Métamateriaux: vers des propriétés optiques sur demande

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Présentation à la Journée nationale des couches minces

18 mars 2016

CENTER FOR METAMATERIALS AND INTEGRATED PLASMONICS

Caroline du Nord

Les Carolines ont été nommées en l'honneur du roi Charles IX de France (*Carolus* en latin) puis de Charles I et Charles II d'Angletère.

Université Duke

- Université privée fondée en 1924 et nommée en l'honneur de la famille Duke, qui a créé sa fondation. Aujourd'hui la fondation possède 6.2 G$.
- Campus de 38 km^2.
- 2 518 employés, 6 244 étudiants sous-gradués, 5 993 etudiants gradués.
- Budget annuel: 2.2 G$ (1.0 G$ pour la recherche).
- Le surnom de *Blue Devils* fait référence aux chasseurs alpins français qui s'illustrèrent pendant la Première Guerre mondiale

Acknowledgements

- The work I will present is that of many members of David Smith's group over the last few years. I would, in particular, like to thank Zhiqin Huang, John Hunt, Xiaojun Liu , and Yu-Ju Tsai, for providing some of the slides I will be presenting.
- The work was done in collaboration with the group of Nan Jokerst: Talmage Tyler fabricated most of the samples.
- Our work is supported by:
  - The Air Force Office of Scientific Research
  - The Army Research Office
  - The Department of Homeland Security
  - The Office of Naval Research

What is a material?

Materials

Material Properties

- **Index-of-refraction**
- **Electric Permittivity**
- **Magnetic Permeability**
- Shear Modulus
- Bulk Modulus
- Thermal Expansion Coefficient
- Conductivity
- Viscosity
- Thermal Conductivity
- Poisson's Ratio
- Ductility
- Flexural Modulus
- Flexural Strength
- Yield Strength
- Luminosity
- Emissivity
- Heat Capacity
- Tensile Strength

What is a material?

Materials are composed of atoms in a specific arrangement.

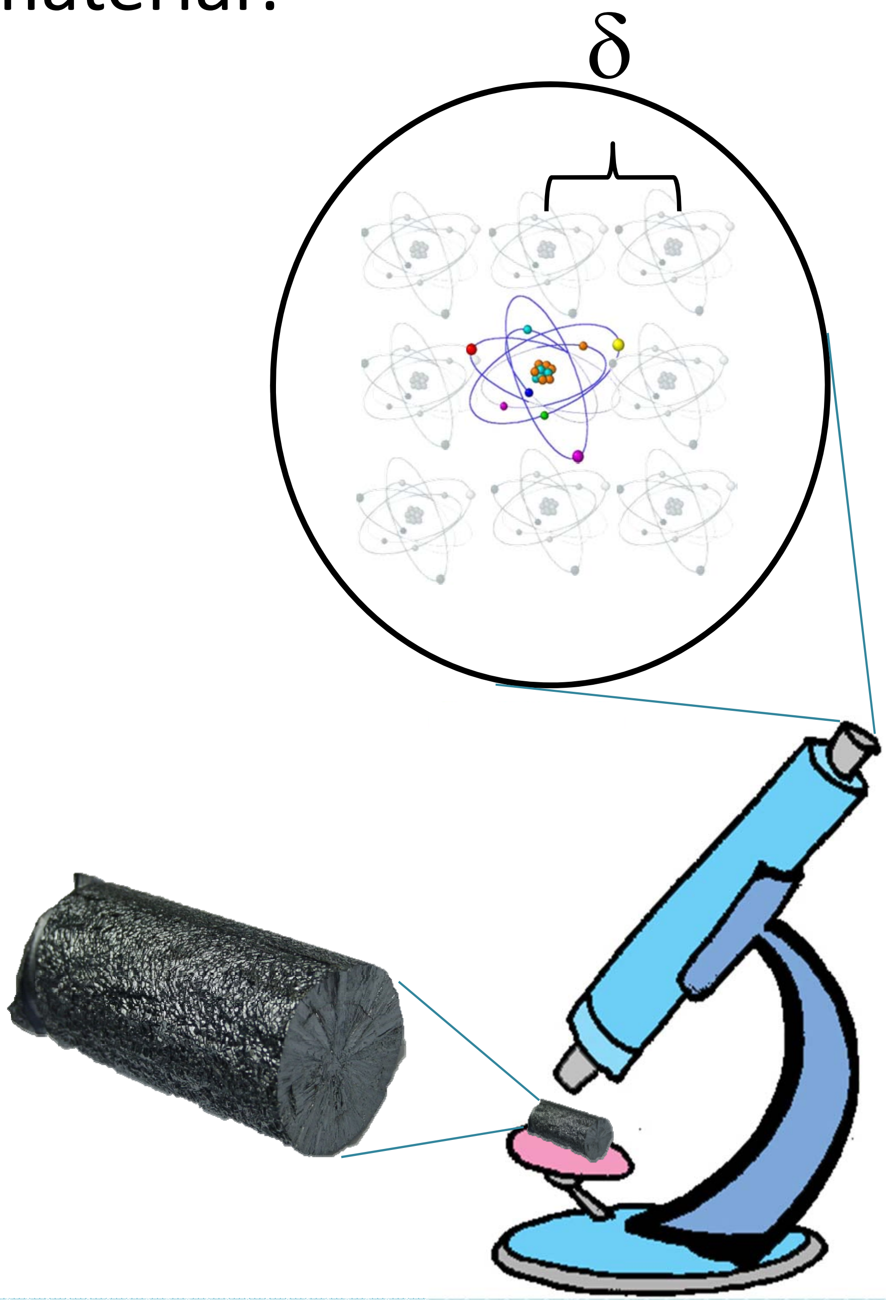
Material properties arise from atoms, molecules, and their interactions.

May also arise from macroscopic inhomogeneity.

δ is molecular scale (~ nm)

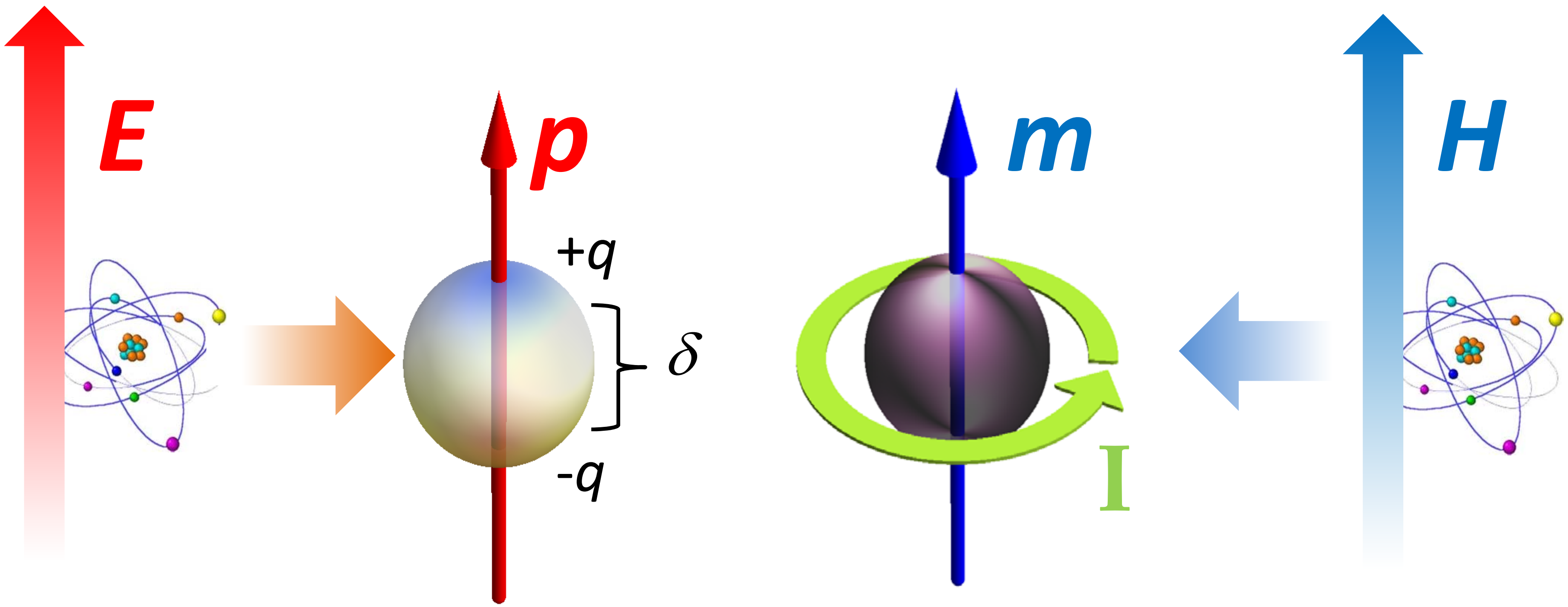
d is scale of inhomogeneity (nm, μm)

λ is scale of physical phenomenon



Electromagnetic response

From the electromagnetic point-of-view, an atom is just an electric or magnetic, *polarizable* dipole.

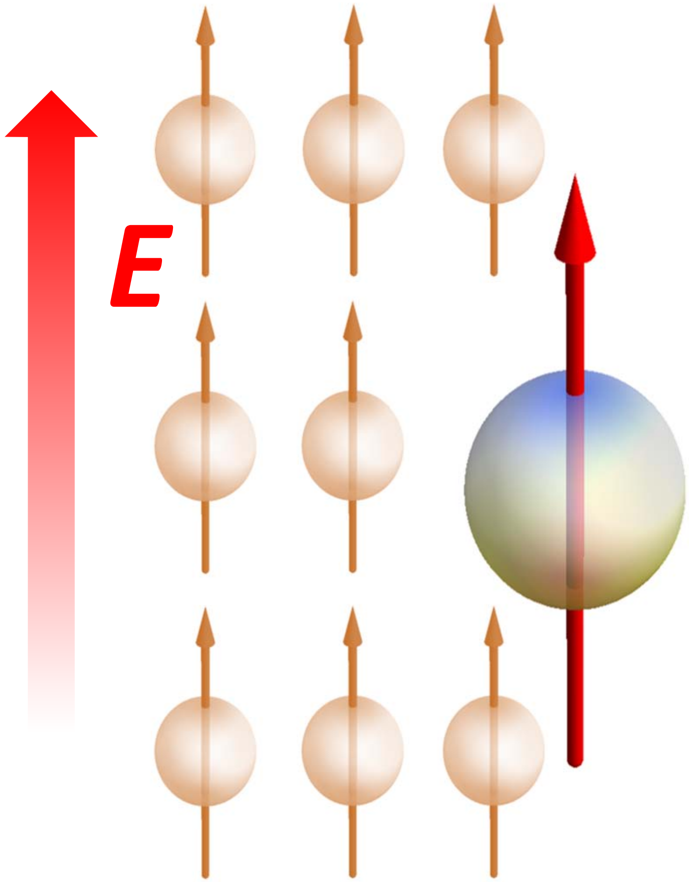


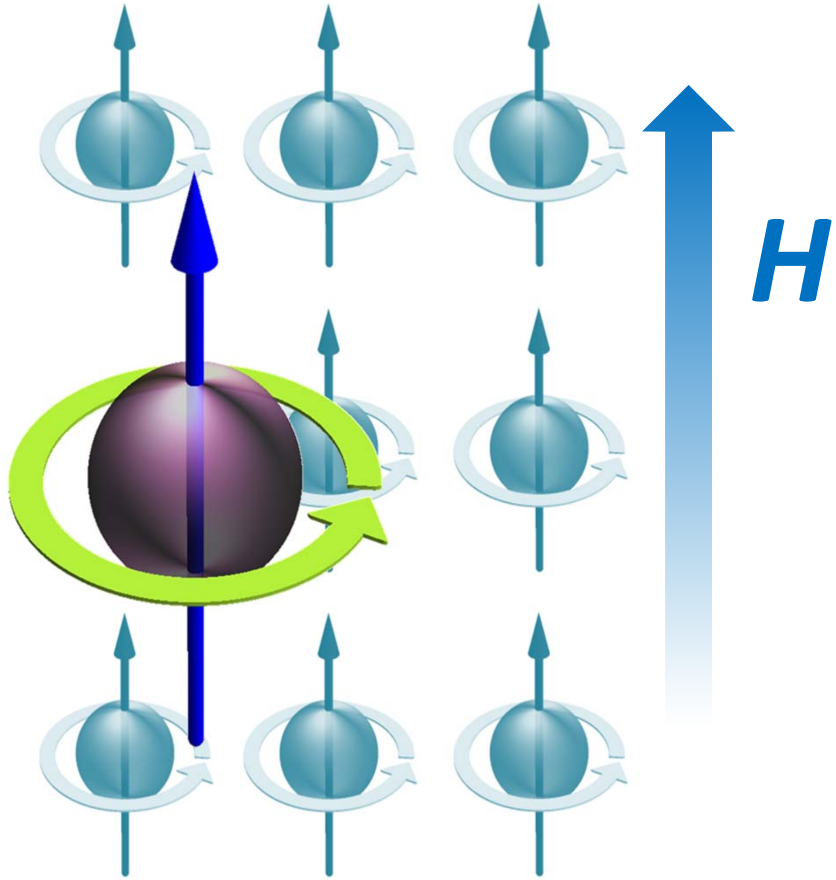
Electric dipole
$p = q\delta$

Magnetic dipole
$m = IA$

Electromagnetic response

A material is a collection of electric and magnetic dipoles.
Homogenization allows this collection to be *continuous*.

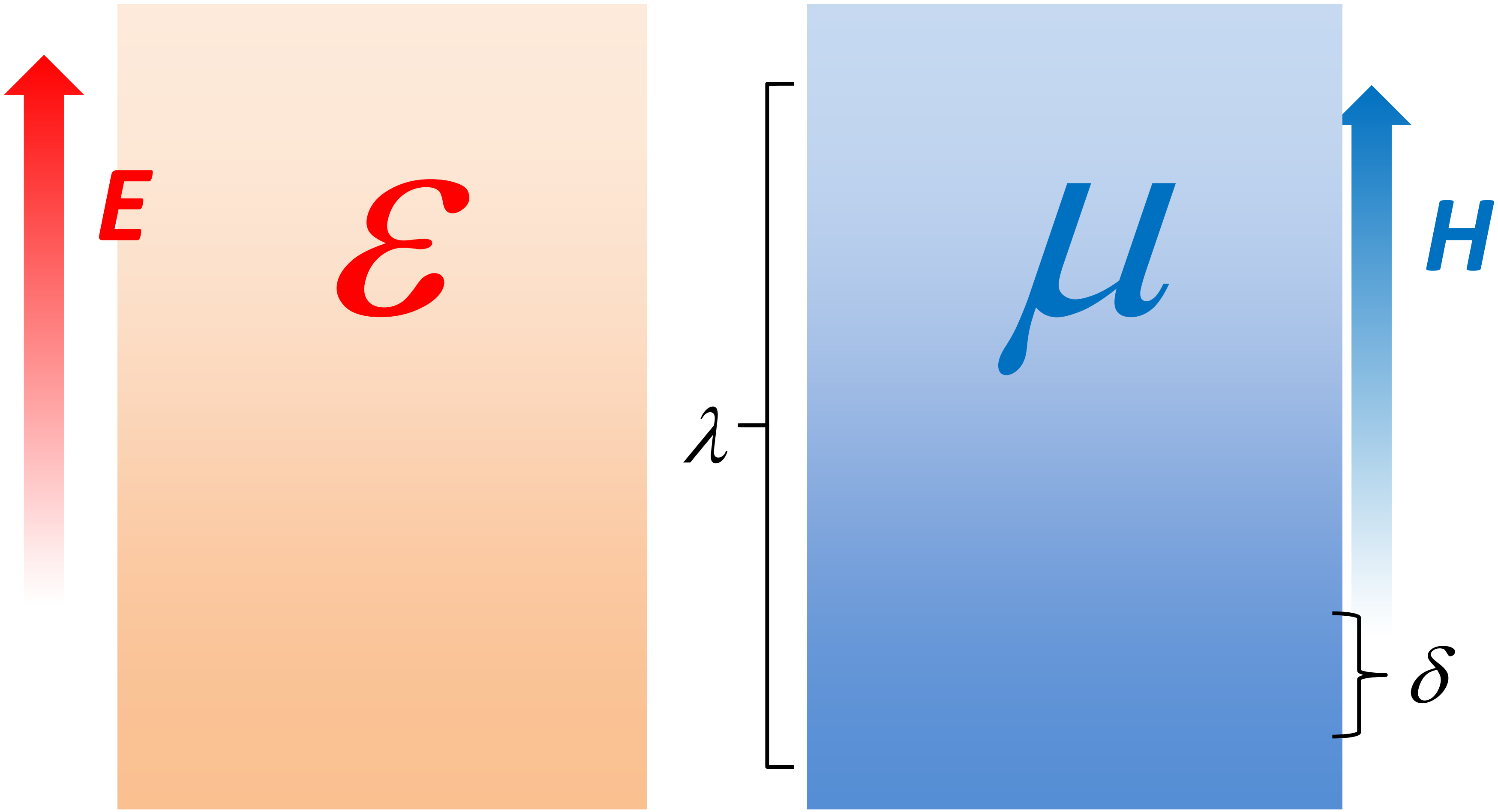




$$\mathbf{P}=\lim_{\Delta V\to 0}\frac{\sum_i \mathbf{p}_i}{\Delta V}=(\varepsilon-1)\mathbf{E}$$

$$\mathbf{M}=\lim_{\Delta V\to 0}\frac{\sum_i \mathbf{m}_i}{\Delta V}=(\mu-1)\mathbf{H}$$

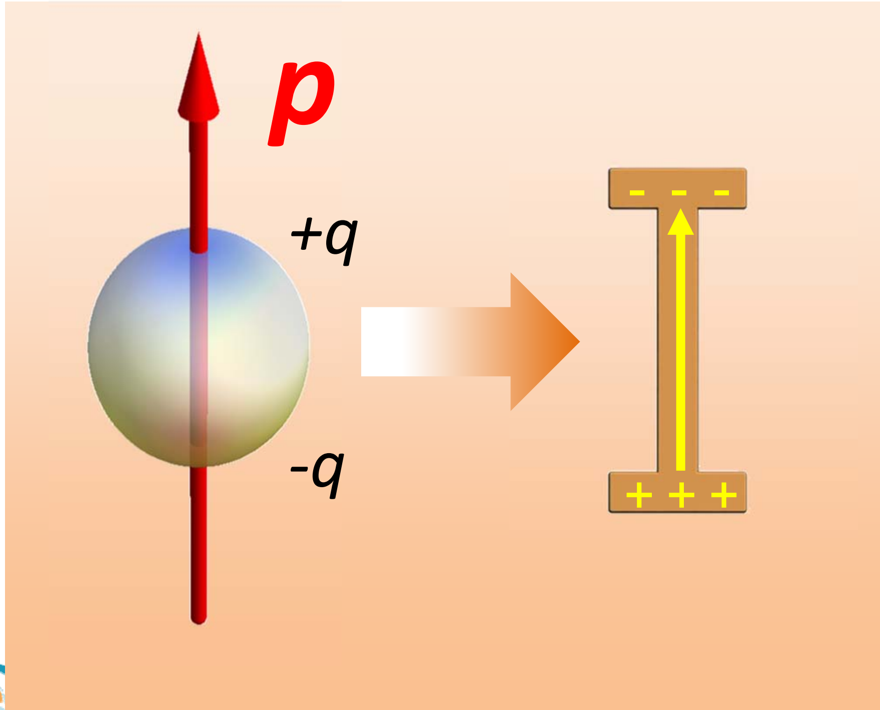
Electromagnetic response

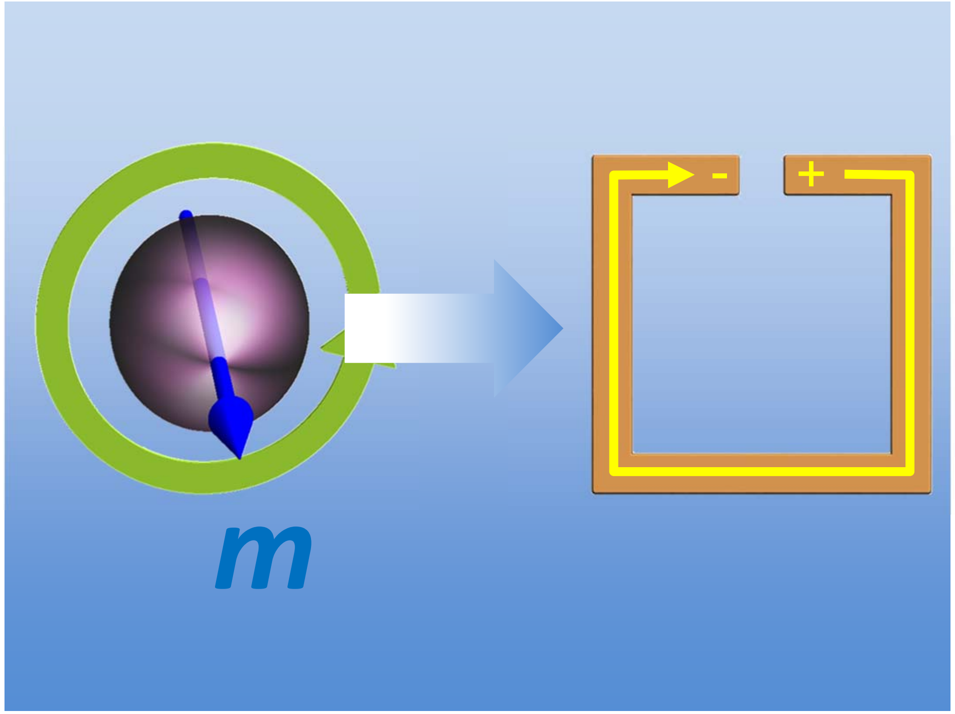


What are metamaterials?

Maxwell's equations do not *know* about atoms or molecules—all they *know* are magnetic and electric dipoles!

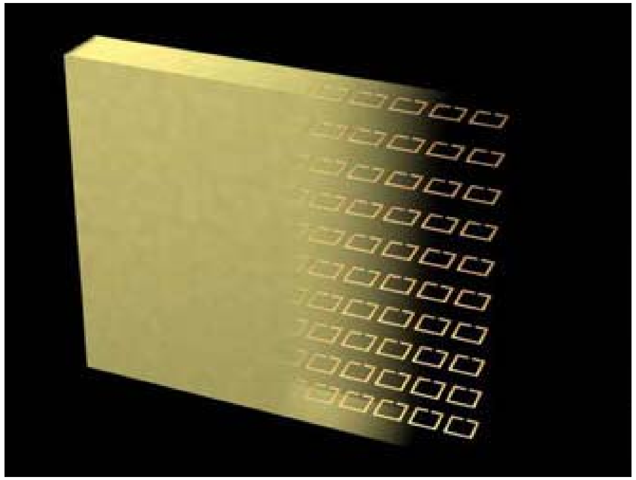
We can use any object to create a dipole response, and use that object to form an artificial material, or metamaterial.

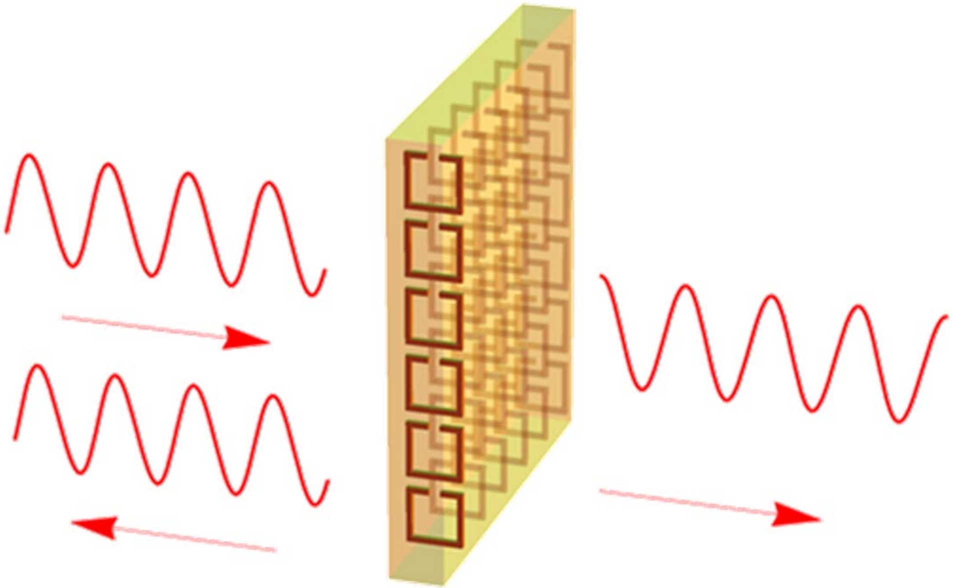




Effective properties and retrieval

Our group has specialized in the interpretation of arrays of complex scattering objects as artificial materials.





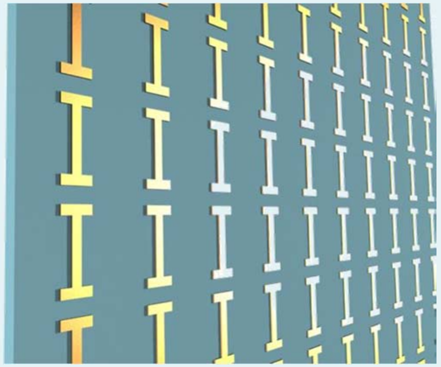
S-Parameters inversion

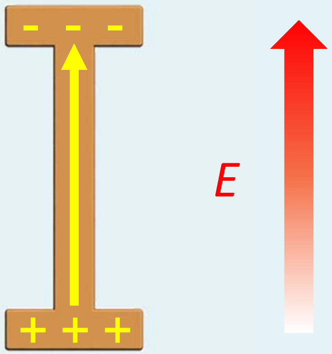
$$n = \frac{1}{k_y d}\left\{\pm\cos^{-1}\left[\frac{1}{2S_{21}}\left(1+S_{21}^2-S_{11}^2\right)\right]+2m\pi\right\}$$

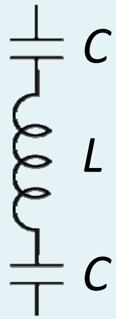
$$z = \pm\sqrt{\frac{\left(1+S_{11}\right)^2-S_{21}^2}{\left(1-S_{11}\right)^2-S_{21}^2}}$$

Circuit metamaterials

I-beam

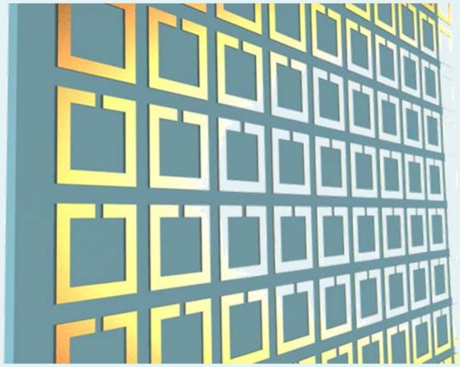


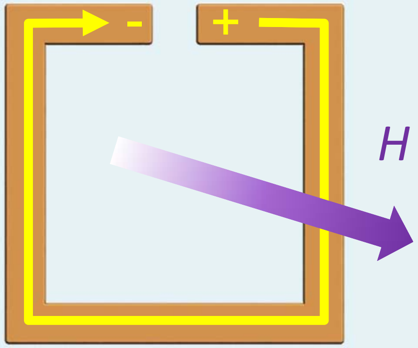


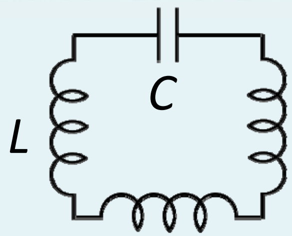


$$p = qd = -\frac{d}{i\omega} I \propto \frac{E}{Z}$$

Split ring resonator (SRR)

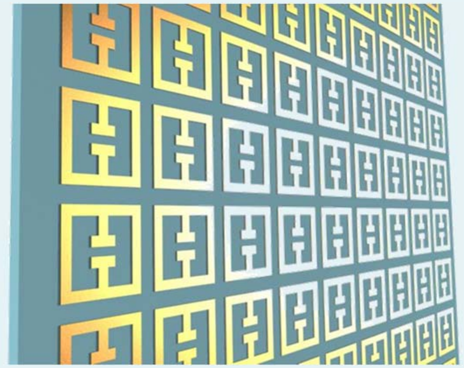


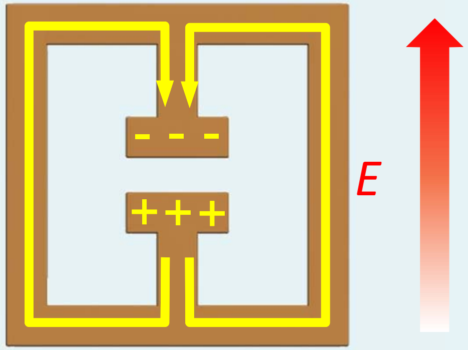


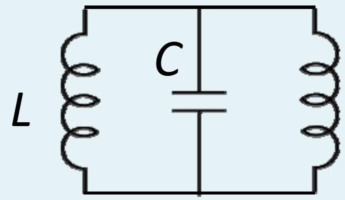


$$m = IA \propto A\frac{E}{Z} \propto A\frac{H}{Z}$$

Electric (ELC) resonator



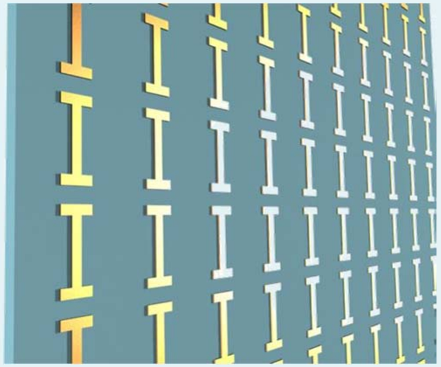


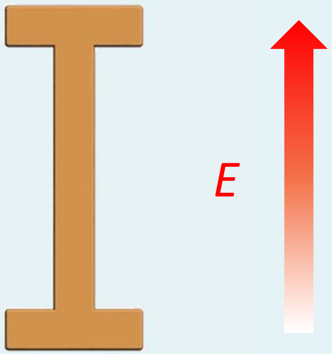


$$p = qd = -\frac{d}{i\omega} I \propto \frac{E}{Z}$$

Circuit metamaterials

I-beam

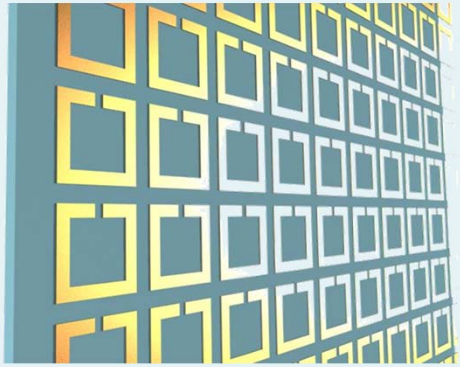


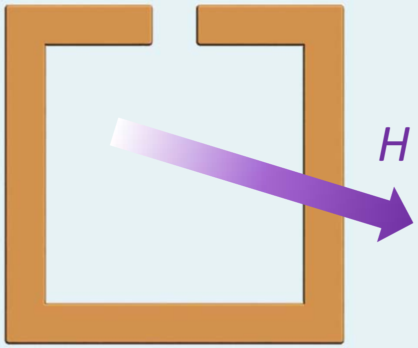


non-resonant, positive dielectric response

$$\varepsilon(\omega) = 1 + \frac{\omega_p^2}{\omega_0^2}$$

Split ring resonator (SRR)

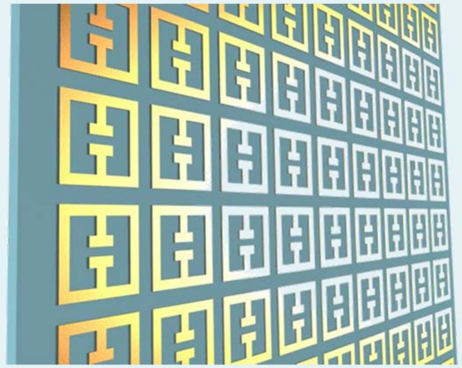


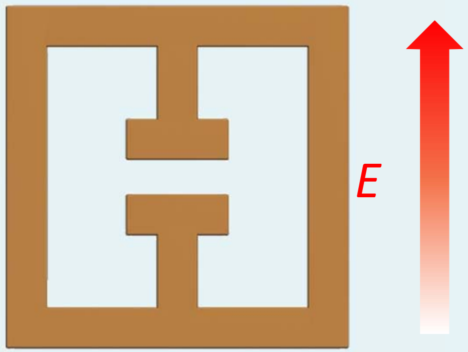


resonant, magnetic response

$$\mu(\omega) = 1 - \frac{F\omega^2}{\omega^2 - \omega_{0,m}^2}$$

Electric (ELC) resonator



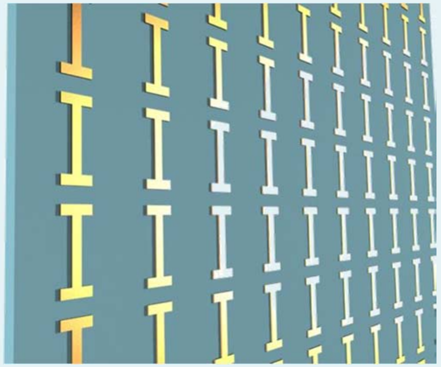


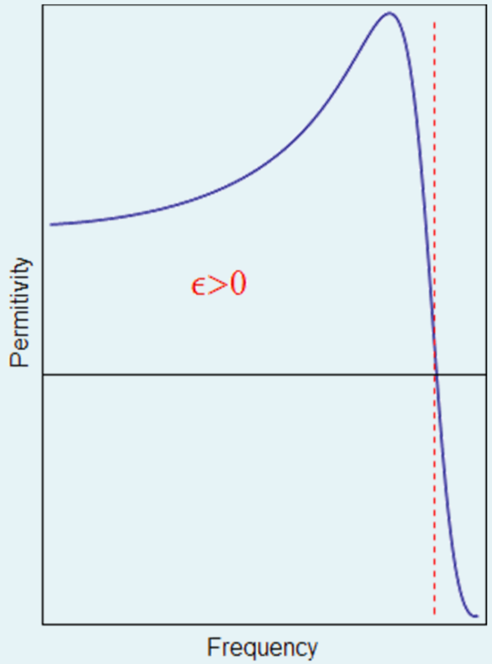
resonant, electric response

$$\varepsilon(\omega) = 1 - \frac{F\omega^2}{\omega^2 - \omega_{0,e}^2}$$

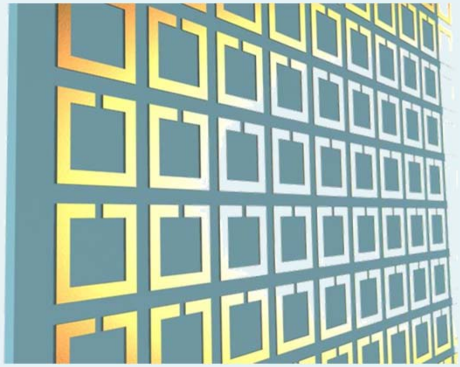
Metamaterial response

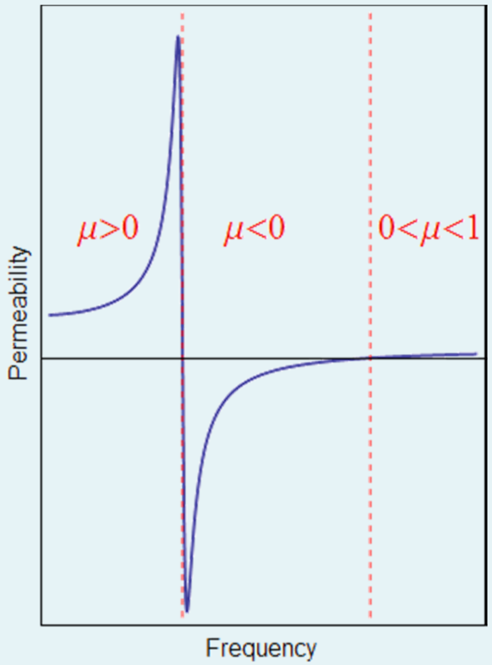
I-beam



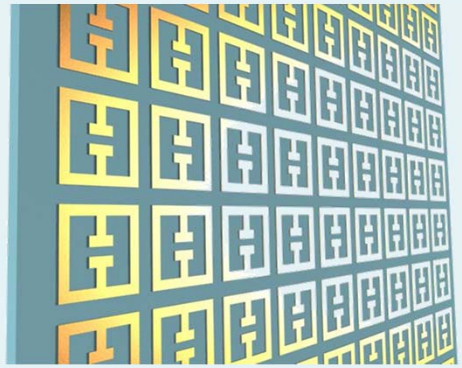


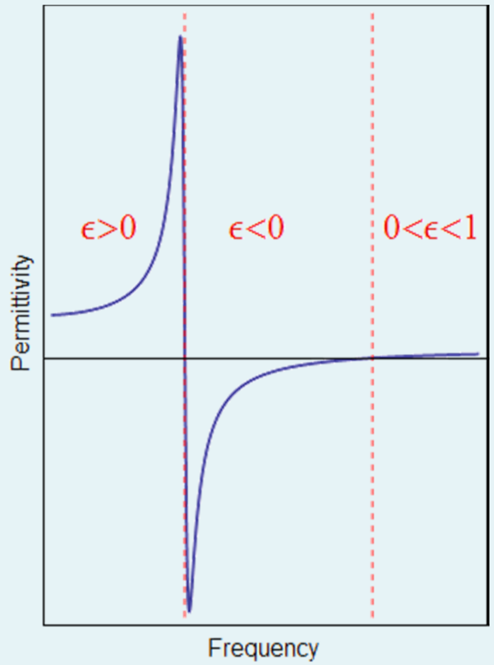
Split ring resonator (SRR)





Electric (ELC) resonator





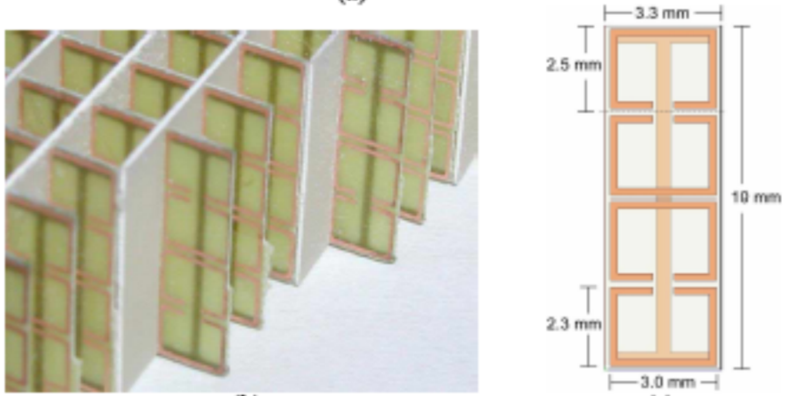
A metamaterial definition

- A metamaterial is an artificially structured material to which we can assign effective properties:
  - possess well defined refractive index and wave admittance;
  - element size and spacing are much smaller than the wavelength.
- Some people also insist that metamaterials must exhibit properties that do not exist in natural materials.
- In our group, we rather consider metamaterials as a design approach for structured electromagnetic media.

Negative refractive index
(experimental demonstration)

ε	-0.85+0.105*i*
μ	-0.53+0.108*i*
n	-0.67+0.110*i*
Z	0.79-0.032*i*

(a)



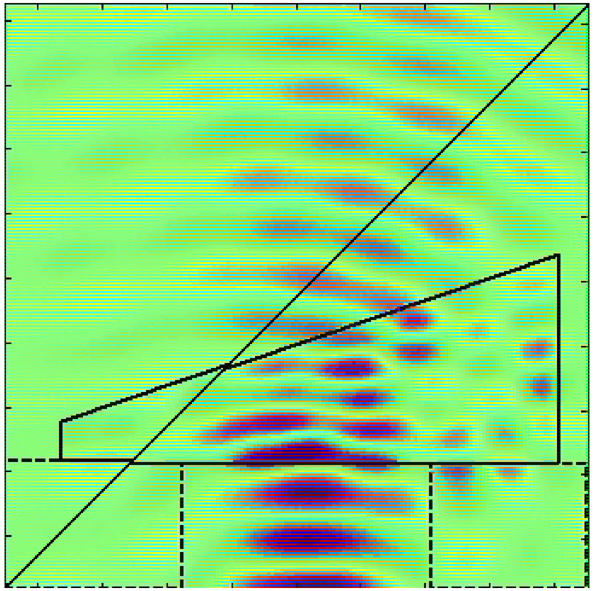
(b) (c)

Fig. 5. Design of the negative index metamaterial. (a) Extracted parameter set from the simulation of a single unit cell at 10.5 GHz. (b) A photograph of the fabricated wedge, showing the elements and construction near the angled surface. (c) A planar view of the unit cell, with dimensions indicated. The gap in the rings is 0.6 mm, while the line width is 0.2 mm. The wire, patterned on the reverse side of the circuit board, has a length of 9.8 mm (including the cross pieces), with a line width of 0.4 mm. The cross pieces extend a length of 3.0 mm. The circuit board material (FR4) has a thickness of 0.20 mm, with a dielectric constant of 3.71. The copper thickness for all structures is 17 μm.

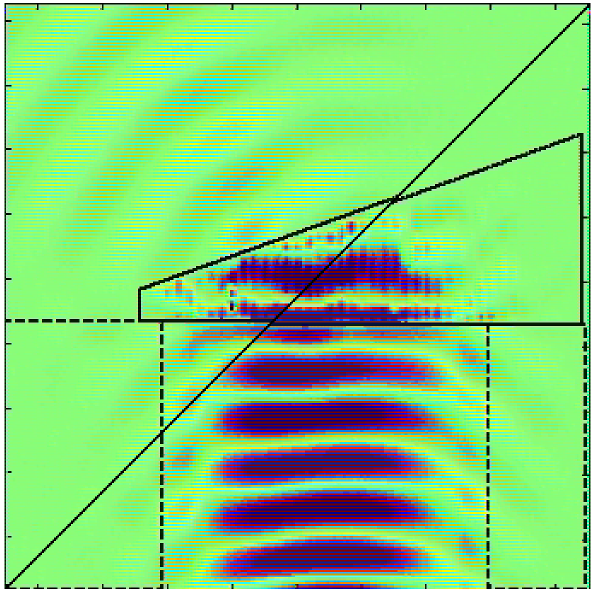
Bryan J. Justice, Jack J. Mock, Liheng Guo, Aloyse Degiron, David Schurig, and David R. Smith, "Spatial mapping of the internal and external electromagnetic fields of negative index metamaterials", *Optics Express*, vol. 85, 2006, pp. 8694–8705.

Negative refractive index (experimental demonstration)

Positive refractive index
(polycarbonate, *N* = 1.61)

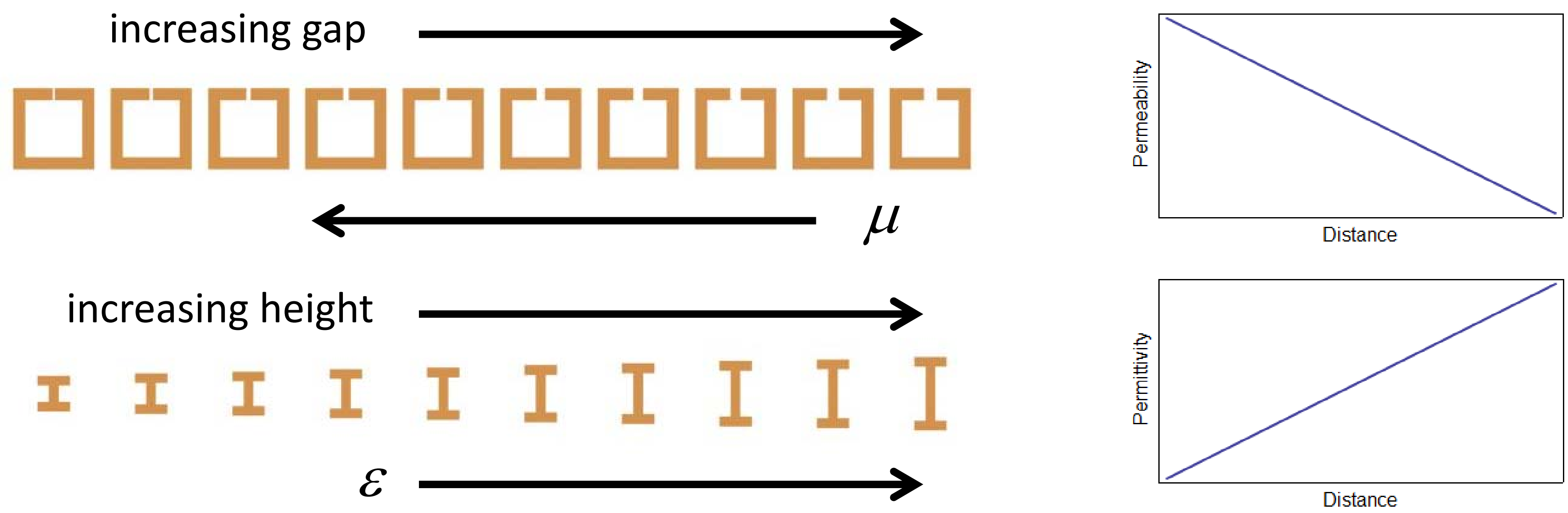


Negative refractive index
(*N* = -0.67 + 0.110i)



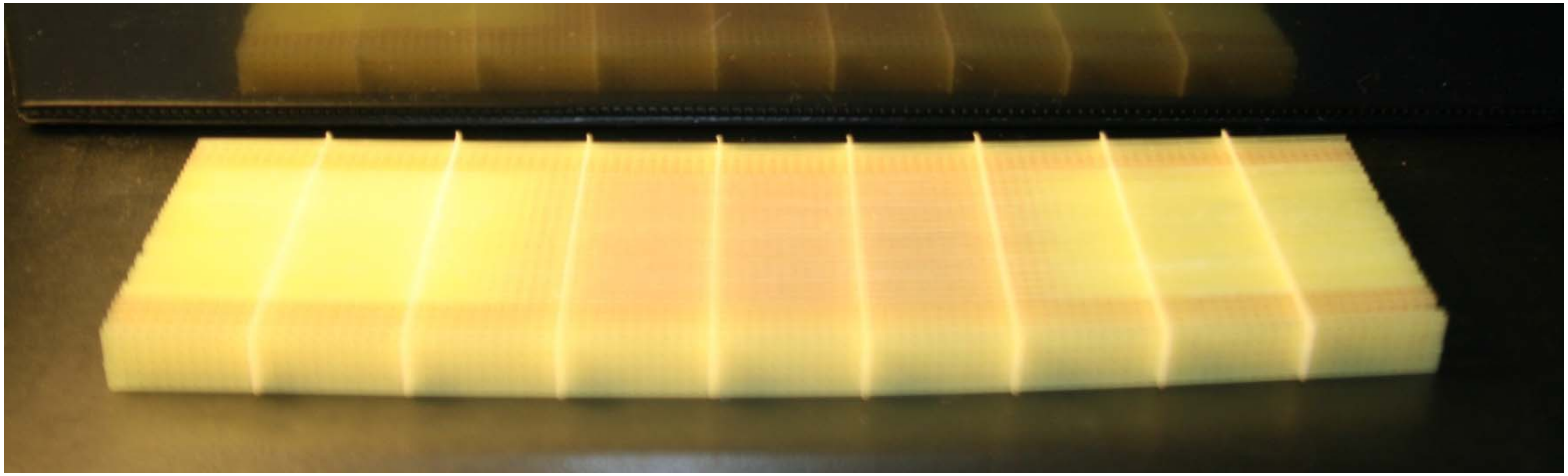
Bryan J. Justice, Jack J. Mock, Liheng Guo, Aloyse Degiron, David Schurig, and David R. Smith, "Spatial mapping of the internal and external electromagnetic fields of negative index metamaterials", *Optics Express*, vol. 85, 2006, pp. 8694–8705.

Gradient metamaterials

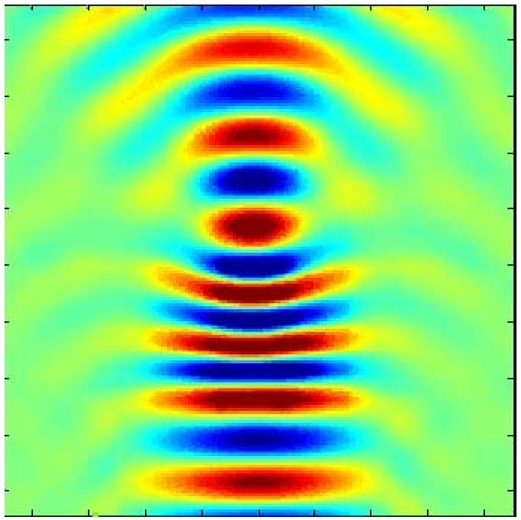


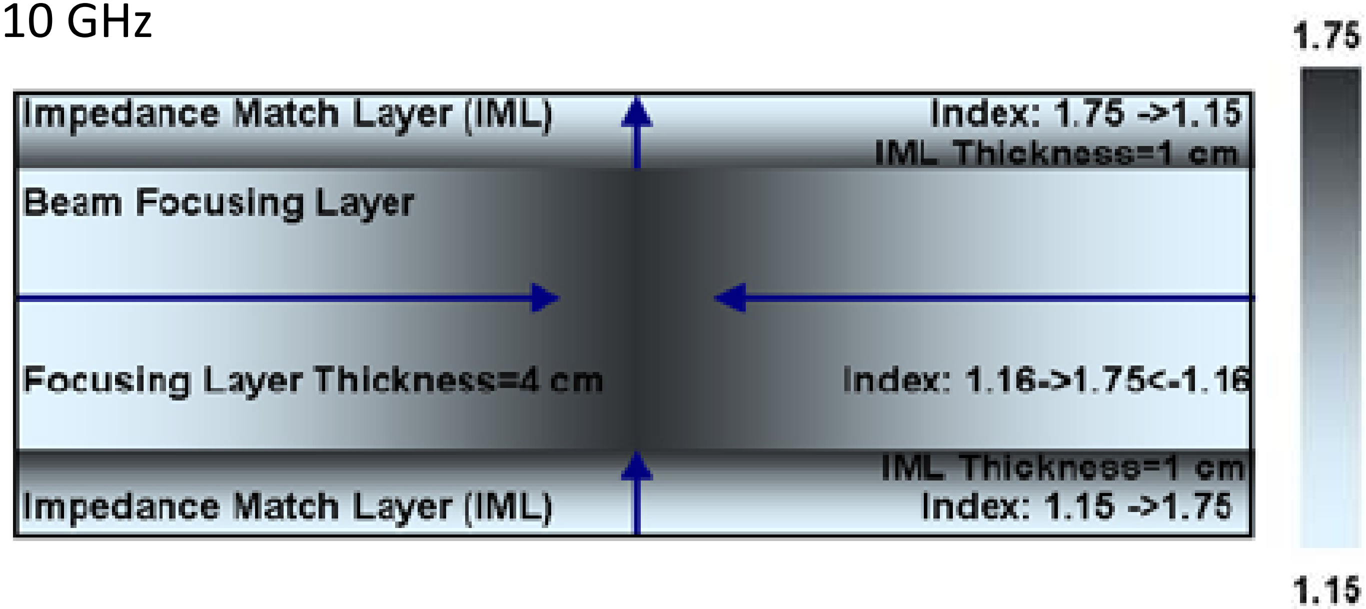
- ✓ Metamaterials are a great match for graded optics!
- ✓ Structured media allow designs with huge optical property variation.
- ✓ Complex gradient patterns easy to engineer in metamaterials.
- ✓ Controlled anisotropy also possible—tremendous freedom in design.

Gradient Index lens



Experimental Measurement, 10 GHz

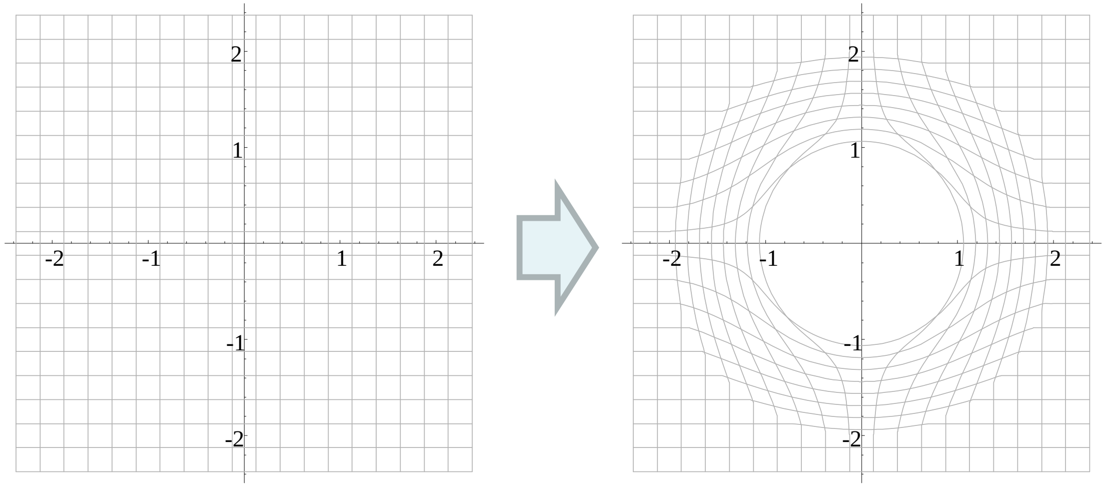




Transformation optics: designing an invisibility cloak

A simple coordinate transformation in 2D:

$$q(r) = \begin{cases} r/2+1 & r<2 \\ r & r>2 \end{cases}$$



Using form-invariance of Maxwell's equations

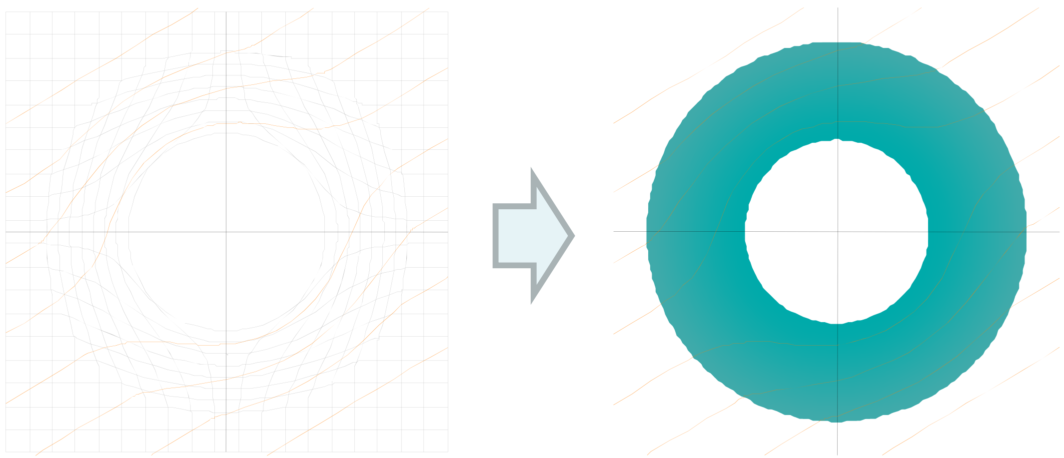
$$\varepsilon^{ij\prime} = \det(\Lambda)^{-1} \Lambda^{i'}{}_{i} \Lambda^{j'}{}_{j} \varepsilon^{ij}$$

$$\mu^{ij\prime} = \det(\Lambda)^{-1} \Lambda^{i'}{}_{i} \Lambda^{j'}{}_{j} \mu^{ij}$$

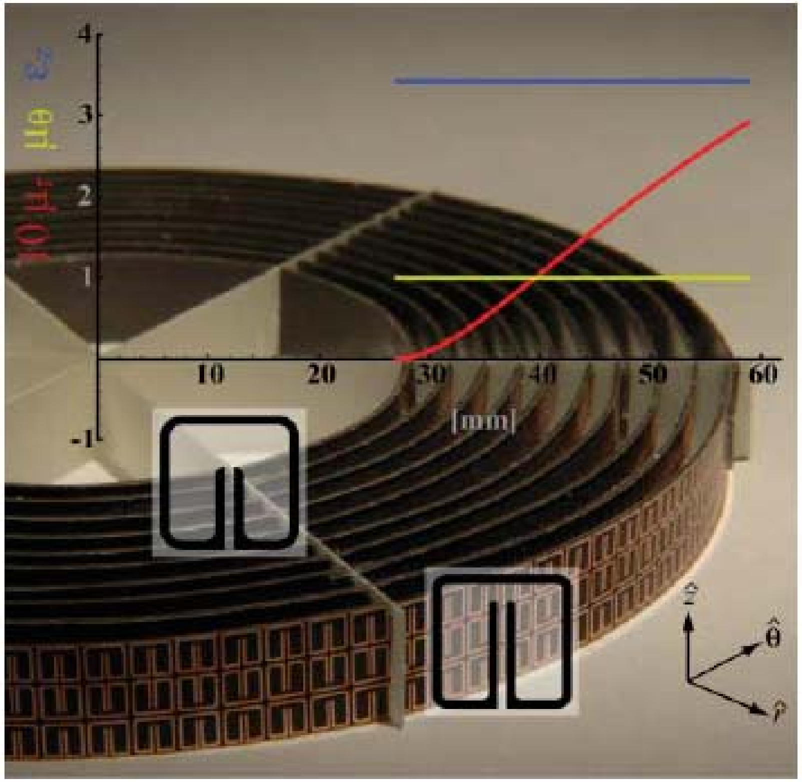
$$x^{i'} = \frac{\partial x^{i'}}{\partial x^{i}} x^{i} = \Lambda^{i'}_{i} x^{i}$$

Topological

Material



Transformation optics: first experimental invisibility cloak



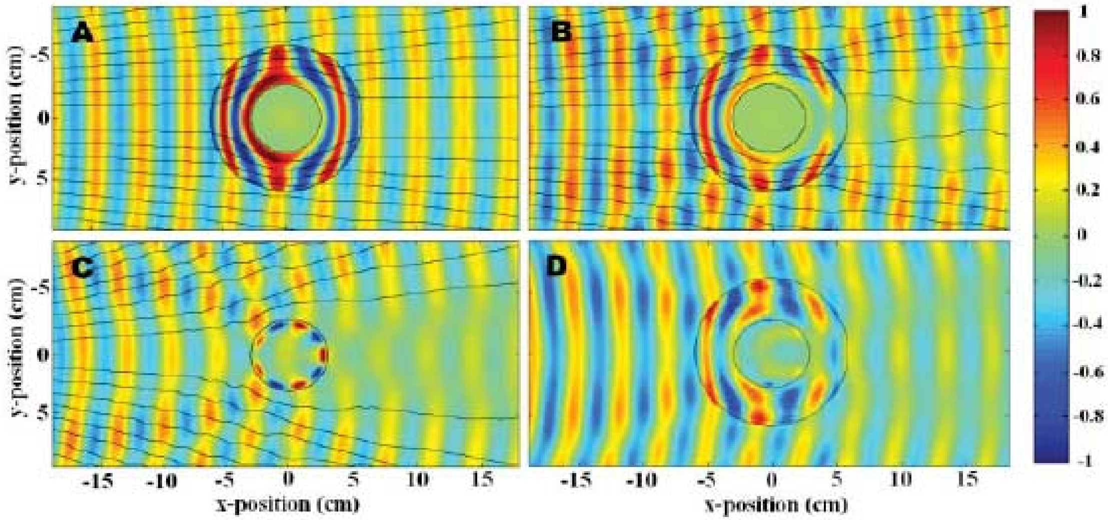


Fig. 4. Snapshots of time-dependent, steady-state electric field patterns, with stream lines [black lines in (A to C)] indicating the direction of power flow (i.e., the Poynting vector). The cloak lies in the annular region between the black circles and surrounds a conducting Cu cylinder at the inner radius. The fields shown are (**A**) the simulation of the cloak with the exact material properties, (**B**) the simulation of the cloak with the reduced material properties, (**C**) the experimental measurement of the bare conducting cylinder, and (**D**) the experimental measurement of the cloaked conducting cylinder. Animations of the simulations and the measurements (movies S1 to S5) show details of the field propagation characteristics within the cloak that cannot be inferred from these static frames. The right-hand scale indicates the instantaneous value of the field.

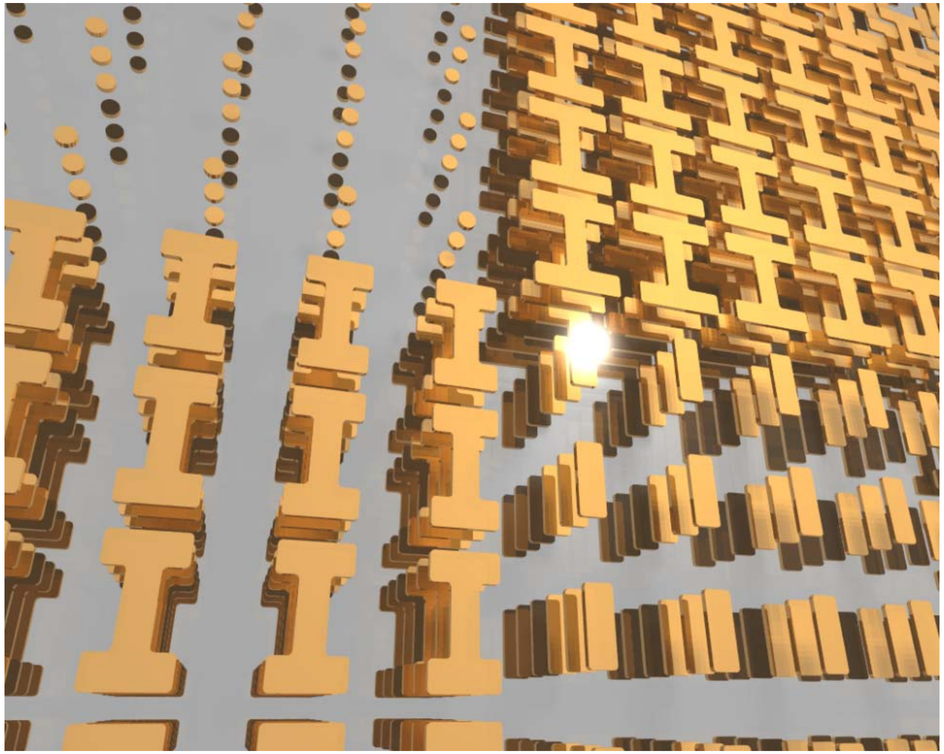
D. Schurig, J. J. Mock, B. J. Justice, S. A. Cummer, J. B. Pendry, A. F. Starr, and D. R. Smith, "Metamaterial Electromagnetic Cloak at Microwave Frequencies", *Science*, vol. 314, 2006, pp. 977–980.

Our work on optical metamaterials

- Our lab continues to work on RF/microwave metamaterials. In particular, we are currently working on a computational imaging system that might become the next generation of airport scanners.
- Today, I will only talk about our work on optical metamaterials. In particular, I will talk about:
  - Far infrared metamaterial
  - Near infrared dual-polarization metamaterial

Our first infrared metamaterial

- Operates at 10.6 µm (CO_2 laser).
- Germanium substrate.
- Many layers of gold elements of various sizes and shapes centered in 1 µm × 1 µm × 0.5 µm cuboids of SiO_2.
- Those materials were chosen as a compromise between their optical properties and process capability.



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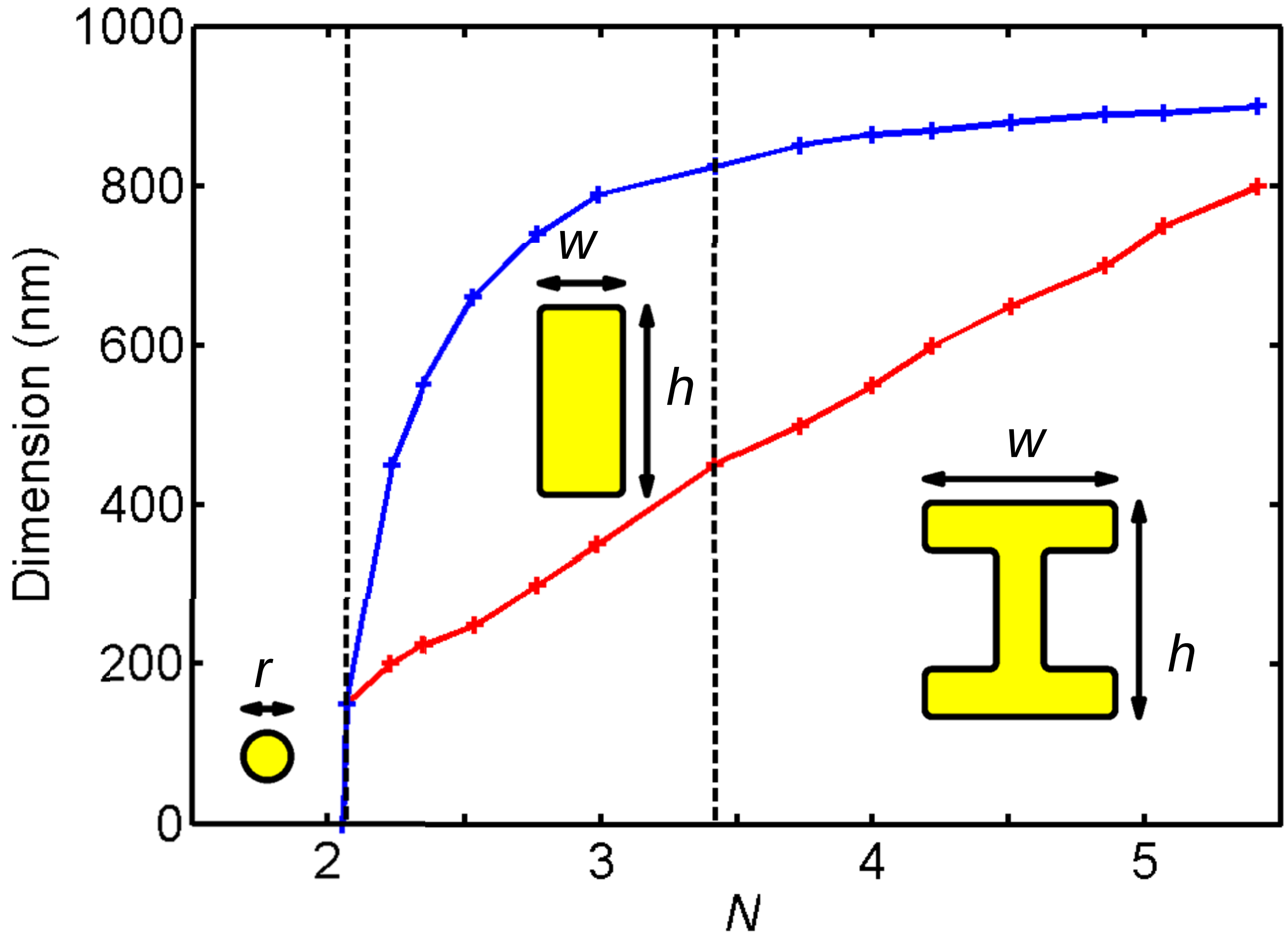
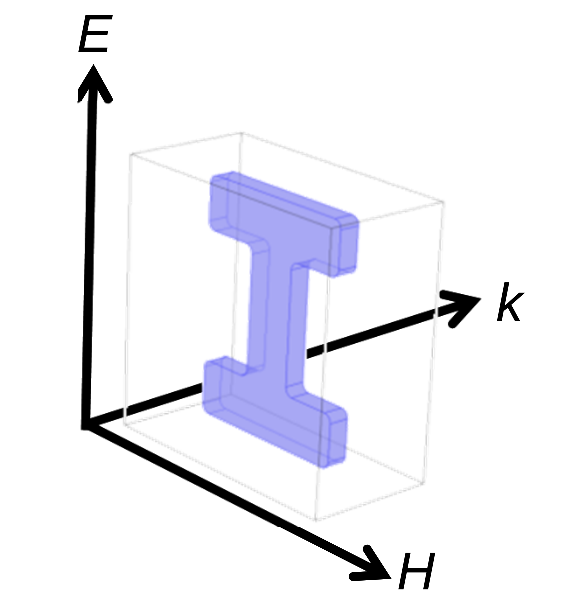
Variable index infrared metamaterial: full wave finite element simulations

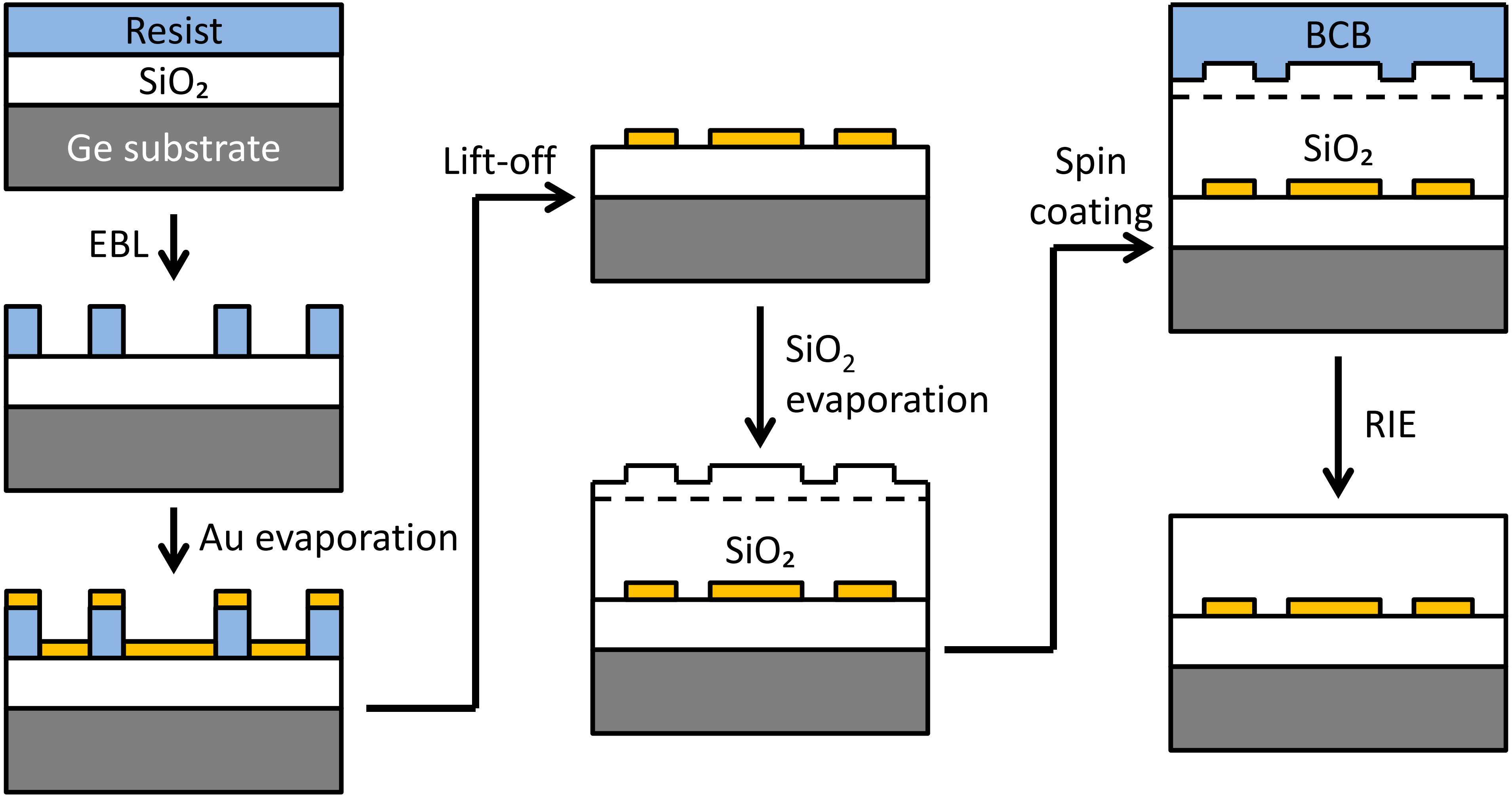




75 nm Au + 3 nm Cr

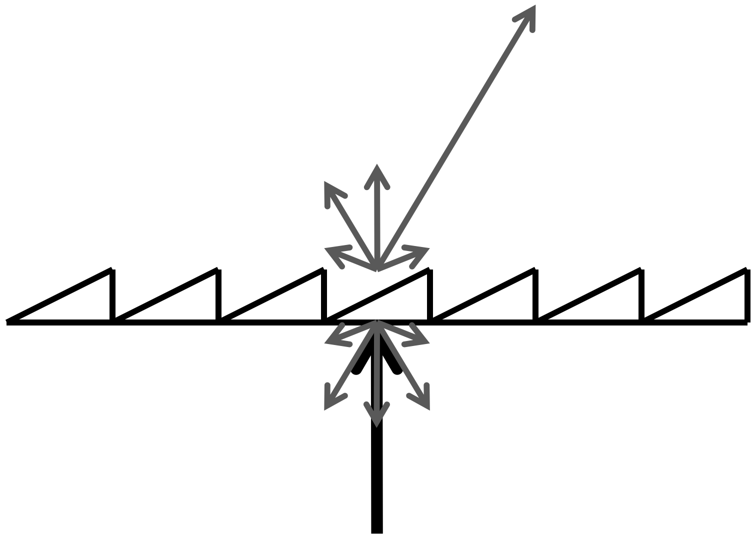
1 µm × 1 µm × 500 nm cuboid of SiO_2

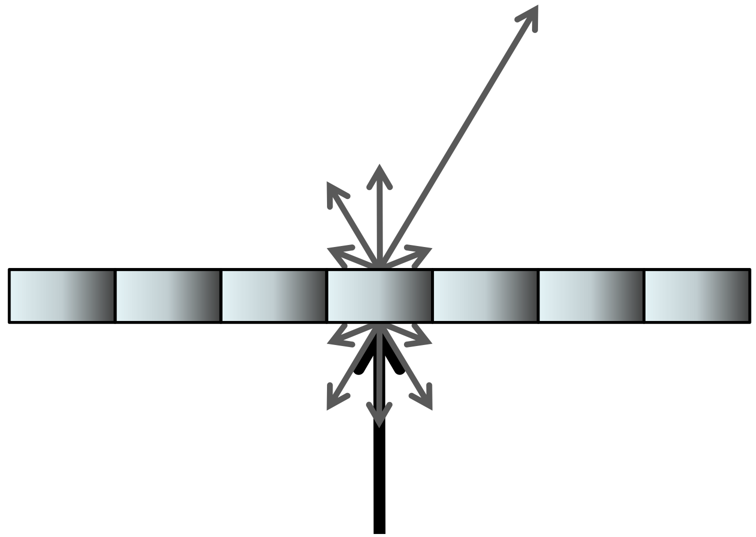
Fabrication process



Blazed gratings

- Blazed gratings are designed to maximize the first diffraction order.
- They are usually fabricated by varying the thickness in a saw-tooth profile.
- They can also be fabricated by varying the refractive index.





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Blazed gratings provide a quantitative evaluation of Δ*n*

Assuming purely phase is modified by the diffractive optic, the strength of diffracted orders can be computed easily from the formula below:

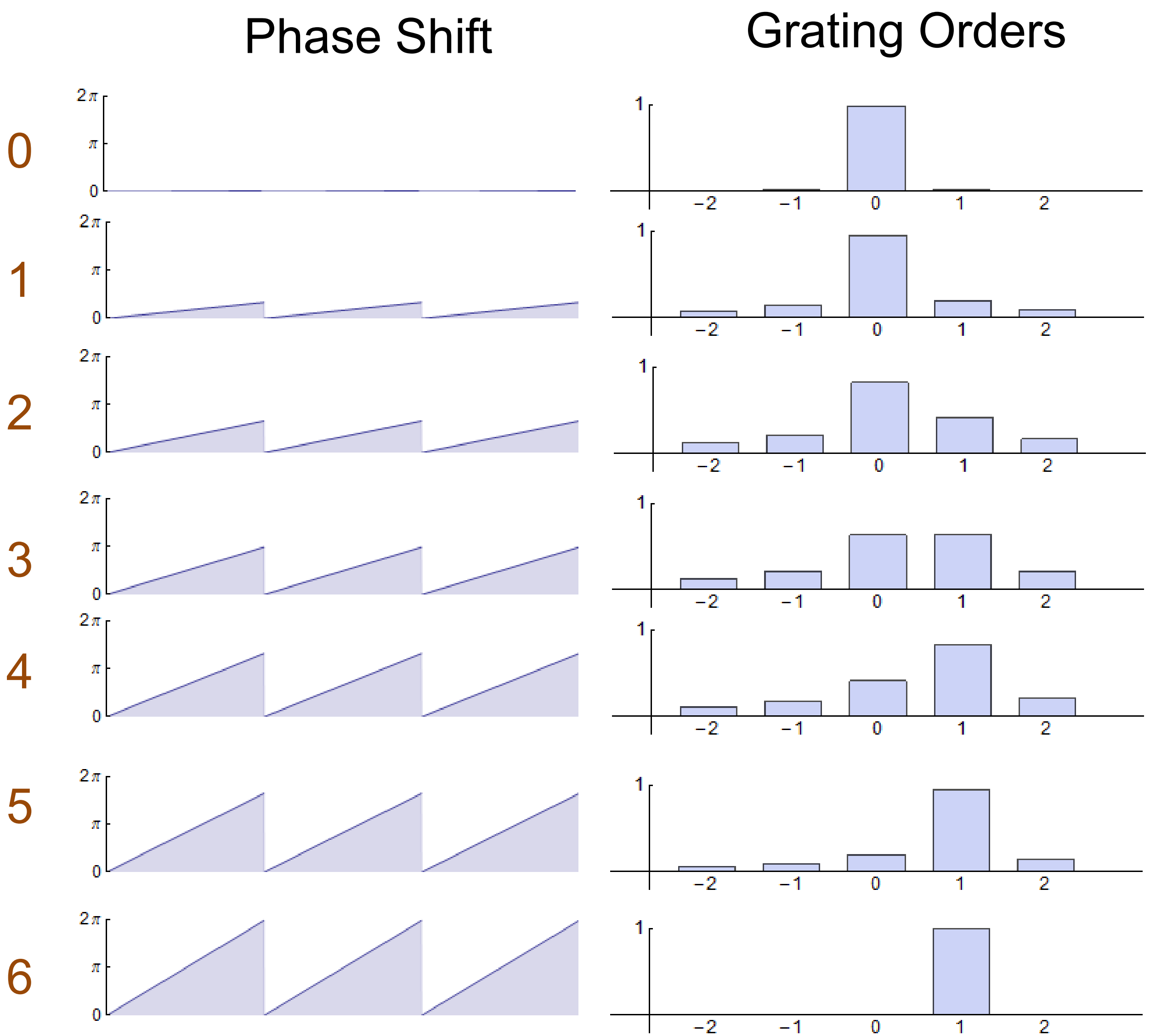
$$a_m = 2\frac{\sin\left[(\varphi - 2\pi m)/2\right]}{(\varphi - 2\pi m)}$$

Grating parameters:

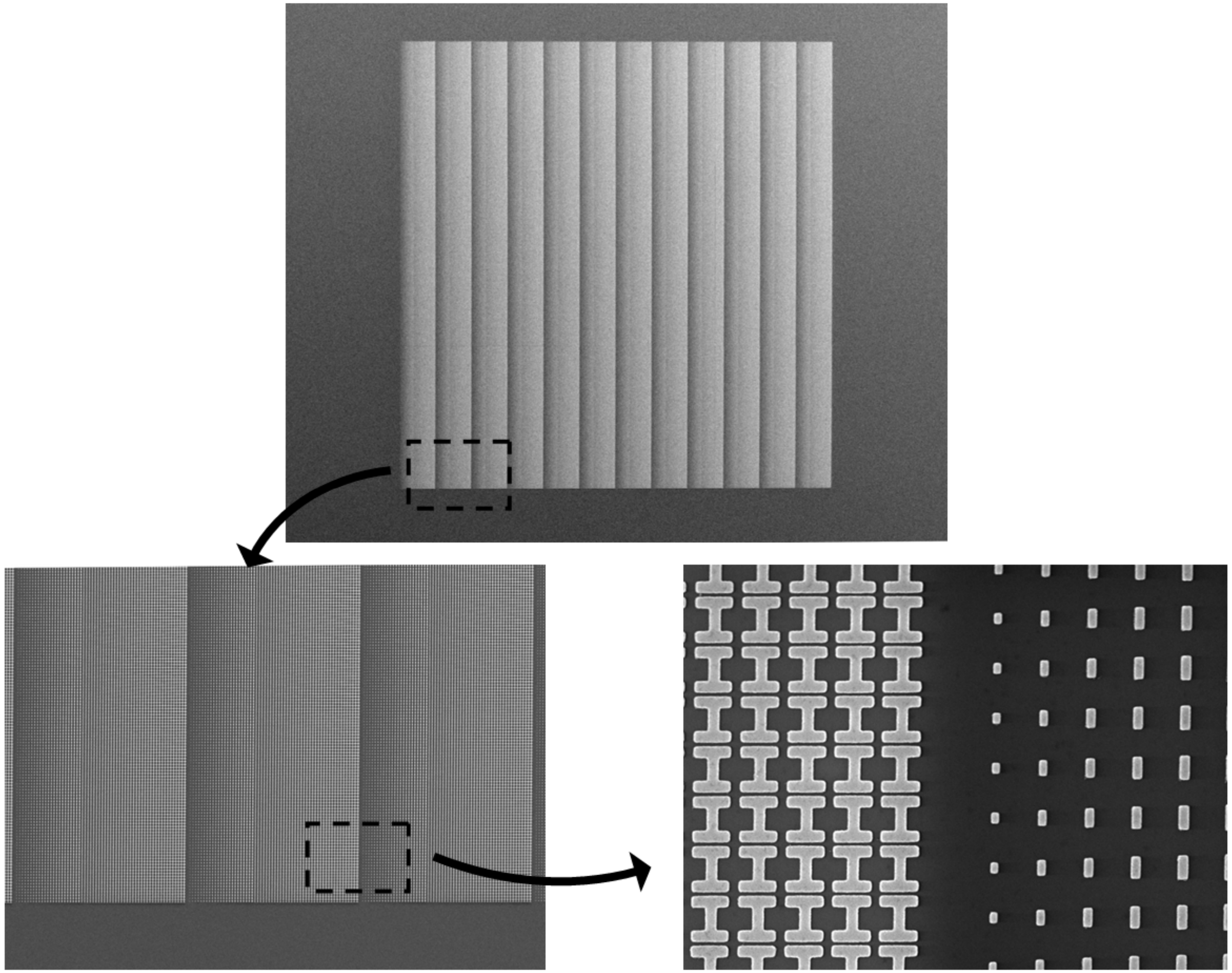
$$\lambda = 10.6\ \mu m$$

$$d = 60\ \mu m$$

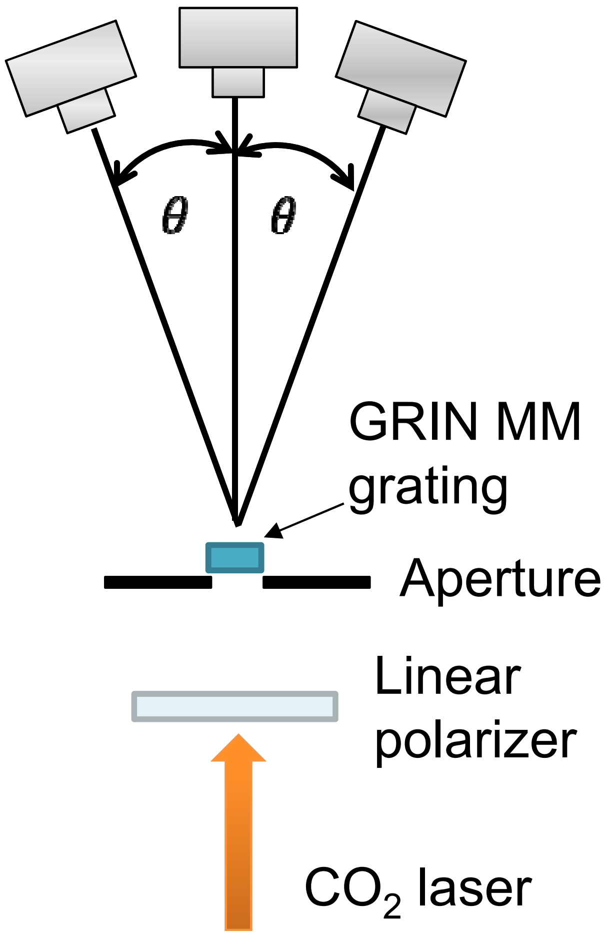
$$t_{layer} = 0.5\ \mu m$$

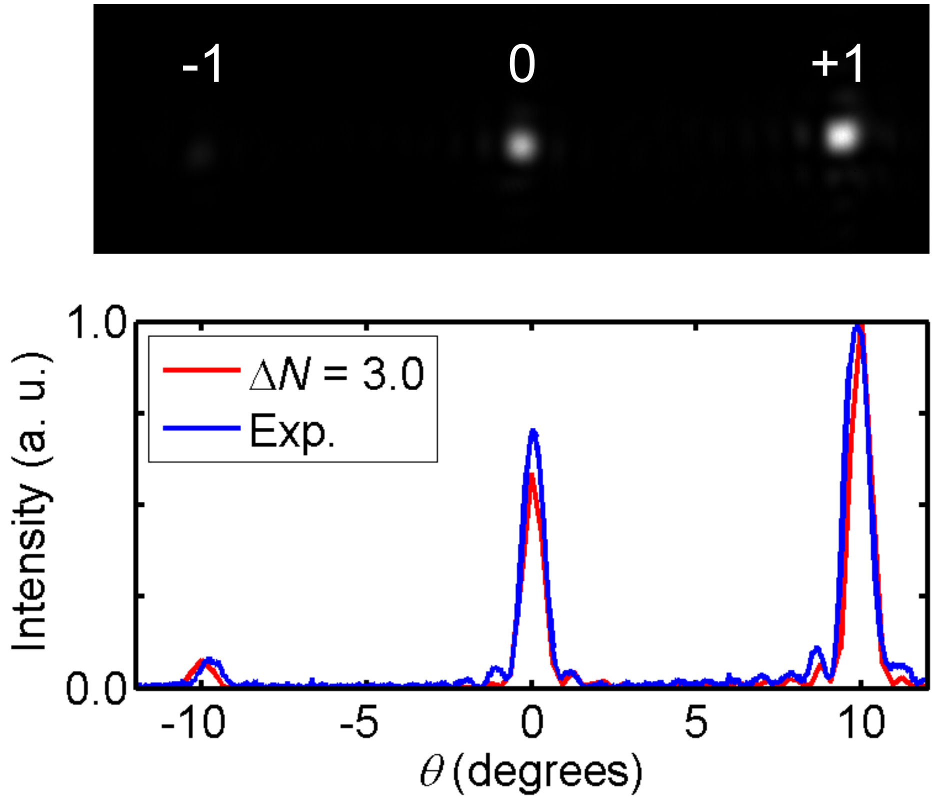


Fabrication of a blazed grating with 61 phase levels



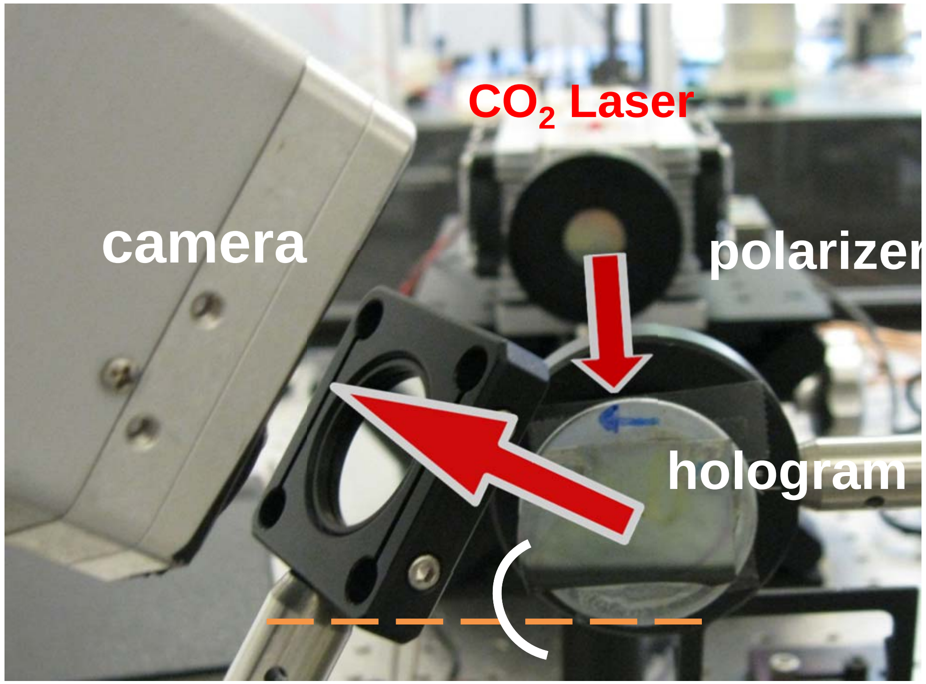
Blazed gratings: results confirm $\Delta n \approx 3.0$

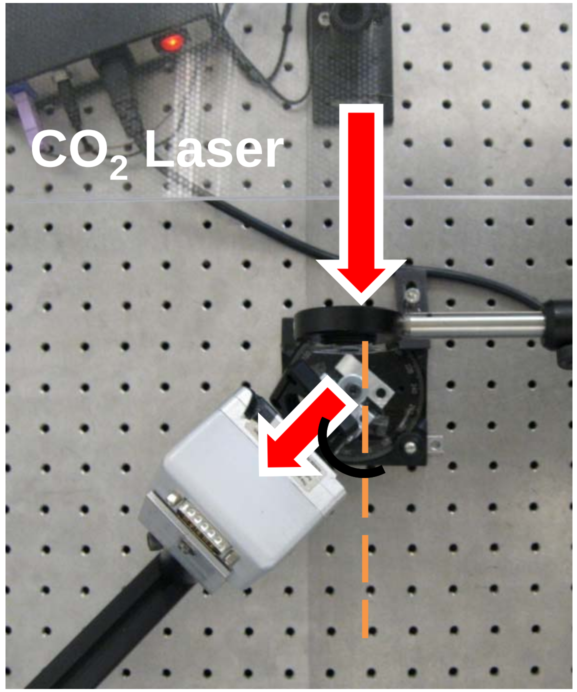




Y.-J. Tsai, S. Larouche, T. Tyler, G. Lipworth, N. M. Jokerst, and D. R. Smith, "Design and fabrication of a metamaterial gradient index diffraction grating at infrared wavelengths", *Optics Express*, vol. 19, 2011, p. 24411.

IR hologram characterization setup

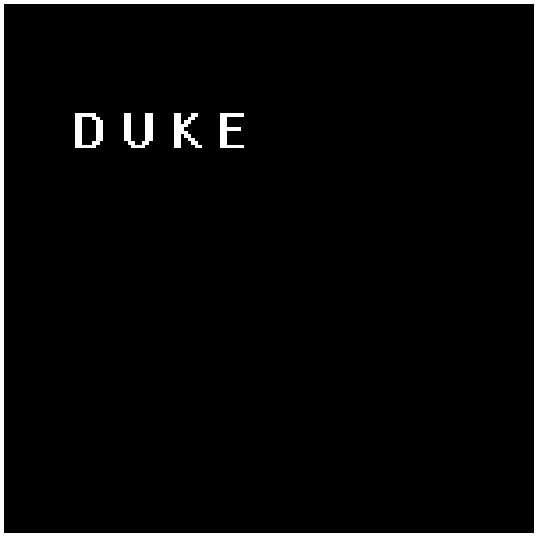




Design of the hologram: Gerchberg–Saxton algorithm

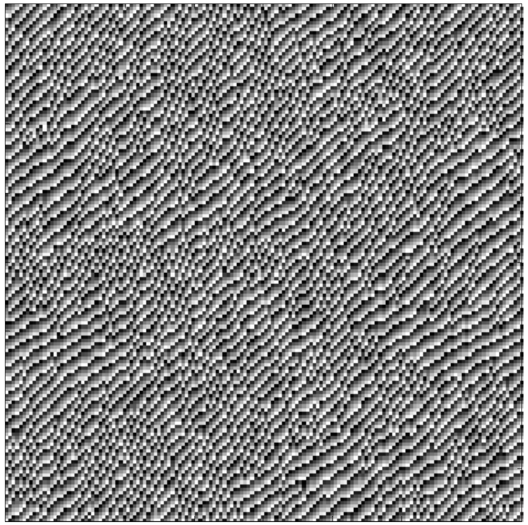
- In the Fraunhofer regime the hologram and its image are related by a Fourier transform.
- An iterative approach, the Gerchberg–Saxton algorithm, allows one to obtain a pure phase hologram while the phase of the image is allowed to vary arbitrarily.

Desired image



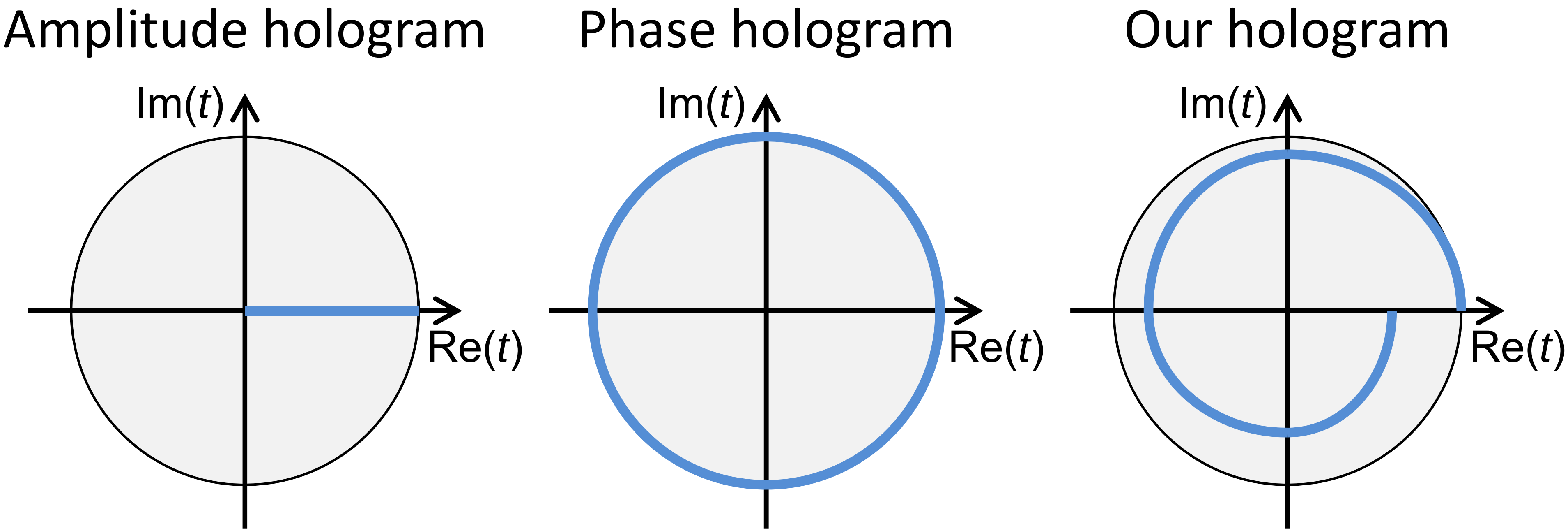
Fourier transform ⟷

Phase hologram



R. W. Gerchberg and W. O. Saxton, "A practical algorithm for the determination of phase from image and diffraction plane pictures", *Optik*, vol. 35, 1972, p, 237.

Amplitude and phase holograms



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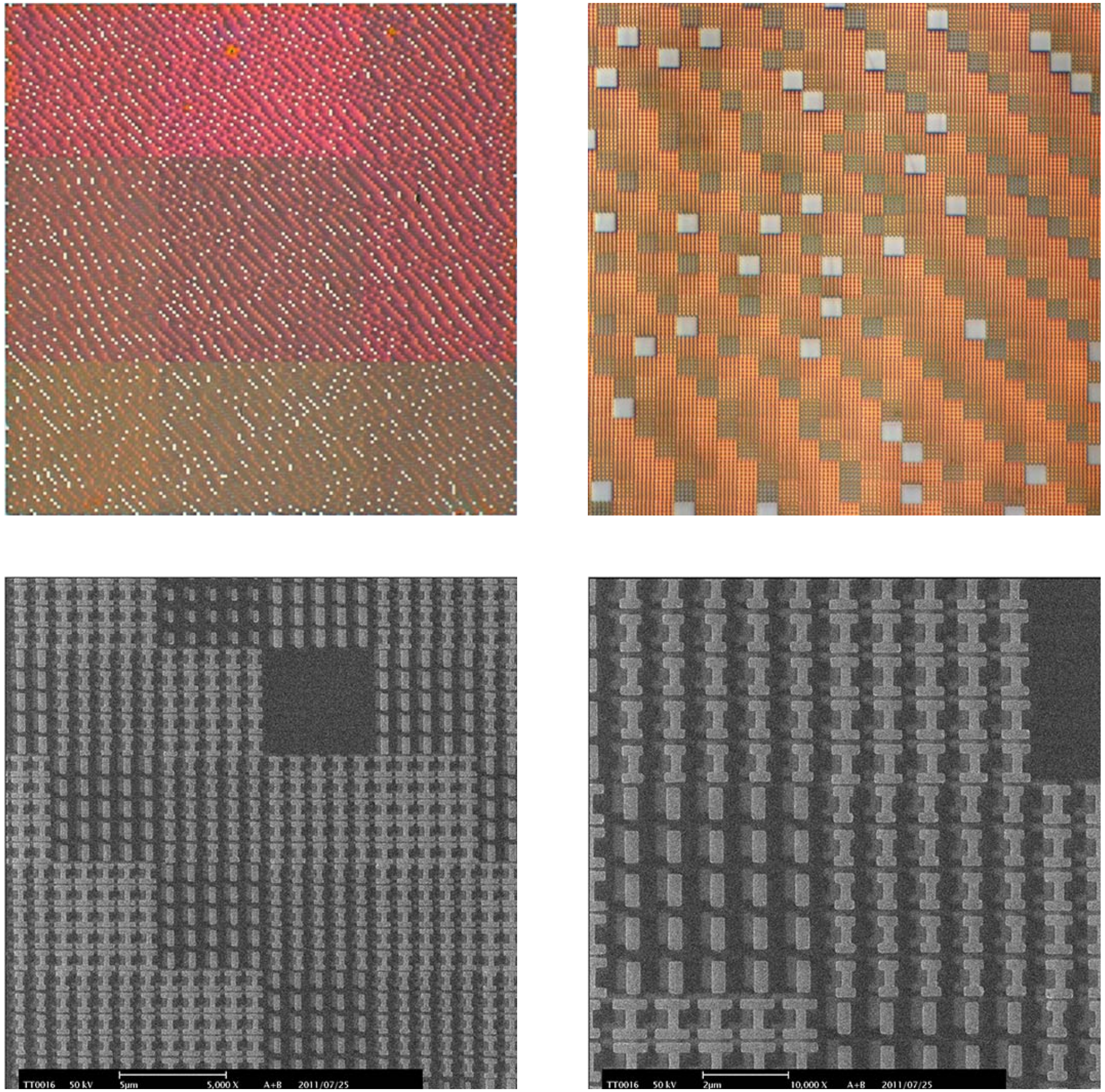
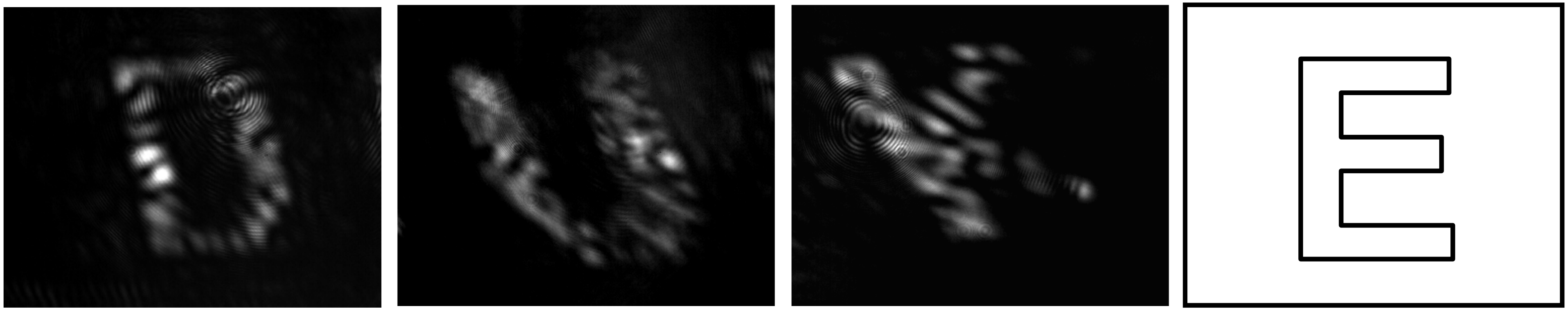
Optical and SEM pictures of fabricated hologram



Results



S. Larouche, Y.-J. Tsai, T. Tyler, N. M. Jokerst and D. R. Smith, "Infrared metamaterial phase holograms", *Nature Materials*, vol. 11, 2012, p. 450.

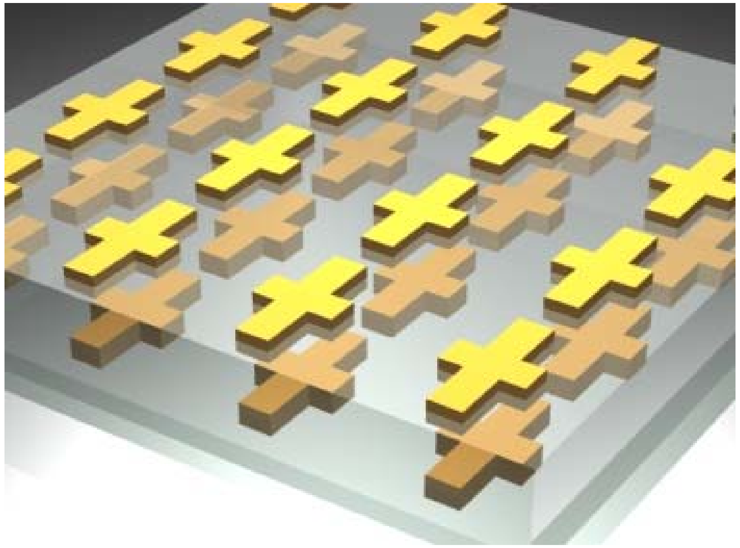
So what?

- We have fabricated a multilayer metamaterial device with a well controlled 2D refractive index distribution operating at optical wavelengths and verified its operation.
- However, this hologram:
  - has significant absorption;
  - operates at a single polarization;
  - is more complicated and costly to fabricate than existing holograms.

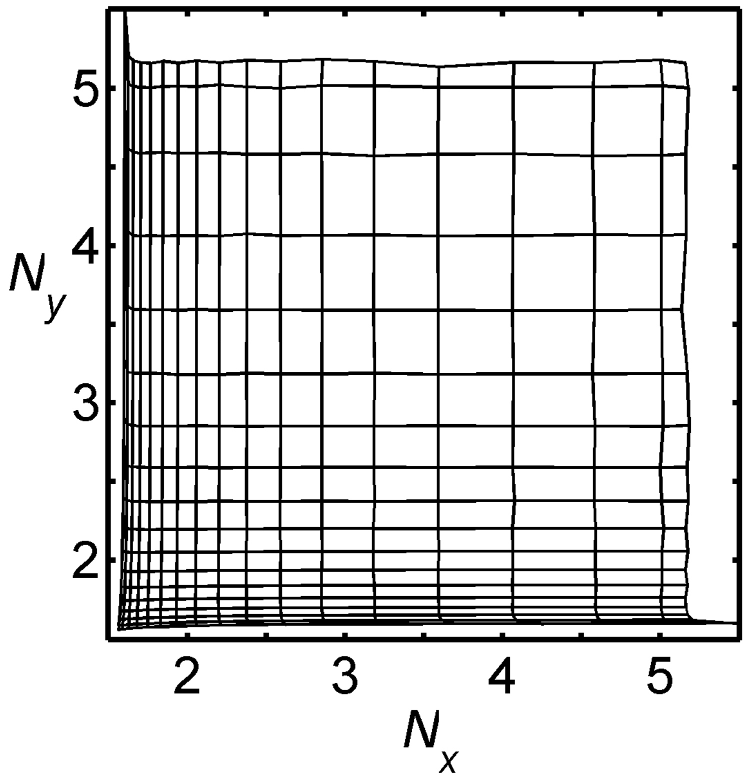
- The device would be more interesting if it included properties not achievable with existing holograms.

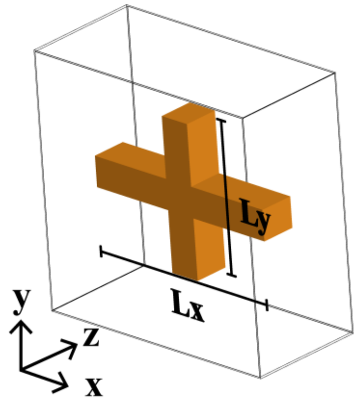
Near infrared anisotropic metamaterial

- Operating at 1550 nm (telecommunication wavelength).
- Silicon substrate.
- Many layers of gold crosses of various size centered in 250 nm × 250 nm × 100 nm cuboids of BCB.
- The refractive index in two orthogonal linear polarization is controlled independently by adjusting separately the arm lengths.

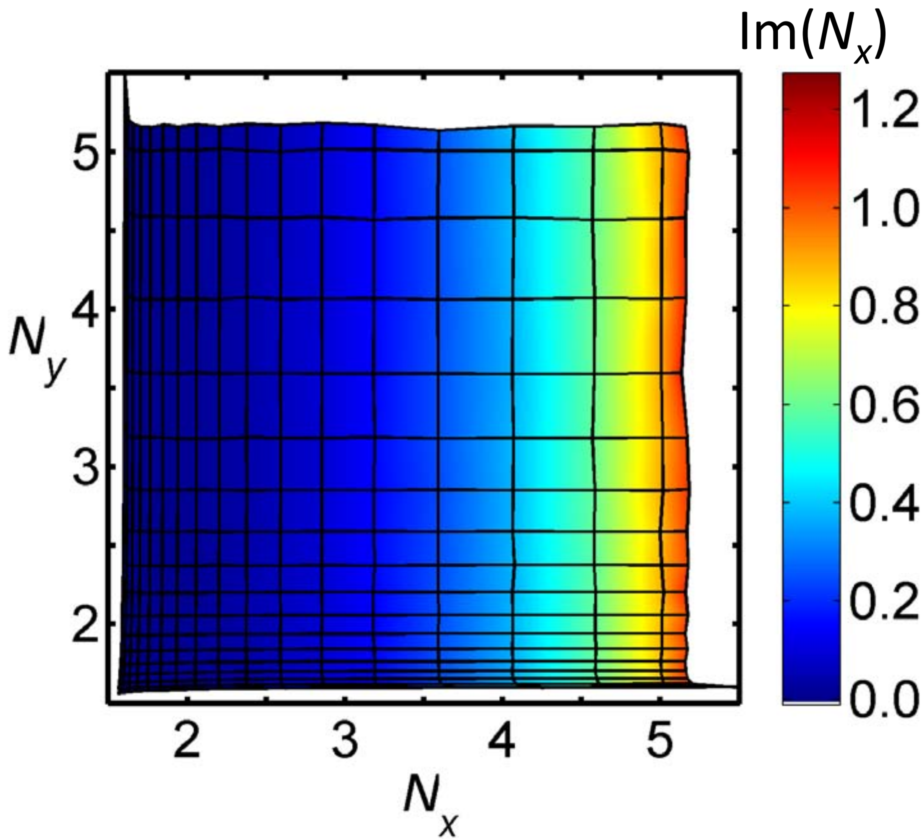


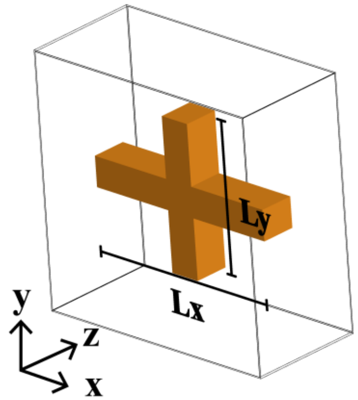
Dual polarization near infrared metamaterial: full wave finite element simulations



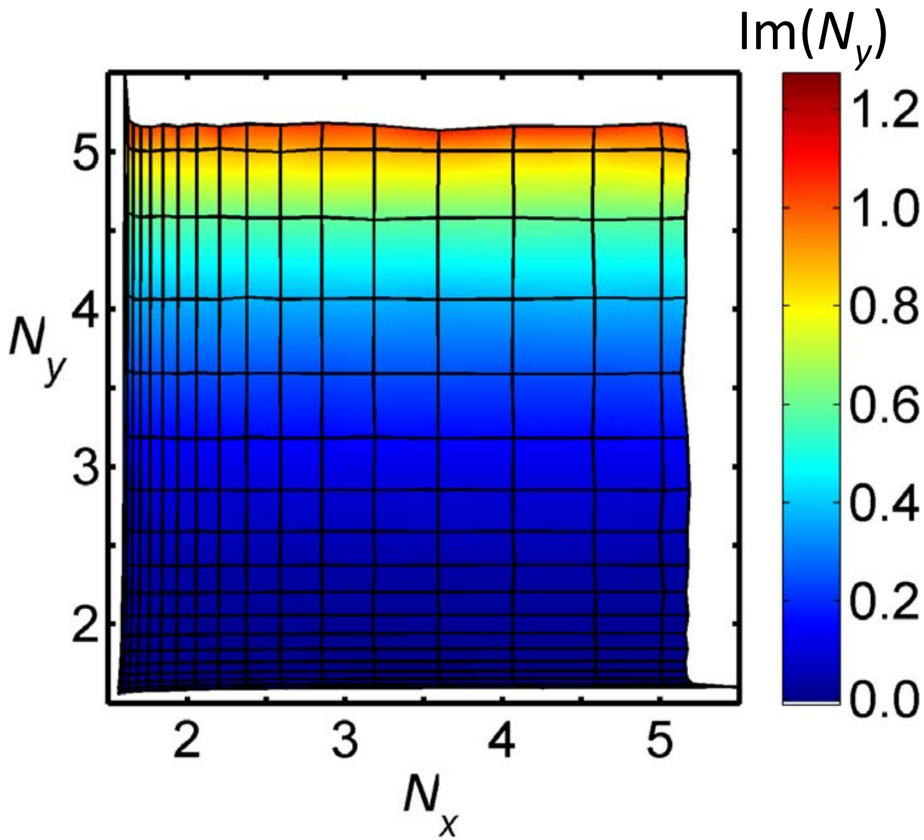


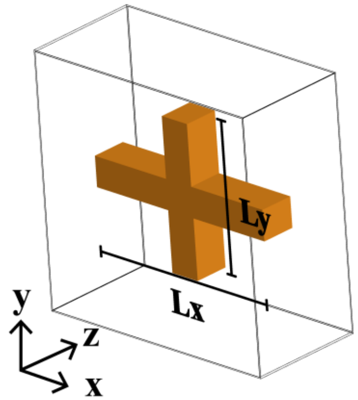
Dual polarization near infrared metamaterial: full wave finite element simulations





Dual polarization near infrared metamaterial: full wave finite element simulations





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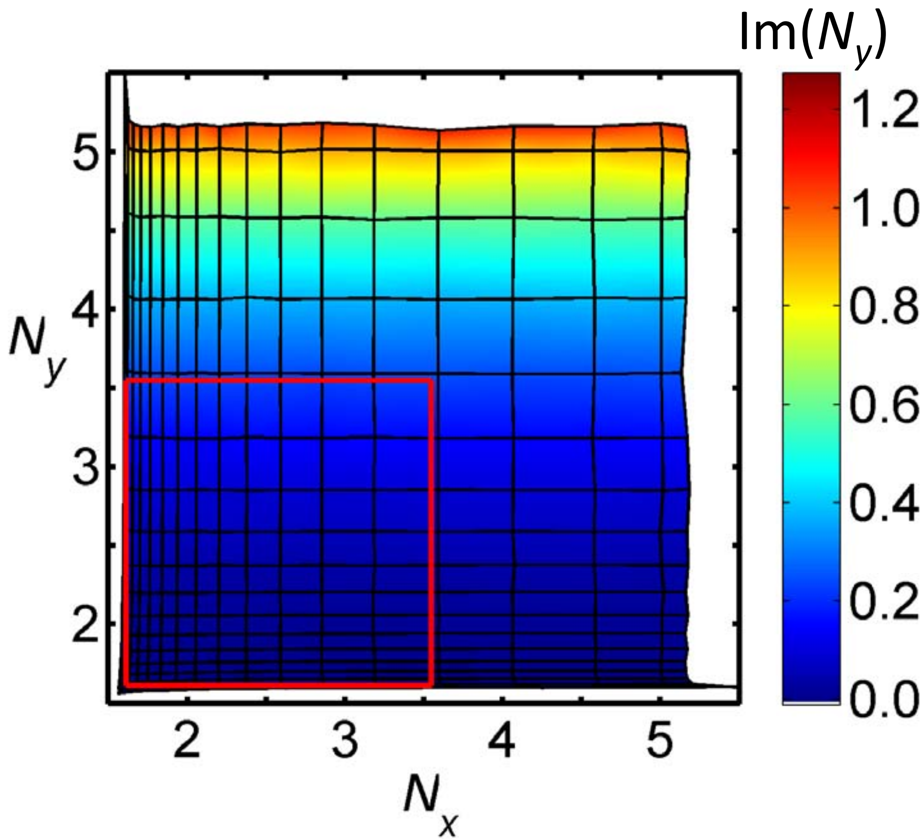
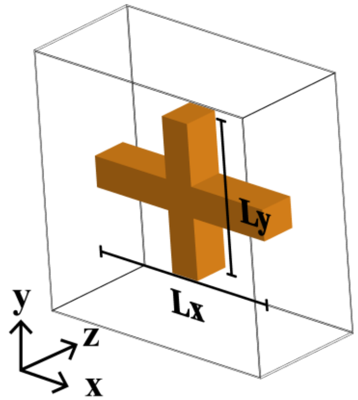
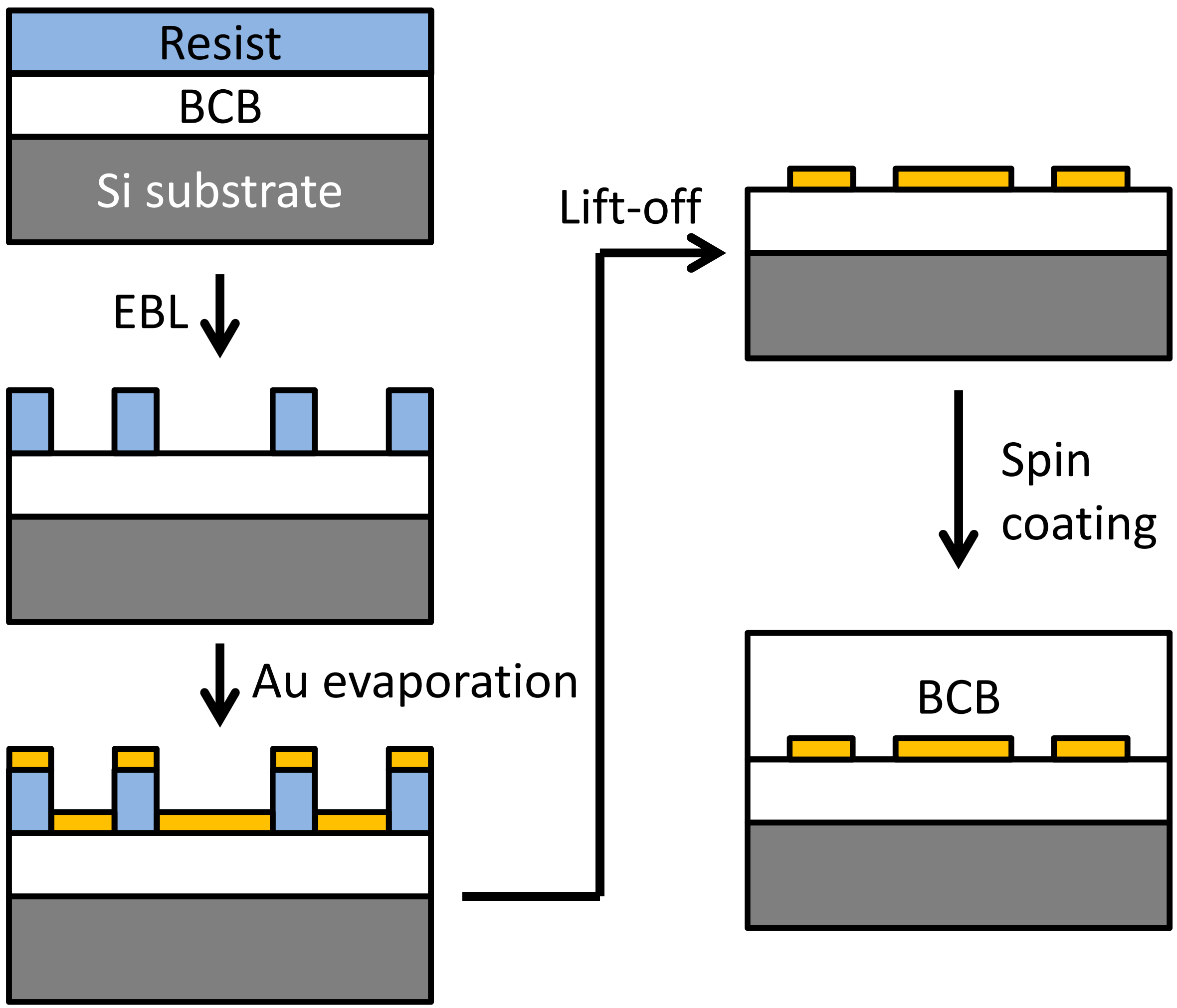
Dual polarization near infrared metamaterial: full wave finite element simulations

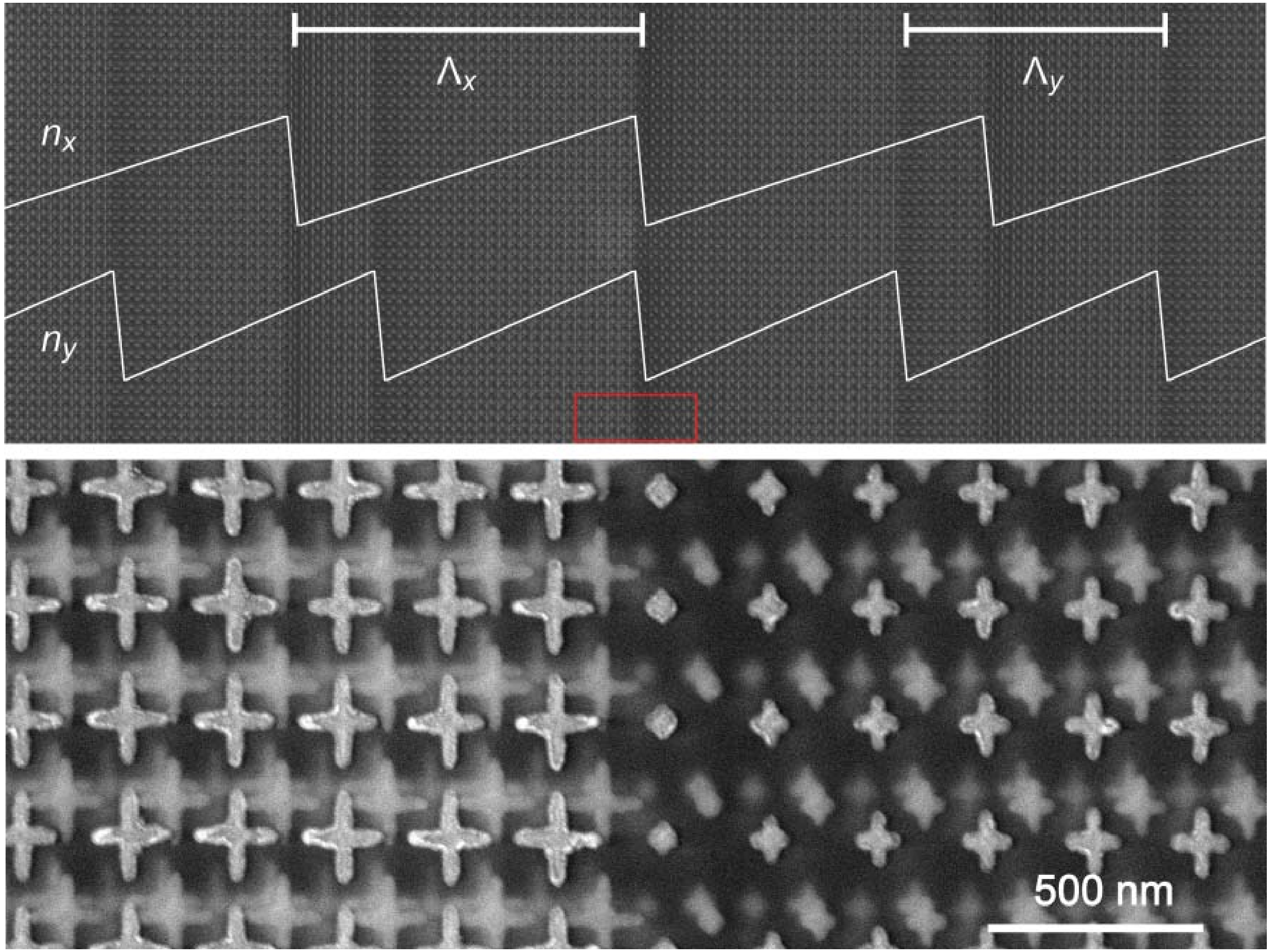




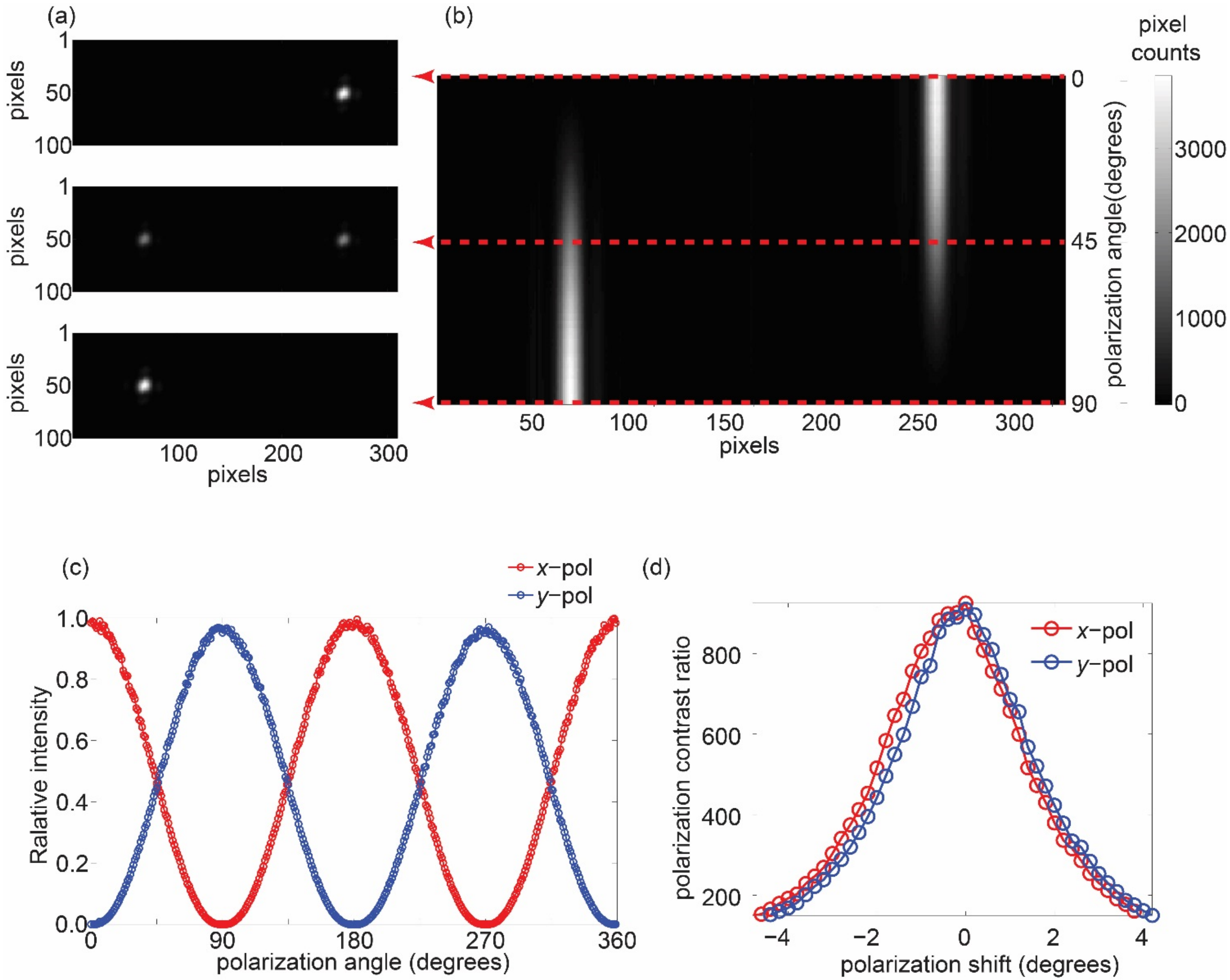
Fabrication process



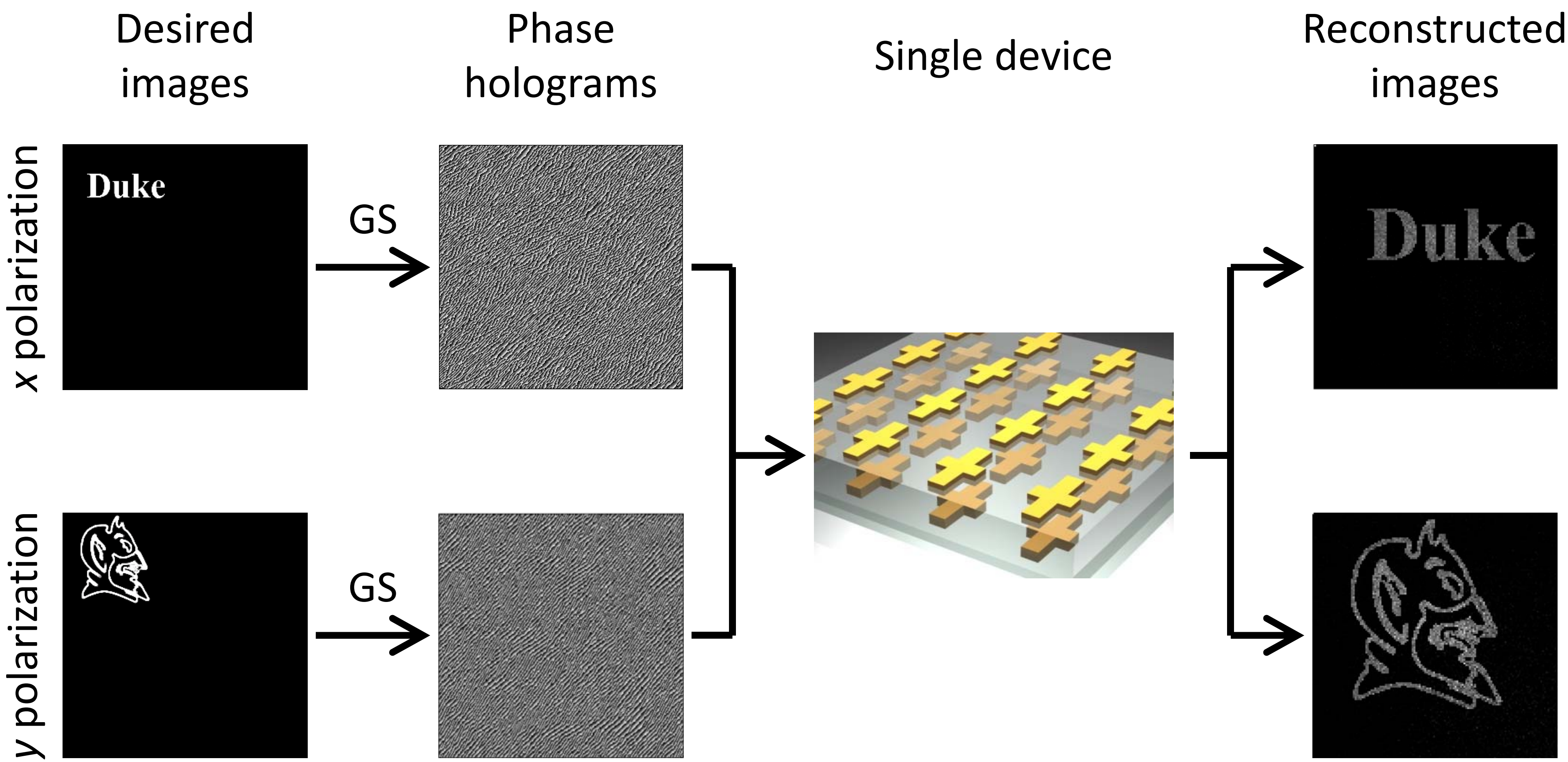
Polarization multiplexed grating



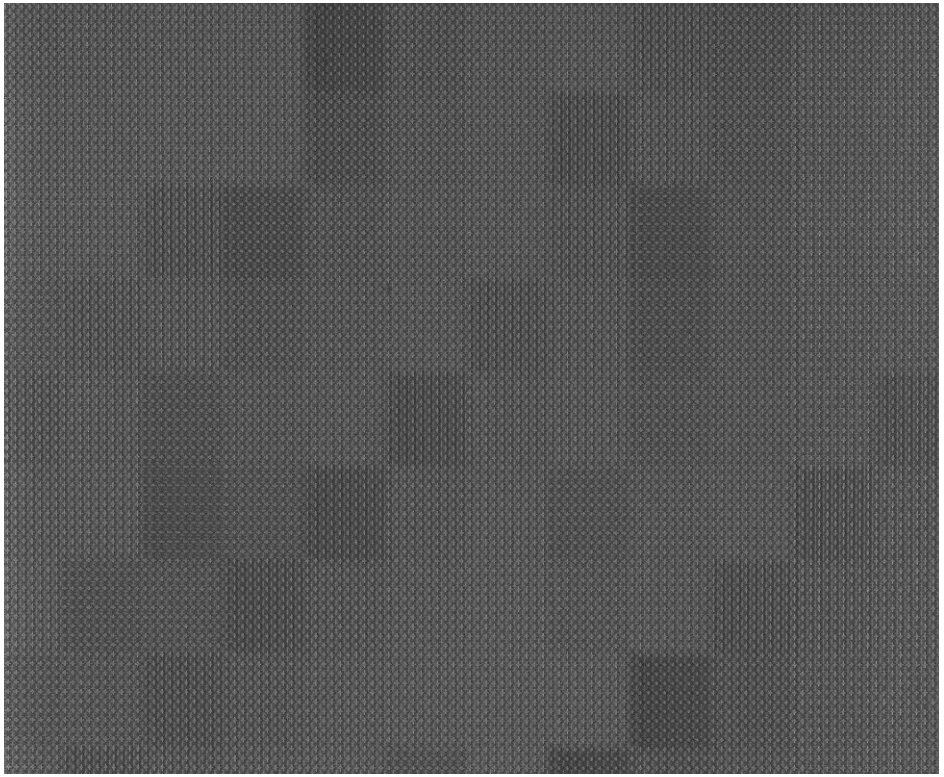
Experimental results from an 8 layer grating

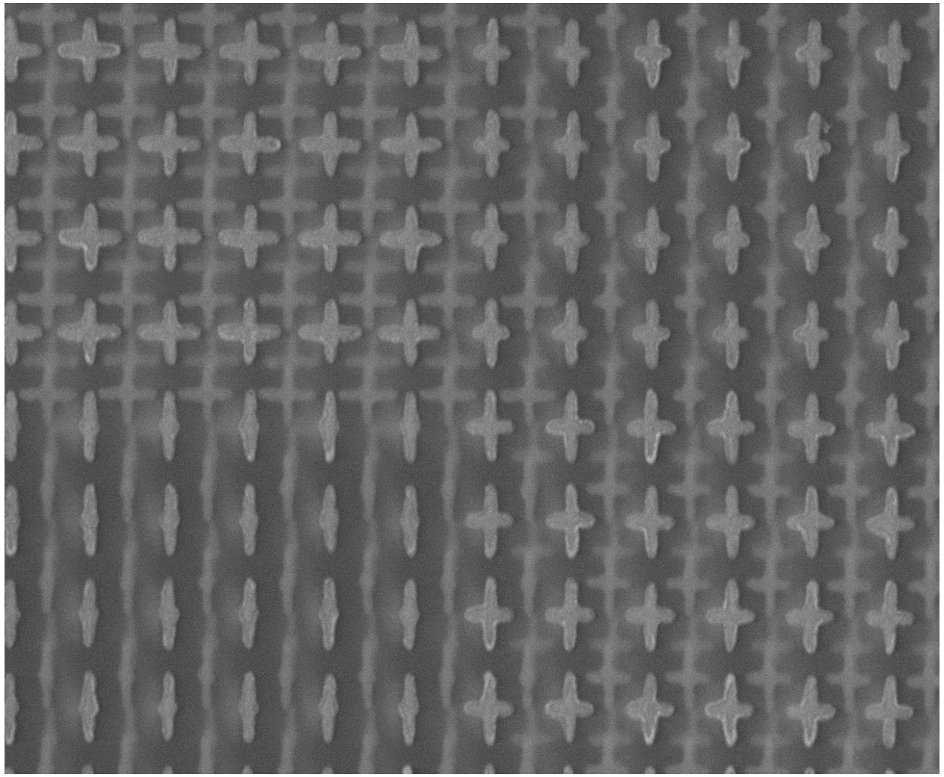


Design of a dual polarization hologram



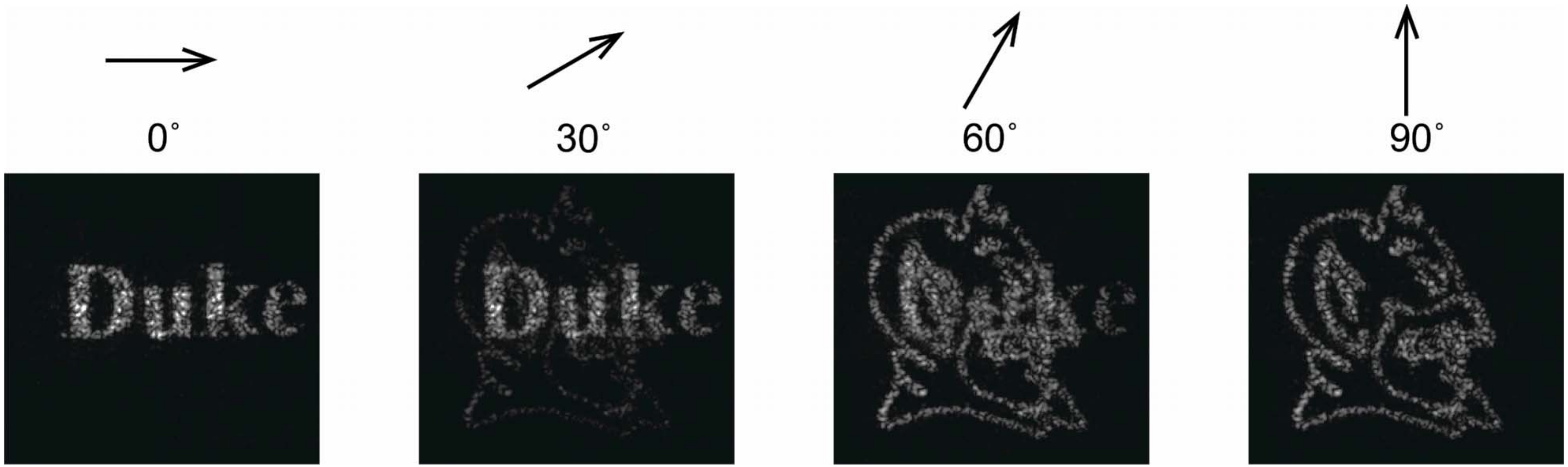
SEM pictures of dual polarization hologram





Characterization of dual polarization hologram

x polarization *y* polarization



Y.-J. Tsai, S. Larouche, T. Tyler, A. Llopis, M. Royal, N. M. Jokerst, and D. R. Smith, "Arbitrary birefringent metamaterials for holographic optics at λ = 1.55 μm", *Opt. Express*, vol. 21, 2013, p. 26620.

Perspectives

- Metamaterials are a design approach allowing you to tailor the properties of materials to the needs of your application.
- Metamaterials are an interesting platform to control anisotropy and inhomogeneity.
- We are currently working on devices that integrate graded-index lenses, polarization dependent properties, and diffractive optics through the use of metamaterials.

- Through field enhancement in small volumes, metamaterials allow amplification of nonlinear effects.