Light Propagation with Phase Discontinuities: Generalized Laws of Reflection and Refraction

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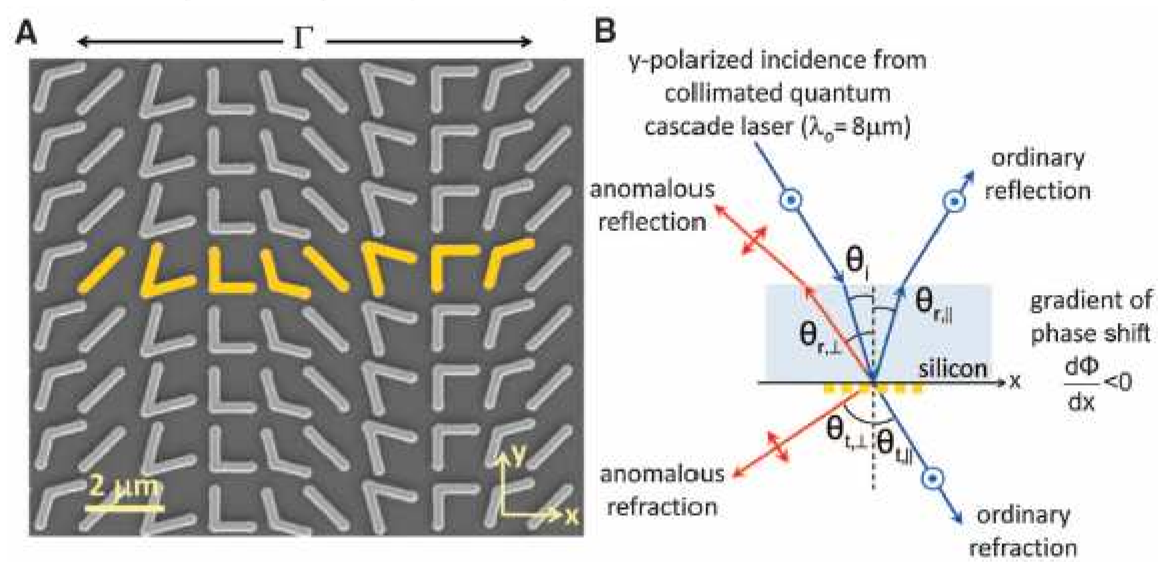
Conventional optical components rely on gradual phase shifts accumulated during light propagation to shape light beams. New degrees of freedom are attained by introducing abrupt phase changes over the scale of the wavelength. A two-dimensional array of optical resonators with spatially varying phase response and subwavelength separation can imprint such phase discontinuities on propagating light as it traverses the interface between two media. Anomalous reflection and refraction phenomena are observed in this regime in optically thin arrays of metallic antennas on silicon with a linear phase variat
agreement with generalized laws derived from F
great flexibility in the design of light beams,
through use of planar designer metallic interf



Rockson Chang – Nov 16th, 2011 Group meeting

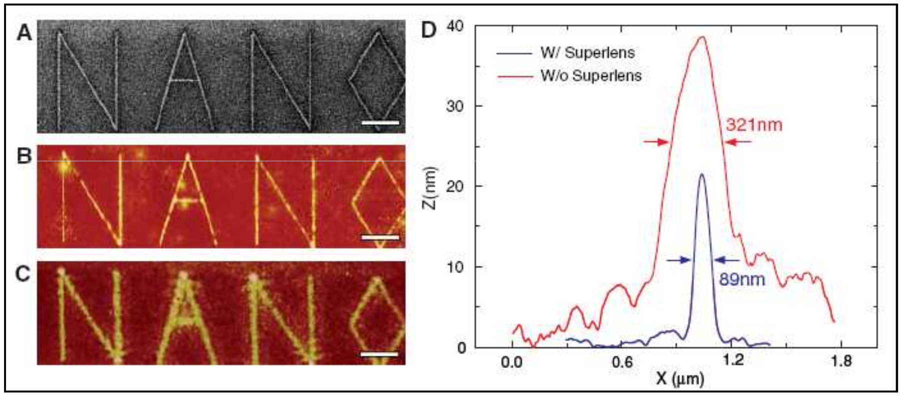
Metamaterials

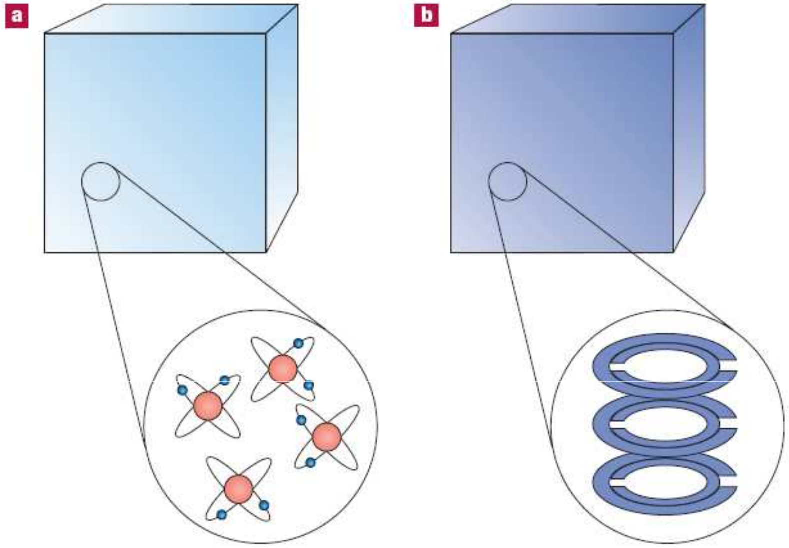
Metamaterials

"Interaction between light and materials is the key to exploiting and controlling the properties of light… These optical properties can be tailored by adjusting the chemical composition of the material. We might, for example, add lead to glass and raise its refractive index. More recently it has been realized that the internal microstructure of a material can be just as important as chemistry in determining its optical properties. In fact, by exploiting both chemistry and microstructure, materials can be produced with properties never found in nature" – John Pendry *Metamaterials in the Sunshine*

Metamaterials

- Materials with artificial optical properties achieved by introducing sub-wavelength structure → engineer ε and μ
- Cloaking
- Negative index materials
  - Anomalous refraction
  - Perfect lens





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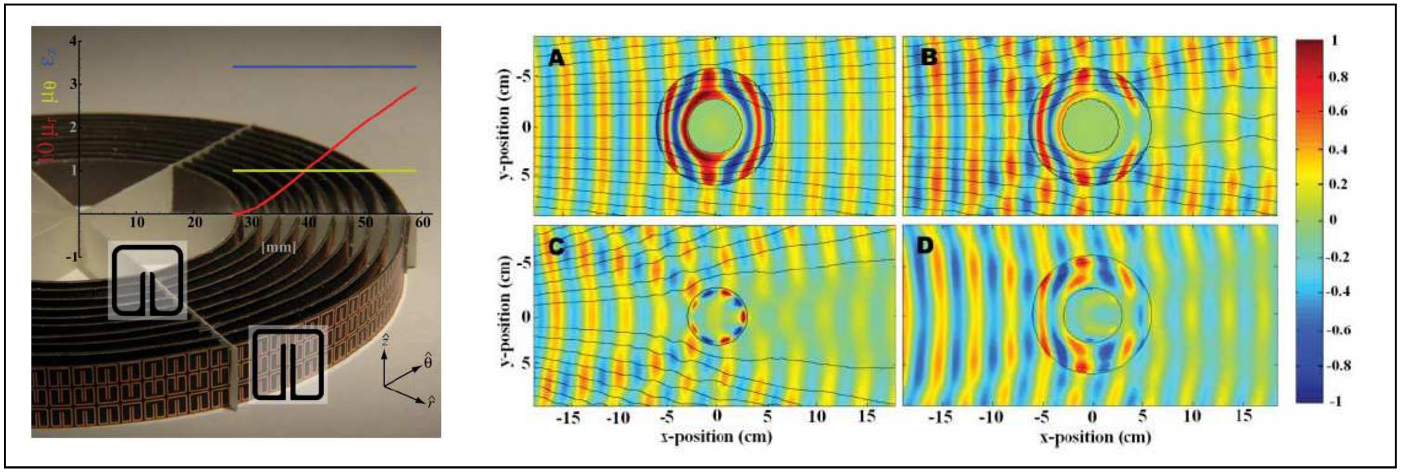


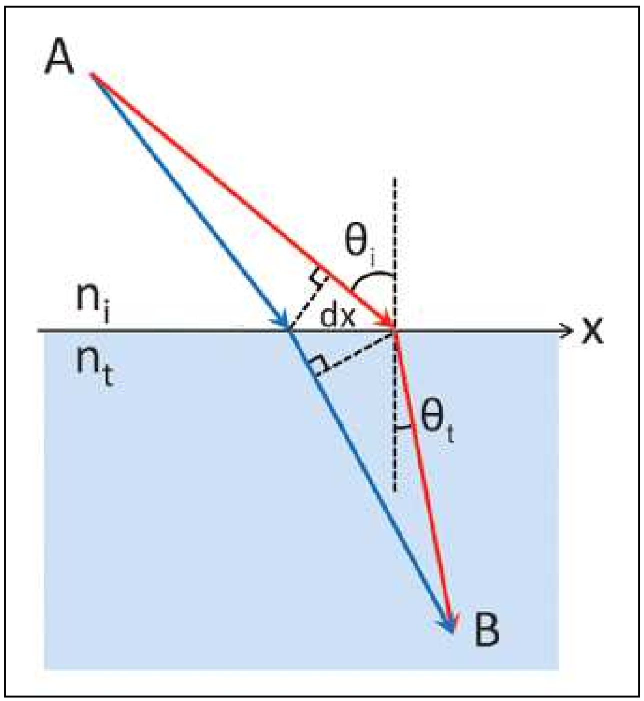
Light Propagation with Phase Discontinuities: Generalized Laws of Reflection and Refraction

- Fermat's principle:

the path a ray takes between two points is the path that minimizes the traversal time

Principle of stationary phase

$$\delta \int_A^B \vec{k} \cdot d\vec{r} = 0$$



$$[k_o n_i \sin(\theta_i) dx\,] - [k_o n_t \sin(\theta_t) dx\,] = 0$$

$$\sin(\theta_t) n_t - \sin(\theta_i) n_i = 0$$

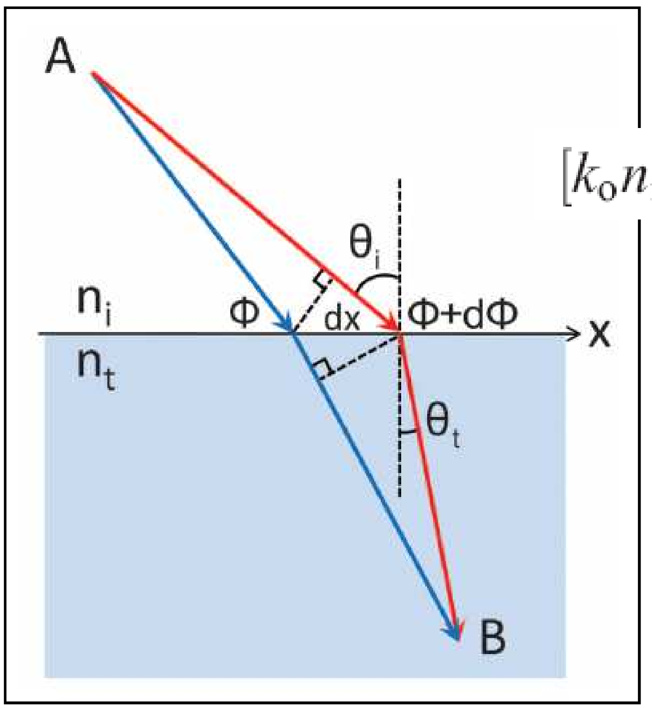
Light Propagation with Phase Discontinuities: Generalized Laws of Reflection and Refraction

- Fermat's principle:

  the path a ray takes between two points is the path that minimizes the traversal time

  Principle of stationary phase

$$\delta\left(\Phi(\vec{r}_s) + \int_A^B \vec{k}\cdot d\vec{r}\right) = 0$$



$$[k_o n_i \sin(\theta_i)dx + (\Phi + d\Phi)] - [k_o n_t \sin(\theta_t)dx + \Phi] = 0$$

$$\sin(\theta_t)n_t - \sin(\theta_i)n_i = \frac{\lambda_o}{2\pi}\frac{d\Phi}{dx}$$

- Anomalous refraction, reflection
- New critical angles for refraction, reflection

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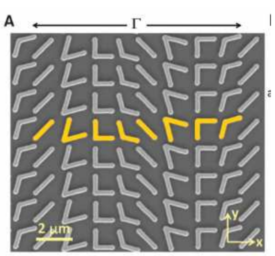
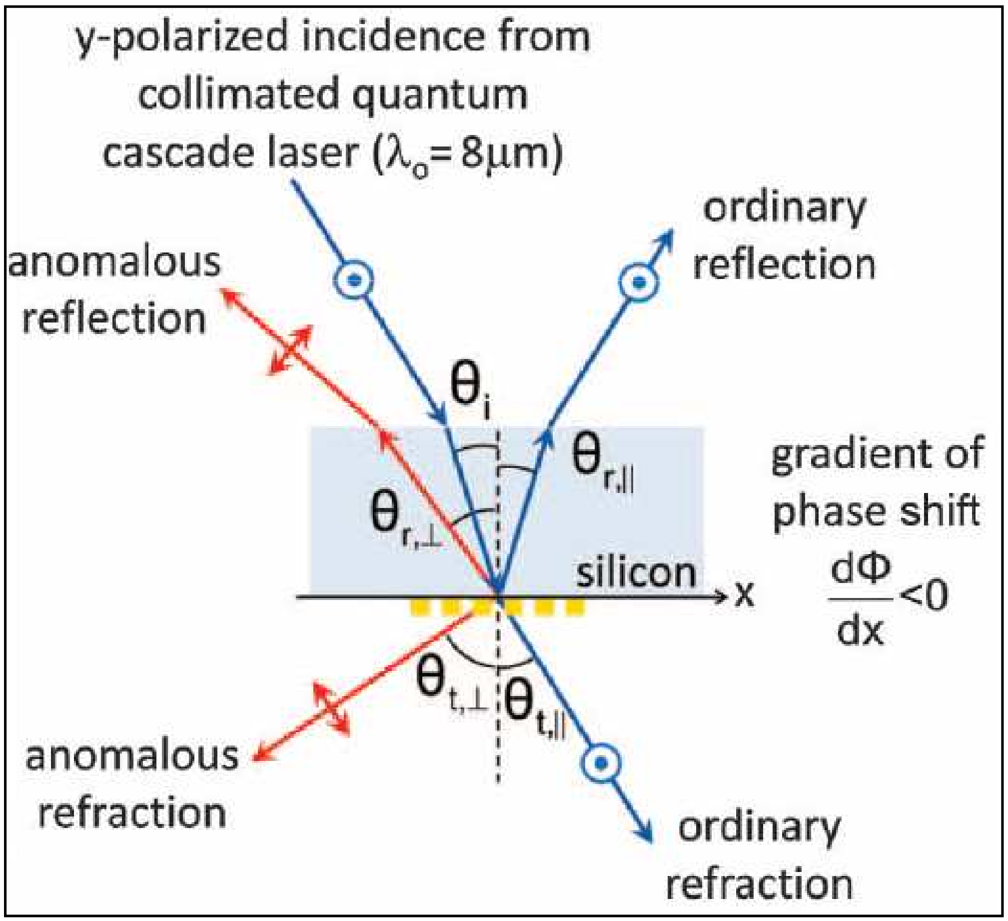
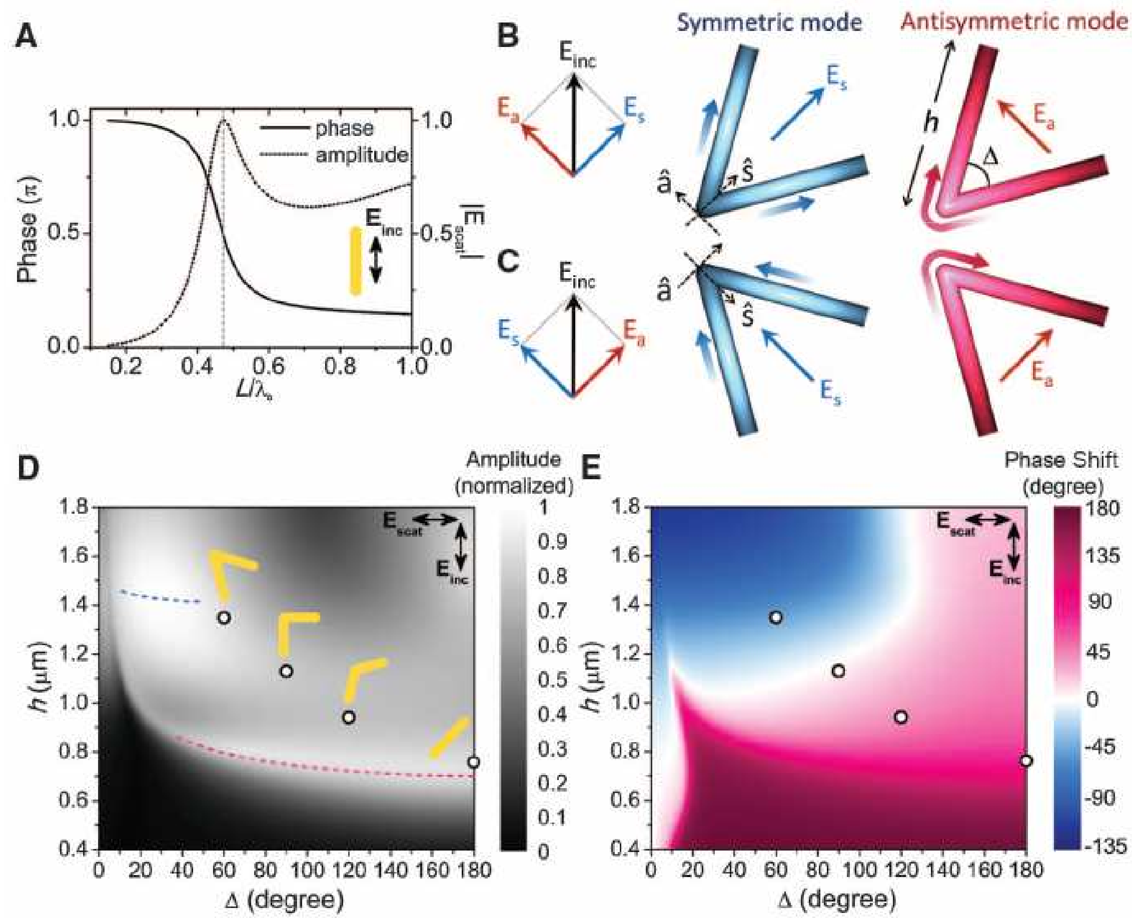


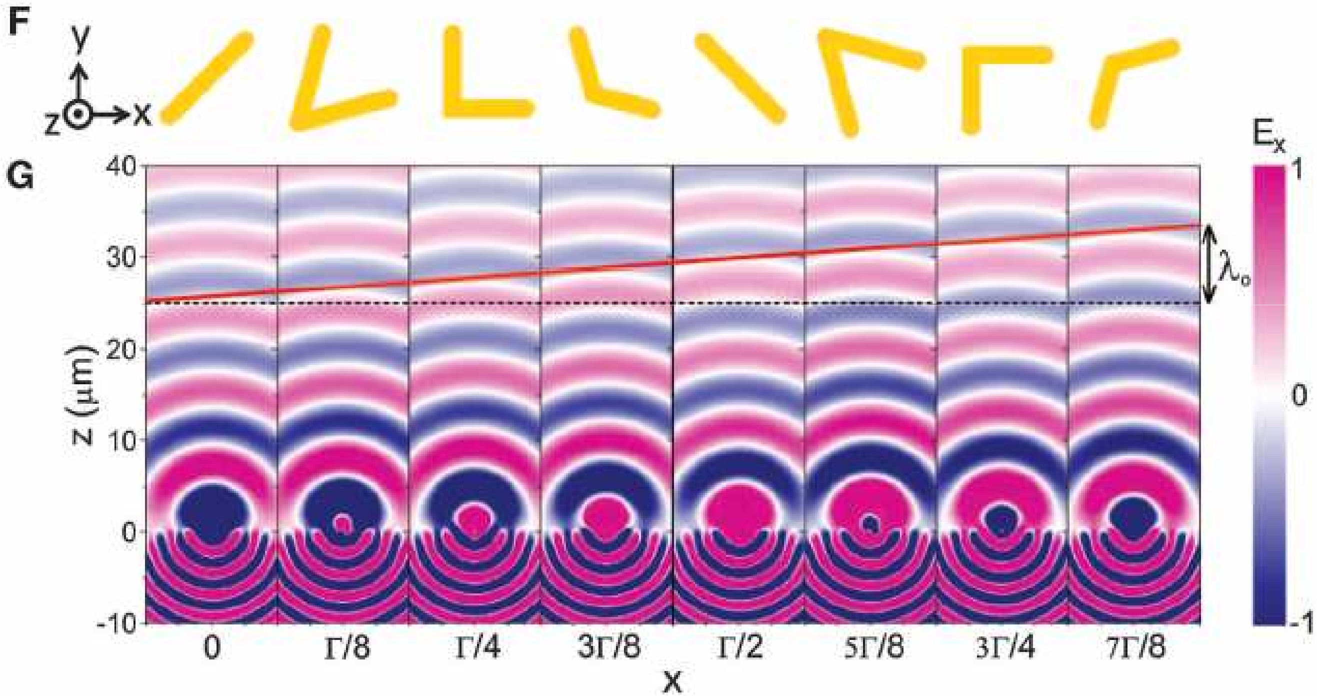


Optical V-antenna

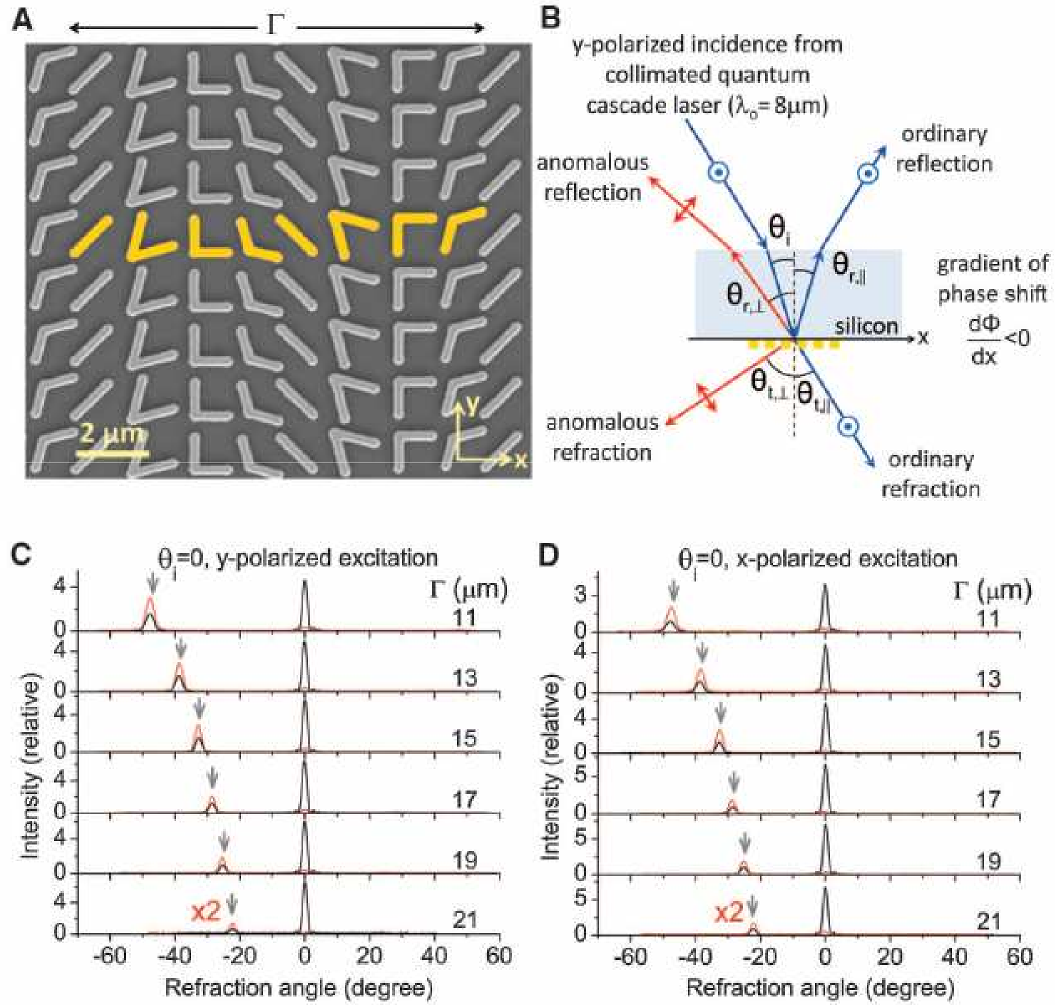
- Symmetric mode excited by E field along ***s***: $h \sim \lambda_{eff}/2$
- Anti-symmetric mode excited by E field along ***a***: $2h \sim \lambda_{eff}/2$
- Incident polarization 45 deg. to ***s*** and ***a***
  - *Study cross polarization*



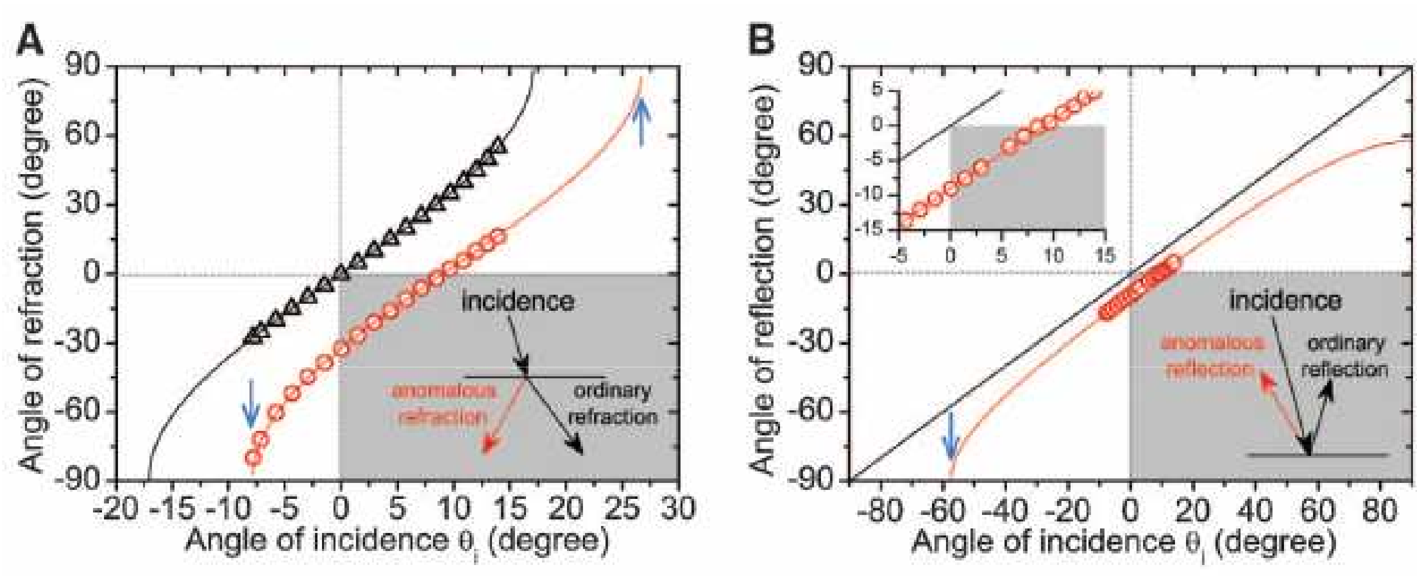
$$\sin(\theta_t)n_t - \sin(\theta_i)n_i = \frac{\lambda_o}{2\pi}\frac{d\Phi}{dx}$$



Anomalous refraction and reflection

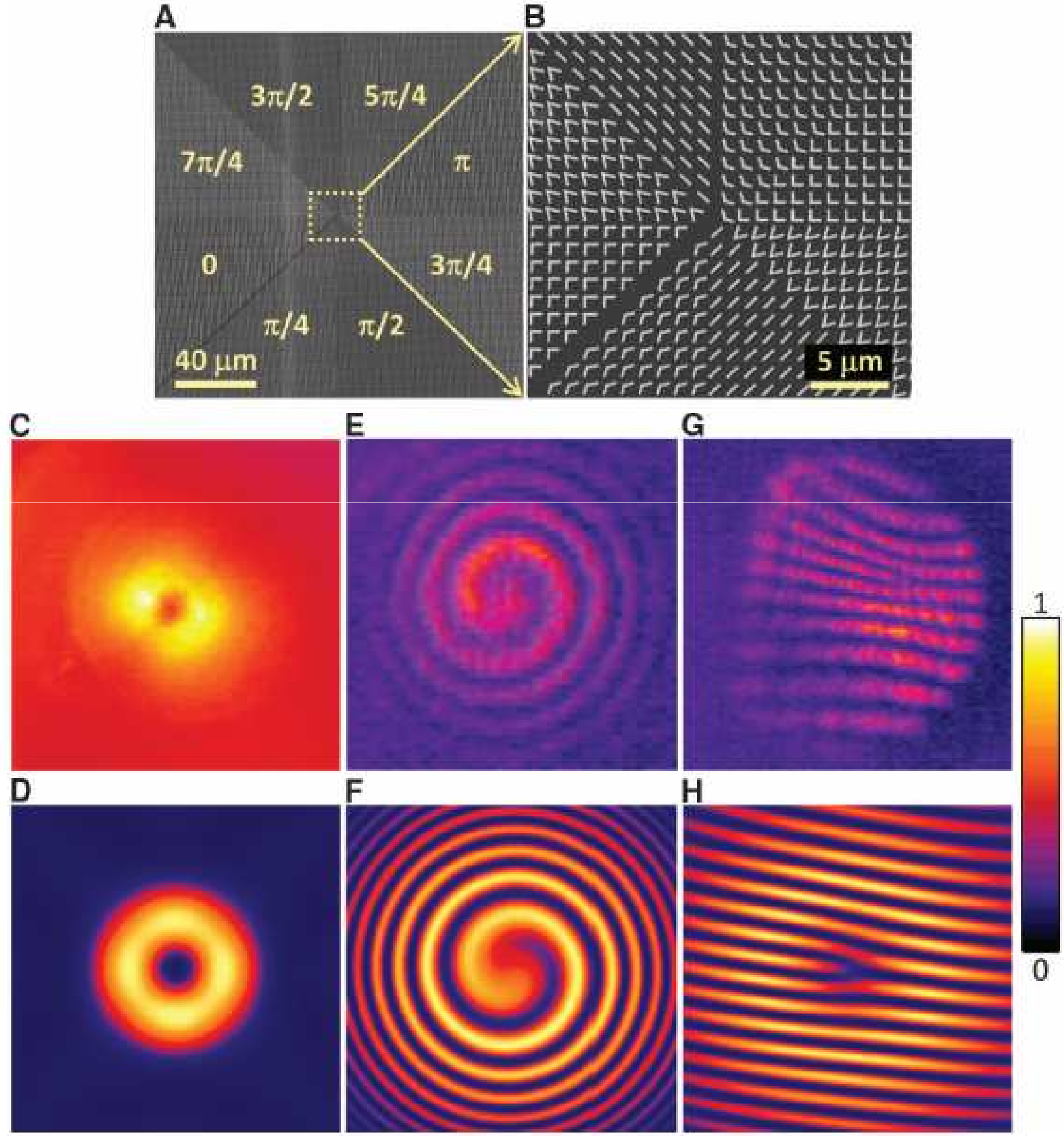


Anomalous refraction and reflection



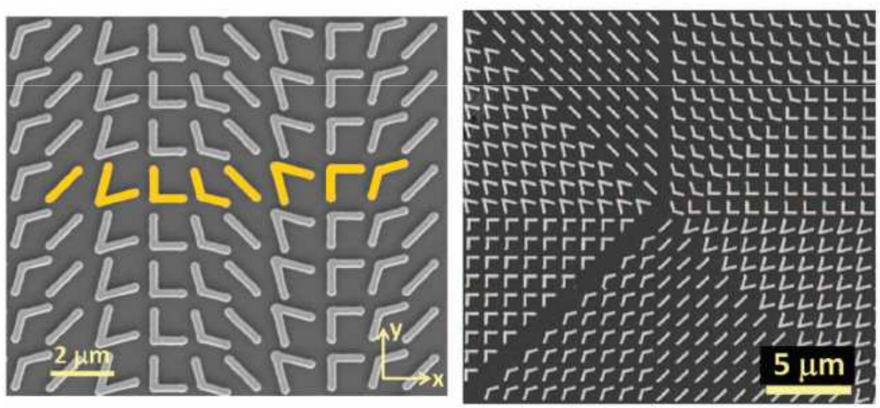
- New critical angles for refraction and reflection

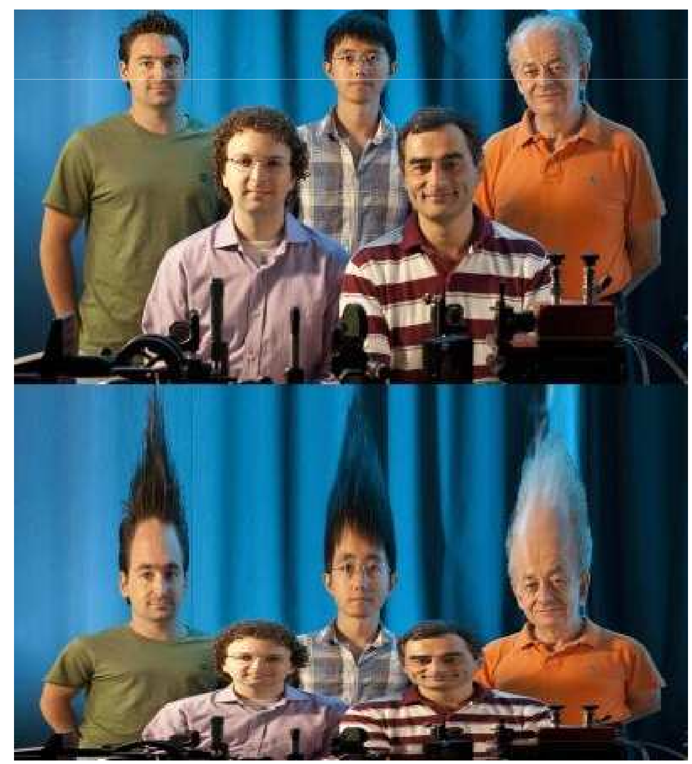
Creation of vortex beams



Summary

- Generalized law for refraction and reflection
  - Includes effects of spatially varying phase discontinuity
- Demonstrated generalized law with a planar meta-material
  - optical properties arise from sub-wavelength structure
- Novel structure for transformation optics
- Expected to revolutionize the fun-house mirror industry





Top, clockwise from left: Patrice Genevet, Nanfang Yu, Federico Capasso, Zeno Gaburro, and Mikhail A. Kats. Bottom: A simulation of the image that would appear in a large mirror patterned with the team's new phase mirror technology. (Credit: Photos by Eliza Grinnell and Nanfang Yu)