Friedrich-Schiller-Universität Jena

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Laser System Modeling with Fast Physical Optics

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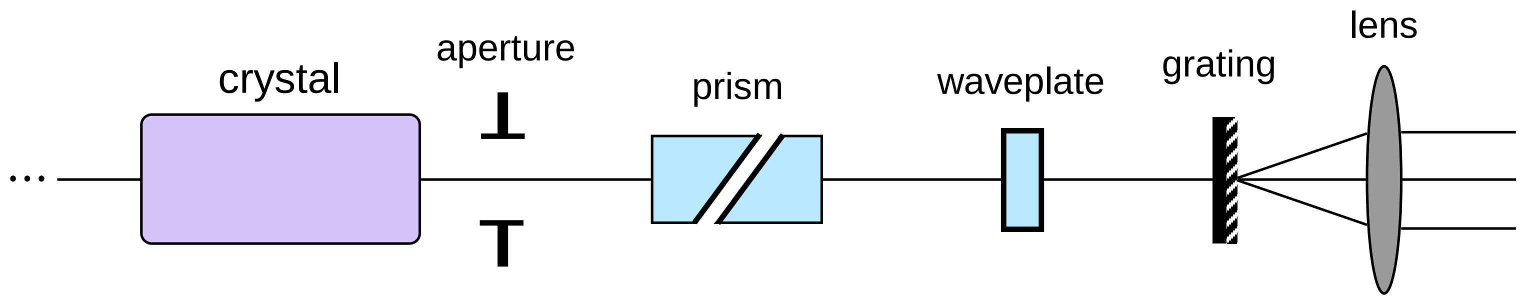
[2] LightTrans International UG, Jena, Germany

[3] Wyrowski Photonics UG, Jena, Germany

Introduction

- Complexity in modern laser systems



  - Various types of components, with different feature sizes, integrated in one optical system

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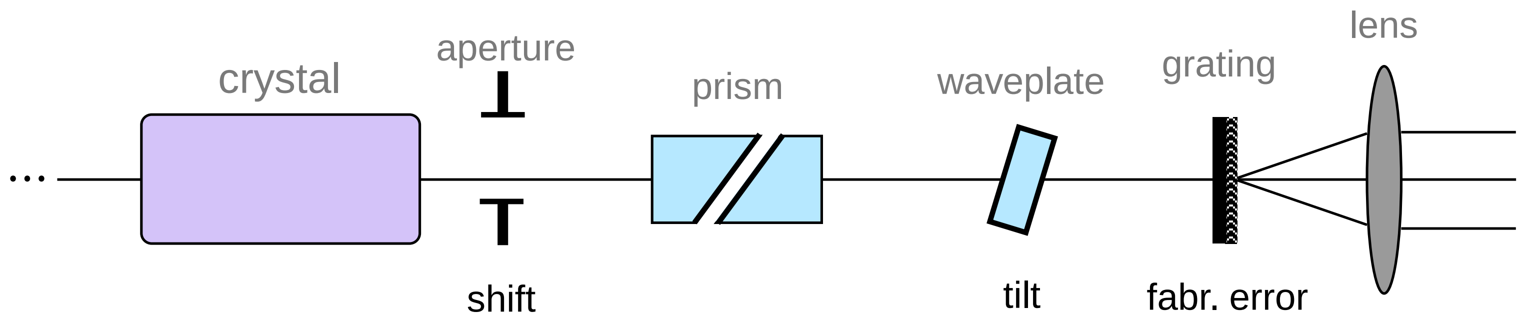

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  - Tolerancing of each component needs to be taken into considertaion so to evaluate system performance

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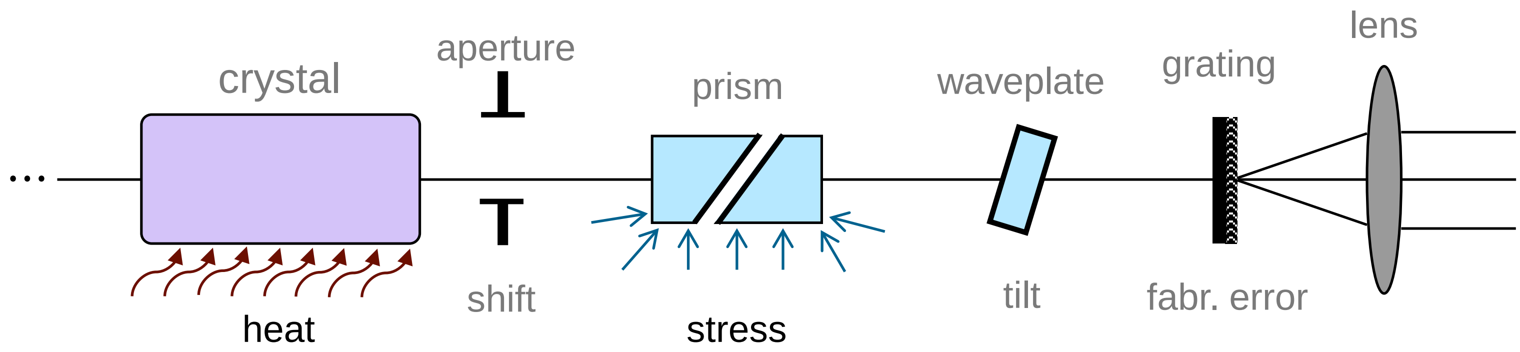
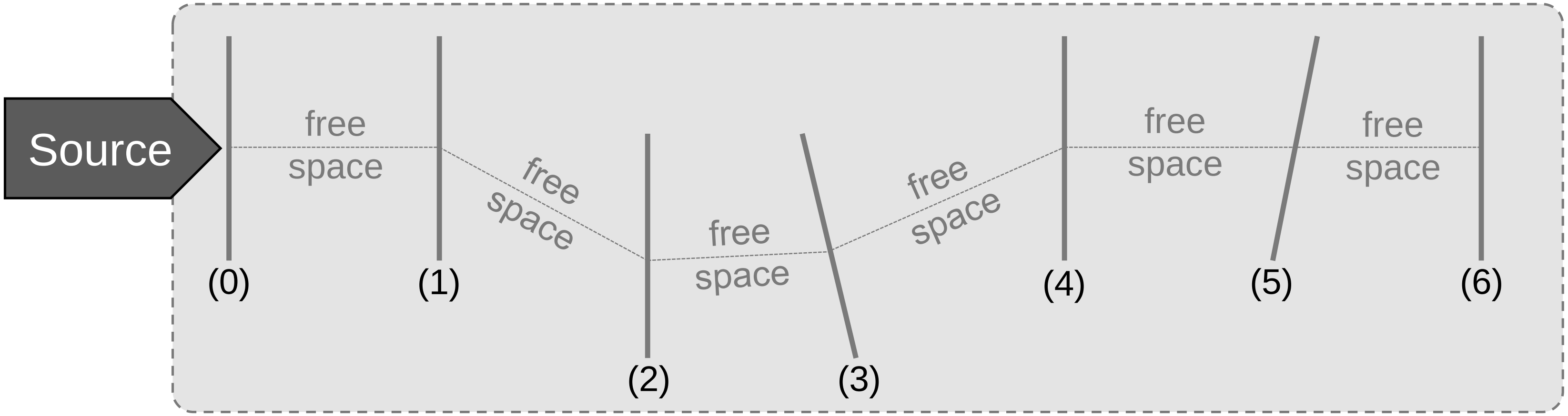
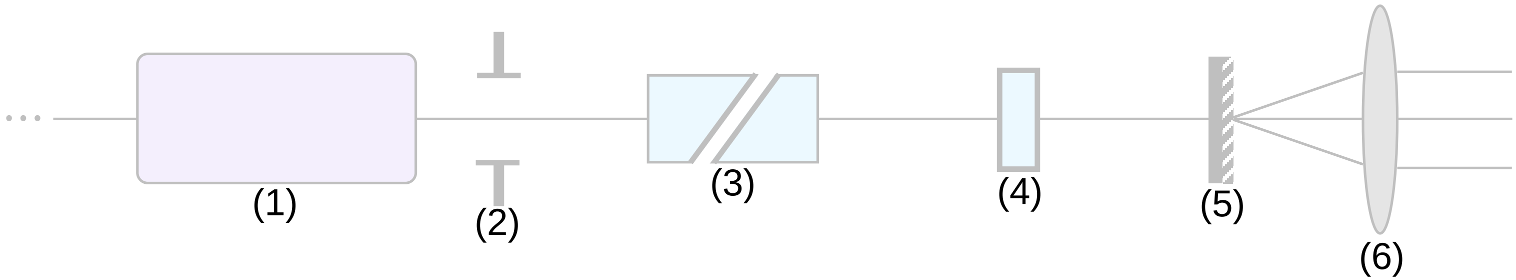


  - Various types of components, with different feature sizes, integrated in one optical system
  - Tolerancing of each component needs to be taken into considertaion so to evaluate system performance
  - Interaction with packaging / thermal / environmental effects is of concern

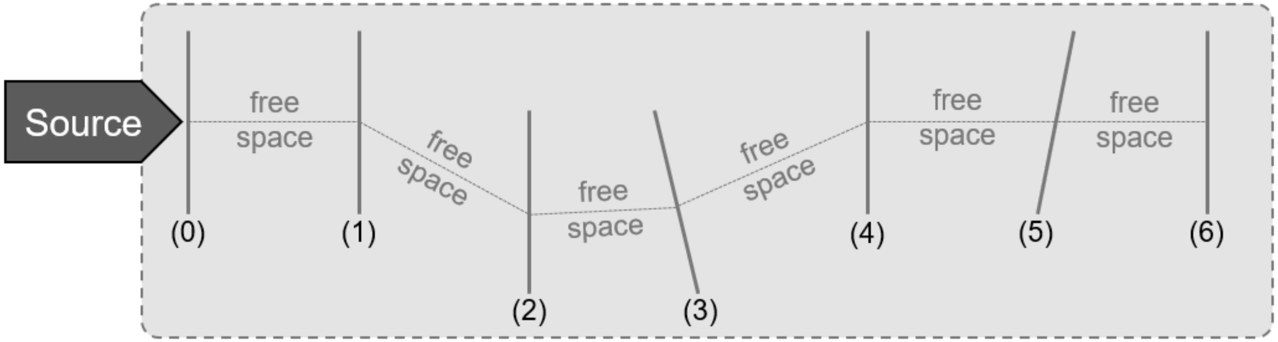
Fast Physical Optics by Field Tracing

- In fast physical optics we comply with the following
  1. Tearing: decomposed the whole optical system into regions and specialized Maxwell solvers are applied locally

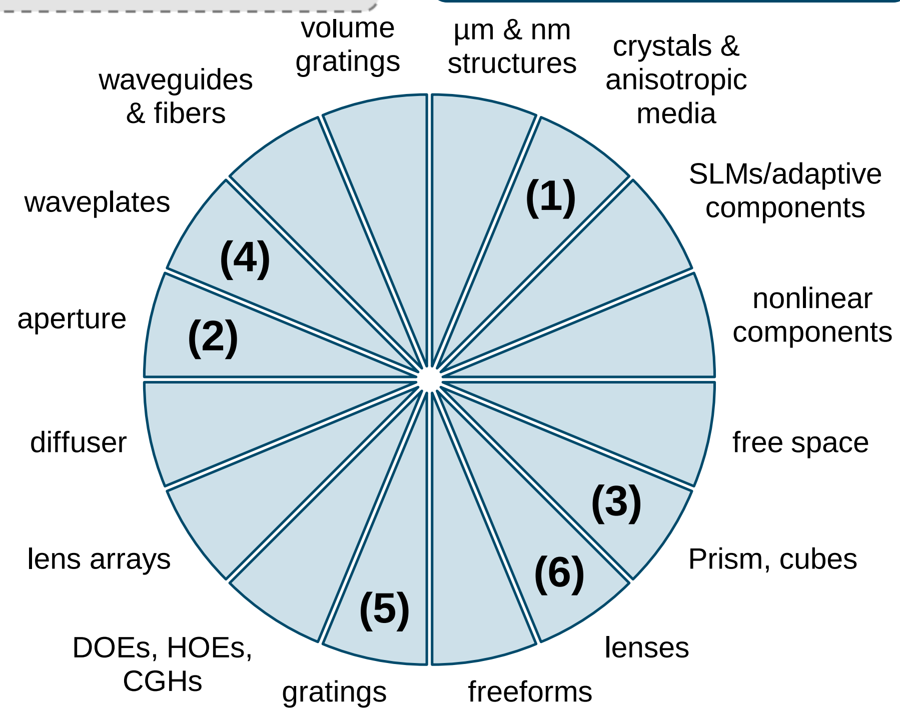




Fast Physical Optics by Field Tracing



Propagation and component operators solve Maxwell's equations per region



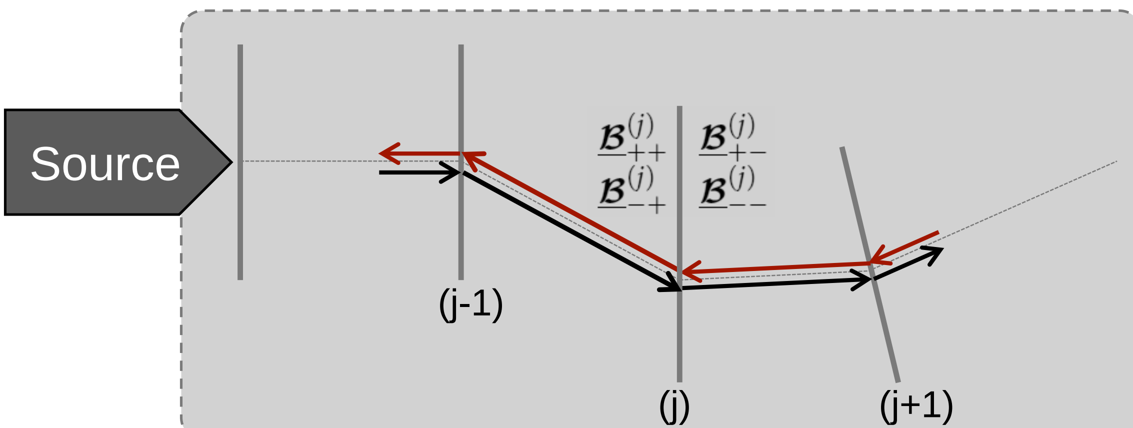
Fast Physical Optics by Field Tracing

- In fast physical optics we comply with the following
  1. Tearing: decomposed the whole optical system into regions and specialized Maxwell solvers are applied locally
  2. Interconnection: solutions in each regions are connected by the general non-sequential field tracing concept

Non-Sequential Optical Field Tracing

Michael Kuhn, Frank Wyrowski, and Christian Hellmann

Kuhn, M.; Wyrowski, F. & Hellmann, C. (2012), Non-sequential optical field tracing, *in* T. Apel & O. Steinbach, ed., 'Finite Element Methods and Applications', Springer-Verlag, Berlin, , pp. 257-274.



Visit our ***Free Optical Design Seminar*** *on Feb. 02 and see more example regarding non-sequential field tracing*

Fast Physical Optics by Field Tracing

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    1. Tearing: decomposed the whole optical system into regions and specialized Maxwell solvers are applied locally
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    3. Field tracing operators should have numerical operation numbers linear with field sampling number N

Rigorous Propagation in Homogeneous Media

Maxwell's equations in x-domain:

$$\nabla \times \boldsymbol{E}(\boldsymbol{r},\omega) = \mathrm{i}\omega\mu_0\boldsymbol{H}(\boldsymbol{r},\omega)$$
$$\nabla \times \boldsymbol{H}(\boldsymbol{r},\omega) = -\mathrm{i}\omega\epsilon_0\check{\epsilon}_\mathrm{r}(\omega)\boldsymbol{E}(\boldsymbol{r},\omega)$$
$$\nabla \cdot \boldsymbol{E}(\boldsymbol{r},\omega) = 0$$
$$\nabla \cdot \boldsymbol{H}(\boldsymbol{r},\omega) = 0$$

Intergal operator is a N^2 operation!

Rigorous propagation in x-domain (Rayleigh-Sommerfeld integral):

$$V^{\mathrm{out}}(\boldsymbol{\rho},z) \propto \int\int_{-\infty}^{\infty} V^{\mathrm{in}}(\boldsymbol{\rho}',z_0)\frac{\exp(\mathrm{i}k_0\check{n}R)}{R}\left(\mathrm{i}k_0\check{n}-\frac{1}{R}\right)\frac{\Delta z}{R}\,\mathrm{d}^2\rho'$$

with $R=\sqrt{(x-x')^2+(y-y')^2+(\Delta z)^2}$.

Rigorous Propagation in Homogeneous Media

Maxwell's equations in x-domain:

$$\nabla \times \boldsymbol{E}(\boldsymbol{r},\omega) = \mathrm{i}\omega\mu_0\boldsymbol{H}(\boldsymbol{r},\omega)$$

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$$\nabla \cdot \boldsymbol{E}(\boldsymbol{r},\omega) = 0$$

$$\nabla \cdot \boldsymbol{H}(\boldsymbol{r},\omega) = 0$$

Maxwell's equations in k-domain:

$$\check{\boldsymbol{k}} \times \tilde{\boldsymbol{E}}(\boldsymbol{\kappa},z,\omega) = \omega\mu_0\tilde{\boldsymbol{H}}(\boldsymbol{\kappa},z,\omega)$$

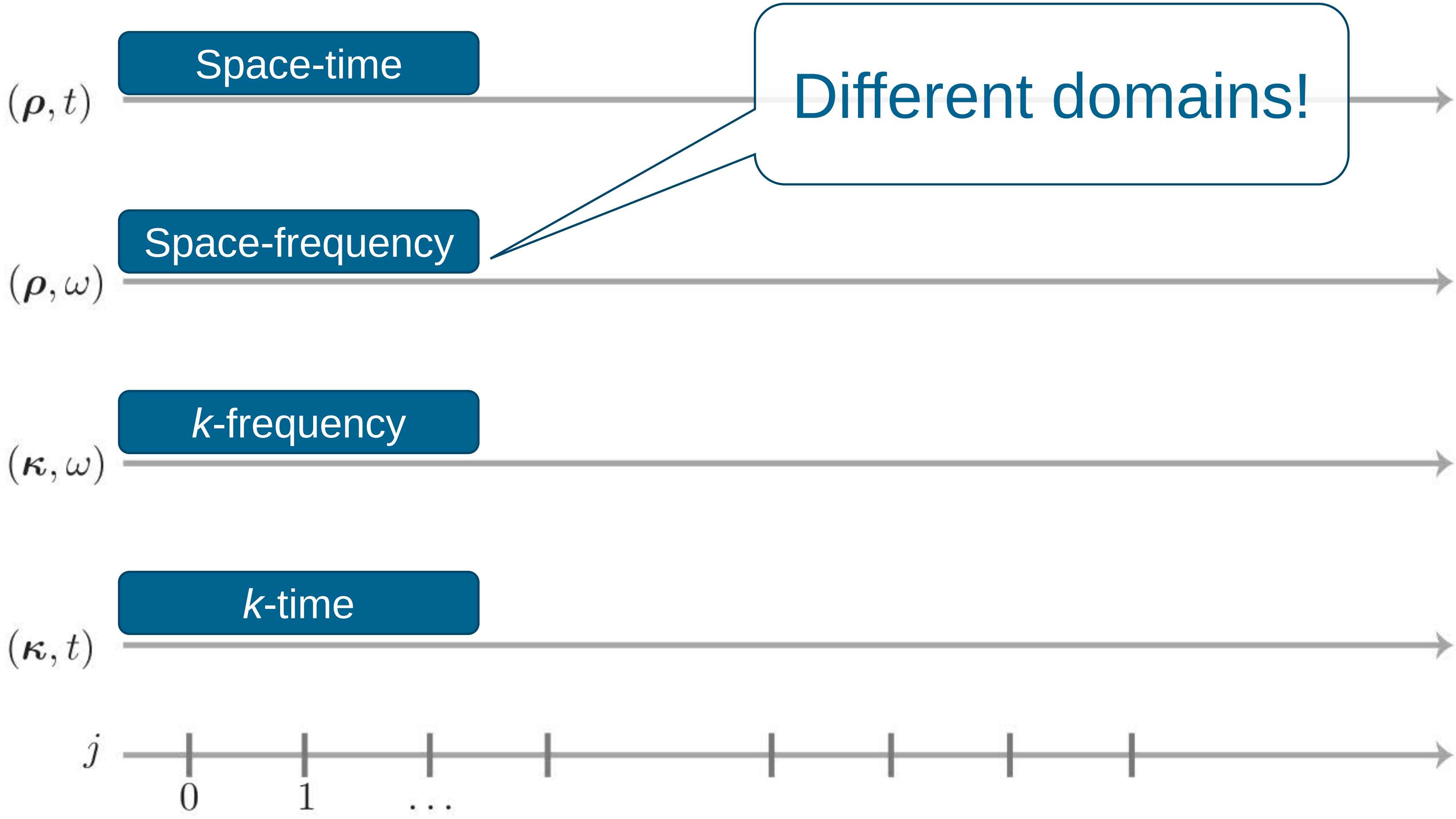
$$\check{\boldsymbol{k}} \; \ldots \;)\tilde{\boldsymbol{E}}(\boldsymbol{\kappa},z,\omega)$$

Simple product is
a *N* operation!

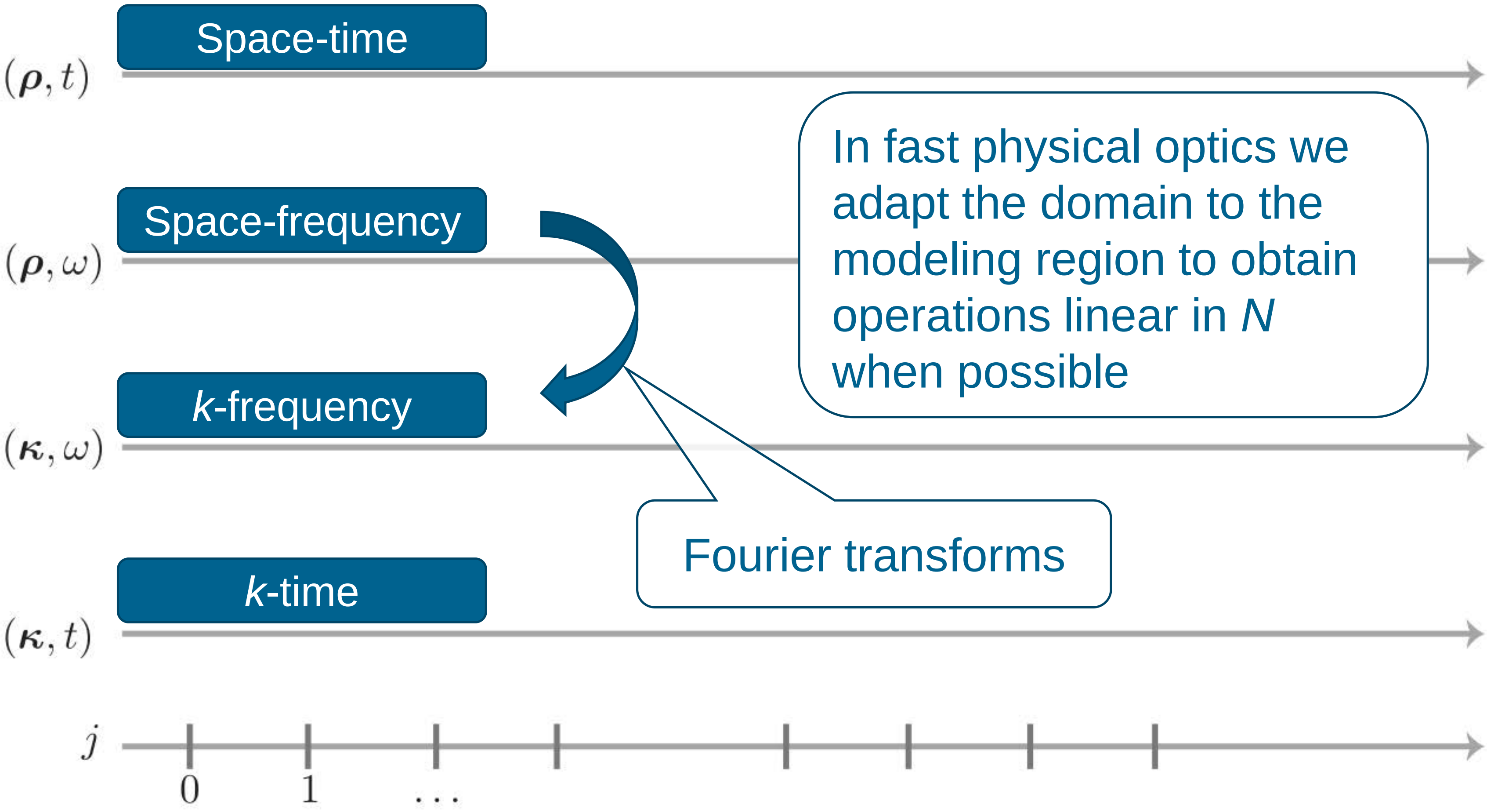
Rigorous propaga n in k-domain:

$$\tilde{V}^{\mathrm{out}}(\boldsymbol{\kappa},z) = \tilde{V}^{\mathrm{in}}(\boldsymbol{\kappa},z_0) \times \exp\left(\mathrm{i}\check{k}_z(\kappa)\Delta z\right)$$

Field Tracing in Different Domains



Field Tracing in Different Domains



Fast Physical Optics by Field Tracing

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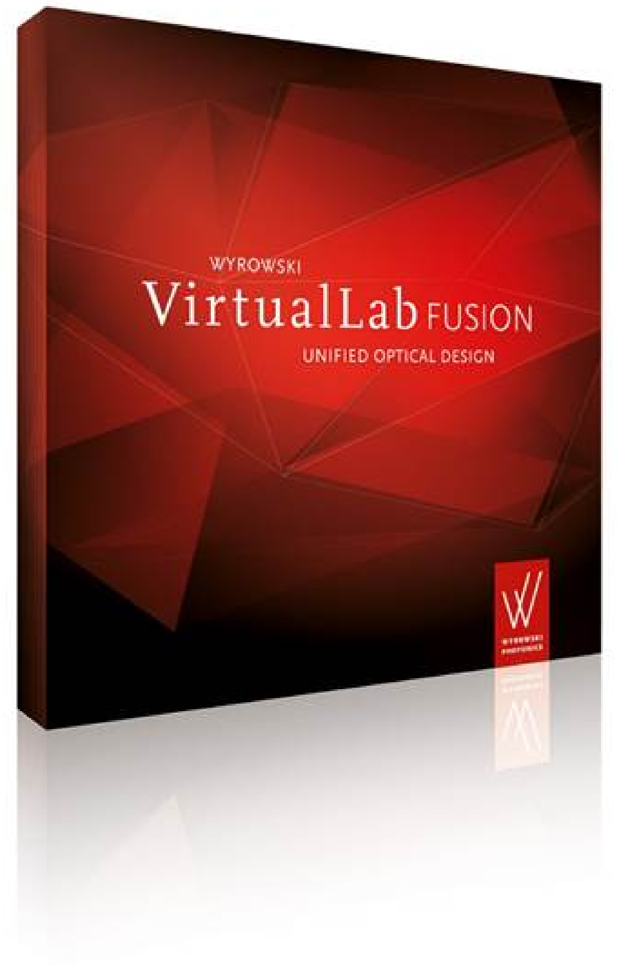
  1. Tearing: decomposed the whole optical system into regions and specialized Maxwell solvers are applied locally
  2. Interconnection: solutions in each regions are connected by the general non-sequential field tracing concept
  3. Field tracing operators should have numerical operation numbers linear with field sampling number *N*
  4. The field sampling number *N* should be minimized

     - Semi-analytical Fourier transform
       Z. Wang *et al*., „The semi-analytical fast Fourier transform," Proc. DGaO (2017)
     - Geometric Fourier transform
       F. Wyrowski *et al*., „The geometric Fourier transform," Proc. DGaO (2017)

Fourier transforms

Implementation

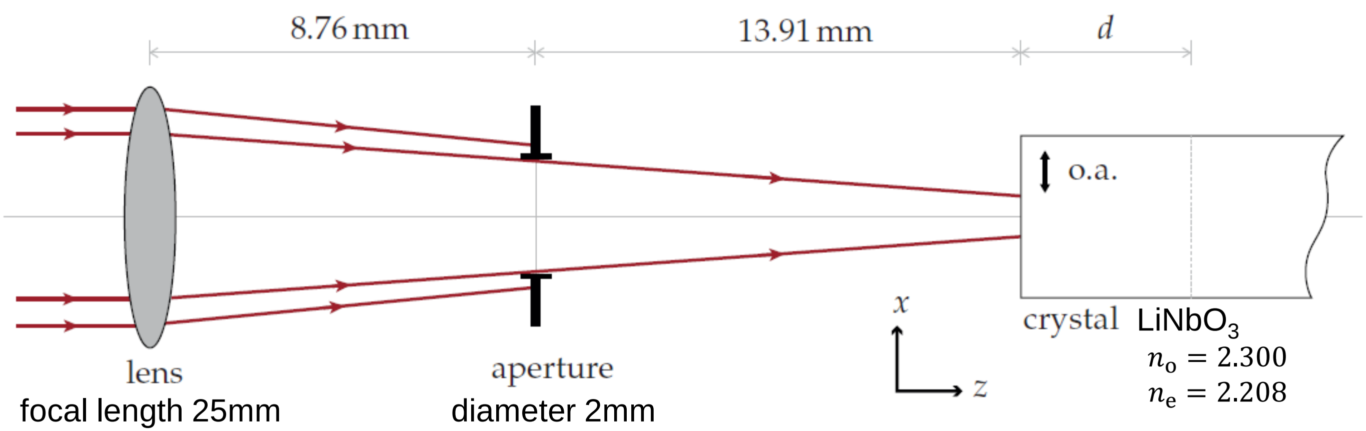
- All algorithms are implemented in the physical optics simulation and design software **VirtualLab Fusion**
- VirtualLab Fusion is developed, following the field tracing concept, by Wyrowski Photonics UG, Jena, Germany
- Visit German pavilion @**booth 4629-48** for more infomation



Example – Focusing Properties inside Crystal

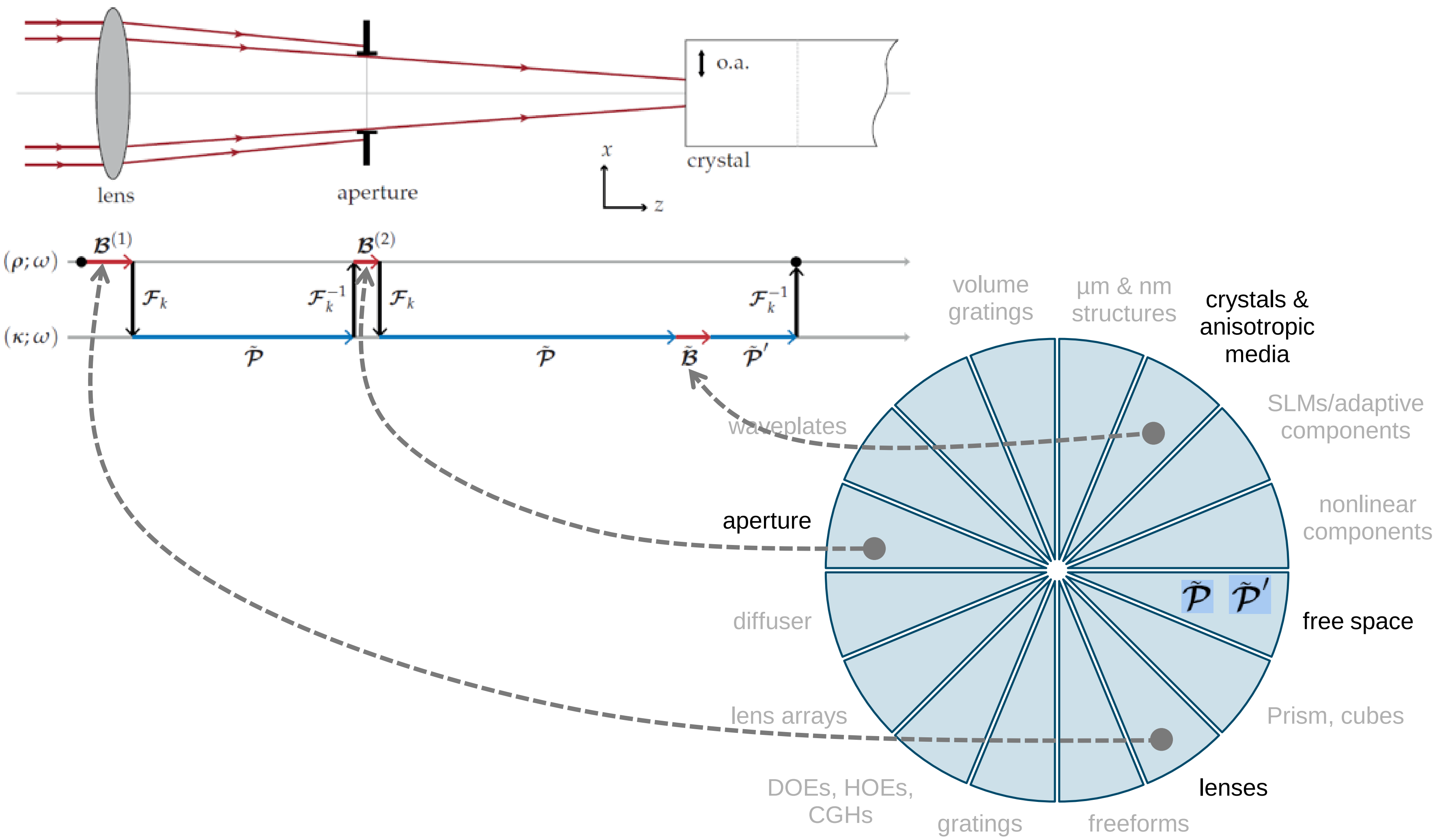
- Many laser crystals are made out of birefringent materials whose optical properties depends strongly on the polarization of light and the orientation of the crystal

Input laser beam
633nm wavelength
linearly polarized
along *x* direction



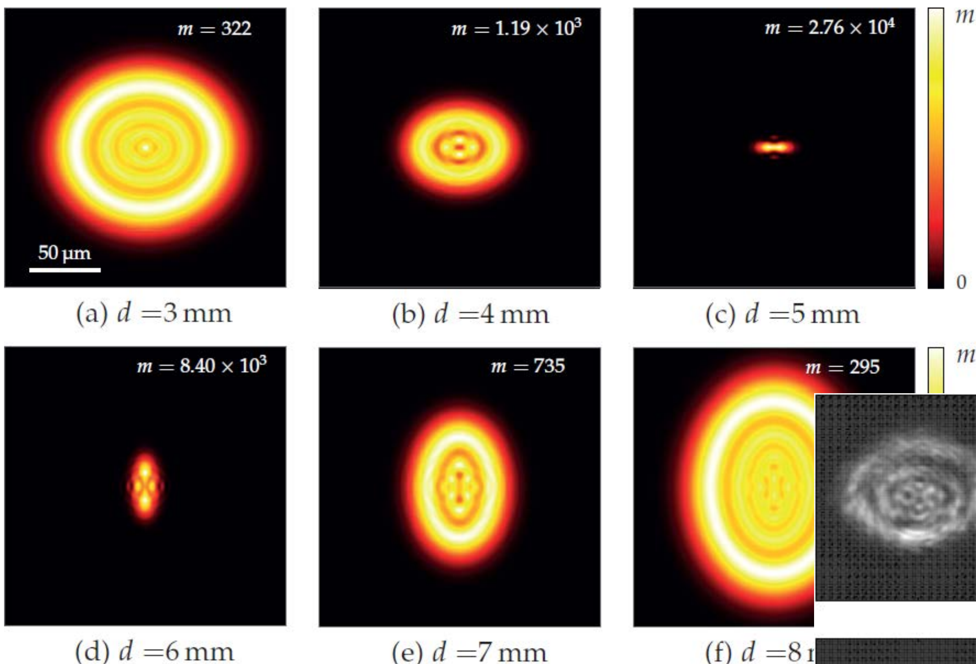
The optic axis of the crystal is first set along the *x* direction, then along the *y* direction

Field Tracing Diagram

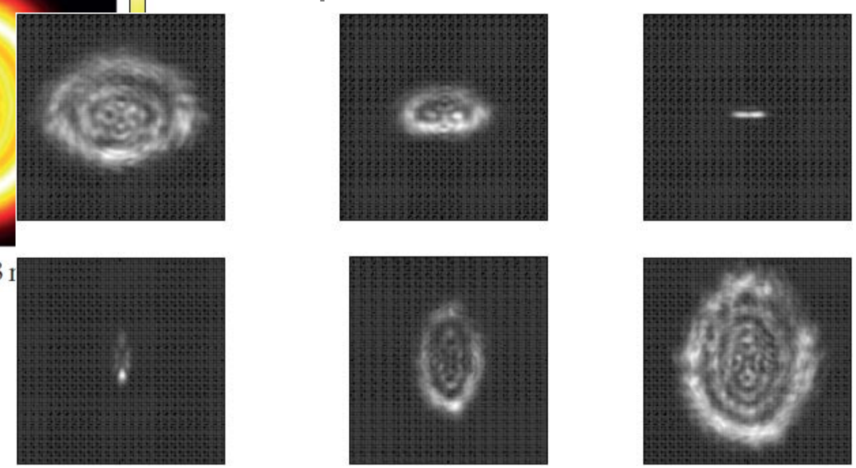


Simulation Results

- Light distribution at different depth (o.a. along *y* direction)



Experimental measurement



Calculation at one depth: ~ **9** s
with Intel Core i7-4910MQ

M. Jain et al., J. Opt. Soc. Am. A 26, 691-698 (2009)

Simulation Results

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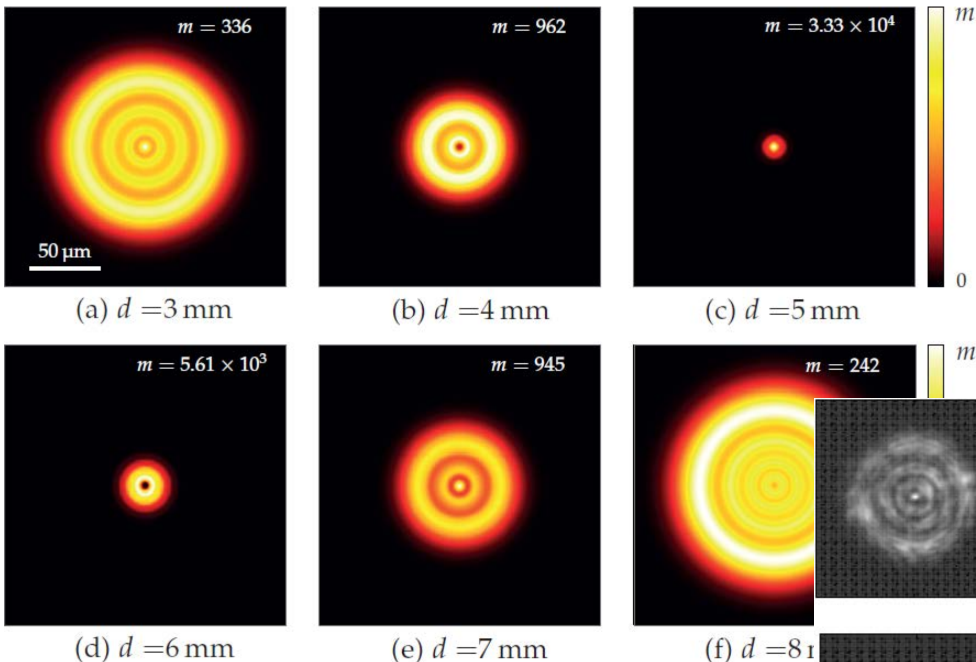

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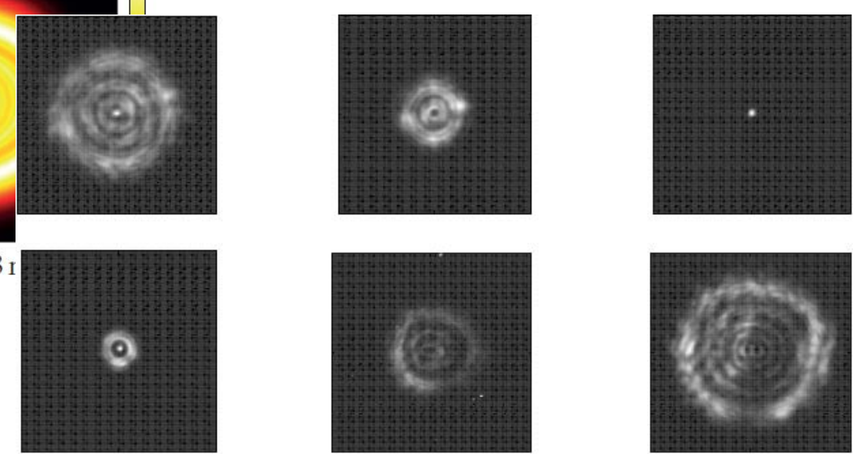

M. Jain et al., J. Opt. Soc. Am. A 26, 691-698 (2009)

Example – Stress Birefringence

- Laser-based soldering
  - Contact free heating, versatile to use
  - Localized and minimized input of energy
  - Flux-free processing, no contamination

P. Ribes-Pleguezuelo *et al.*, Opt. Express **25**, 5927-5940 (2017)

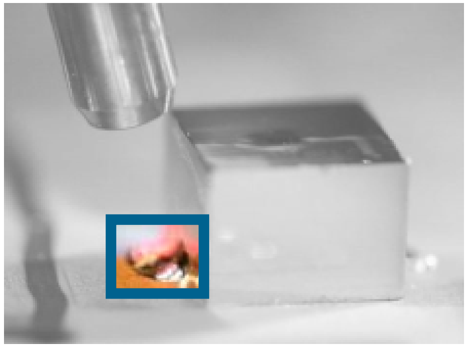

Photo from Fraunhofer IOF

- ANSYS
  - Structural/material definition
  - Transient thermal analysis
  - Stress simulation inside crystal component
- VirtualLab
  - Convert stress into optical permittivity data
  - Simulation of field propagation through birefringent materials

From Stress to Birefringence

- Convert stress to optical permittivity
  (for each layer inside stratified medium)

Stress tensor

$$\begin{pmatrix} \sigma_1 & \sigma_6 & \sigma_5 \\ \sigma_6 & \sigma_2 & \sigma_4 \\ \sigma_5 & \sigma_4 & \sigma_3 \end{pmatrix} \xrightarrow{\quad ? \quad} \begin{pmatrix} \epsilon_1 & \epsilon_6 & \epsilon_5 \\ \epsilon_6 & \epsilon_2 & \epsilon_4 \\ \epsilon_5 & \epsilon_4 & \epsilon_3 \end{pmatrix}$$

Permittivity tensor

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Piezo-optic constant

$$\Delta B_m = \pi_{mn} \sigma_n$$

Changes in
impermeability tensor

$$\begin{pmatrix} \Delta B_1 & \Delta B_6 & \Delta B_5 \\ \Delta B_6 & \Delta B_2 & \Delta B_4 \\ \Delta B_5 & \Delta B_4 & \Delta B_3 \end{pmatrix}$$

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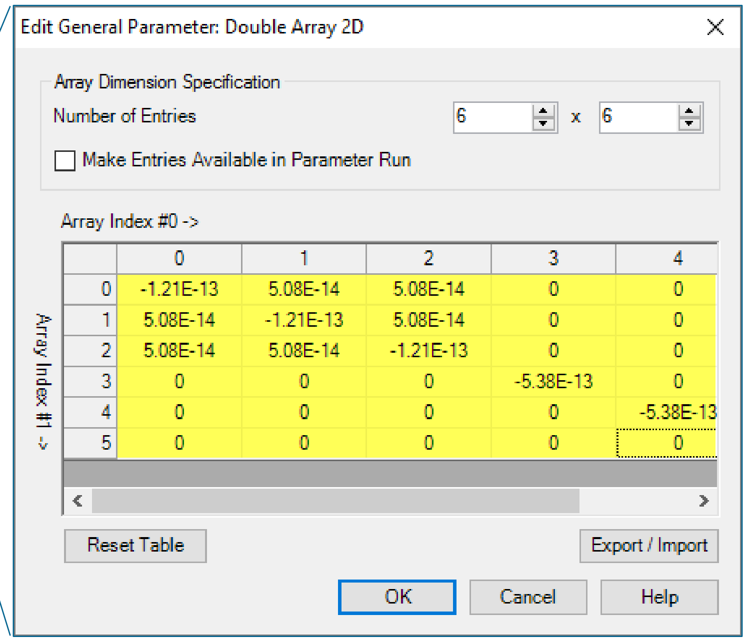

	0	1	2	3	4
0	-1.21E-13	5.08E-14	5.08E-14	0	0
1	5.08E-14	-1.21E-13	5.08E-14	0	0
2	5.08E-14	5.08E-14	-1.21E-13	0	0
3	0	0	0	-5.38E-13	0
4	0	0	0	0	-5.38E-13
5	0	0	0	0	0

Example: piezo-optic constant tensor for YAG crystal

From Stress to Birefringence

- Convert stress to optical permittivity
  (for each layer inside stratified medium)

Stress tensor

$$\begin{pmatrix} \sigma_1 & \sigma_6 & \sigma_5 \\ \sigma_6 & \sigma_2 & \sigma_4 \\ \sigma_5 & \sigma_4 & \sigma_3 \end{pmatrix}$$

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Changes in impermeability tensor

$$\begin{pmatrix} \Delta B_1 & \Delta B_6 & \Delta B_5 \\ \Delta B_6 & \Delta B_2 & \Delta B_4 \\ \Delta B_5 & \Delta B_4 & \Delta B_3 \end{pmatrix}$$

$$B_m = \boxed{B_{0,m}} + \Delta B_m$$

Stress-free values (related to refractive index/indicies)

Impermeability tensor

$$\begin{pmatrix} B_1 & B_6 & B_5 \\ B_6 & B_2 & B_4 \\ B_5 & B_4 & B_3 \end{pmatrix}$$

From Stress to Birefringence

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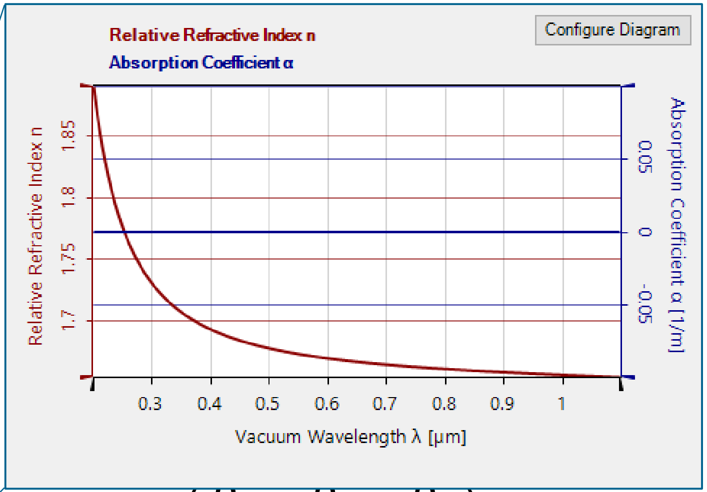
$$B_m = B_{0,m} + \Delta B_m$$

$$\begin{pmatrix} B_1 & B_6 & B_5 \\ B_6 & B_2 & B_4 \\ B_5 & B_4 & B_3 \end{pmatrix}$$

Example: ordinary refractive index for BBO crystal



Stress-free values
(related to refractive index/indicies)

From Stress to Birefringence

- Convert stress to optical permittivity
  (for each layer inside stratified medium)

Stress tensor

$$\begin{pmatrix} \sigma_1 & \sigma_6 & \sigma_5 \\ \sigma_6 & \sigma_2 & \sigma_4 \\ \sigma_5 & \sigma_4 & \sigma_3 \end{pmatrix}$$

Piezo-optic constant

$$\Delta B_m = \boxed{\pi_{mn}} \sigma_n$$

Changes in impermeability tensor

$$\begin{pmatrix} \Delta B_1 & \Delta B_6 & \Delta B_5 \\ \Delta B_6 & \Delta B_2 & \Delta B_4 \\ \Delta B_5 & \Delta B_4 & \Delta B_3 \end{pmatrix}$$

$$B_m = \boxed{B_{0,m}} + \Delta B_m$$

Stress-free values

(related to refractive index/indicies)

Impermeability tensor

$$\begin{pmatrix} B_1 & B_6 & B_5 \\ B_6 & B_2 & B_4 \\ B_5 & B_4 & B_3 \end{pmatrix}$$

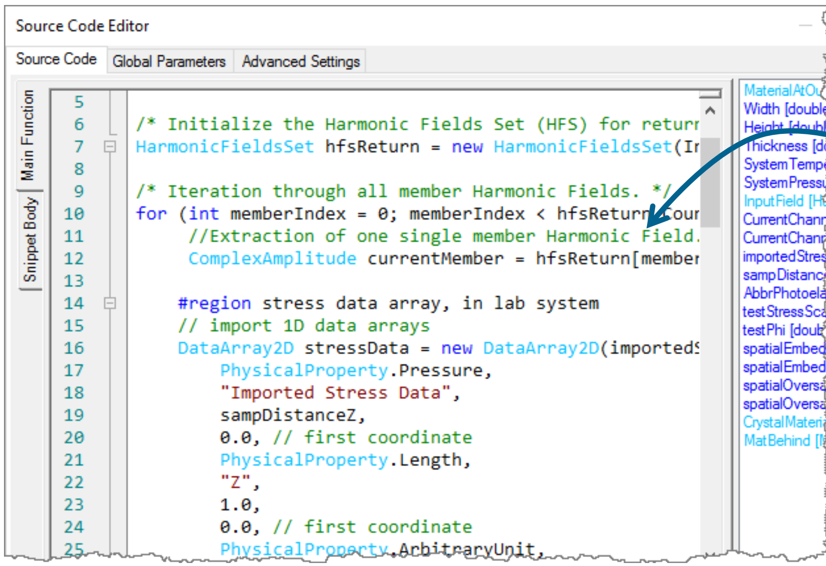
$$[\epsilon_{ij}]^{-1} = [B_{ij}]$$

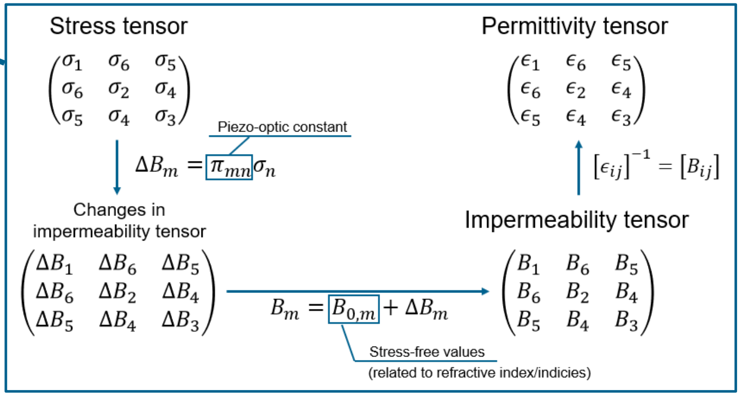
Permittivity tensor

$$\begin{pmatrix} \epsilon_1 & \epsilon_6 & \epsilon_5 \\ \epsilon_6 & \epsilon_2 & \epsilon_4 \\ \epsilon_5 & \epsilon_4 & \epsilon_3 \end{pmatrix}$$

VirtualLab Simulation

- Convert stress to optical permittivity



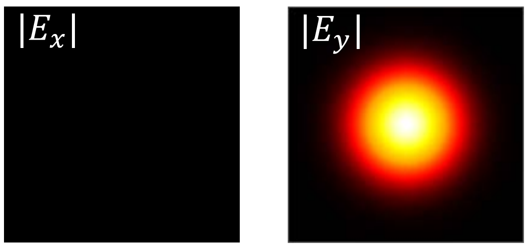


Conversion from stress tensor to the corresponding permittivity tensor is implemented by using the programmable component in VirtualLab

Simulation Results

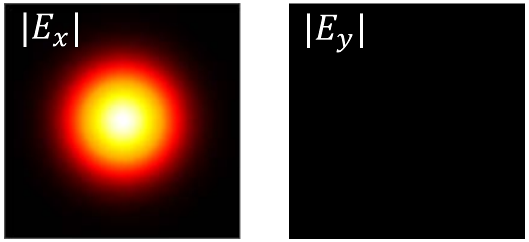
- Input field

1) @1064 nm



(waist radius 50 µm)

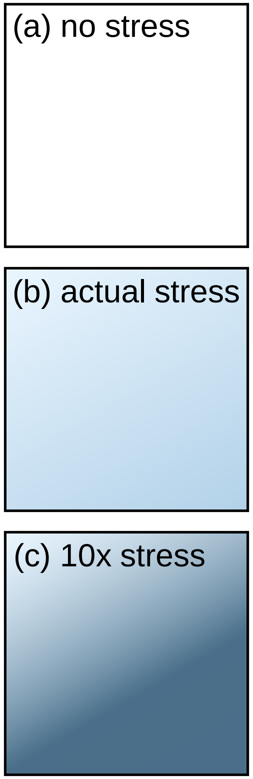
2) @532 nm



(waist radius 50 µm)

Note: we set the polarization according to the SHG configuration

- Applied stress

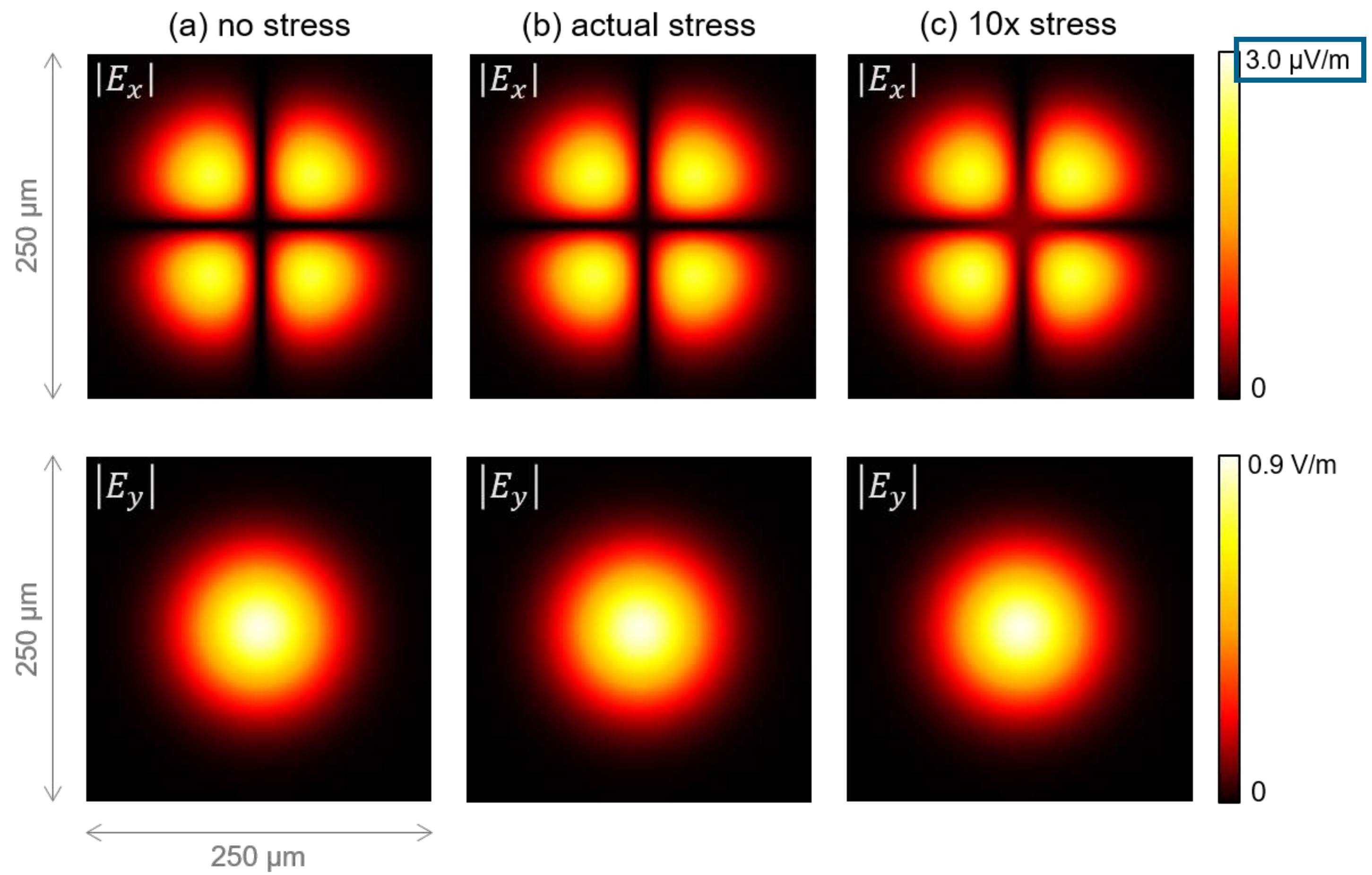


- Output field

?

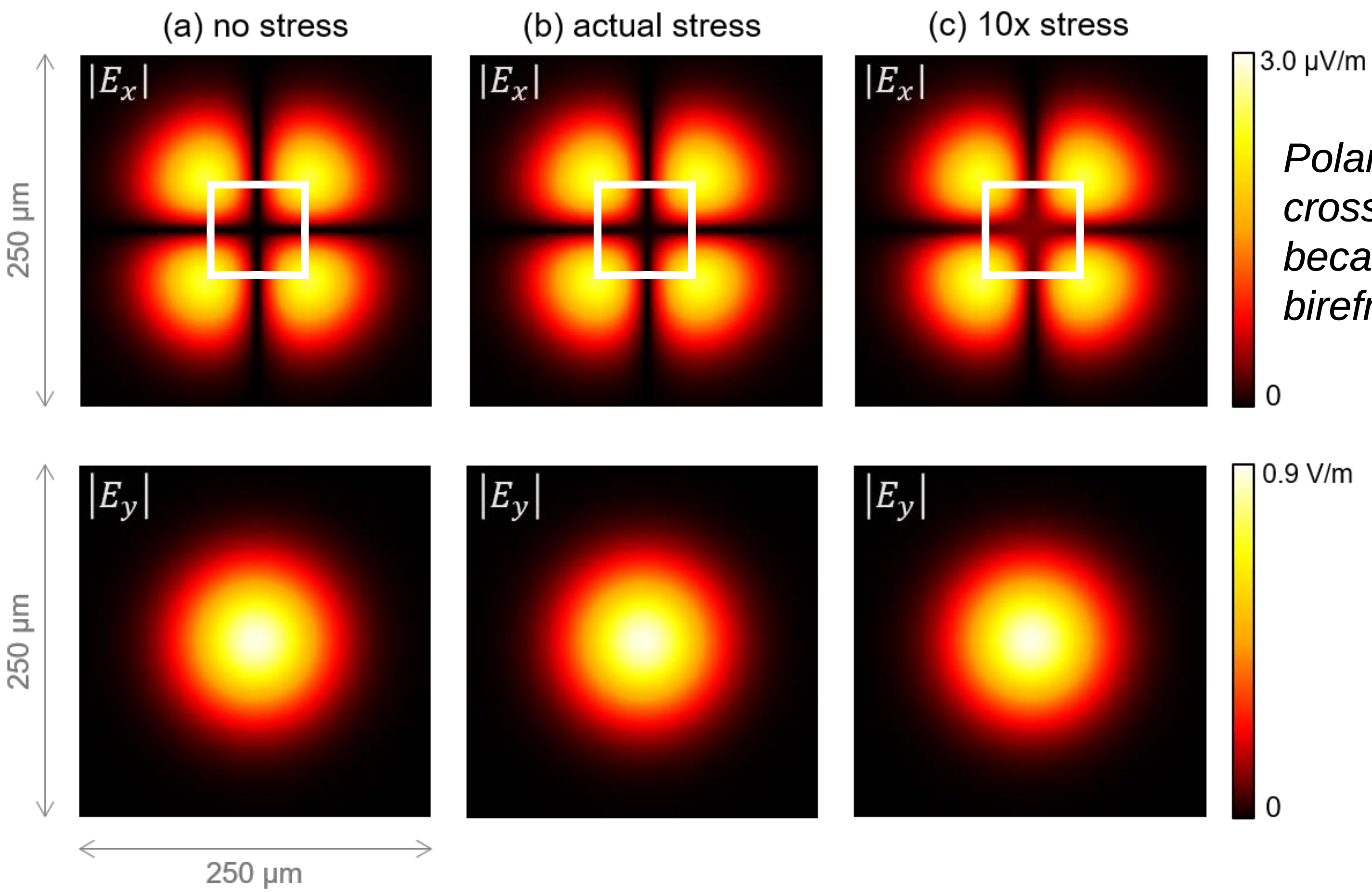
Simulation Results

- YAG crystal with 1064 nm input field (Ey)



Simulation Results

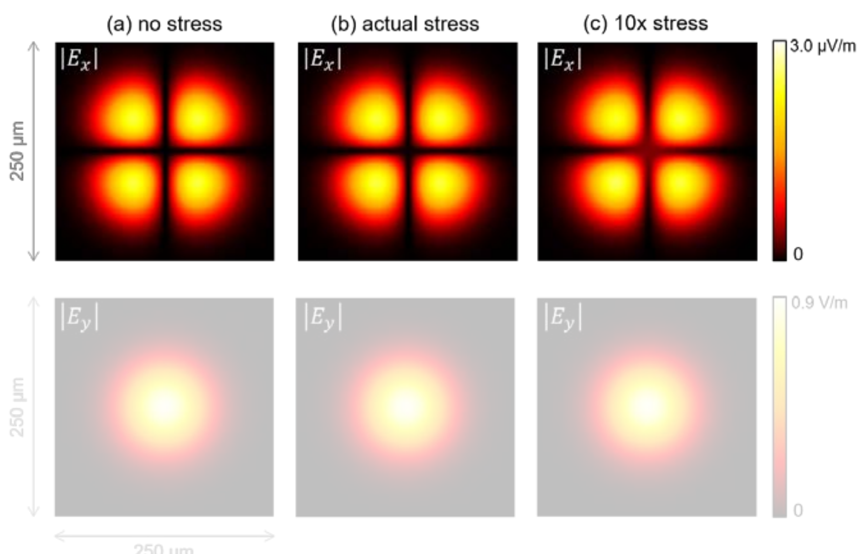
- YAG crystal with 1064 nm input field (Ey)



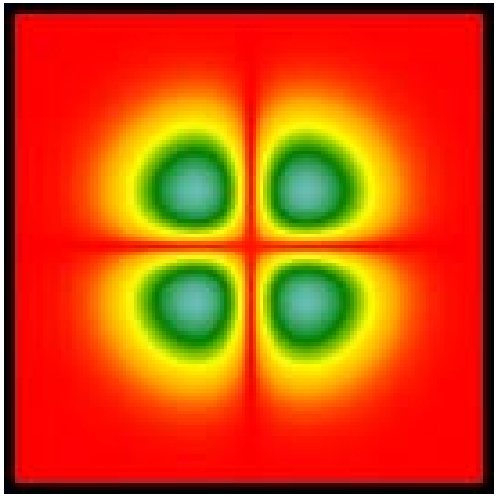
Polarization crosstalk (center) because of birefringence

Simulation Results

- YAG crystal with 1064 nm input field (Ey)
  - Further check on the influence of stress-induced birefringence, we perform parameter run from 1x to 201x stresses (with 101 steps)



from 1x to 201x stress

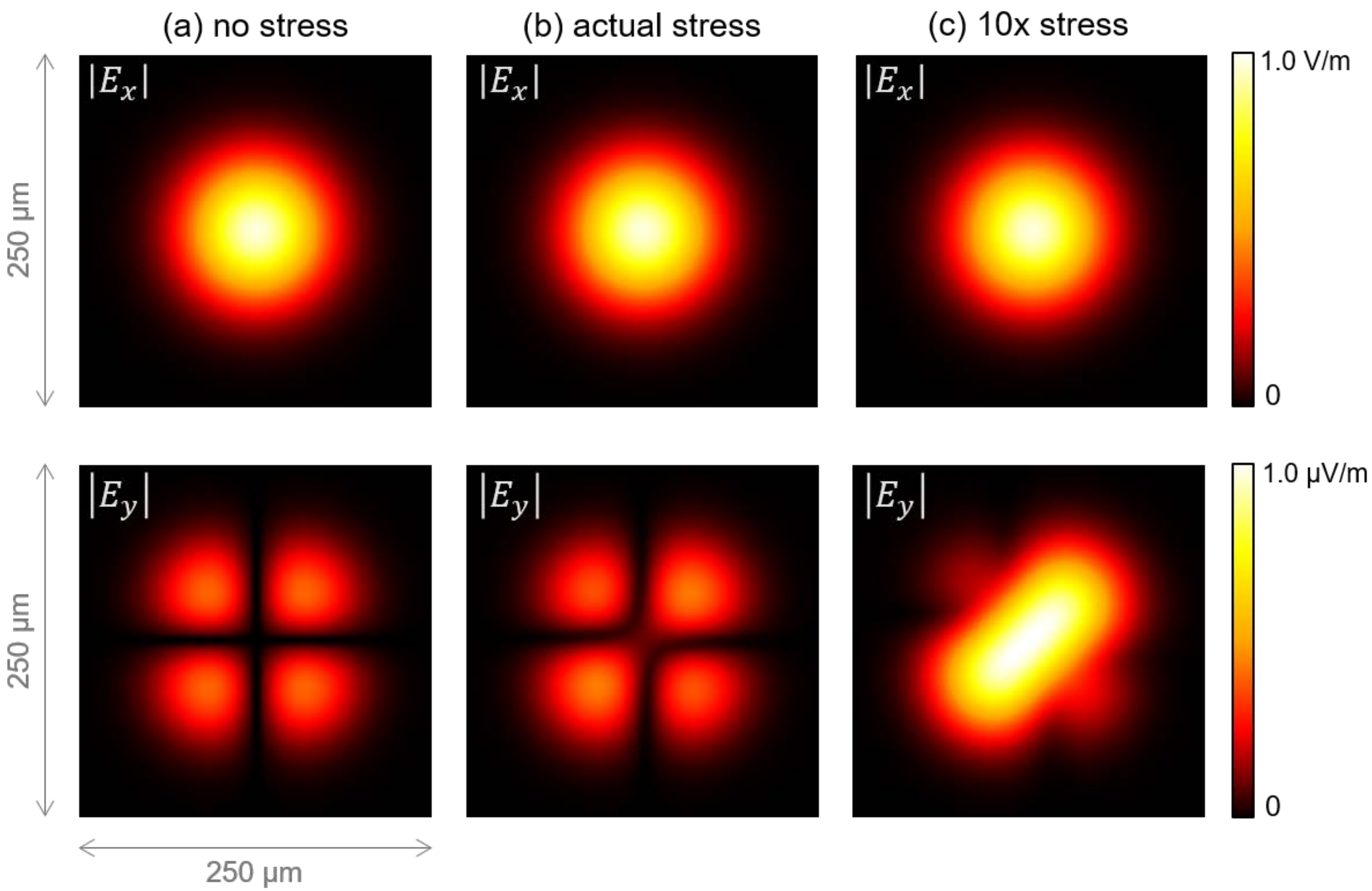


(logarithm color for better visibility)

Calculation of 101 steps: ~ **90** s
with Intel Core i7-4910MQ

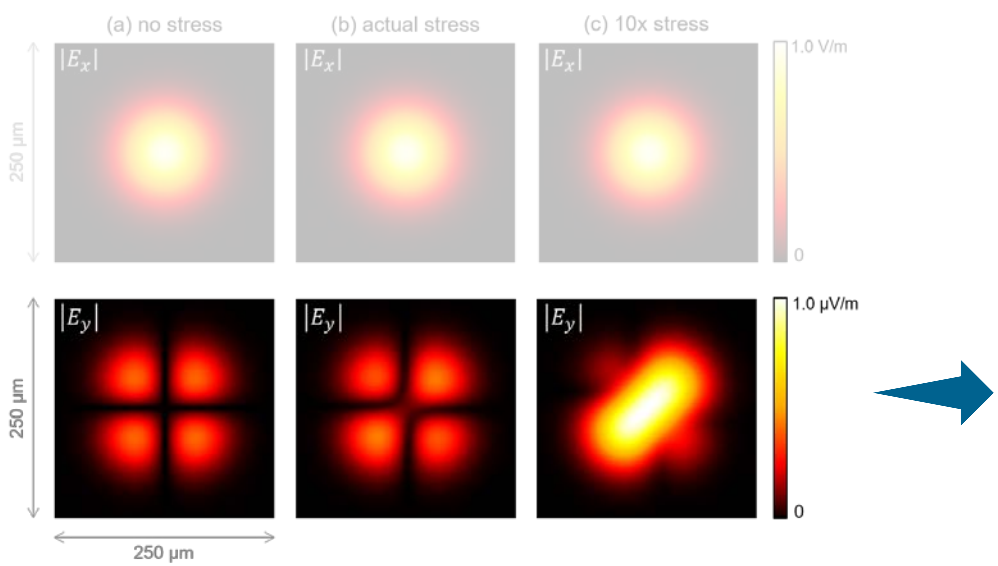
Simulation Results

- YAG crystal with 532 nm input field (Ex)

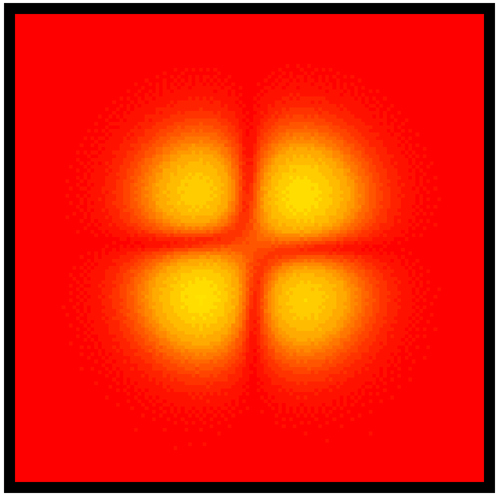


Simulation Results

- YAG crystal with 532 nm input field (Ex)
  - Further check on the influence of stress-induced birefringence, we perform parameter run from 1x to 51x stresses (with 101 steps)

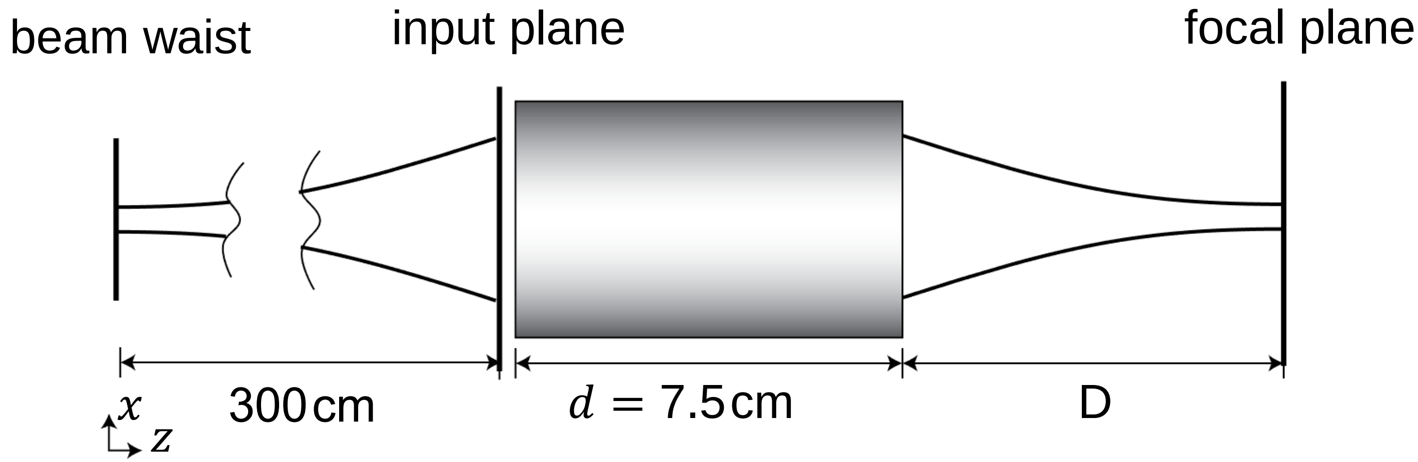


from 1x to 51x stress



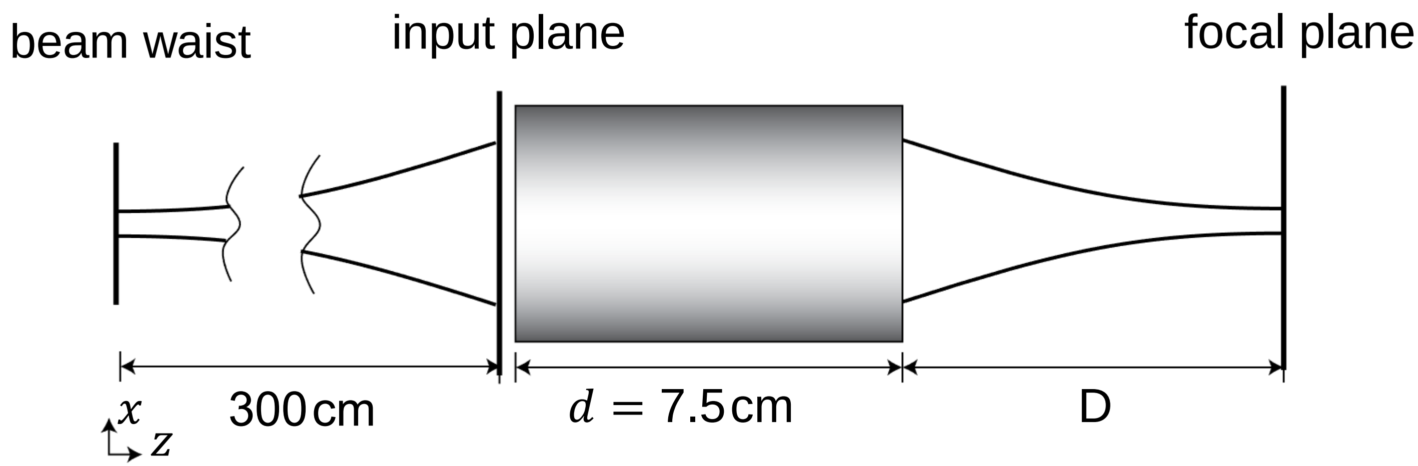
(logarithm color for better visibility)

Example – Thermal Lens Effect



- simulation of a Gaussian beam focused by thermal lens effect induced by a high power laser.
- the refractive index $n(x, y)$ of the thermal lens changes with varying input power.

Specifications: Light Source



Parameter	Description / Value
coherence/mode	single Laguerre Gaussian (0,0) and (1,0) mode
wavelength	632.8 nm
polarization	linear in x-direction (0°)
beam waist radius	simulation 1: (0,0) mode: 760 µm
	simulation 2: (1,0) mode: 1 mm

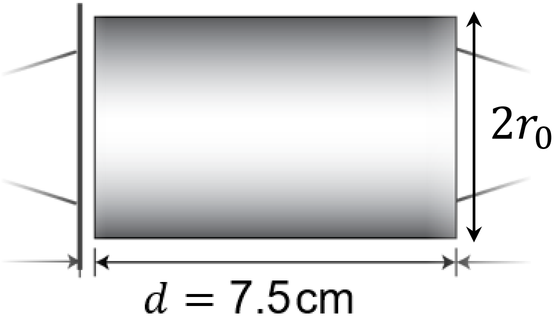
Specifications: Thermal Lens

- Refractive index is

$$n(x,y) = n_0 - \frac{\eta P_{\mathrm{in}}}{4K\pi d} \cdot \frac{\delta n}{\delta T} \cdot \frac{r^2}{r_0^2}$$

with $r = \sqrt{x^2 + y^2}$, r_0 and d are shown in the figure, P_{in} is input power, K, η and $\frac{\delta n}{\delta T}$ are temperature-related parameters which can be found in [1]

- Here the values are
  - $r_0 = 0.31$cm, $d = 7.5$cm
  - $K = 11.1$ W/(cm℃), $\eta = 0.05$, $\frac{\delta n}{\delta T} = 7.3 \times 10^{-6}$℃$^{-1}$

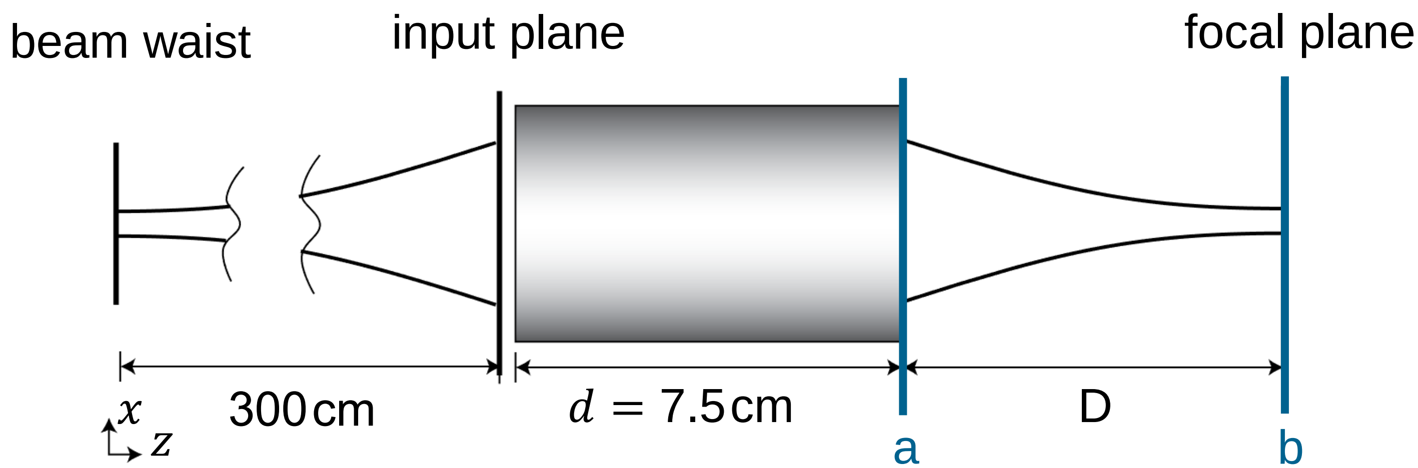


Highlight

arbitrarily customizable refractive index profile

[1] W. Koechner, "Thermal lensing in a nd:yag laser rod," Appl. Opt. **9**, 2548–2553 (1970).

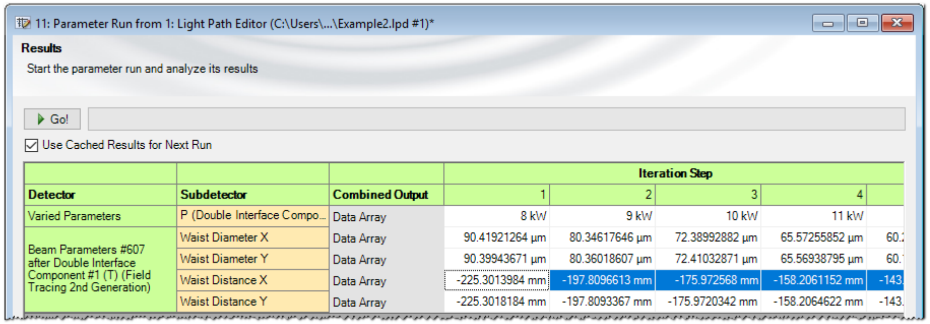
Specifications: Detector



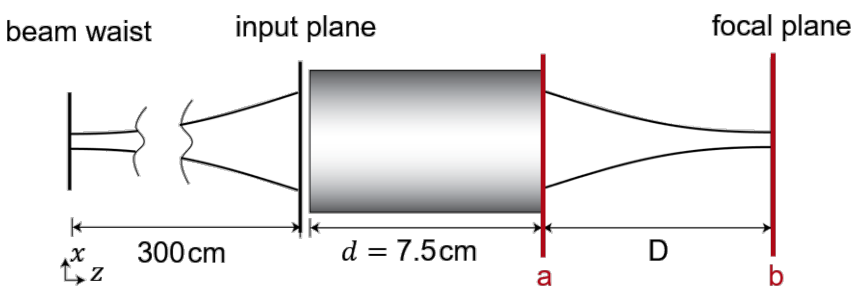
Position	Modeling Technique	Detector/Analyzer
a	field tracing	beam parameters for different input beams and input power values
b	field tracing	amplitude of E_x, E_y, E_z when input is (1,0) mode

Results: (0,0) Mode

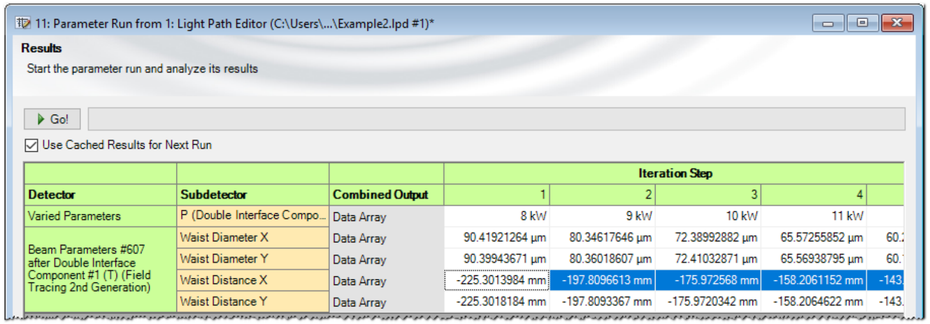
- Using the *Parameter Run* document, one can calculate the output beam parameters for input powers varying from 8 kW to 20 kW. The detector is at position *a.*
  - Absolute value of *Waist Distance* (distance *a* with respect to *b*) is distance *D.*
  - *Waist Diameter* is the waist diameter in focal plane (position *b*).



			Iteration Step				
Detector	Subdetector	Combined Output	1	2	3	4	
Varied Parameters	P (Double Interface Compo...	Data Array	8 kW	9 kW	10 kW	11 kW	
Beam Parameters #607 after Double Interface Component #1 (T) (Field Tracing 2nd Generation)	Waist Diameter X	Data Array	90.41921264 µm	80.34617646 µm	72.38992882 µm	65.57255852 µm	60.
	Waist Diameter Y	Data Array	90.39943671 µm	80.36018607 µm	72.41032871 µm	65.56938795 µm	60.
	Waist Distance X	Data Array	-225.3013984 mm	-197.8096613 mm	-175.972568 mm	-158.2061152 mm	-143.
	Waist Distance Y	Data Array	-225.3018184 mm	-197.8093367 mm	-175.9720342 mm	-158.2064622 mm	-143.



Results: (0,0) Mode



			Iteration Step				
Detector	Subdetector	Combined Output	1	2	3	4	
Varied Parameters	P (Double Interface Compo...	Data Array	8 kW	9 kW	10 kW	11 kW	
Beam Parameters #607 after Double Interface Component #1 (T) (Field Tracing 2nd Generation)	Waist Diameter X	Data Array	90.41921264 µm	80.34617646 µm	72.38992882 µm	65.57255852 µm	60.
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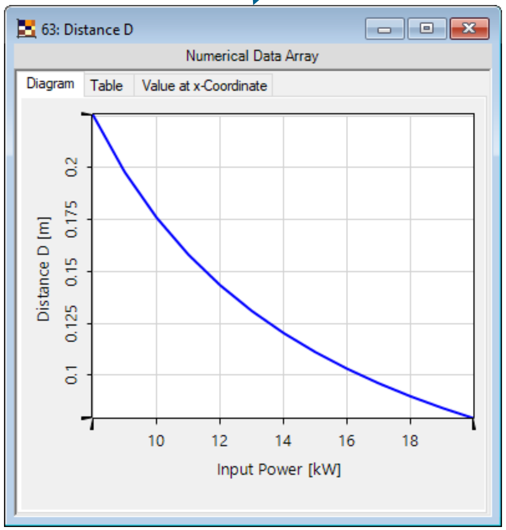
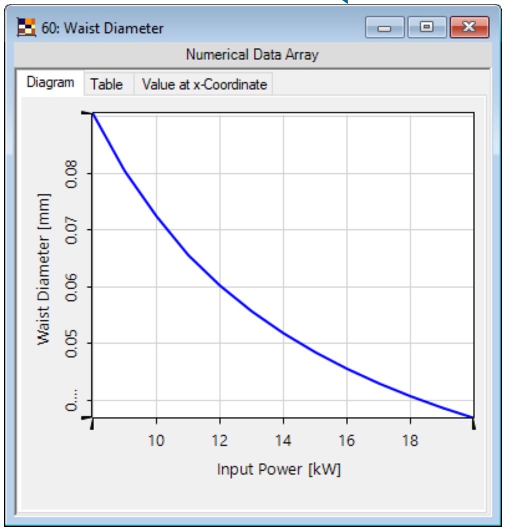
Highlight

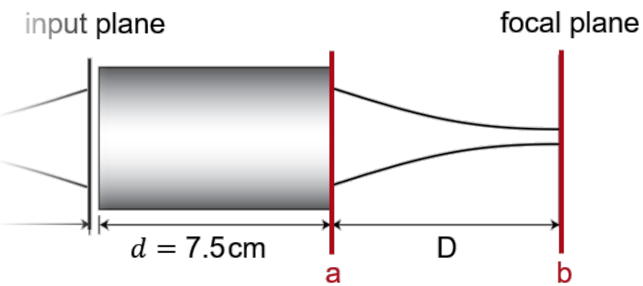
simulate conveniently one system with varying parameters



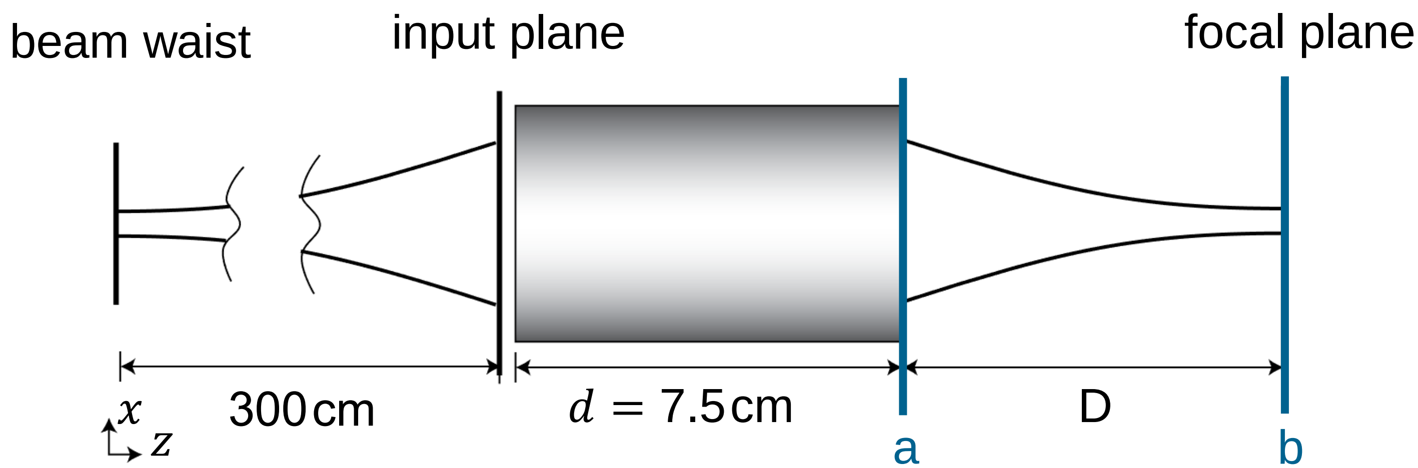
distance *D*



waist diameter at *b*



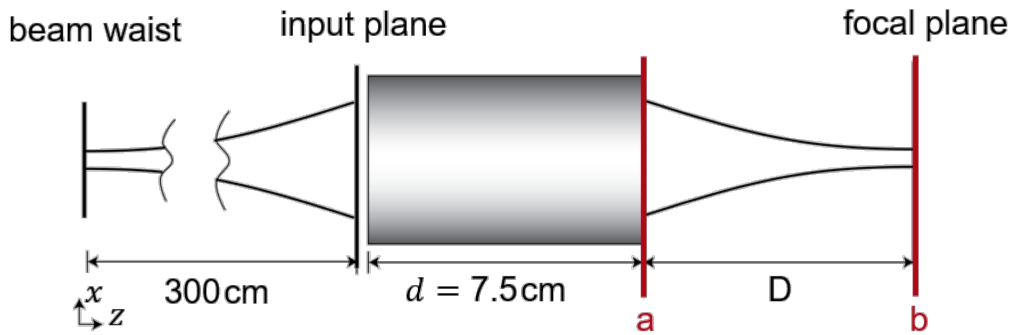
Results: (1,0) Mode



- For the thermal lens with applied 18 kW the simulated distance *D* is 91.0 mm.
- The technique to propagate fields through the thermal lens is described in [2].
- The technique to propagate fields from position *a* to *b* is diffractive propagation integral [3].

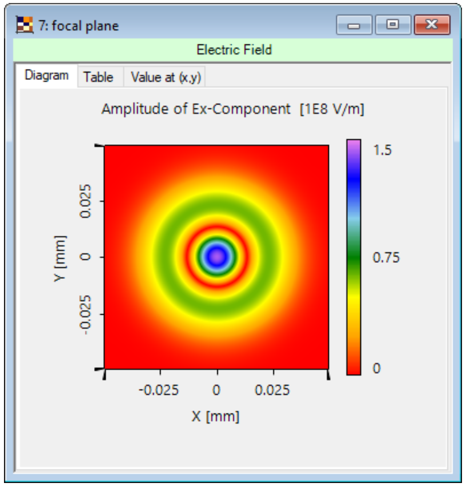
[2] H., Zhong, “Fast propagation of electromagnetic fields through Graded-Index Media,” submitted in JOSA A
[3] F. Wyrowski, “Unification of the geometric and diffractive theories of electromagnetic fields,” Proc. DGaO (2017).

Results: (1,0) Mode

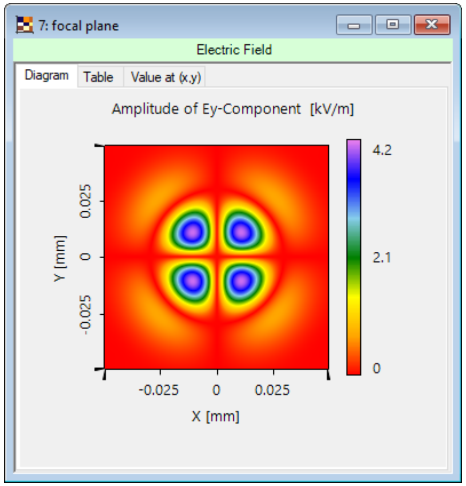


Highlight

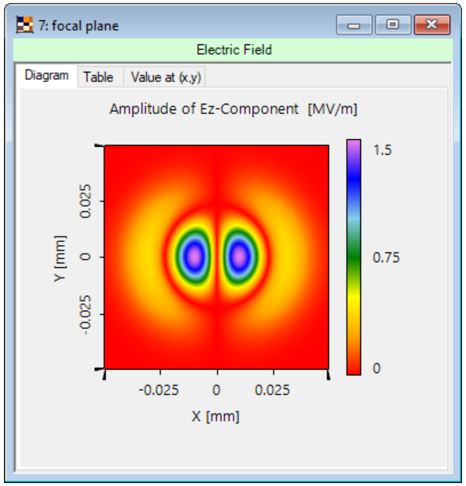
combination of different field tracing techniques



E_x



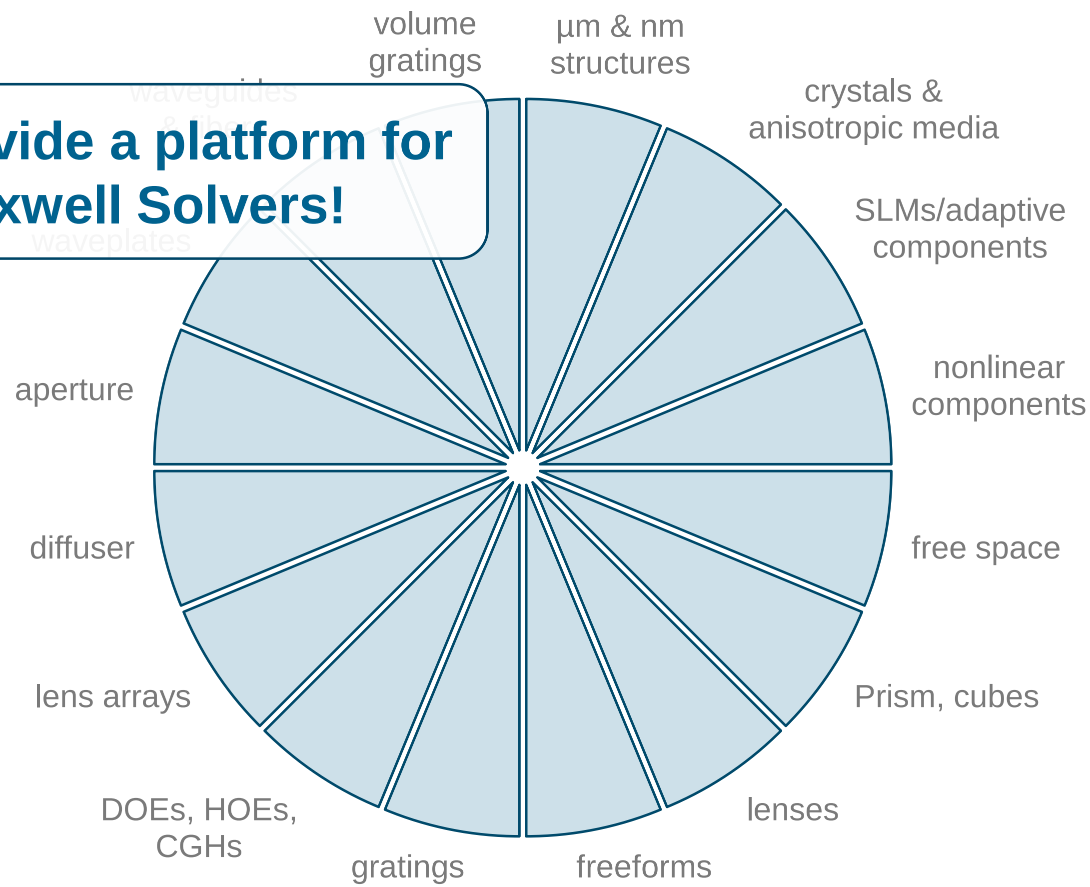
E_y



E_z

Summary

We provide a platform for fast Maxwell Solvers!



Announcement

- „**Fast propagation of electromagnetic field through graded-index media**", H. Zhong *et al*., 30 January 2018, 3:05 – 3:25 PM

- „**Non-paraxial diffractive and refractive laser beam shaping**", L. Yang *et al*., 1 February 2018, 2:25 – 2:45 PM

Free Optical Design Seminar

- „**Analysis and Design of Diffractive and Micro-Optical Systems with VirtualLab Fusion**"
  2 Feburary 2018, 09:30 – 16:15