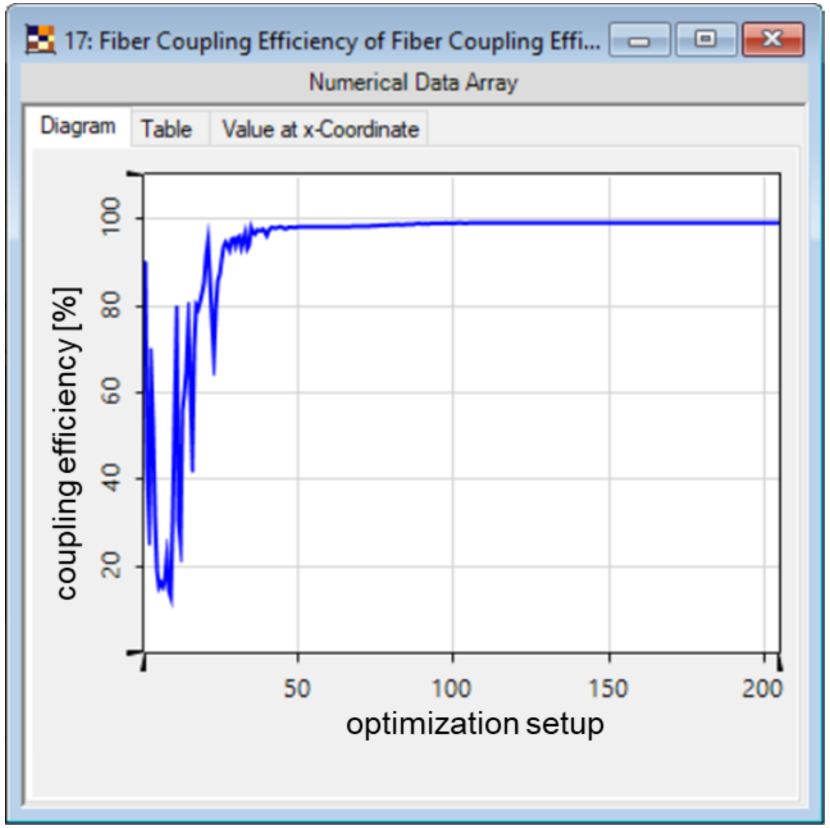
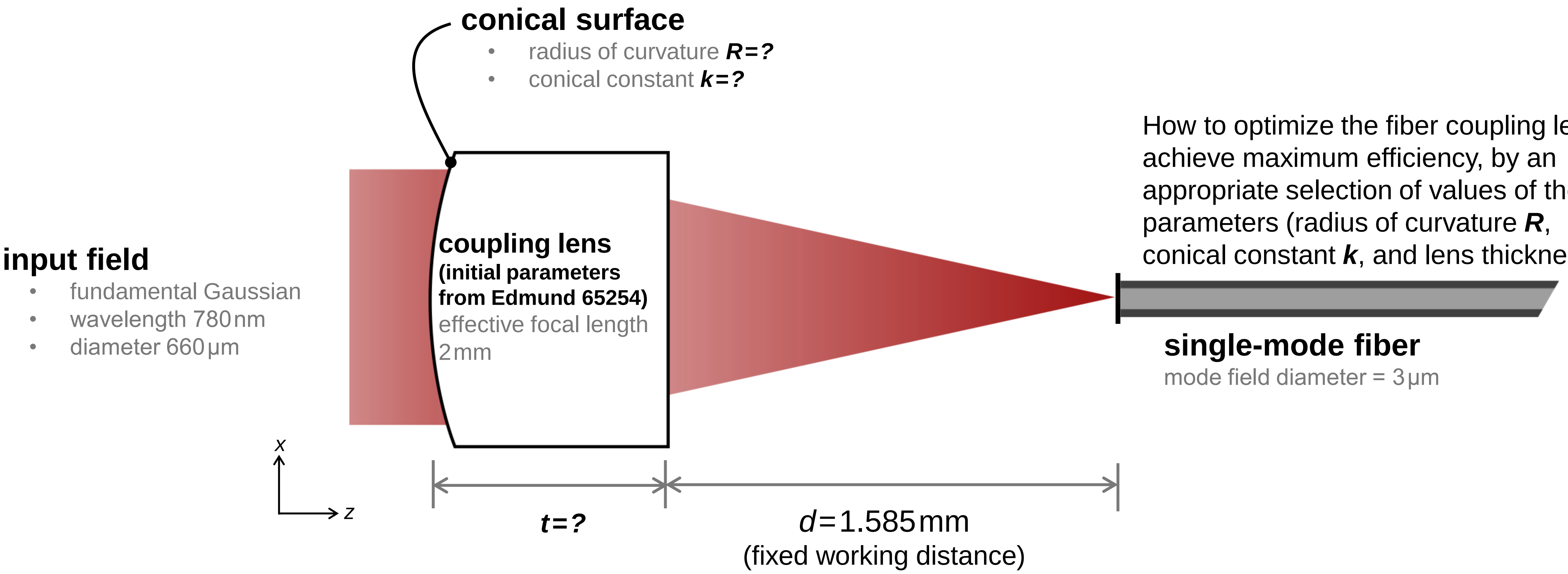
Parametric Optimization of Fiber Coupling Lenses

Abstract



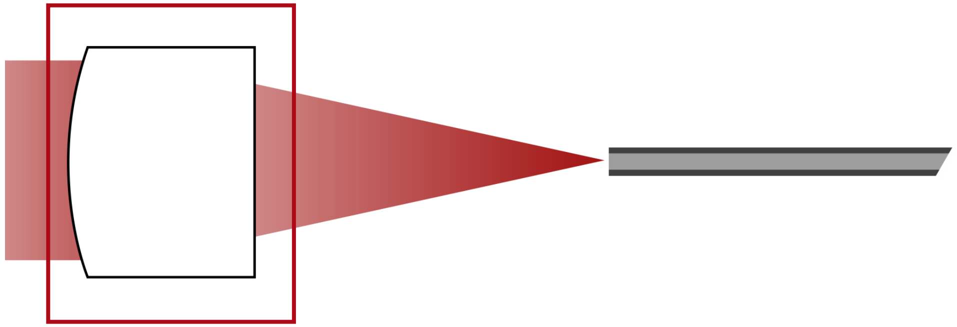
Fibers are some of the most versatile components in modern optics. One of their most valued characteristics is their capacity to transport optical energy with very low losses across vast distances (even several kilometers). On the flip side, coupling light into a fiber in a way that achieves as high an efficiency as possible is often a very delicate endeavor: among other things, the fiber coupling lens must be well designed to ensure that the focal spot matches the propagating modes of the fiber as closely as possible. With the fast physical optics simulation and the parametric optimization in VirtualLab Fusion, we show the design of a plano-convex lens with a conical surface for the task of coupling light into a single-mode fiber.

Design Task

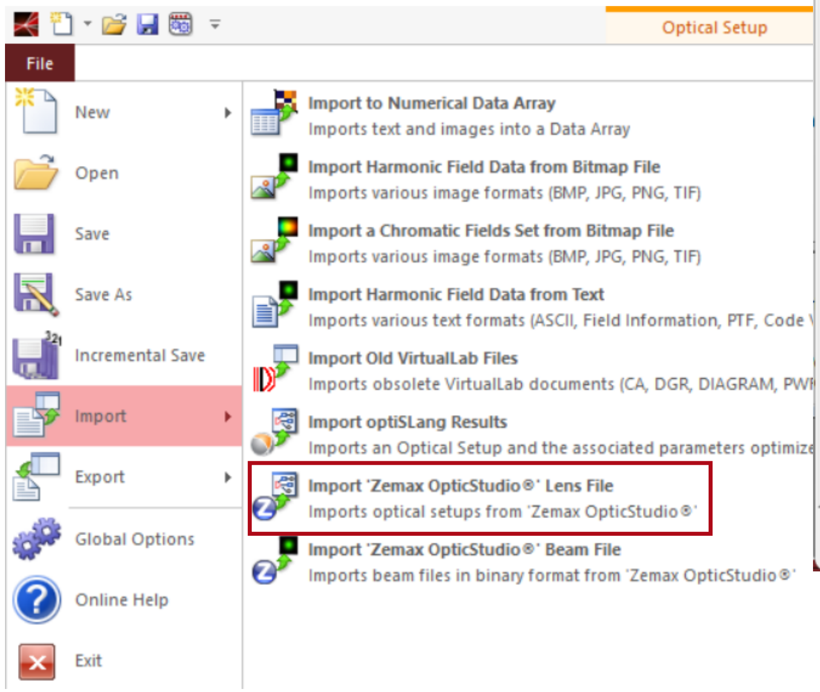


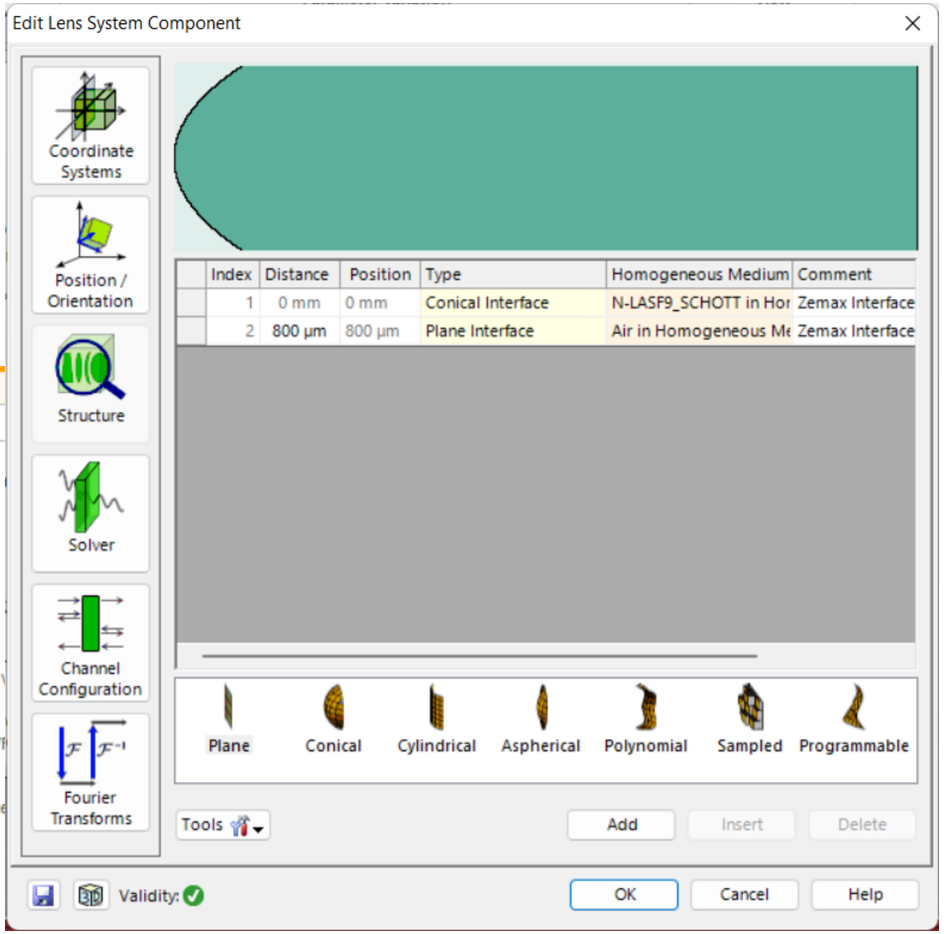
How to optimize the fiber coupling lens to achieve maximum efficiency, by an appropriate selection of values of the lens parameters (radius of curvature ***R***, conical constant ***k***, and lens thickness ***t***)?

System Building Blocks – Imported Lens File

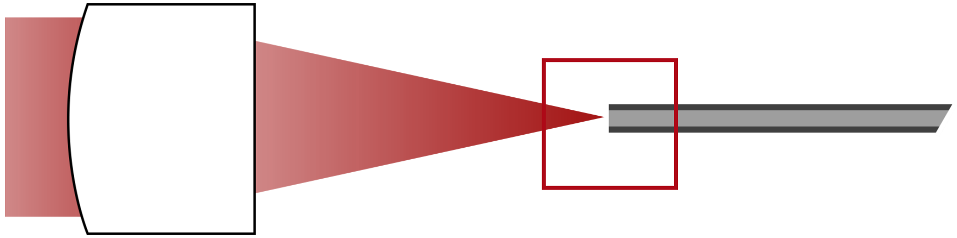


Lens systems, such as the coupling lens in this application, can either be configured by the user from scratch or imported from information provided by the manufacturer.

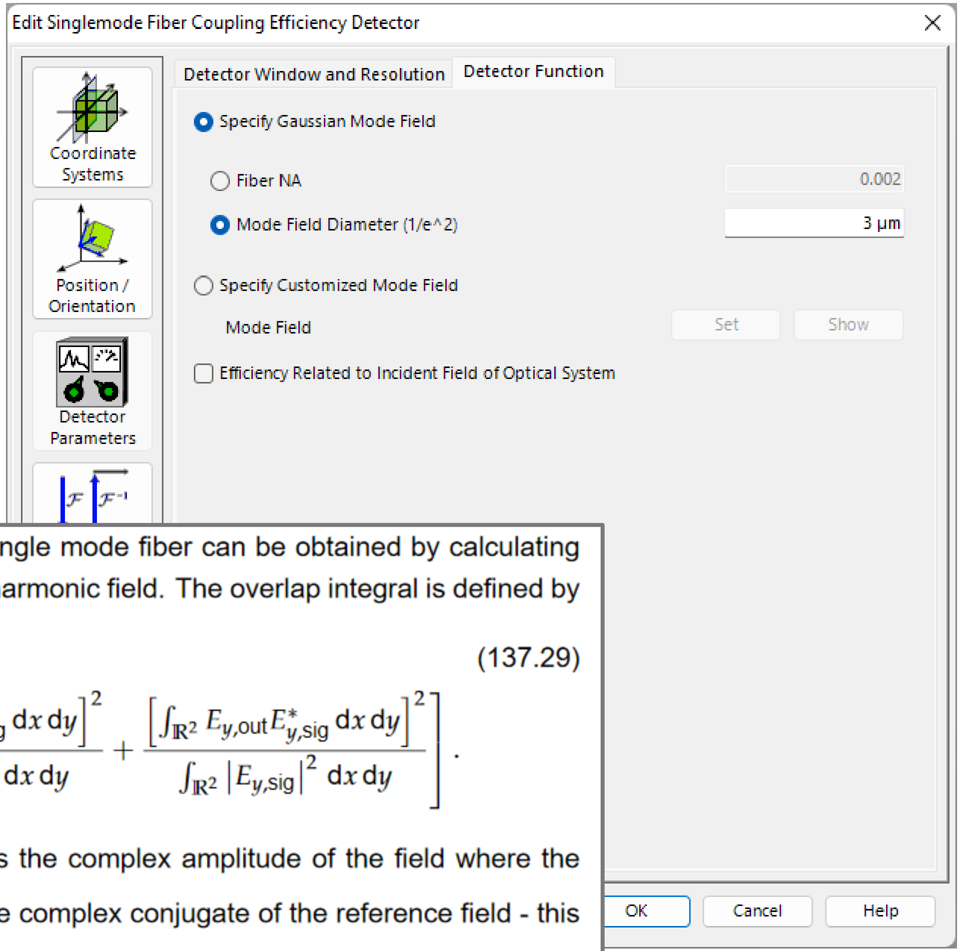




System Building Blocks – Fiber Efficiency Detector



The *Singlemode Fiber Coupling Efficiency Detector* calculates the efficiency as the normalized overlap integral of the incoming field and the (single) eigenmode of the fiber. Please note that, as its name implies, this detector only works for a singlemode fiber.



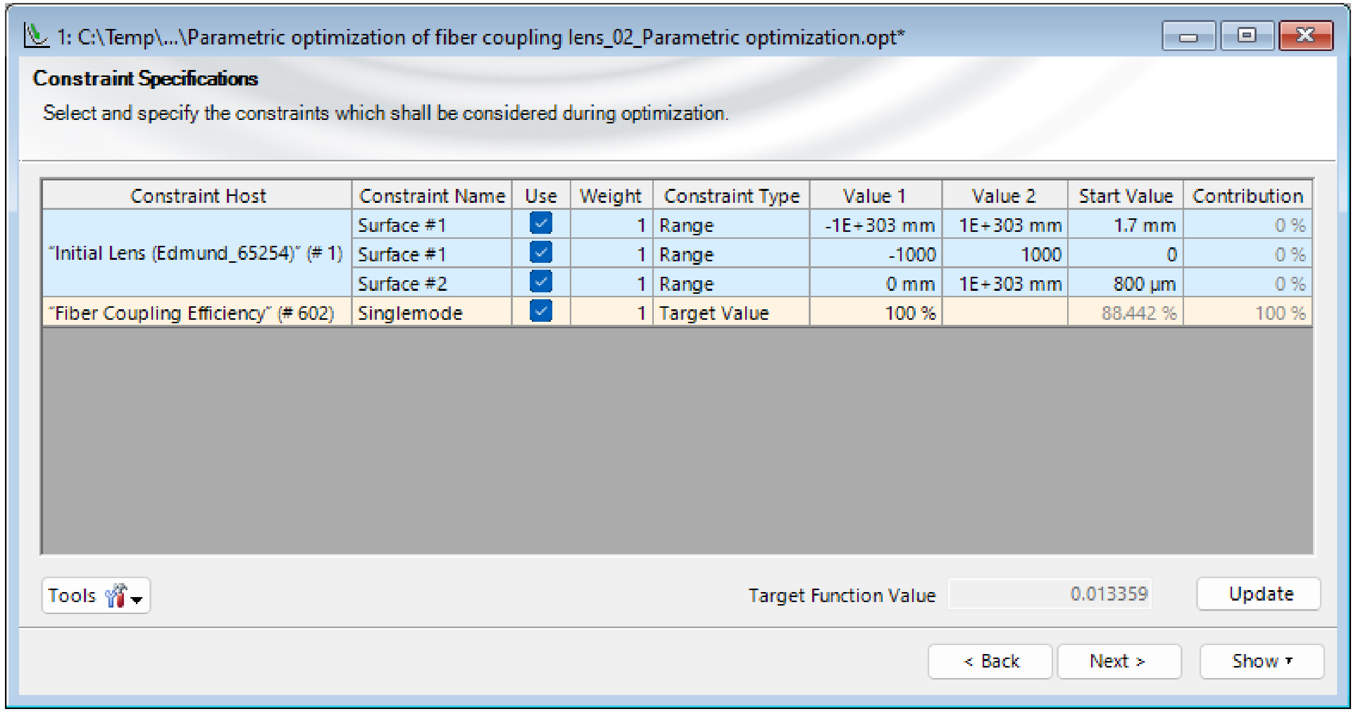
From VirtualLab Fusion Manual:

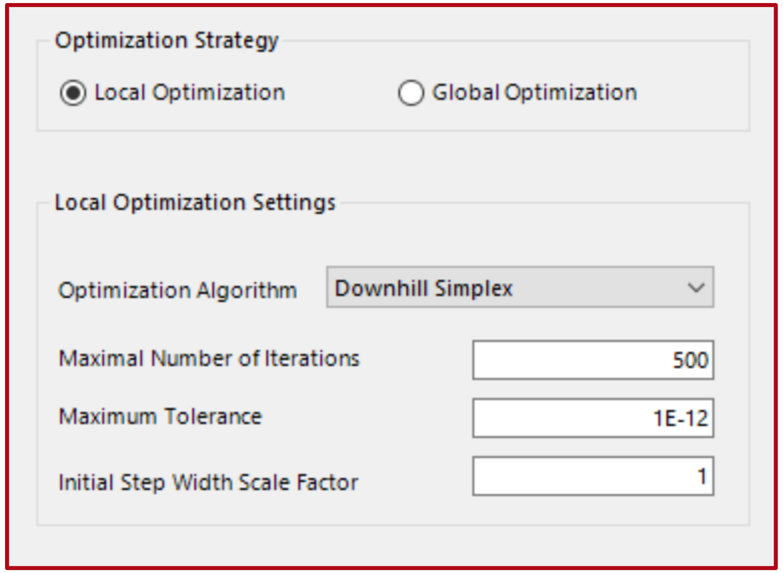
The coupling efficiency of an arbitrary harmonic field into a single mode fiber can be obtained by calculating the complex overlap integral between the fiber mode and the harmonic field. The overlap integral is defined by

$$\begin{aligned}\eta_{\mathrm{coupl}} &= \eta_{\mathrm{x,coupl}} + \eta_{\mathrm{y,coupl}} \\ &= \frac{1}{\int_{\mathbb{R}^2} |E_{\mathrm{xy,in}}|^2 \,\mathrm{d}x\,\mathrm{d}y} \left[\frac{\left[\int_{\mathbb{R}^2} E_{x,\mathrm{out}} E^*_{x,\mathrm{sig}} \,\mathrm{d}x\,\mathrm{d}y\right]^2}{\int_{\mathbb{R}^2} |E_{x,\mathrm{sig}}|^2 \,\mathrm{d}x\,\mathrm{d}y} + \frac{\left[\int_{\mathbb{R}^2} E_{y,\mathrm{out}} E^*_{y,\mathrm{sig}} \,\mathrm{d}x\,\mathrm{d}y\right]^2}{\int_{\mathbb{R}^2} |E_{y,\mathrm{sig}}|^2 \,\mathrm{d}x\,\mathrm{d}y} \right].\end{aligned} \qquad (137.29)$$

$E_{\mathrm{xy,in}}$ is the complex amplitude of the incident field, $\binom{E_{x,\mathrm{out}}}{E_{y,\mathrm{out}}}$ is the complex amplitude of the field where the coupling efficiency should be calculated from and $\binom{E^*_{x,\mathrm{sig}}}{E^*_{y,\mathrm{sig}}}$ is the complex conjugate of the reference field - this means the harmonic field of the fiber mode. Typically as the reference field the Gaussian base mode of the fiber should be used.

Optimization

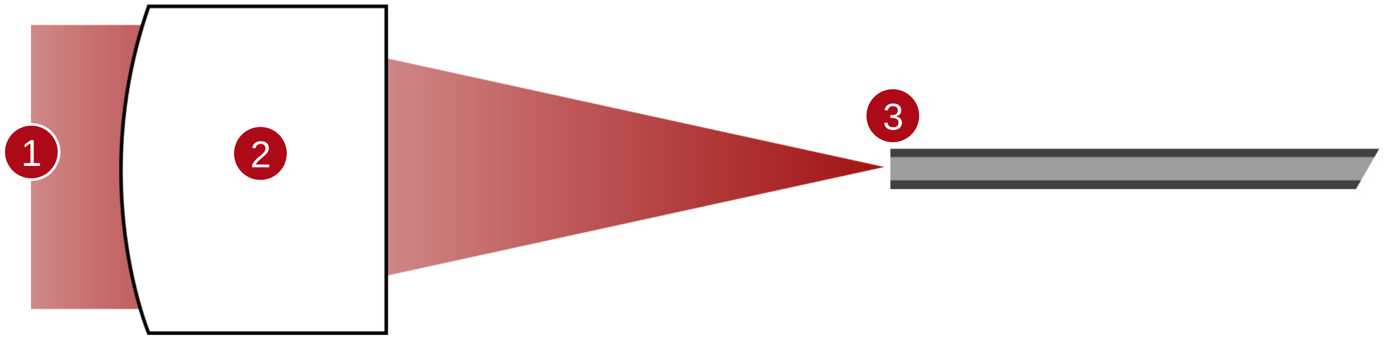




In order to find an optimized set of parameters for the lens, the *Optimization* document enables the definition of parameter constraints and weights for the target values. Find more information under:

[Introduction to the Parametric Optimization Document]

Summary – Components...



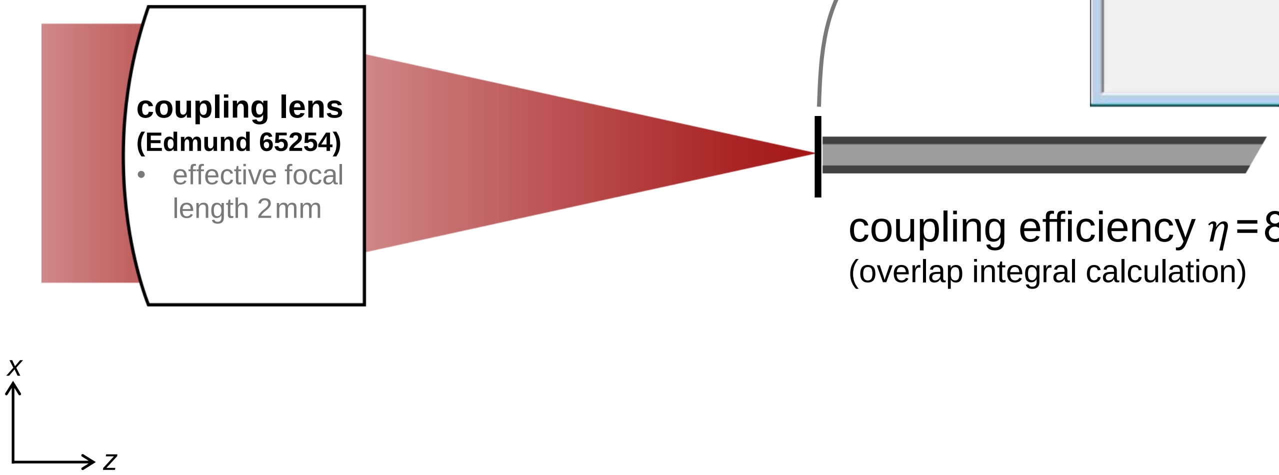
… of Optical System	… in VirtualLab Fusion	Model/Solver/Detected Value
1. source	*Gaussian Wave*	spatial Gaussian function
2. coupling lens	*Lens System Component*	Local Plane Interface Approximation (LPIA)
3. fiber	*Fiber Coupling Efficiency*	overlap integral calculation

Evaluation of Initial Lens

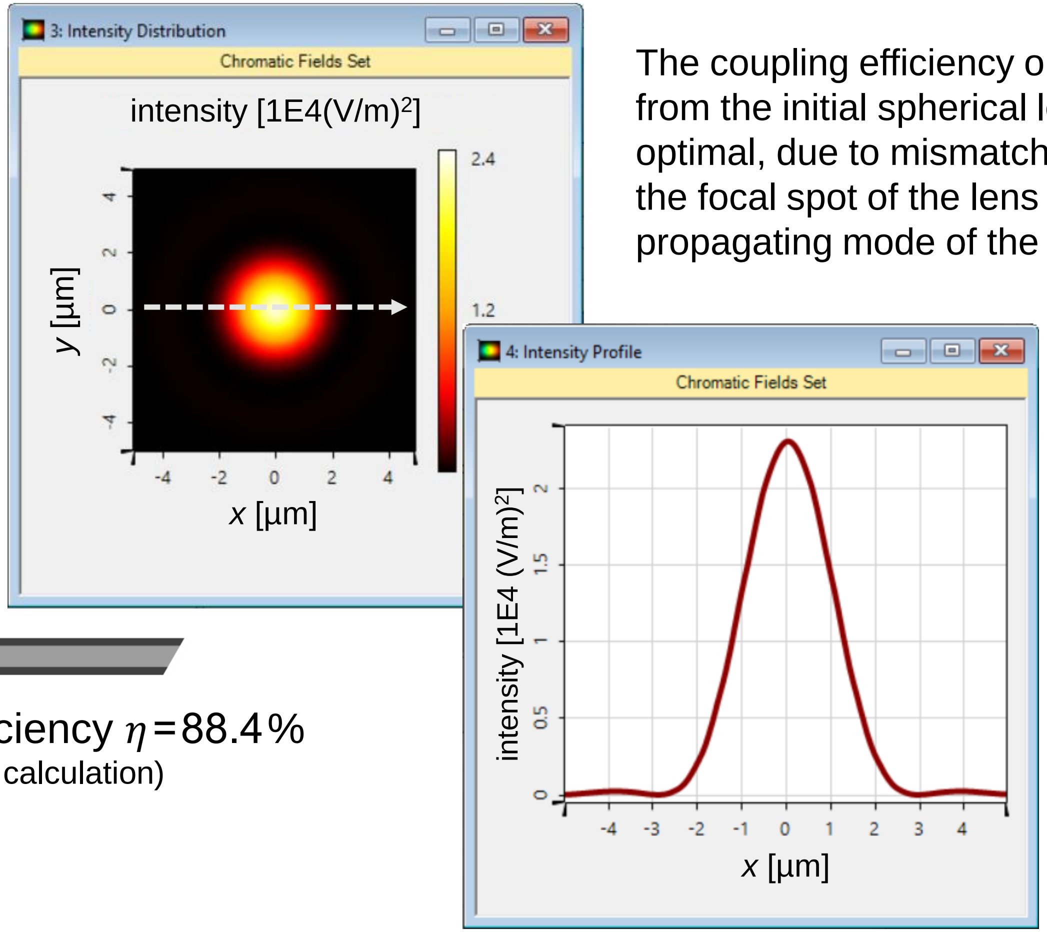
The coupling efficiency obtained from the initial spherical lens is not optimal, due to mismatch between the focal spot of the lens and the propagating mode of the fiber.

Initial lens parameters

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



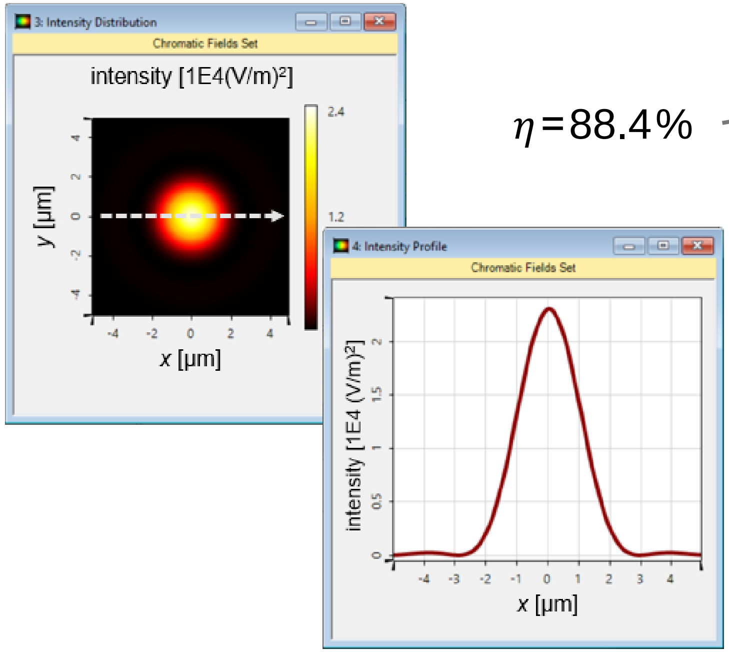
coupling efficiency η=88.4 %
(overlap integral calculation)



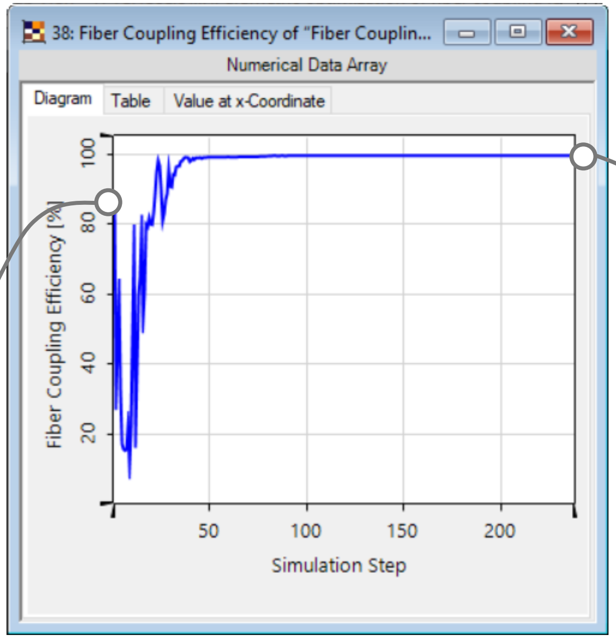
Parametric Optimization

Initial lens parameters

- radius of curvature $R = 1.7\,\text{mm}$
- conical constant $k = 0$
- lens thickness $t = 0.8\,\text{mm}$

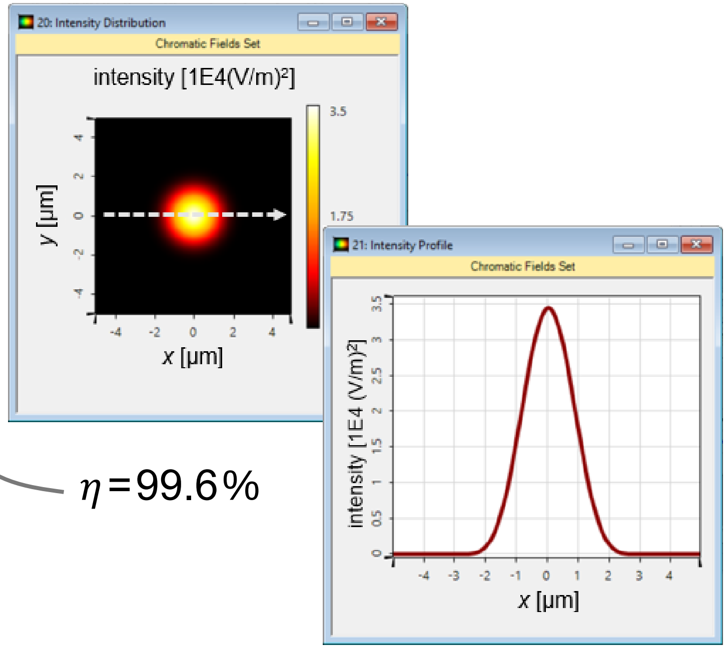


$\eta = 88.4\%$



parametric optimization of coupling efficiency with downhill simplex algorithm

$\eta = 99.6\%$



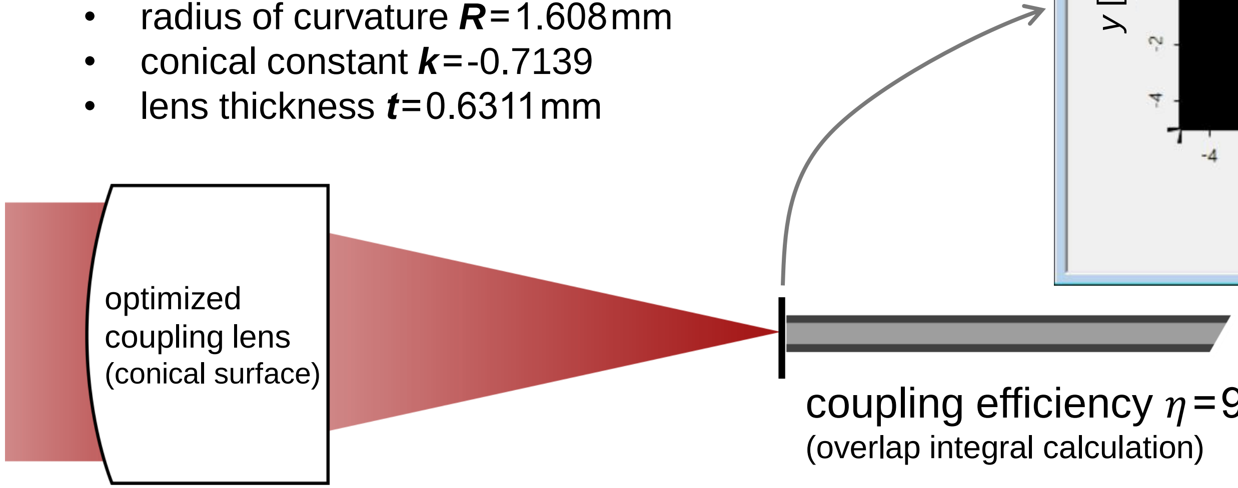
optimized lens parameters

- radius of curvature $R = 1.608\,\text{mm}$
- conical constant $k = -0.7139$
- lens thickness $t = 0.6311\,\text{mm}$

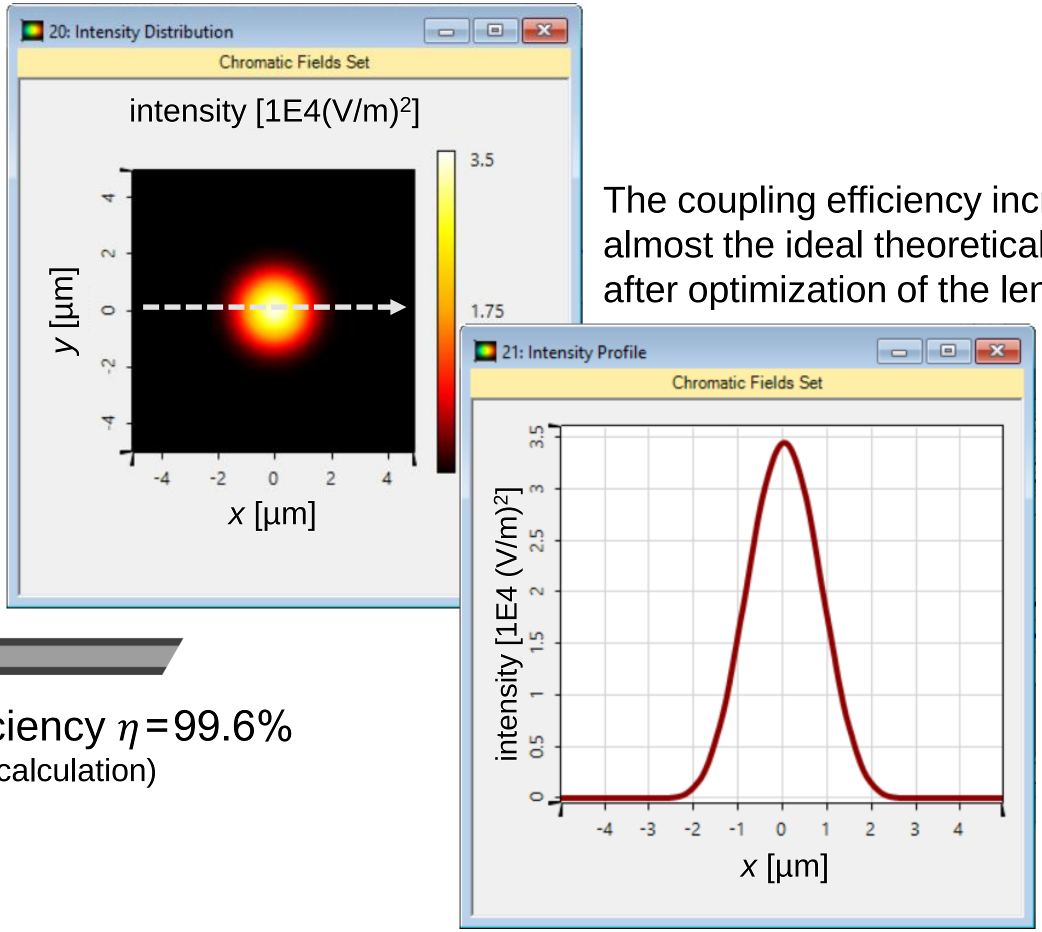
Evaluation of Optimized Lens

optimized lens parameters

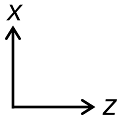
- radius of curvature ***R***=1.608 mm
- conical constant ***k***=-0.7139
- lens thickness ***t***=0.6311 mm



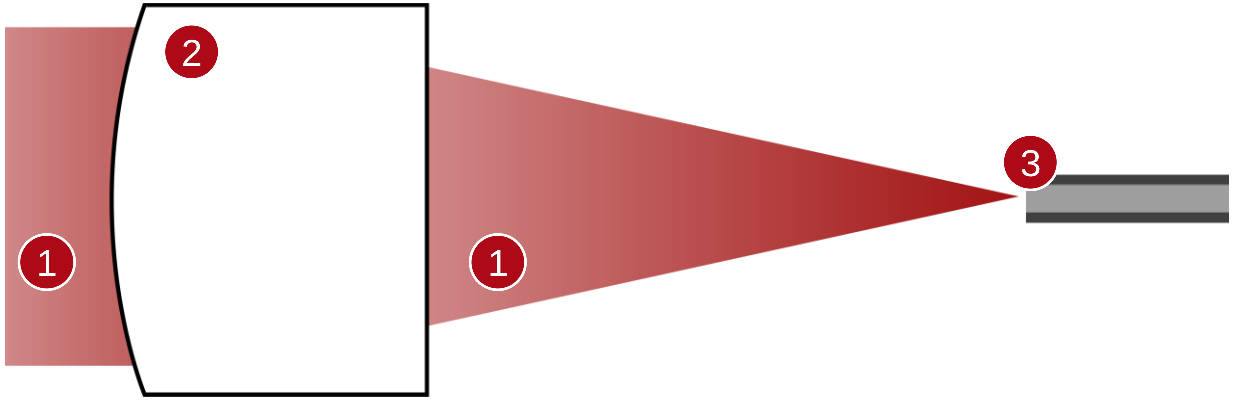
coupling efficiency η=99.6%
(overlap integral calculation)

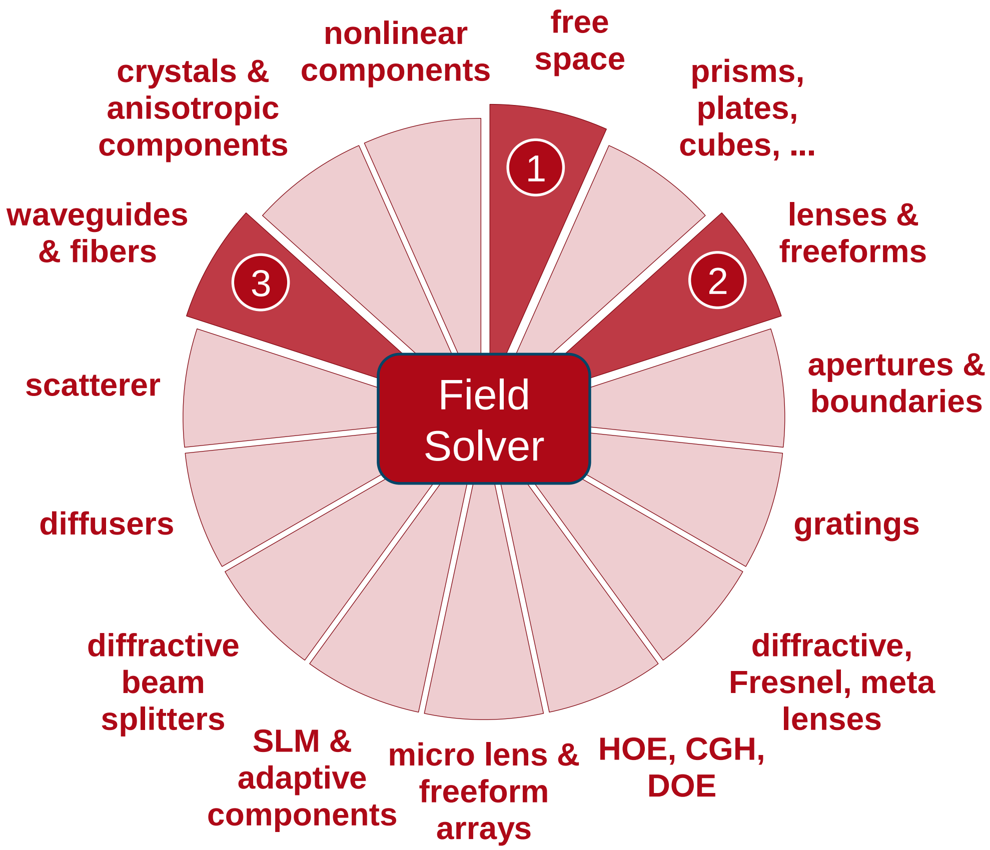


The coupling efficiency increases to almost the ideal theoretical value after optimization of the lens.



VirtualLab Fusion Technologies





Document Information

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further reading	- Optimal Working Distance for Coupling Light into Single-Mode Fibers - Comparison of Different Lenses for Fiber Coupling - Introduction to the Parametric Optimization Document