SPIE Optics & Photonics, 12 August 2019

Physical-Optics-Based Tolerance Analysis for Fiber Coupling Systems

Huiying Zhong[1], Wenxiu Wang[1], Site Zhang[2], Christian Hellmann[3], and Frank Wyrowski[2]

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Jena, Germany

LightTrans International

LightTrans

- Distribution of VirtualLab Fusion, together with distributors worldwide
- Technical support, seminars, and trainings
- Engineering projects

University of Jena

Applied Computational Optics Group R&D in optical modeling and design with emphasis on physical optics

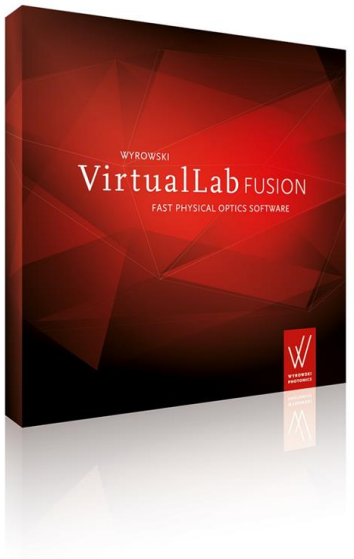
LIGHTTRANS

Wyrowski Photonics

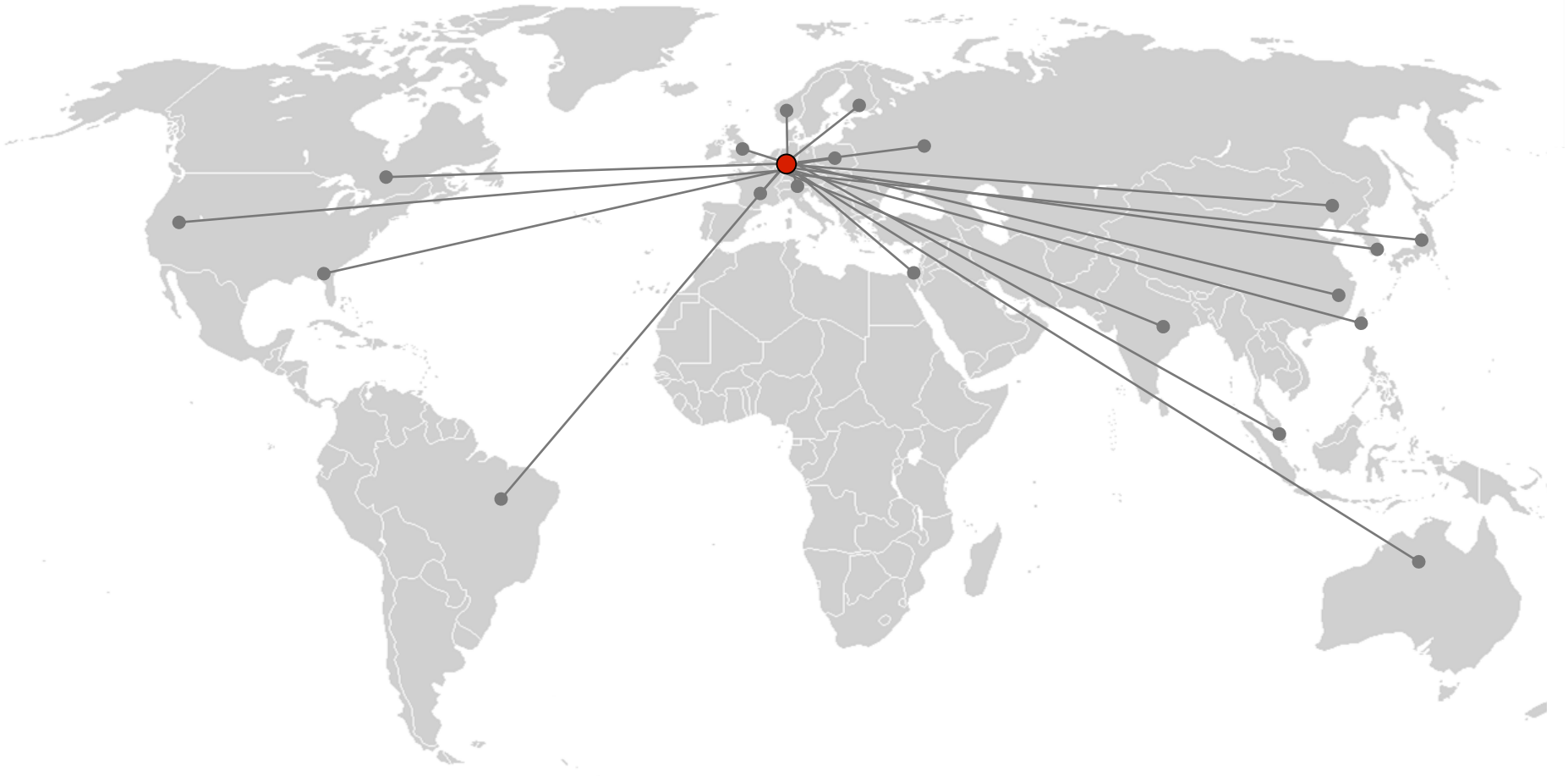
Wyrowski Photonics
Development of fast physical optics software VirtualLab Fusion

WYROWSKI PHOTONICS

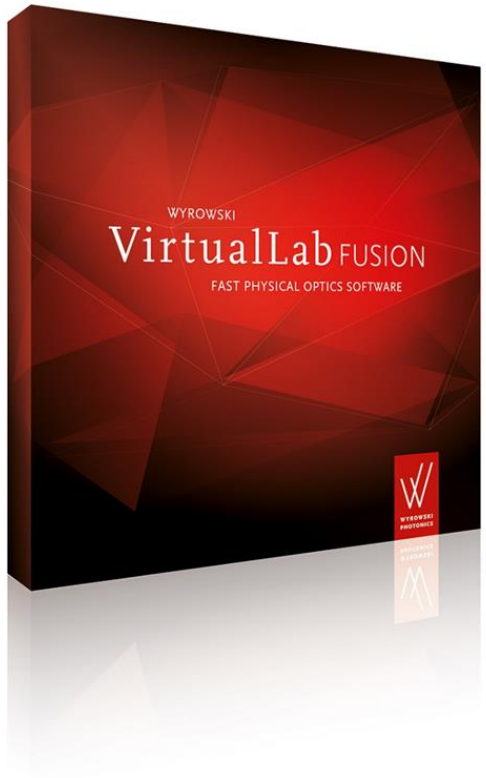
LIGHTTRANS



Optical Design Software and Services

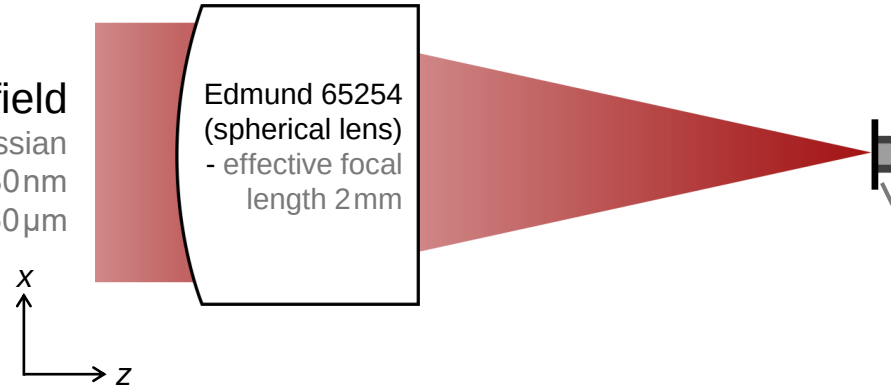


Booth #110



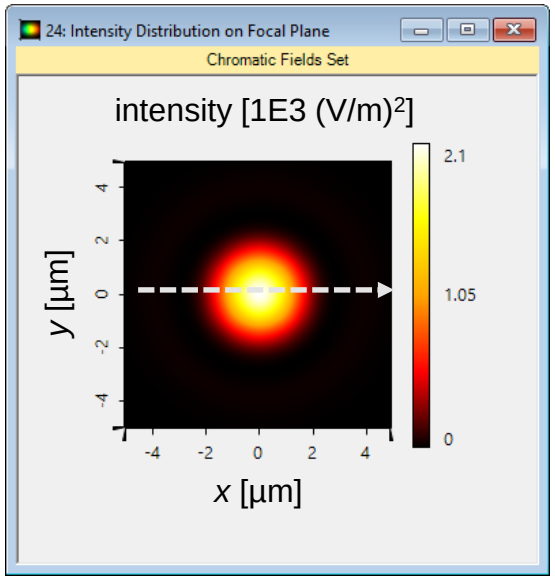
Modeling of Fiber Coupling Systems

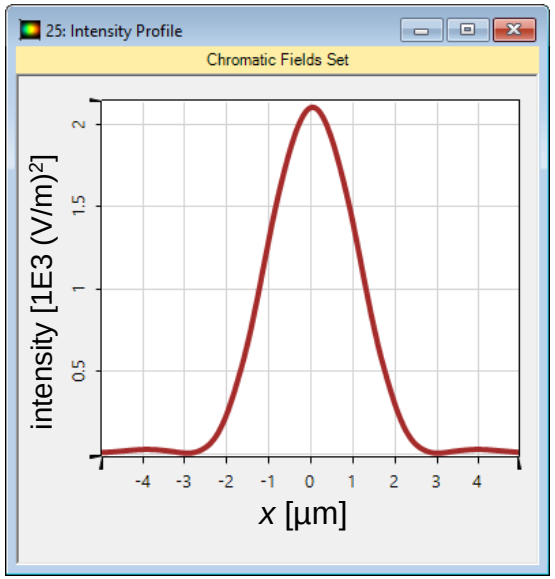
input field
- fundamental Gaussian
- wavelength 780 nm
- diameter 660 µm



coupling efficiency $\eta = 88.6\%$
(overlap integral calculation)

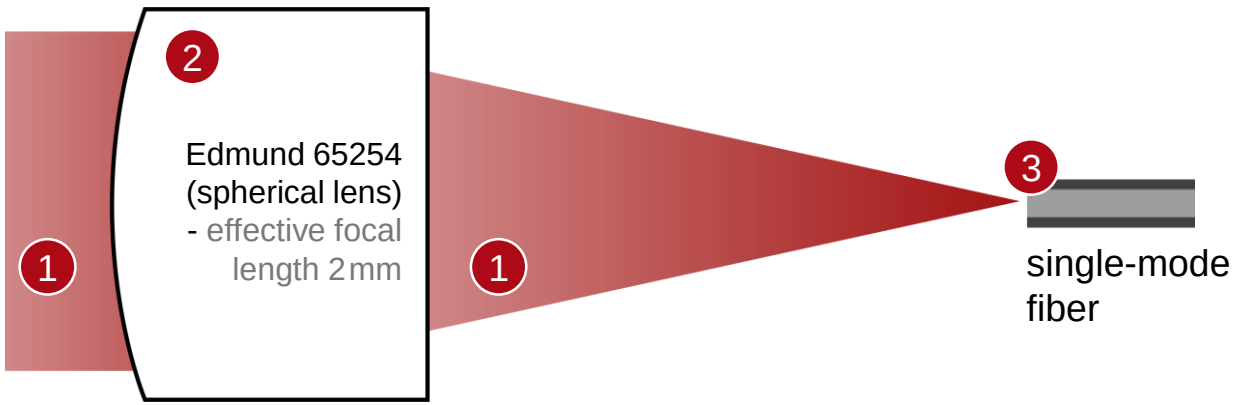
How to modeling such an optical system for fiber coupling?



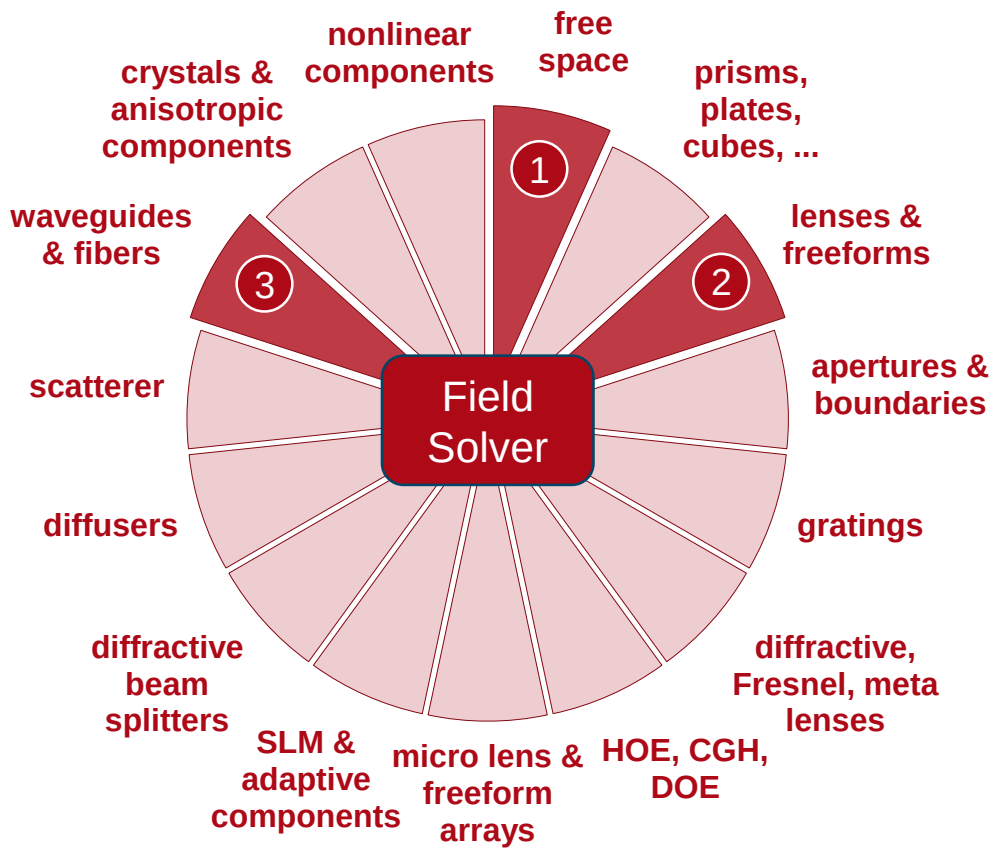


Field Tracing – Connecting Field Solvers

R. Shi, *et al*., "Physical-optics propagation through curved surfaces," J. Opt. Soc. Am. A 36, 1252-1260 (2019)



S. Zhang, *et al*., "Propagation of electromagnetic fields between non-parallel planes: a fully vectorial formulation and an efficient implementation," Appl. Opt. 55, 529-538 (2016)



Typical Application Scenarios

- How to find the optimal working distance for off-the-shelf fiber coupling lenses
- Compare the performances of different commercially available lenses
- Design a coupling lens with parametric optimization
- Perform tolerance and sensitivitiy analysis of fiber coupling setup

Typical Application Scenarios

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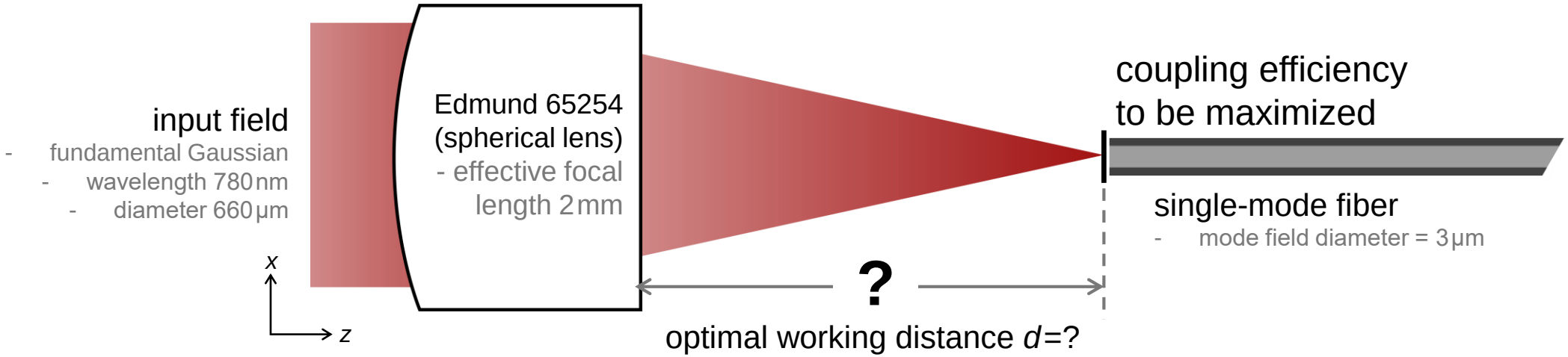
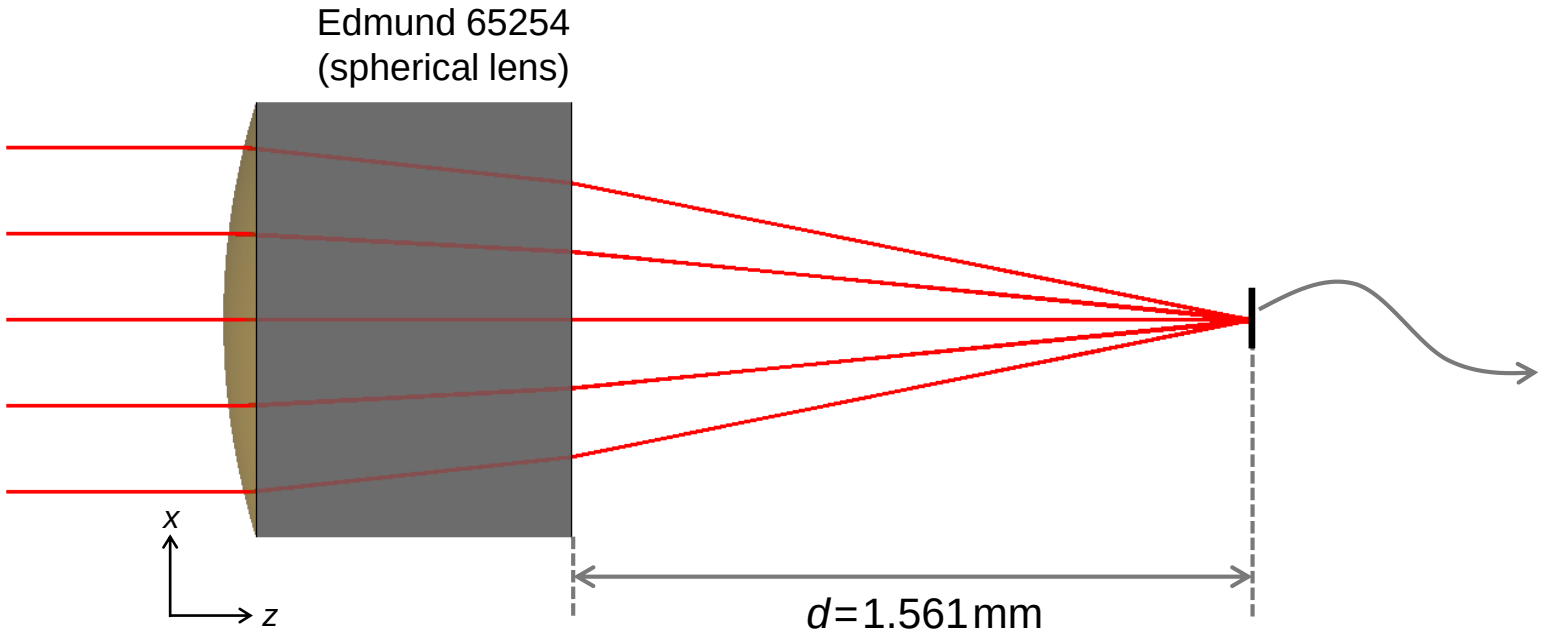
Optimal Working Distance for Coupling Light into Single-Mode Fibers

Modeling Task

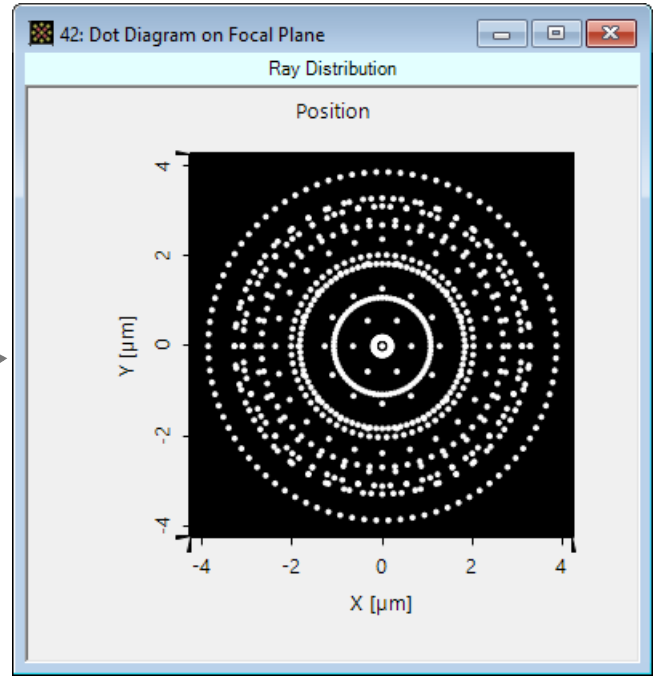


- Is it the best solution to place the fiber end at the ray-optics focal plane behind the lens?
- How to find the optimal working distance to achieve maximum coupling efficiency?

Focal Distance Found by Using Ray Tracing



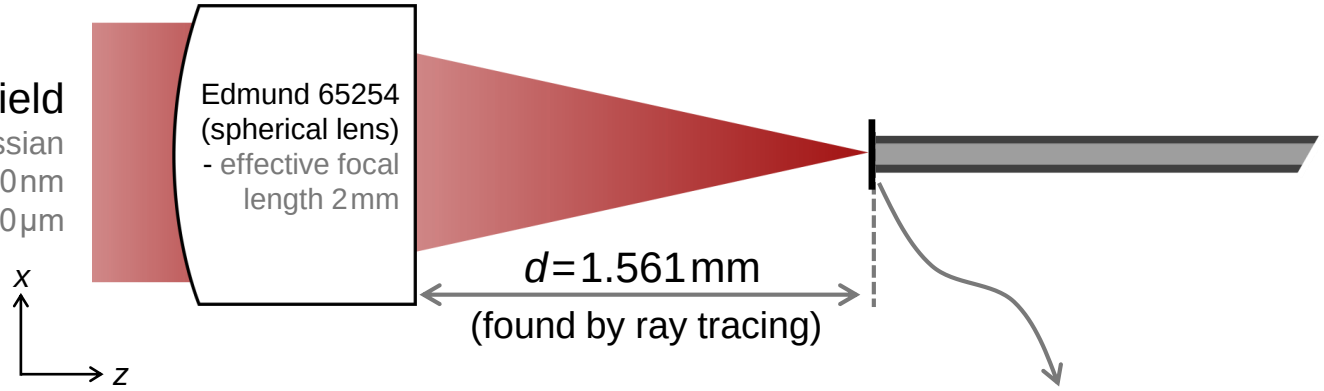
Focal distance for the spherical lens is found first by using ray tracing in VirtualLab.



The beam diameter (RMS) evaluated with ray tracing is 5.11 µm.

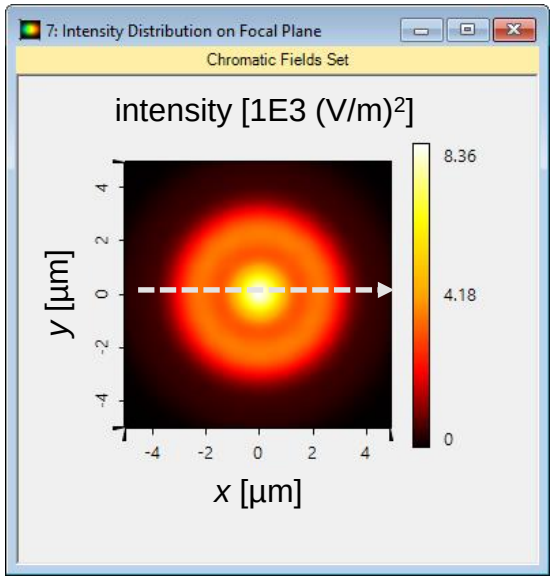
Field Tracing Evaluation at Ray-Optics Focal Distance

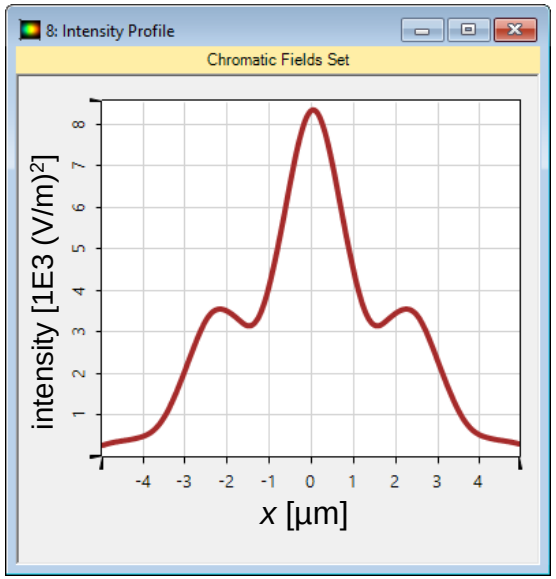
input field
- fundamental Gaussian
- wavelength 780 nm
- diameter 660 µm



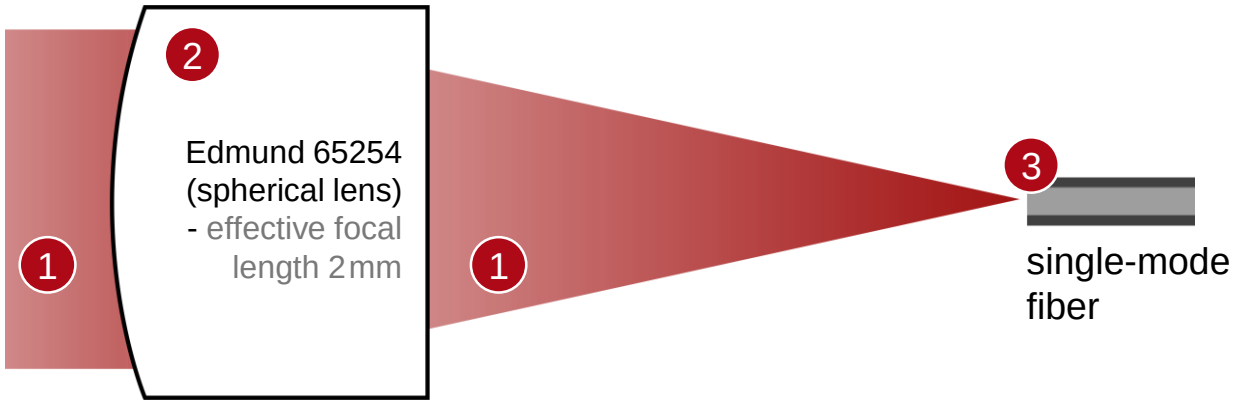
coupling efficiency $\eta = 29.4\%$
(overlap integral calculation)

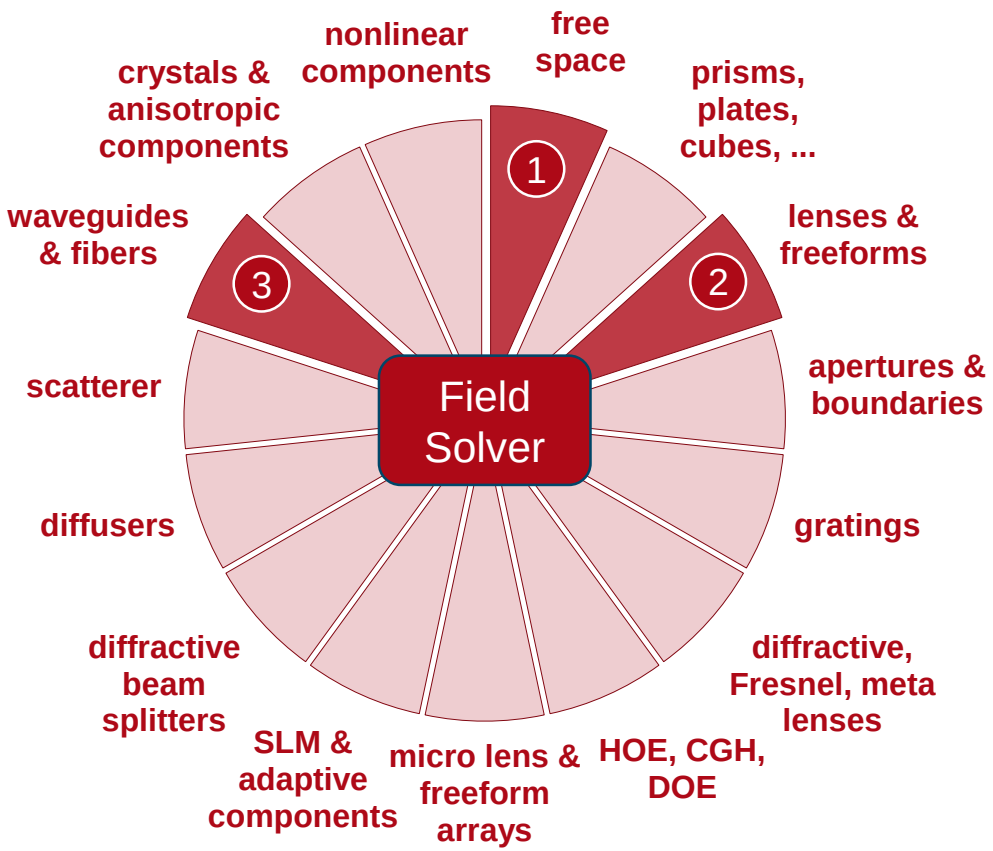
Field tracing in VirtualLab provide access to the full field information at any desired plane in the system.





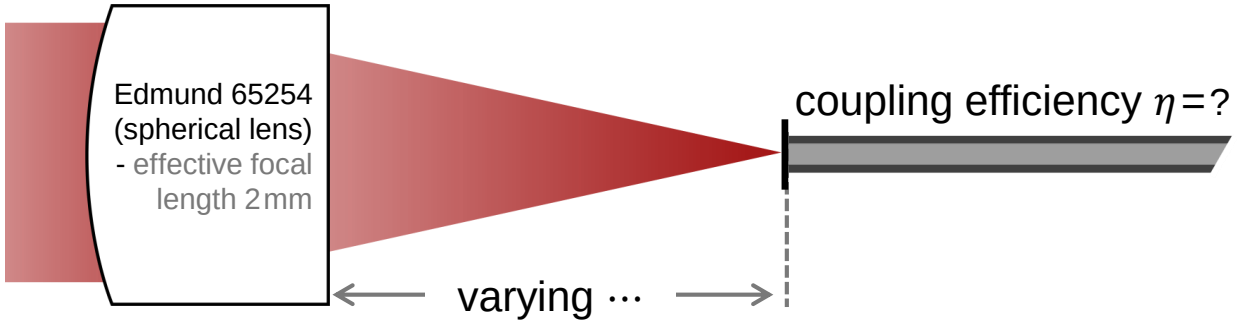
Field Tracing – Connecting Field Solvers

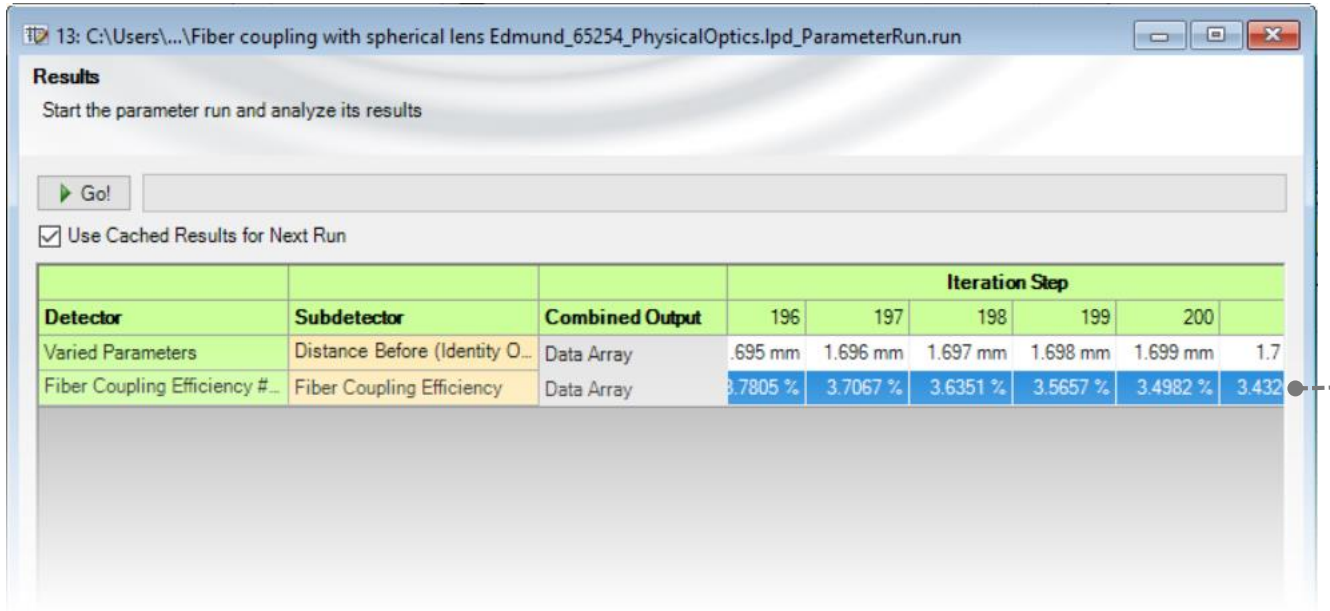


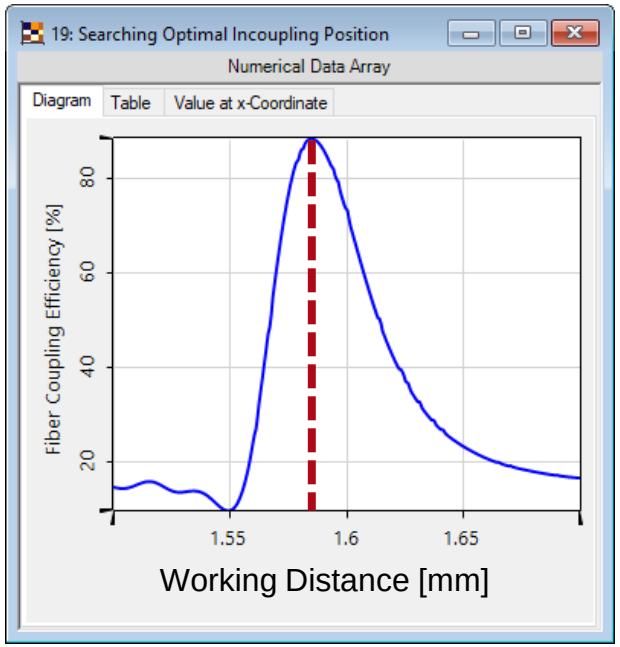


Find Optimal Working Distance by Using Field Tracing

input field
- fundamental Gaussian
- wavelength 780 nm
- diameter 660 µm



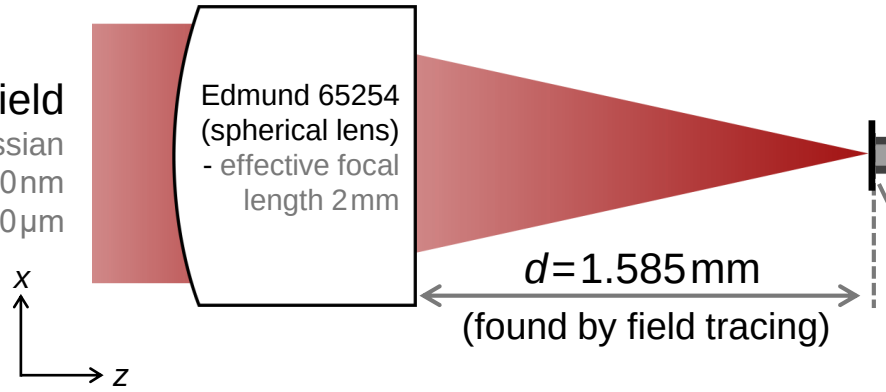




The optimal working distance found by field tracing is 1.585 mm.

Evaluation at Optimal Working Distance

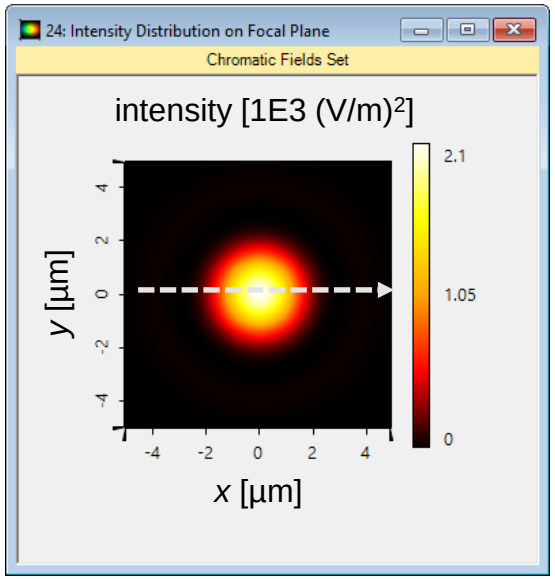
input field
- fundamental Gaussian
- wavelength 780 nm
- diameter 660 µm

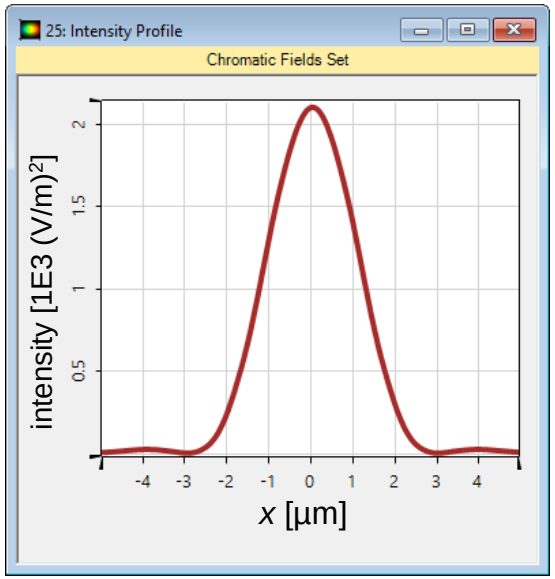


$d = 1.585$ mm
(found by field tracing)

coupling efficiency $\eta = 88.6\%$
(overlap integral calculation)

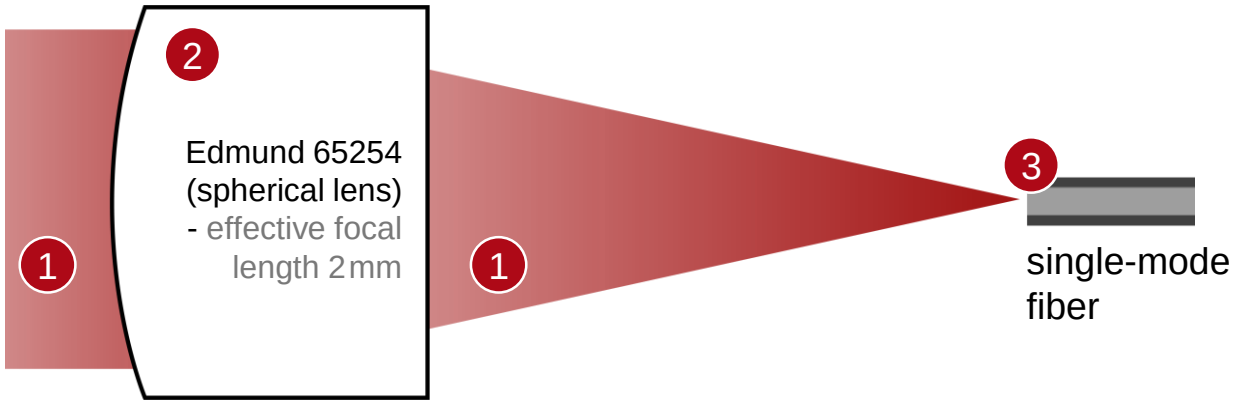
The calculation of the focal spot and the evaluation of the coupling efficiency takes only 2 seconds!





VirtualLab Fusion Technologies

R. Shi, *et al*., "Physical-optics propagation through curved surfaces," J. Opt. Soc. Am. A 36, 1252-1260 (2019)



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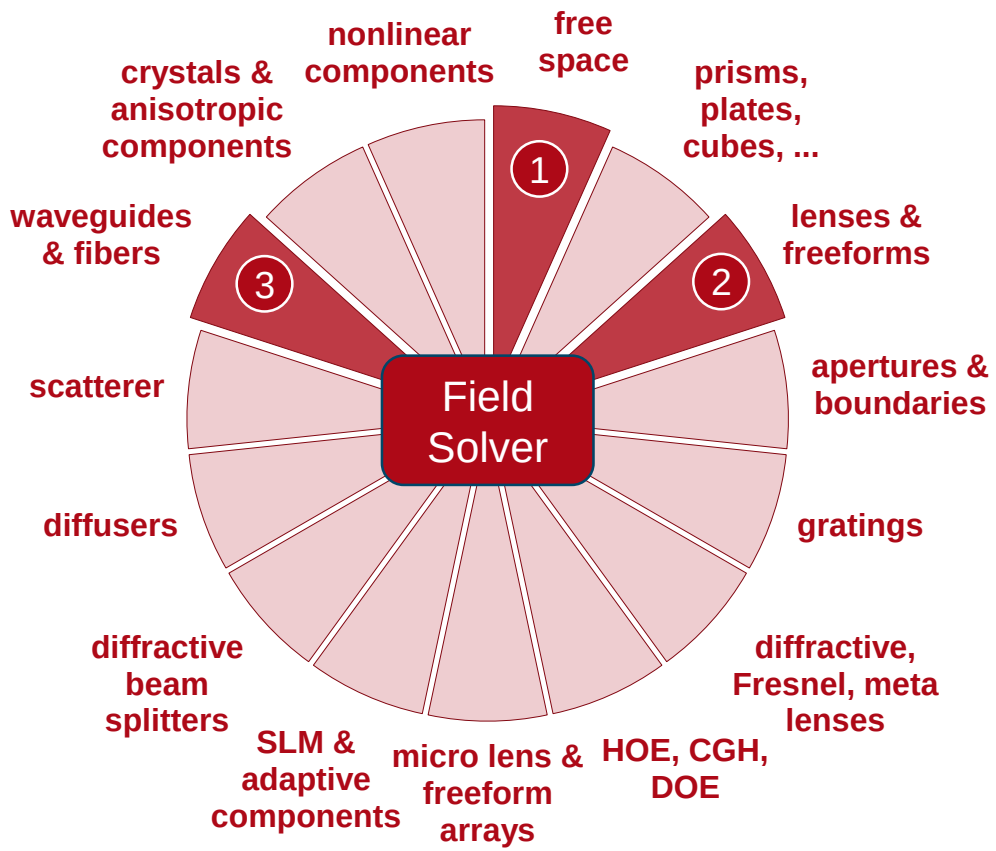

Typical Application Scenarios

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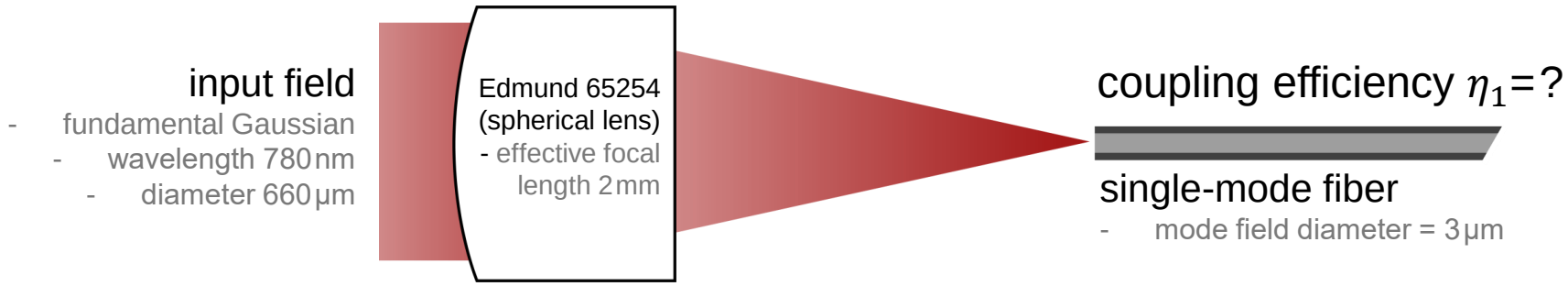
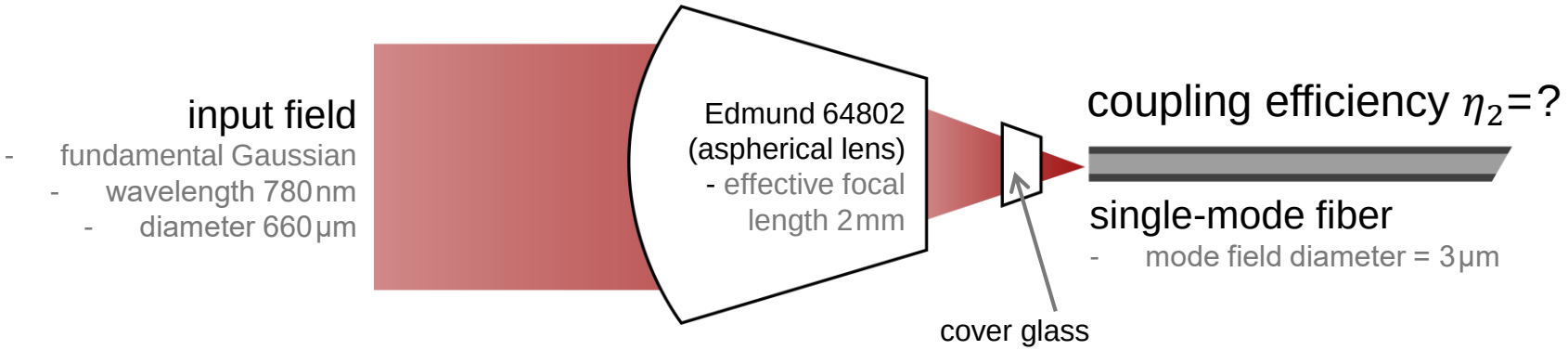
- **Compare the performances of different commercially available lenses**
- Design a coupling lens with parametric optimization
- Perform tolerance and sensitivitiy analysis of fiber coupling setup

Comparison of Different Lenses for Fiber Coupling

Modeling Task

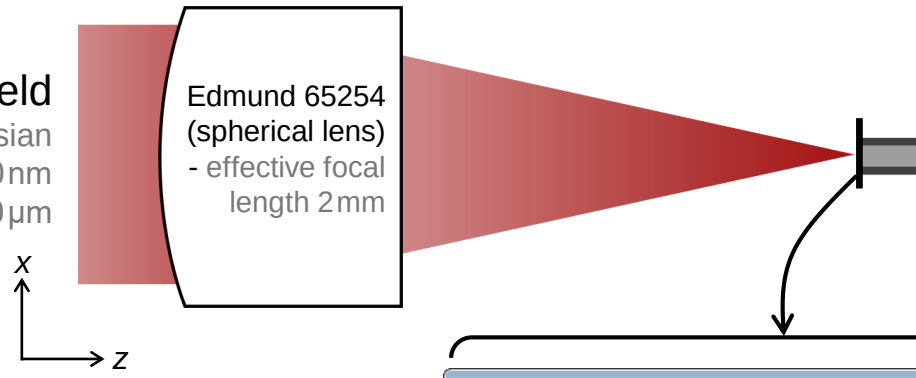


When two lenses with the same effective focal length are available for fiber coupling task, how to evaluate their performance in terms of coupling efficiency?



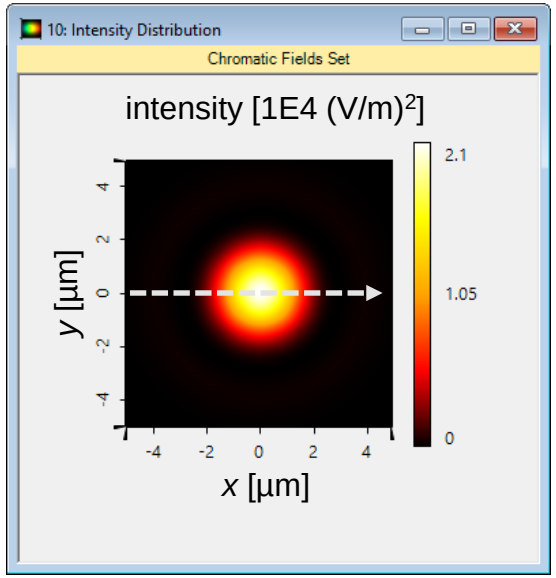
Simulation Results

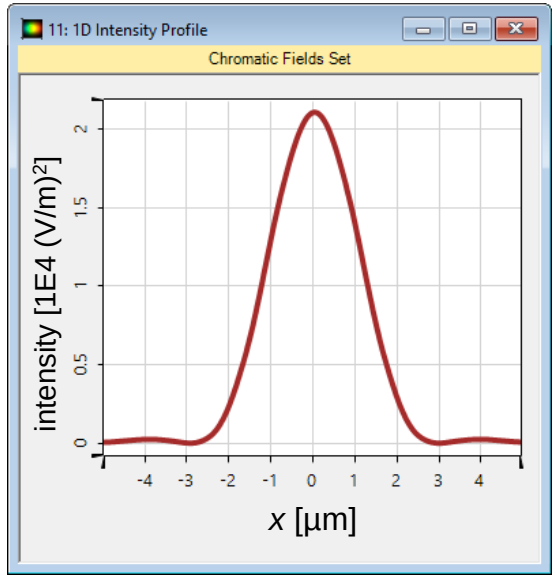
input field
- fundamental Gaussian
- wavelength 780 nm
- diameter 660 µm



coupling efficiency $\eta_1 = 88.6\%$
(overlap integral calculation)

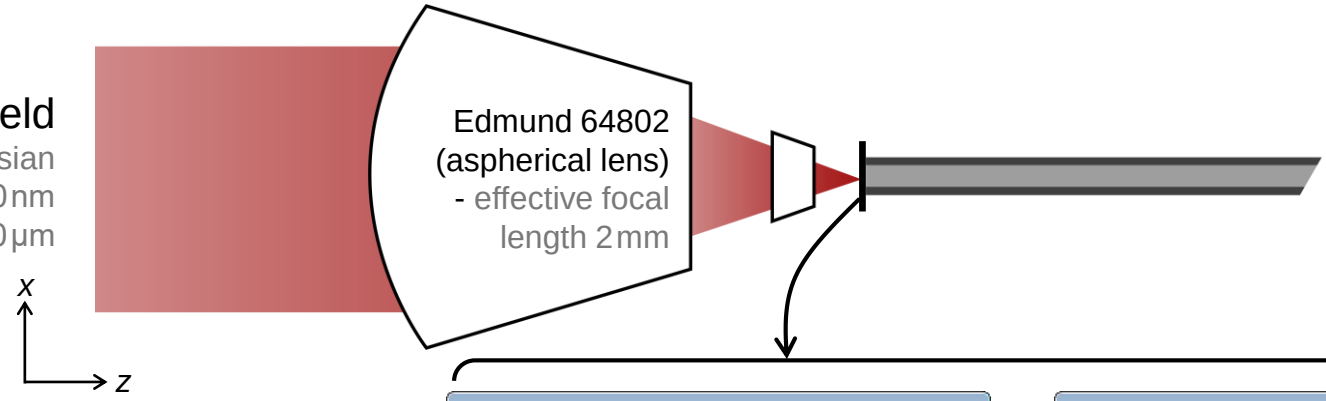
Due to aberrations from the spherical lens, the focal spot at the end of the fiber deviates from a Gaussian mode, and therefore it leads to poor coupling efficiency.





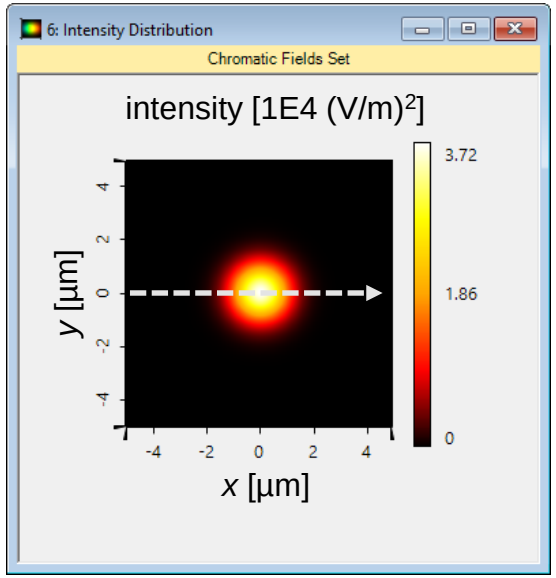
Simulation Results

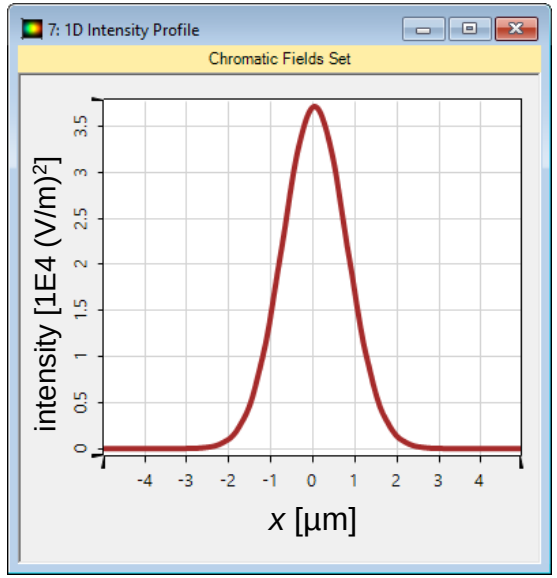
input field
- fundamental Gaussian
- wavelength 780 nm
- diameter 660 µm



coupling efficiency $\eta_1 = 99.9\%$
(overlap integral calculation)

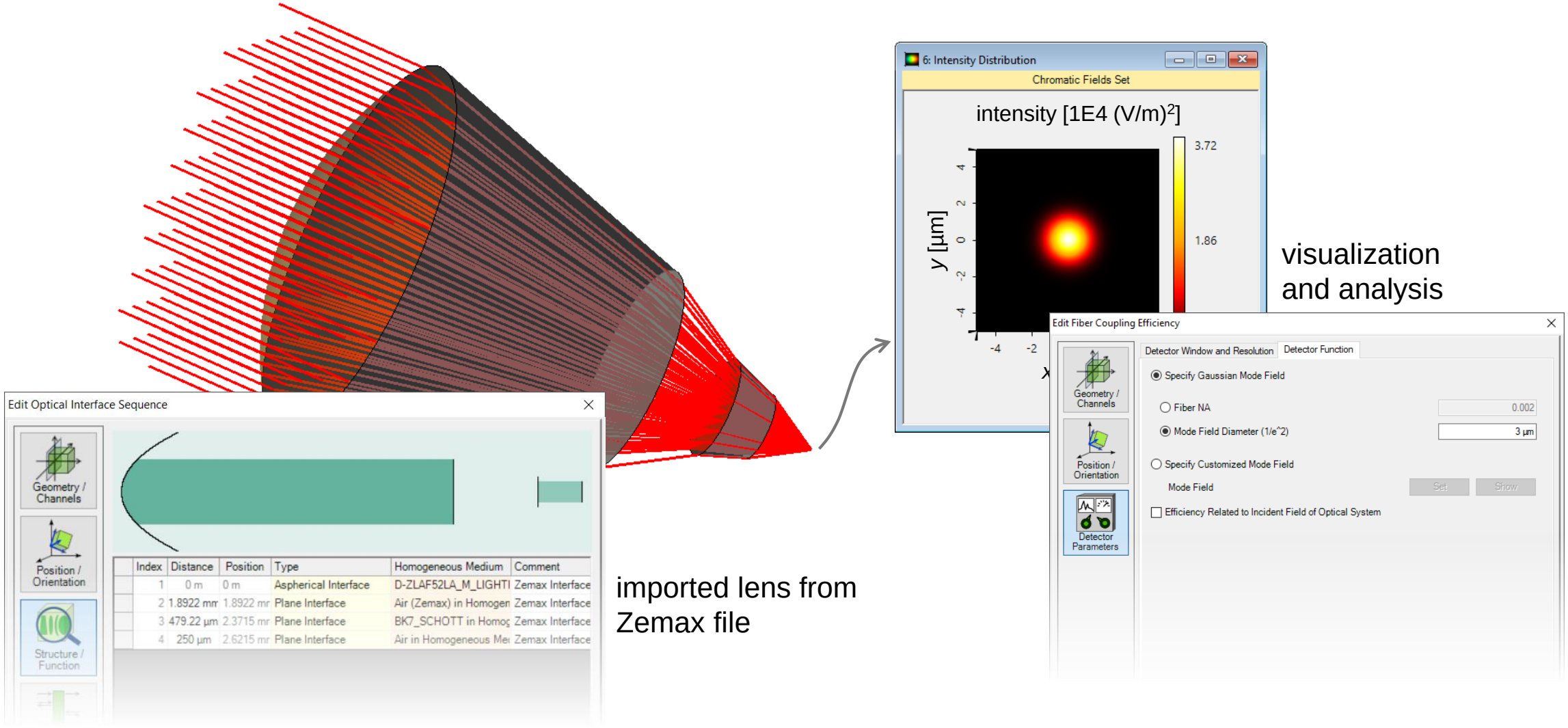
Aspherical lens controls the aberrations well and that guarantees a focal spot in smaller size, and with Gaussian profile that fits to the fiber.





Field tracing simulation of the fiber coupling system takes only 2 seconds.

Peak into VirtualLab Fusion



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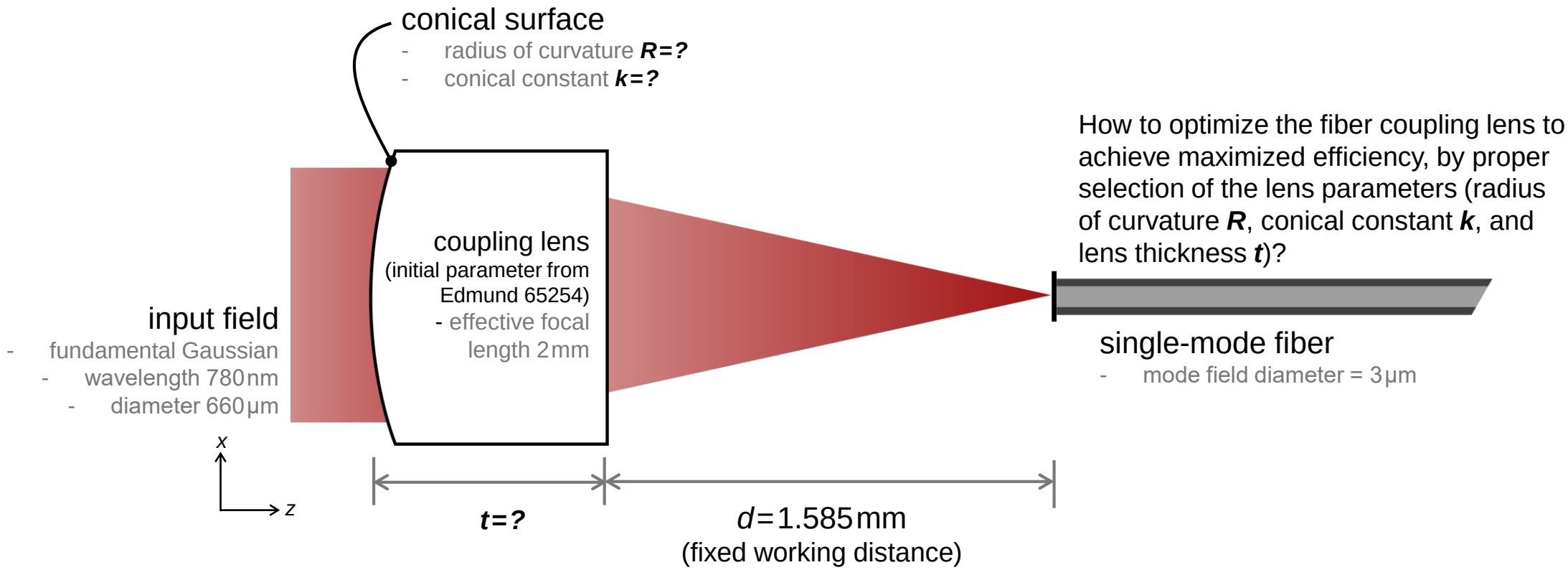
- Compare the performances of different commercially available lenses
- **Design a coupling lens with parametric optimization**
- Perform tolerance and sensitivitiy analysis of fiber coupling setup

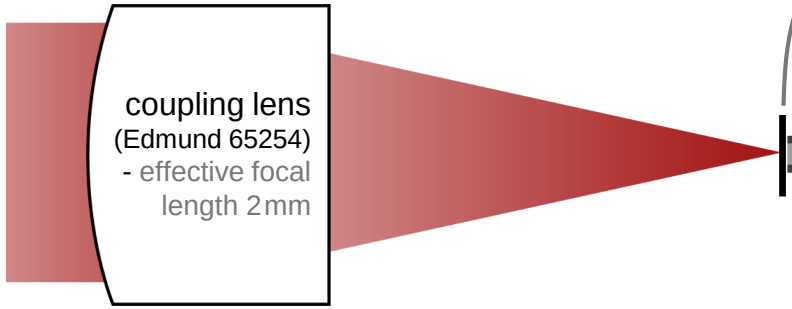
Parametric Optimization of Fiber Coupling Lenses

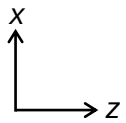
Design Task


conical surface
- radius of curvature R=?
- conical constant k=?
How to optimize the fiber coupling lens to achieve maximized efficiency, by proper selection of the lens parameters (radius of curvature R, conical constant k, and lens thickness t)?
coupling lens
(initial parameter from Edmund 65254)
- effective focal length 2mm
input field
- fundamental Gaussian
- wavelength 780nm
- diameter 660μm
single-mode fiber
- mode field diameter = 3μm
x
z
t=?
d=1.585mm
(fixed working distance)

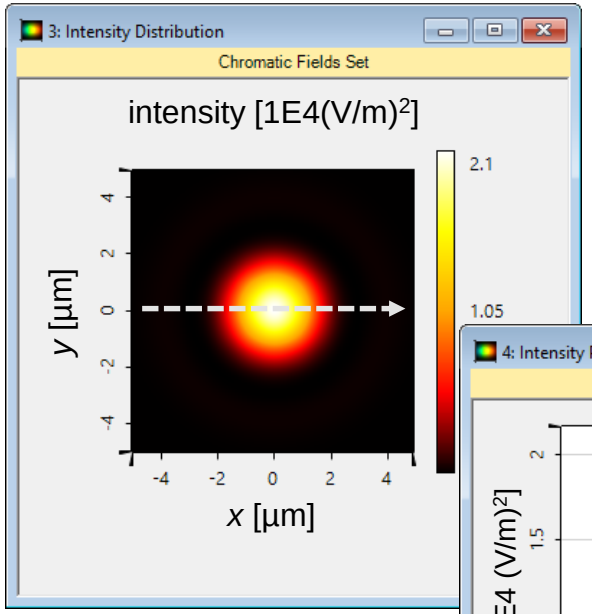
Evaluation of Initial Lens

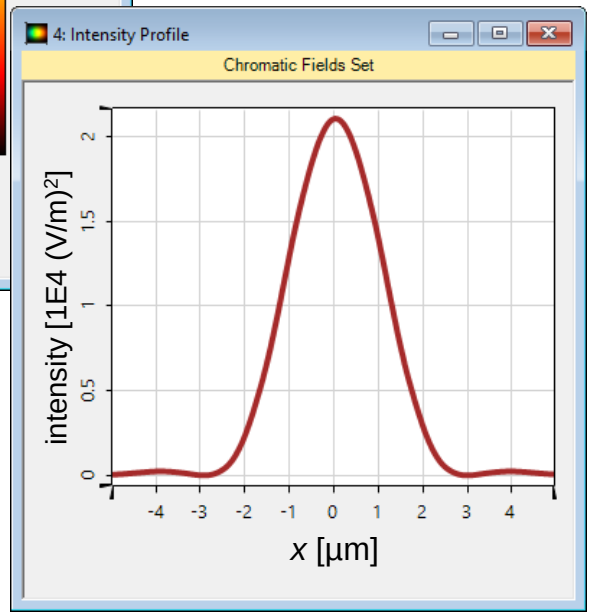
initial lens parameters
- radius of curvature ***R***=1.7mm
- conical constant ***k***=0
- lens thickness ***t***=0.8mm





coupling efficiency η=88.6%
(overlap integral calculation)



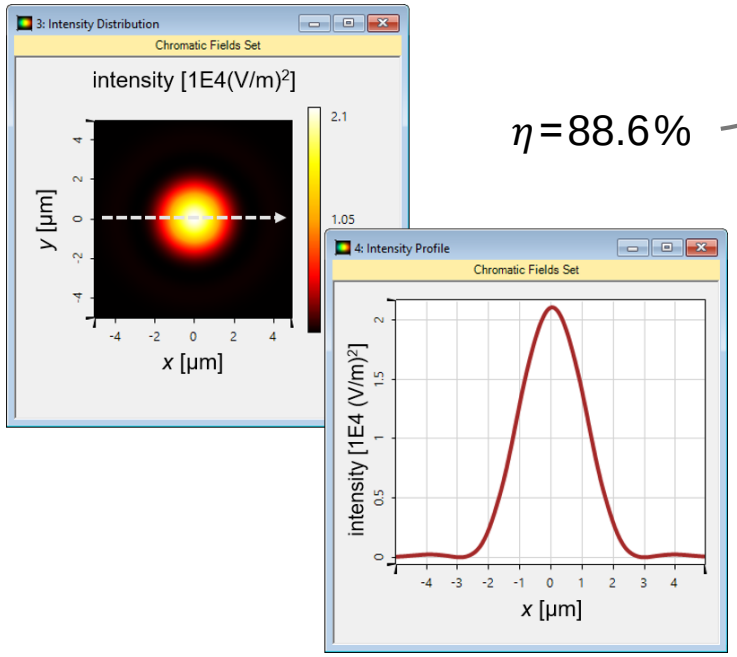


The coupling efficiency obtained from the initial spherical lens is not optimal, due to mismatch to the mode inside the single-mode fiber.

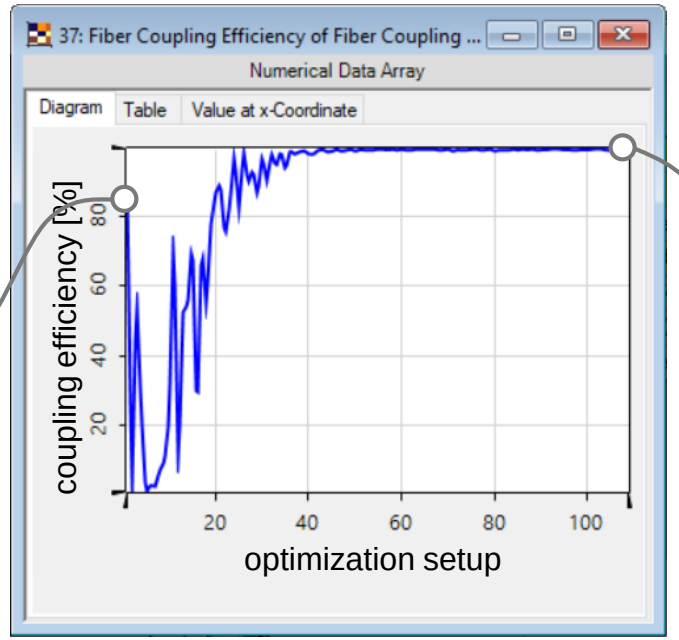
Parametric Optimization

initial lens parameters

- radius of curvature ***R***=1.7mm
- conical constant ***k***=0
- lens thickness ***t***=0.8mm

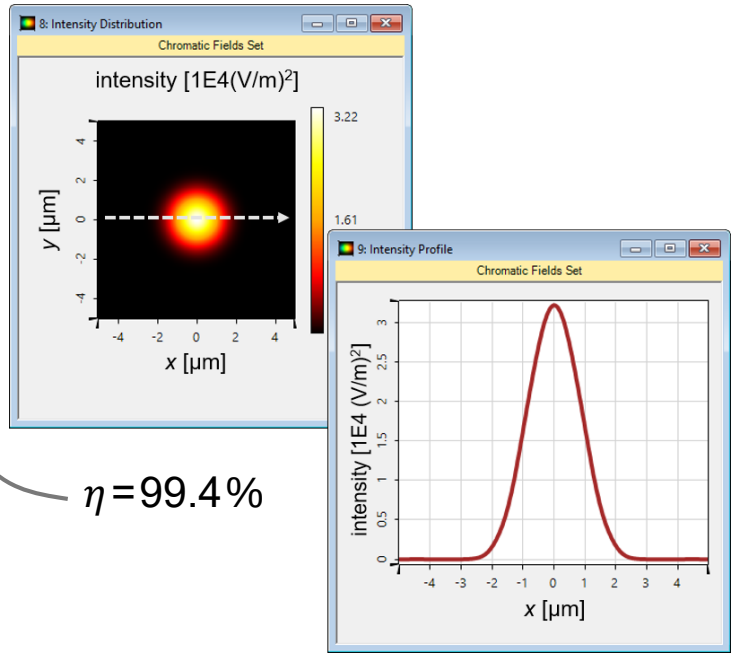


$\eta = 88.6\%$



parametric optimization of coupling efficiency with downhill simplex algorithm

$\eta = 99.4\%$



optimized lens parameters

- radius of curvature ***R***=1.704mm
- conical constant ***k***=-0.67278
- lens thickness ***t***=0.841mm

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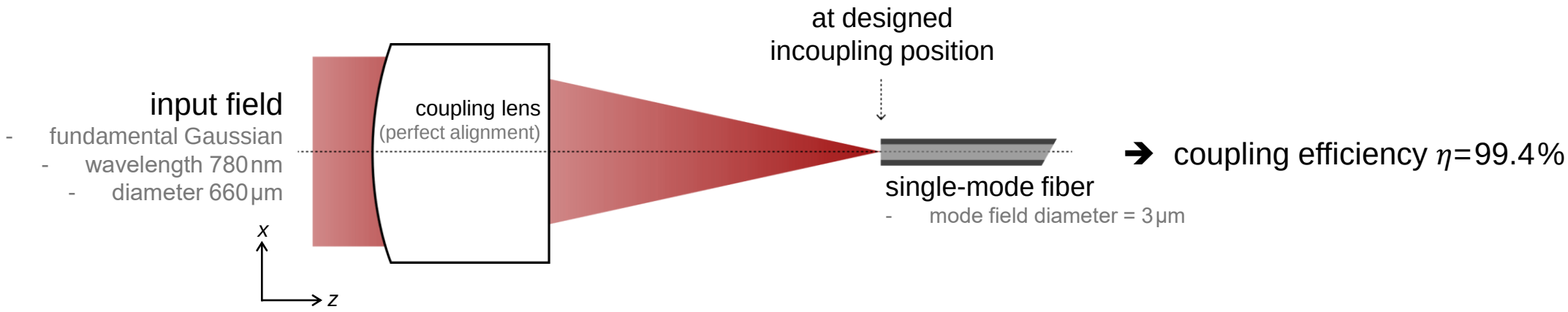
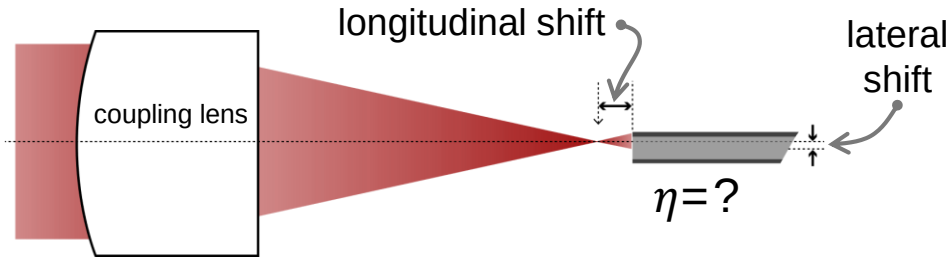
Tolerance Analysis of a Fiber Coupling Setup

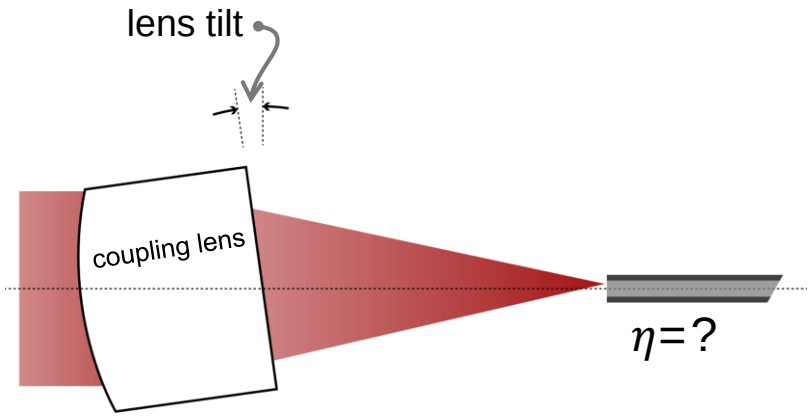
Modeling Task



How does the coupling efficiency change with respect to alignment tolerance factors?

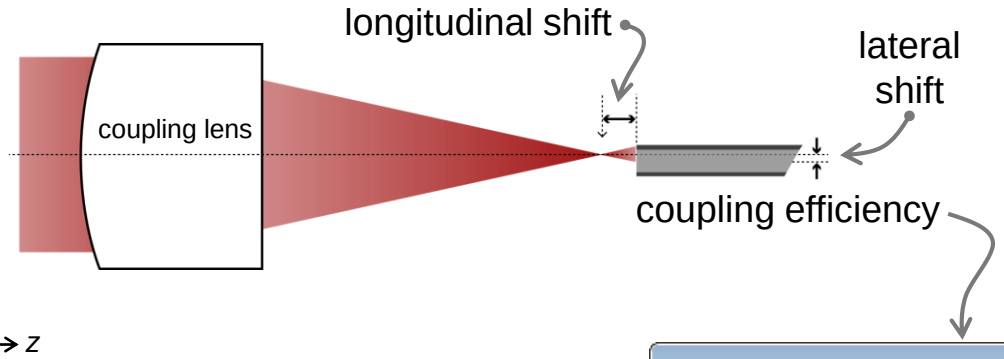


(a) shift of fiber end position



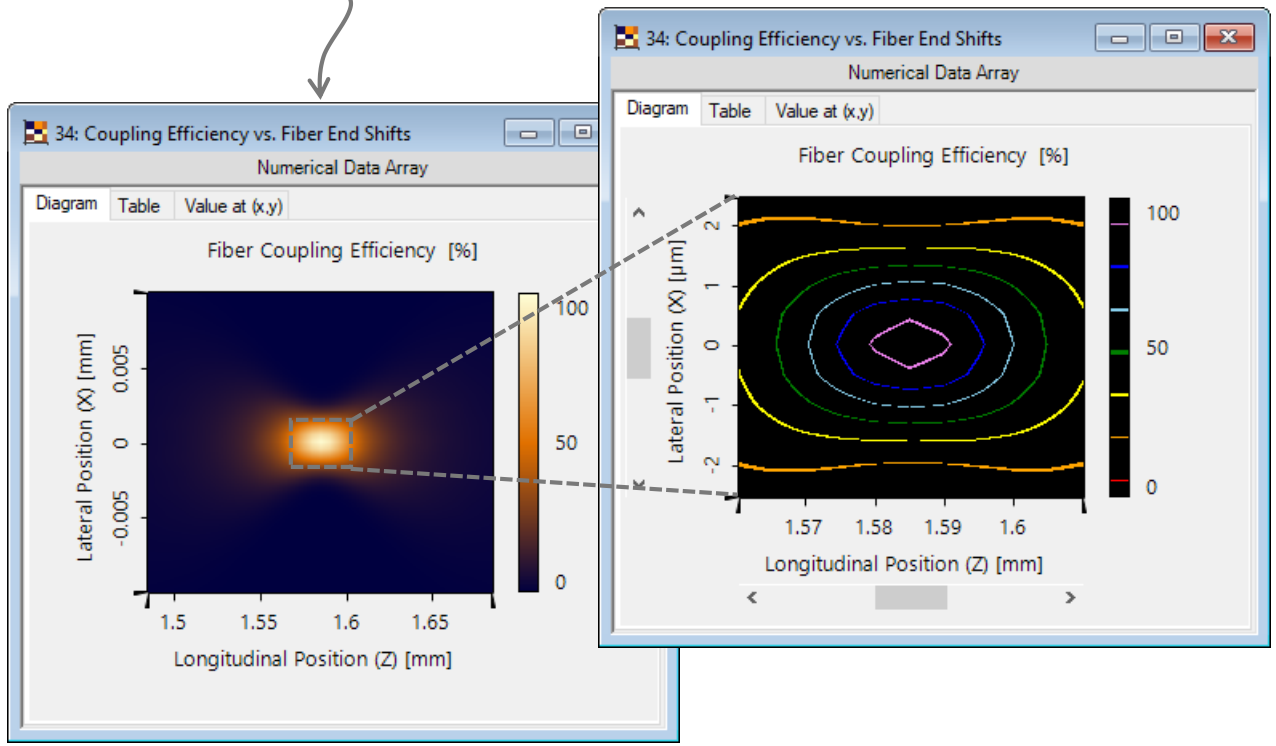
(b) tilt of coupling lens

Coupling Efficiency vs. Fiber End Position Shift

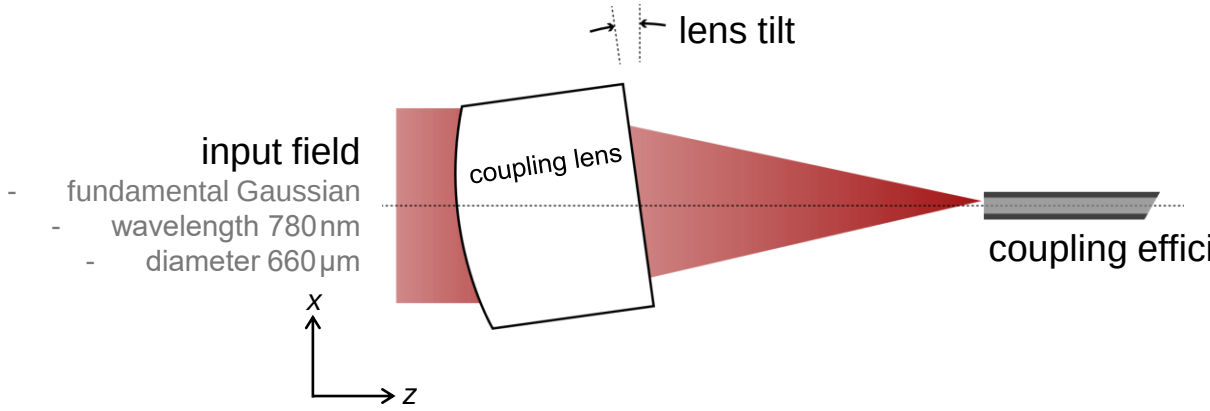


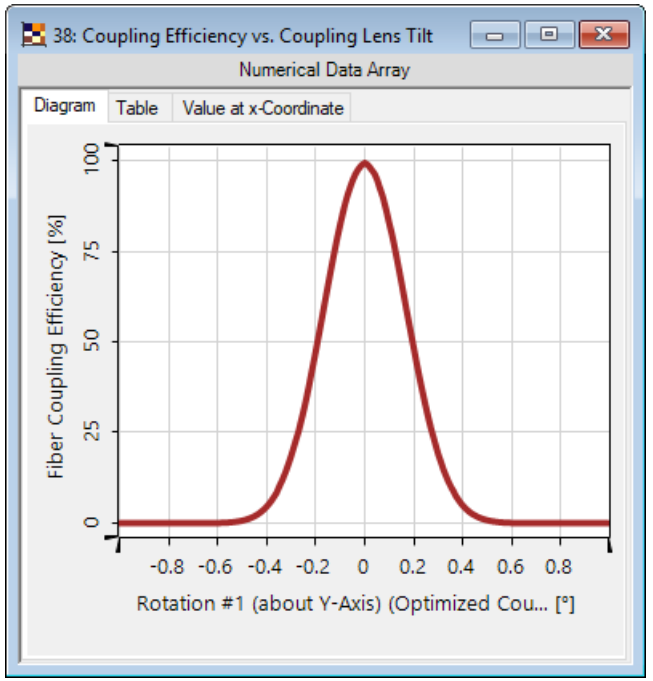
Contour plot helps with the identification of the parameter range for desired coupling efficiency threshold.

The coupling efficiency is scanned with respect to the fiber position shifts along both axial and lateral directions.



Coupling Efficiency vs. Coupling Lens Tilt

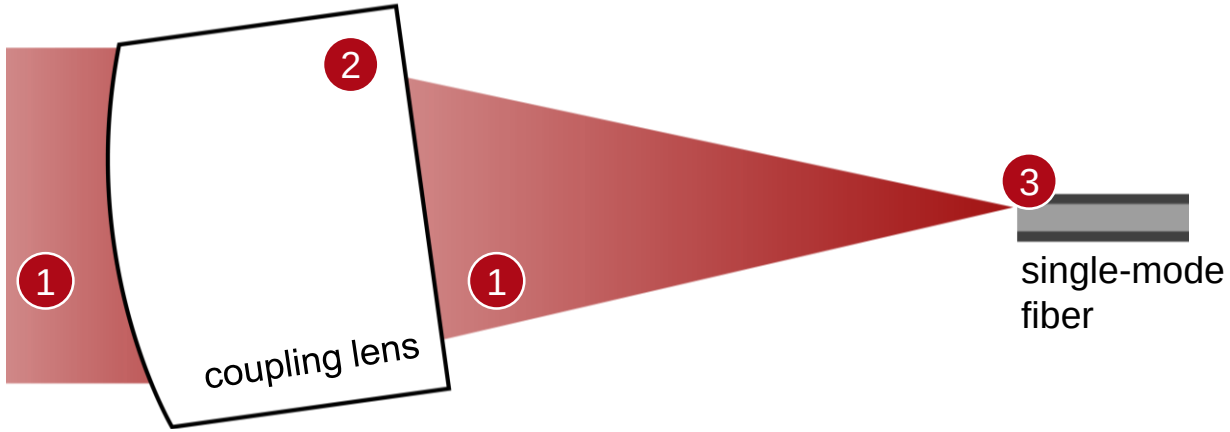




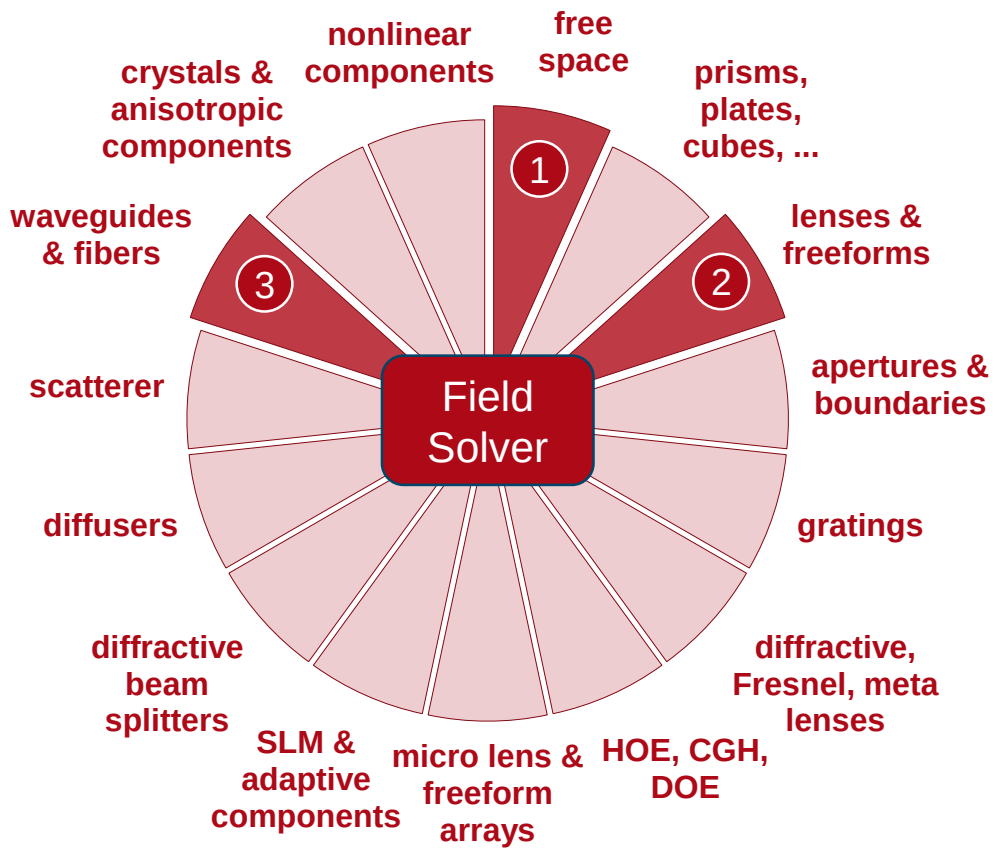
Physical-optics analysis of the coupling efficiency with respect to lens tilt, over 200 angles, takes only 50 seconds.

VirtualLab Fusion Technologies

R. Shi, *et al*., "Physical-optics propagation through curved surfaces," J. Opt. Soc. Am. A 36, 1252-1260 (2019)



S. Zhang, *et al*., "Propagation of electromagnetic fields between non-parallel planes: a fully vectorial formulation and an efficient implementation," Appl. Opt. 55, 529-538 (2016)



Benefits

- **All-in-one software platform** with ray tracing and field tracing (physical optics modeling)
- **Accurate calculation of field in focal region** and therefore also of the fiber coupling efficiency
- **Parametric design of coupling lens** or direct import from Zemax OpticStudio
- **Full tolerance analysis** including shift and tilt of fiber end position
- **Handling of special-cut / microstructured fiber end**

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