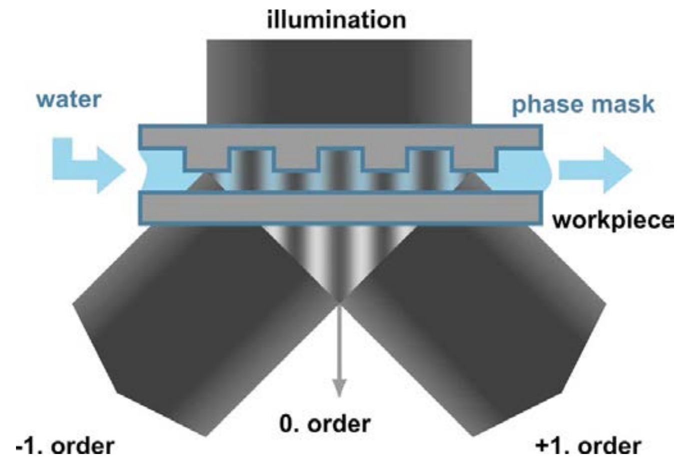
- Phase mask setup for submicron structures

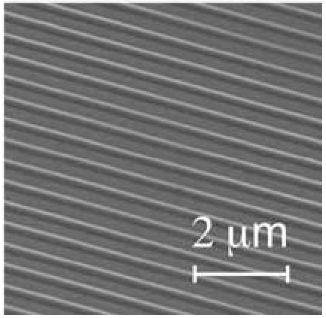




Experimental set-up for the generation of sub-micron gratings by laser-ablation

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





Principle of the proximity phase mask setup with water immersion

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