**Background**

- Combine Fresnel lens theory with a generalized form of Snell’s Law to refract light incident upon a planar interface that mimics the phase gradient of a bulk lens.
- Normal incidence light couples to “anomalous refraction” mode, creating a broadside angle of propagation through constructive interference of discrete scattering elements.
- Flat lenses rely on accurate knowledge of scattered phase/amplitude, but complex geometries and mutual coupling make analytical solutions intractable, driving the need for a design toolbox to properly characterize metasurface performance.

**Goals**

- Use COMSOL Multiphysics to characterize various subwavelength structures and architectures as fundamental building blocks for metasurface lens designs.
- Fabricate and measure metasurface lenses and validate against COMSOL results.
- Further develop COMSOL-based design tool for complex geometries, new architectures and lens optimization of flat lens performance.

**Metasurface Low-Profile Lens Concept**

- Single air/silicon (Si) interface patterned with gold (Au) V-antennas for control of phase/amplitude.
  - Coupling between dipole arms provides sufficient access to full 2π phase space.
  - Each V-antenna scatterer provides unique phase (φ = Ar(2π/E)) and amplitude (|E|) driven by its vertex angle (h), dipole length (l), interface and material properties (ε_m/ε_h0).
- To induce lensing function, neighboring elements must possess both a proper, constant phase gradient and equal amplitudes in order to produce a uniform broadside phasefront.

**Approach**

- Model individual Au V-antenna scattering elements 65 nm thick and 250 nm wide on Si substrate in air at two wavelengths (5 & 8 μm).
- Extract phase and amplitude of scattered cross-polarized fields, E_{scatt} = E_{total} - E_{bg}.
- Identify N elements that meet the constraints to populate lens array:
  - Δφ = Φ_{i+1} - Φ_i = 2π/N
  - Δ|E| = |E_{i+1}^{scatt}| - |E_{i}^{scatt}| = 0
  - N = number of discrete elements
  - i = element index (1, N)

**Far-field Calculation**

Applied to near-field, based on Stratton-Chu formula:

\[ E(θ, φ) = \frac{ik}{4\pi} \int dS \left( \nabla \times E - \frac{1}{f^2} \varepsilon_{r0} \varepsilon_{r} \nabla \times \nabla \cdot E \right) \varepsilon^{i k r} r \]

**Lenses Phenomenology**

- Interpolated COMSOL output is input for MATLAB optimization algorithm which finds Δφ and MAX(|ΔE(N)|) to within desired tolerances, if exists.
- Region cut-offs of common phase dictated by Fresnel lens phase calculation:

\[ Δφ = \frac{2π}{N} \sqrt{x^2 + y^2 + f^2 - f} \]

- Regions are filled based on COMSOL/MATLAB optimized design elements.

**Fabrication**

- Accomplished at Sandia National Labs using in-house MATLAB GDS script.
- 19 unique lenses/8 unique metasurfaces, varying several parameters:
  - Incident wavelength, λ_o.
  - f/8 (focal length / diameter).
  - Number of unique elements, N.
  - Packing density (intracell periodicity).
- Significant rounding of edges, but good preservation of dipole angle/length.

**Computational Information**

- 2 Xeon CPUs/16-cores/128GB RAM.
- 4GB solved model/200K mesh/2.2M DoF.
- WaveOptics module + Frequency Domain (efwd) + Statical Solver + Batch Sweep.
- 5 cores/parameter solution.
- Time steps taken over the range: Δt = 4/155° & h ≤ 0.05μm/130μm.
- Single parameter solver time: ~15min.

**Conclusion**

- Through the use of COMSOL as a design/characterization tool, we successfully recreated planar lenses at 5 μm & 8 μm over the focal ranges f = 25 – 200 mm using variants of Harvard’s seminal metasurface design [1-4], and validated the future use of the COMSOL for a comprehensive investigation of design optimization.
- While an analytic approach is more rapid for simple geometry and architectures, COMSOL has demonstrated an equal ability to quickly design metasurface lenses, with the added benefit of being able to expand functionality to more complex structures and architectures needed for optimized performance.

**References**