Thermo-optical effects

Oliver Puncken

Outline

- Overview on thermo-optical effects in lasers
  - Thermal lensing
  - Birefringence
  - Depolarization
- Aberrations and the PSL working point
- Attempts for optimization of the PSL laser crystals
  - Different doping concentrations
  - Segmented crystals
  - Intrinsic depolarization compensation

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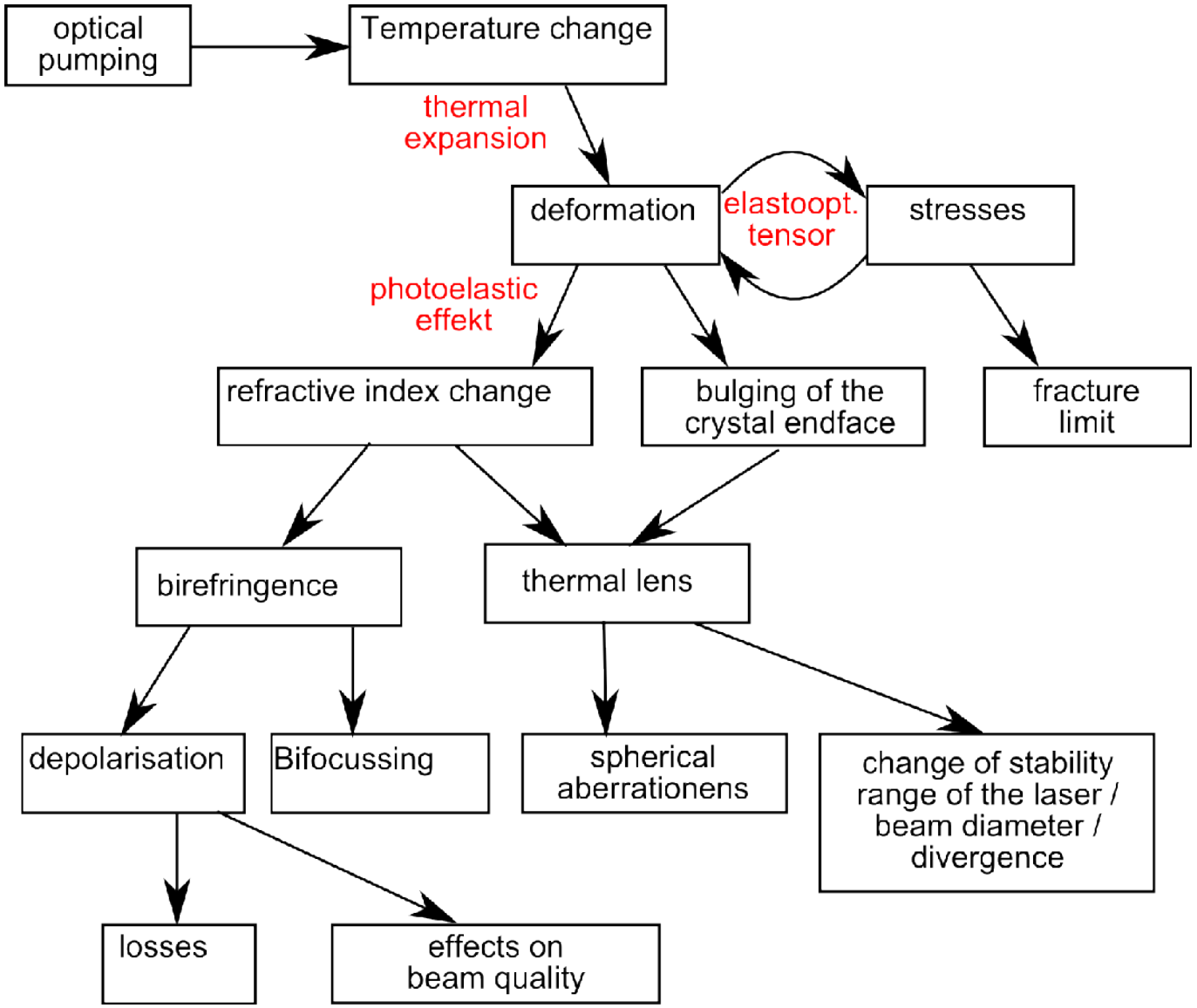
Thermo-optical effects



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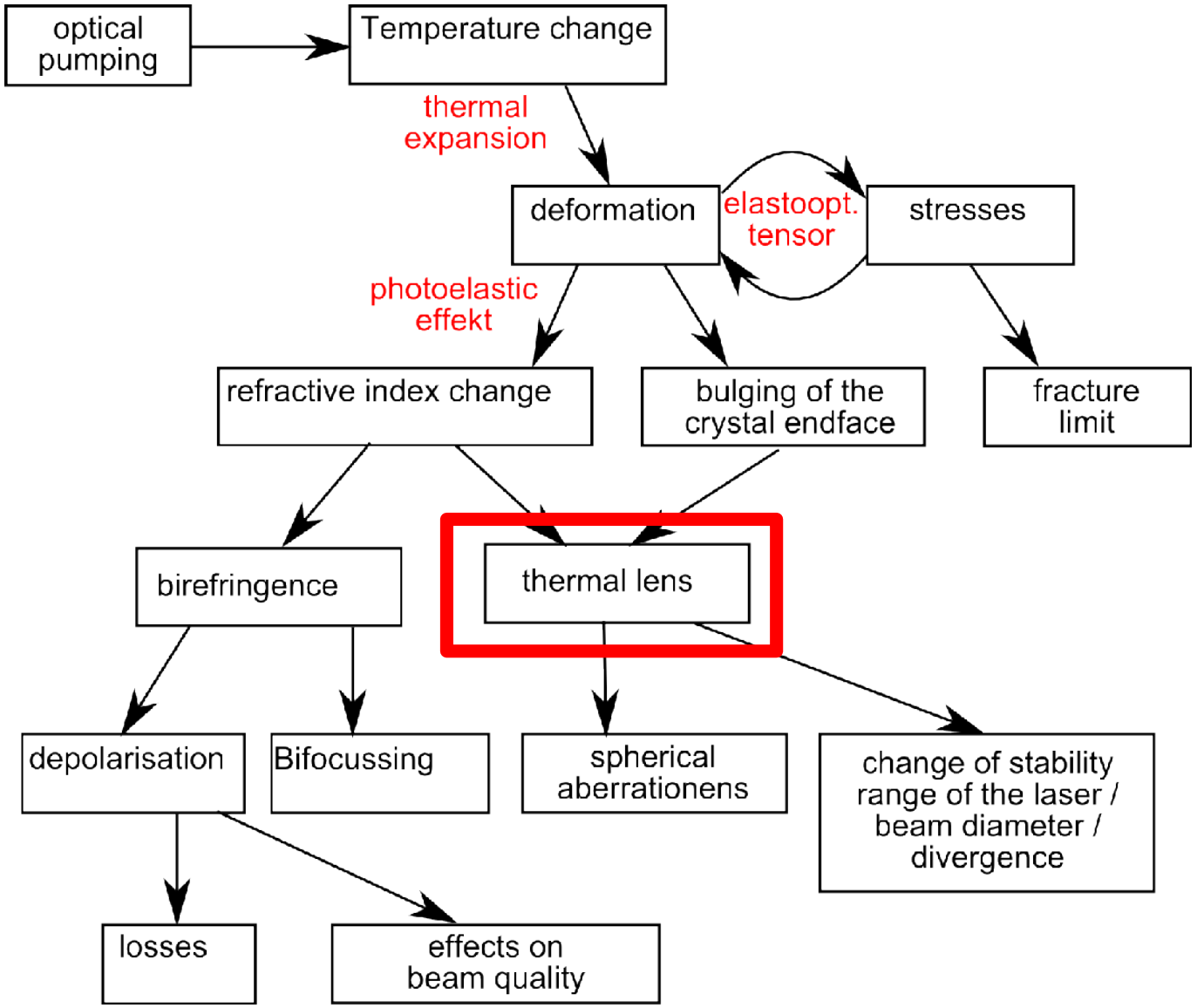
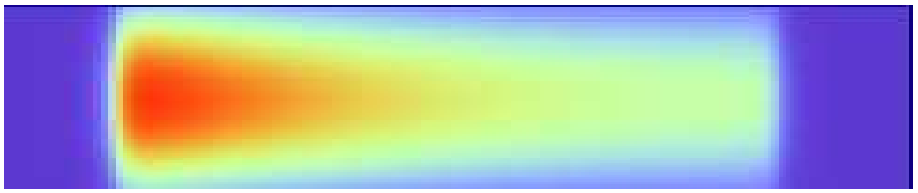


Thermal lensing

- Pump light is partly converted to heat
- Cooling of barrel → temperature gradient
- Thermal lensing in longitudinal pumped laser rods:
  - Time independent heat conduction equation:

    $\nabla^2 T(x,y,z) = -Q(x,y,z) / k$,

    where Q: thermal energy,
    k: conductivity



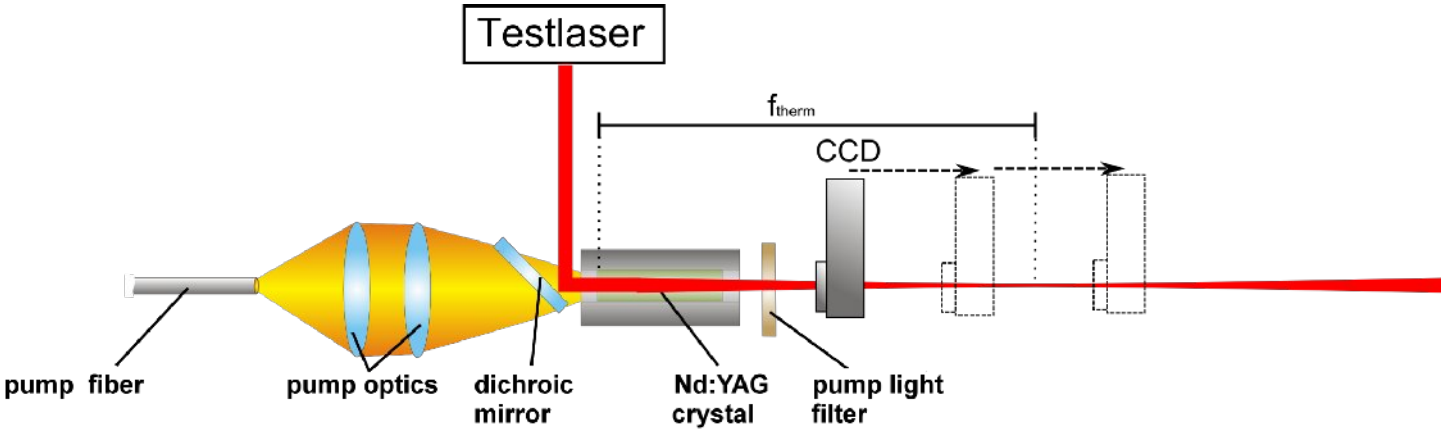
  - Refractive index change

$$n(r) = n_0 \cdot (1 - y r^2),$$

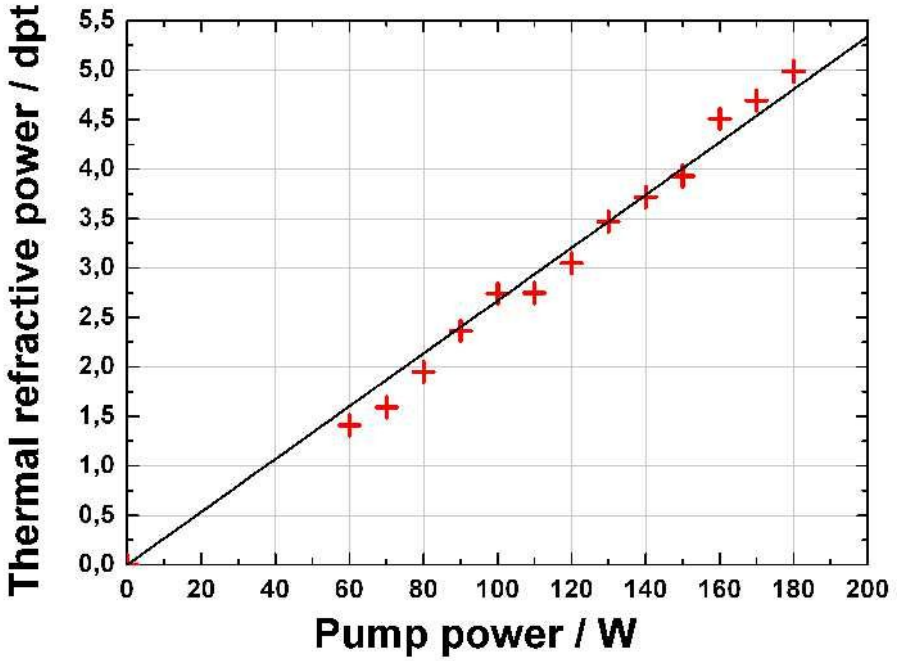
where $y = y$(pump power, **created heat**, heat conductivity, crystal length, dn/dT, ...)

- → thermal lens with refractive power, which rises linear with the pump power

Thermal lensing

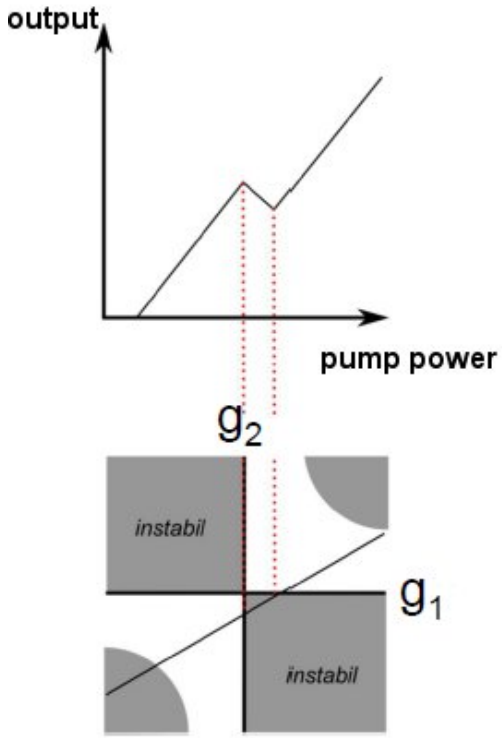


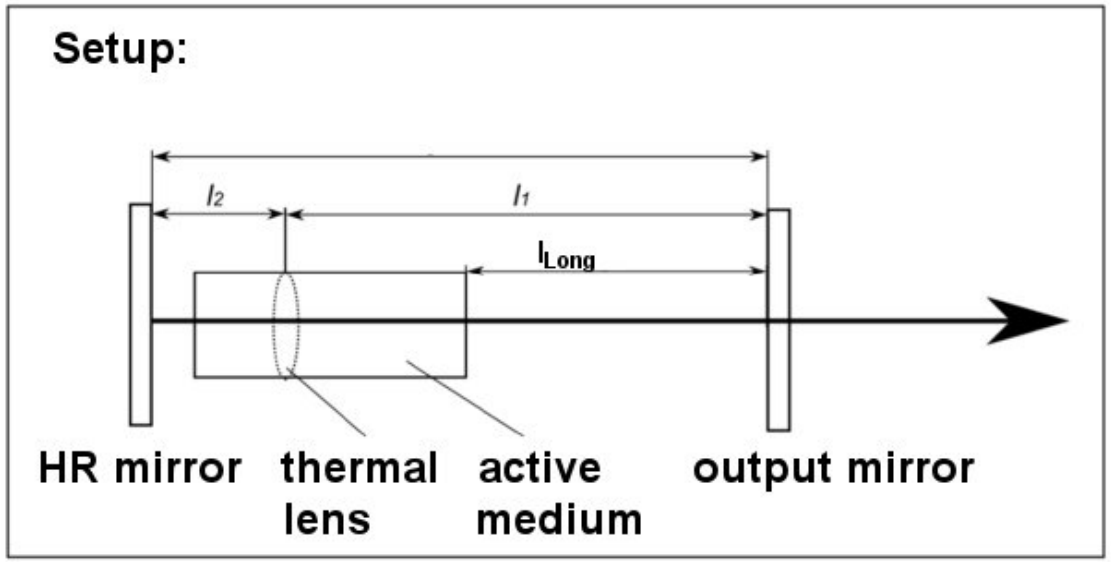
- Testbeam:
  - 980 nm DFB diode, fundamental mode
  - 650 µm beam radius
  - → thermal refractive power of 0.027 dpt/W.



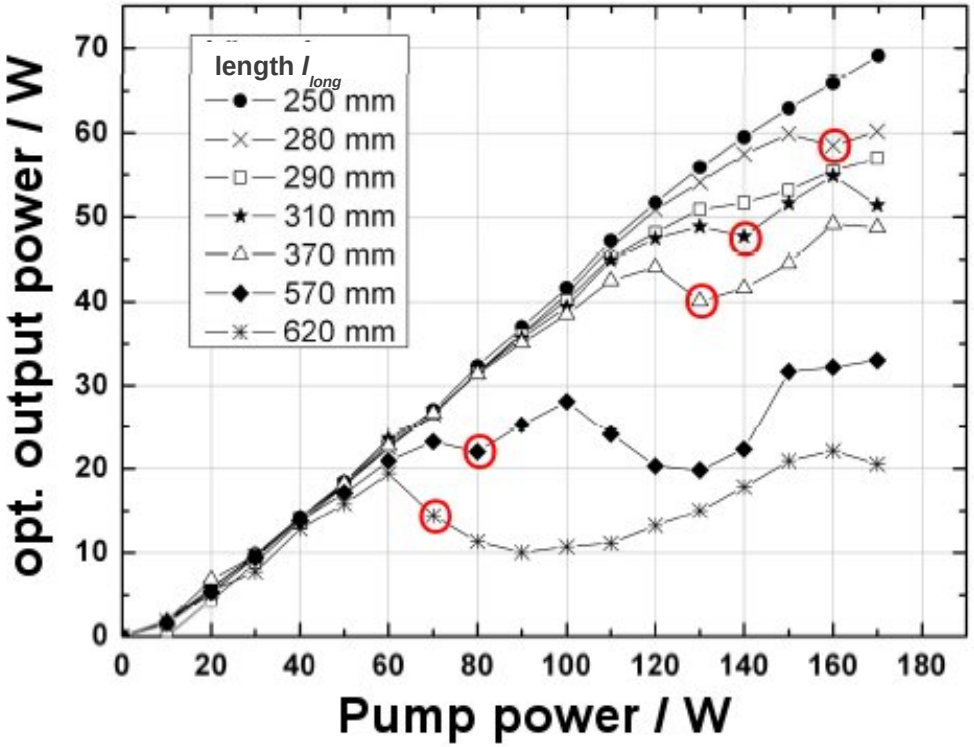
Thermal lensing

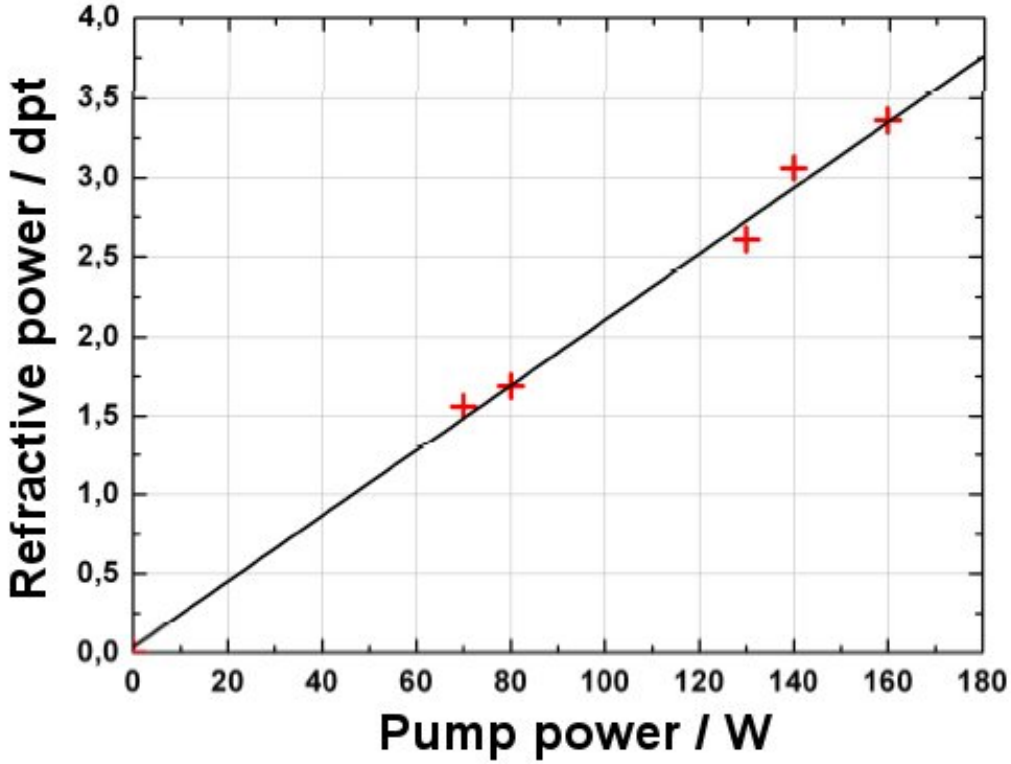
- Laser stability:
  - Increase pump power in asymmetric resonator until it becomes unstable
  - Thermal lens at this point: $D=1/(l_{long}+L/(2n))$





Thermal lensing



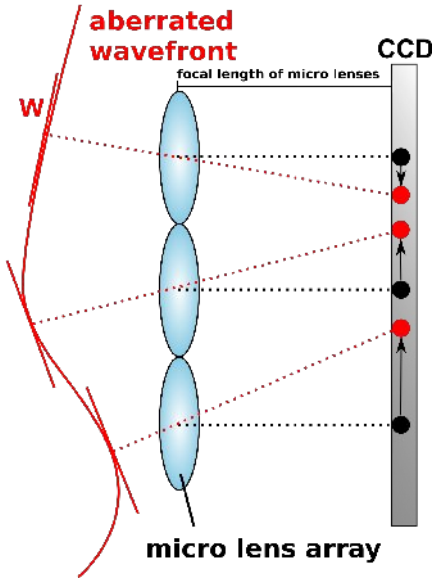


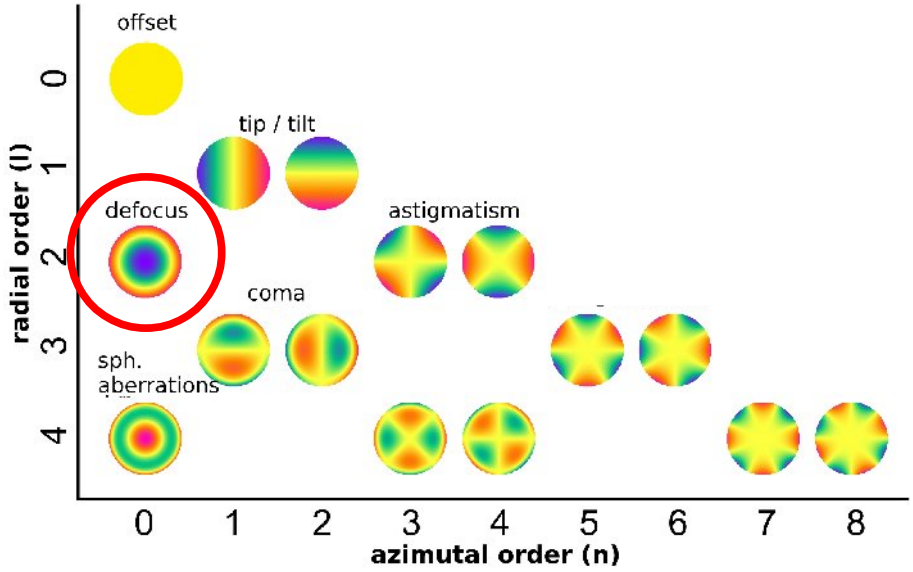
- Thermal refractive power: 0.021 dpt/W

Thermal lensing

- Wavefront sensor
  - Quite sensitive for fluctuations → big errors
  - Thermal refractive power from Zernike defocus coefficient c_{20}:

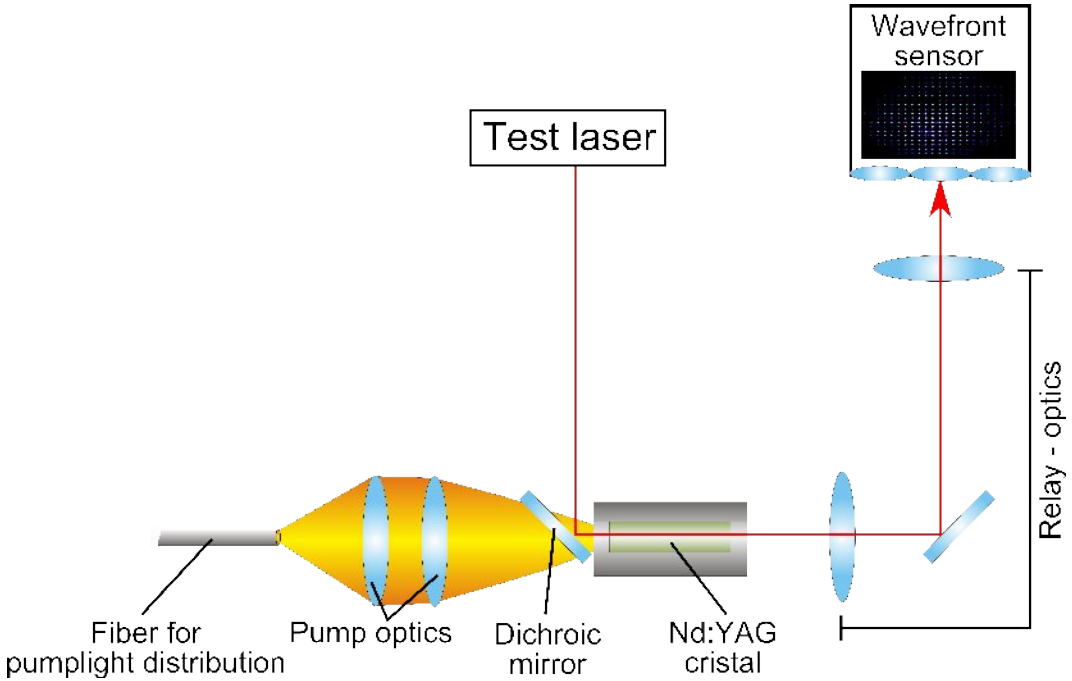
$$D = 4 \cdot c_{20} \cdot \lambda / r_0^2$$

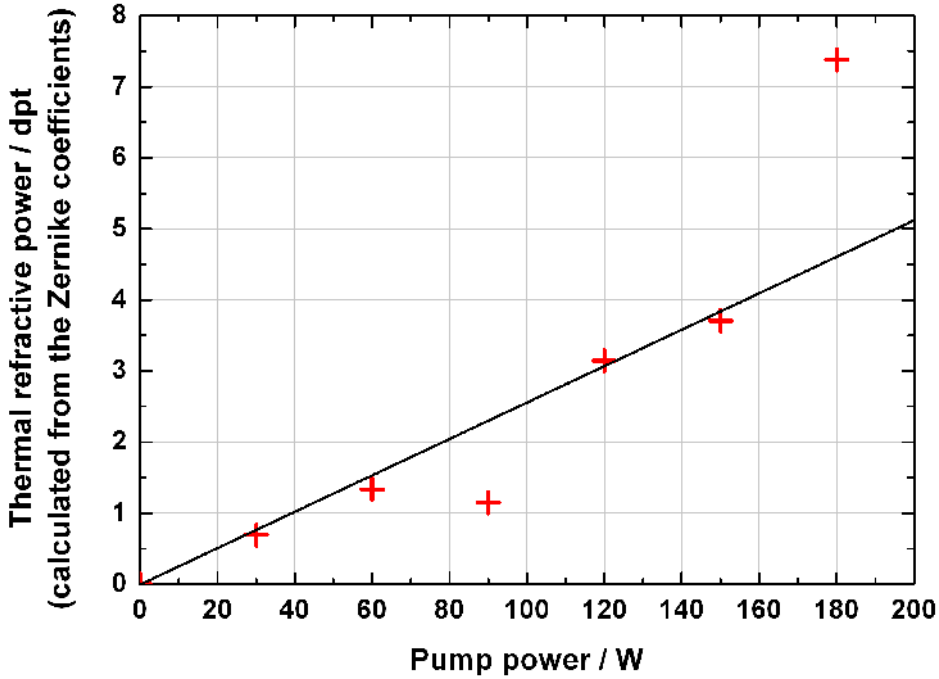




Thermal lensing

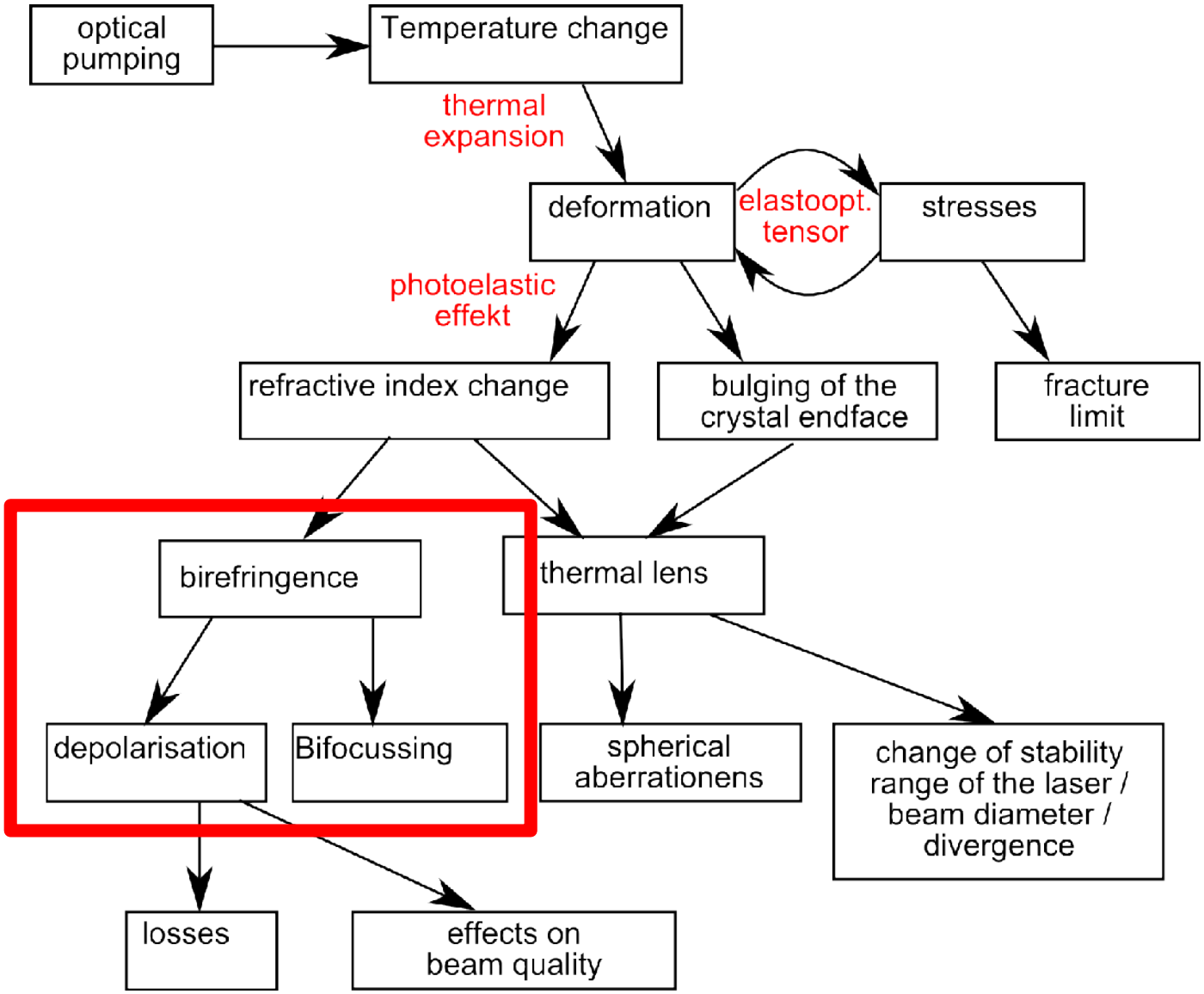
- Wavefront sensor





Refractive power: about 0.025 dpt/W

Thermo-optical effects



Birefringence and bifocussing

Heating power

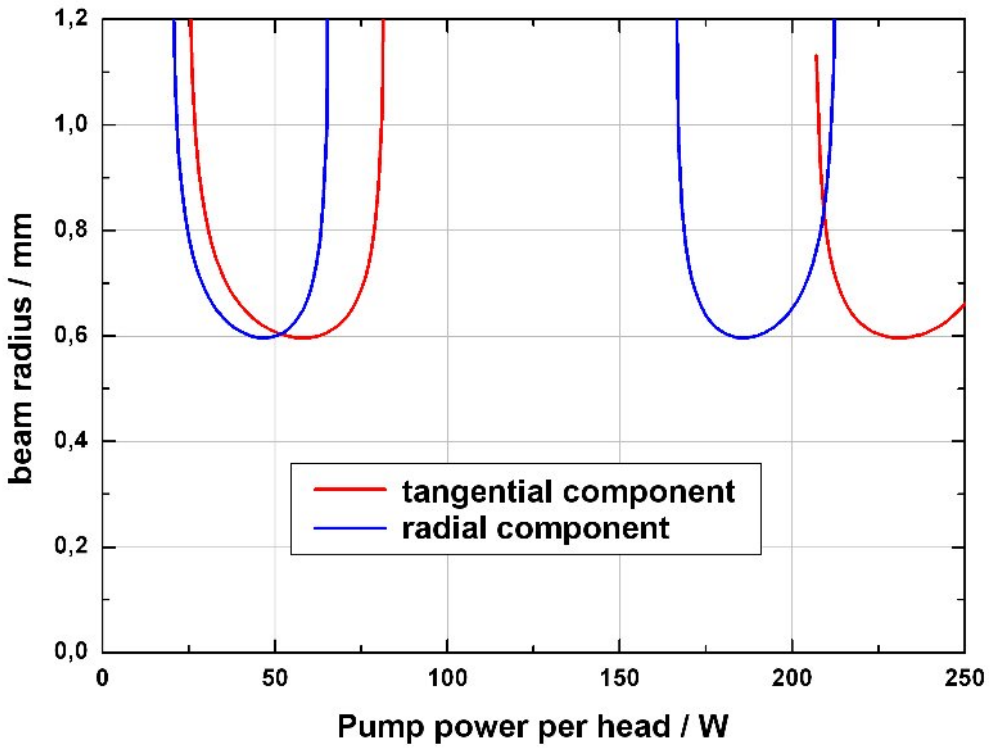
⇩

Different refractive indices for radial and tangential polarization components of the laserlight (**birefringence**)

⇩

Bifocussing

Effect on the mode radius of an asymmetric two head resonator



Birefringence and bifocussing

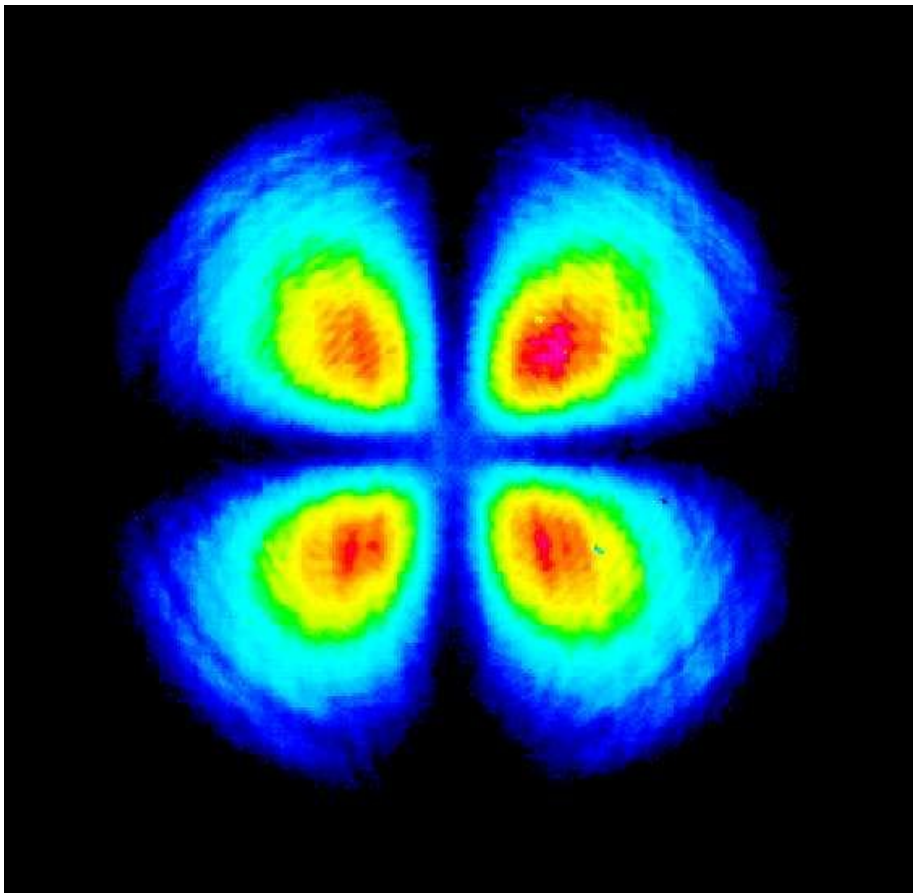
Heating power

⇩

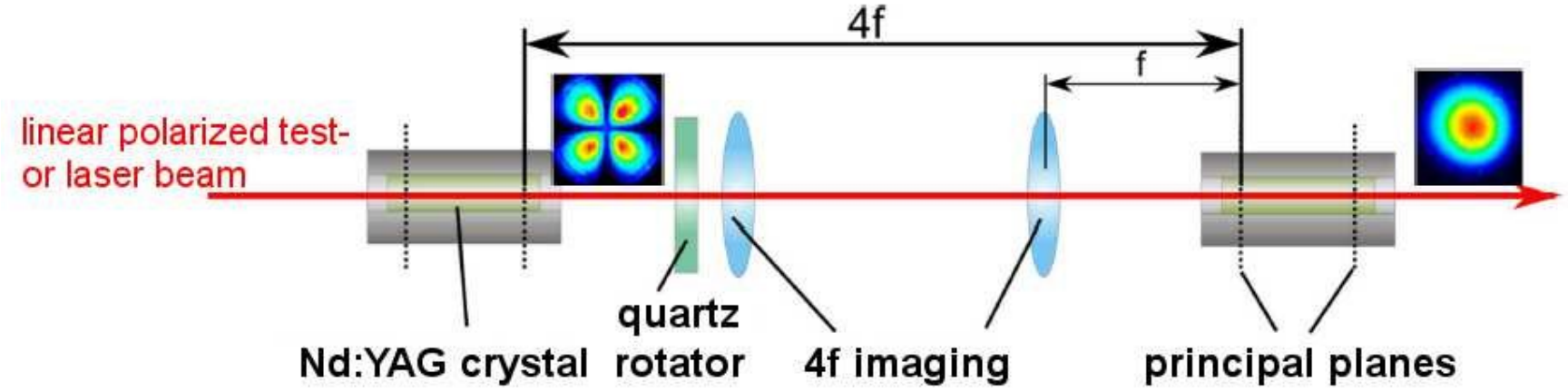
Different refractive indices for radial and tangential polarization components of the laserlight (**birefringence**)

⇩

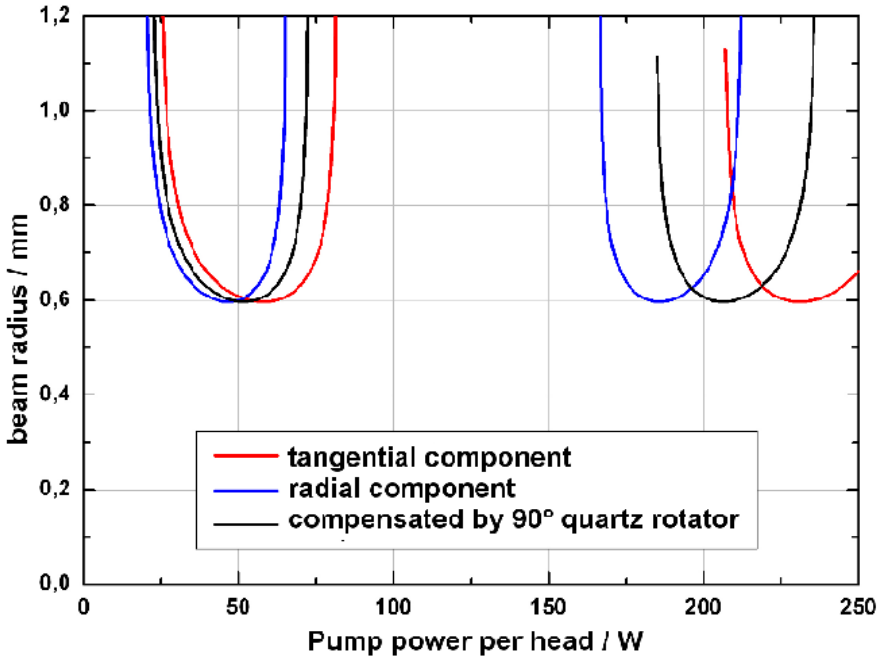
Phase shift for pol. components depends on the radial position → **Depolarization**



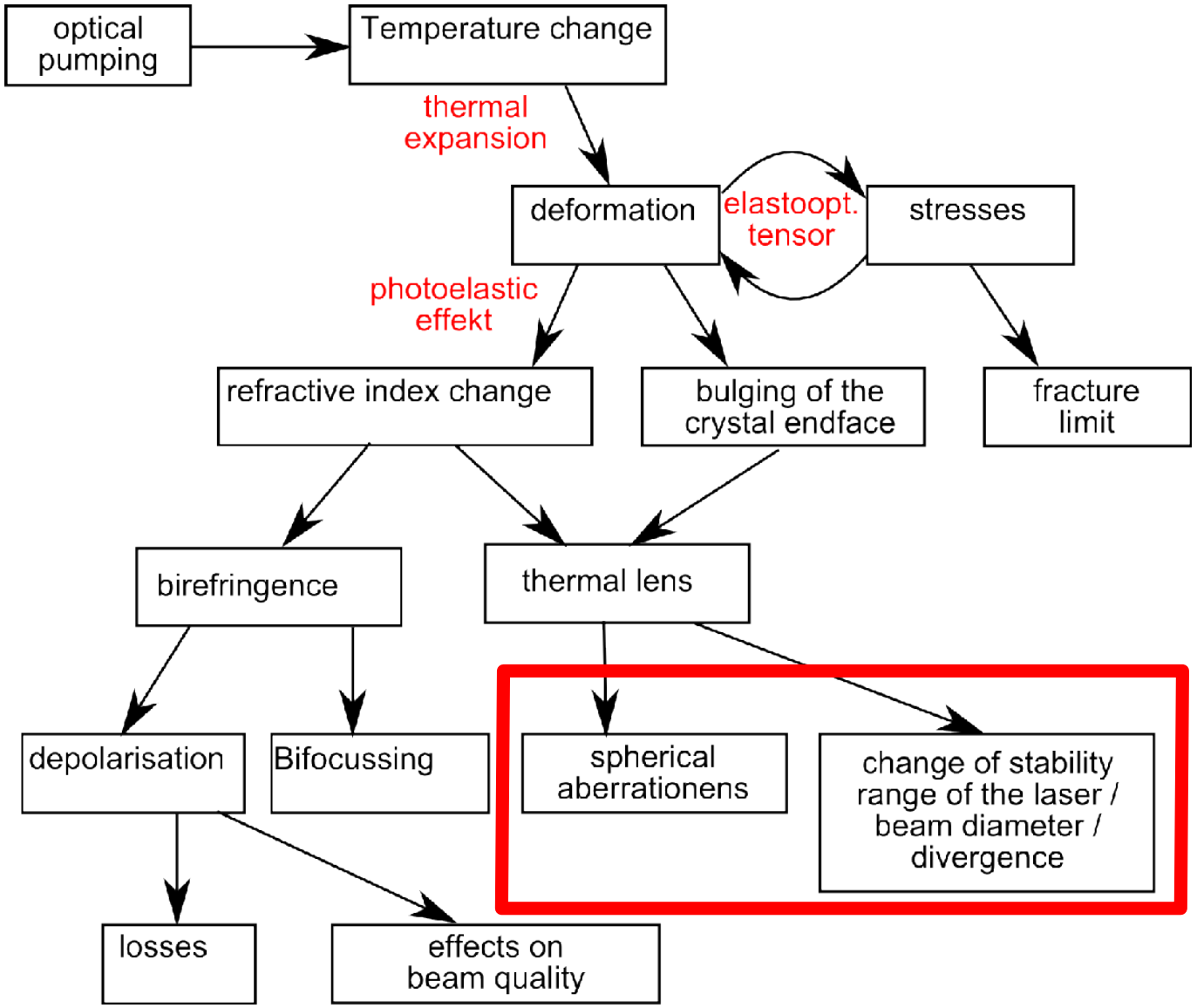
Birefringence compensation



- Principle:
  - Exchange polarization components by 90° rotation between crystal passes
  - Imaging of the thermal lens' principal planes results in compensation of phase shifts



Thermo-optical effects



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  - Thermal lensing
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- **Aberrations and the PSL working point**
- Attempts for optimization of the laser crystals
  - Different doping concentrations
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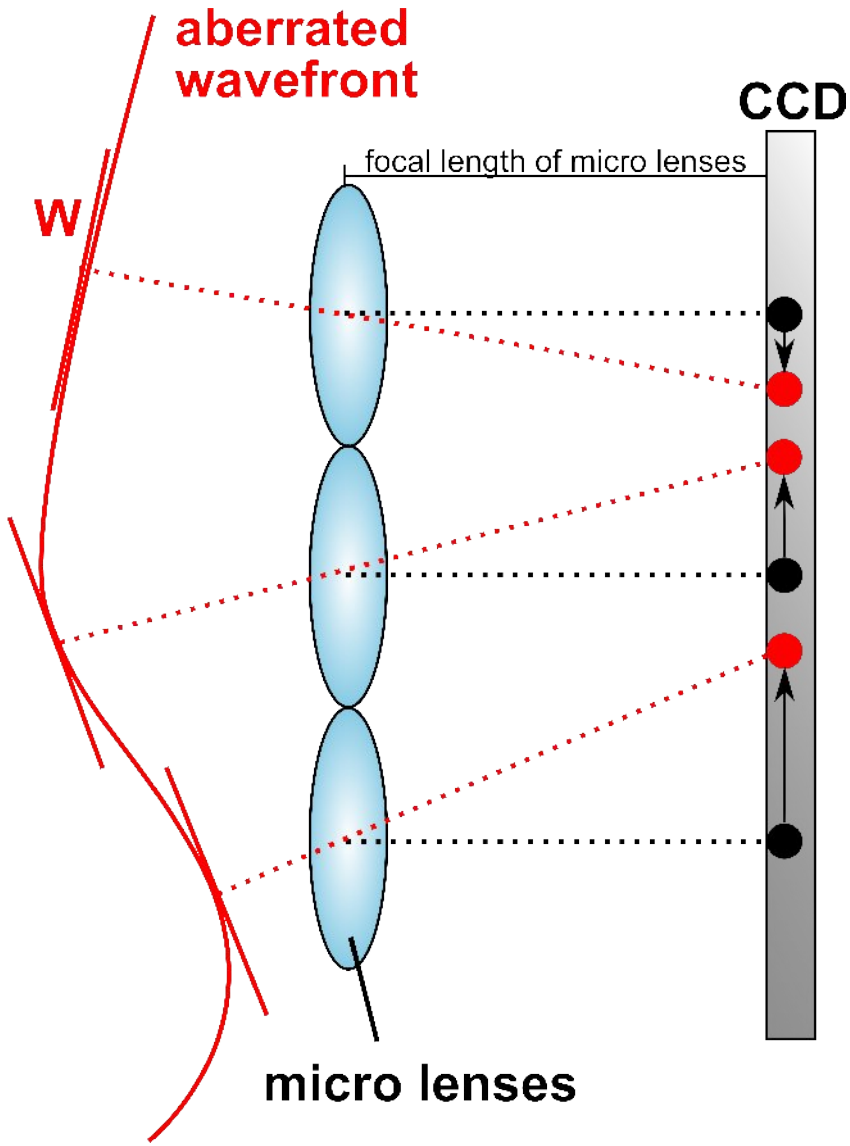
Aberrations

- Thermal lens as a result of absorption of pump- (and laser-) light
- For homogenious pumplight distribution: radially parabolic temperature profile
- For radially inhomogenious pumplight distribution: radially parabolic temperature profile might be roughly true, but (mainly spherical) aberrations appear

Measurement of aberrations

- Shack Hartmann sensor
  - The lateral position of a (micro-) lens spot depends on the mean slope of the incoming wavefront
  - The mean slope of the wavefront can be calculated from the spot-displacement



Zernike Polynomials

- The optical path difference of a wavefront *W* can be developed as a sum of polynomials and their coefficients
- Zernike polynomials are common, because each polynom correspond to a kind of aberration

$$W(\rho,\theta) = \lambda \cdot [c_{00} + \sum_{n=1}^{\infty} \sum_{l=-n}^{n} c_{nl} Z^{l}_{n}]$$

Azimutal order

$$Z^{l}_{n} = R^{m}_{n}(\rho) \cdot \cos(m \cdot \theta), \text{ if } l > 0$$

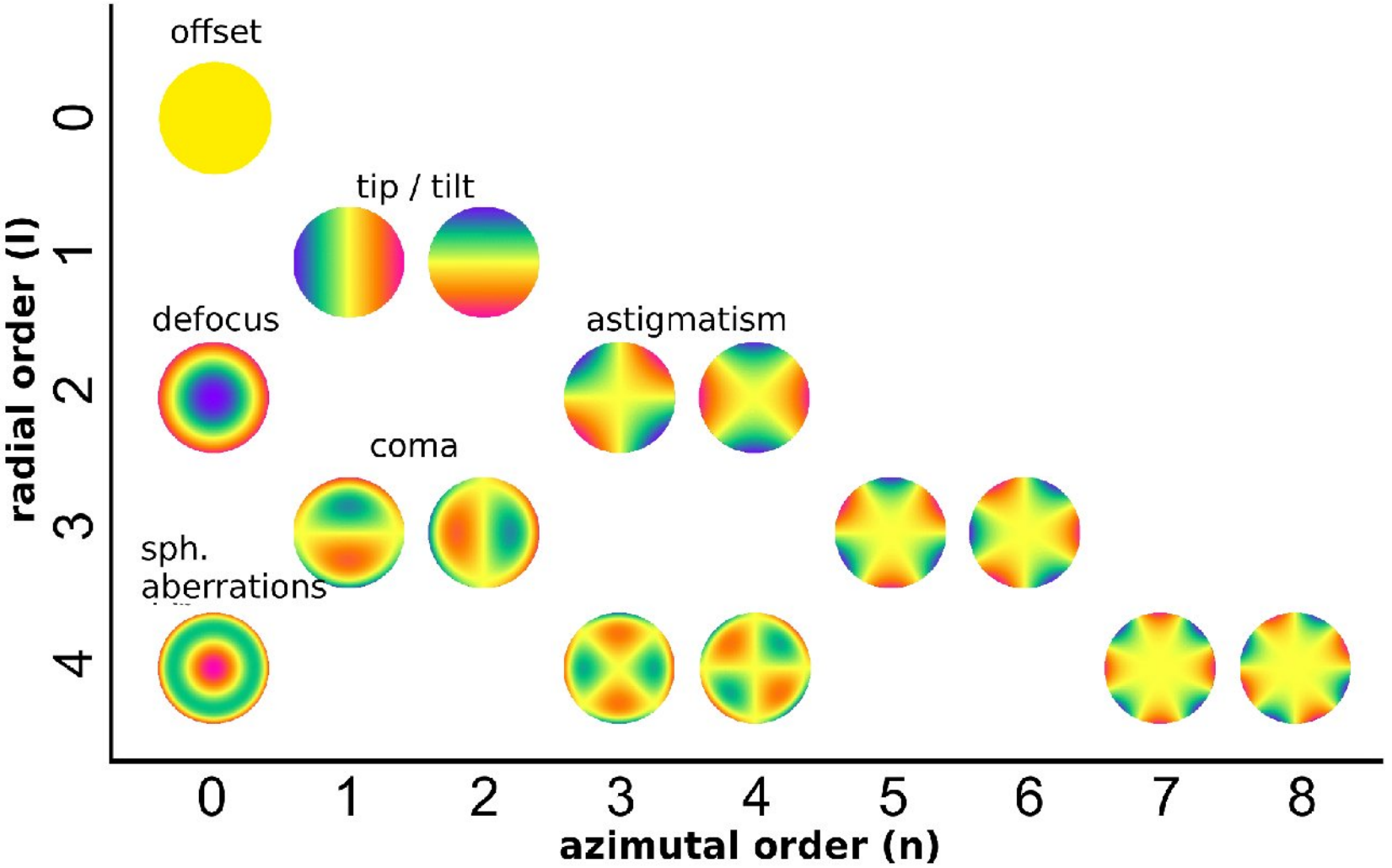
$$Z^{l}_{n} = R^{m}_{n}(\rho) \cdot \sin(m \cdot \theta), \text{ if } l < 0$$

Radial order

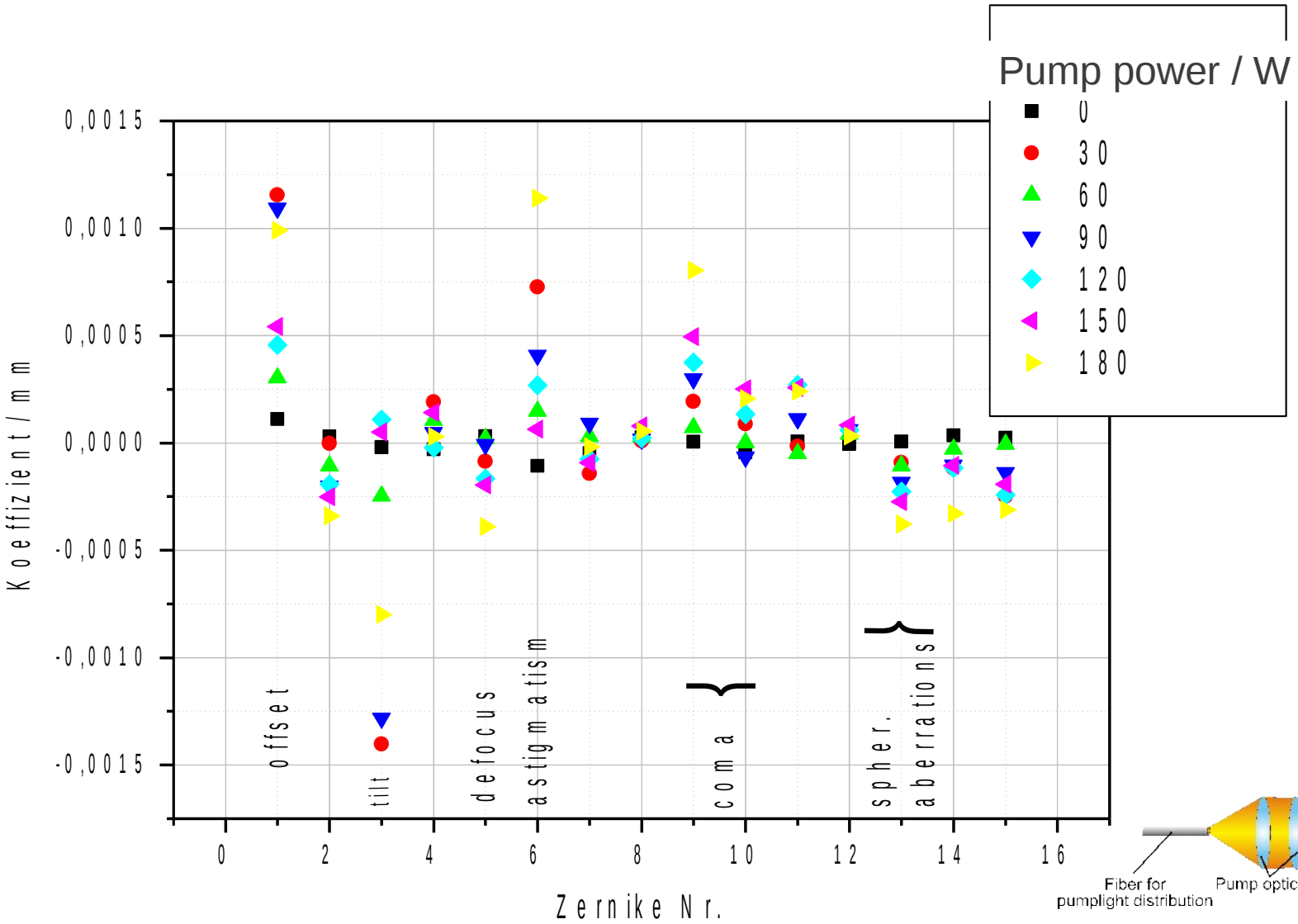
Radial polynomial

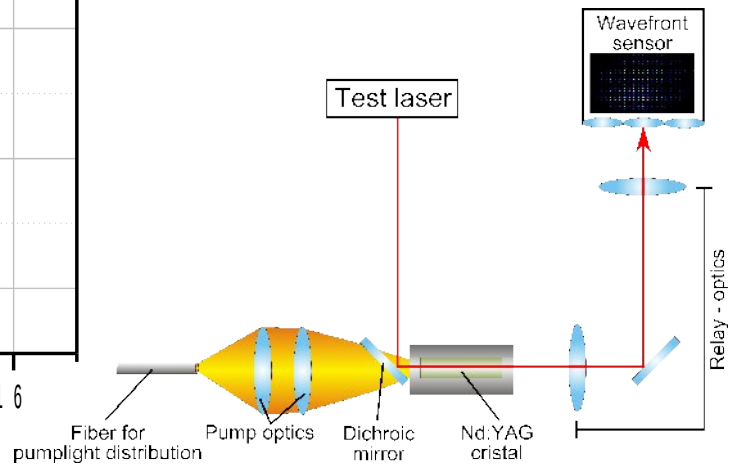
angular function

Zernike Polynomials

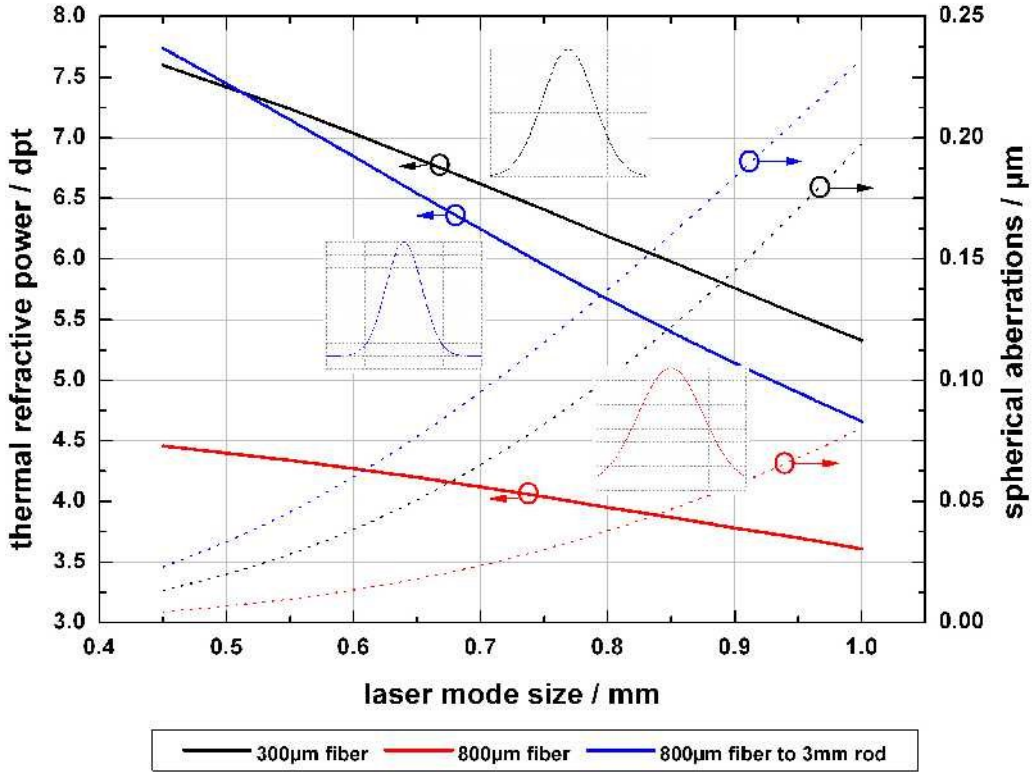


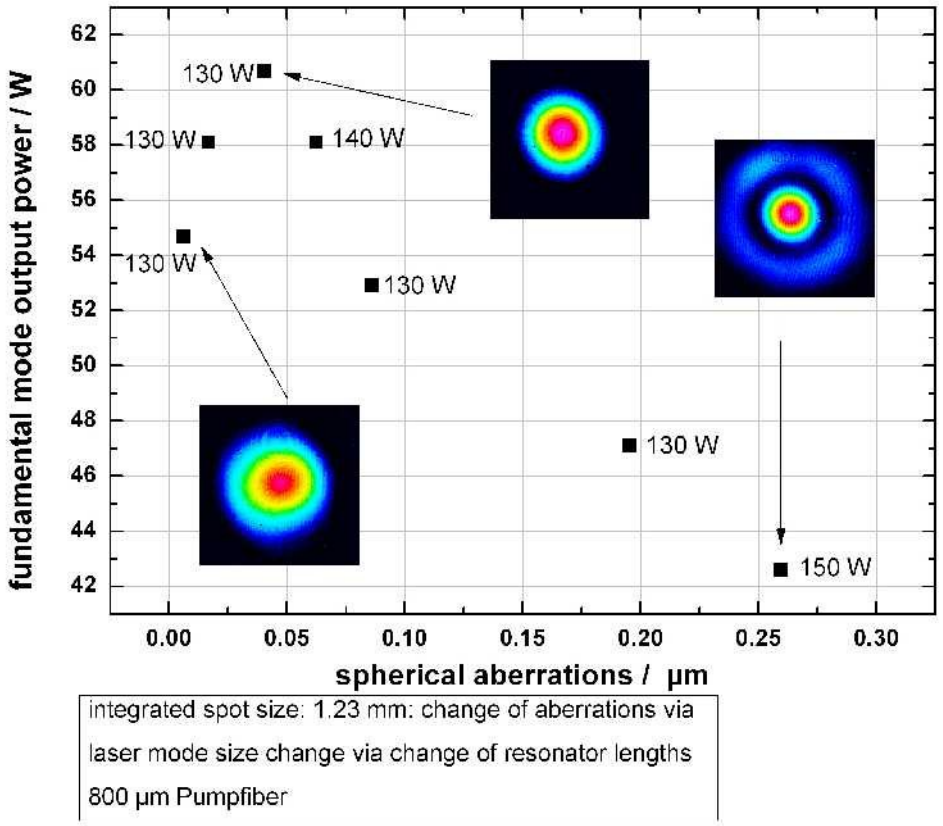
Test setup – Results for LIGO xtal





Experimental investigations



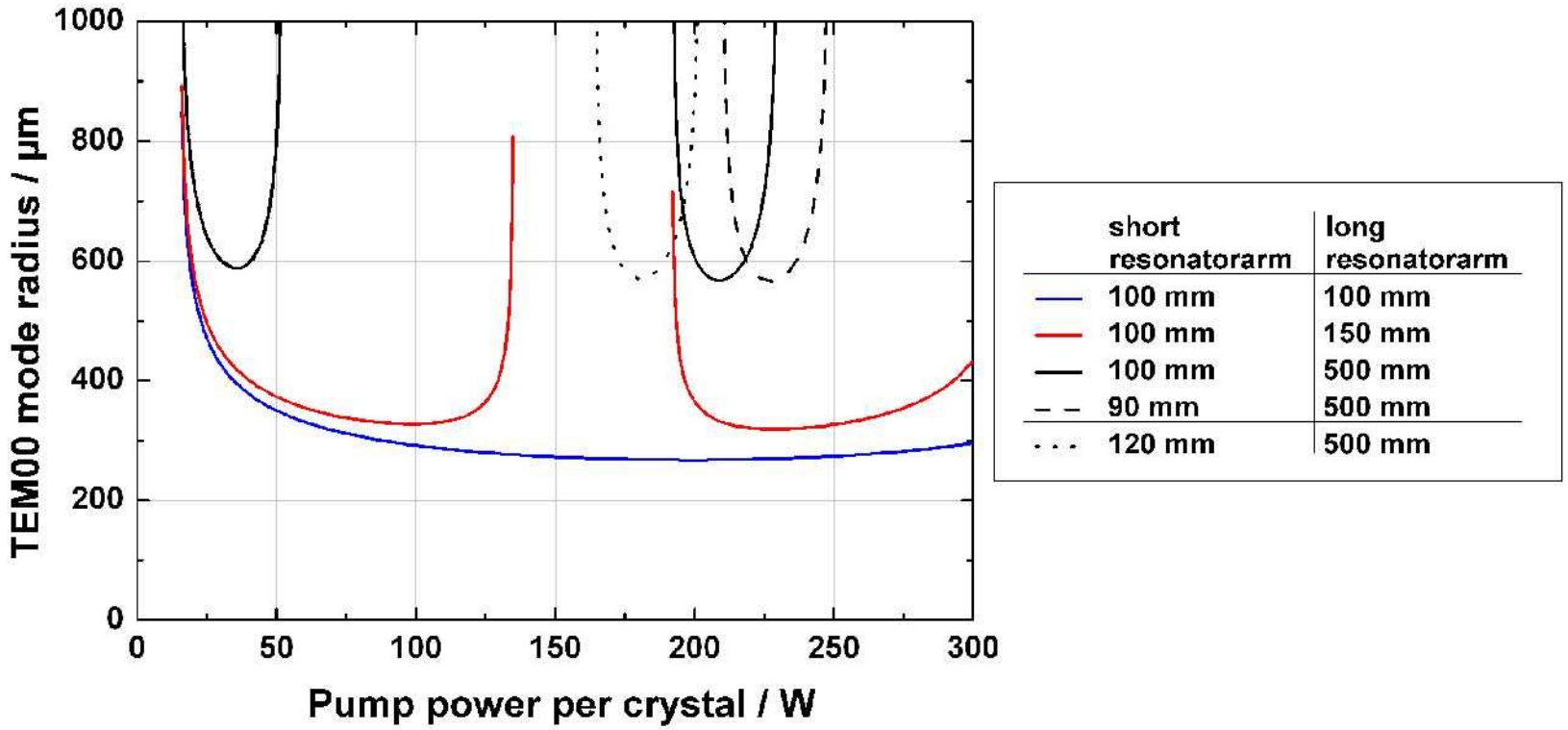


The smaller the laser mode size, the higher the thermal refractive power (defocus), but the lower the spherical aberrations

Influence of spherical aberrations on beam profile

Effects on the PSL working point

- Asymmetric resonator splits the stability range into two parts with respect to the pump power

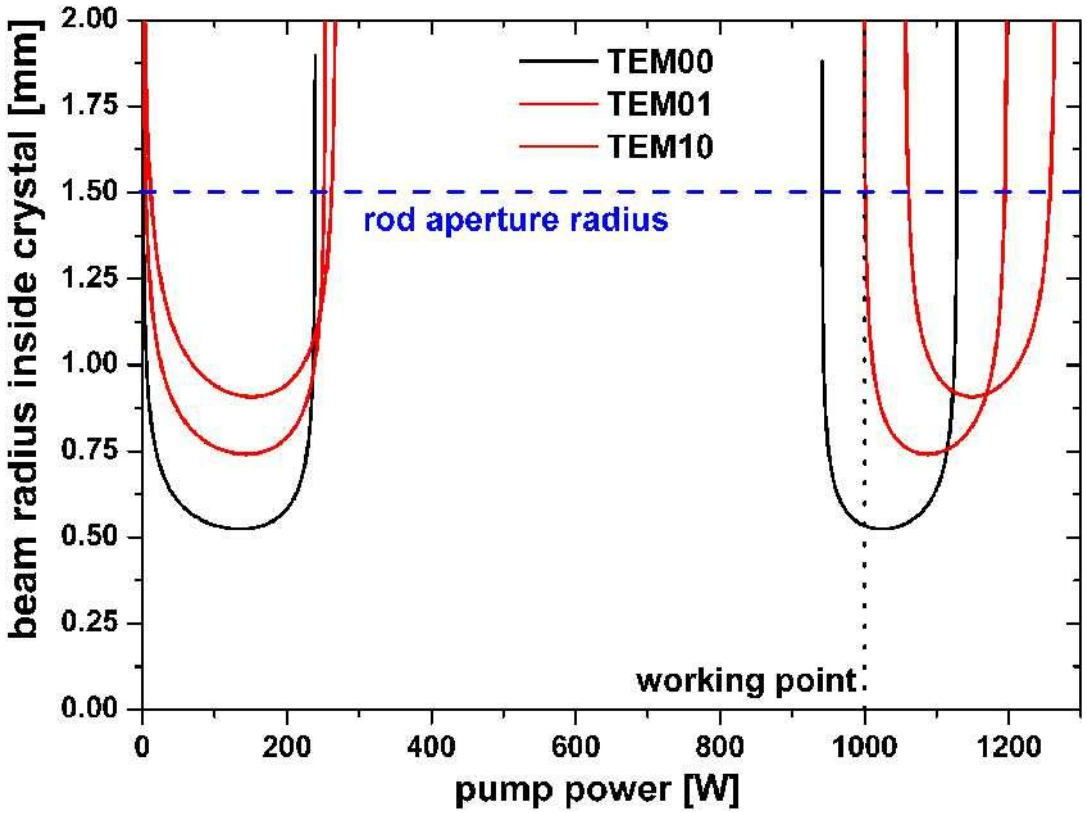


Effects on the PSL working point

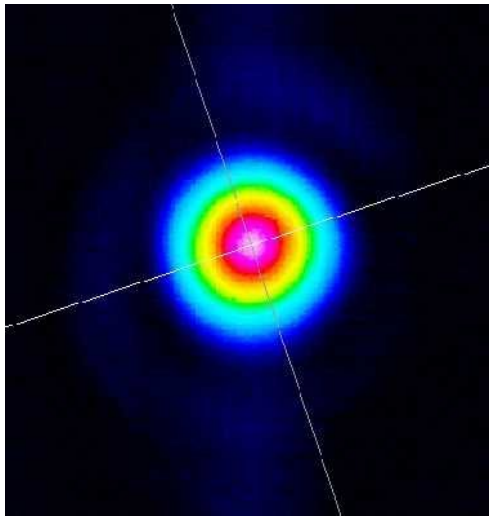
- Asymmetric resonator splits the stability range into two parts with respect to the pump power
- Spherical aberration are used as control mechanism for TEM_{00} working point:

  Higher order modes experience a lower effective thermal lens!

Effects on the PSL working point

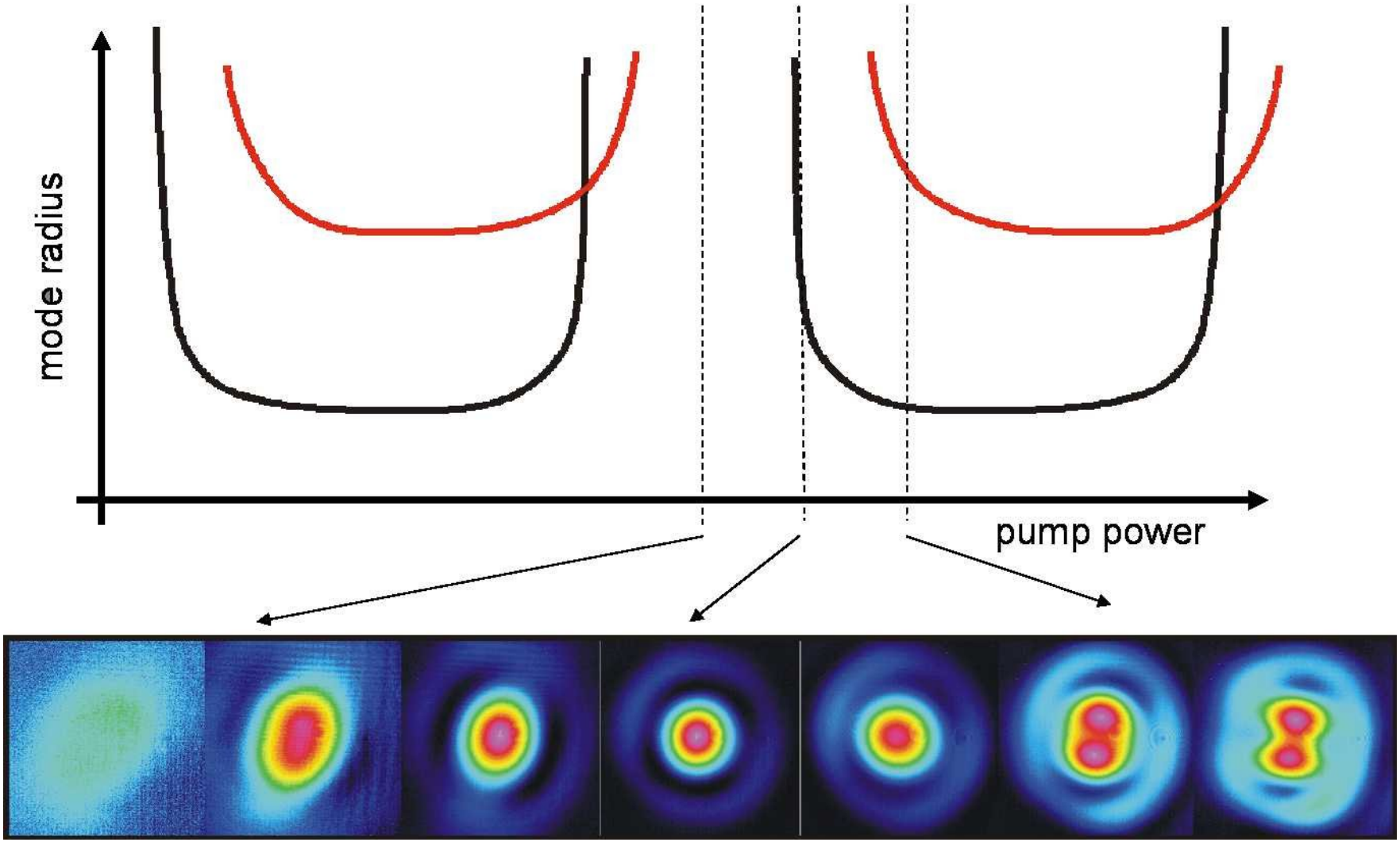


- Laser mode radius in first crystal
- Mode radius = stability criterium
- Higher order modes → larger radius
- Aberrations of the thermal lens → HOM shifted towards higher pump powers
- Values derived by an ABCD calculation of the actual resonator including the thermal lens



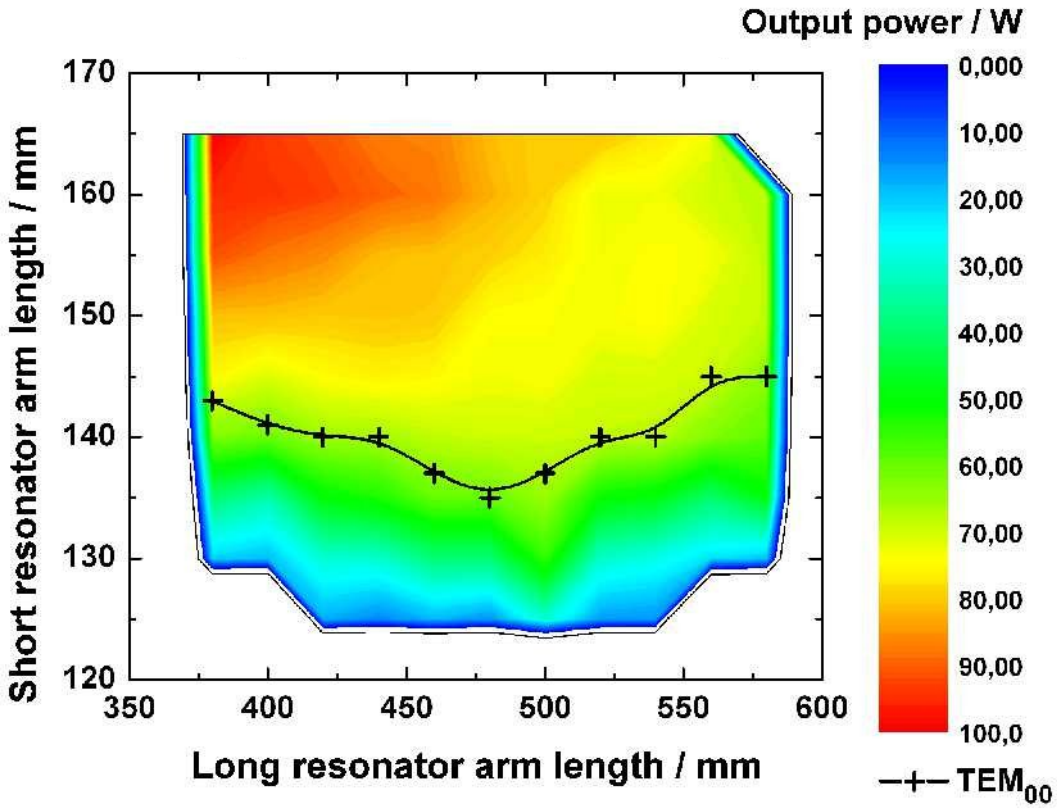
- Output beam profile of the free running laser oscillator at an output power of 176 W

Effects on the PSL working point



Experimental experiences
(2-head resonator)

- Birefringence compensated two head resonator
- 0.1 at.% doped crystals
- 200W pump power per crystal
- Homogenizer, 2mm diameter

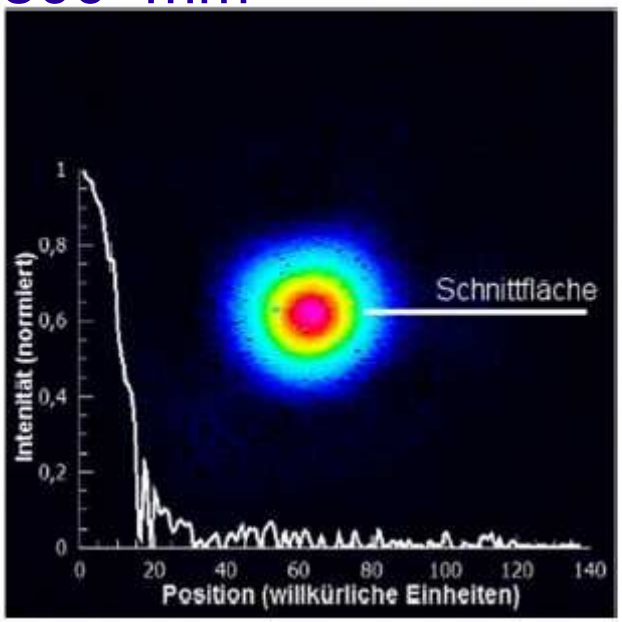


Experimental experiences
(2-head resonator)

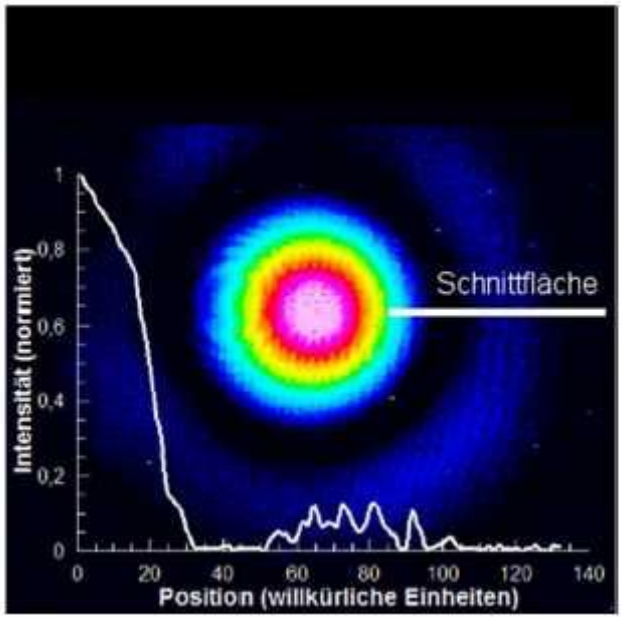
- 200W pump power per crystal
- Length of the short resonator arm: 130 mm

Length of the long resonator arm:

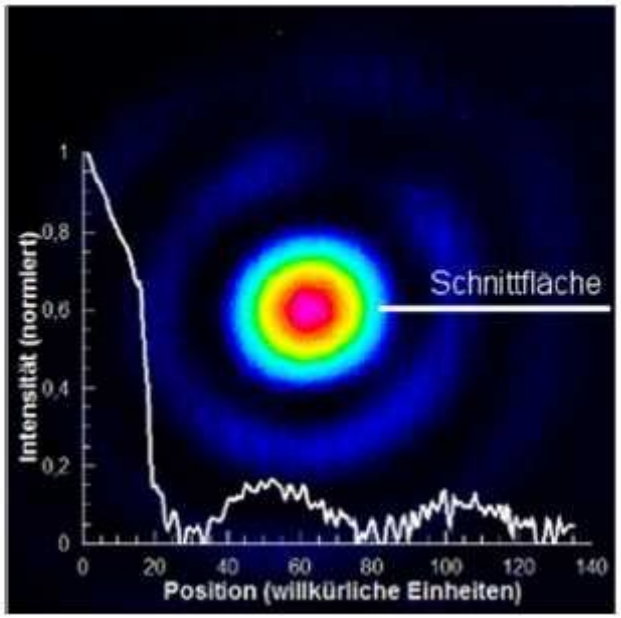
500 mm



550 mm



600 mm



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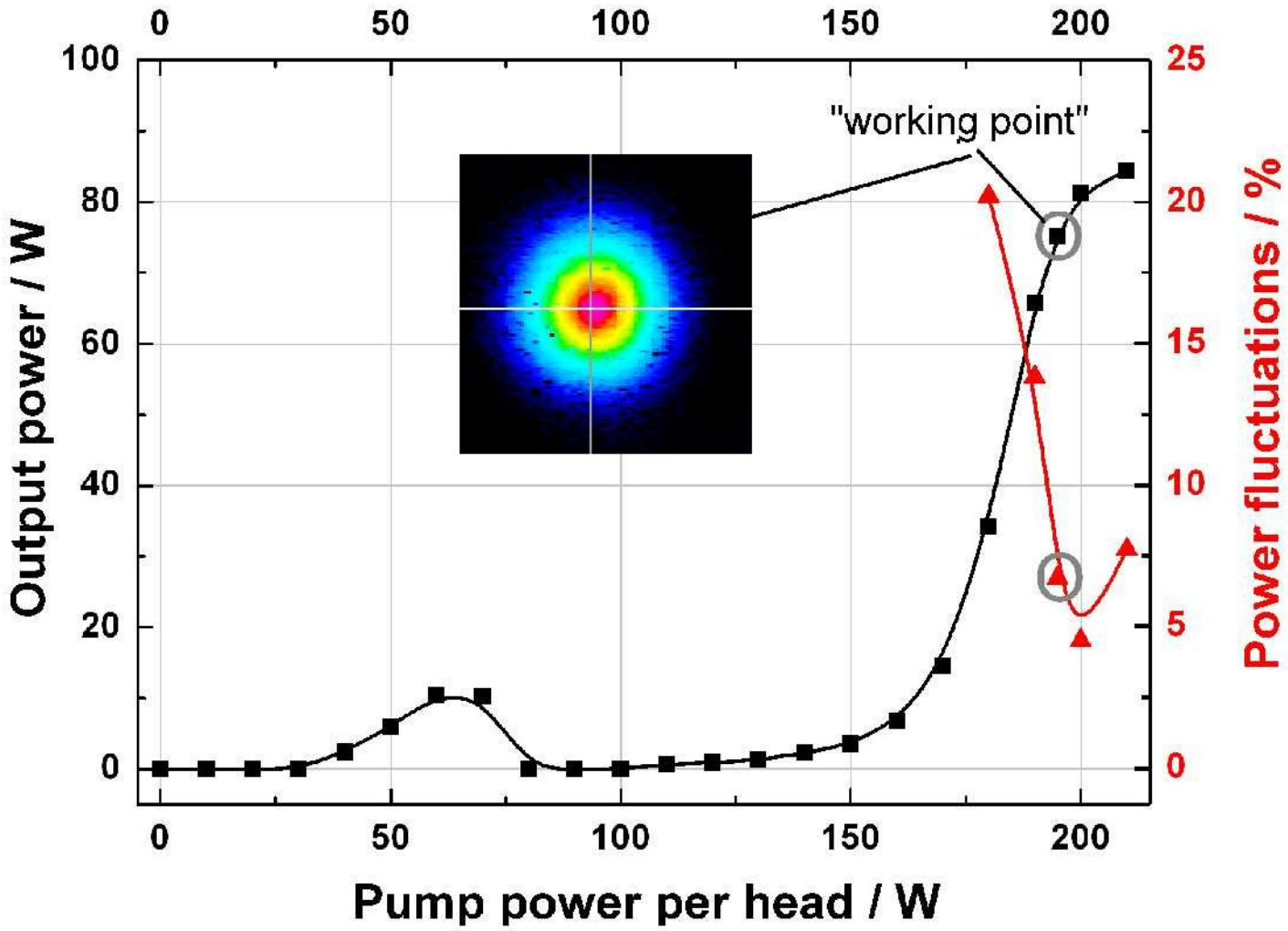
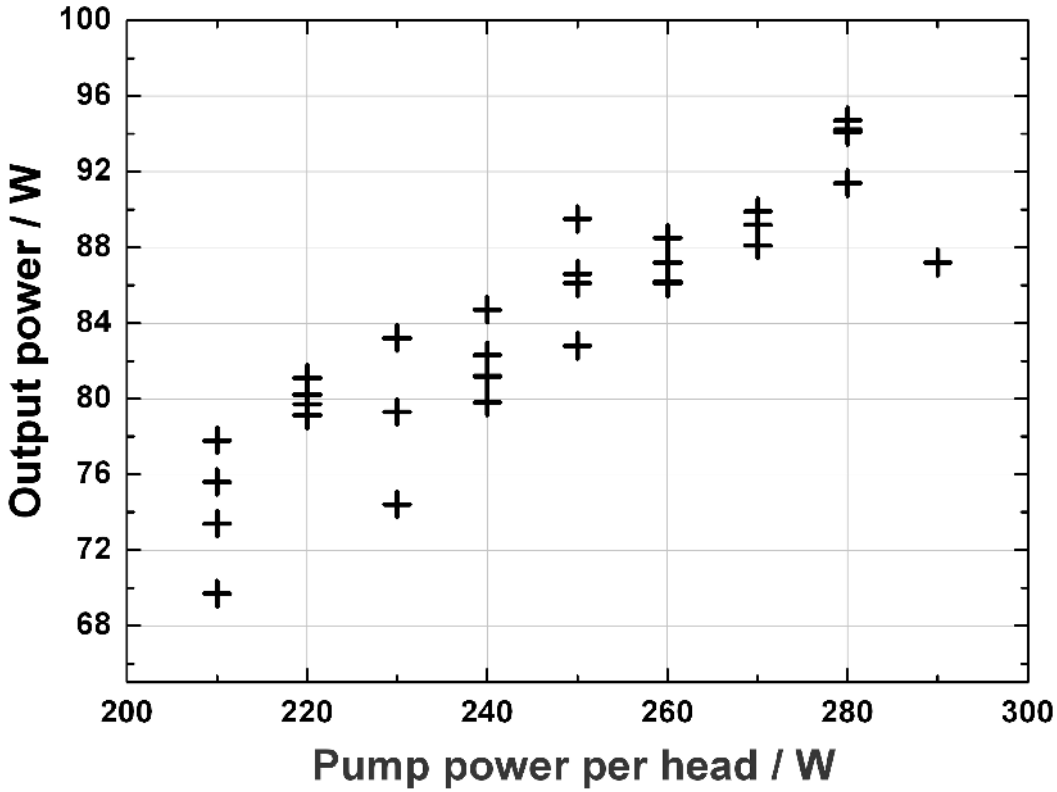


Power scaling
(2-head resonator)

- In general:
  More pump power → more output power
- Adapt resonator to get TEM_{00}-operation
- Limits:
  - pump power
  - mechanics



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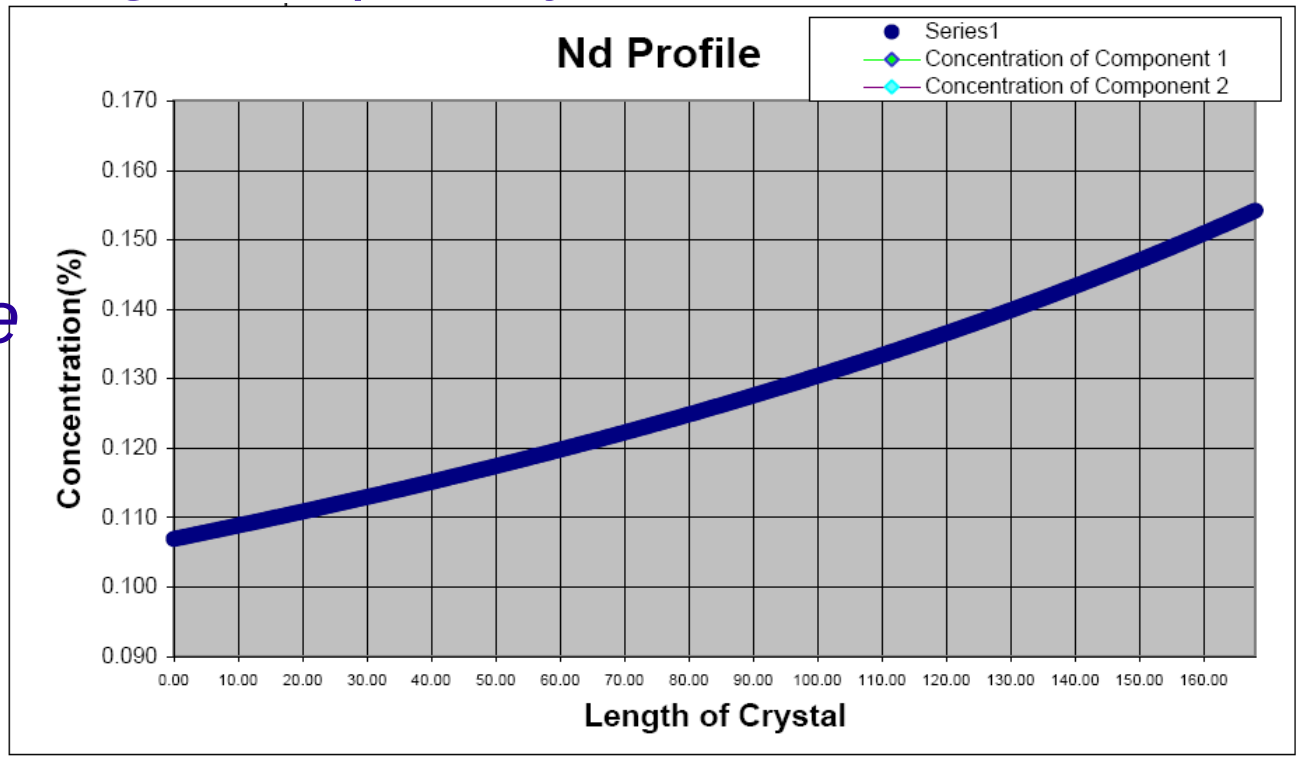
Highly doped crystals

- Typical accuracy in Nd:YAG doping specified as 0.01 at.%
  - 10% for 0.1 at.% doped crystals
  - 1% for 1 at.% doped crystals
    → The properties of higher doped crystals are more reliable
- Manufacturing process causes a longitudinal *absolute* doping gradient
- Higher doped crystals are more common

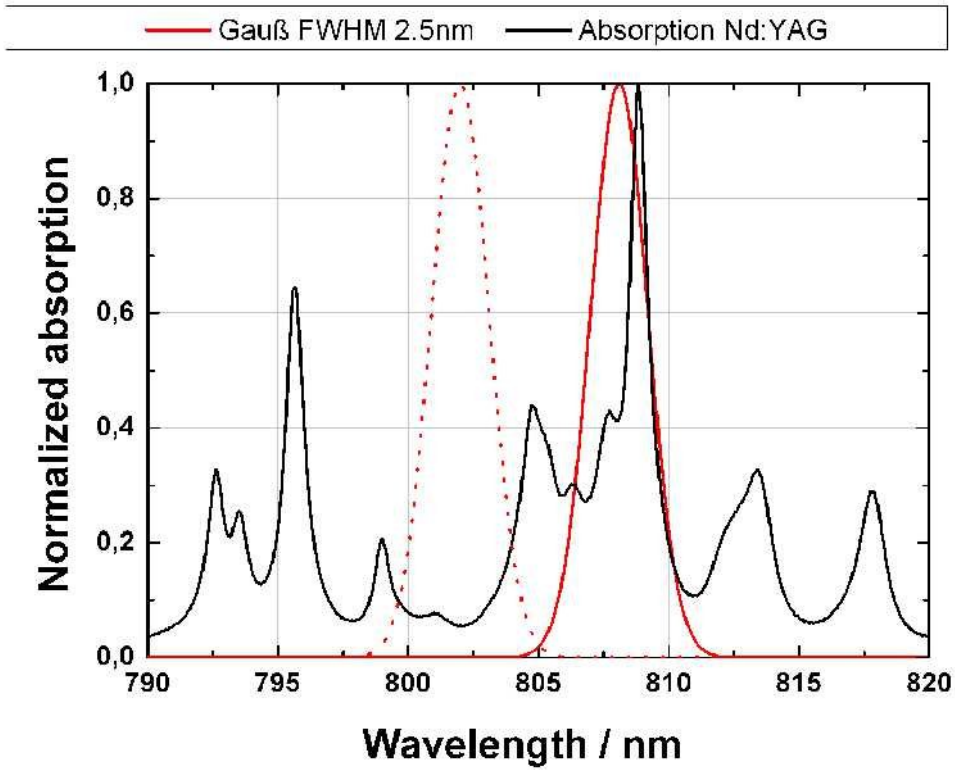


Data: Onyx Optics Inc.

Highly doped crystals

- Pump wavelength needs to be shifted to get less absorption in order to avoid extreme stresses

  → which pump wavelength is needed, if everything is supposed to be identical (except the doping) ?



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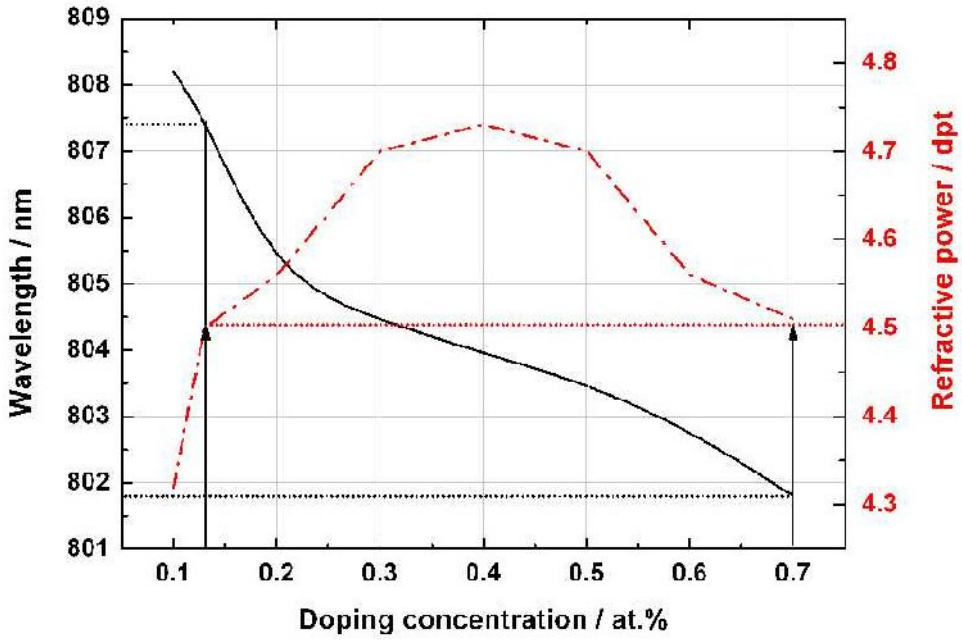
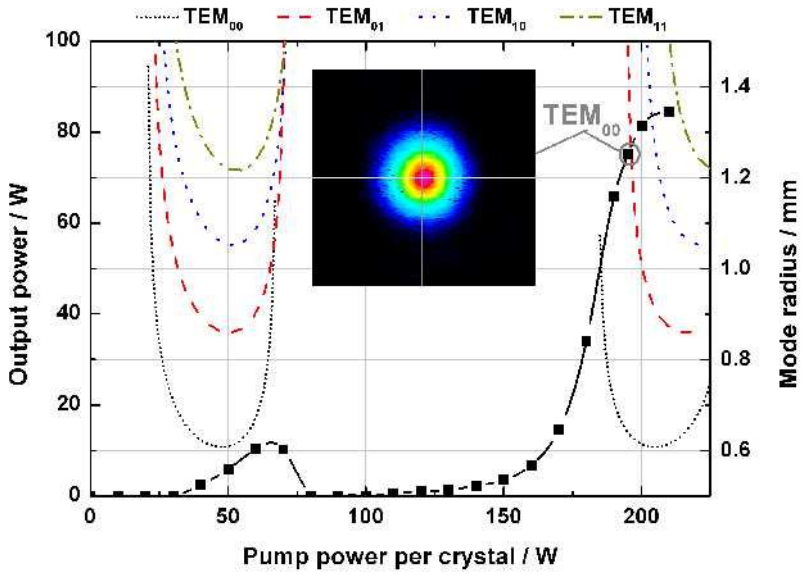


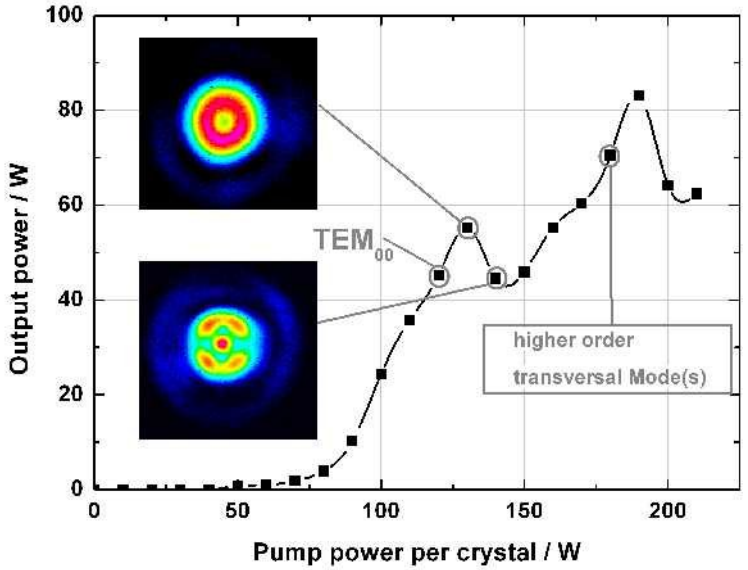
Note: this calculation is based on a constant heat fraction!

Highly doped crystals

- Comparison with standard crystal – in identical setups



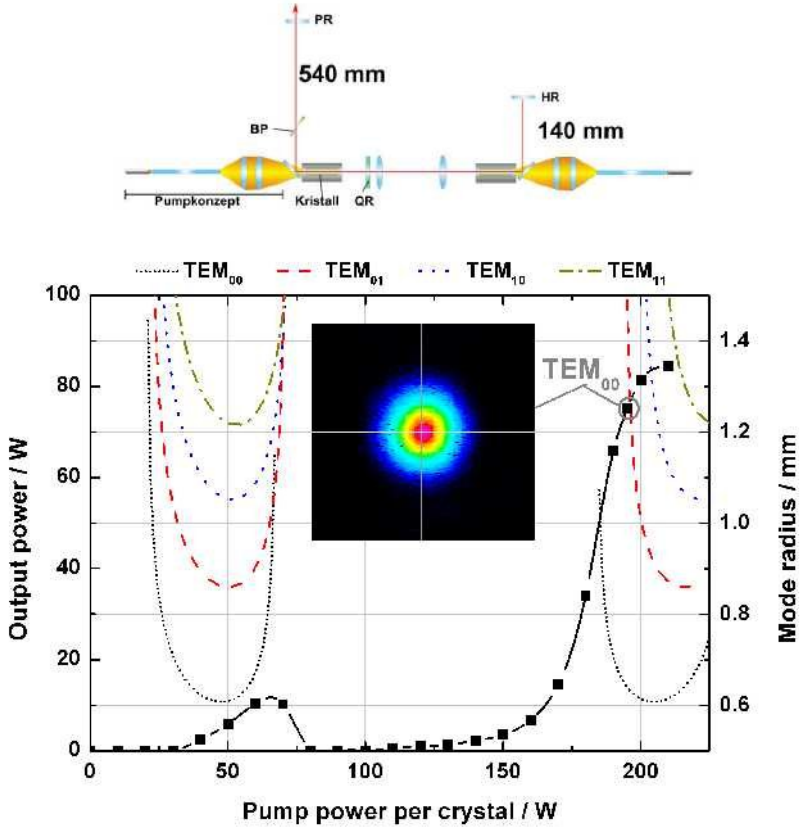
0.13 at.%, 808 nm



0.68 at.%, 802 nm

Highly doped crystals

- Comparison with standard crystal – in adapted setups



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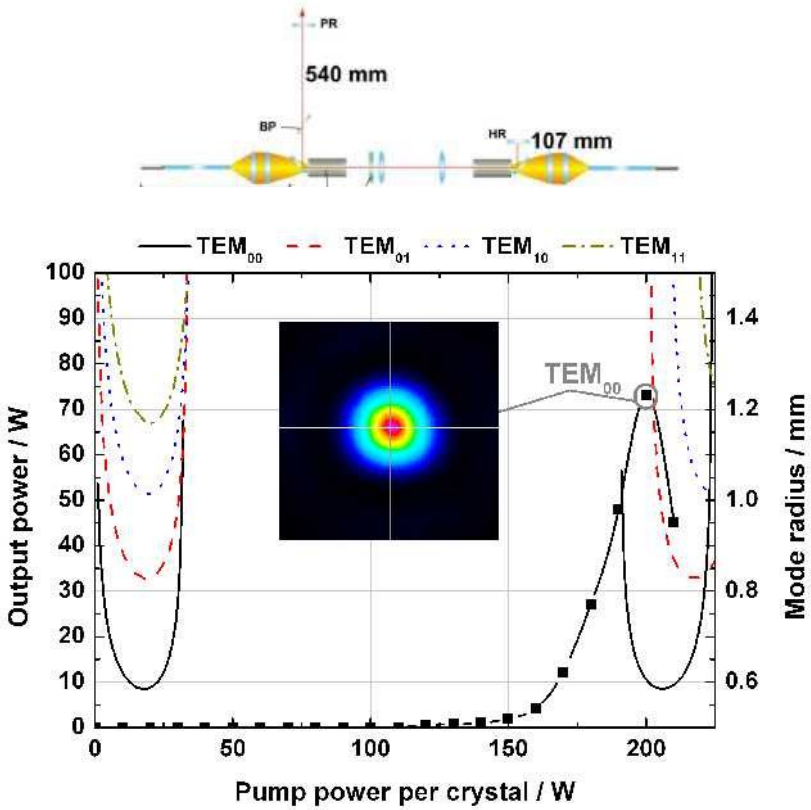

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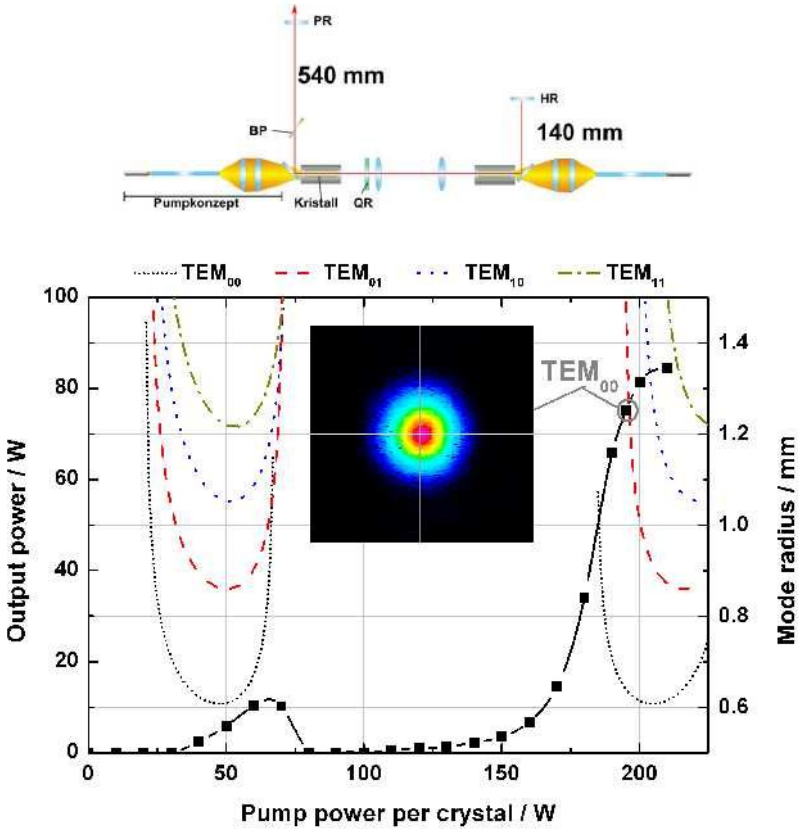
Highly doped crystals

- Comparison with standard crystal – in adapted setups



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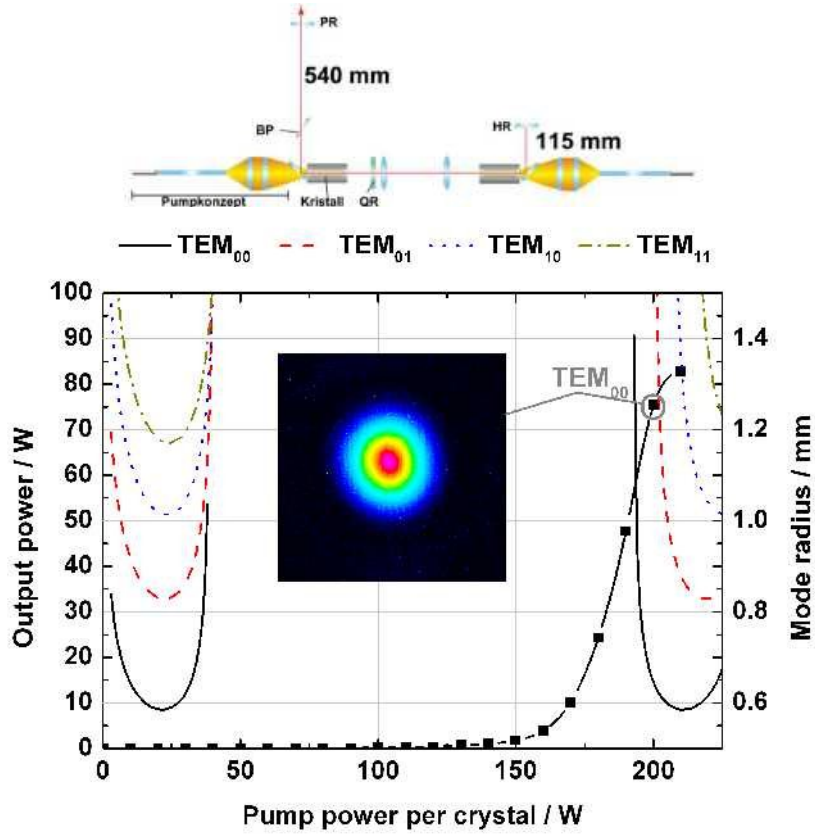
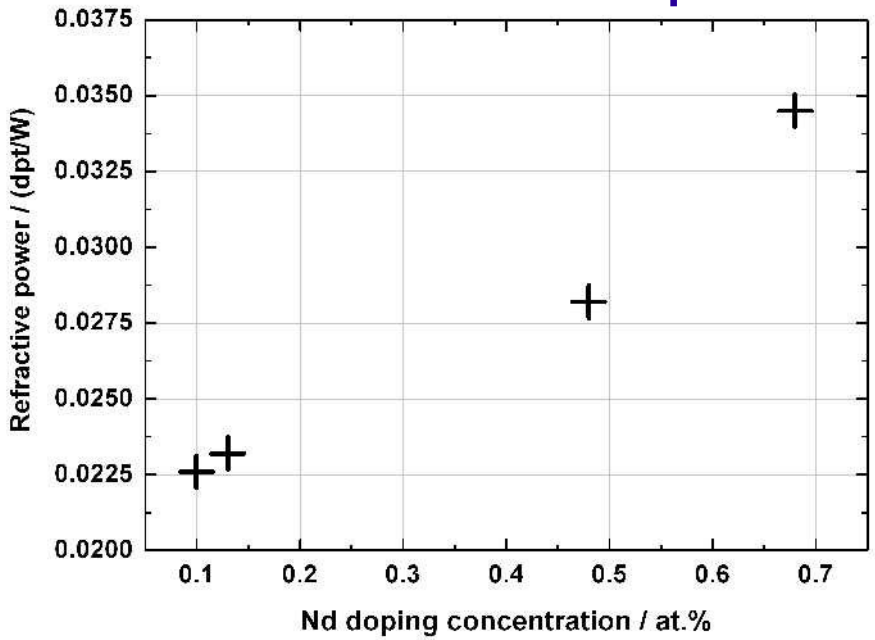


0.48 at.%, 802 nm

Highly doped crystals

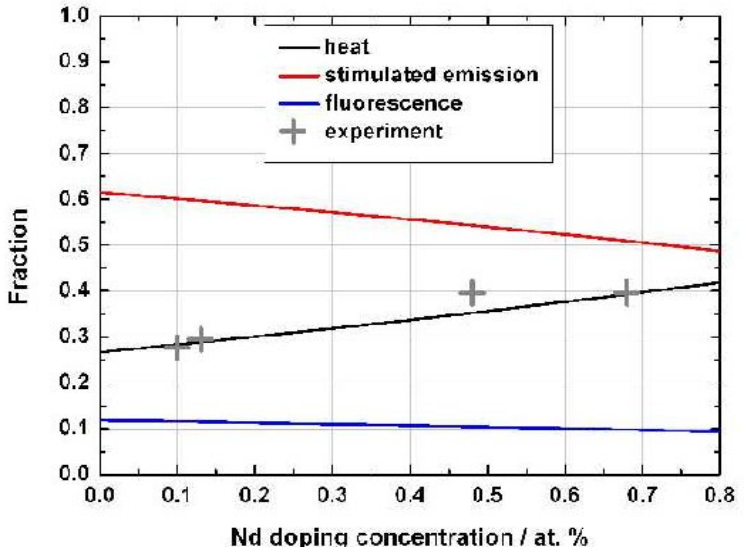
- Learned from these Experiments:
  - Thermal refractive power can be estimated from the resonator length
  - The fraction of pump light, converted into heat can be estimated from the refractive power



Highly doped crystals

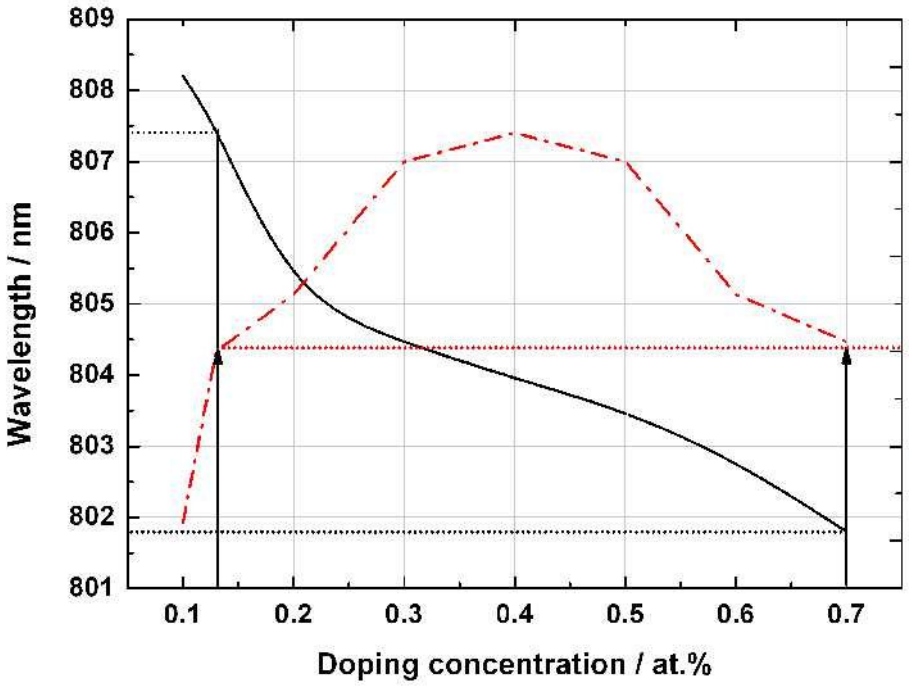
- Learned from these Experiments:
  - Thermal refractive power can be estimated from the resonator length
  - The fraction of pump light, converted into heat can be estimated from the refractive power
  - The fraction of fluorescense, stimulated emission, and inactive Nd ions ("dead sites") can be estimated

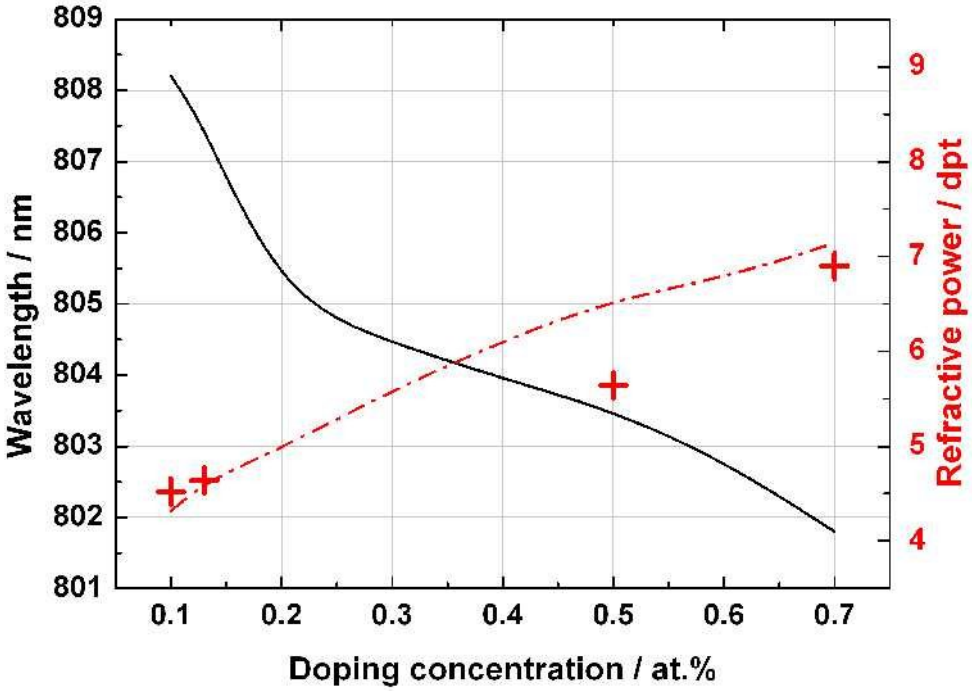
Here:
22% of the ions
are assumed to be
optically inactive



D. C. Brown, IEEE J. Quantum Electron., 34, 560 (1998)
O. Puncken et al.: Appl. Opt., 51, 7586 (2012)

Highly doped crystals: non-constant heat coefficient





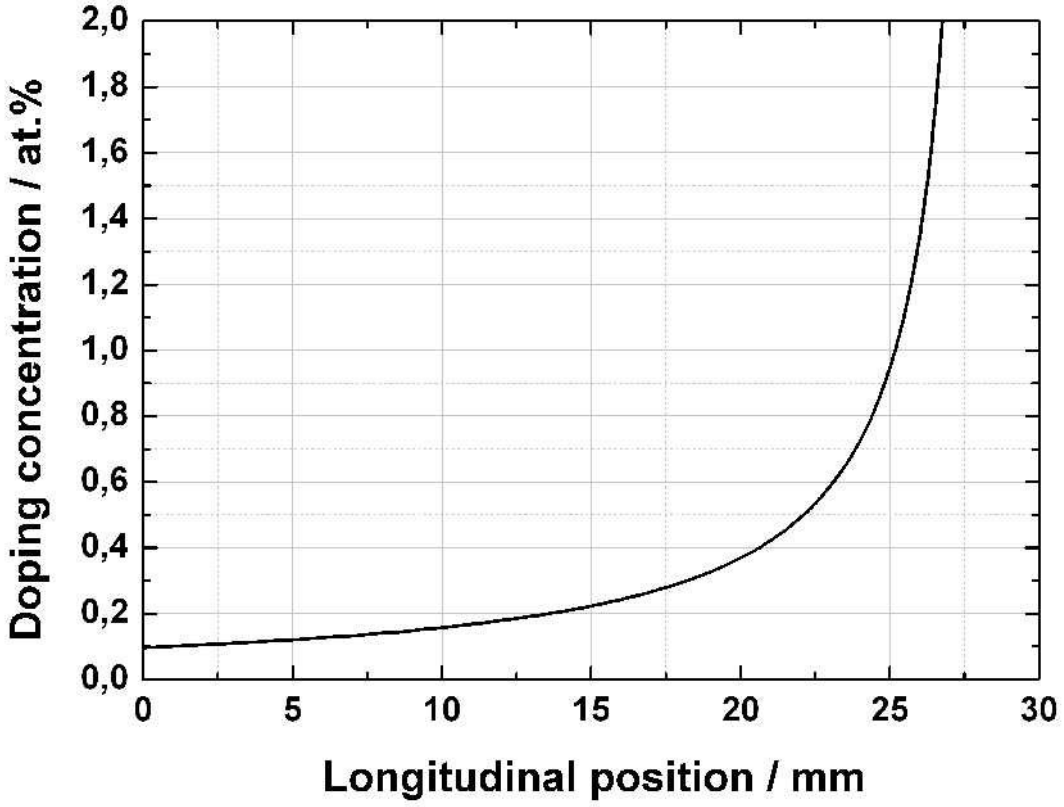
Outline

- **Overview on thermo-optical effects in lasers**
  - Thermal lensing
  - Birefringence
  - Depolarization
- Aberrations and the PSL working point
- **Attempts for optimization of the laser crystals**
  - Different doping concentrations
  - **Segmented crystals**
  - Intrinsic depolarization compensation

Segmented crystals

- The maximal pump power (and therefore output power) is limited by the induced heat and occuring stresses
  - Longitudinally homogeneous temperature distribution
  - Optimum: longitudinal hyperbolic doping gradient* (Figure: 807 nm, FWHM 2.5 nm, 95% absorption)

    ☹ complex manu-facturing process

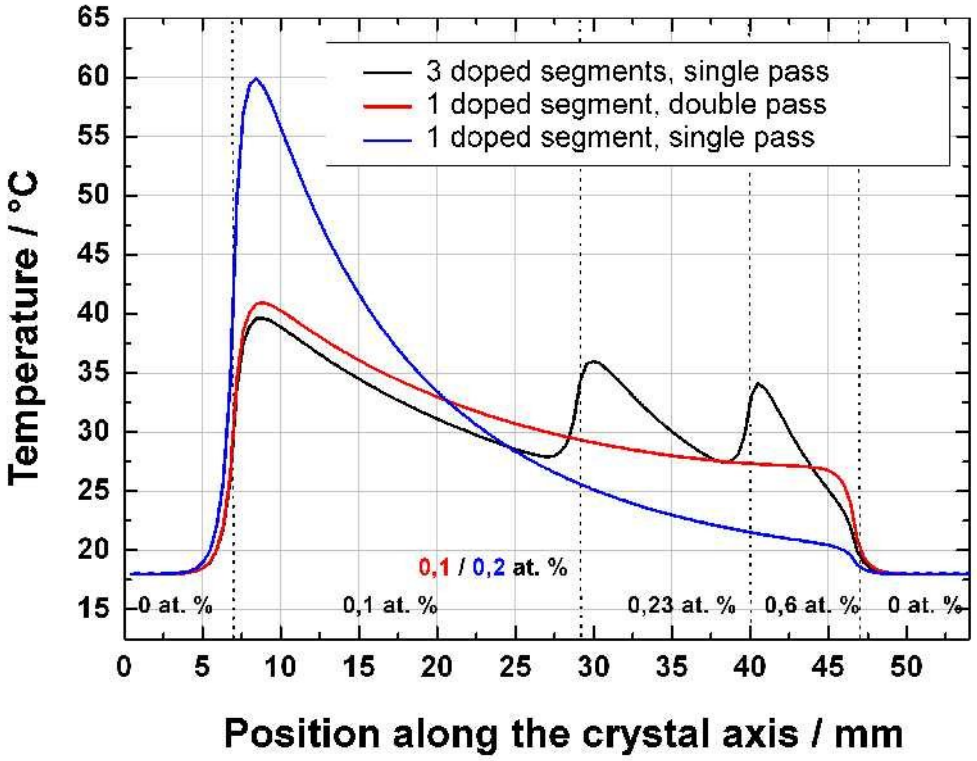


*R. Wilhelm et al: Opt. Express, 16, 20106 (2008)

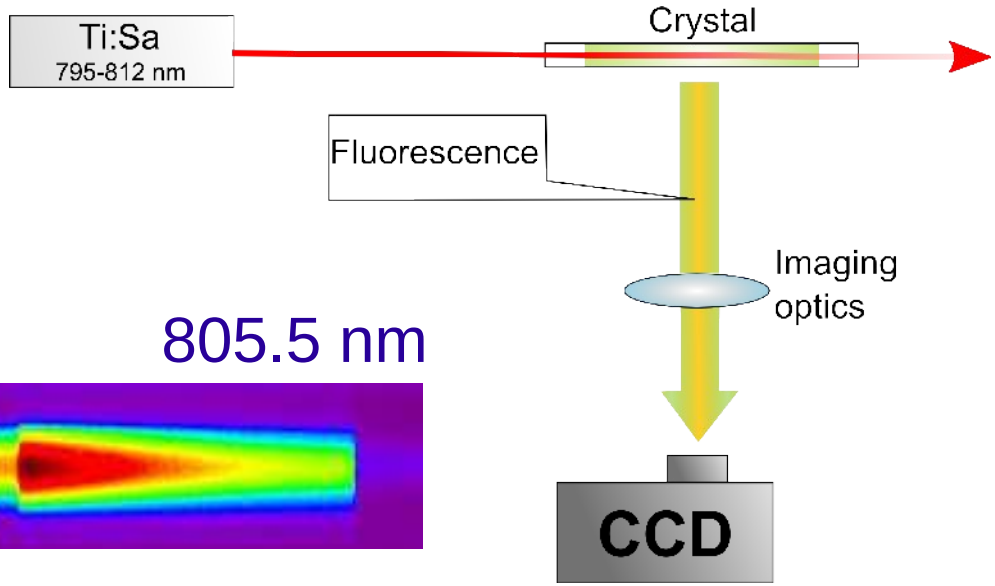
Segmented crystals

- ☺ Tradeoff: segmented crystals
  - Pump wavelength: 807.8 nm
  - Doped length: 40 mm
  - 3 doped segments

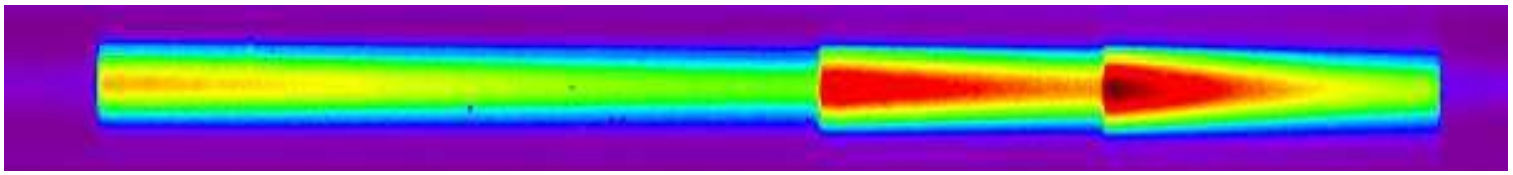
Segment	Length	Doping
1	7 mm	0 at.%
2	22 mm	0.1 at.%
3	11 mm	0.23 at.%
4	7 mm	0.6 at.%
5	7 mm	0 at.%



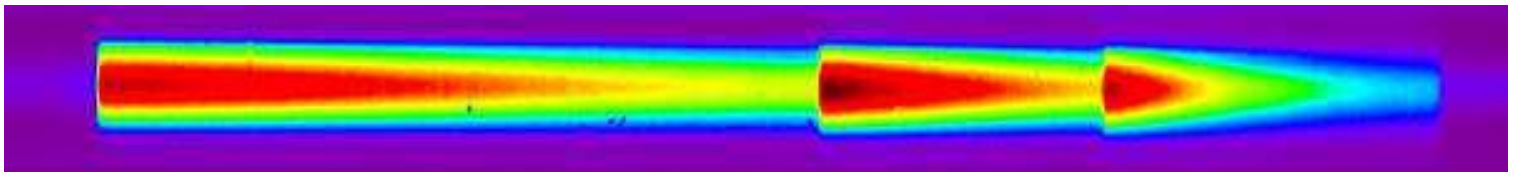
Optimal pump wavelength



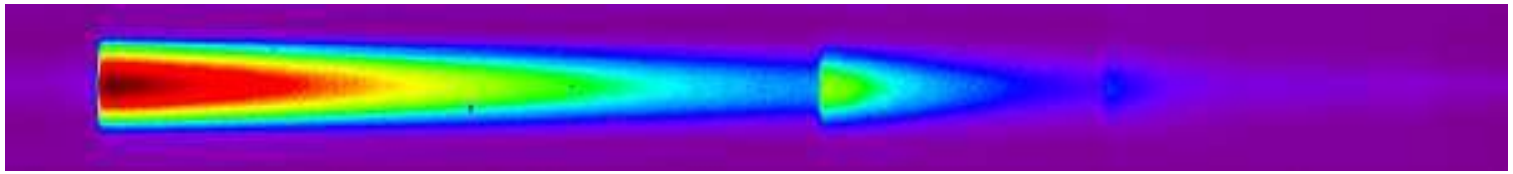
805.5 nm



807 nm

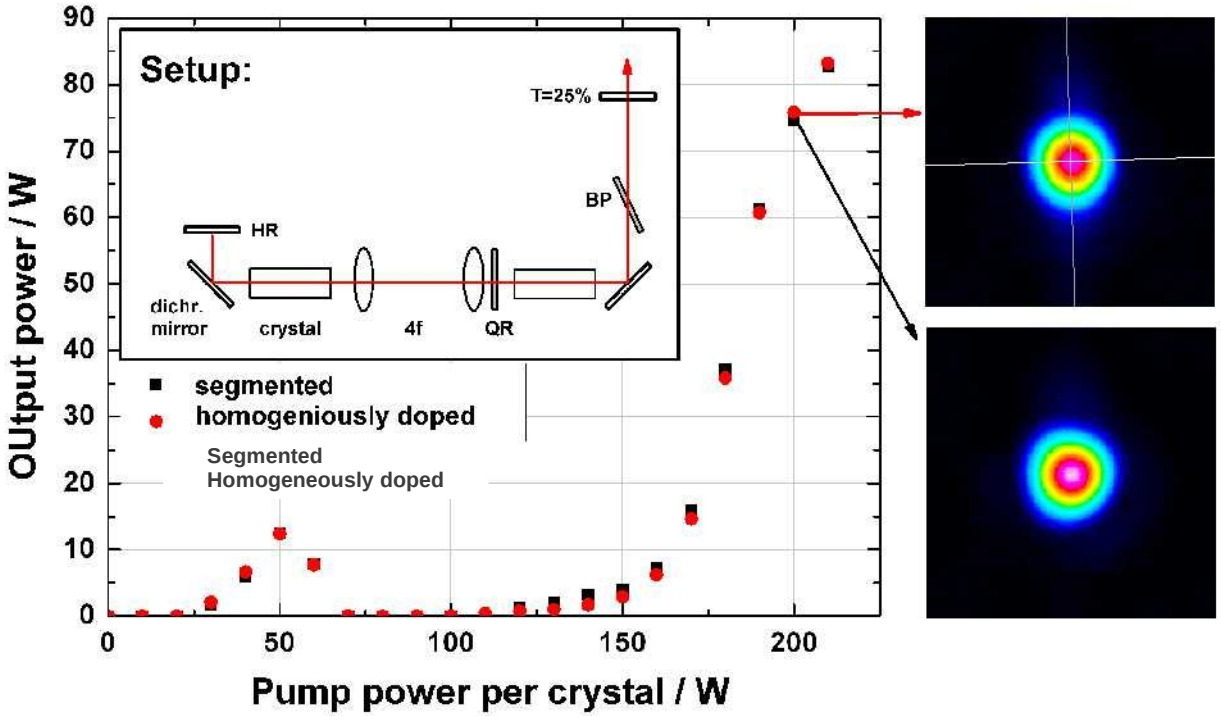


808.5 nm



Segmented crystals

- Comparison with "standard crystal"



- No difference in laser performance
- No pump light double-pass
- Complex in manufacturing

Outline

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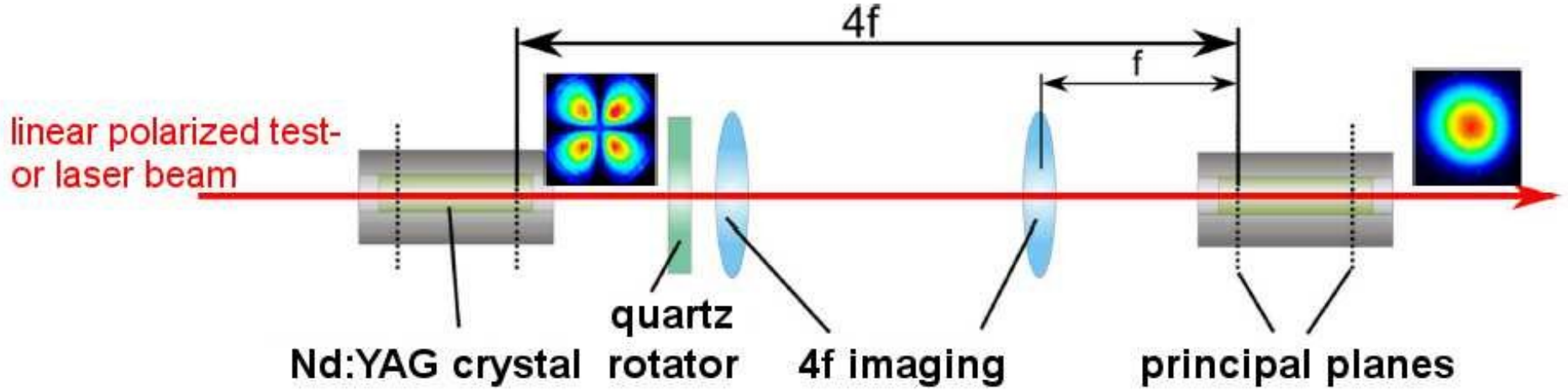
Standard birefringence compensation



- **+** very effective
  (depolarization losses < 1 %)
- **-** Additional components inside the resonator
  (absorption, thermal effects, spots,...)
- **-** Alignment sensitivity

Intrinsic birefringence reduction

Pumped crystal becomes birefringent

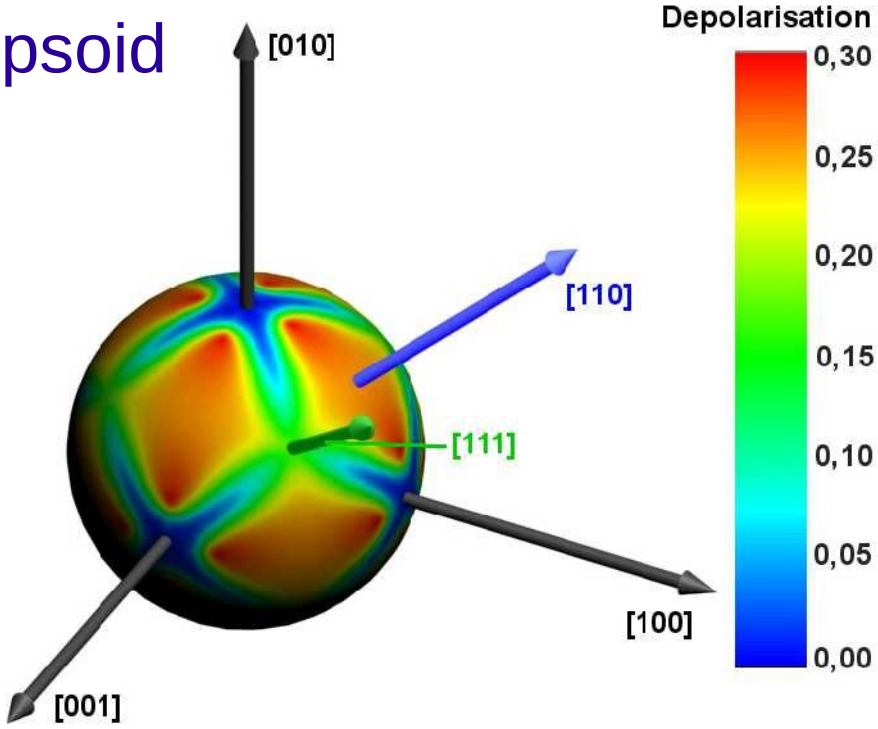
→ **Depolarisation *D***

$$D(x,y)=\sin^2(2(\theta(x,y)-\gamma))\,\sin^2(\psi(x,y)/2)$$

θ Angle between input polarization and principal axis of the birefringence ellipsoid

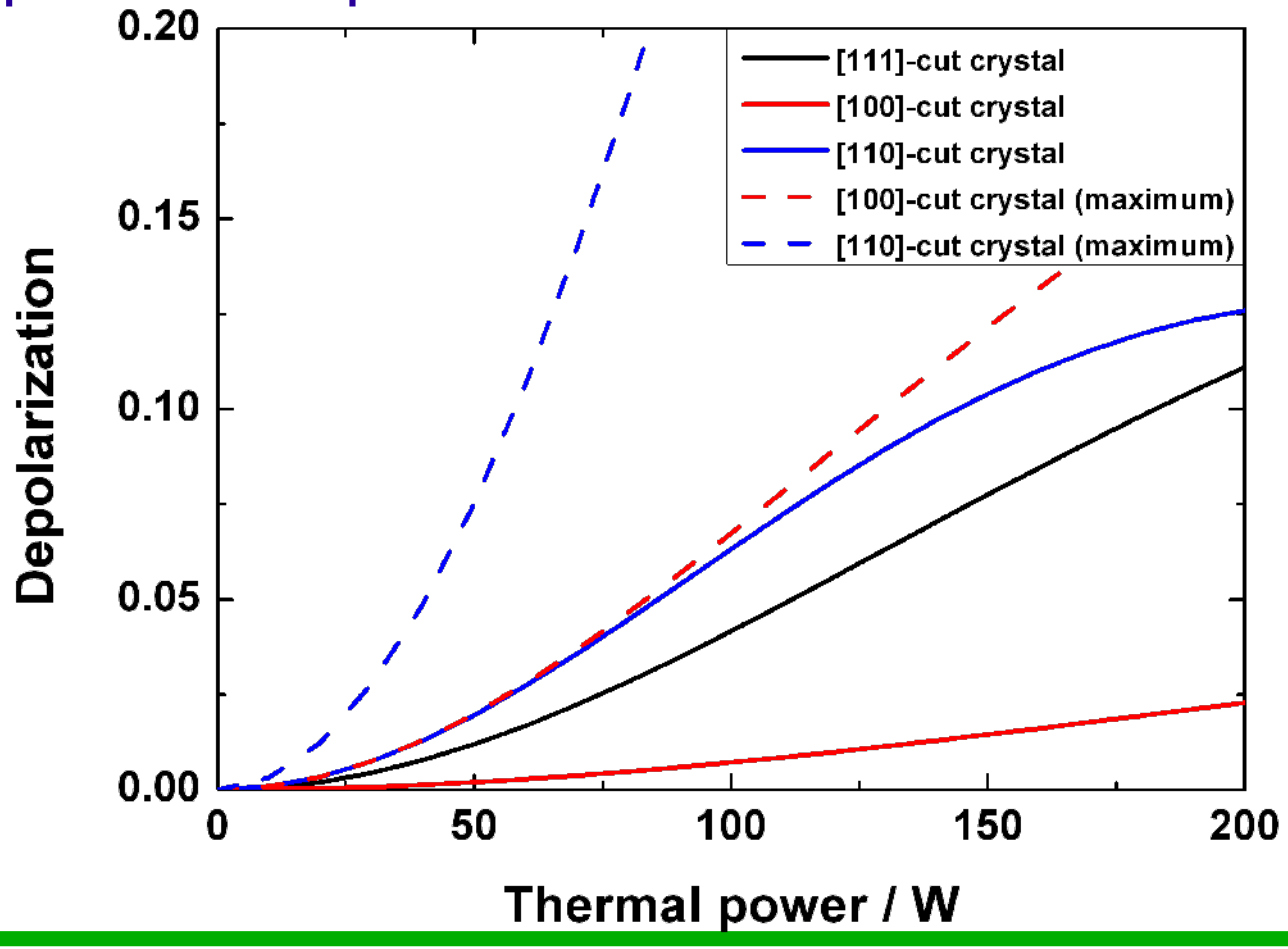
γ Angle between input polarization and x-axis of the reference system

Ψ Phase-shift between radial and tangential polarization, **depends on crystal cut!**



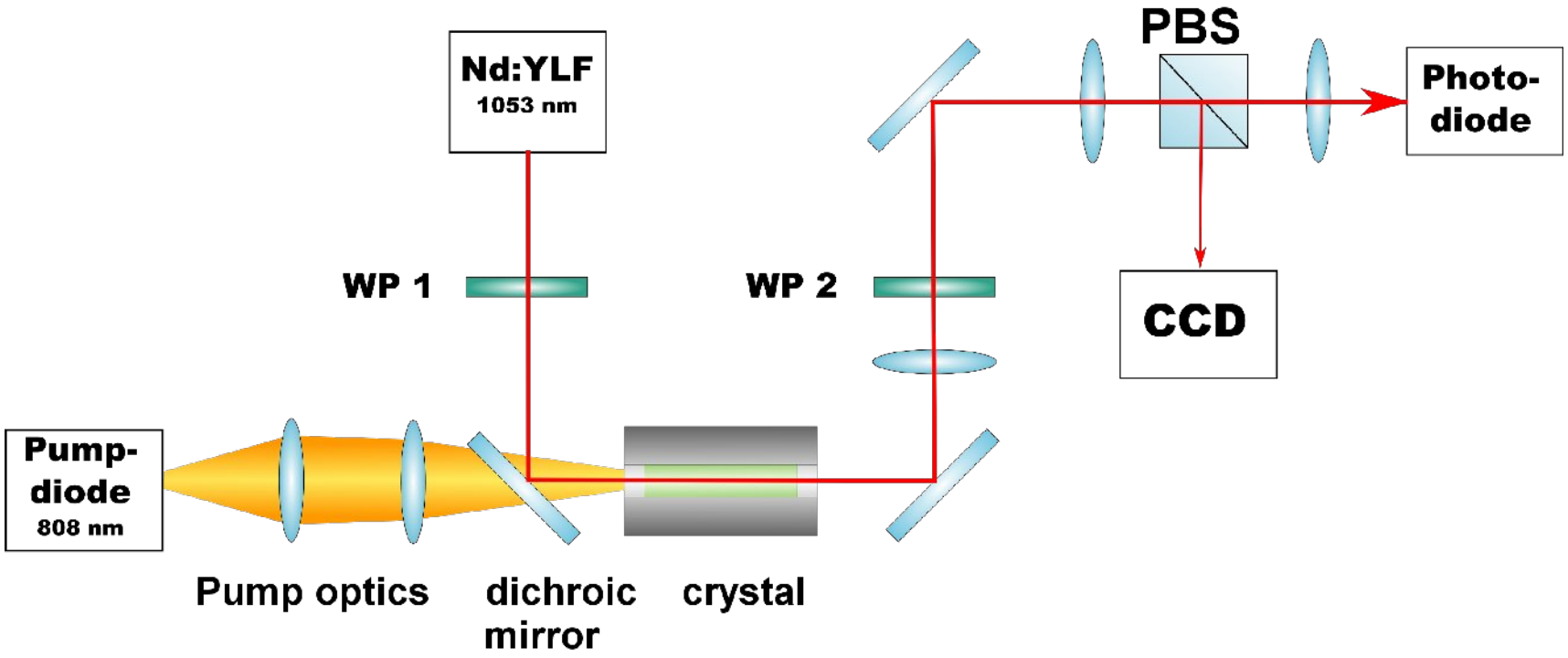
Intrinsic birefringence reduction

- For [100]- and [110]-cut crystals:
  The depolarization depends on the orientation of the crystal with respect to the polarization orientation of the laser



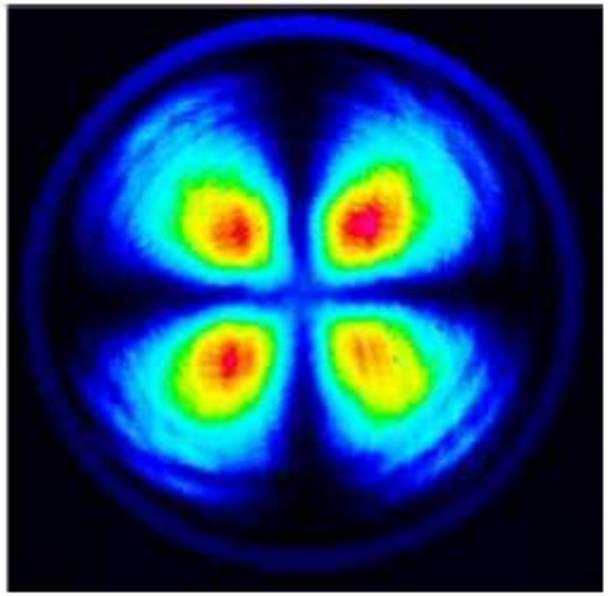
Investigations with test laser

- Wavelength: 1053 nm
  - No amplification in pumped Nd:YAG crystal
  - Close to Nd:YAG laser wavelength



Investigations with test laser

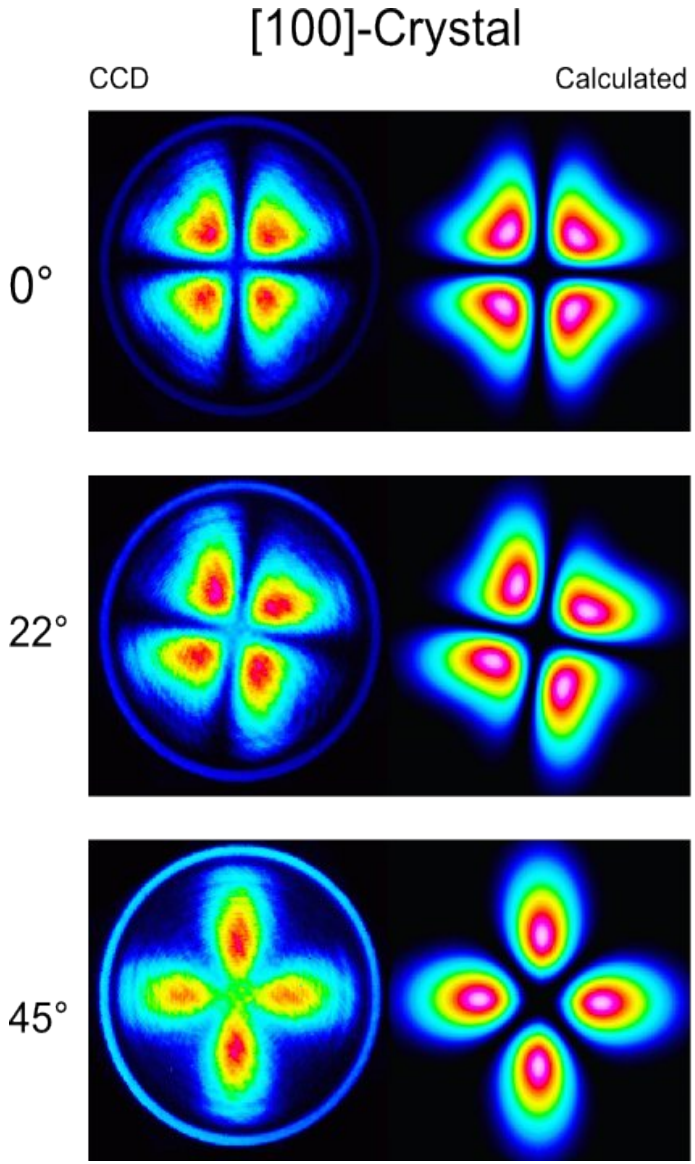
- [111]-cut: beam pattern rotates



Investigations with test laser

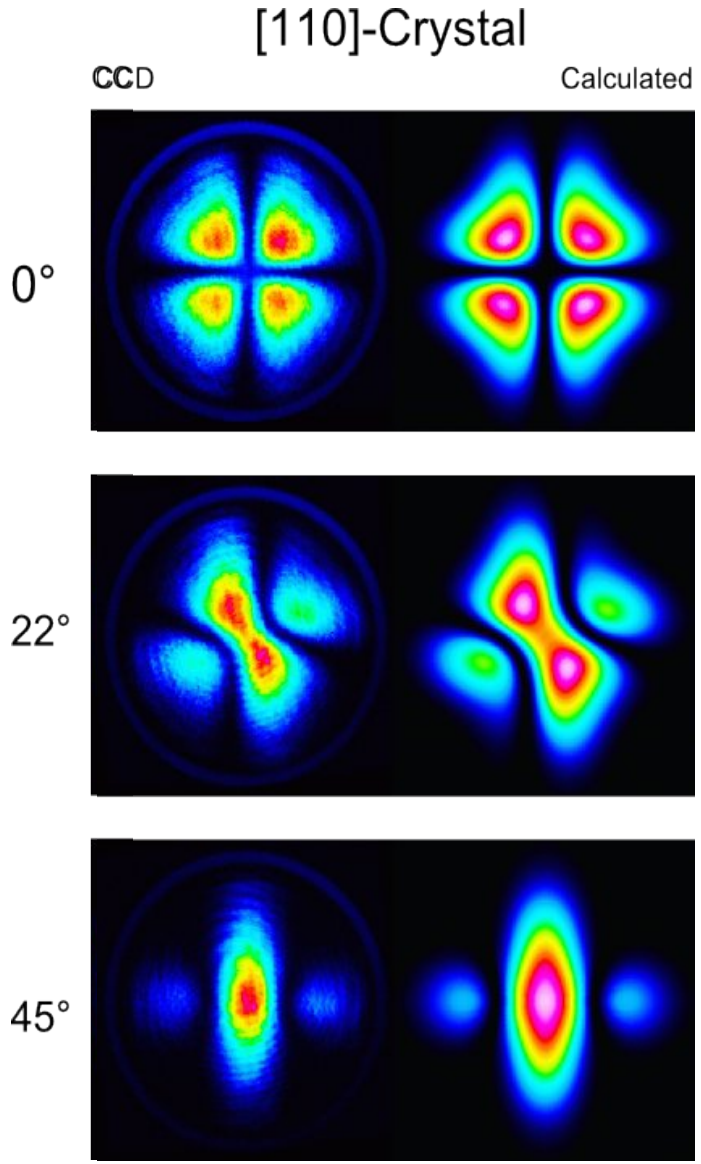
- [111]-cut: beam pattern rotates

- [100]-cut: beam pattern changes with respect to input polarization
  Principal axis of the refractive index ellipsoid are no longer radially/tangentially oriented

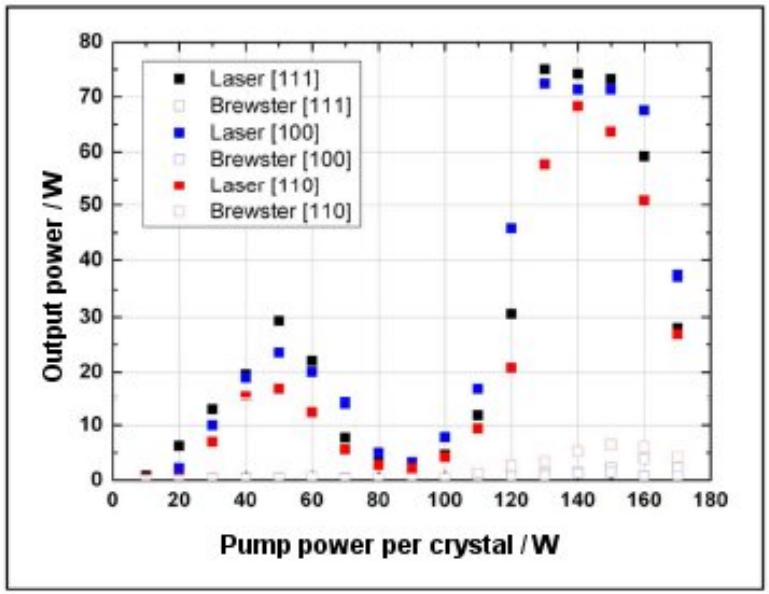


Investigations with test laser

- [111]-cut: beam pattern rotates
- [100]-cut: beam pattern changes with respect to input polarization
  Principal axis of the refractive index ellipsoid are no longer radially/tangentially oriented
- [110]-cut: Elliptical pattern at 45° with maximum at the center



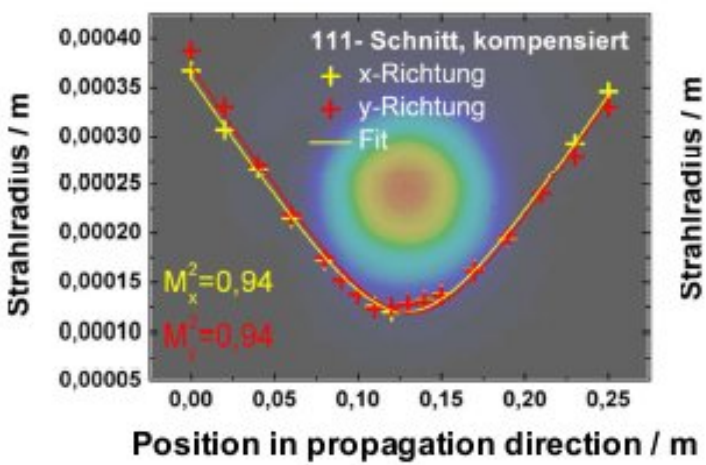
Investigations with asymmetric two-head laser

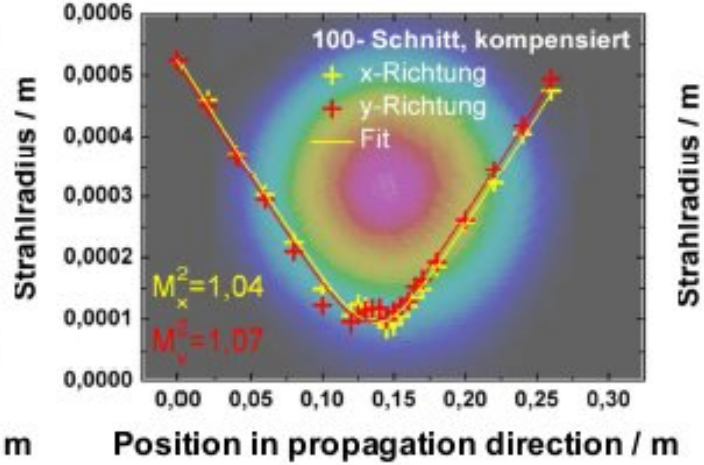


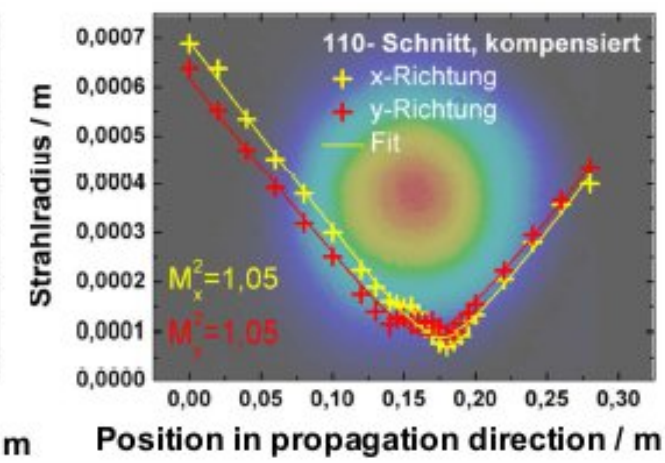
H.Tünnermann, O. Puncken, P. Wessels, M. Frede, J. Neumann, D. Kracht: Optics Express 19,12992 (2011)

Investigations with asymmetric two-head laser

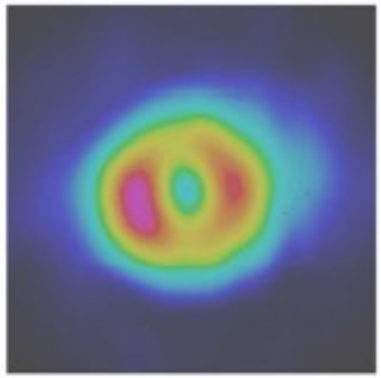
compensated

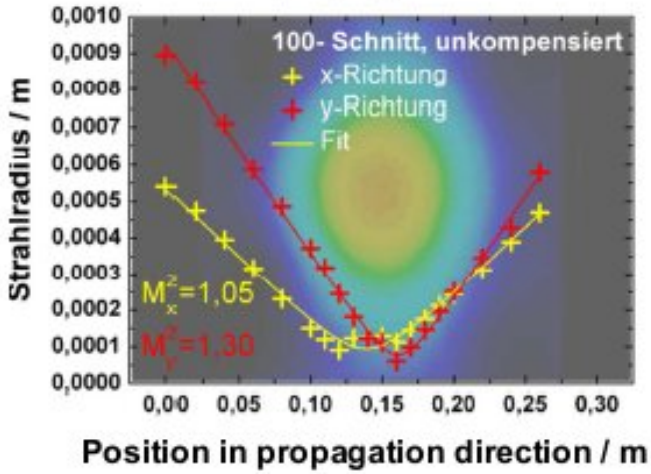


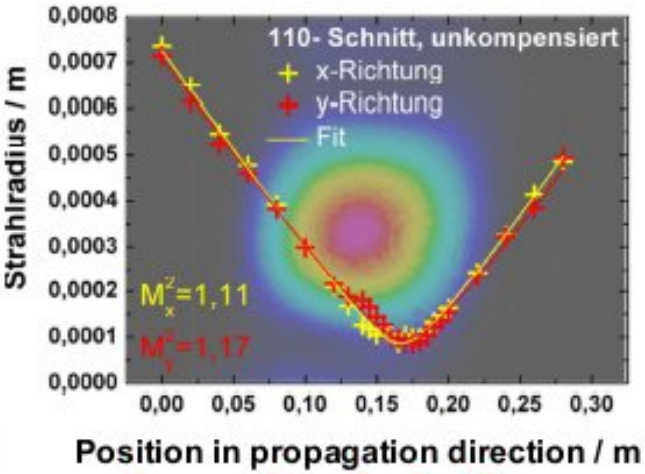




uncompensated







huge depolarization losses!

Acknowledgment

Data and pictures taken from:

(former) LZH researchers: Oliver Puncken, Marcin Damjanic, Maik Frede, Raphael Kluzik, Dietmar Kracht, Bastian Schulz, Christian Veltkamp, Peter Weßels, Ralf Wilhelm, Lutz Winkelmann et al.

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Thanks!