COMSOL CONFERENCE 2016 BOSTON

Design of IR Metasurfaces for Low-Profile Optics Using COMSOL Multiphysics

Sandia National Laboratories

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Overview

Motivation

Background of Metasurface-Based Flat Optics

Motivation for Flat Lenses

- Problem: M/LWIR lenses for imaging are large & bulky
  - Focusing adds to bulk curvature
  - Resolution adds to radial dimension
  - Both aspects add material mass

- Goal:

  Create a low-profile planar lens in the infrared regime that performs a refractive focusing function of a bulk curved lens in a sub-band between $3 - 12\ \mu\text{m}$

- Current Issues:
  - Lens efficiency is quite low—on the order of $1\% - 20\%$
  - Only one lens made; few topologies/materials have been explored

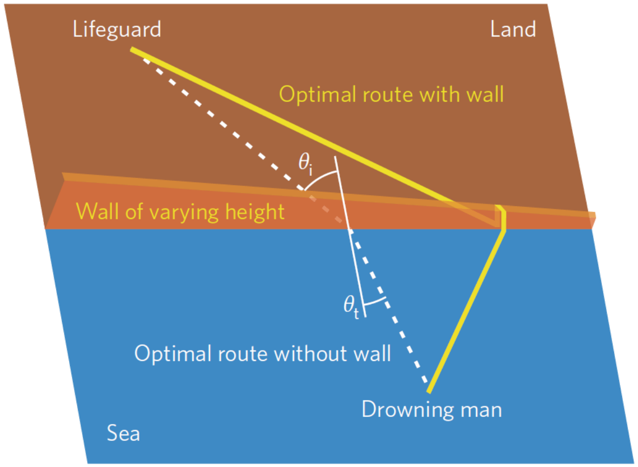
- Solution: Use COMSOL Multiphysics as a design optimization tool
  - But first validate against analytical results of a simple design!

Motivation for Flat Lenses

- Seminal paper:
  Nanfang Yu et al., Science **334**, 333, 2011
- "Generalized" Snell's Law:

$$\sin[\theta_{II}]\, n_{II} = \sin[\theta_I]\, n_I + \frac{\lambda_0}{2\pi}\frac{d\phi}{dx}$$

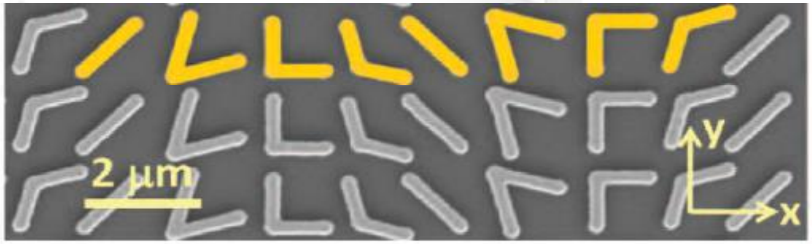
- Metasurfaces used to control phase gradient ϕ' across a surface:



Yu et al., Science **334**, 333, 2011

$$\sum_{i=1}^{N} \Delta\phi_i = 2\pi$$

$\Delta\phi_1$ $\Delta\phi_2$ $\Delta\phi_3$ $\Delta\phi_4$ ... ... $\Delta\phi_N$



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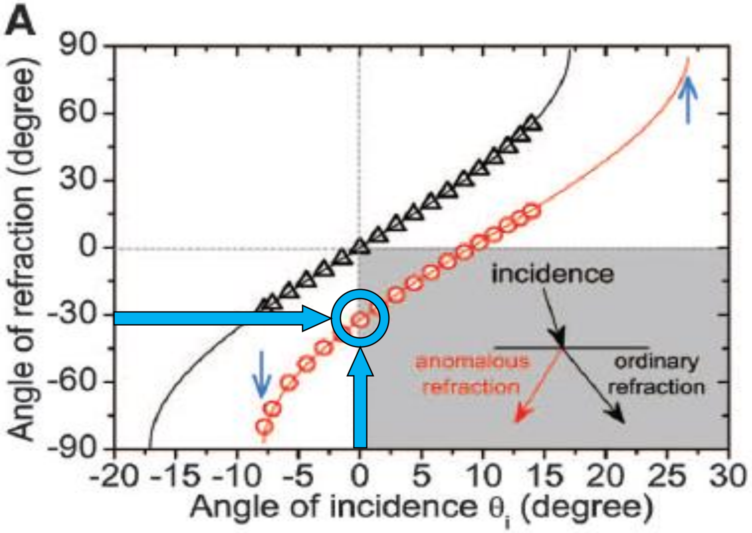
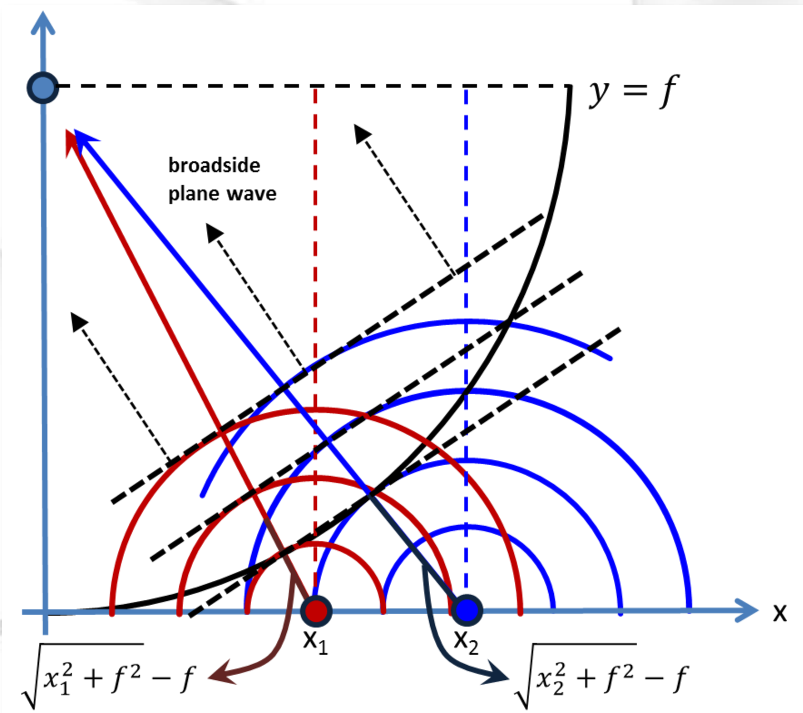
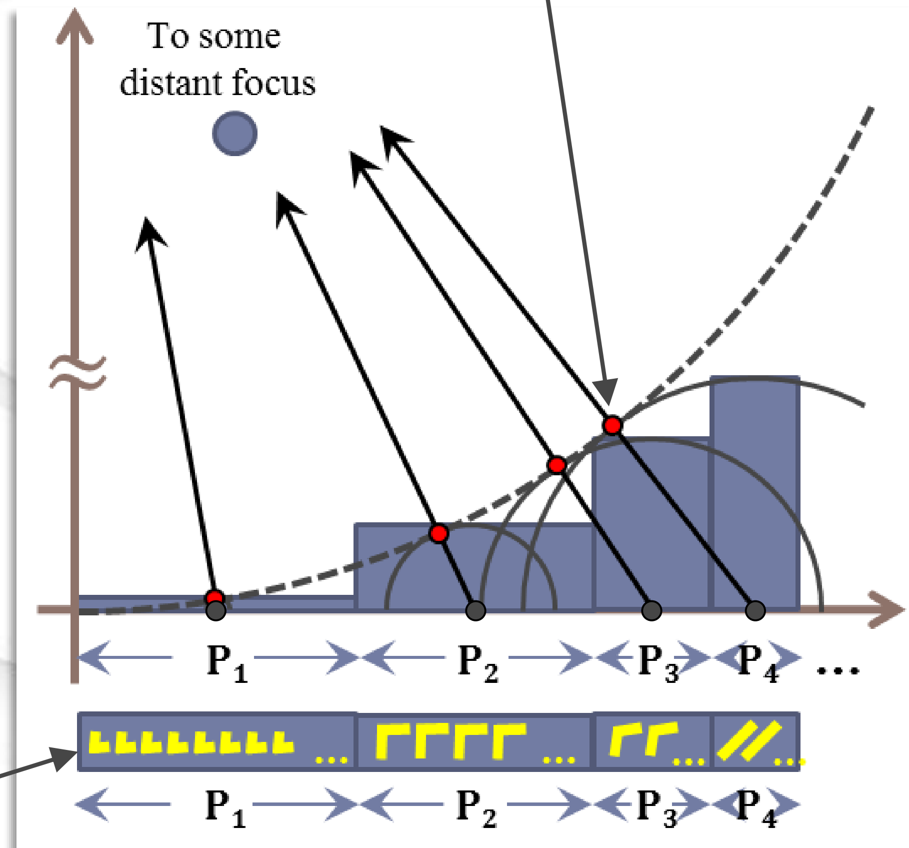


Yu et al., Science **334**, 333, 2011

Lensing From Surface Array of Scatterers

1-D Phase calculation for focusing: $\varphi_i = \frac{2\pi}{\lambda_0}\left(\sqrt{x_i^2 + f^2} - f\right) + \varphi_0$





<u>This</u> is why we need COMSOL!

COMSOL Model

Purpose, Setup and Solving

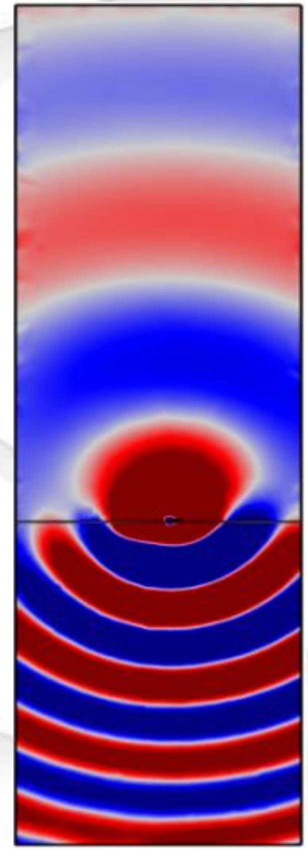
COMSOL Model, Part 1

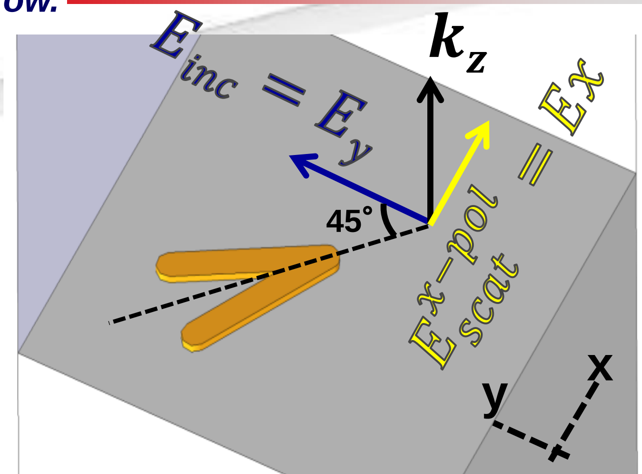
- Objective:

  Simulate V-antenna response over a large parameter space by varying:
  - Incident wavelength, λ_0 $(5 \,\&\, 8\mu m)$
  - Dipole half-length, $h/2$
  - Antenna vertex angle, Δ

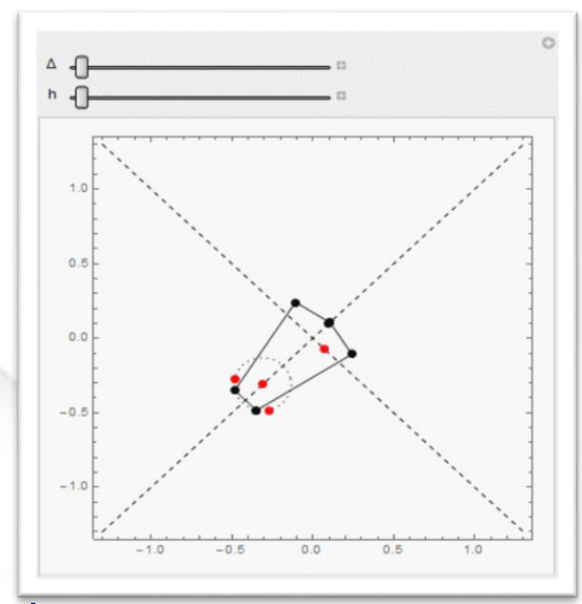
- Tasks:
  - Extract scattered cross-polarized electric field $\boldsymbol{E}_{scat}^{x-pol}\left(\frac{h}{2},\Delta\right)$
  - Calculate phase, $\varphi = Arg\left[\boldsymbol{E}_{scat}^{x-pol}\right]$ and amplitude, $\left|\boldsymbol{E}_{scat}^{x-pol}\right|$
  - ***Identify*** N ***<u>unique</u> elements which meet the constraints to populate lens array***:
    - $\Delta\varphi = \varphi_{i+1} - \varphi_i = 2\pi/N$
    - $\Delta|\boldsymbol{E}| = \left|\boldsymbol{E}_i^{x-pol}\right| - \left|\boldsymbol{E}_{i+1}^{x-pol}\right| \approx 0$

$\boldsymbol{E}_{scat}^{x-pol}(h/2,\Delta)$





Field Components



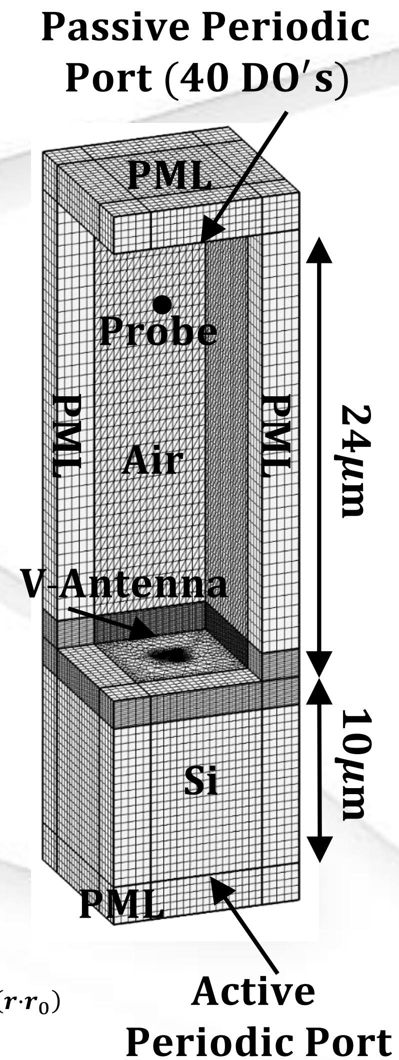
COMSOL Model, Part 2

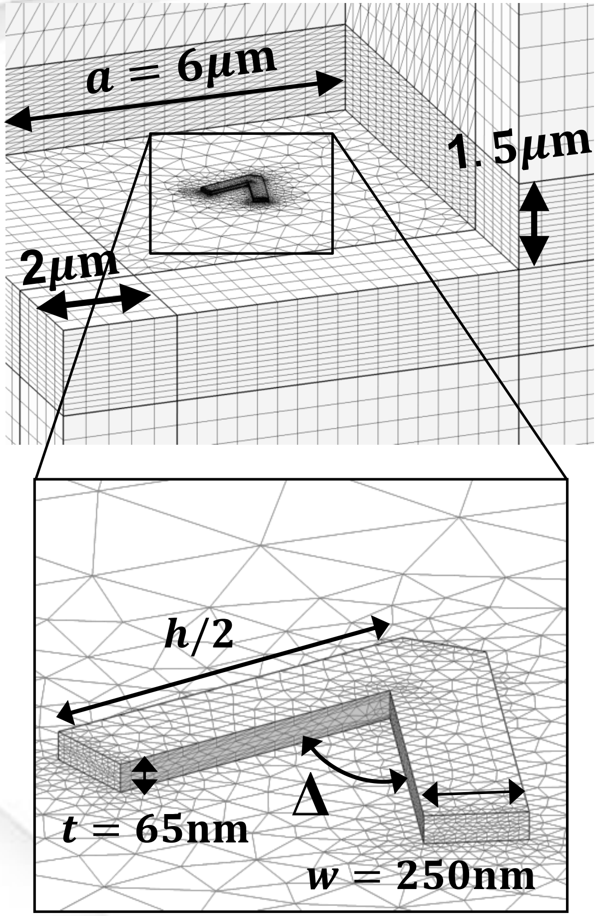
- Wave Optics + Frequency Domain (ewfd) + Stationary Solver (PARDISO direct) + Batch Sweeps
- Based on “Scatterer on Substrate” library model, 2 ewfd physics domains:
  - *Interface w/o scatterer:* uses periodic ports and BCs to get total field $\boldsymbol{E}'_{tot}$ which is used as background field for 2nd ewfd domain ↓
  - *Interface w/ scatterer*: uses perfectly-matched layers (PML) and $\boldsymbol{E}_{bg} = \boldsymbol{E}'_{\mathrm{tot}}$ to obtain true scattered field:

$$\boldsymbol{E}_{scat} = \boldsymbol{E}_{total} - \boldsymbol{E}_{bg}$$

- Far-field calculation on internal boundaries, via Stratton-Chu:

$$\boldsymbol{E}(\theta,\phi) = \frac{ik}{4\pi}\boldsymbol{r}_0 \times \int d\boldsymbol{S}\left[\boldsymbol{n}\times\boldsymbol{E} - \sqrt{\mu/_\epsilon}\,\boldsymbol{r}_0 \times (\boldsymbol{n}\times\boldsymbol{H})\right] e^{ik(\boldsymbol{r}\cdot\boldsymbol{r}_0)}$$





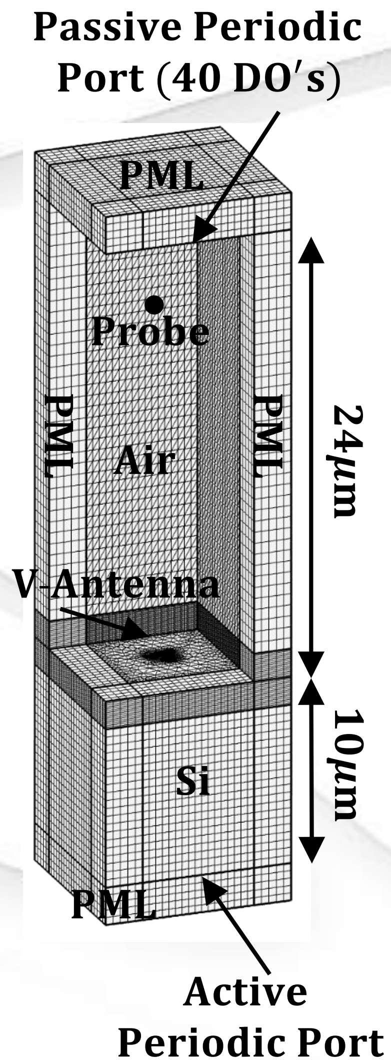
COMSOL Model, Part 3

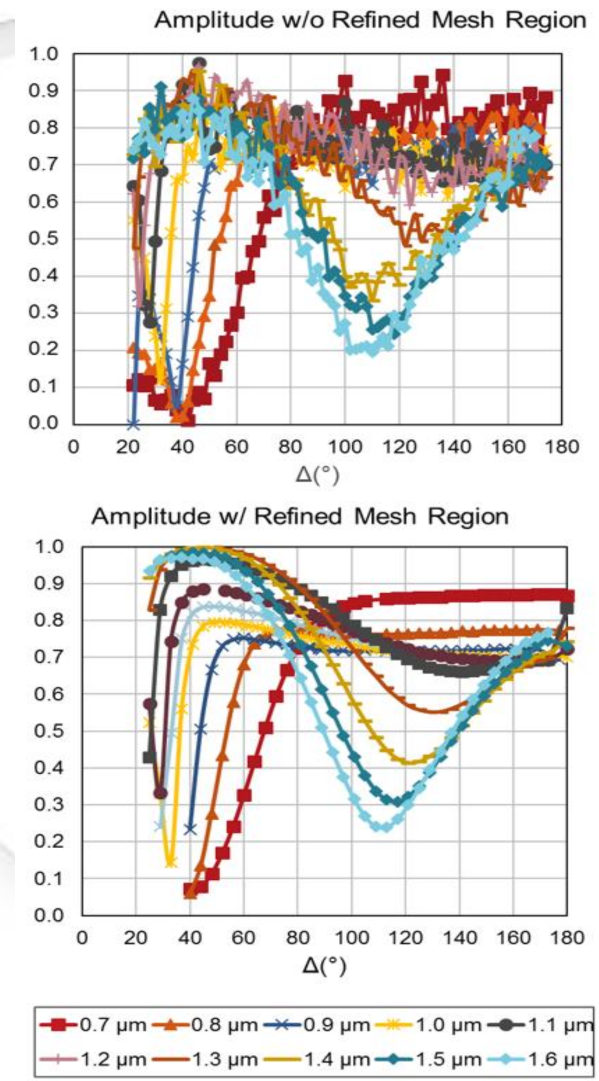
The AFIT of Today is the Air Force of Tomorrow.

- Mesh:
  - Boundary layers on surface of metal
  - Required highly-refined mesh $\sim \pm 1.5\mu\text{m}$ around scatterer for acceptable uncertainty

- Data collection:
  - Batch Sweeps of Δ & $h/2$ using PARDISO
  - Parametric steps taken/over the range:
    $\Delta = 4°/155°$ & $h/2 = 0.05\mu\text{m}/1.30\mu\text{m}$
    $\rightarrow 1000 +$ parameters to solve!

- Computer/solver specs:
  - 2 Xeon CPUs/16-cores/128GB RAM
  - 40GB solved model/200K mesh/2.2M DoF
  - 5 cores/parameter solution → 3 per batch
  - Batch solver time:
    ~15 mins x 350+ batches = ~3.6 days



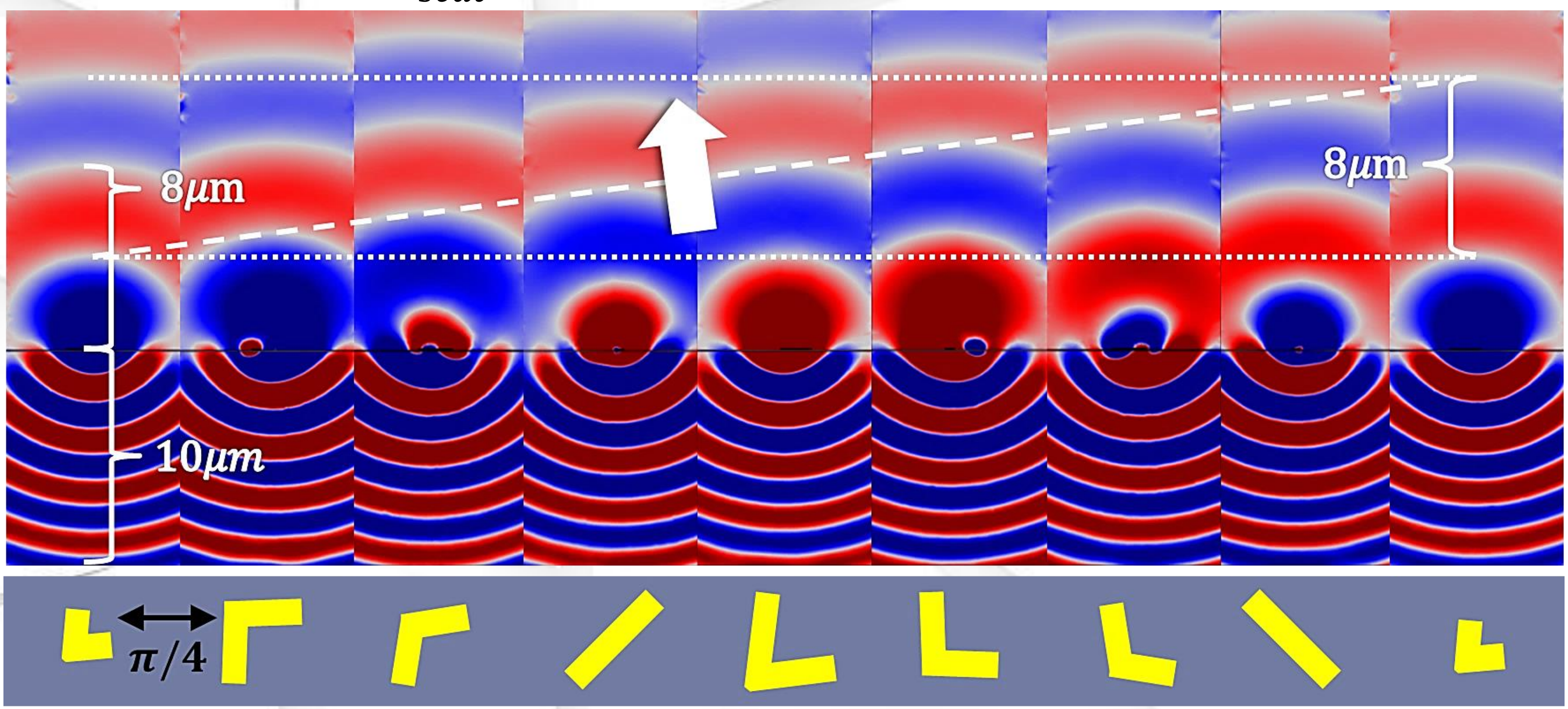


COMSOL Results

Parameter Sweeps of Dipole Length (h/2)
and V-antenna Angle (Δ)

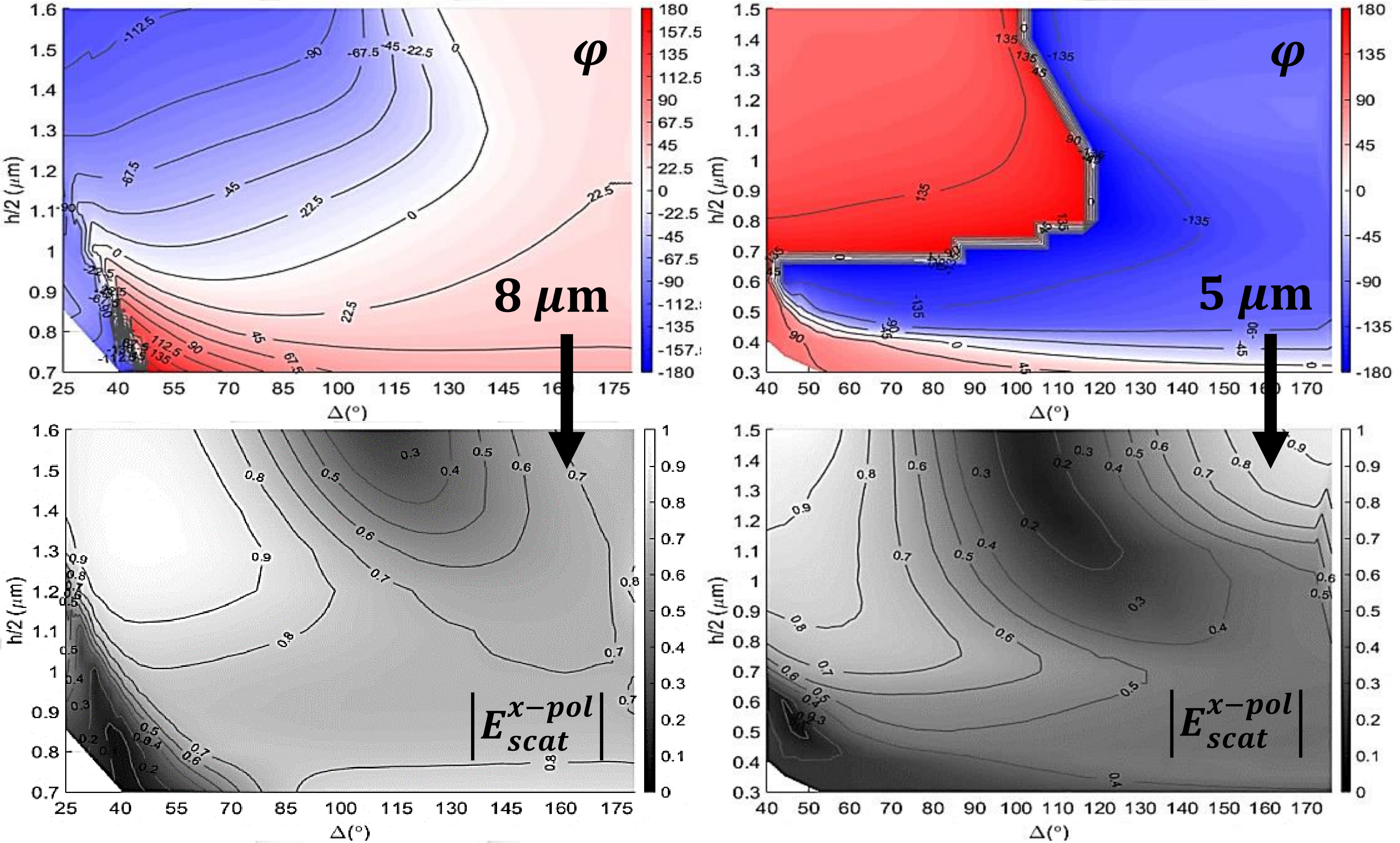
COMSOL Validation of Anomalous Refraction

$E_{scat}^{x-pol}(y,z)$ for 8-element metasurface



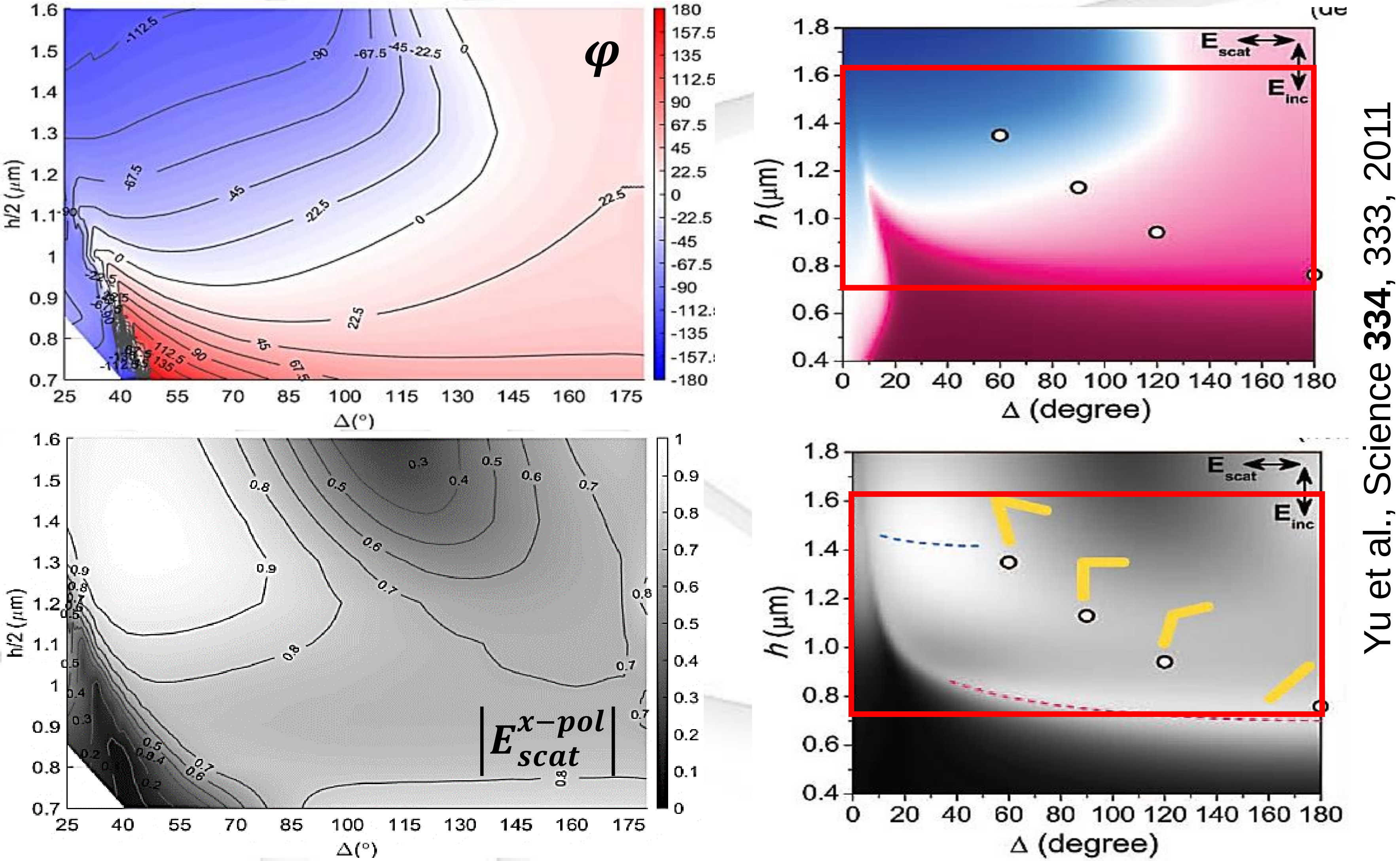
Phase/Amplitude Profiles
(Array Interpolated)

The AFIT of Today is the Air Force of Tomorrow.



Comparison to Analytical

The AFIT of Today is the Air Force of Tomorrow.



Air University: The Intellectual and Leadership Center of the Air Force

Aim High…Fly - Fight - Win

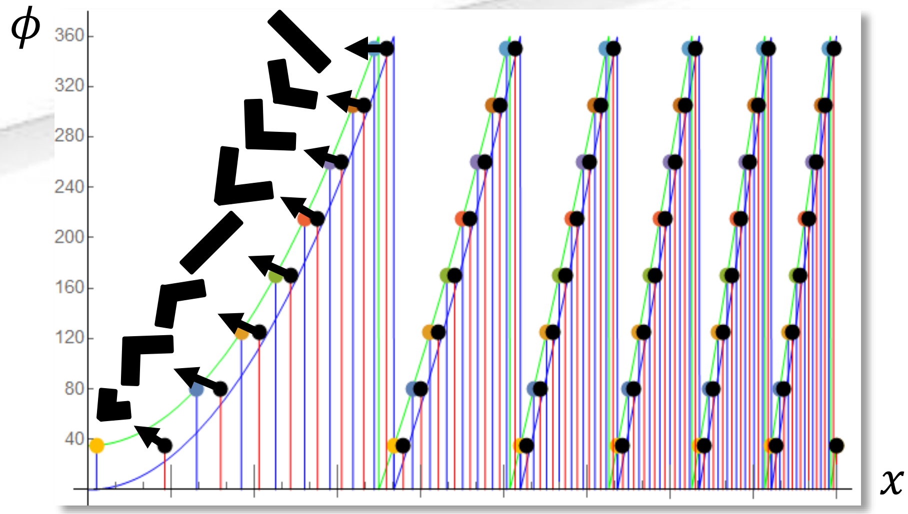
Lens Fabrication

Phase Region Calculations

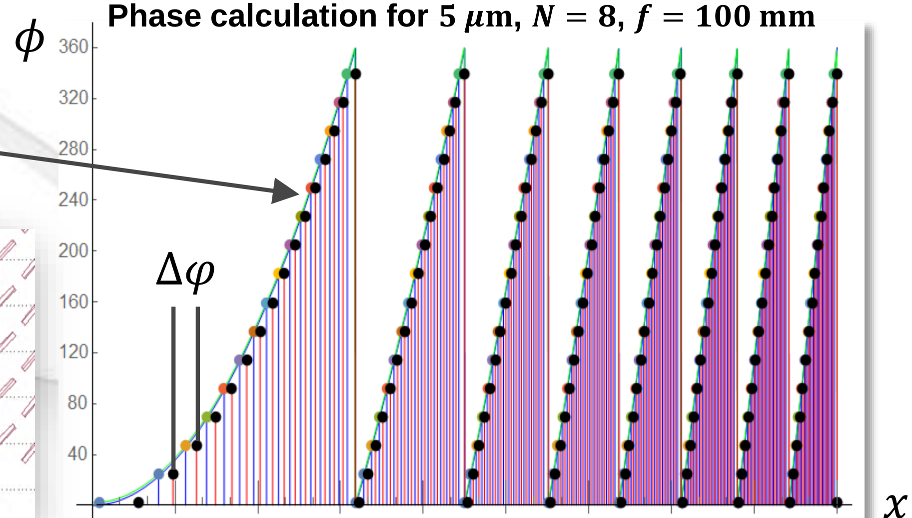
Phase Calculations for Lens

- Used COMSOL results to pick elements which best fit phase region calculations:
  - $\Delta\varphi = \varphi_{i+1} - \varphi_i = 2\pi/N$
  - $\Delta|\boldsymbol{E}| = \left|E_i^{x-pol}\right| - \left|E_{i+1}^{x-pol}\right| \approx 0$
  - $\phi_i = \frac{2\pi}{\lambda_0}\left(\sqrt{x_i^2 + f^2} - f\right) + \varphi_0$

GDS layout for $N = 16$ lens



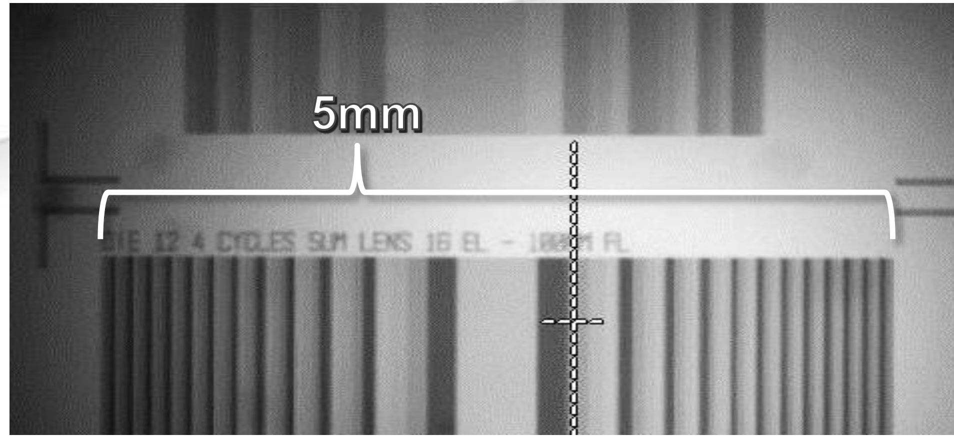
Phase calculation for 5 μm, $N = 8$, $f = 100$ mm

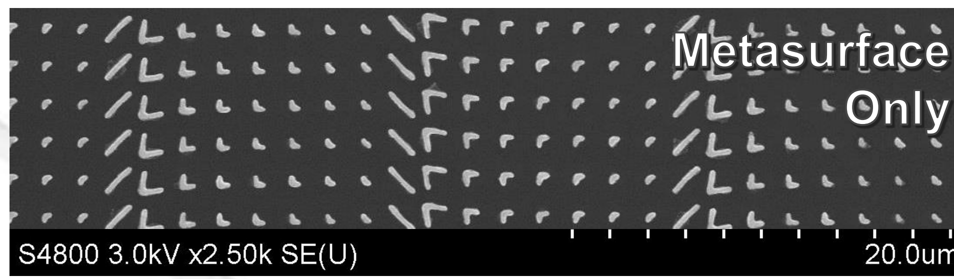


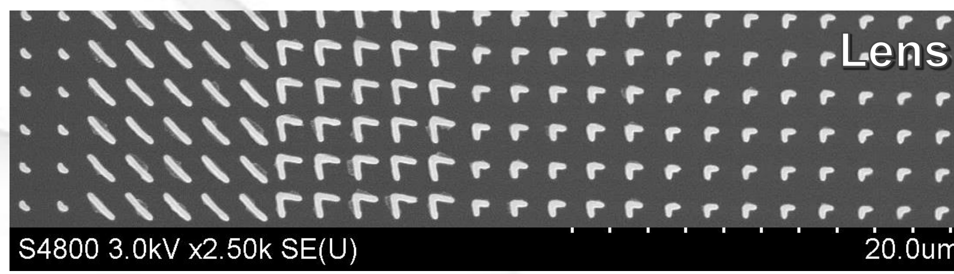
Phase calculation for 8 μm, $N = 16$, $f = 50$ mm

Wafer Images

- Fabrication done at SNL
- 19 unique lenses/8 unique metasurfaces, varying several parameters:
  - Incident wavelength, λ_0
  - $\mathcal{F}/\#$ (focal length f and diameter)
  - Number of unique elements, N
  - Packing density (intracell periodicity)
- Au/Si and TiN/Si variants

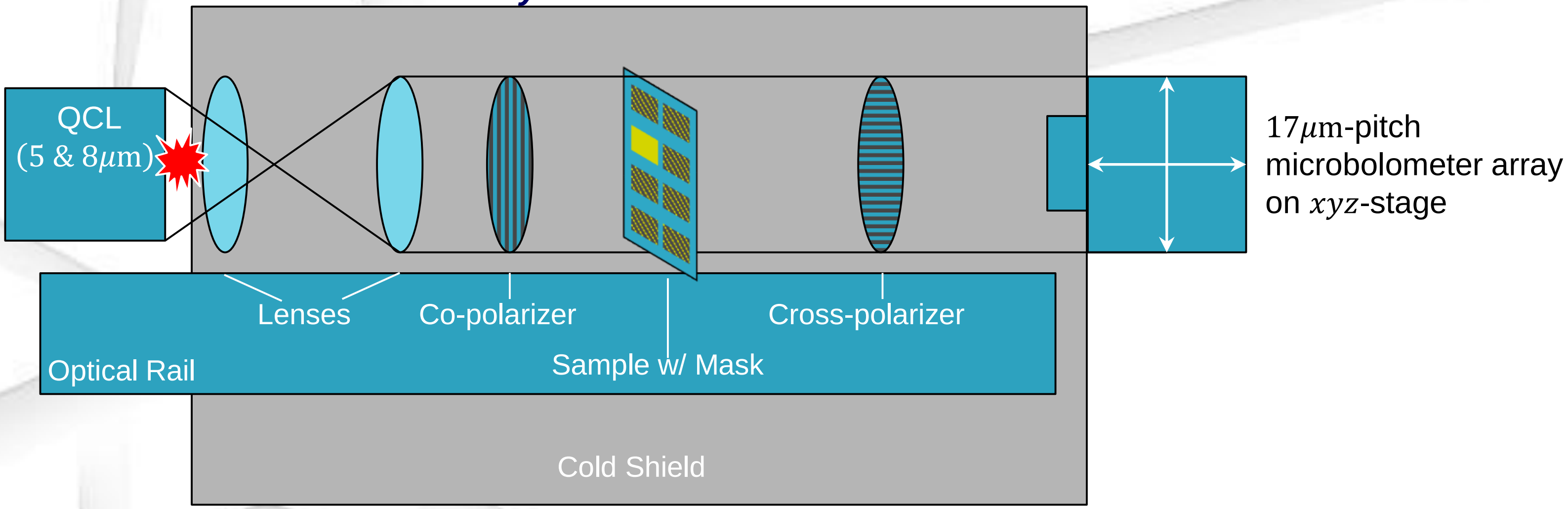






Experimental Setup

The AFIT of Today is the Air Force of Tomorrow.



- Measurements underway currently at AFIT
- Illuminate sample with polarized plane wave
  - QCL has poor waist quality, so lenses blow up beam
  - Co-polarizer cleans up beam prior to sample
  - Wafer is masked to isolate individual lens/metasurface
- FLIR microbolometer array scans along optical axis (OA)
  - Linear slices compiled along OA gives intensity of focal region
  - Assess depth-of-field and accuracy of focal lengths dictated by COMSOL design elements

Conclusion

- **Through the use of COMSOL** as a design/characterization tool, **we successfully recreated planar lenses** at $5\ \mu m$ & $8\ \mu m$ 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 a more rapid solution for simple geometries 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.
- Thank you for your attention! Contact: bryan.adomanis@us.af.mil