# Plasmonics and Metasurfaces for Extreme Manipulation of Light

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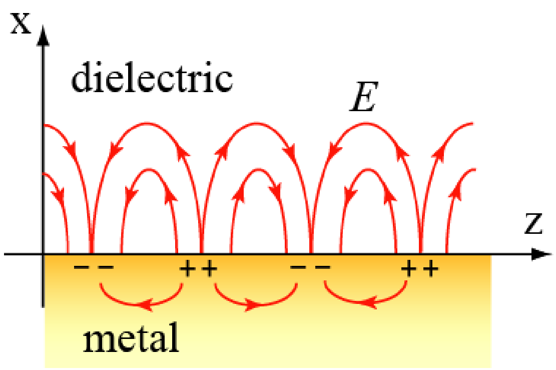
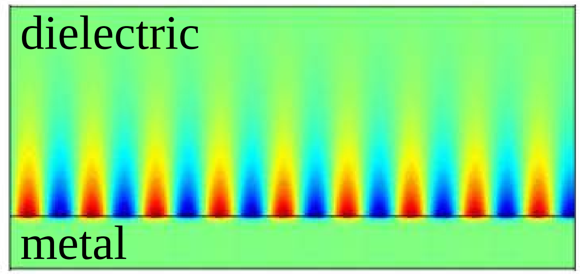
# Outline

- **Introduction to Plasmonics and Metasurfaces**
- **Reconfigurable Plasmonic Lenses in Fluids**
- **Circular Dichroism Metamirror with Perfect Extinction Ratio**
- **Hyperbolic Metasurfaces to Control Surface Plasmons**
- **Conclusions**

# Surface Plasmon Polaritons

Plasmonics focuses on the novel properties and applications of **Surface Plasmon Polaritons** (SPP), which are collective electron oscillations coupled with light.



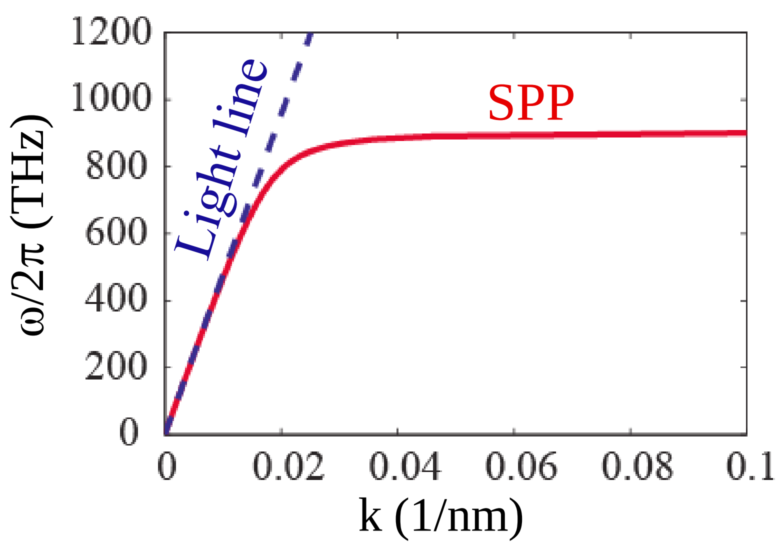

SPP dispersion relation:

$$k_{SPP} = \frac{\omega}{c}\sqrt{\frac{\varepsilon_d \varepsilon_m}{\varepsilon_d + \varepsilon_m}}$$

$$k_{SPP} > k_{dielectric}$$

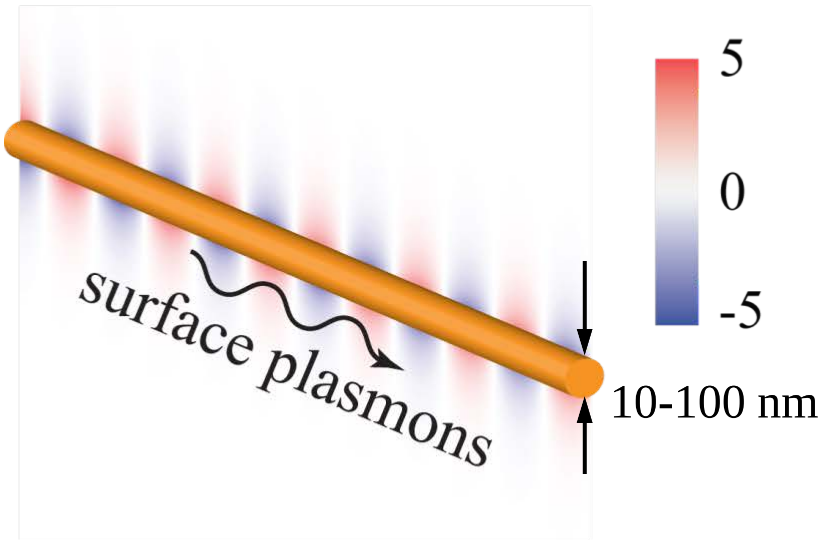
⬇

$$\lambda_{SPP} < \lambda_{dielectric}$$

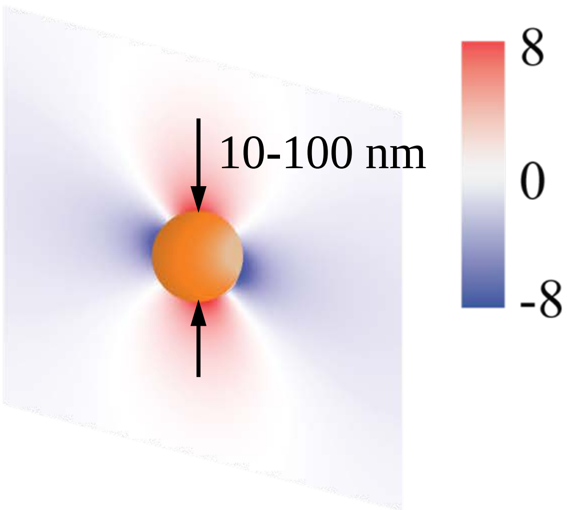


# Localized Surface Plasmon Polaritons

metallic nanowire




metallic nanoparticle




**Unique properties:**

- Tight field confinement (beyond the diffraction limit)
- Strong field enhancement
- Tunability arising from geometry and dielectric environment

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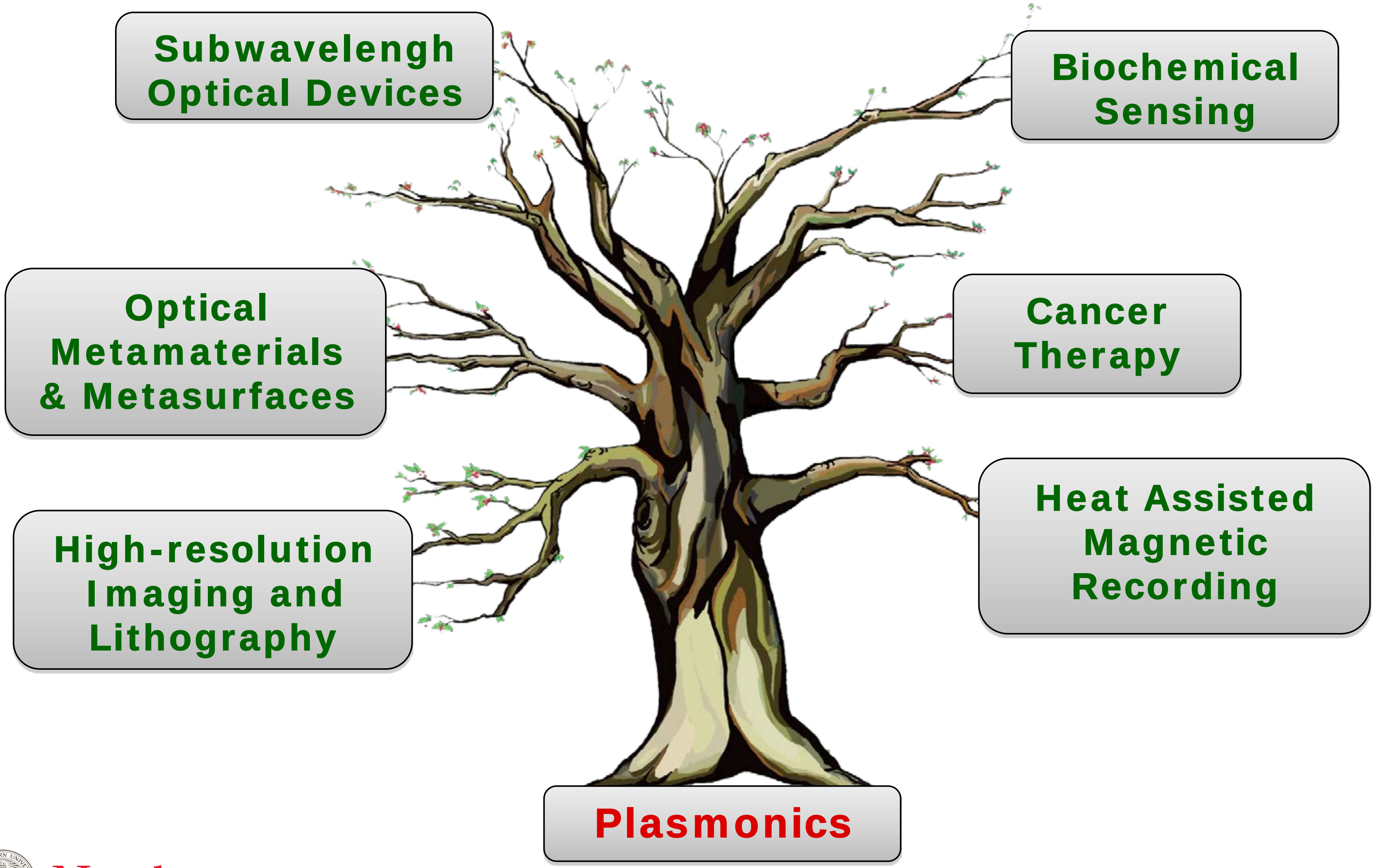
*K. Yao and Y. M. Liu, Nanotech. Reviews. 3, 177 (2014)*

# Various Applications of Plasmonics

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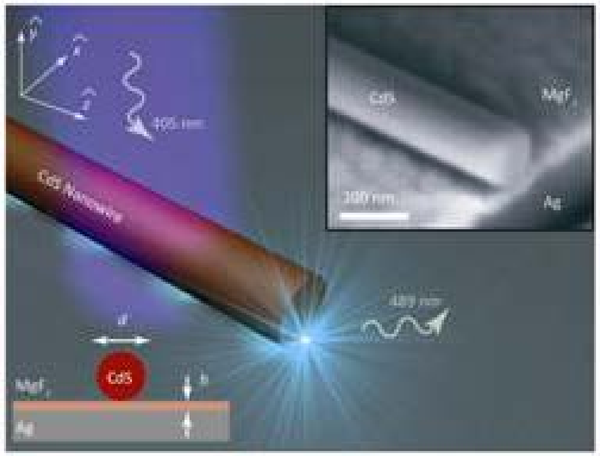
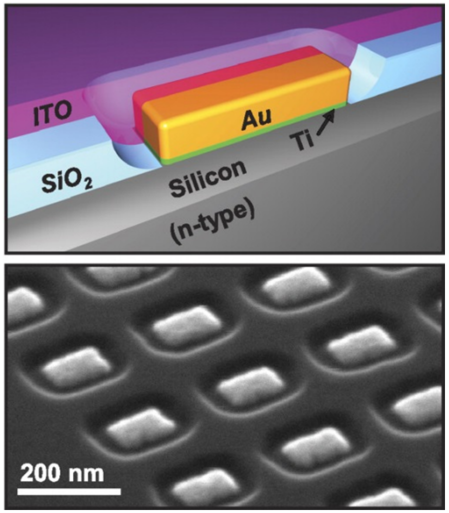
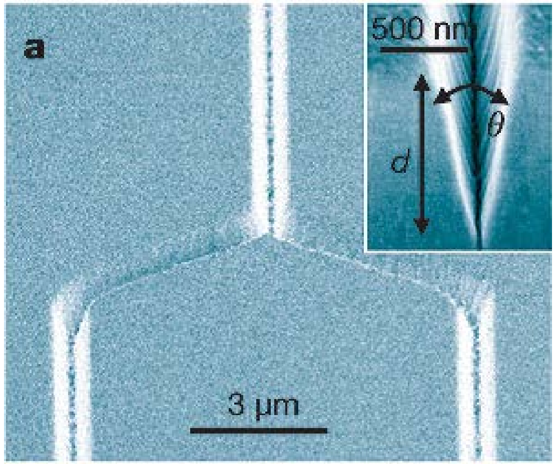
# Novel Plasmonic Elements



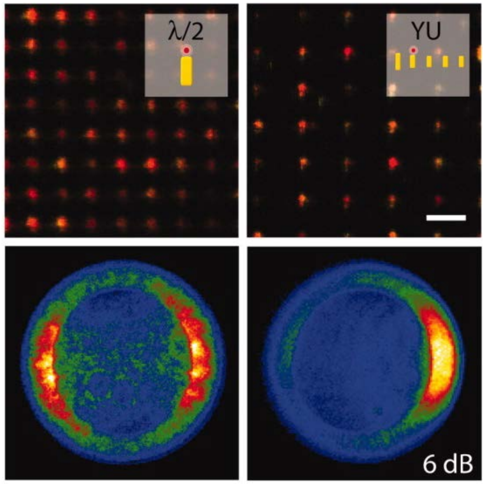

Plasmonic Nano Laser: Nature 460, 1110 (2009); Nature 461, 629 (2009)




Plasmonic Photodetector: Nature Photonics 2, 226 (2008); Science 332, 702 (2011)

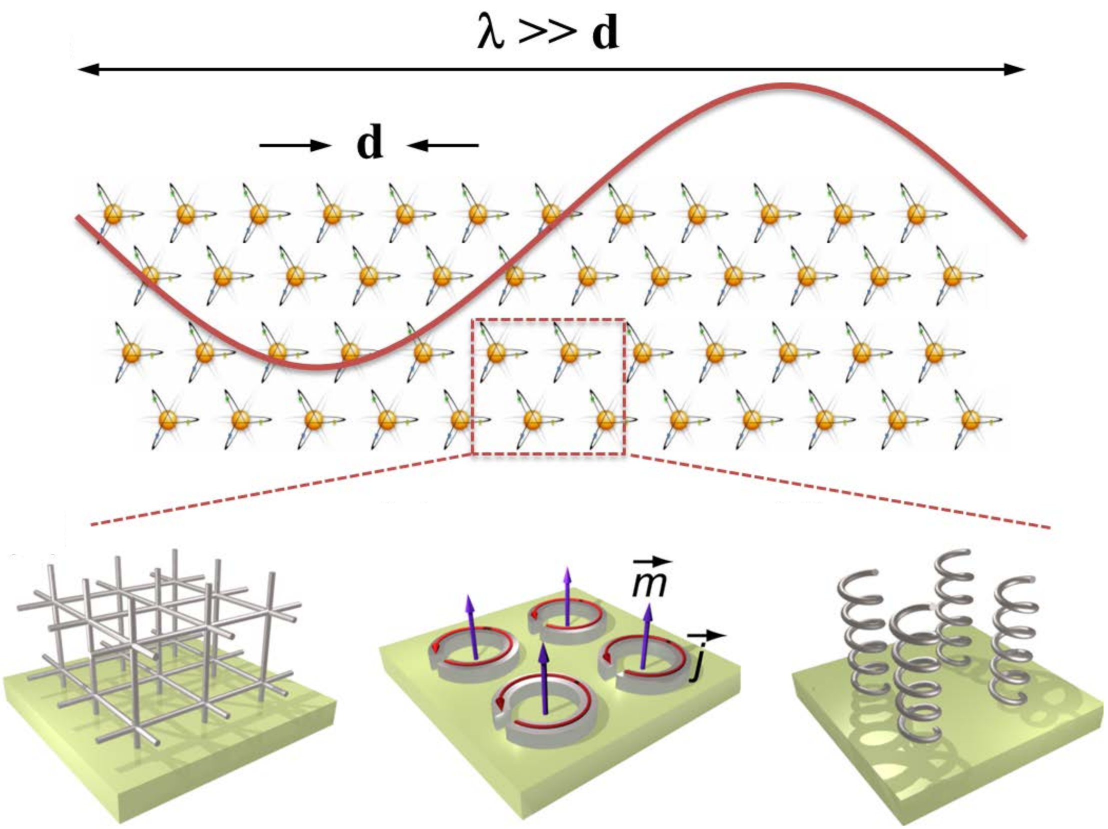



Plasmonic Waveguide: Nature 440, 508 (2006); Nature Photonics 2, 496 (2008)




Plasmonic Antenna: Science 308, 1607 (2005); Science 329, 930 (2010)

# Metamaterials: beyond Natural Materials




- Metamaterials are artificial composite materials with engineered “atoms”.
- The size and spacing of the unit cell are much smaller than the wavelength.
- Effective material properties can be defined, which are primarily dependent on the structure, rather than the chemical constituent.

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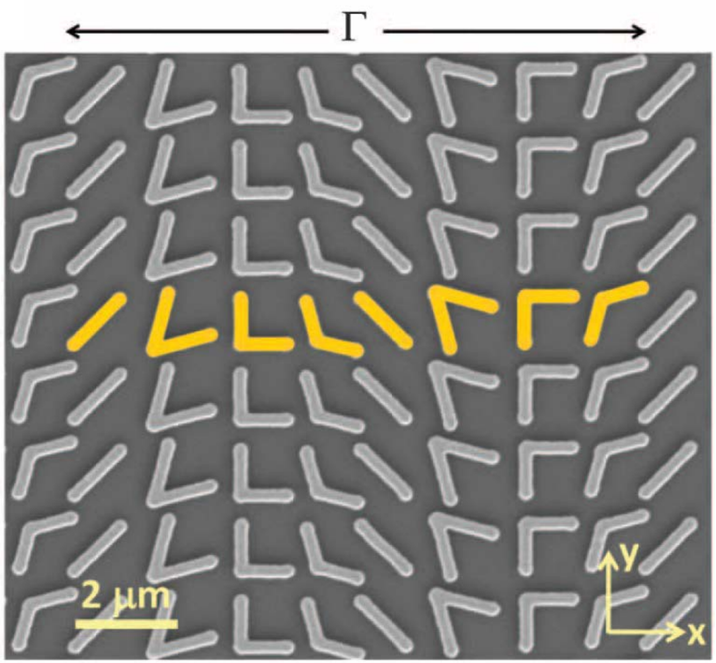
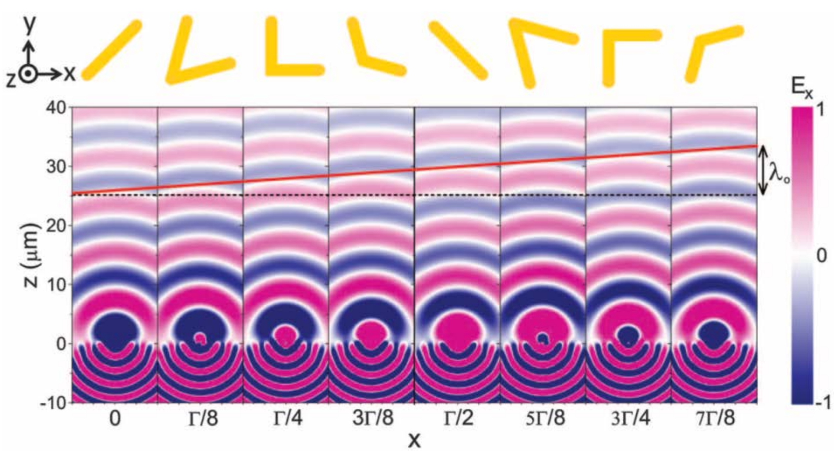
*Liu and Zhang, Chemical Society Reviews 40, 2494 (2011)*

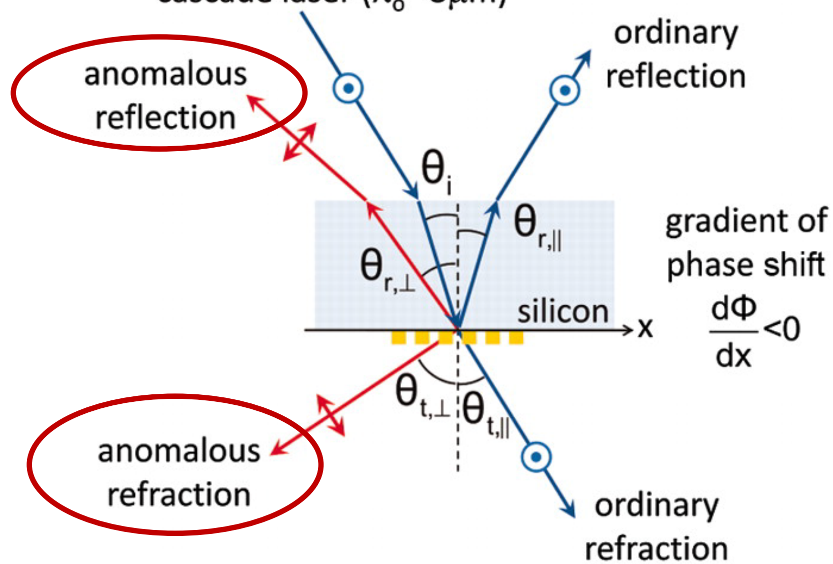
# Metasurfaces: A New Class of 2D Metamaterials




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

Reflection: $$\sin(\theta_r) - \sin(\theta_i) = \frac{\lambda_o}{2\pi n_i}\frac{d\Phi}{dx}$$




*N. F. Yu et al., Science 334, 333 (2011);*
*X. J. Ni et al., Science 335, 427 (2011)*

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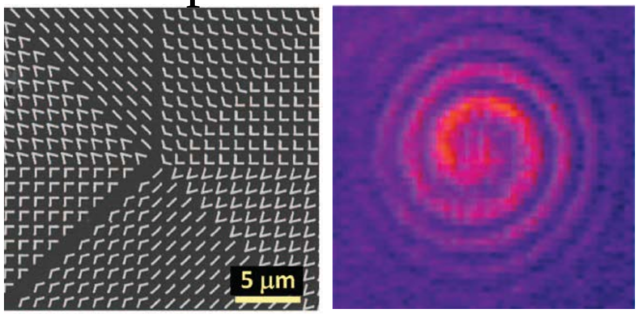
# Novel Applications based on Metasurfaces

## Optical Lenses

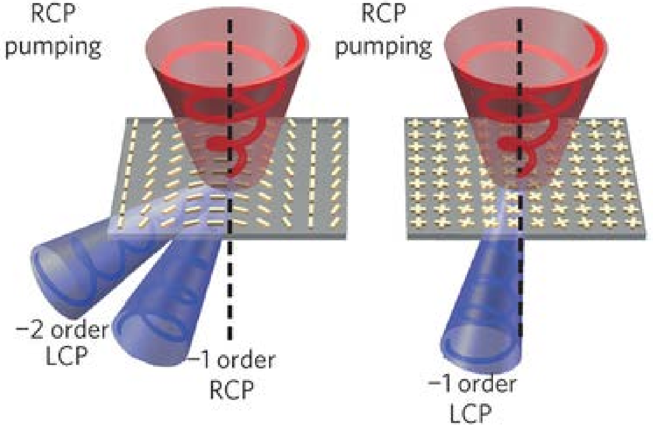



*Science 334, 333 (2011); Nature Commun. 3, 1198 (2012); Science, 345, 298, (2014)*

## Hologram


*Nature Commun. 4, 2807 (2013); Nature Commun. 4, 2808 (2013)*

## Nonlinear Optics




*Nature Materials 14, 607 (2015)*

**Advantages:**
- planar platform, hence ideal for integration
- low loss

*Review: Science 339, 1232009 (2013); Nature Materials 13, 139 (2014)*

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# Directional Surface Plasmon Source

SEM Image

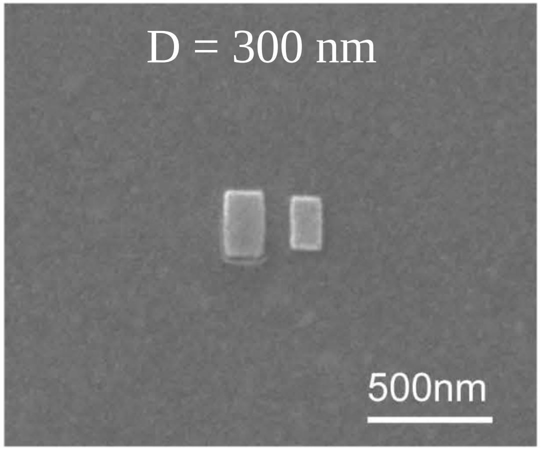
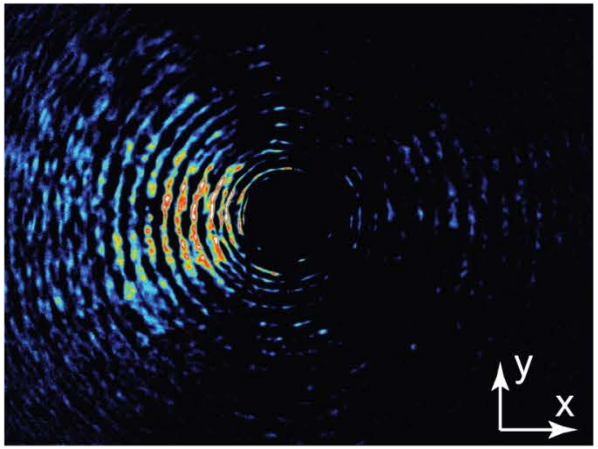
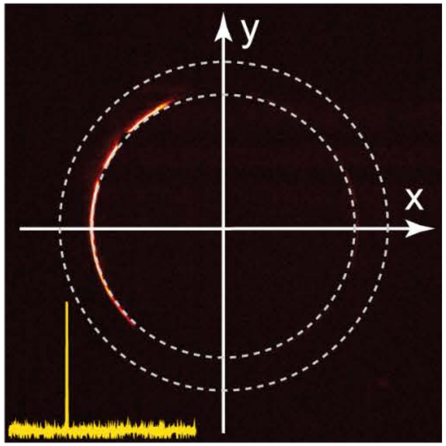



Image Plane

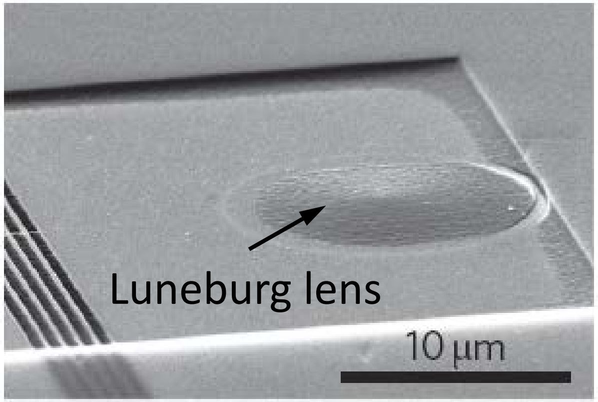


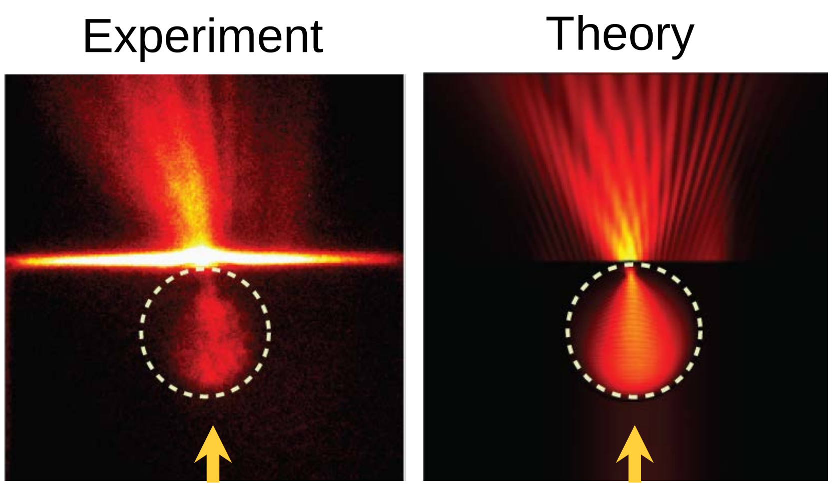

Fourier Plane




*Y. M. Liu et al., Nano Lett., 12, 4853 (2012)*

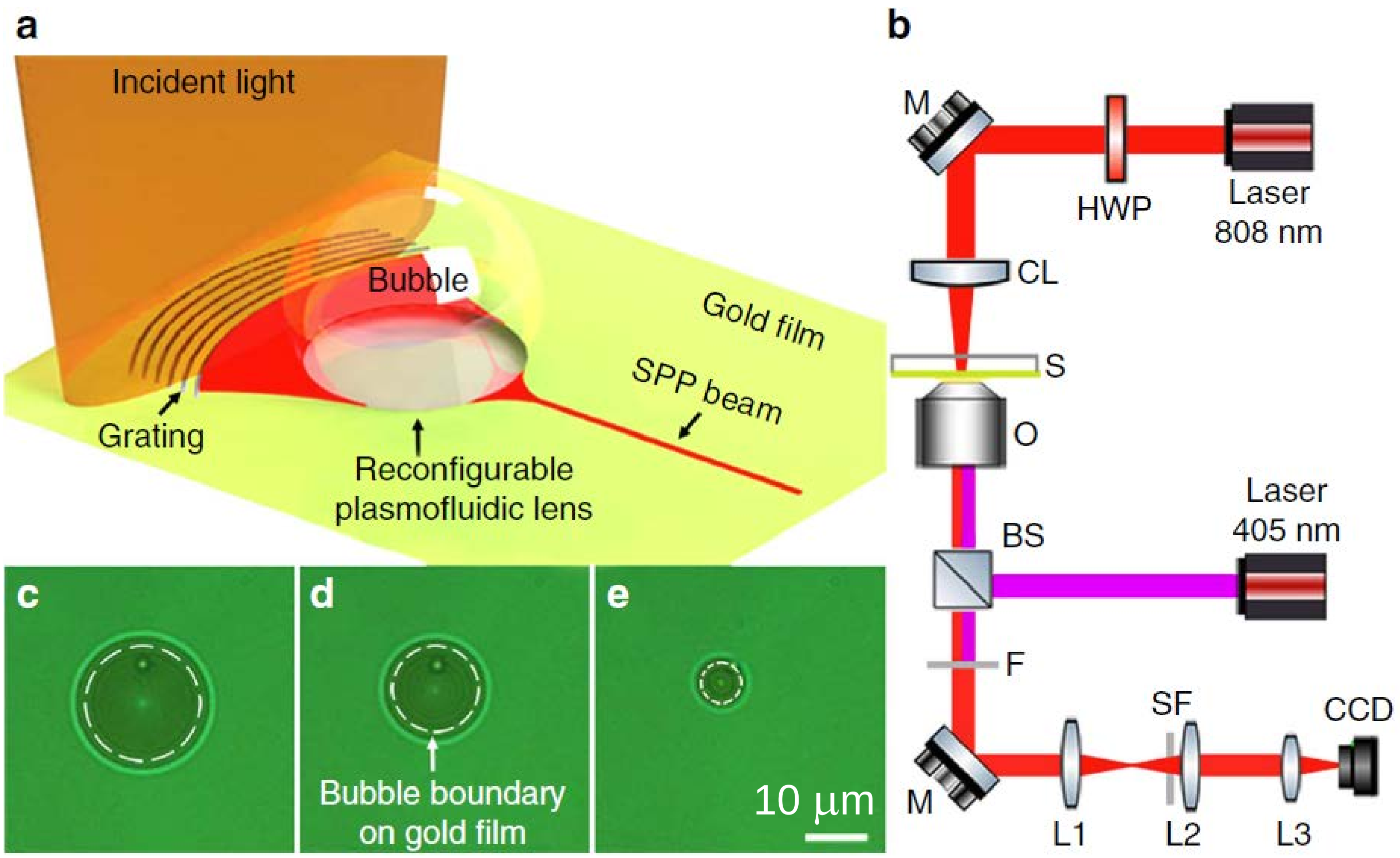
# Plasmonic Luneburg and Eaton Lenses




*Y. M. Liu et al., Nano Letters 10, 1991 (2010);*
*T. Zentgraf et al., Nature Nanotech. 6, 151 (2011)*

# Reconfigurable Plasmofuidic Lenses

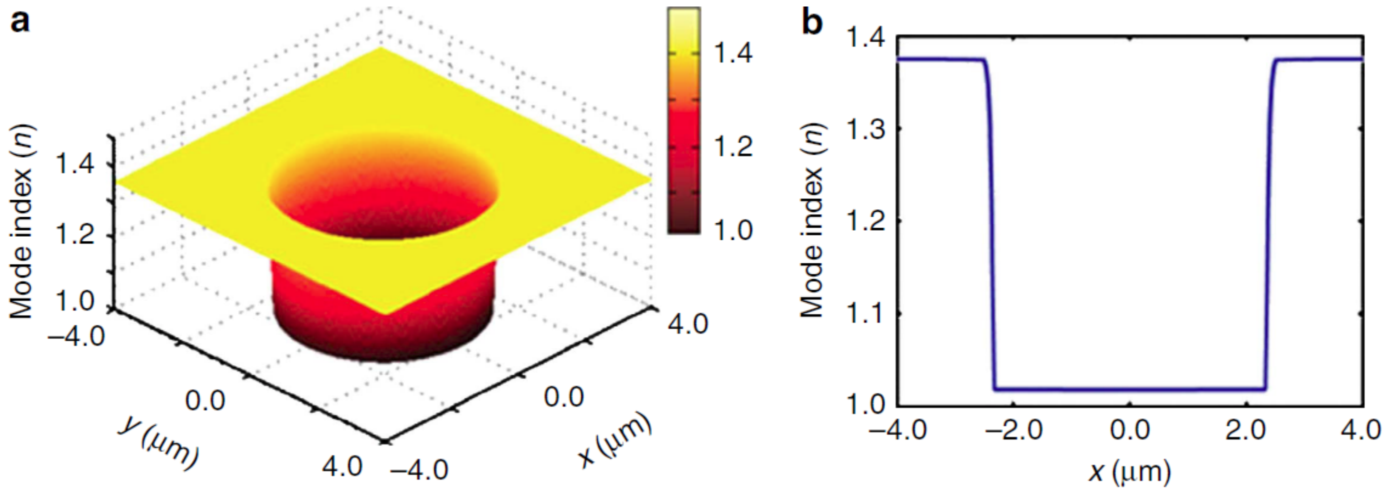



- Combining plasmonics with microfluidics enables reconfigurable plasmofluidic devices for multiple functionalities
- Laser induced surface bubbles function as reconfigurable lenses to dynamically control the propagation of SPPs

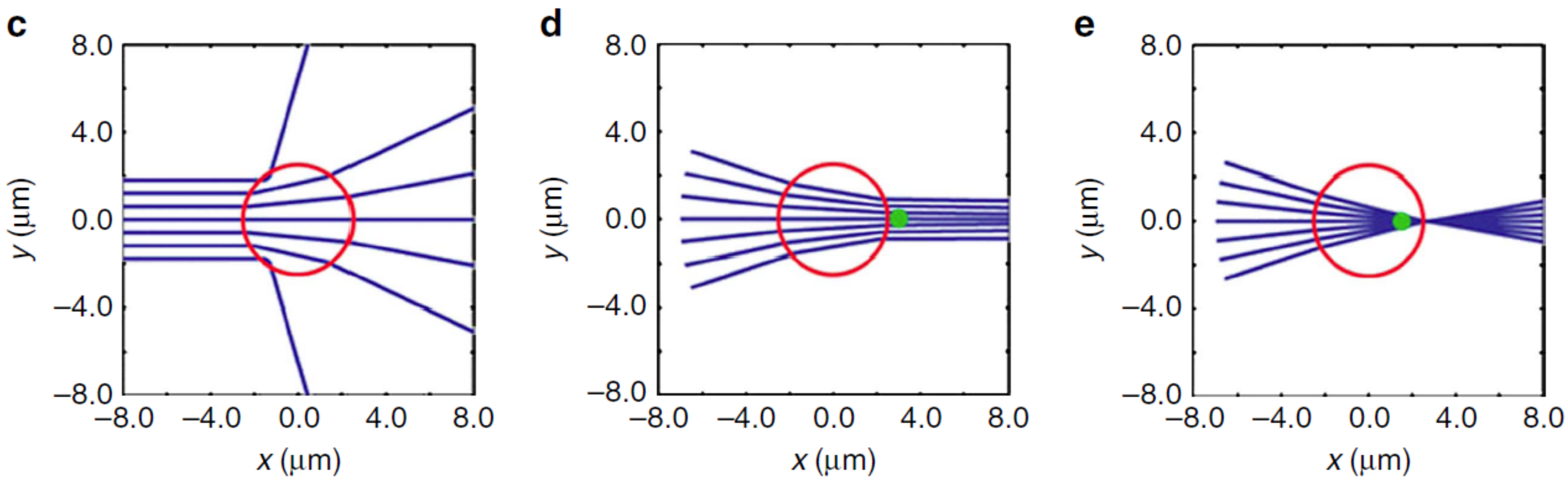
*C. L. Zhao et al., Nature Comm. 2305 (2013)*

# Functions of the Plasmofuidic Lens

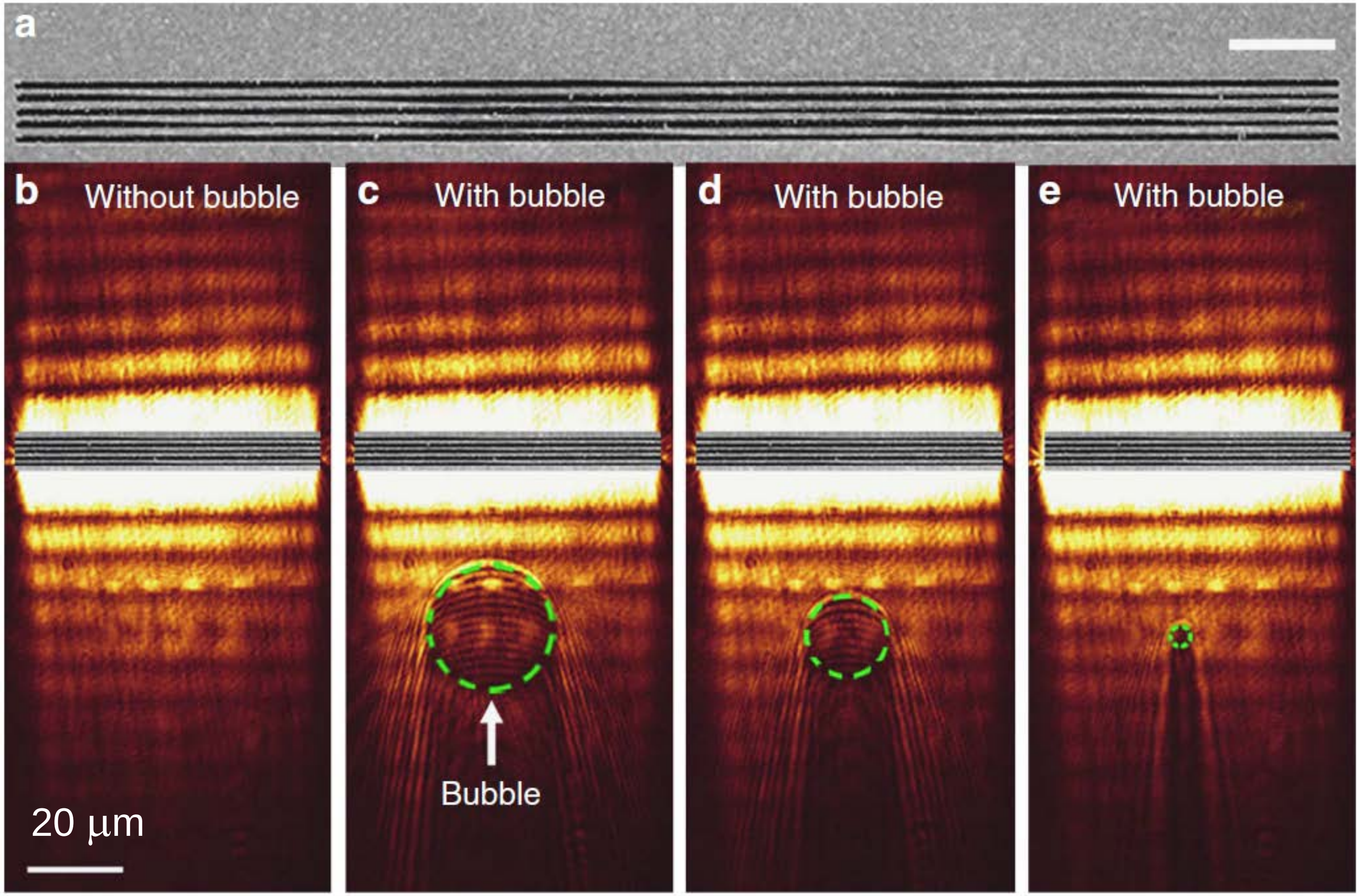
Mode index profile




Ray tracing results



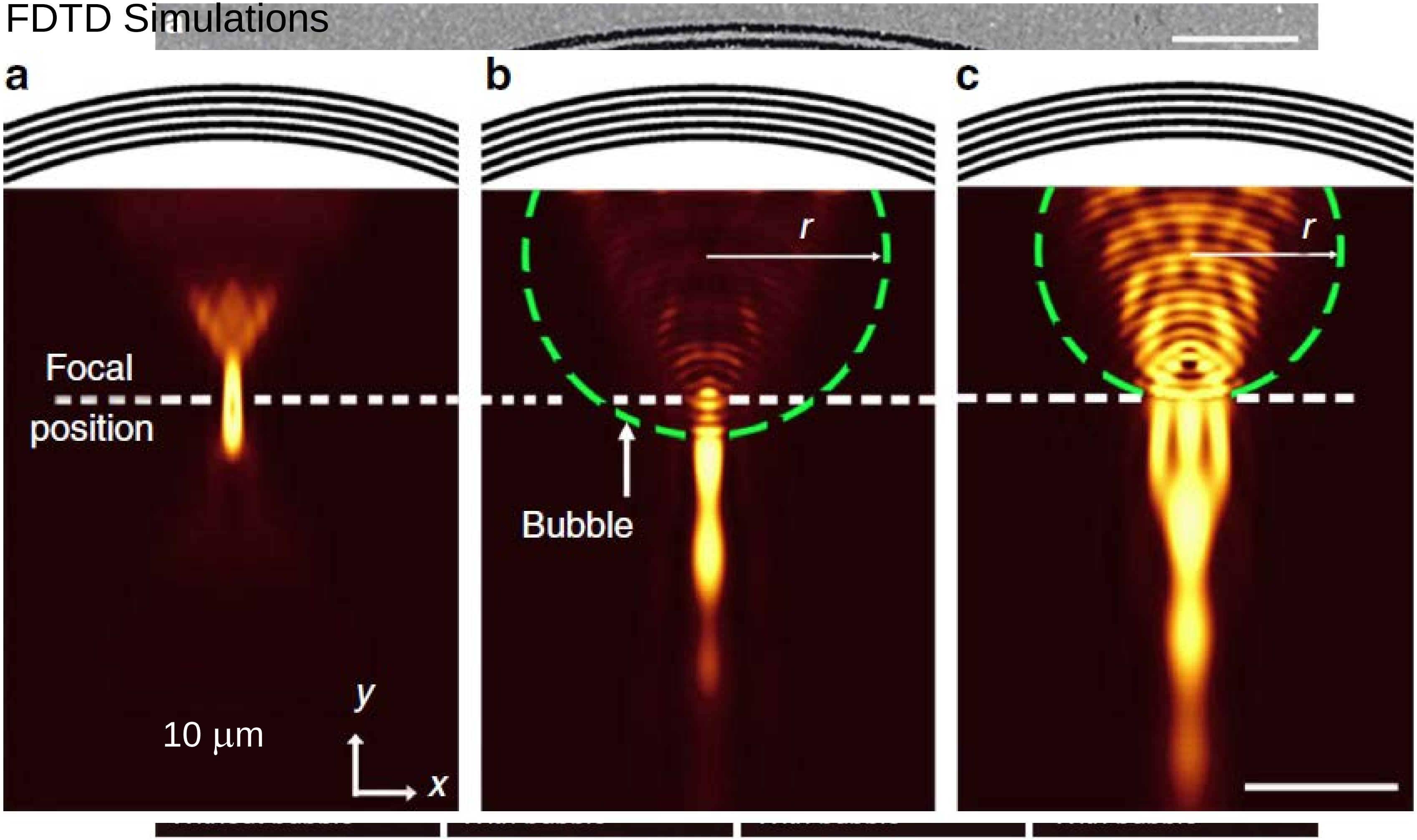
# Divergence of SPPs




*C. L. Zhao et al., Nature Comm. 2305 (2013)*

# Focusing and Collimation of SPPs

FDTD Simulations




*C. L. Zhao et al., Nature Comm. 2305 (2013)*

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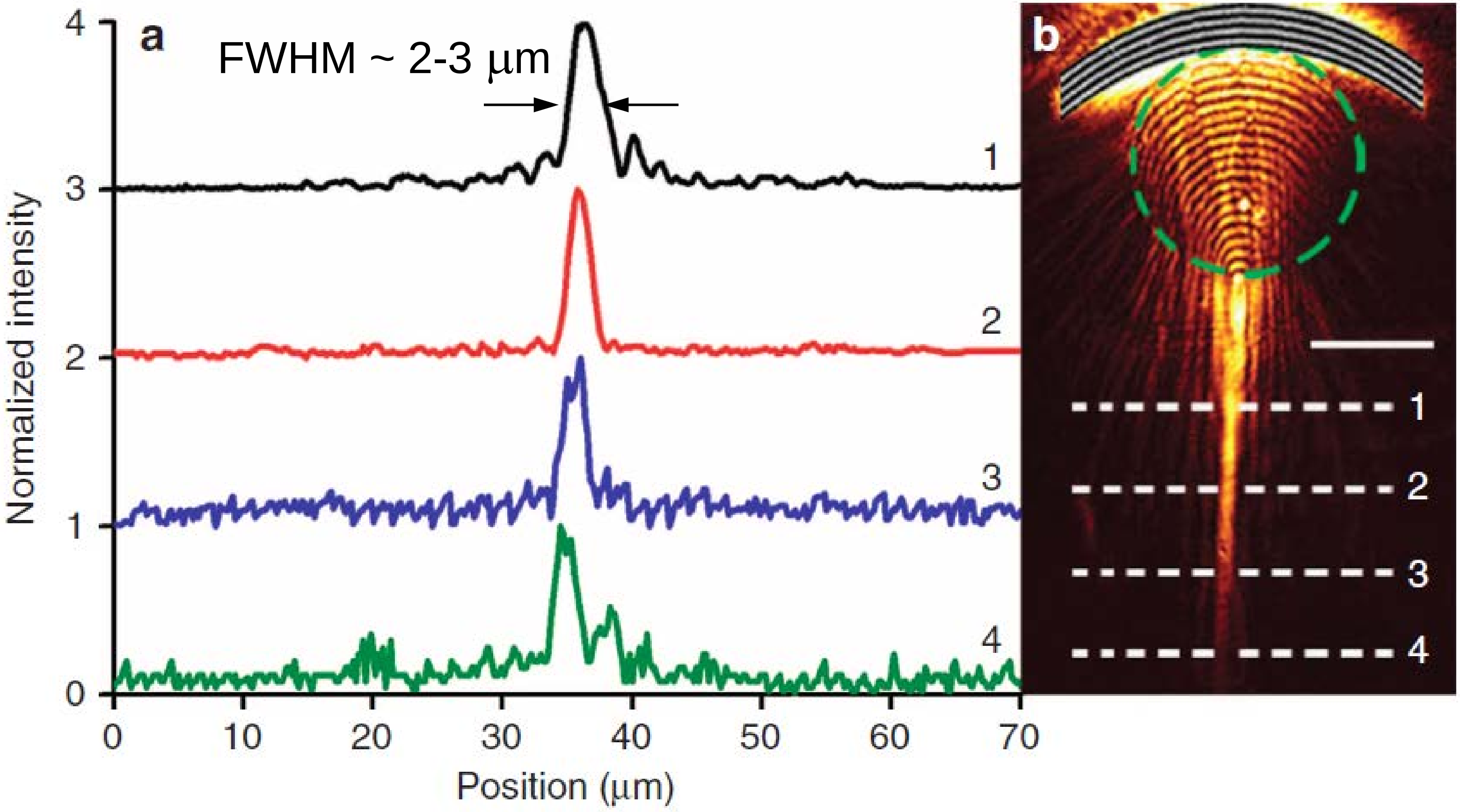
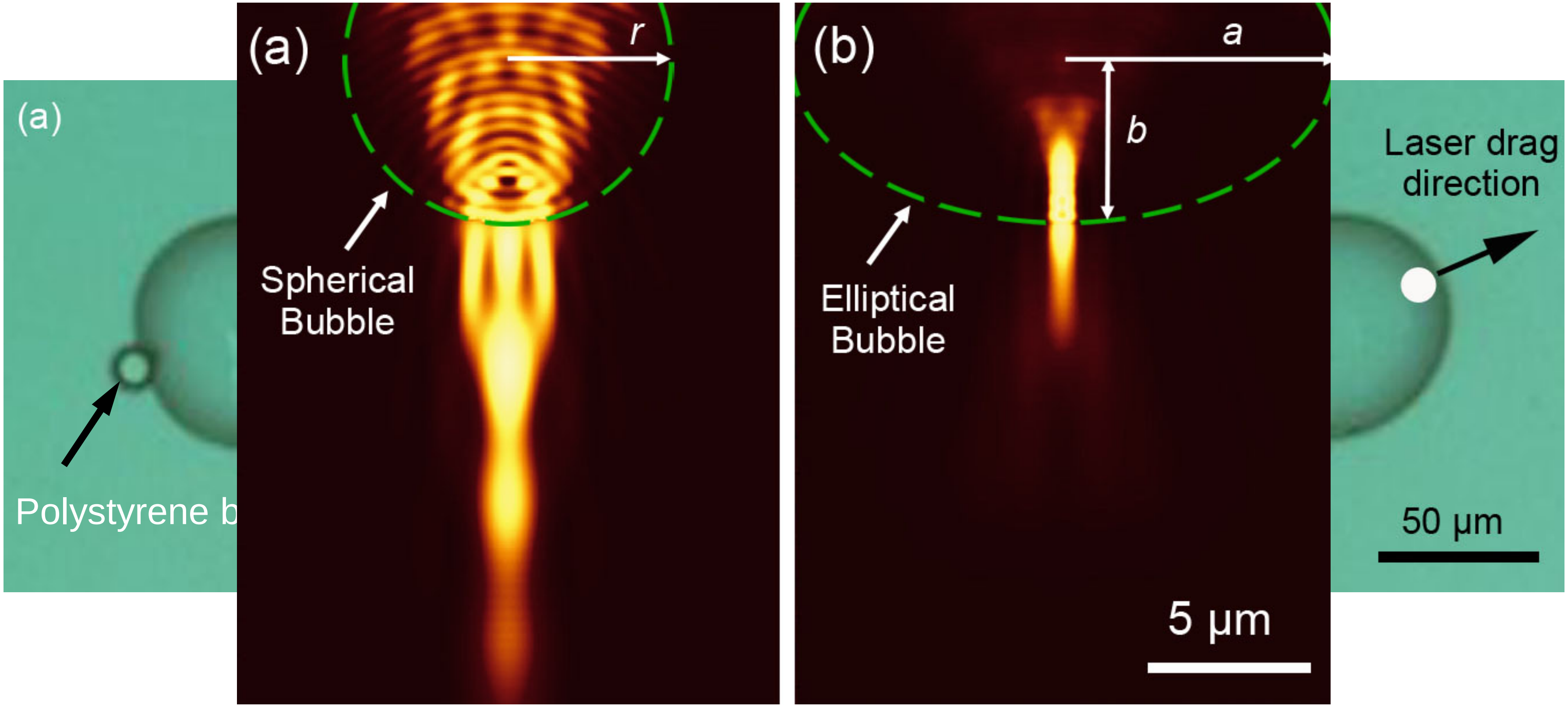
# Collimated Surface Plasmon Beam

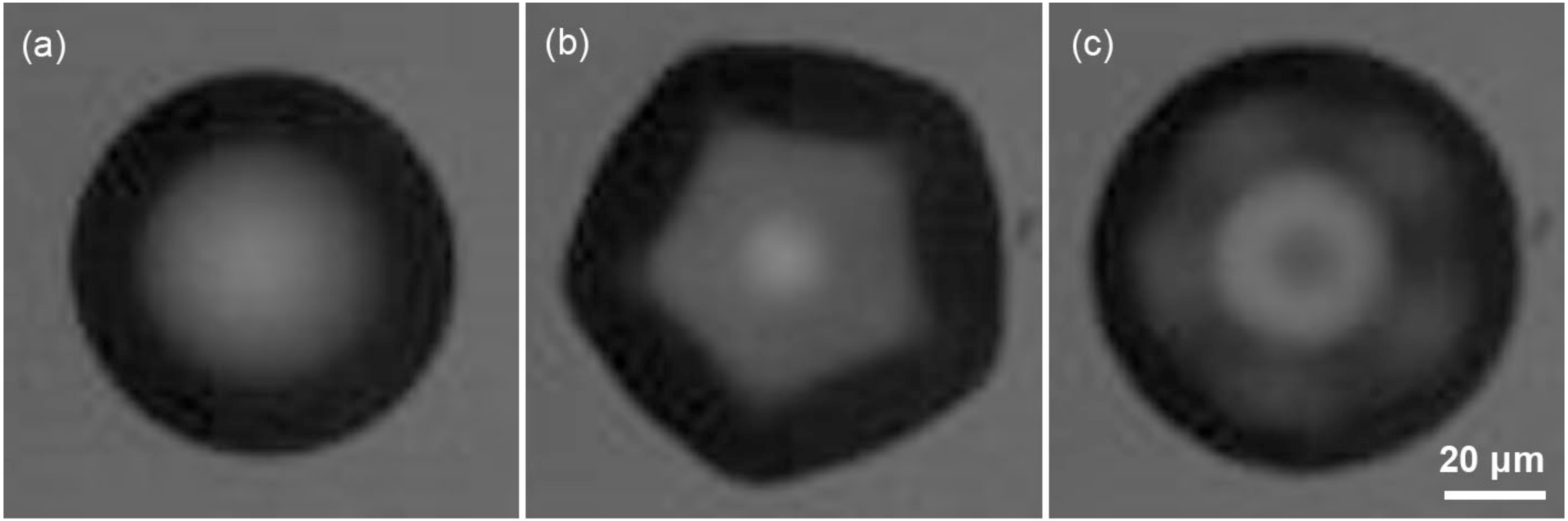



The collimated surface plasmon beam shows small divergence even for 40 μm propagation distance. The FWHM is well maintained about 2-3 μm.

# Non-spherical Surface Bubbles



# Non-spherical Surface Bubbles (cont'd)




Acoustic Wave Off Acoustic Wave On

A piezo transducer (bonded to the sample surface) was actuated to generate acoustic waves. The bubble oscillates near the 5th harmonic mode.

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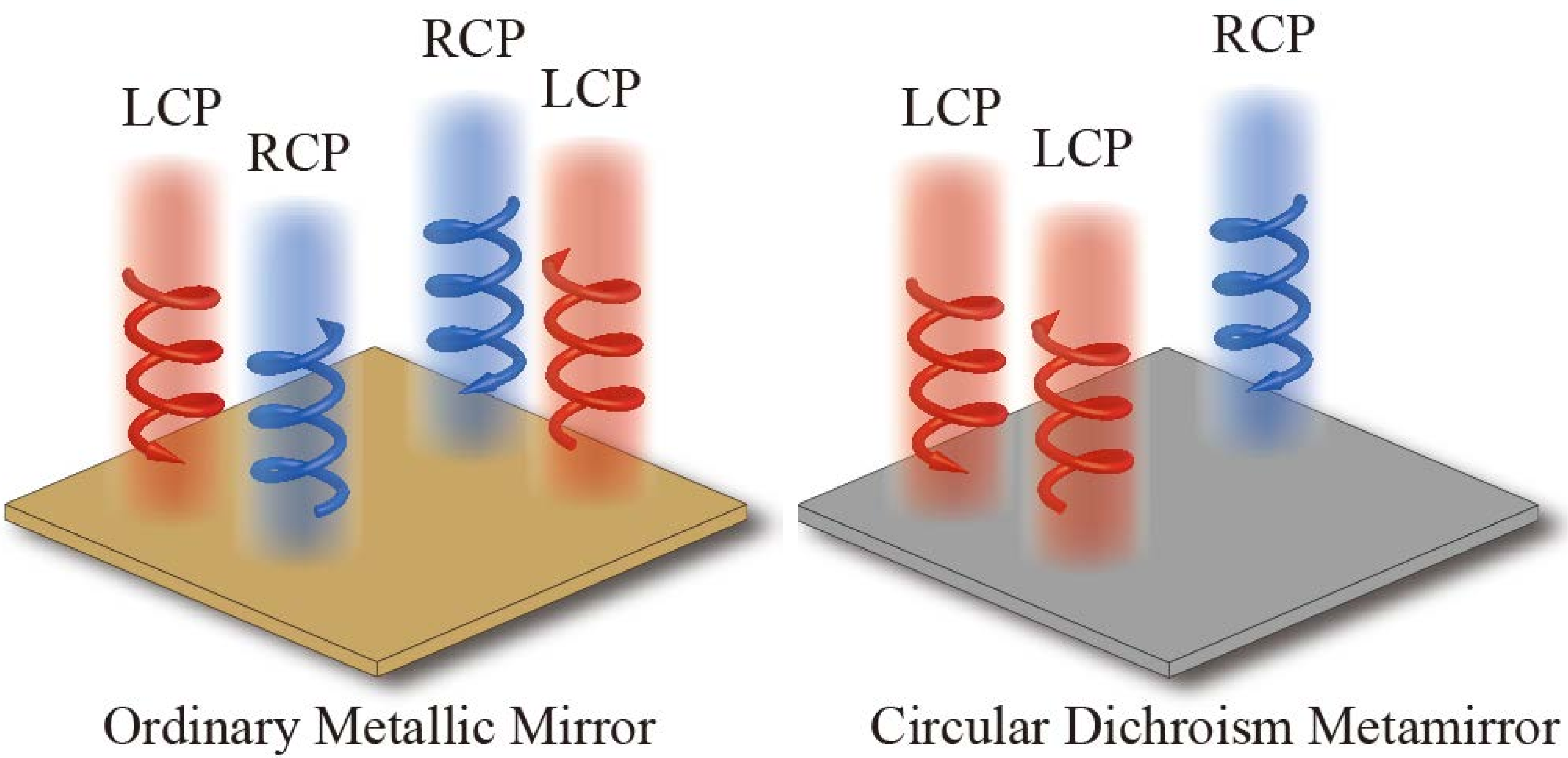
# Reflection from Mirrors

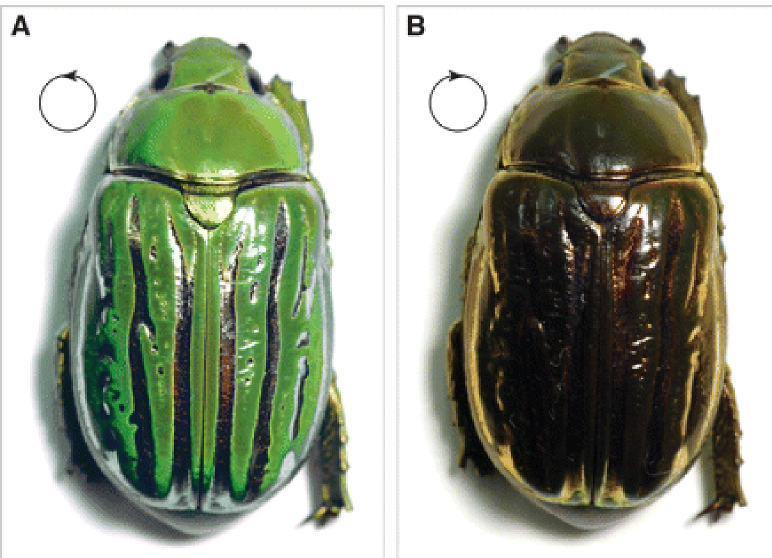


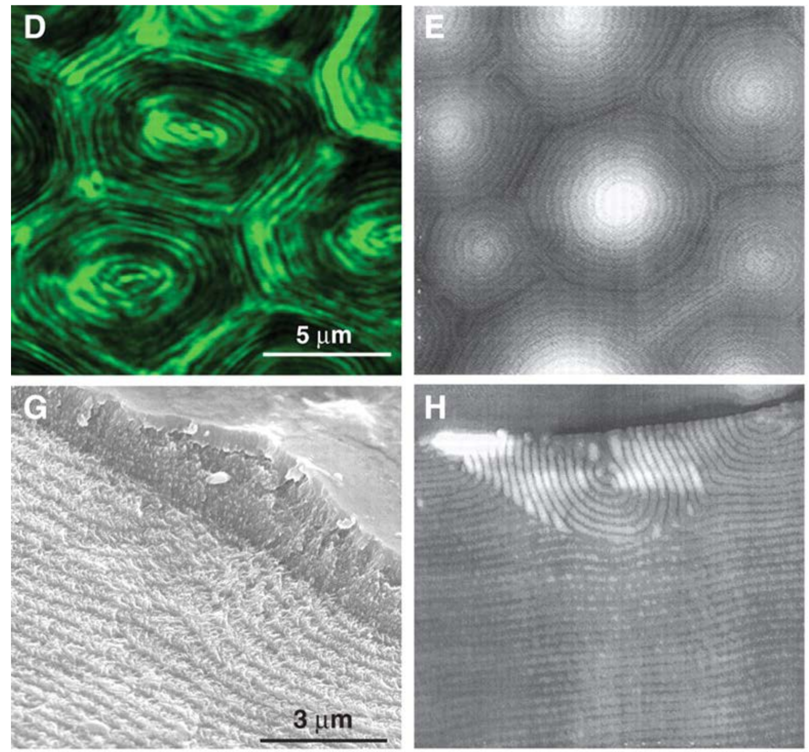

Circularly polarized light reverses its helicity upon reflection from a normal metallic mirror. For large incident angles, the reflected light becomes elliptically polarized.

Can we design circular dichroism metamirror to selectively reflect desired circularly polarized light and maintain its helicity?

# Circular Dichroism (CD) Mirrors from Nature

LCP illumination RCP illumination



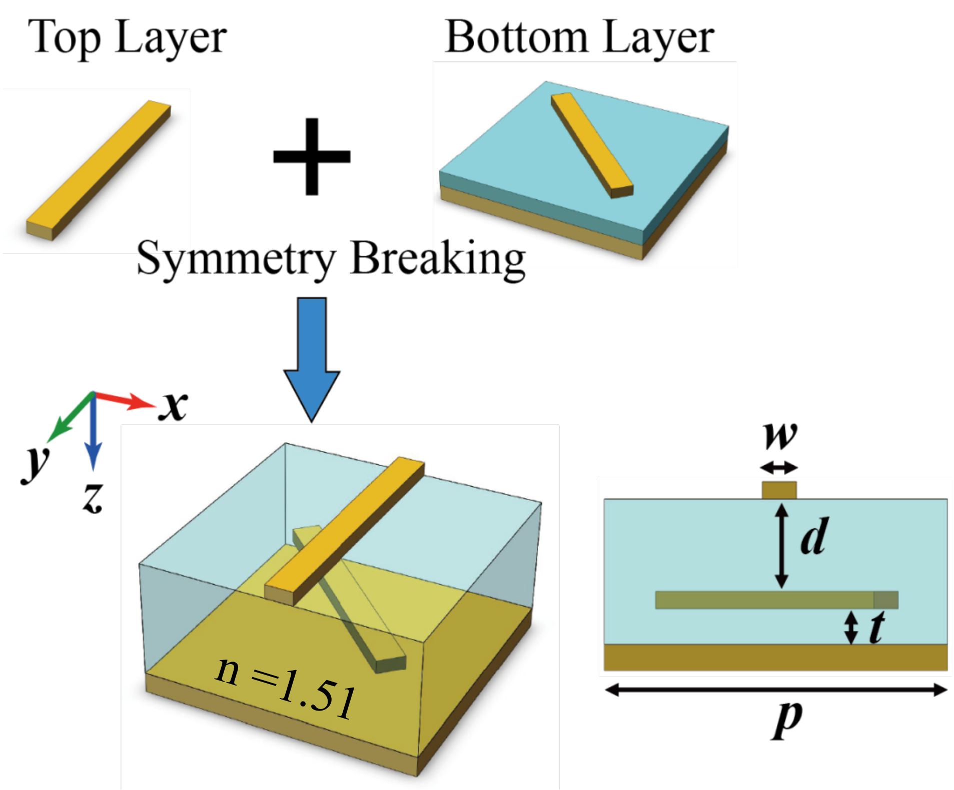

- The beetle C. gloriosa derives distinct iridescence under LCP and RCP illumination.
- The optical effect arises from the complex structure of the exoskeleton.
- Moreover, the reflection contrast is not high (about 40% for LCP, 5% for RCP).

*V. Sharma et al., Science 325, 449 (2009)*

# Requirement of Structural Symmetry

Through rigorous analyses based on Jones calculus, we find the general structural requirement for CD metamirrors:

Simultaneous breaking of the *n*-fold rotational (*n* >2) and mirror symmetries

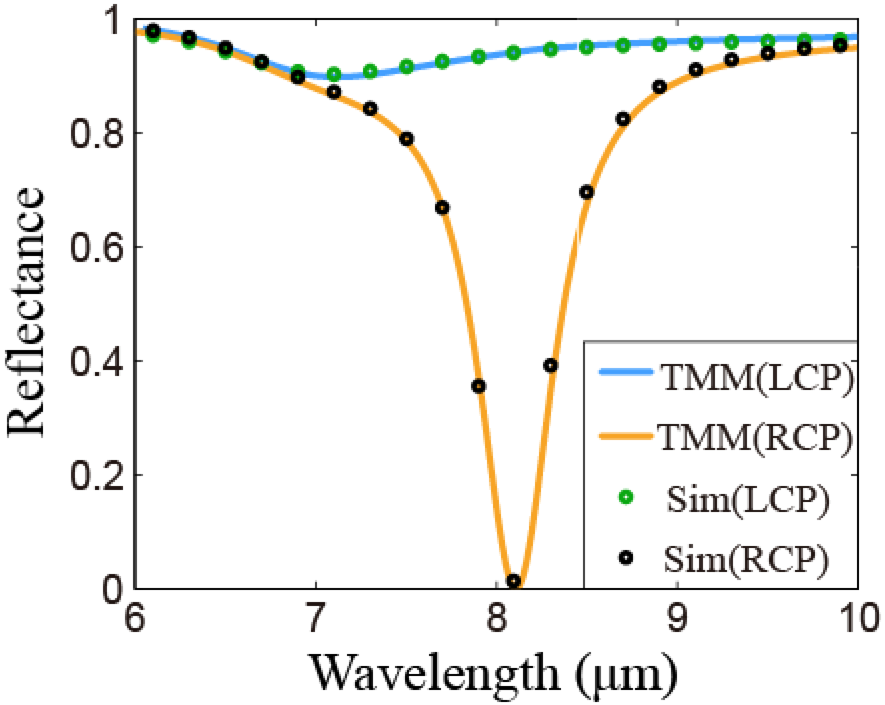



$p$ = 2.5 μm
$t$ = 0.09 μm
$d$ = 2.5 μm
$w$ = 2.5 μm



*Z. J. Wang et al., arXiv:1506.00971, under review*

# Simulated Optical Response of the CD Metamirror

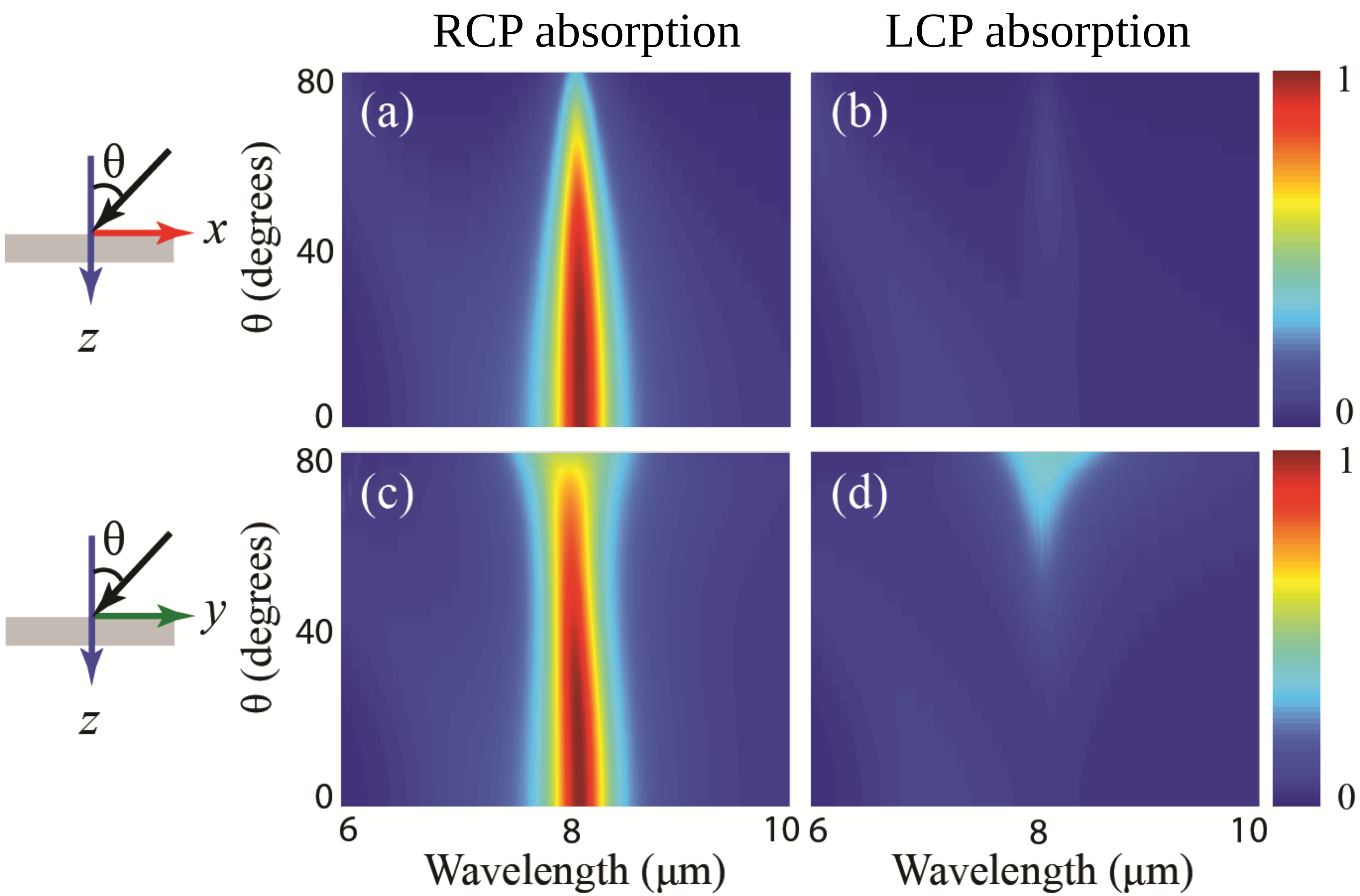



Reflection is 94.7% for LCP light, while only 0.7% for RCP light at 8.1 μm wavelength



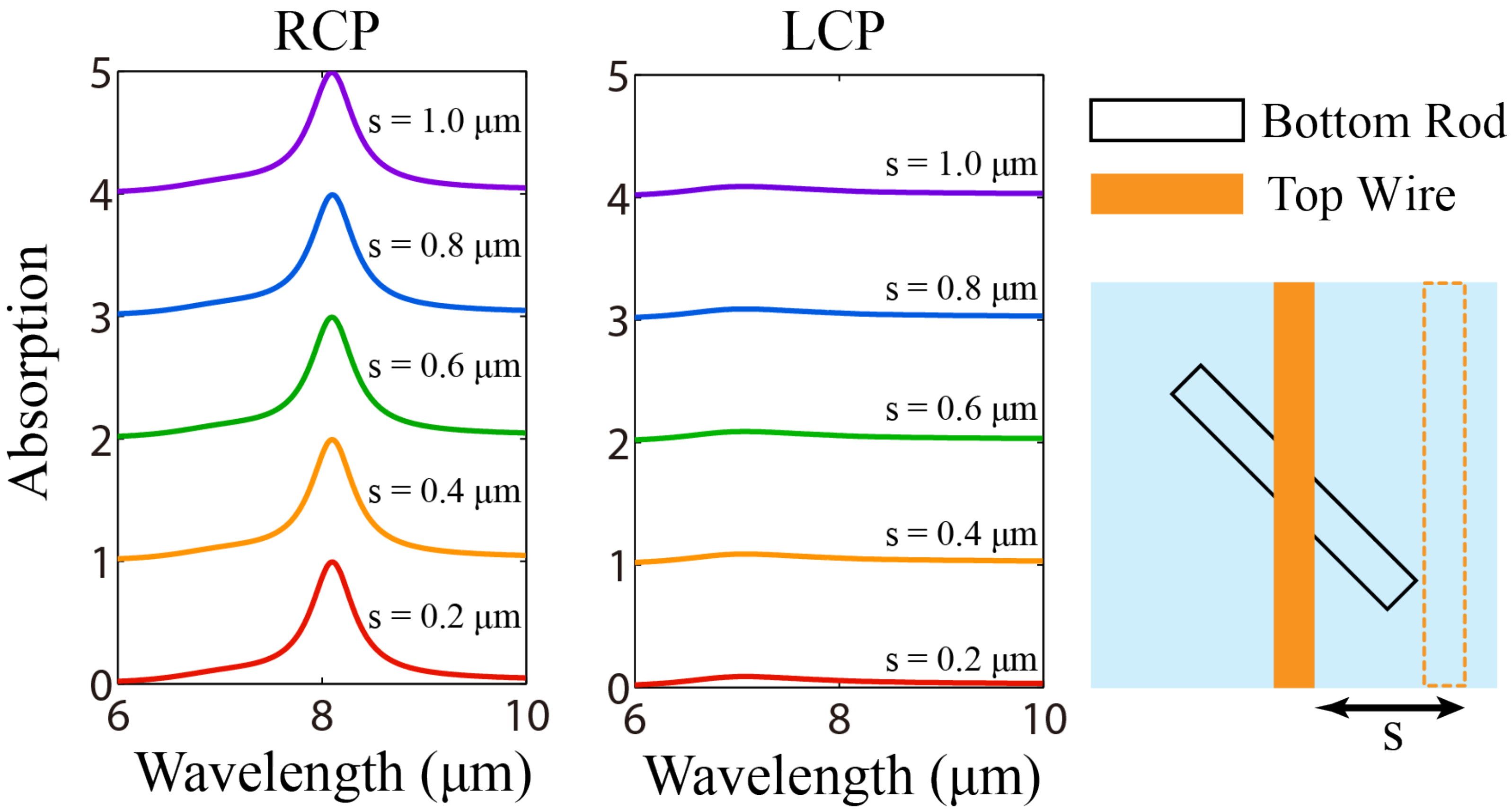
*Z. J. Wang et al., arXiv:1506.00971, under review*

# Omnidirectional Performance




Z. J. Wang et al., arXiv:1506.00971, under review

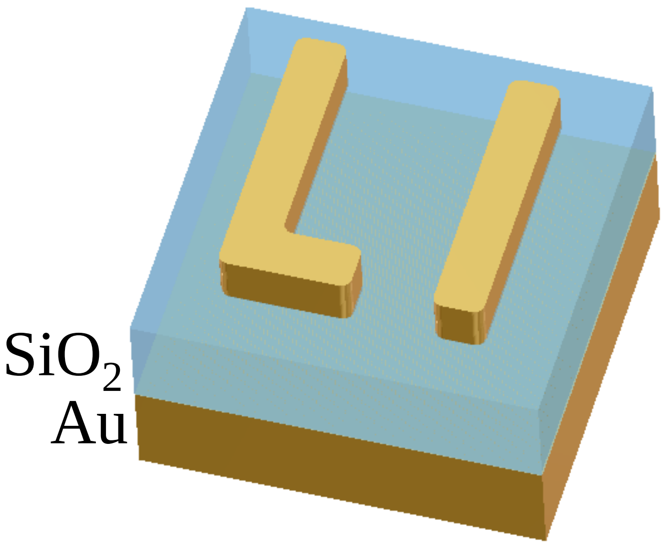
# Insensitivity on the Geometry Offset

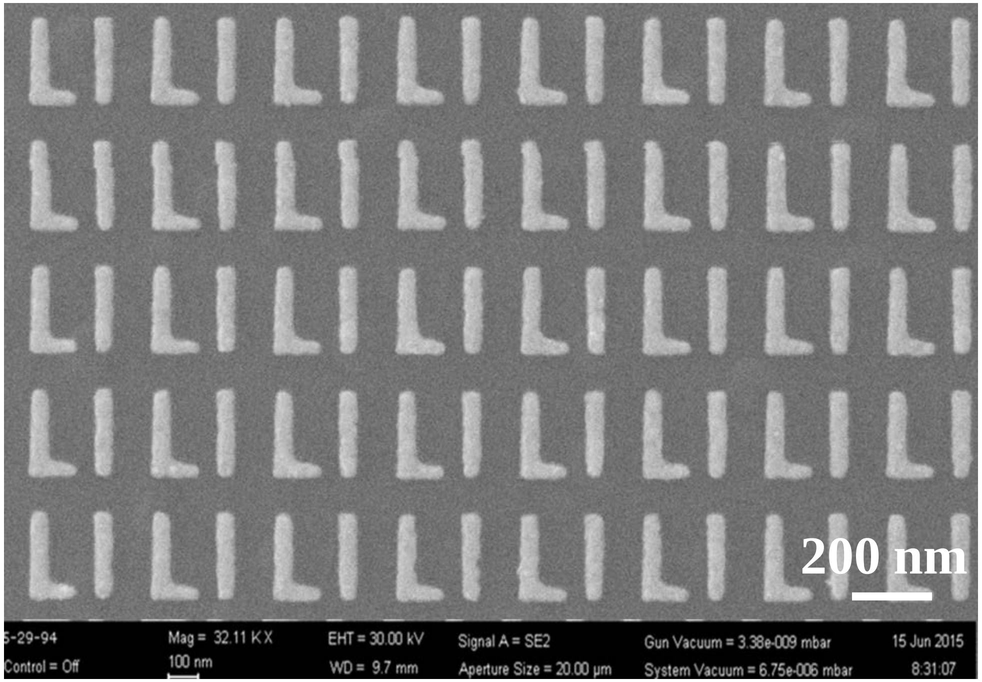




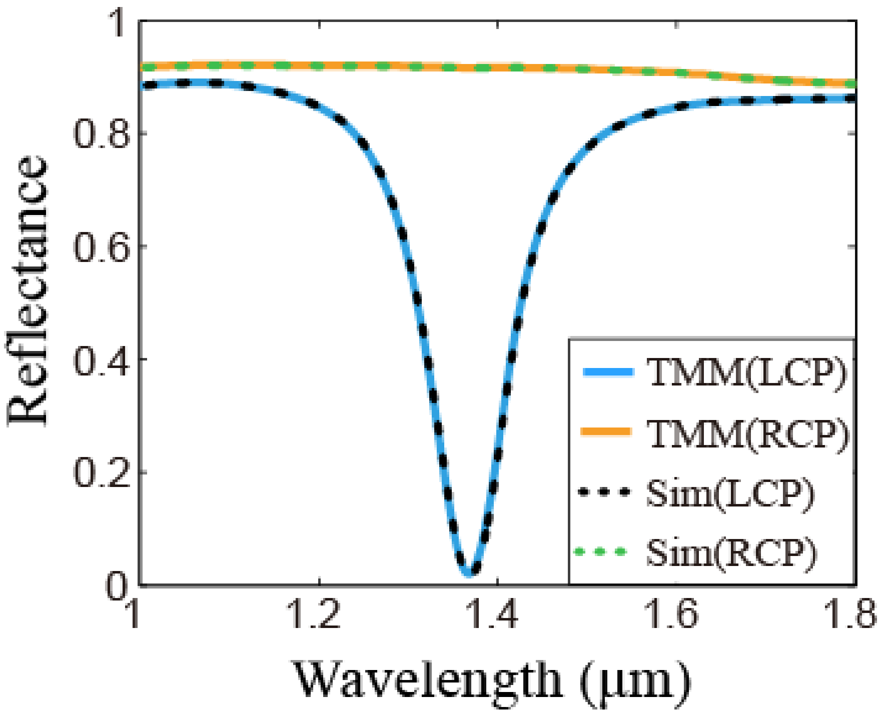

*Z. J. Wang et al., arXiv:1506.00971, under review*

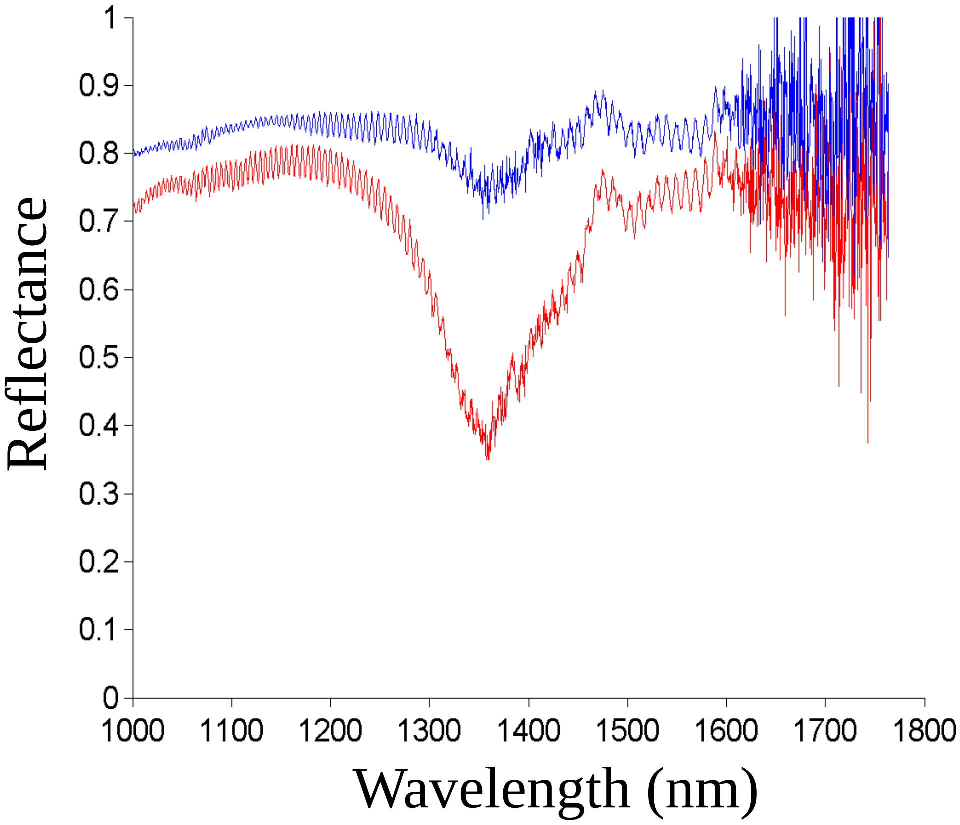
# Single-layer CD Mirror in the Near-IR Region



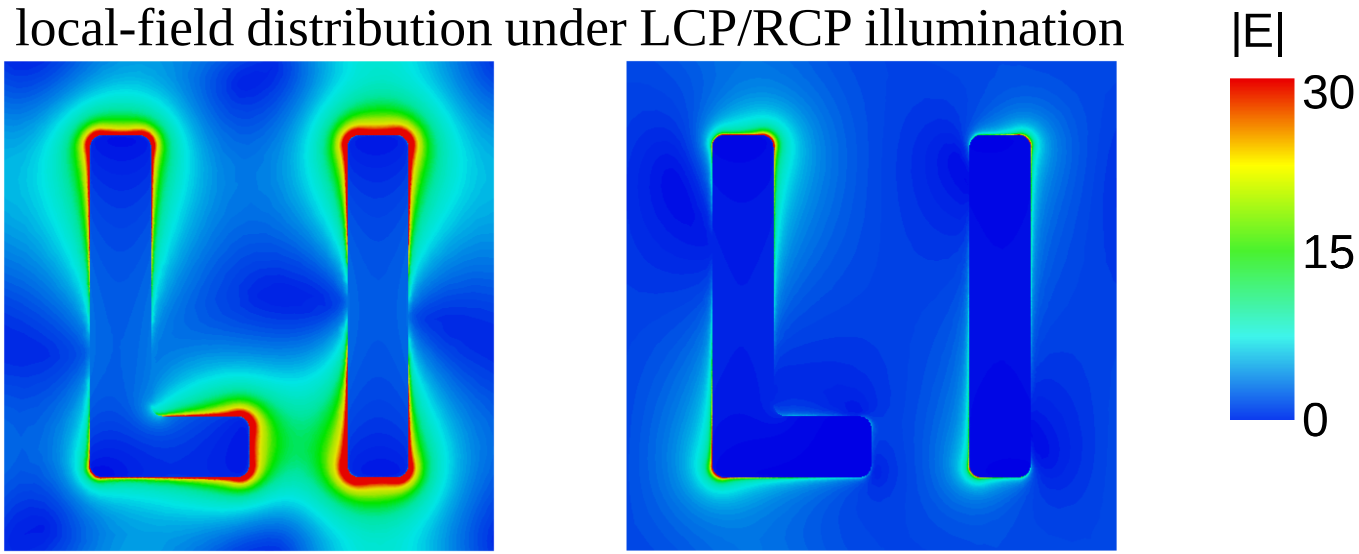
# Single-layer CD Mirror in the Near-IR Region



# Potential Applications of CD Metamirrors

local-field distribution under LCP/RCP illumination




- Chiral molecule sensing
- Polarimetric imaging and detection
- Novel cavities for chiral lasers
- Quantum optical information processing

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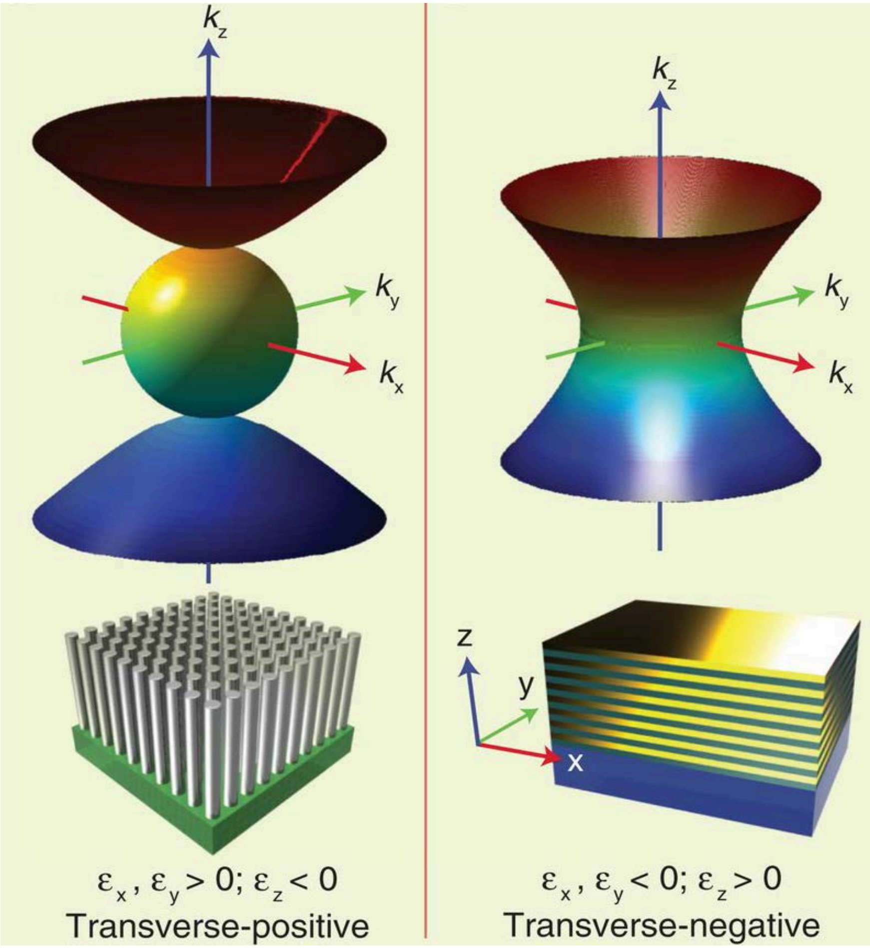
# Hyperbolic Metamaterials

Anisotropic media with diagonal permittivity tensor

$$\overleftrightarrow{\varepsilon} = \varepsilon_0 \begin{pmatrix} \varepsilon_x & 0 & 0 \\ 0 & \varepsilon_y & 0 \\ 0 & 0 & \varepsilon_z \end{pmatrix}$$

Dispersion relation:

$$\frac{{k_x}^2 + {k_y}^2}{\varepsilon_z} + \frac{{k_z}^2}{\varepsilon_x} = \frac{\omega^2}{c^2}$$

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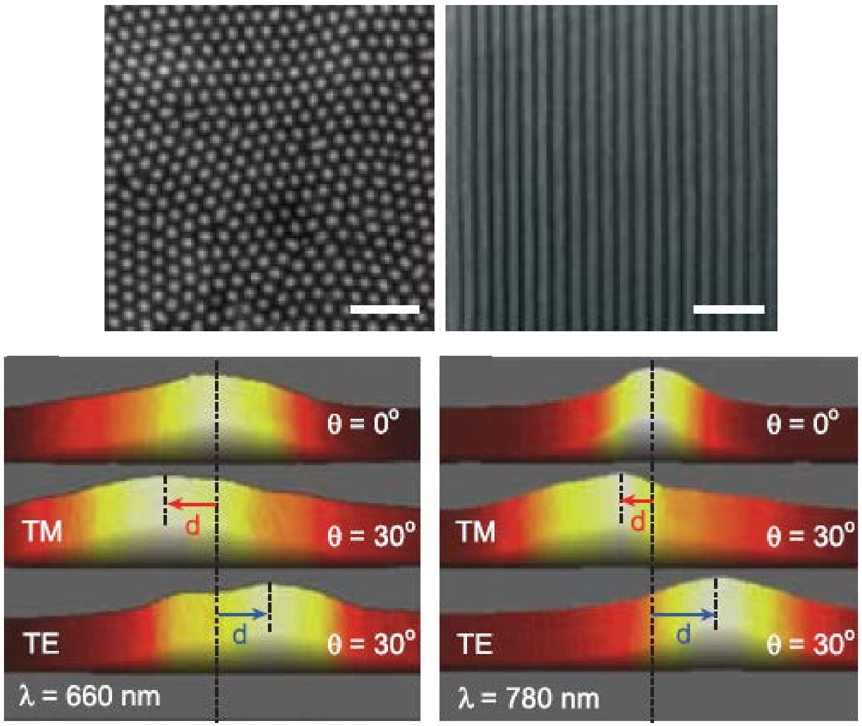
*Review: Science 339, 1232009 (2013); Nature Photonics 7, 948 (2013)*

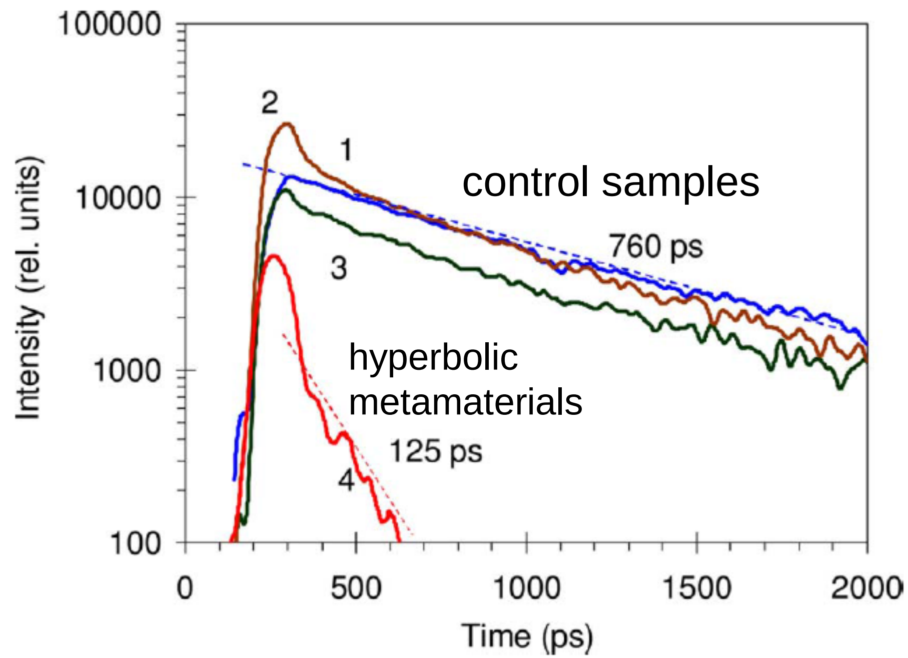
# Novel Properties of Hyperbolic Metamaterials

## broadband negative refraction



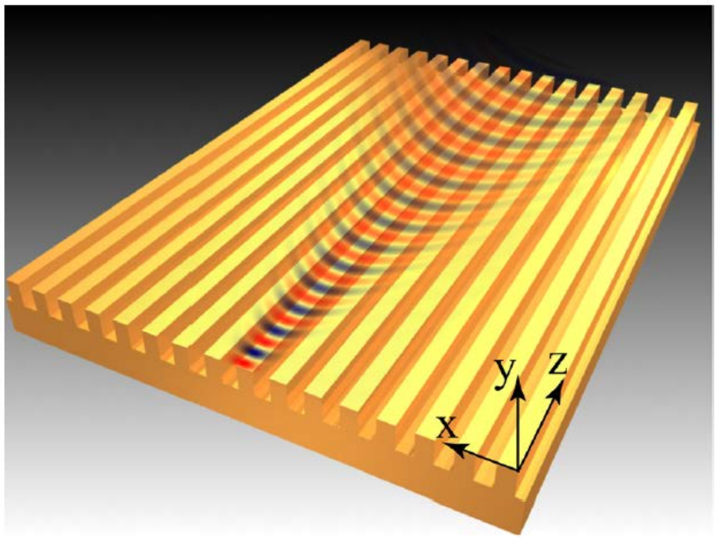

*Yao et al., Science 321, 930 (2008)*

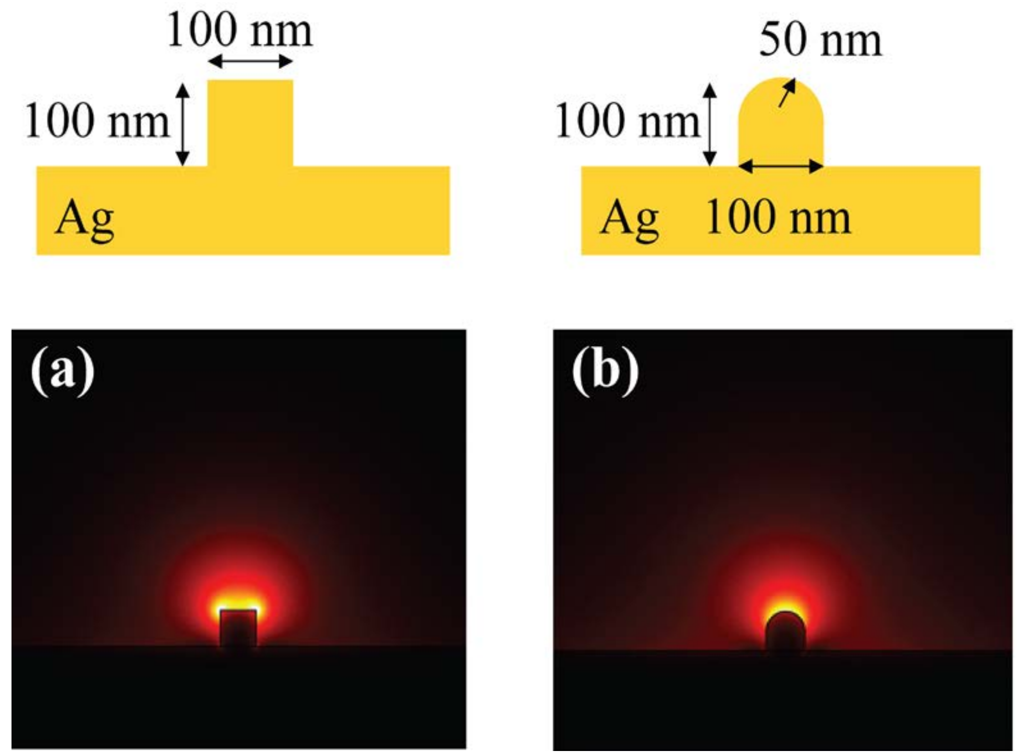
## enhanced spontaneous emission




*Opt. Lett. 35, 1863–1865 (2010); APL 100, 181105 (2012)*

# Hyperbolic Metasurfaces

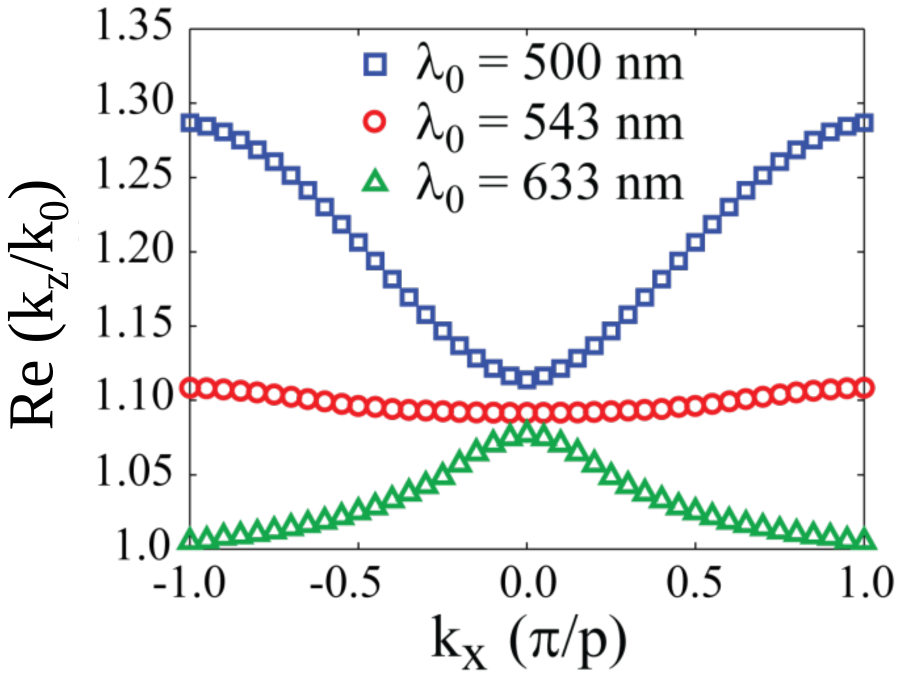



*Y. M. Liu and X. Zhang, APL 103, 141101 (2013)*

Surface plasmons are localized at the top of the ridges, which are insensitive to the geometry deviation.

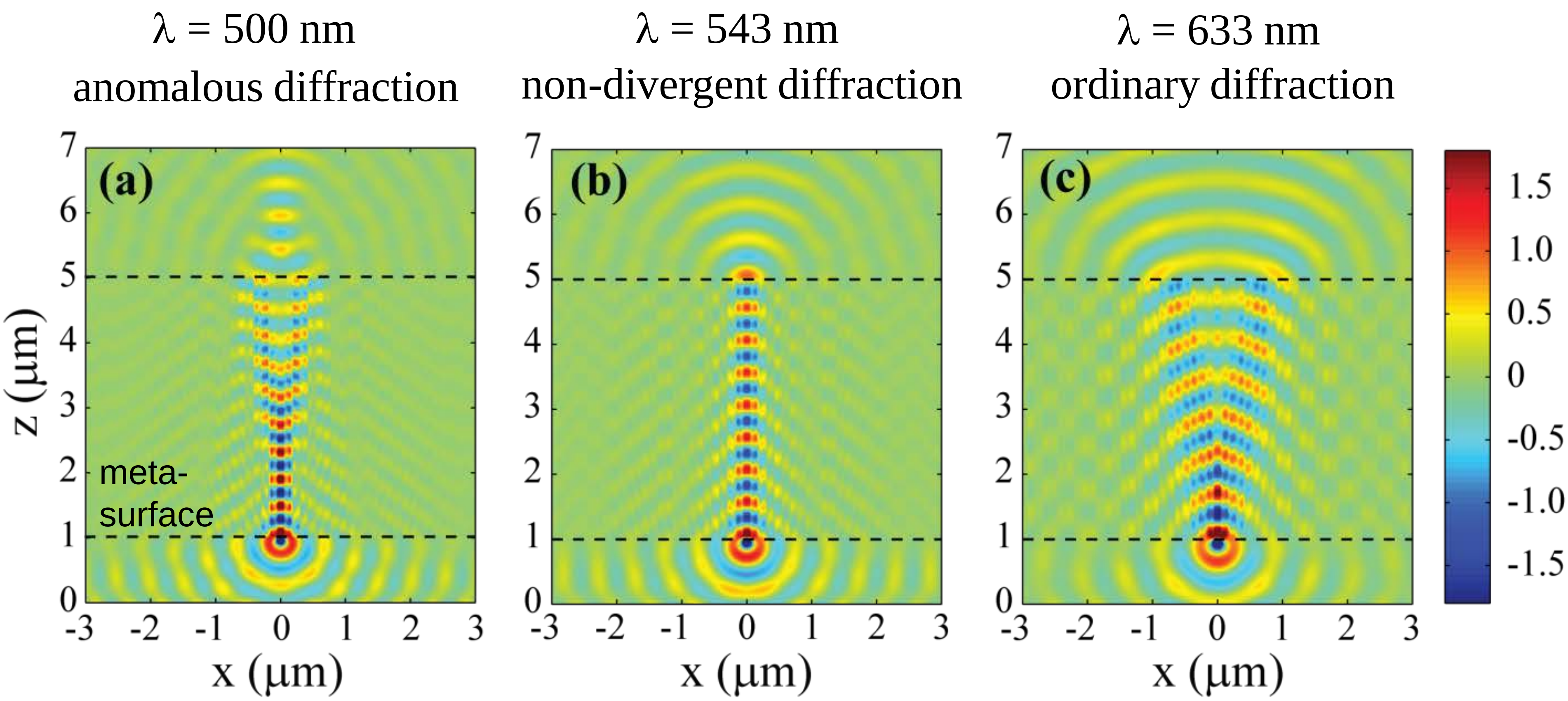
# Constant Frequency Contour




periodicity: 120 nm, width: 60 nm, and height: 80 nm

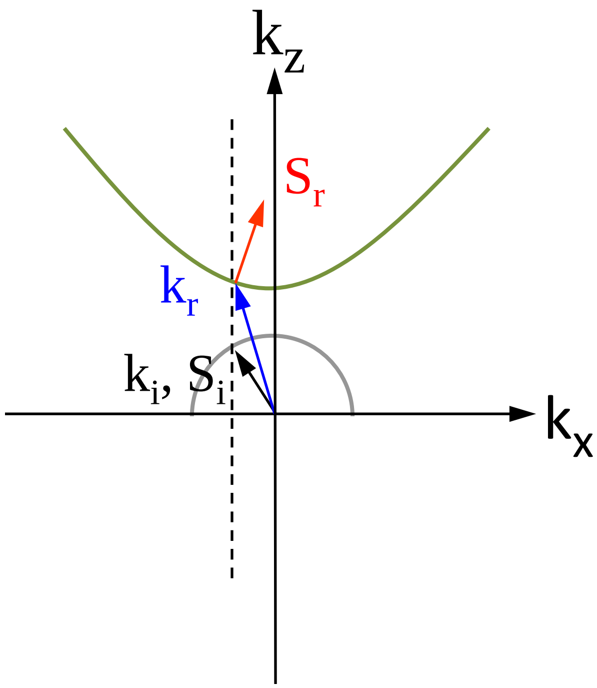
- Coupled mode theory: $k_z$=b+2C *cos*($k_x$p), where *C* is the coupling coefficient
- The shape of the constant frequency contour depends on the sign of *C*

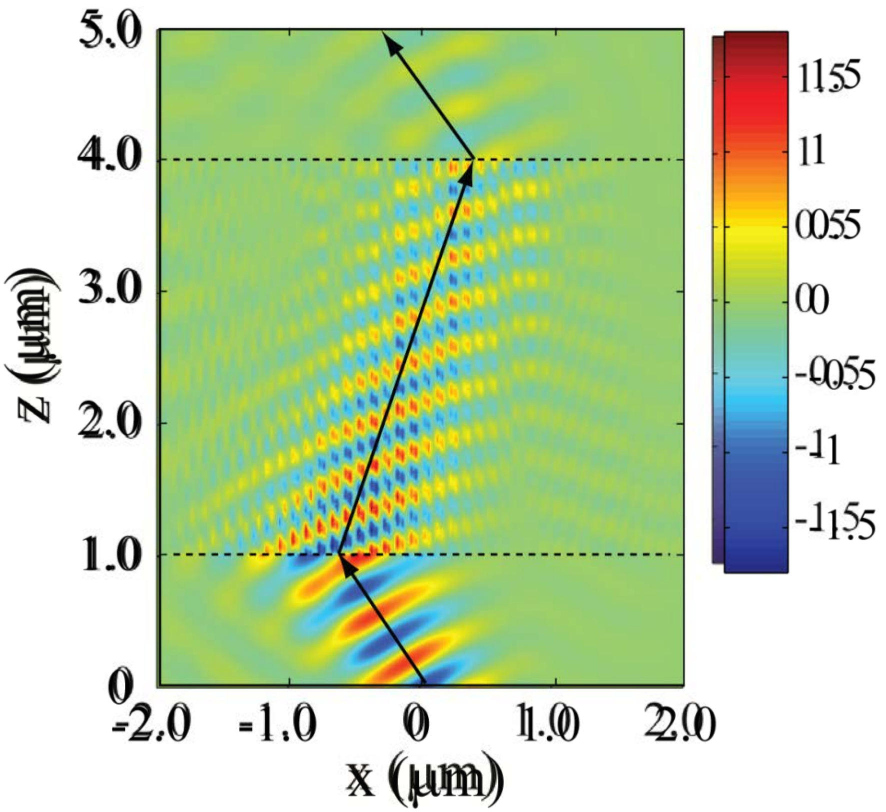
# Distinct Characteristics of SPP Propagation




*Y. M. Liu and X. Zhang, APL 103, 141101 (2013)*

# Negative Refraction of SPPs



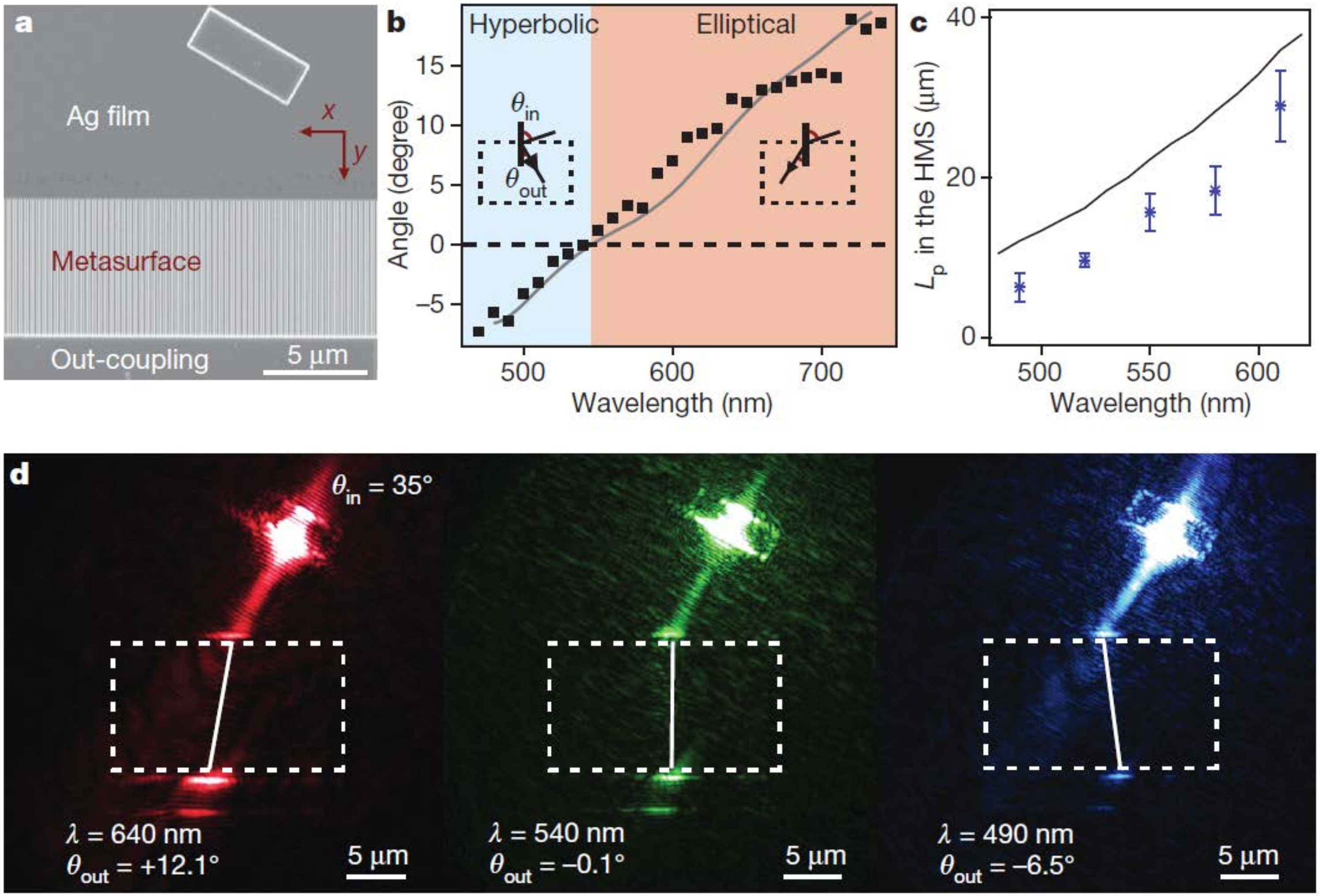




7.5% disorder in periodicity



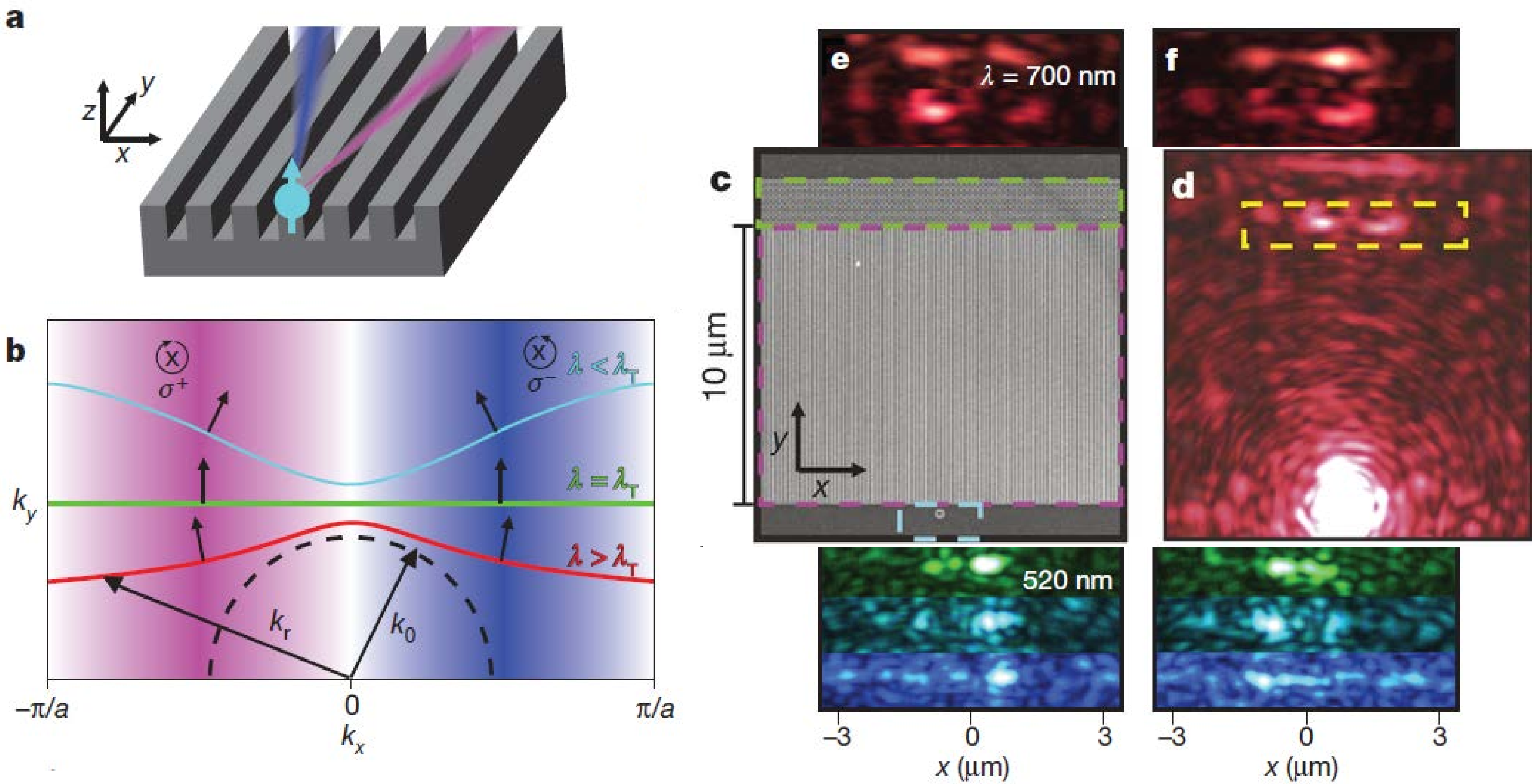
*Y. M. Liu and X. Zhang, APL 103, 141101 (2013)*

# Experimental Demonstration of Hyperbolic Metasurfaces




*A. A. High et al., Nature 522, 192 (2015)*

# Plasmonic Spin-Hall Effect

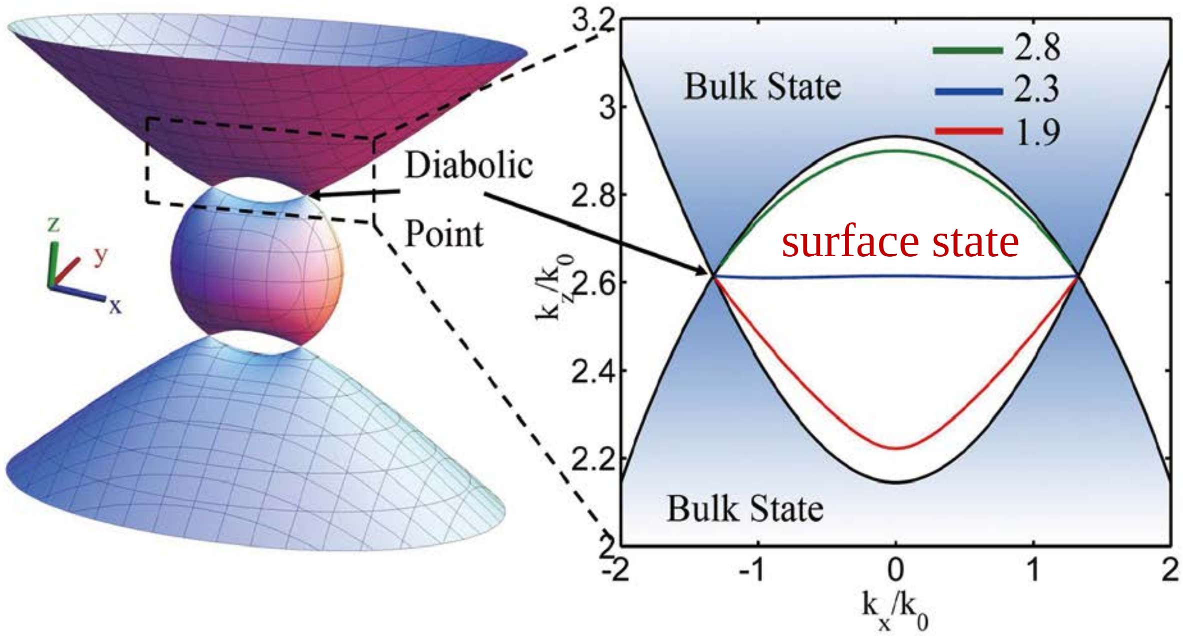



A. A. High et al., Nature 522, 192 (2015)

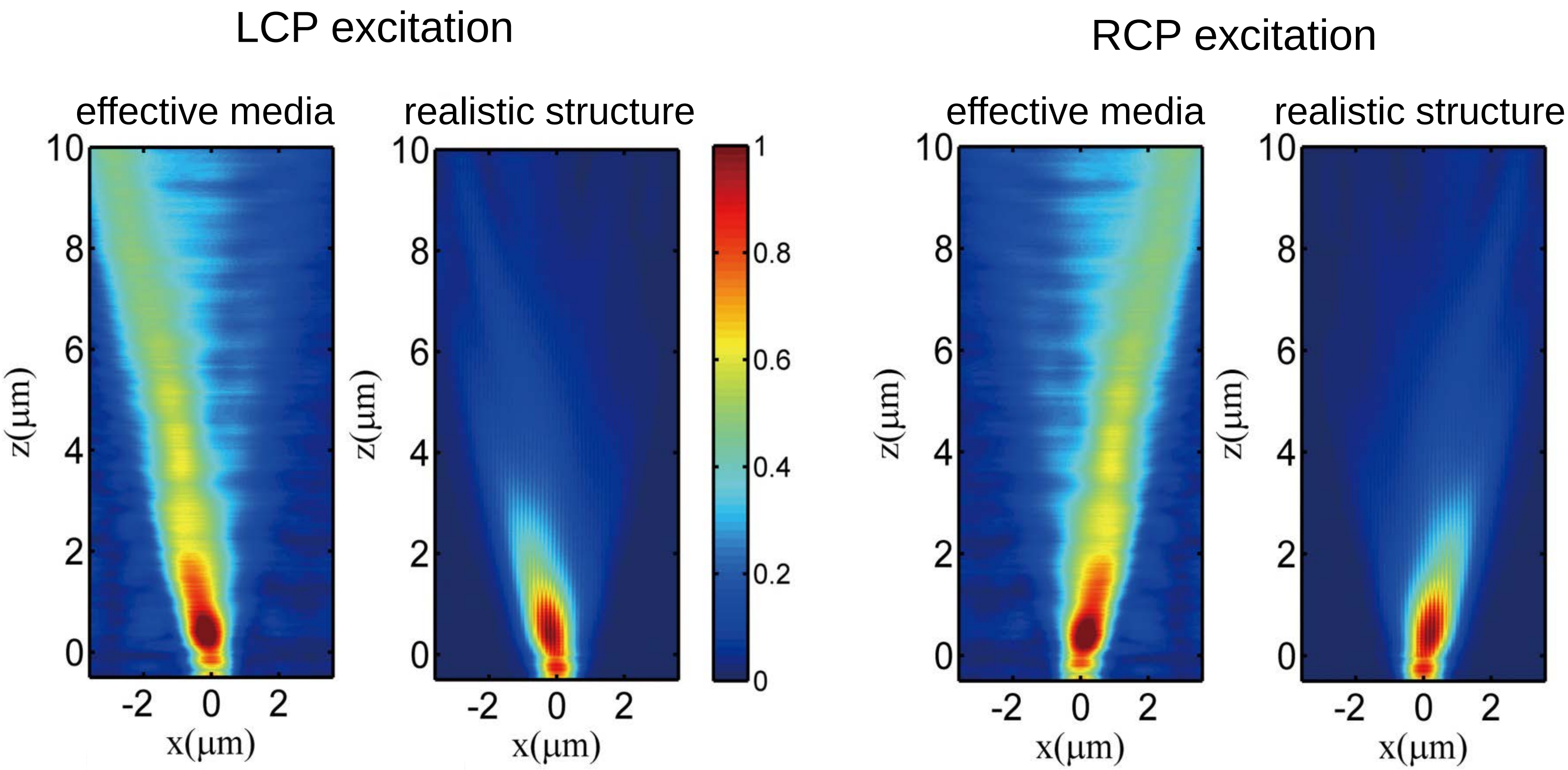
# Biaxial Hyperbolic Metamaterials

permittivity tensor: $\overleftrightarrow{\varepsilon} = \varepsilon_0 \begin{pmatrix} \varepsilon_x & 0 & 0 \\ 0 & \varepsilon_y & 0 \\ 0 & 0 & \varepsilon_z \end{pmatrix}$

consider the case: $\varepsilon_x > \varepsilon_y > 0$ and $\varepsilon_z < 0$



# Helicity-Dependent Surface Waves

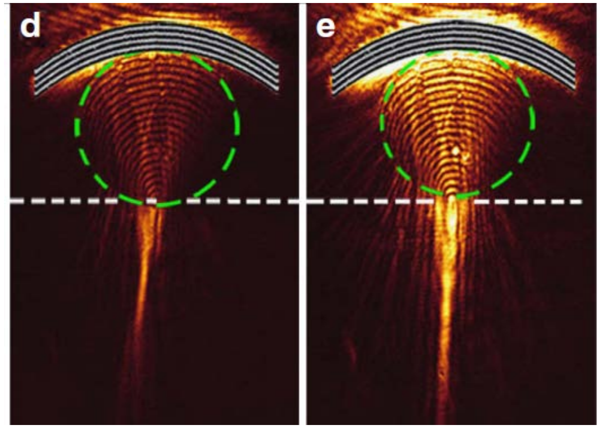


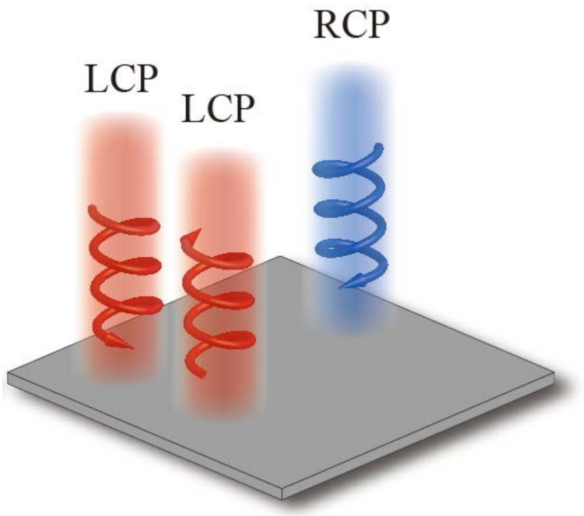

The surface wave has TE and TM components, which have $\pi/2$ phase difference. We can selectively control the surface wave propagation by the handedness.

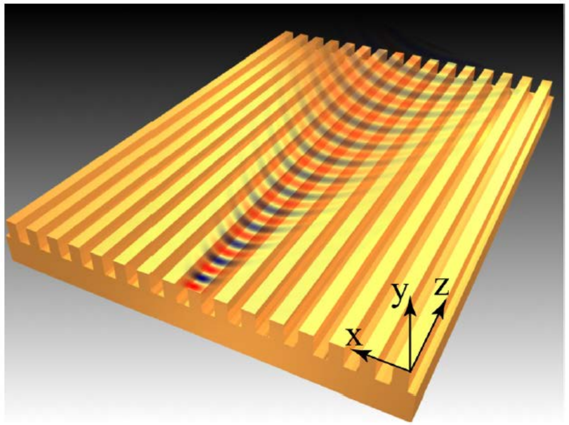
Northeastern

*Gao et al., Light: Science and Applications, in press*

# Conclusions




- A reconfigurable plasmofluidic lens, which could implement multiple functionalities and potentially reduce the size of optofluidic devices below the diffraction limit.
- A new concept of circular dichroism metamirrors is proposed to selectively reflect/absorb circularly polarized light and maintain its helicity.
- We demonstrate that hyperbolic metasurfaces exhibit anomalous dispersions, allowing collimation and negative refraction of surface plasmons. Furthermore, helicity-dependent surface waves can be exited.