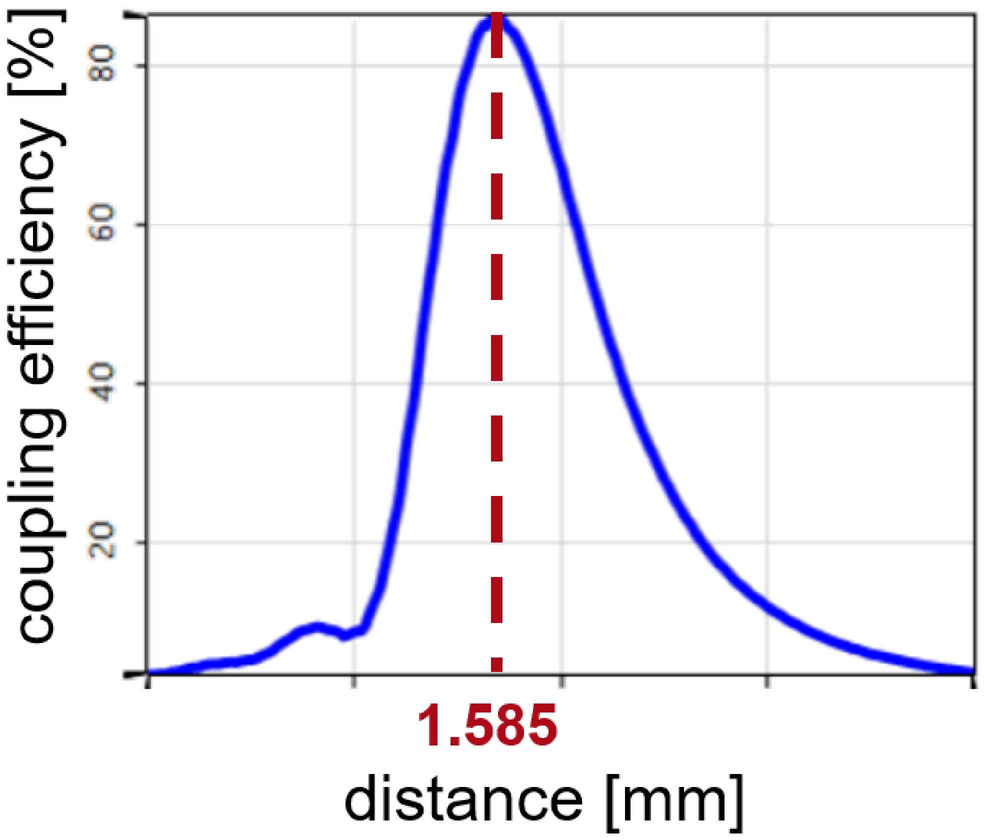
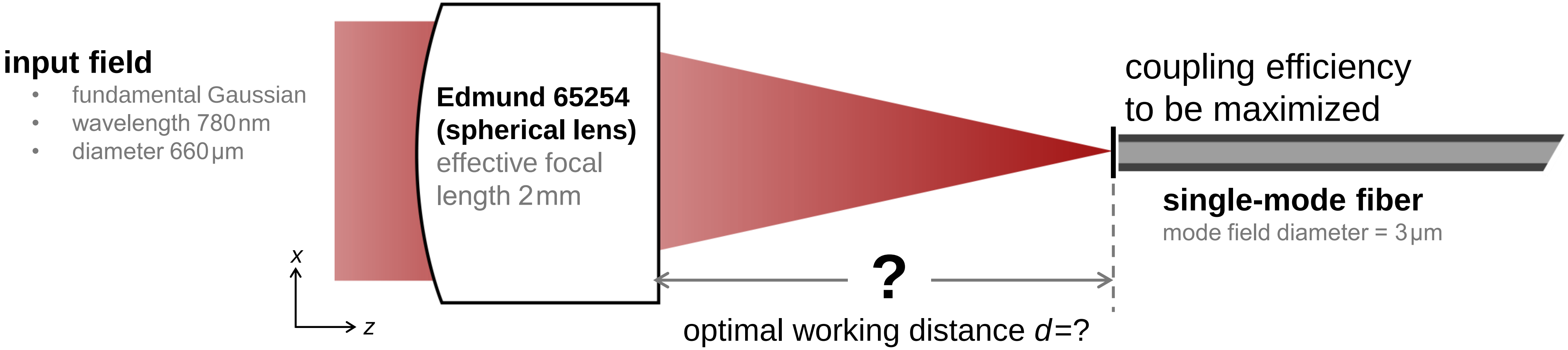
Optimal Working Distance for Coupling Light into Single-Mode Fibers

Abstract



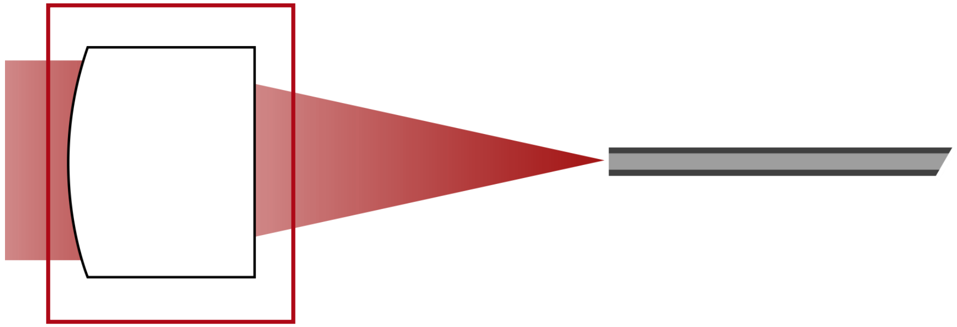
Fibers are some of the most versatile components in modern optics. One of their most valued characteristics is their capacity to transport optical energy with very low losses across vast distances (even several kilometers). On the flip side, coupling light into a fiber in a way that achieves as high an efficiency as possible is often a very delicate endeavor: good alignment, for example, is crucial. In this example, we select a commercially available lens, and show how to find the optimal working distance to achieve maximum coupling efficiency. Particularly, we demonstrate that the optimal working distance found by field tracing differs from the focal distance of the lens as predicted by ray optics.

Modeling Task

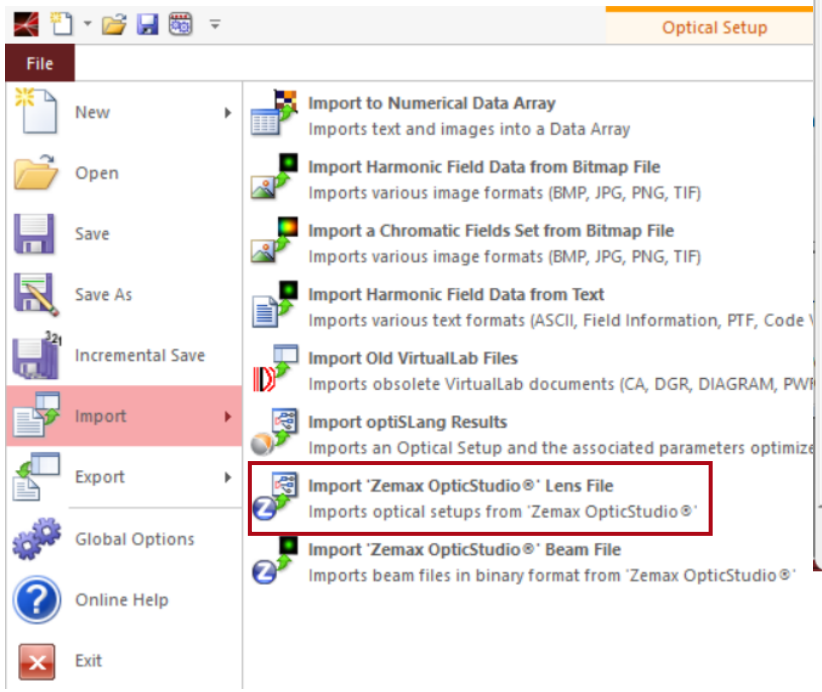


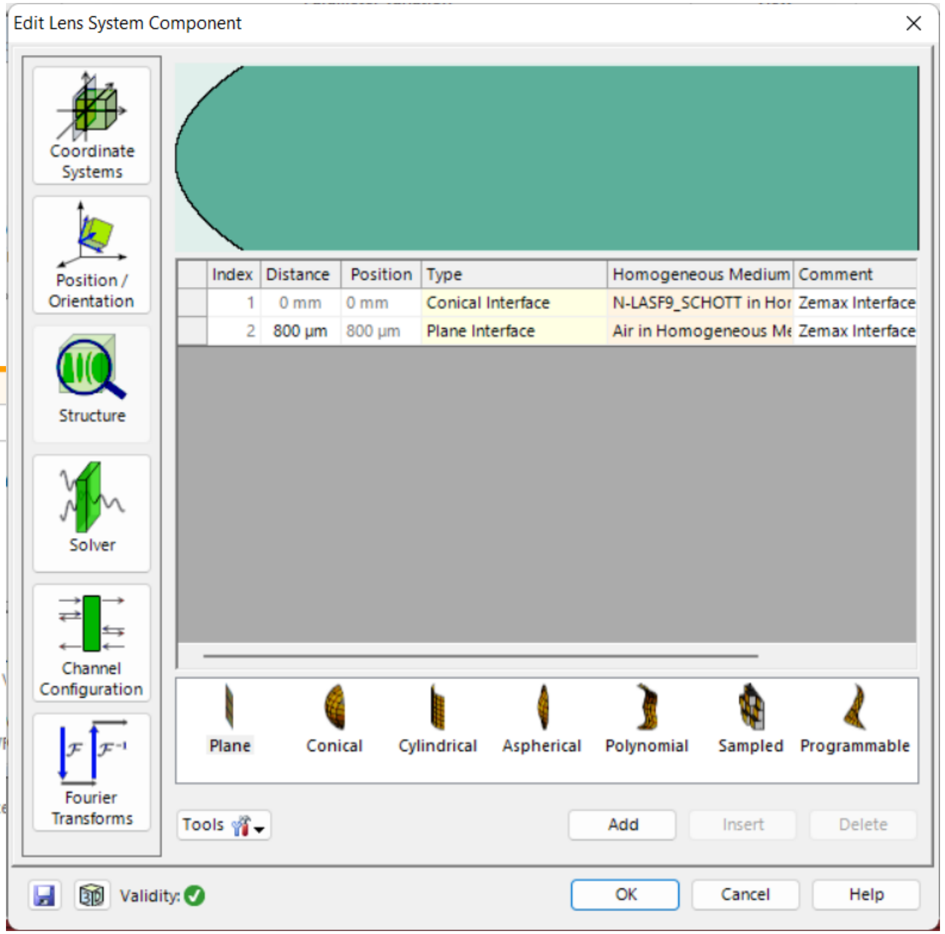
- Is it the best solution to place the fiber end at the ray-optics focal plane behind the lens?
- How to find the optimal working distance to achieve maximum coupling efficiency?

System Building Blocks – Imported Lens File

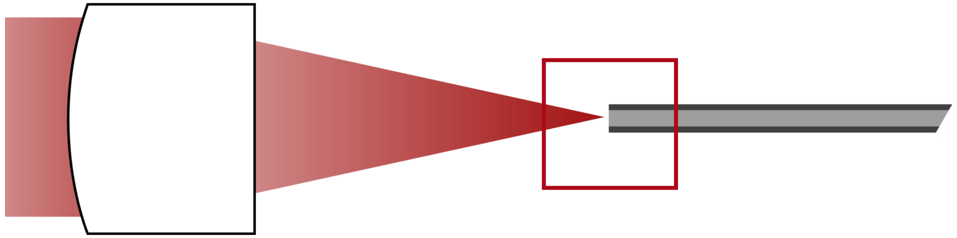


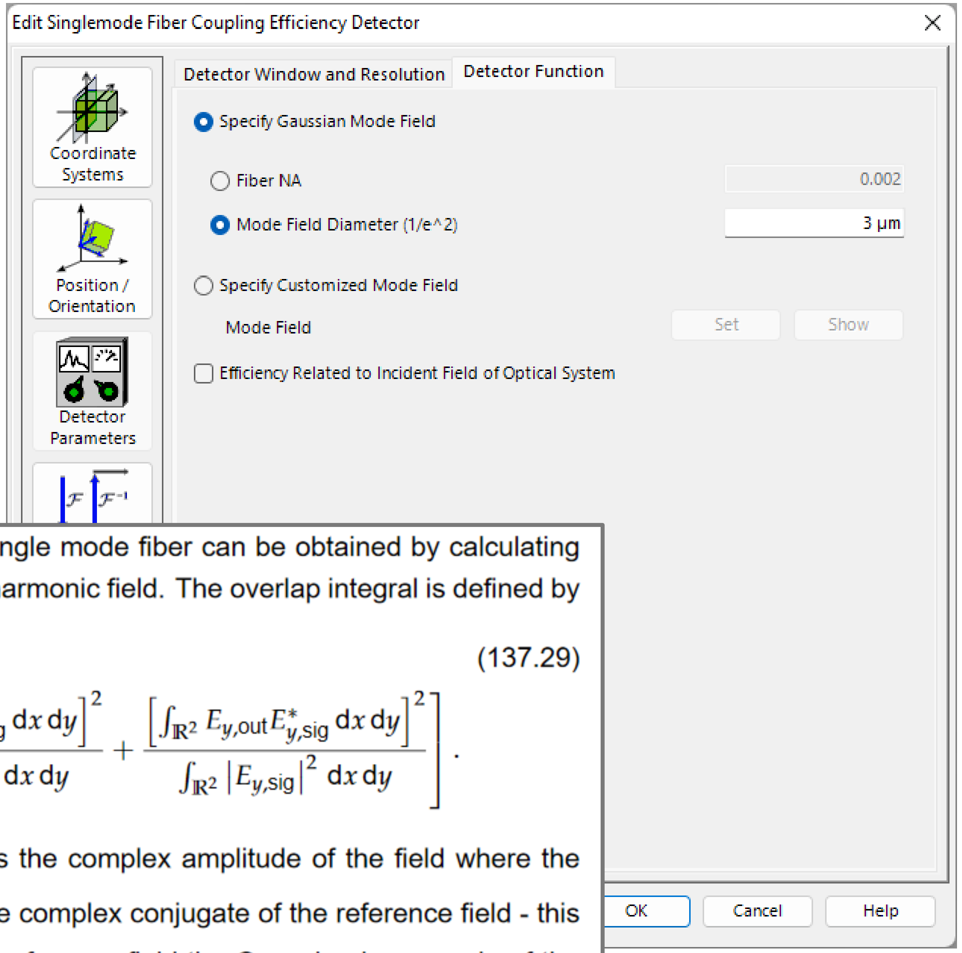
Lens systems, such as the coupling lens in this application, can either be configured by the user from scratch or imported from information provided by the manufacturer.





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.

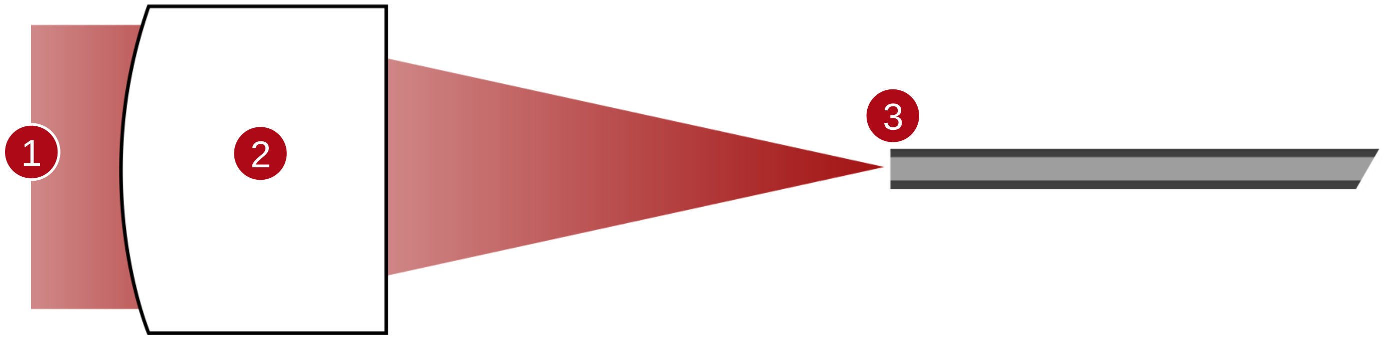
From VirtualLab Fusion Manual:

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

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

$E_{\mathrm{xy,in}}$ 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.

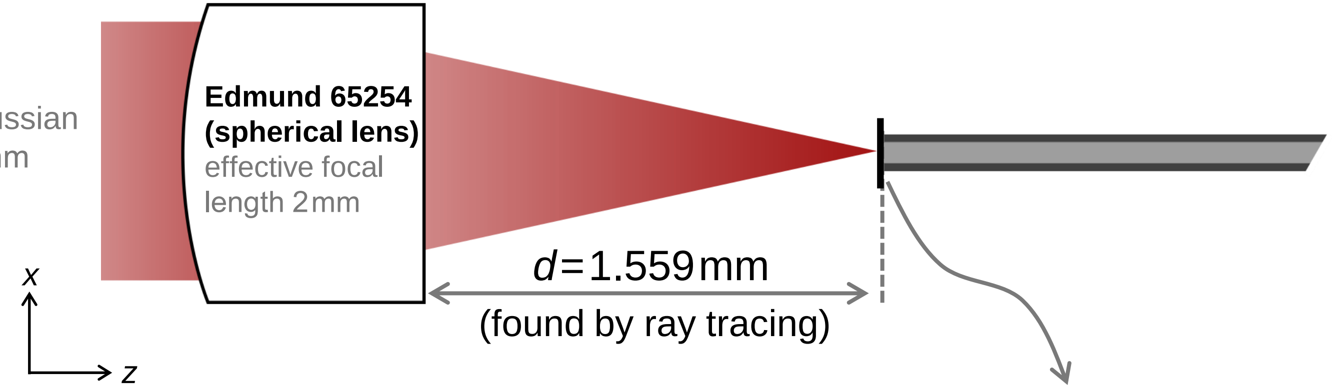
Summary – Components...



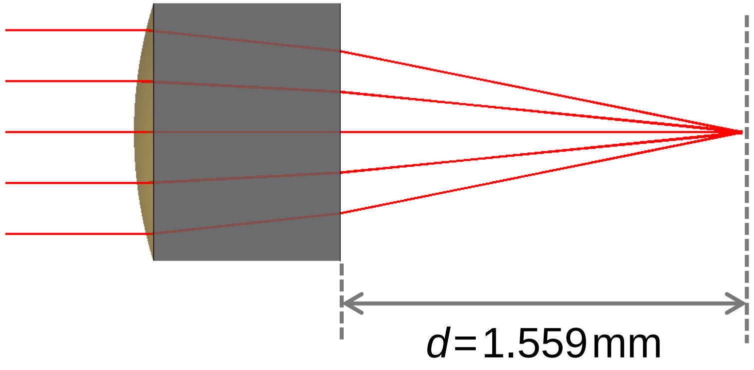
… of Optical System	… in VirtualLab Fusion	Model/Solver/Detected Value
1. source	*Gaussian Wave*	spatial Gaussian function
2. coupling lens	*Lens System Component*	Local Plane Interface Approximation (LPIA)
3. fiber	*Fiber Coupling Efficiency*	overlap integral calculation

Field Tracing Evaluation at Ray-Optics Focal Distance

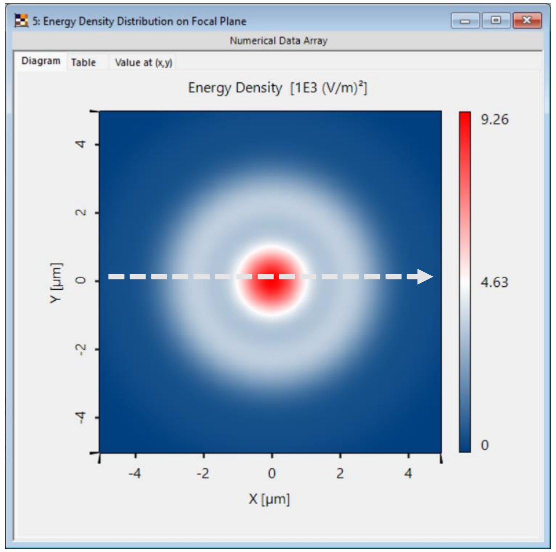
input field
- fundamental Gaussian
- wavelength 780 nm
- diameter 660 µm

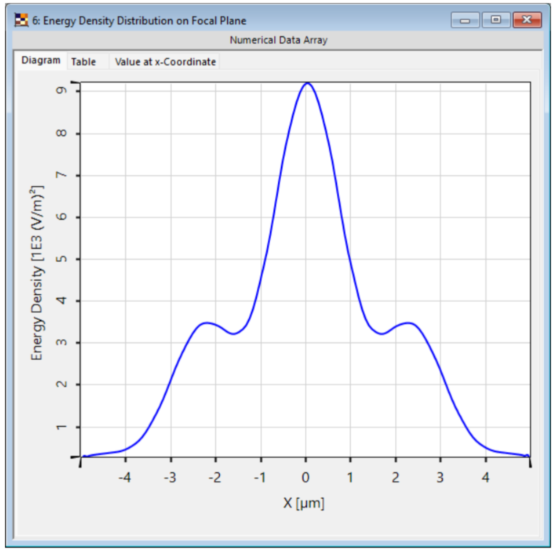


coupling efficiency $\eta = 32.2\%$
(overlap integral calculation)



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

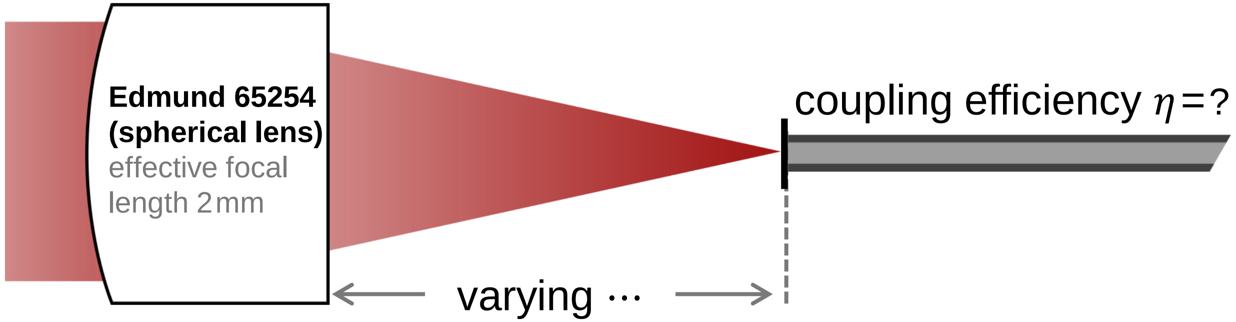


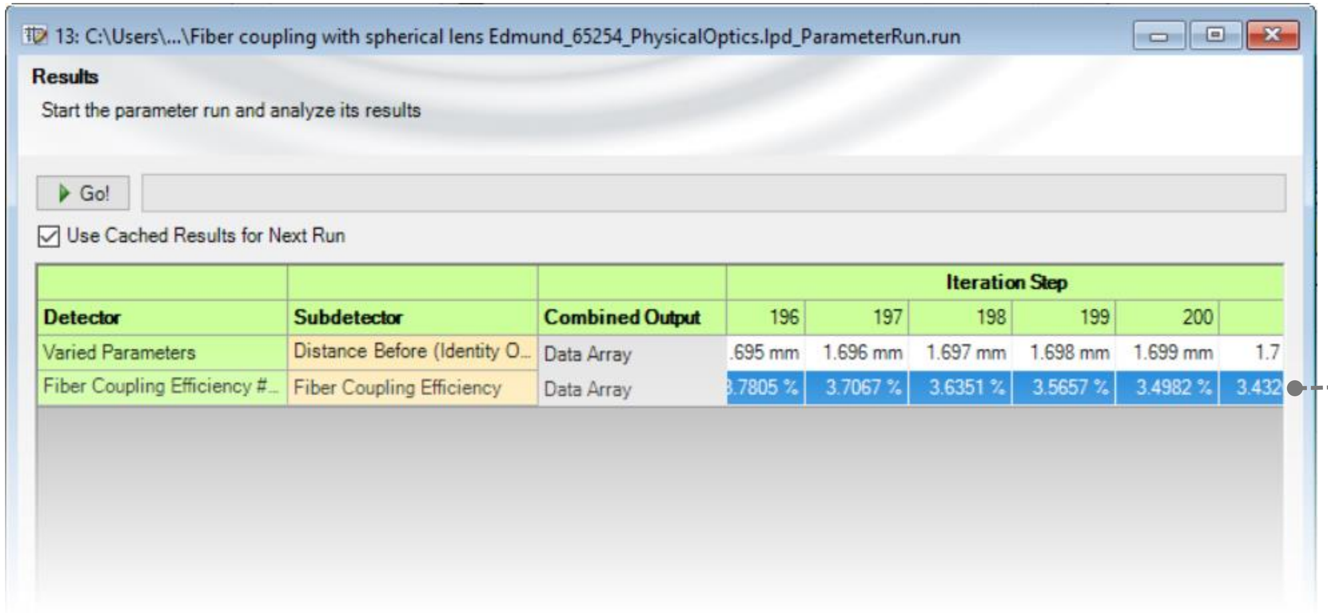


Field tracing in VirtualLab Fusion provides access to the full field information at any desired plane in the system.

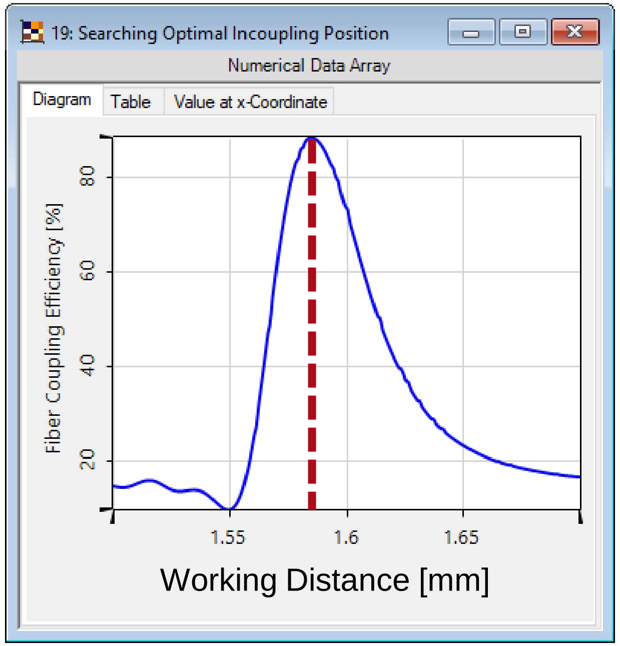
Optimal Working Distance by Field Tracing

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





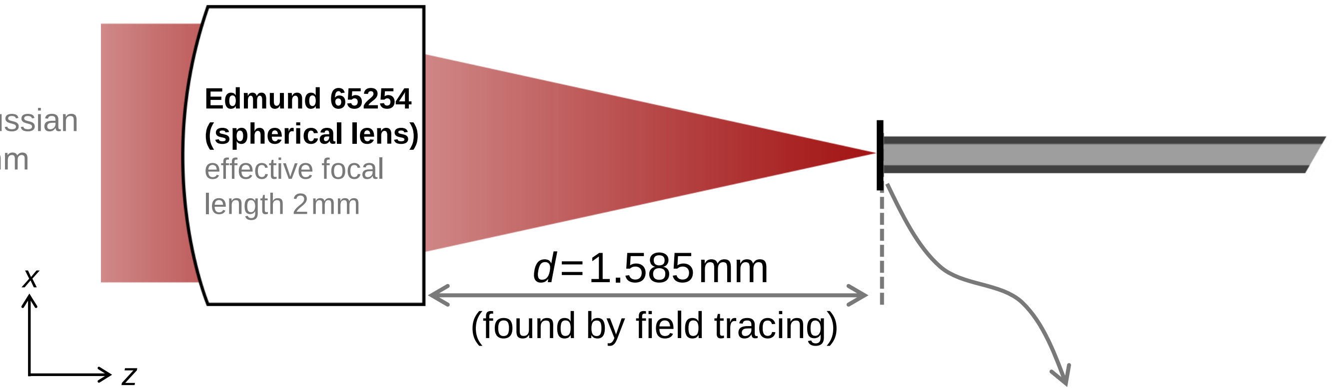
			Iteration Step					
Detector	Subdetector	Combined Output	196	197	198	199	200	
Varied Parameters	Distance Before (Identity O...	Data Array	.695 mm	1.696 mm	1.697 mm	1.698 mm	1.699 mm	1.7
Fiber Coupling Efficiency #...	Fiber Coupling Efficiency	Data Array	3.7805 %	3.7067 %	3.6351 %	3.5657 %	3.4982 %	3.432



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

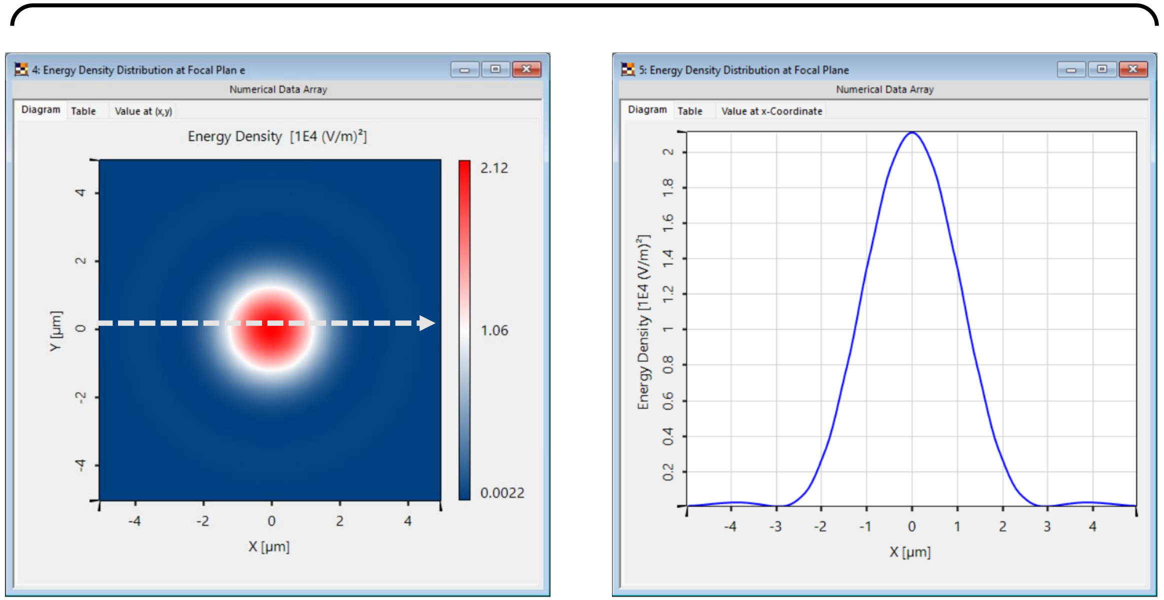
Evaluation at Optimal Working Distance

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

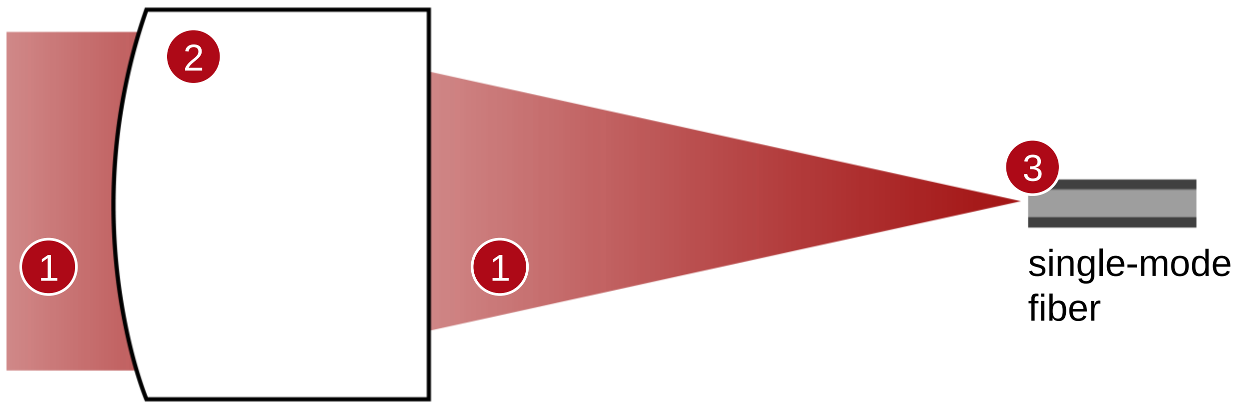


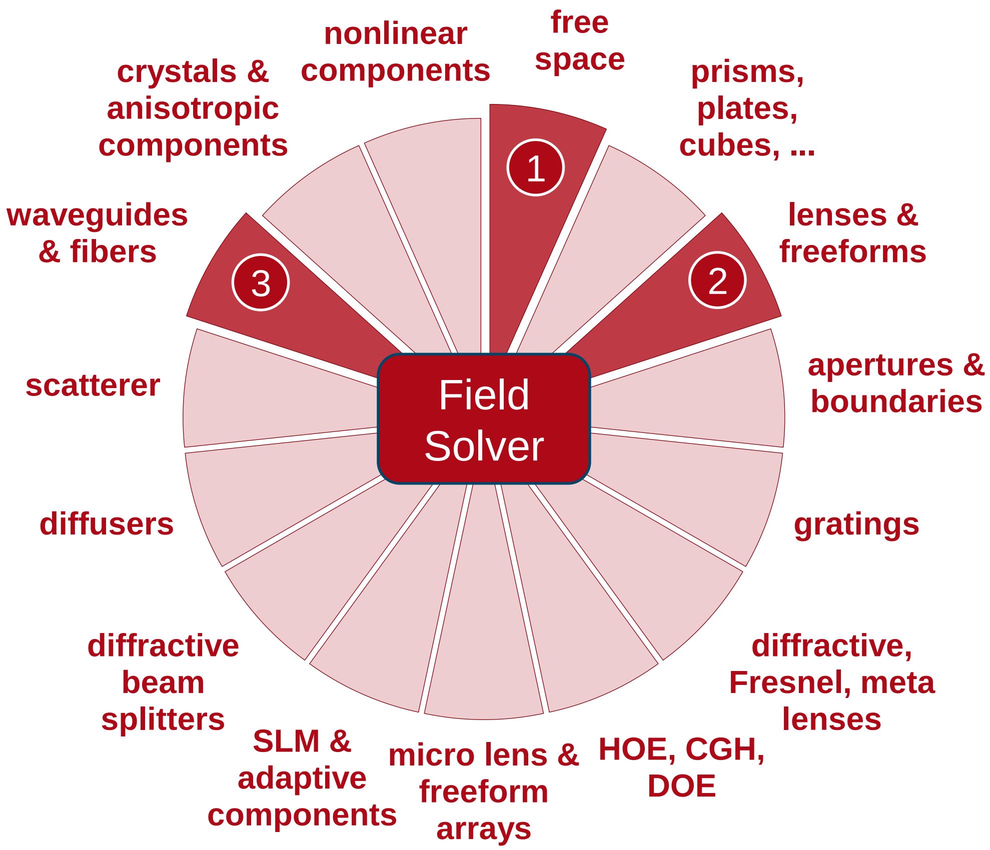
coupling efficiency $\eta = 88.4\%$
(overlap integral calculation)

The focal spot with highest coupling efficiency has similar shape to the fiber mode.



VirtualLab Fusion Technologies





Document Information

title	Optimal Working Distance for Coupling Light into Single-Mode Fibers
document code	FCP.0001
version	3.1
edition	VirtualLab Fusion Basic
software version	2021.1 (Build 1.180)
category	Application Use Case
further reading	- Comparison of Different Lenses for Fiber Coupling - Parametric Optimization of Fiber Coupling Lens