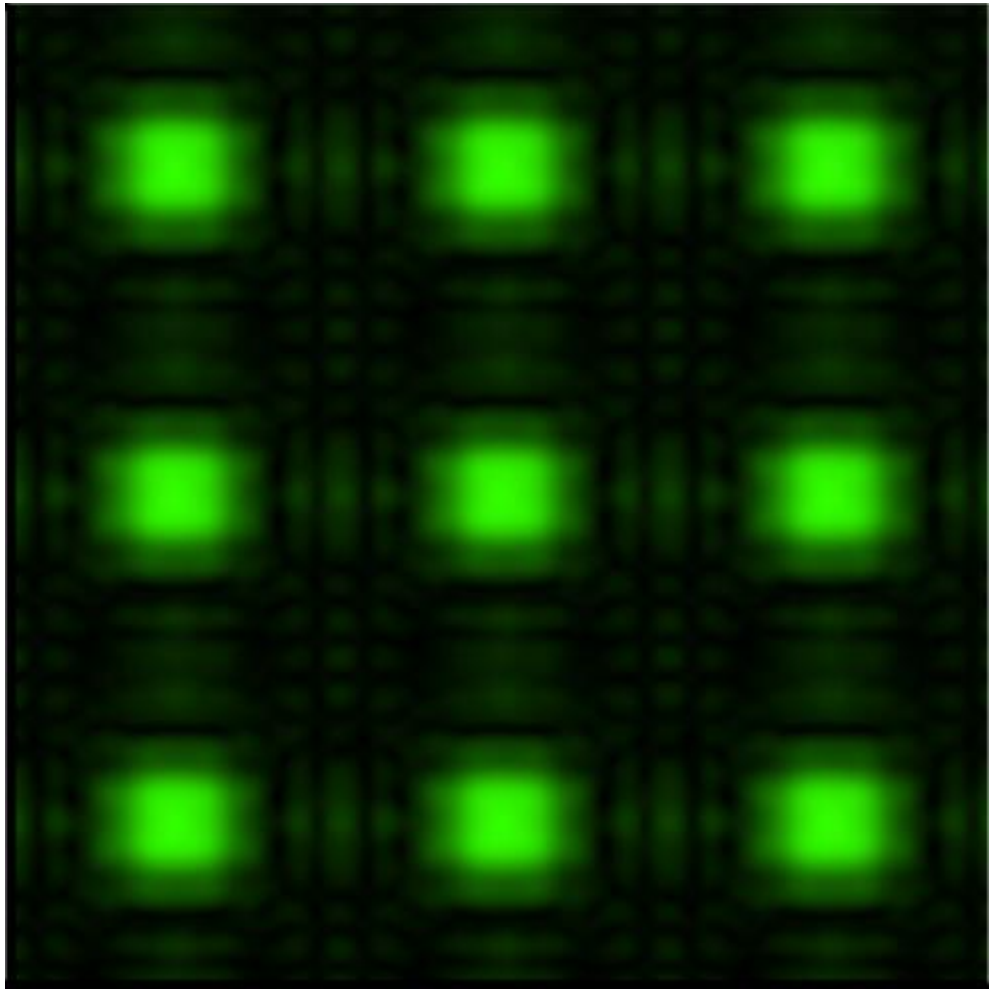
# Analysis of CMOS Sensors with Microlens Array

# Abstract

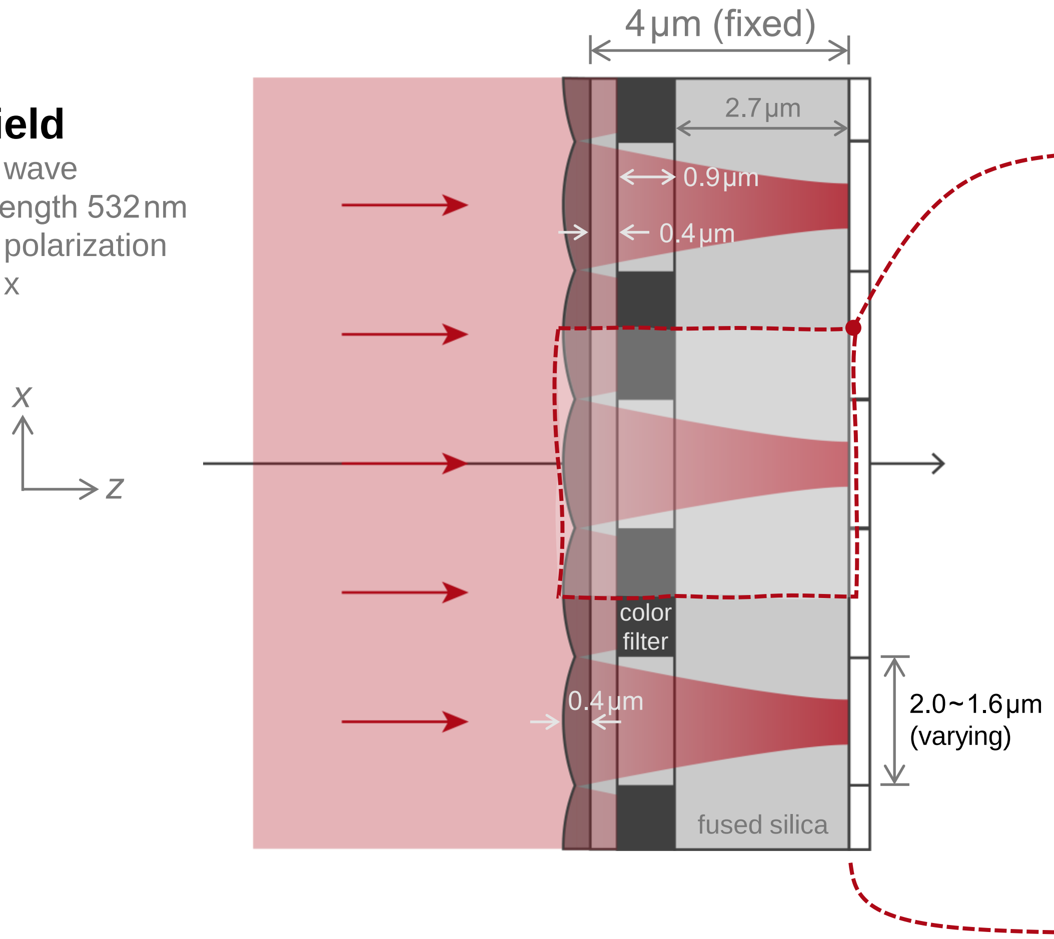


In recent decades, the pixel size of CMOS sensors has scaled down from ~10 µm to ~2 µm or even smaller. By decreasing the pixel size, higher spatial resolution can be achieved. At the same time, it brings into question the functionality of the microlenses sitting on top of each pixel. In this example, we investigate the performance of a CMOS sensor with pixel size equal to or below 2 µm. The rigorous FMM/RCWA is employed for the simulation to check the effectiveness of the microlenses.

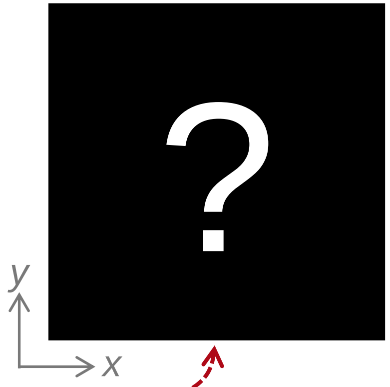
# Modeling Task

**input field**

- plane wave
- wavelength 532 nm
- linear polarization along x




How does the field behind the microlens array behave – is the focusing function still valid?




What is the field distribution like on the final pixel array?

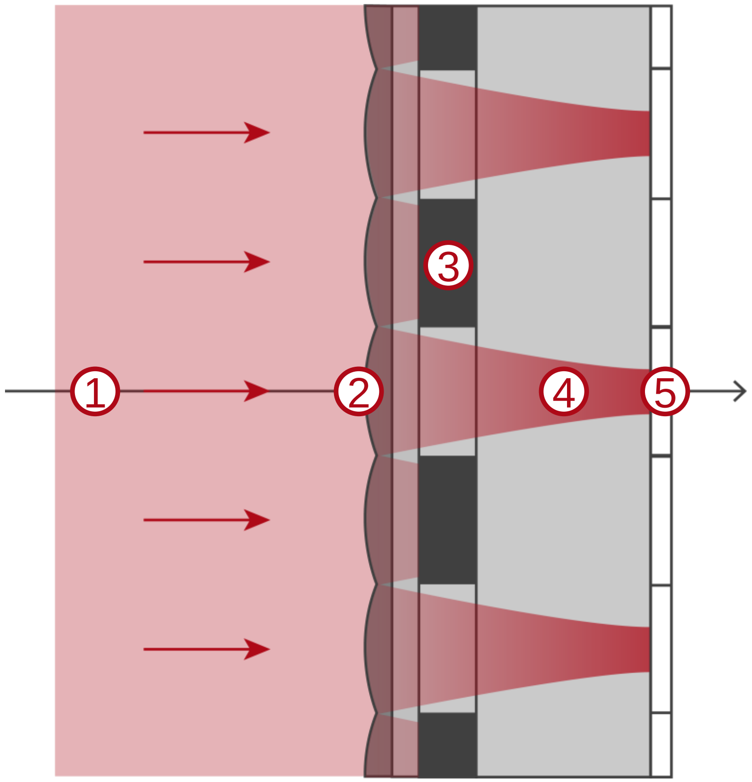
geometry parameters adapted from Y. Huo, *et al*., Opt. Express 18, 5861-5872 (2010)

# Simulation & Setup: Single Platform Interoperability

# Single-Platform Interoperability of Modeling Techniques

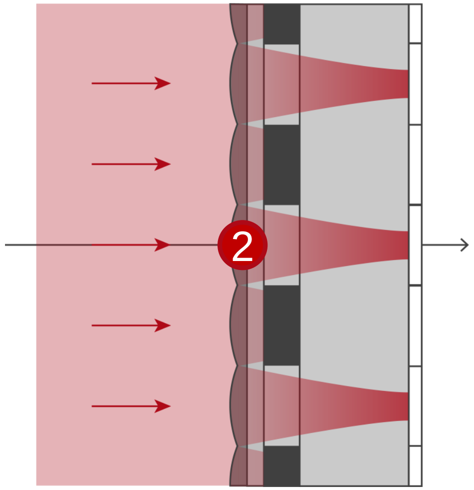
Striking the correct accuracy-speed balance in a simulation requires using a different modeling technique for each part of the system that can take the relevant effects into account without overkill.

① plane-wave source
② microlens array
③ color filter (absorbing media)
④ propagation through substrate
⑤ detection



# Connected Modeling Techniques: Microlens

1. plane-wave source
2. microlens array
3. color filter (absorbing material)
4. propagation through substrate
5. detector



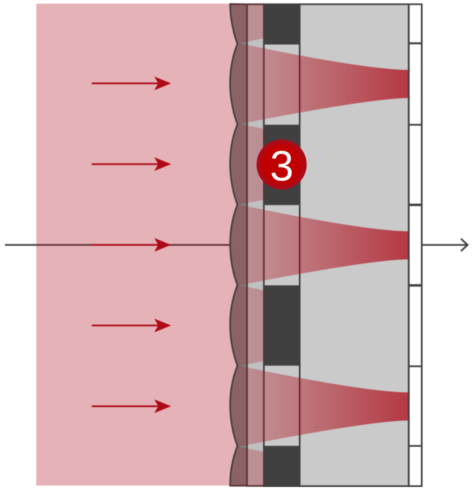

Available modeling techniques for microlens arrays:

| Methods | Preconditions | Accuracy | Speed | Comments |
|---|---|---|---|---|
| Fourier Modal Method (FMM) | none | Very High | High | **small periods** |
| Thin Element Approximation | Large periods & features, thin | High | Very High | Thickness about wavelength; period & features larger than about ten wavelengths |
| Local Planar Interface Approximation | Surface not in focal region of beam, large features | High | Very High | Local application of S matrix; LPIA; x-domain |

As a rigorous eigenmode solver, the Fourier modal method (also known as rigorous coupled wave analysis, RCWA) provides a very high accuracy. Due to the relatively small lenses and distances in this setup, the calculation speed is fast. We also take advantage of the periodic boundary conditions in this inherently periodic structure. FMM is then the best compromise of accuracy and speed.

# Connected Modeling Techniques: Color Filter

1. plane-wave source
2. microlens array
3. color filter (absorbing material)
4. propagation through substrate
5. detector

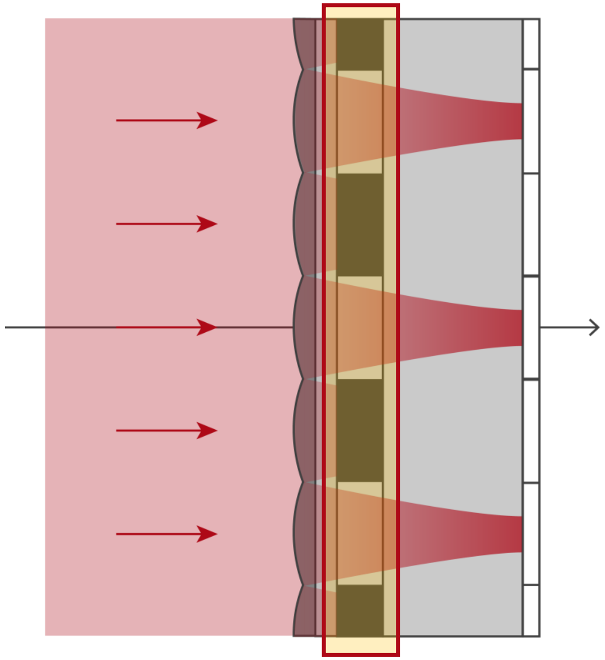


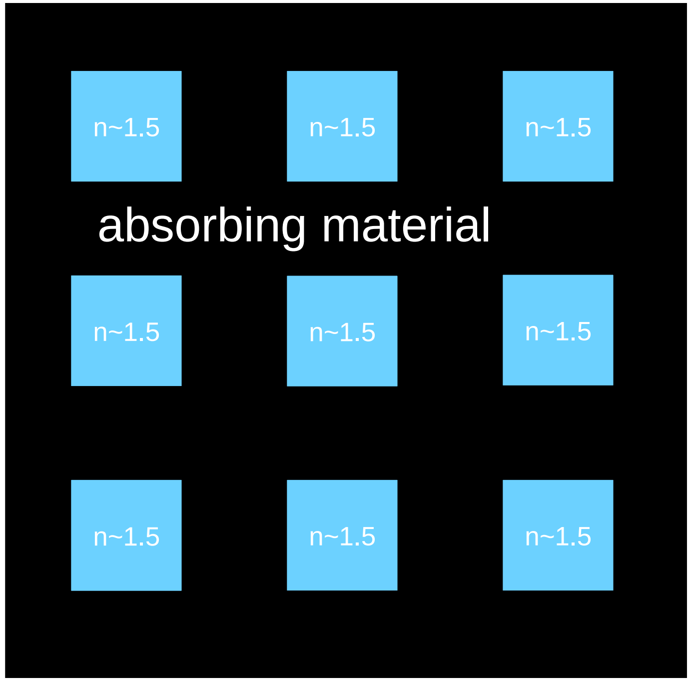

Available modeling techniques for periodic micro and nano structures:

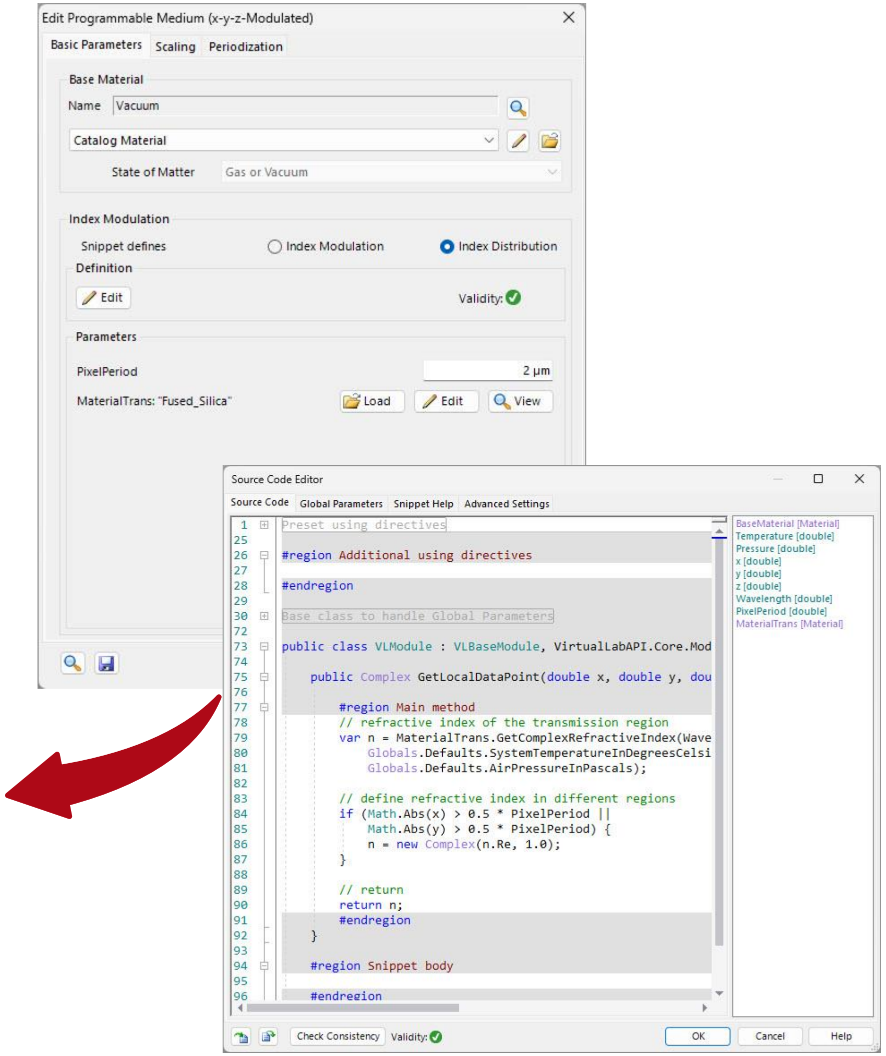
| Methods | Preconditions | Accuracy | Speed | Comments |
|---|---|---|---|---|
| Fourier Modal Method (FMM) | none | Very High | High | **small periods** |
| Thin Element Approximation | Large periods & features, thin | High | Very High | Thickness about wavelength; period & features larger than about ten wavelengths |

The same argumentation is true for the color filter behind the microlens array.

# Connected Modeling Techniques: Programmable Medium



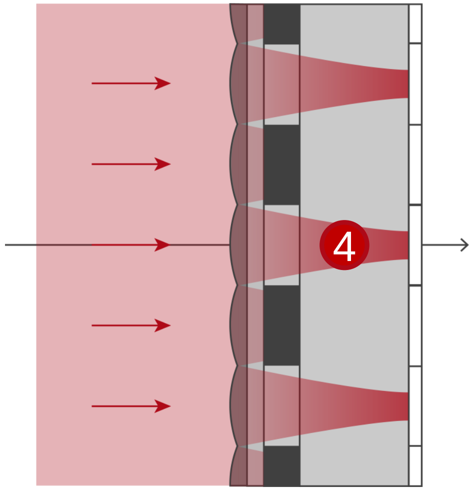



The special shape of the color filter layer can be represented by a programmable medium, which allows for the custom specification of the refractive index in all dimensions (x,y,z).

# Connected Modeling Techniques: Free-Space Propagation

1. plane-wave source
2. microlens array
3. color filter (absorbing material)
4. **propagation through substrate**
5. detector




Available modeling techniques for free-space propagation:

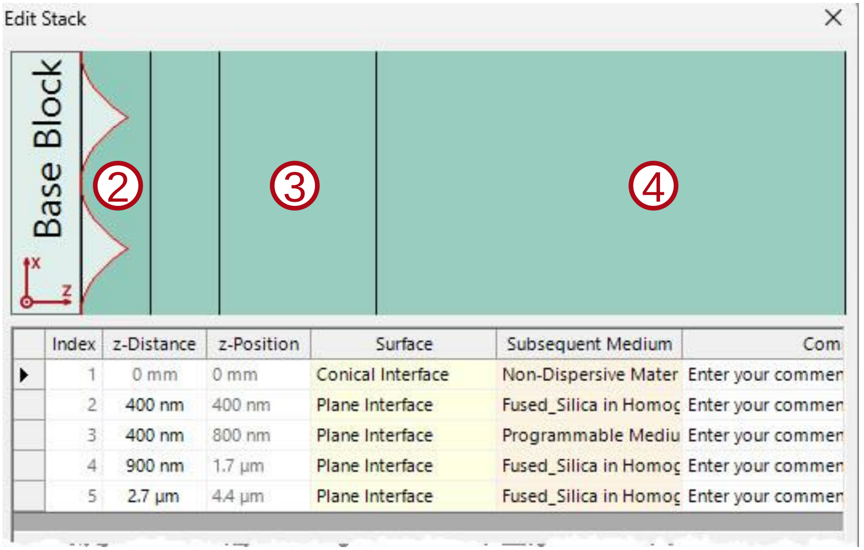
| Methods | Preconditions | Accuracy | Speed | Comments |
|---|---|---|---|---|
| Rayleigh Sommerfeld Integral | None | Very High | Low | Rigorous solution |
| Fourier Domain Techniques | None | High | High | Rigorous mathematical reformulation of RS integral |
| Fresnel Integral | **Paraxial** | High | High | Assumes paraxial light; moderate speed for very short distances |
| | Non-paraxial | Low | High | |
| Geometric Propagation | **Low diffraction** | High | Very high | Neglects diffraction effects |
| | Otherwise | Low | Very high | |
| Fourier Modal Method (FMM) | none | Very High | High | **small periods, includes evanescent modes** |

Although this is not a typical choice for free-space propagation, we again take advantage here of the periodic nature of the system and, considering also the evanescent modes, we continue using FMM for this step. The fact that the propagation distance is short, in addition, helps support this choice.

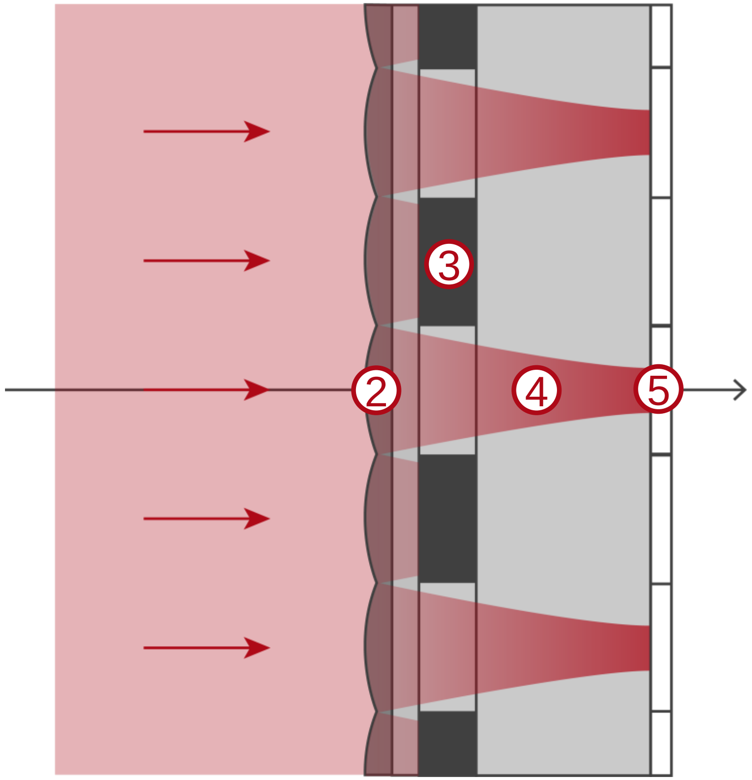
# Connected Modeling Techniques: Stacks

*Stacks* are a convenient way to configure structures with small feature sizes and distances in VirtualLab Fusion. In these containers, multiple types of surfaces and media can be included to represent the various aspects of the structure. Please note that the same modeling technique is used for the entire stack.

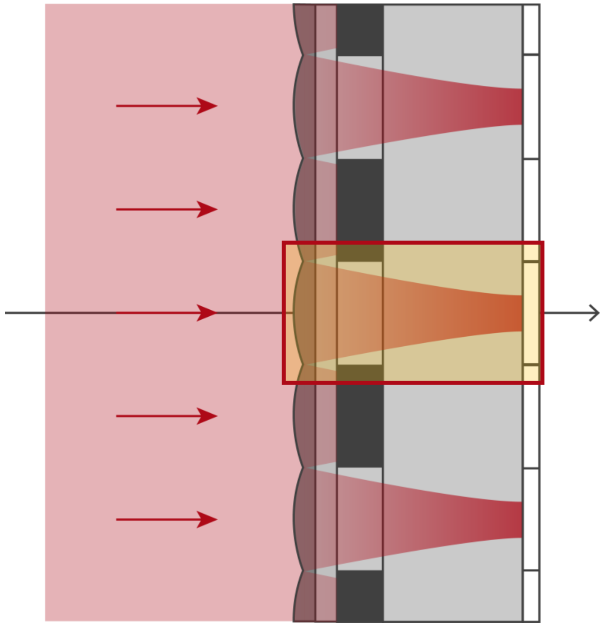
② microlens array
③ color filter (absorbing media)
④ substrate
⑤ detection

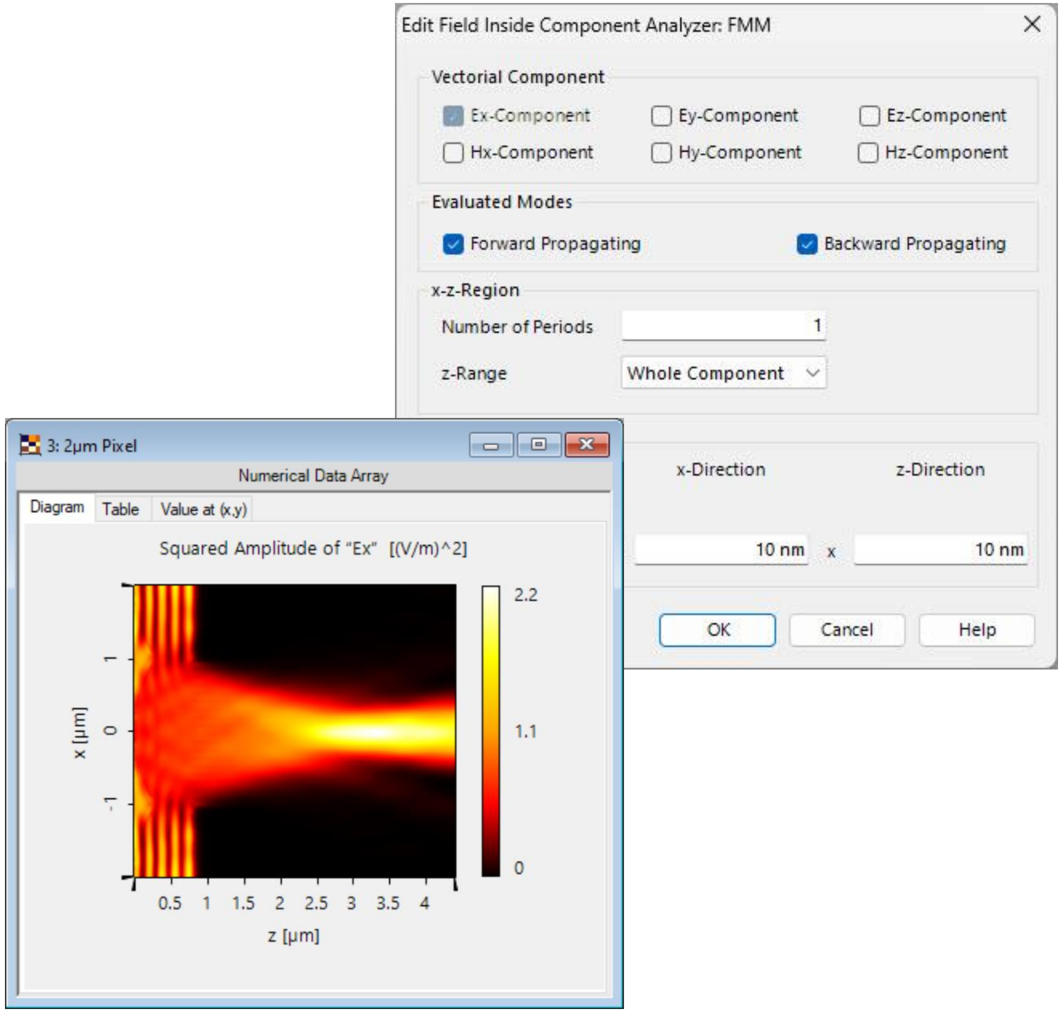



| | Index | z-Distance | z-Position | Surface | Subsequent Medium | Com |
|---|---|---|---|---|---|---|
| ▶ | 1 | 0 mm | 0 mm | Conical Interface | Non-Dispersive Mater | Enter your commen |
| | 2 | 400 nm | 400 nm | Plane Interface | Fused_Silica in Homog | Enter your commen |
| | 3 | 400 nm | 800 nm | Plane Interface | Programmable Mediu | Enter your commen |
| | 4 | 900 nm | 1.7 µm | Plane Interface | Fused_Silica in Homog | Enter your commen |
| | 5 | 2.7 µm | 4.4 µm | Plane Interface | Fused_Silica in Homog | Enter your commen |



# Field Inside Component Analyzer: FMM

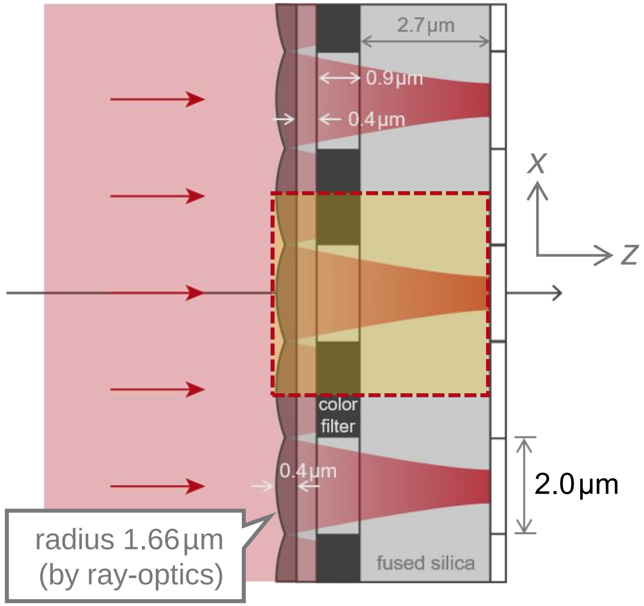




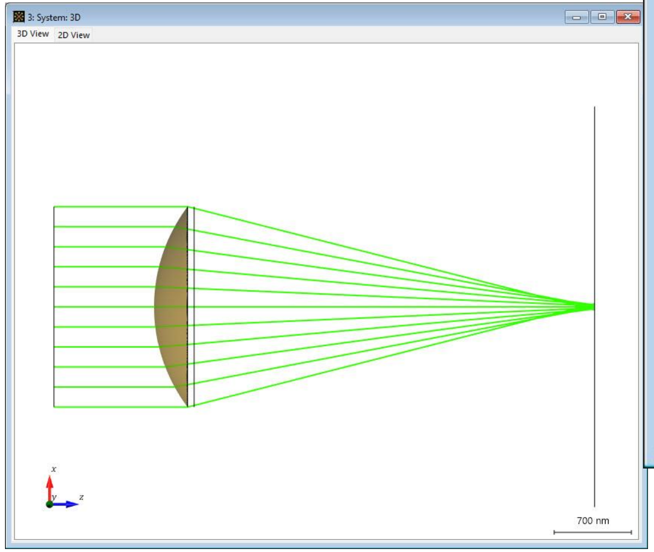

To visualize the actual field propagation inside a *Stack* and illustrating its evolution, the *Field Inside Component Analyzer: FMM* allows the user to calculate a 1D cross section of the field at various steps inside a given component and to display the aggregated results in 2D. More information under:
[Field Inside Component Analyzer: FMM]

# Simulation Results

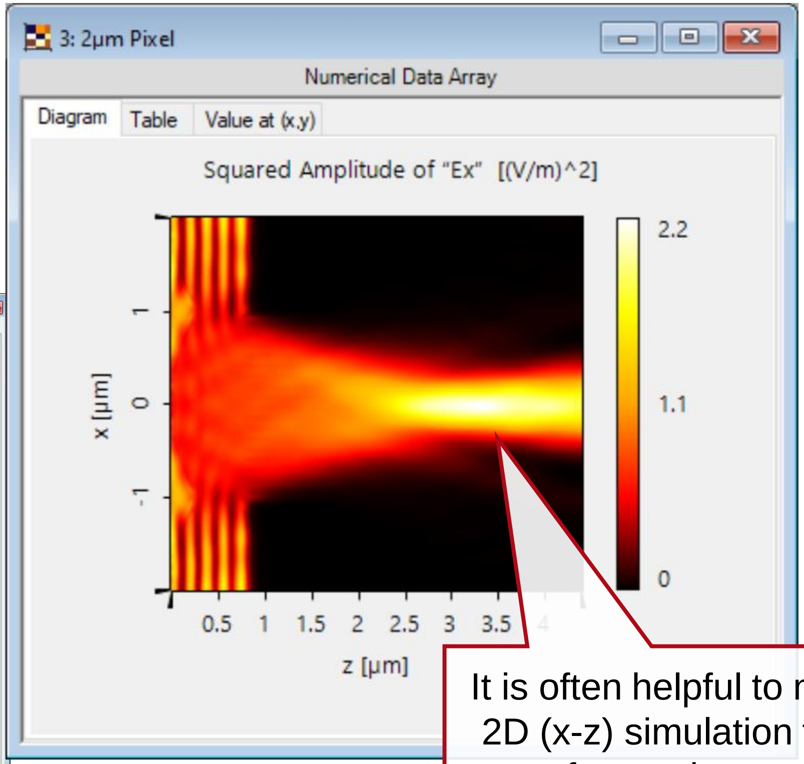
# Microlens for Pixel Size of 2.0 µm (Simulation in x-z Plane)




ray-optics design (single lens)

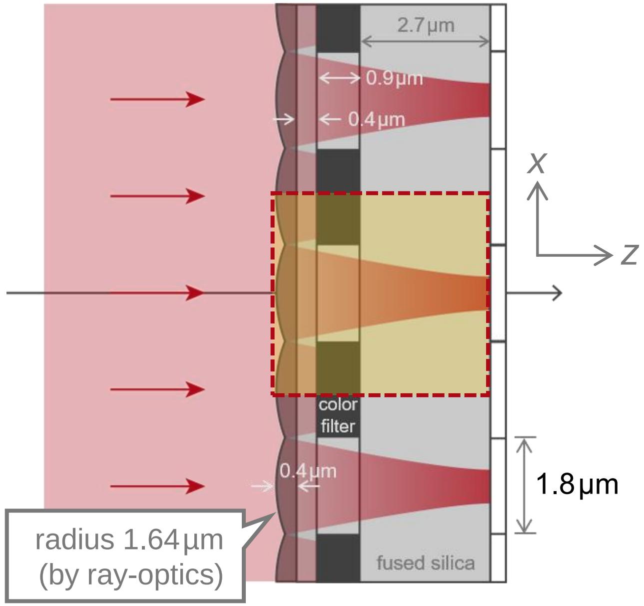



FMM/RCWA simulation (x-z plane)

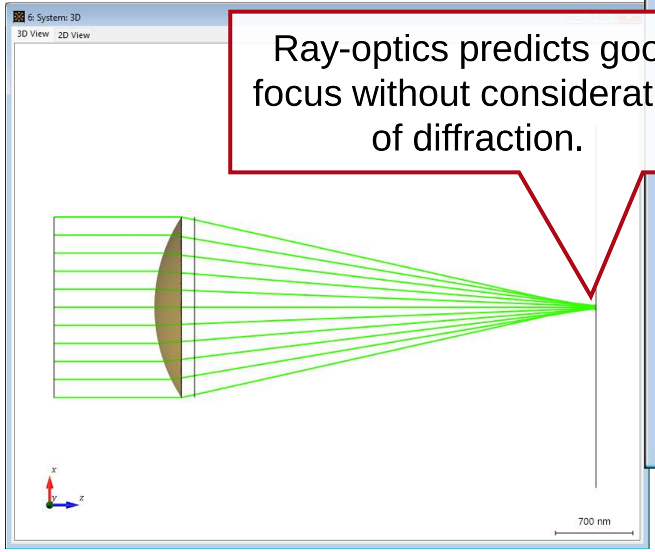



It is often helpful to make a 2D (x-z) simulation first to get a fast understanding of the situation.

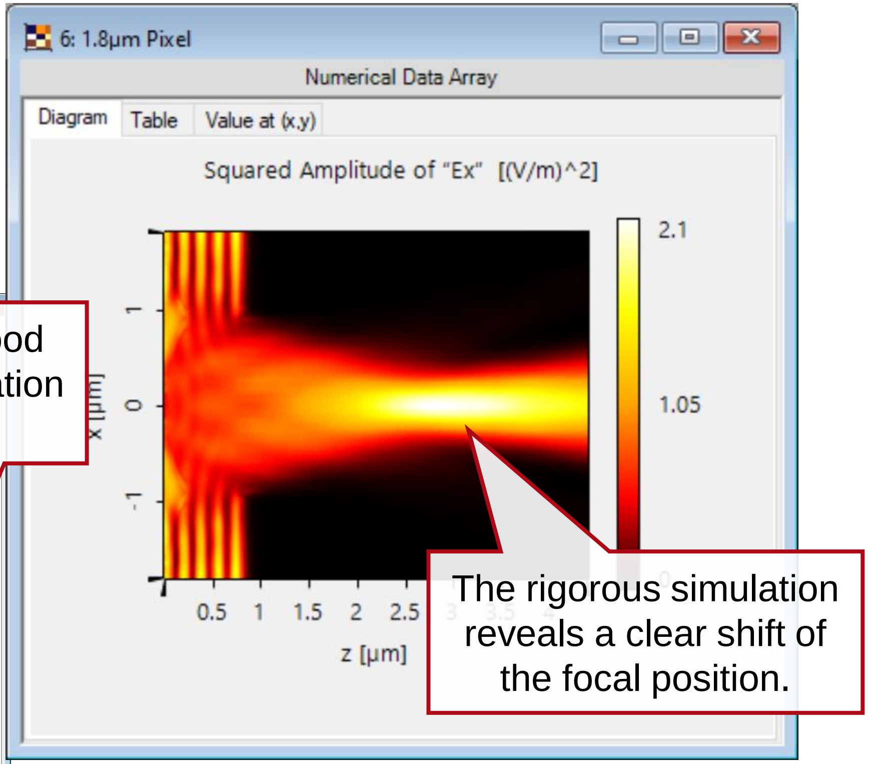
# Microlens for Pixel Size of 1.8 µm (Simulation in x-z Plane)



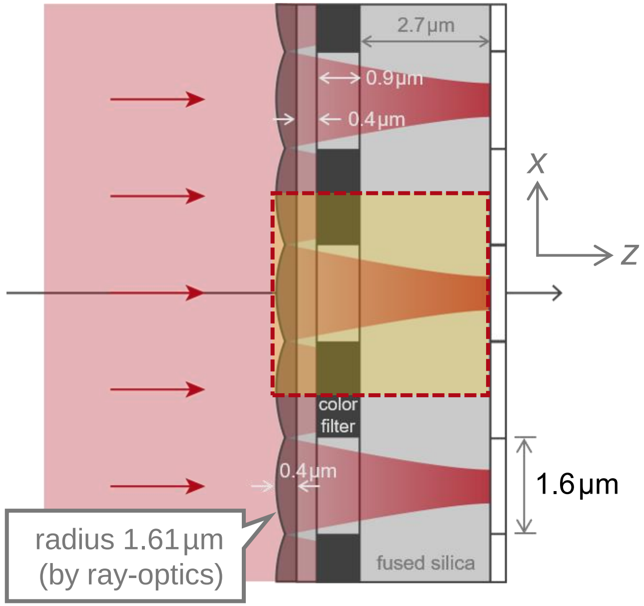

ray-optics design (single lens)



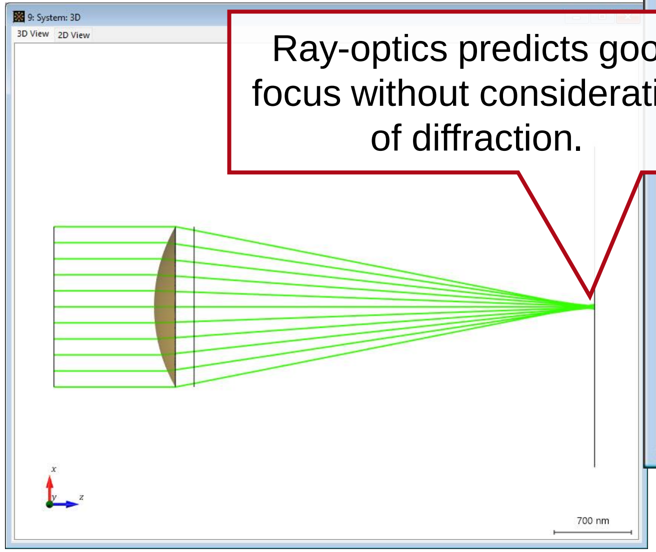

FMM/RCWA simulation (x-z plane)



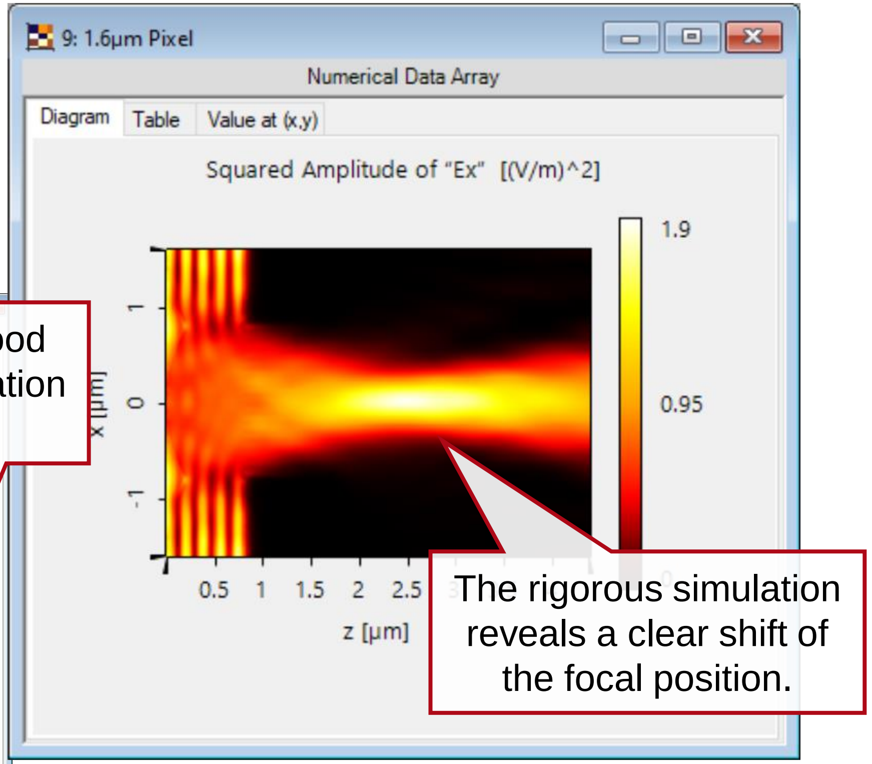
# Microlens for Pixel Size of 1.6 µm (Simulation in x-z Plane)



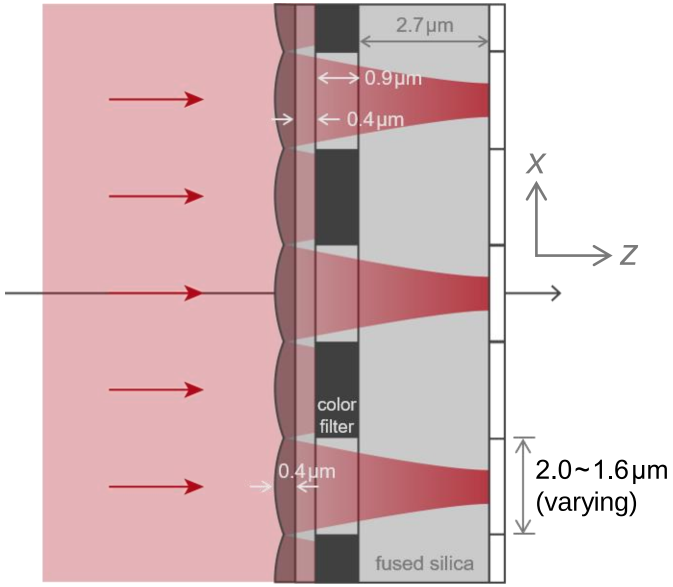

ray-optics design (single lens)



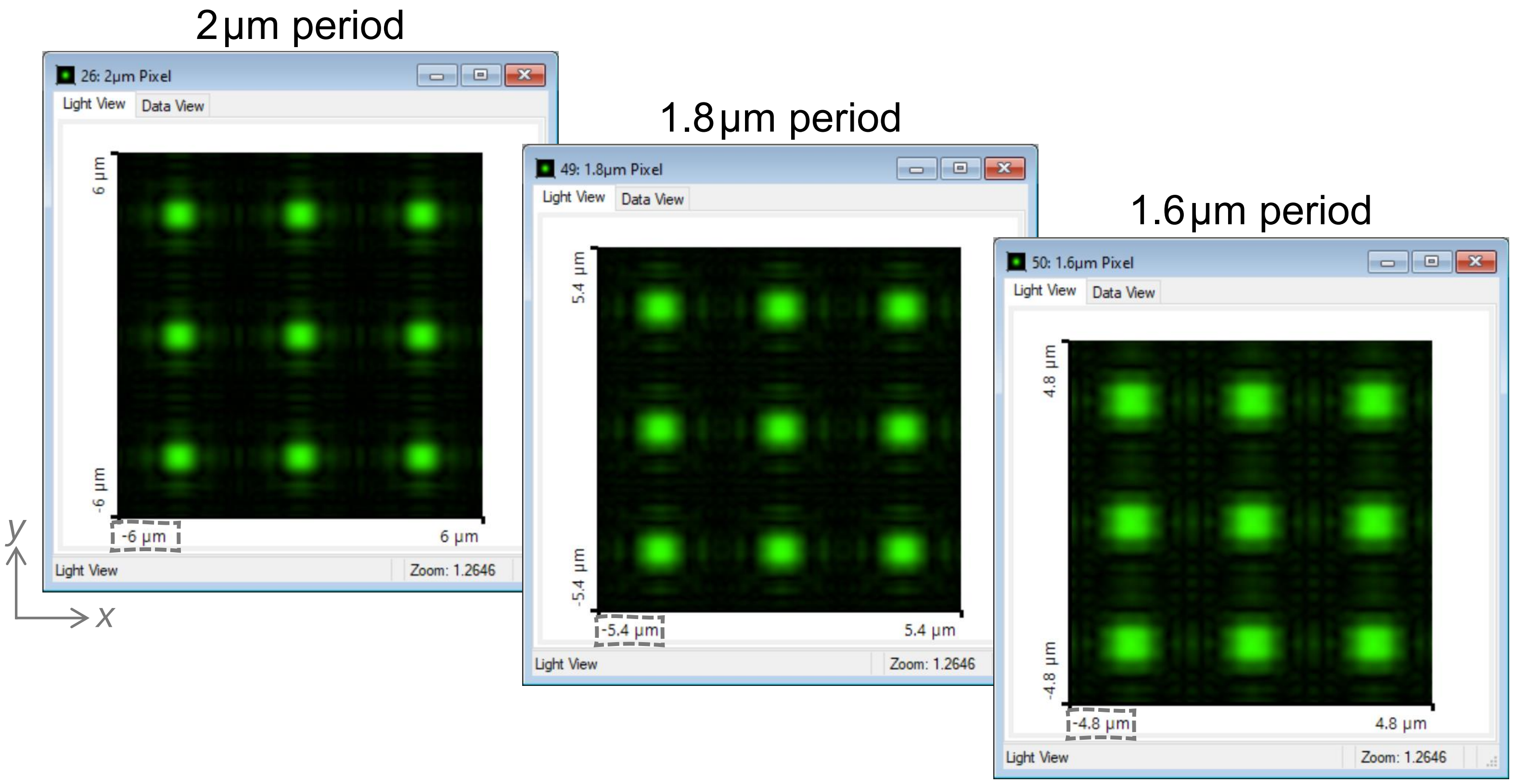

FMM/RCWA simulation (x-z plane)



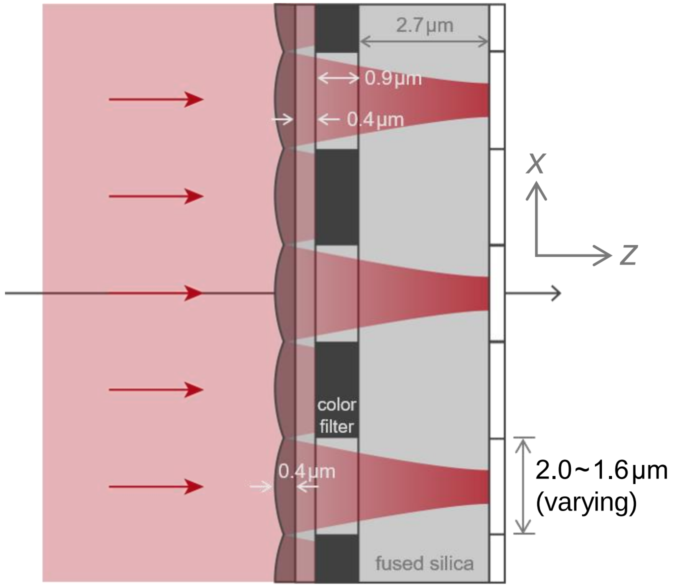
# 3D Simulation and Comparison of Results




check the results at this plane

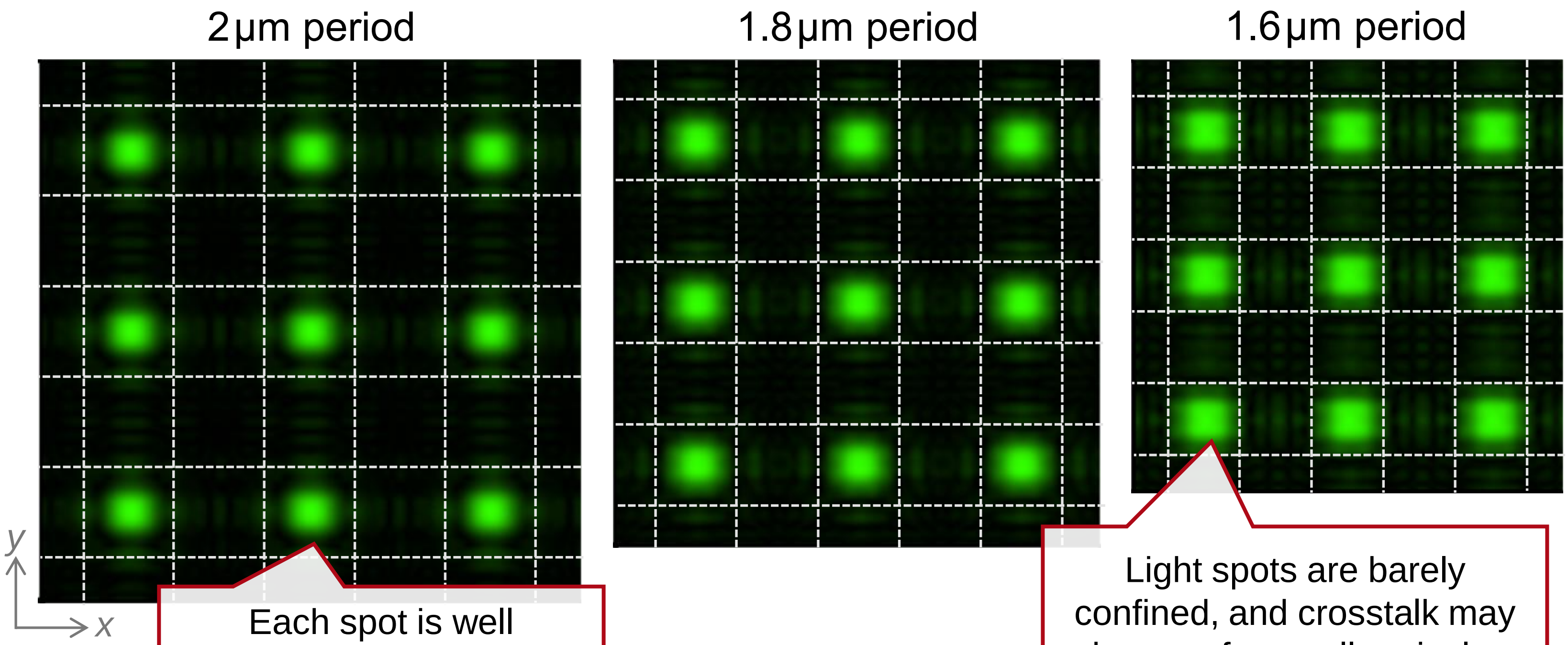


# 3D Simulation and Comparison of Results




check the results on this plane

same scaling for all the result figures




Each spot is well confined within the corresponding pixel area.

Light spots are barely confined, and crosstalk may happen for smaller pixels.

# Document Information

| | |
|---|---|
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| software version | 2023.1 (Build 1.556) |
| category | Application Use Case |
| further reading | • Ultra-Sparse Dielectric Nano-Wire Grid Polarizers<br>• Configuration of Grating Structures by Using Interfaces<br>• Configuration of Grating Structures by Using Special Media |