Analysis of CMOS Sensors with Microlens Array
Abstract

In recent decades, the pixel size of CMOS sensors has scaled down from \( \sim 10\,\mu\text{m} \) to \( \sim 2\,\mu\text{m} \) or even smaller. By decreasing the pixel size, higher spatial resolution has been 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\( \mu\text{m} \). 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?

<table>
<thead>
<tr>
<th>x</th>
<th>z</th>
</tr>
</thead>
<tbody>
<tr>
<td>4 µm (fixed)</td>
<td>2.7 µm</td>
</tr>
<tr>
<td>0.9 µm</td>
<td>0.4 µm</td>
</tr>
<tr>
<td>2.0 ± 1.6 µm (varying)</td>
<td>fused silica</td>
</tr>
</tbody>
</table>

- color filter
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
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 periods 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.
Available modeling techniques for periodic micro and nano structures:

<table>
<thead>
<tr>
<th>Methods</th>
<th>Preconditions</th>
<th>Accuracy</th>
<th>Speed</th>
<th>Comments</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fourier Modal Method (FMM)</td>
<td>none</td>
<td>Very High</td>
<td>High</td>
<td>small periods</td>
</tr>
<tr>
<td>Thin Element Approximation</td>
<td>Large periods &amp; features, thin</td>
<td>High</td>
<td>Very High</td>
<td>Thickness about wavelength; period &amp; features larger than about ten wavelengths</td>
</tr>
</tbody>
</table>

The same argumentation is true for the color filter behind the microlens array.
The special shape of the color filter layer can be represented by a programmable medium, which allows for a custom specification of the refractive index in (x,y,z).
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.

Available modeling techniques for free-space propagation:

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

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

- Microlens array
- Color filter (absorbing media)
- Propagation through substrate
- Detection
To visualize the actual field propagation inside a Stack, the Field Inside 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, illustrating the evolution of the profile. More information under:
Field Inside Component Analyzer: FMM
Simulation Results
Microlens for 2µm Pixel (x-z Simulation)

It is often helpful to make a 2D (x-z) simulation first to get a fast understanding of the situation.
Microlens for 1.8 µm Pixel (x-z Simulation)

- Radius: 1.64 µm (by ray-optics)
- FMM/RCWA simulation (x-z)
Microlens for 1.6μm Pixel (x-z Simulation)

The rigorous simulation shows a clear shift of the focal position.

Ray-optics predicts good focus without consideration of diffraction.

FMM/RCWA simulation (x-z)

The rigorous simulation shows a clear shift of the focal position.
3D Simulation and Results Comparison

Check the results on this plane.

2.0~1.6 µm (varying)

2 µm period

1.8 µm period

1.6 µm period
3D Simulation and Results Comparison

Each spot is well confined within the corresponding pixel area.

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

Check the results on this plane.

Same scaling for all the result pictures.
## Document Information

<table>
<thead>
<tr>
<th>title</th>
<th>Analysis of CMOS Sensors with Microlens Array</th>
</tr>
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<tbody>
<tr>
<td>document code</td>
<td>GRT.0026</td>
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<tr>
<td>version</td>
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<td>edition</td>
<td>VirtualLab Fusion Advanced</td>
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<td>software version</td>
<td>2023.1 (Build 1.556)</td>
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<tr>
<td>category</td>
<td>Application Use Case</td>
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| further reading        | - Ultra-Sparse Dielectric Nano-Wire Grid Polarizers  
                         | - Configuration of Grating Structures by Using Interfaces  
                         | - Configuration of Grating Structures by Using Special Media |