# COMSOL Multiphysics® Software As a Metasurfaces Design Tool for Plasmonic-Based Flat Lenses

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## Abstract

Introduction:
Flat lenses require precise control of a phase gradient across an interface, which is enabled through the application of engineered surfaces, such as Metasurfaces [1]. Periodic arrays of plasmonic antennas have been utilized to generate this desired phase gradient, which dictates the angle of "anomalous" refraction of the cross-polarized field scattered from a normal-incidence beam. However, the designs utilized to-date have been simple geometries, due to the challenges of numerical modeling more complex forms, and as a result scattering efficiencies have been unacceptable for real-world application. Therefore, an optimization effort is necessary to improve the performance. In order to establish confidence before proceeding with complex designs, the COMSOL Multiphysics® software was used to generate several simple plasmonics-based flat lens designs, which were then fabricated and measured for validation of the simulated results. These lenses were assessed for characterization of their depth-of-field under a changing focal ratio (f/#) in the long-wave infrared (LWIR) regime.

Use of the COMSOL® software:
Controlling the phase gradient requires understanding of the phase and amplitude profile of the field scattered from the plasmonic antenna. Mimicking the original numerical model of a v-antenna [2], the COMSOL Multiphysics® software was used to produce these profiles as a function of the antenna geometries: dipole length and the relative angle of separation of the dipoles. These profiles were used to select which N elements will form the basis of the lens design. These elements must meet the two constraints of having phase separation 2π/N apart while also maintaining equal field amplitudes:

$\Delta\varphi=\varphi_{i+1}-\varphi_i=2\pi/N$
$|E_i^{x\text{-pol}}|=|E_{i+1}^{x\text{-pol}}|$

Following the "Scatterer on a Substrate" model library, the Wave Optics Module of the COMSOL® software is used to sequentially calculate an input field based on the full-field results of the substrate-only model. The N antenna elements were each isolated within perfectly matched layer (PML) boundaries and illuminated with this input field, with the phase and amplitude of the scattered cross-polarized field extracted at the ports. These elements are aligned in a "supercell" and again illuminated with the input field to validate the overall anomalous refraction. This supercell was then expanded into a rectangular

lens architecture spanning several 2π phase periods and output to a file suitable for e-beam lithographic mask production.

Results:
The scattered field phase and amplitude profiles were sufficiently recreated from the original work to generate basis elements for the flat lens designs (Fig.1). Fig.2 shows a supercell design and the phase broadside generated by the metasurface, giving rise to an anomalous refraction. The measured depth-of-field and the numerical calculations and compare favorably (Fig.3), validating the design process.

Conclusion:
The COMSOL Multiphysics® simulations demonstrated how novel metasurfaces can be confidently generated in the early stages of flat lens designs to focus infrared light across a single, flat interface. By validating the design of a simple numerical model (v-antenna), the computational tool can now be used by optical engineers to explore a vast parameter space of metasurface inclusions and materials which would be inaccessible using simplified numerical models alone.

## Reference


[1] N. Yu and F. Capasso, "Flat Optics with Designer Metasurfaces," Nature Materials, vol. 13, pp. 139-150, 2014.
[2] F. Aieta, et al., "Aberration-Free Ultrathin Flat Lenses and Axicons at Telecom Wavelengths Based on Plasmonic Metasurfaces," Nano Letters, vol. 12, no. 9, pp. 4932-4936, 2012.


## Figures used in the abstract

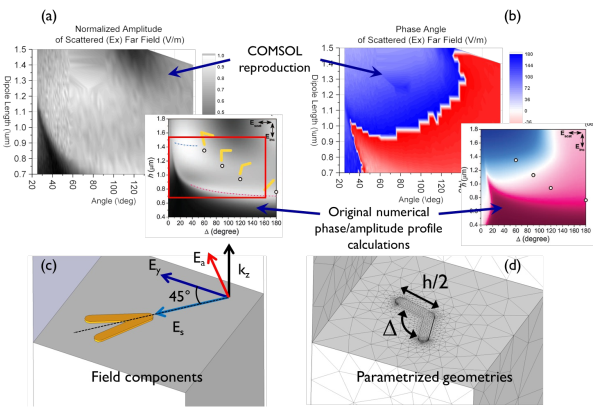


**Figure 1**: COMSOL reproduction of the scattered field amplitude (a) and phase (b) from Yu’s original work (insets). Orientation of the incident field (c) and parametrized geometries which define the scattering behavior (d).

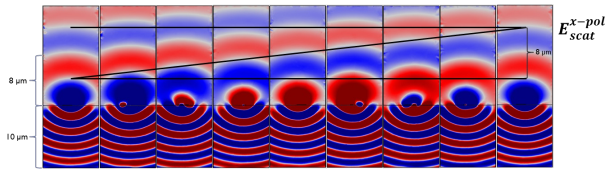


Figure 2: COMSOL results for the scattered field from individual v-antenna elements illuminated at normal incidence. Elements were chosen from profiles in Fig. 1 to meet the criteria that neighboring elements differ by Δφ=π⁄4 but with equal amplitudes. A clear broadside "anomalous" refraction is suggested, if the elements were to be arrayed in a line and neighboring elements do not exhibit significant mutual coupling.