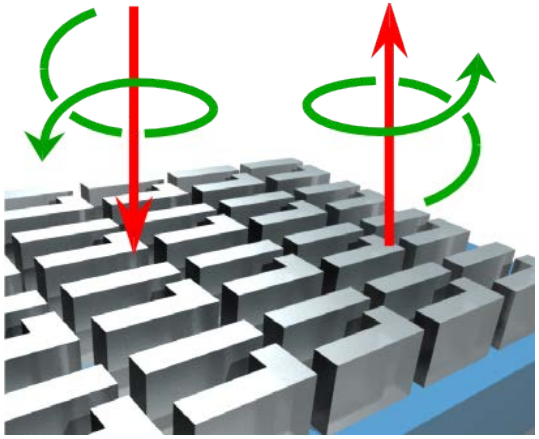
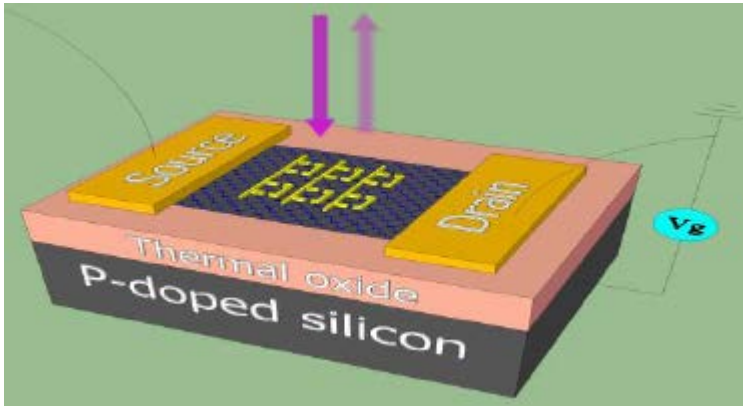
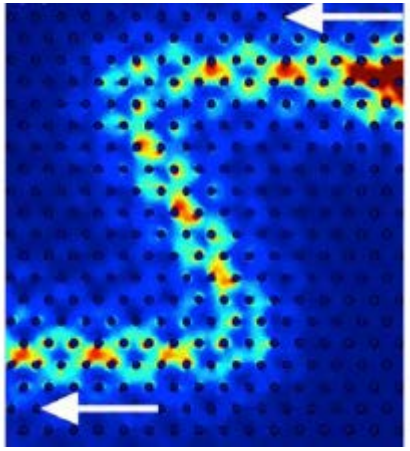
Metamaterials-Inspired Electromagnetics and Photonics

Gennady Shvets, The University of Texas at Austin

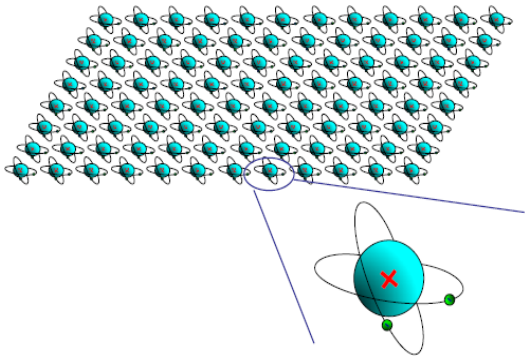




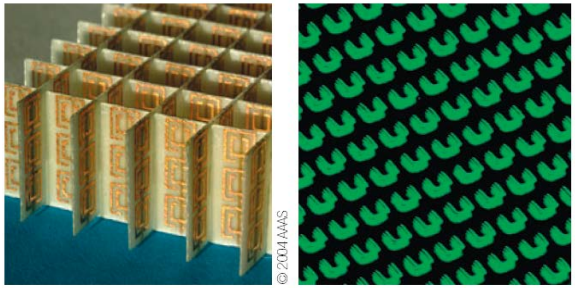


Condensed Matter and Materials Research Committee Spring Meeting, National Academies' Keck Center, Washington, DC, May 1, 2014

Meta-Materials: Mesoscopic EM Materials



Natural materials: unit cell is an atom << radiation wavelength

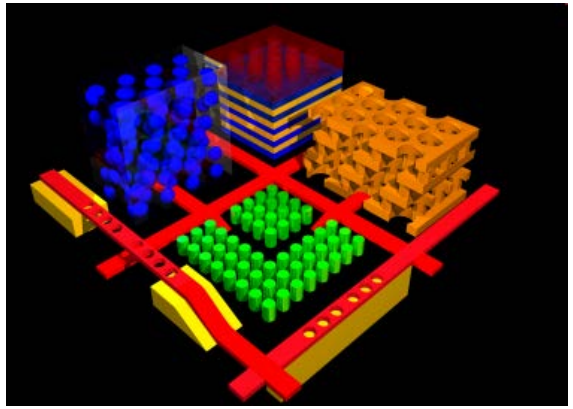


MetaMaterials: atom << unit cell < λ

Unit cell is small enough→ effective medium description (homogenization, constitutive parameters ε, μ)

Carefully designed resonant unit cells (e.g. split rings etc.)

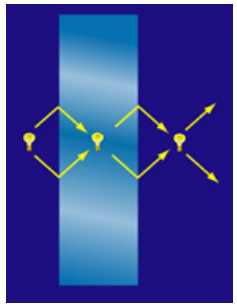
Remarkable optical/EM properties enabled by finite cell size → spatial dispersion, optical magnetism, bi-anisotropy

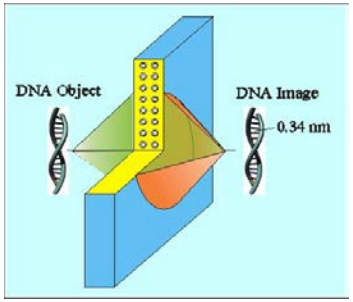


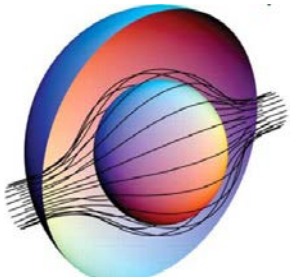
Photonic crystals: unit cell is sized to ½ of the radiation wavelength

Evolution of Metamaterials Research

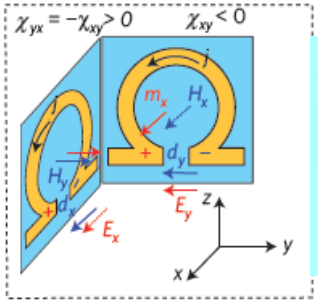
- **Early days: focus on exotic bulk properties → negative refractive index, super-lensing, "cloaking"**

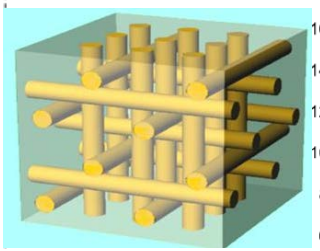


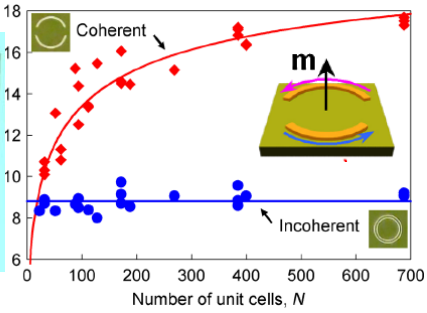




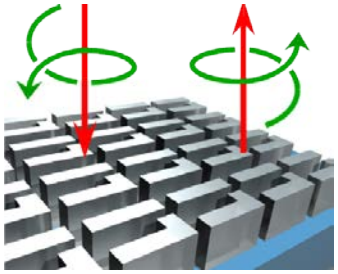
- **Understanding of the EM properties of MMs and their building blocks: high-frequency magnetism, bi-anisotropy, homogenization**

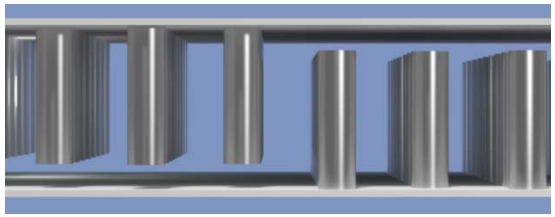






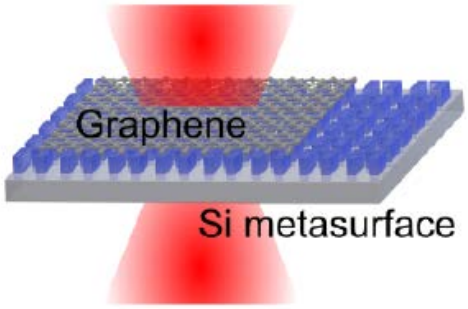
- **Modern Era: Metamaterials-inspired Electromagnetics in two and three dimensions**

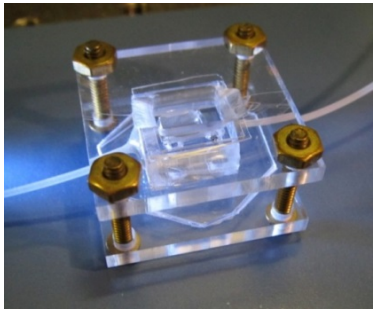




Spectrally Selective Field-Concentrating Optical Resonators Inspired by MMs

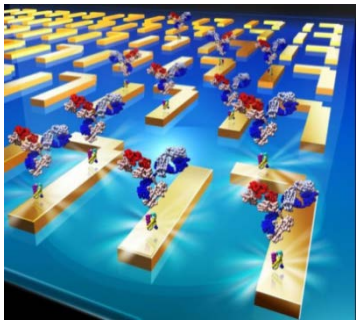
High-Precision graphene spectroscopy and ultrafast optoelectronic devices

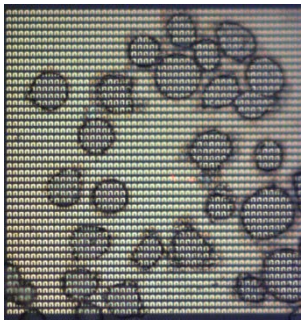


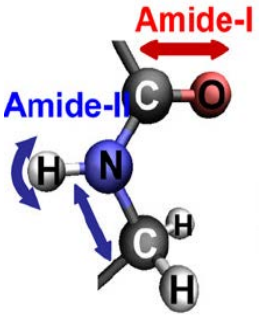


Wu et. al. (Shvets), Nature Comm. (2014, in print)

IR Bio-Spectroscopy: from designing better immunosensors to single-cell fingerprinting





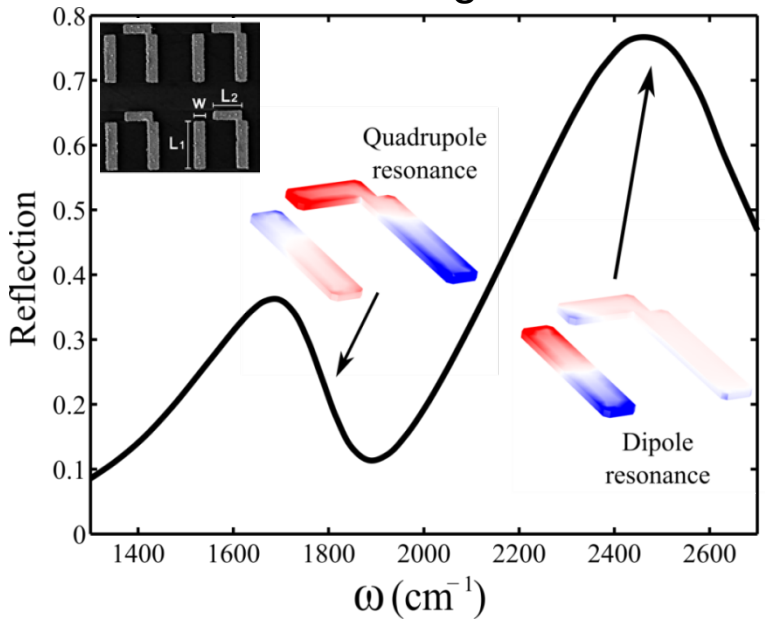


Wu et. al. (Altug & Shvets), Nature Mat. **11,** 69 (2012)

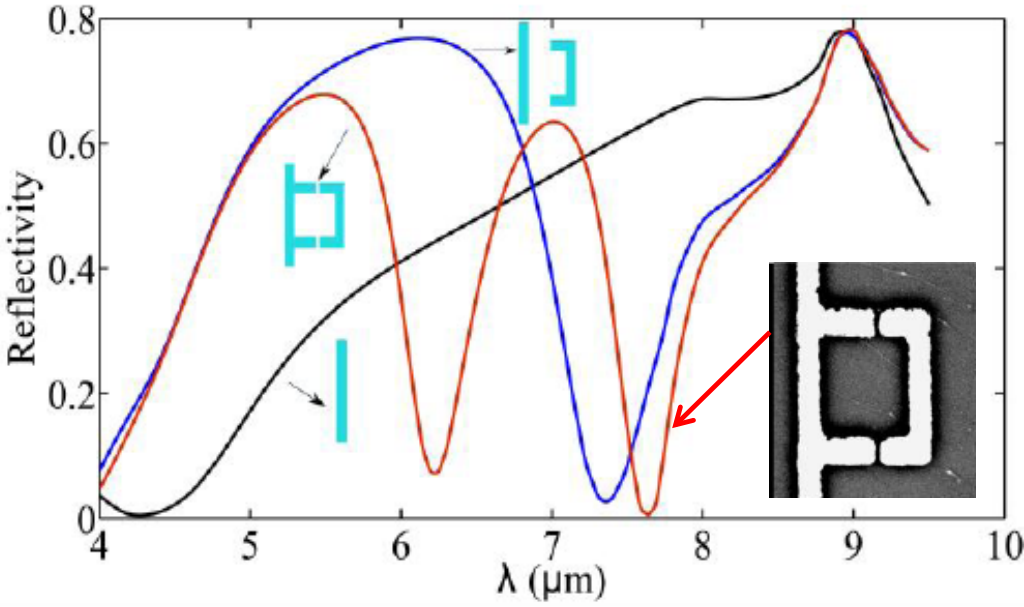
- **Narrow resonances (high-Q) + Strong field enhancements → Small changes of local environment can strongly affect optical response**
- **Controlling optical response using minute amounts of material, e.g. atomic monolayer of graphene, protein monolayers**
- **Ultra-sensitive fingerprinting/characterization of trace amounts of biological matter (protein monolayers, single cells, etc.)**

Meta-Surfaces Based on Split Rings

One dark and one bright resonance



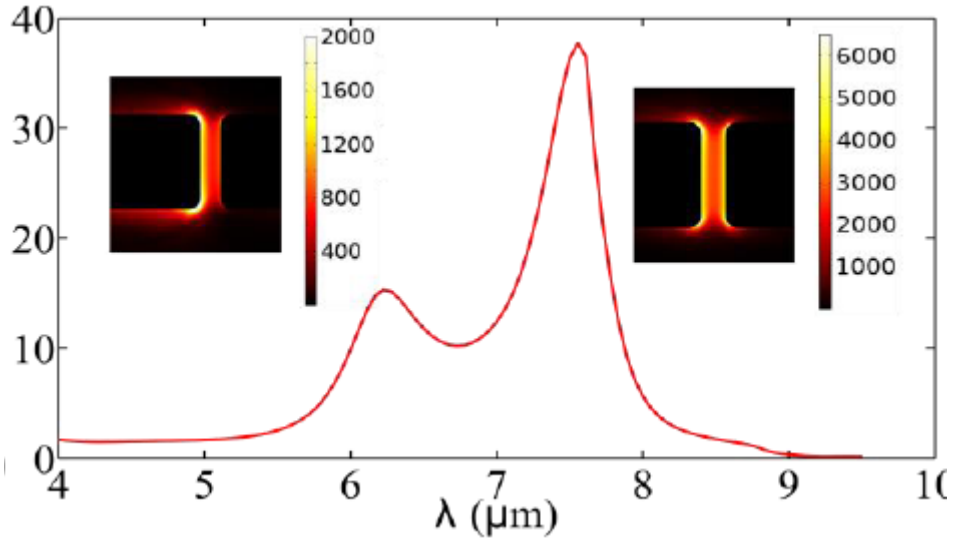
Continuum + 2 dark resonances



Easy to turn "Fano"-resonant metasurfaces into active ones:

(a) Strong field enhancement → small amounts of active material (e.g., graphene) is needed

(b) Even small spectral shifts translate into large changes in transmission/reflection



Outline of the Talk

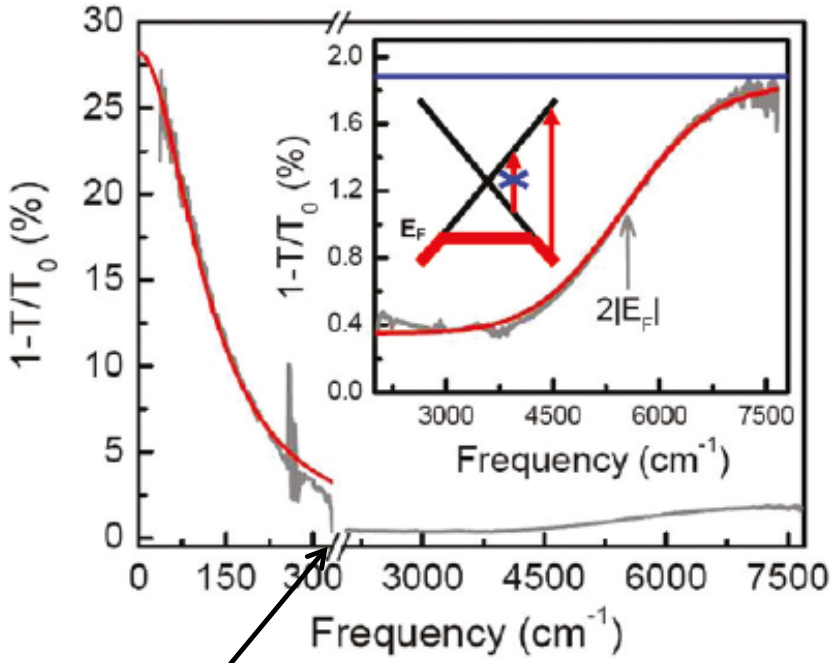
- **Plasmonic Meta-Surfaces Functionalized with Graphene**
- **The All-Dielectric Metasurfaces: Beating the Ohmic Loss**
- **Emulating the electron spin in photons using metamaterials: Photonic Topological Insulators**
- **Metamaterials-enhanced IR spectroscopy in life sciences: from proteins to cells**

Metamaterials and metamaterials-inspired photonic structures are already contributing to investigating condensed and soft matter materials such as graphene, proteins, cells

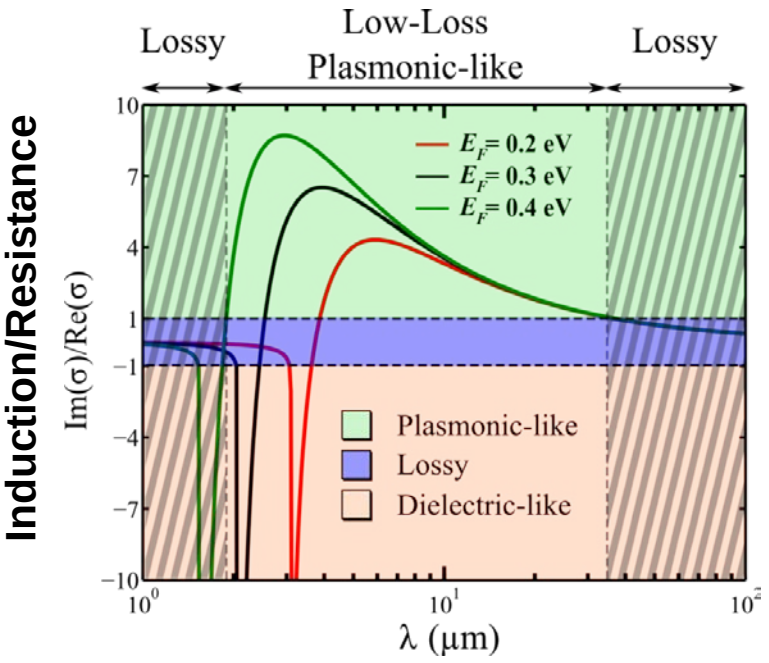
They may soon contribute to emulating many-body interactions in condensed matter systems such as topological insulators

The most exciting future work is likely to be done at the meso-scale, e.g., "slightly" sub-wavelength, "somewhat" coherent MMs interacting with wavelength-scale objects (i.e. biological cells)

Mid-IR Meta-Surfaces Enhance Graphene's Response and Can be Controlled by SLG



SLG's mid-IR response is weak: small Drude conductivity and no interband transitions, but…

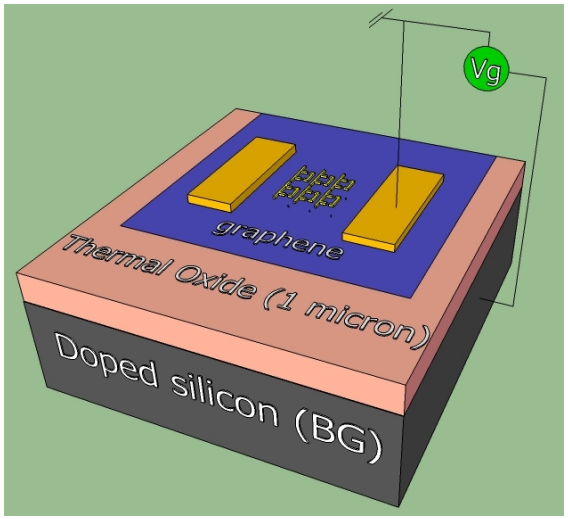


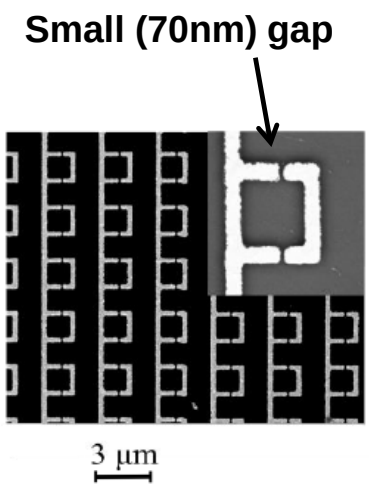
Graphene is a low-loss plasmonic material in mid-infrared

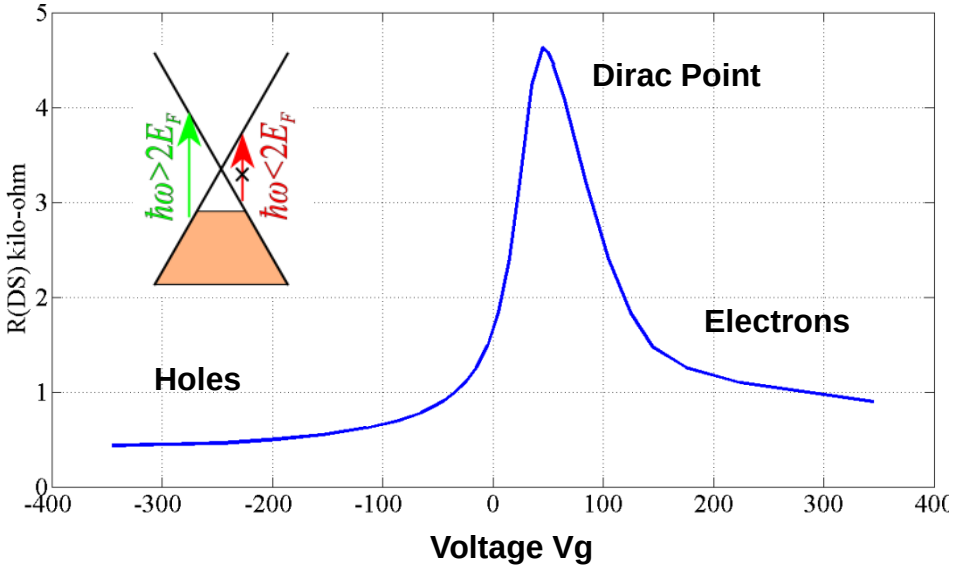
- **Metasurface tuning using "lossless" SLG**
- **MMs enable graphene characterization in mid-IR**

. S. H. Mousavi et. al., Nano Letters **13,** 1111 (2013).

Integration of MMs with Gated SLG

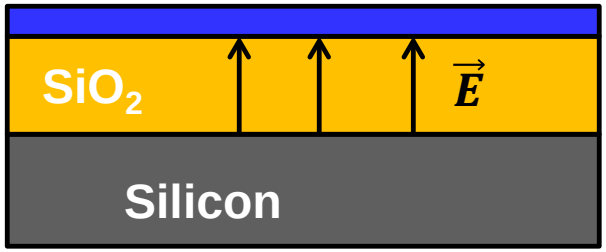






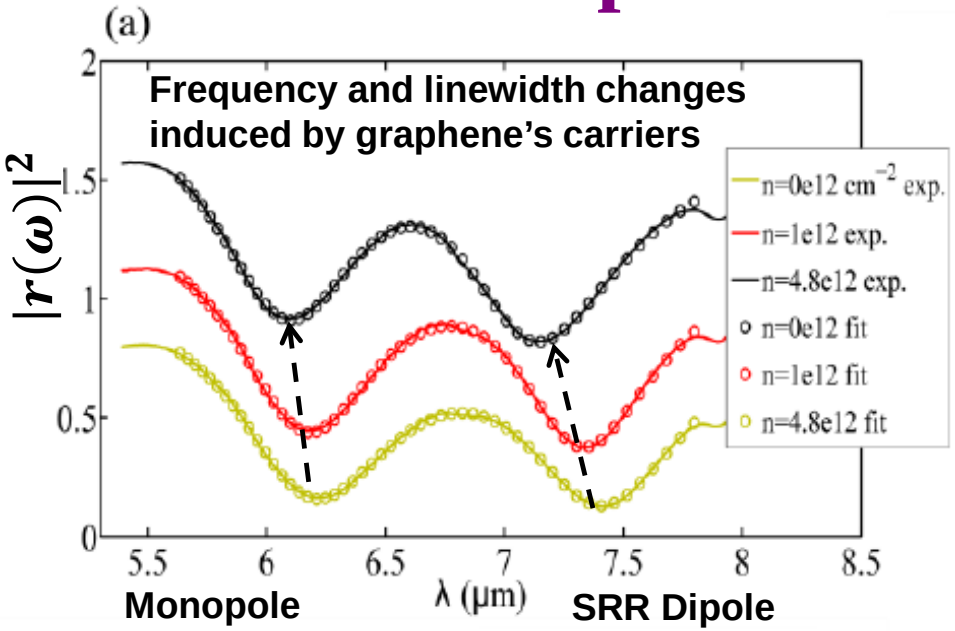
- **Back-gating injects carriers into graphene → shifts Fermi energy, changes conductivity**
- **Graphene's conductivity affects metamaterial's resonances → graphene spectroscopy**
- **Frequency shift comparable to linewidth → strongly-coupled regime of graphene-MM interaction**

Graphene: free + bound carriers



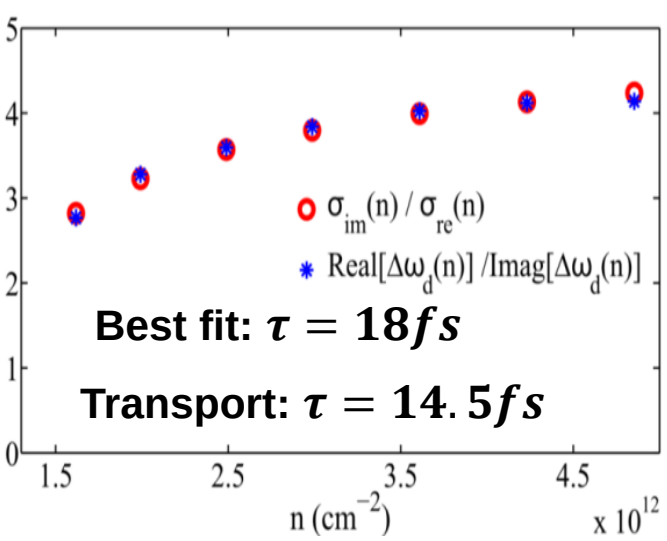
Antenna arrays: N. K. Emani et. al., Nano Lett. **12,** 5202 (2012);
Y. Yao et. al., NanoLetters **13,** 1257 (2013)

Double-Fano Resonance Fit Used to Extract Graphene's Optical Properties



$$\frac{Re(\Delta\omega_{m,d})}{Im(\Delta\omega_{m,d})} = \frac{Im(\sigma)}{Re(\sigma)}$$

Calculate Fermi energy E_F and carrier relaxation time τ in the Drude model of graphene conductivity

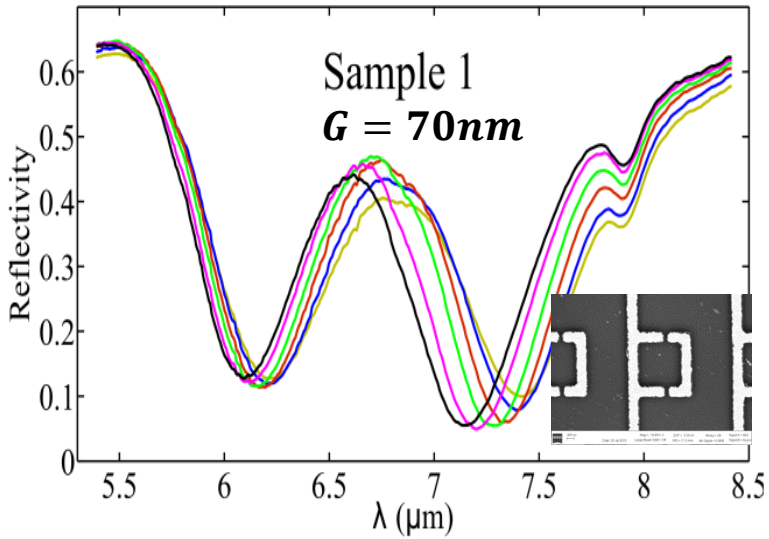


$$r(\omega) = \frac{A_0}{i\omega + 1/\tau_0} + \frac{A_m}{i(\omega-\omega_m)+1/\tau_m} + \frac{A_d}{i(\omega-\omega_d)+1/\tau_d}$$

$$\sigma_D = \frac{ie^2}{\pi\hbar}\left\{\frac{E_F}{\hbar(\omega + i\tau^{-1})}\right\}$$

Amplitude Modulator Based on MM/SLG

Modulate reflectivity around Dirac point by back-gating graphene



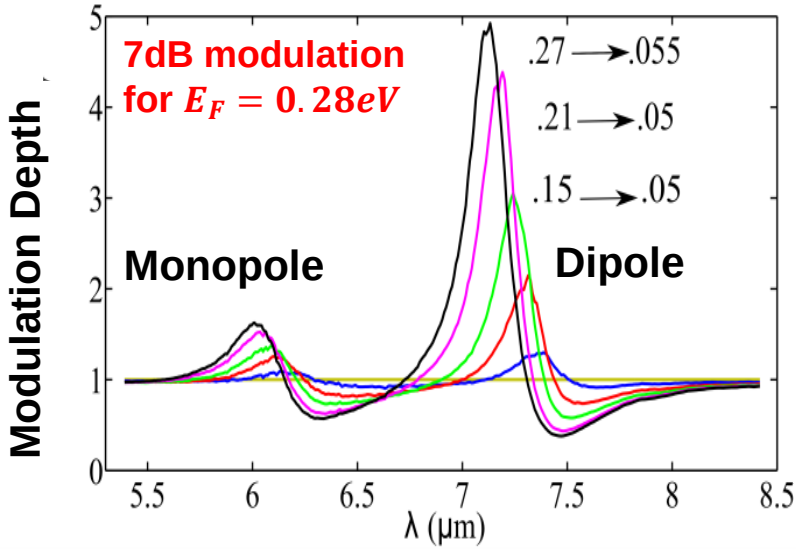
Two properties satisfied by efficient modulators:

(a) High baseline "on" reflectivity ($E_F = 0$)

(b) High modulation depth (maximum E_F)

Metamaterials + graphene have both

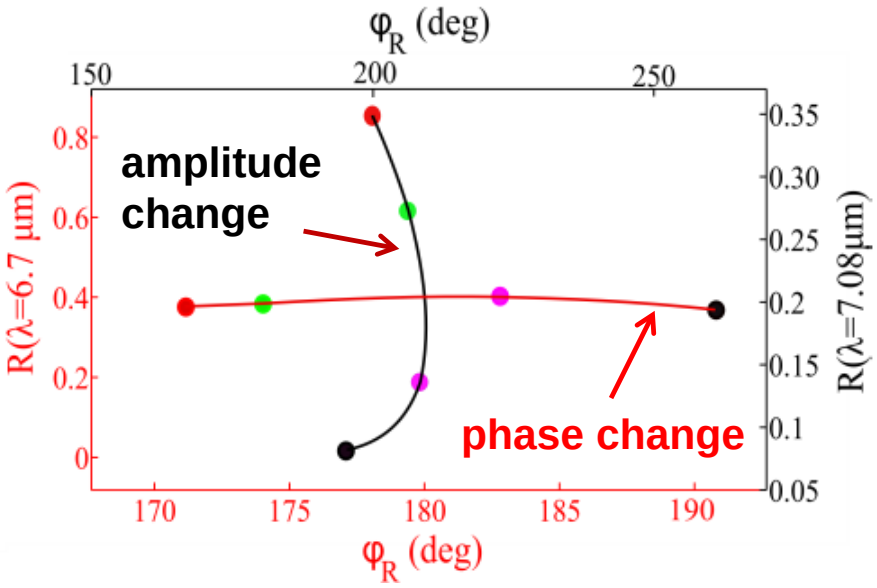
(c)

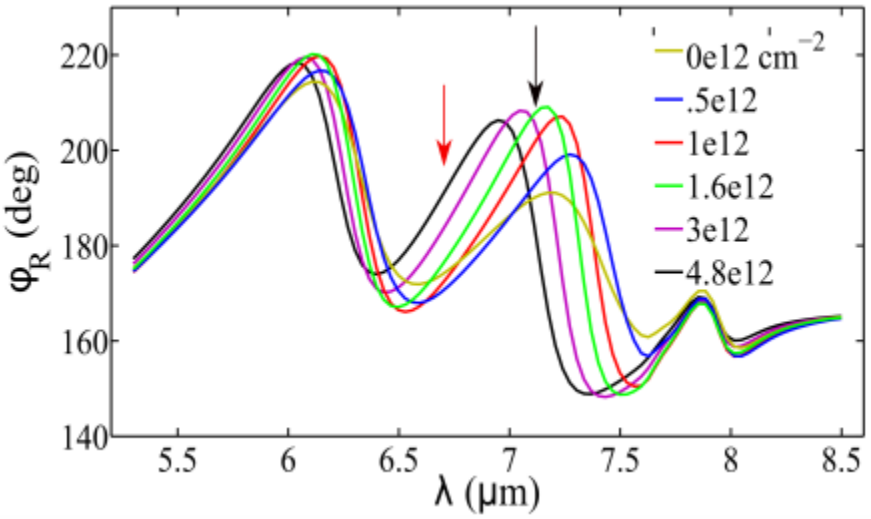


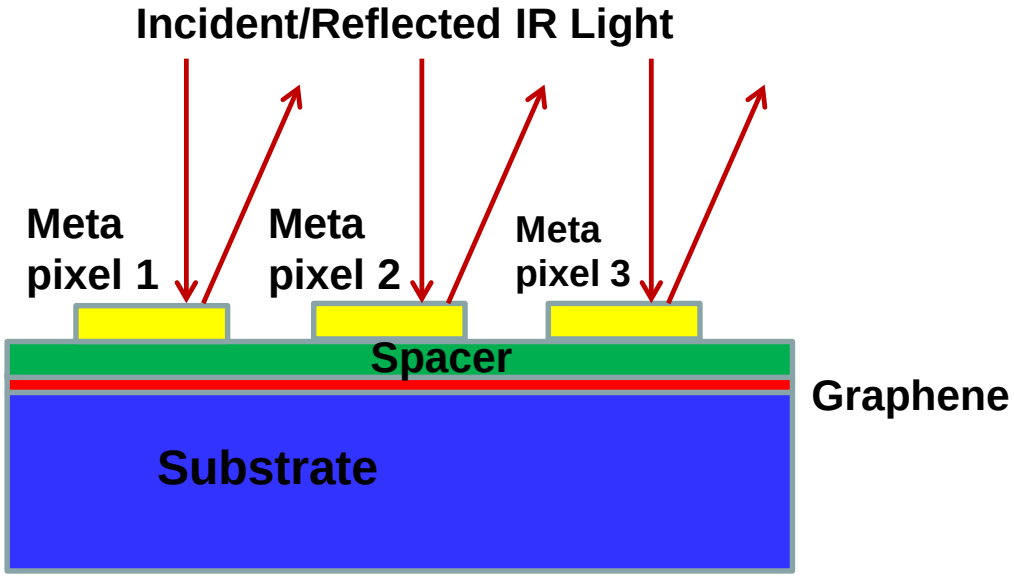
Modulation Depth: $R(\lambda; E_F = 0)/R(\lambda; E_F)$

- 0e12 / 0 V
- .5e12 / -40 V
- 1e12 / -80 V
- 1.6e12 /-130V
- 3e12 / -240 V
- 4.8e12 /-390V

IR Amplitude/Phase Modulator with SLG

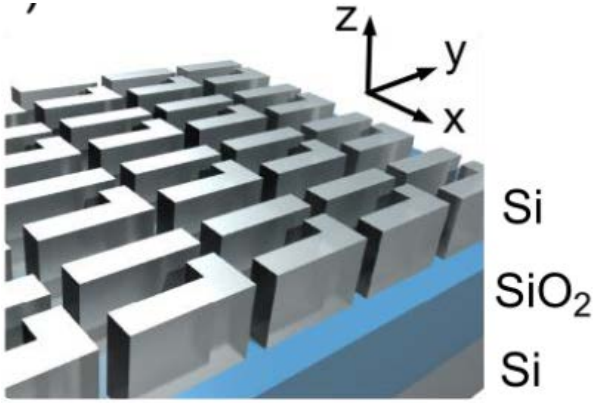


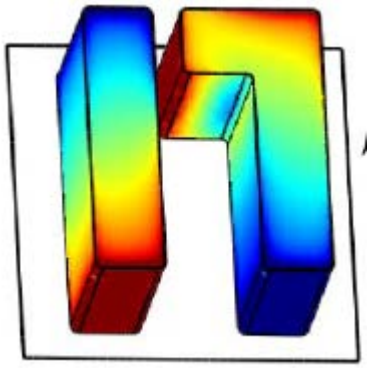




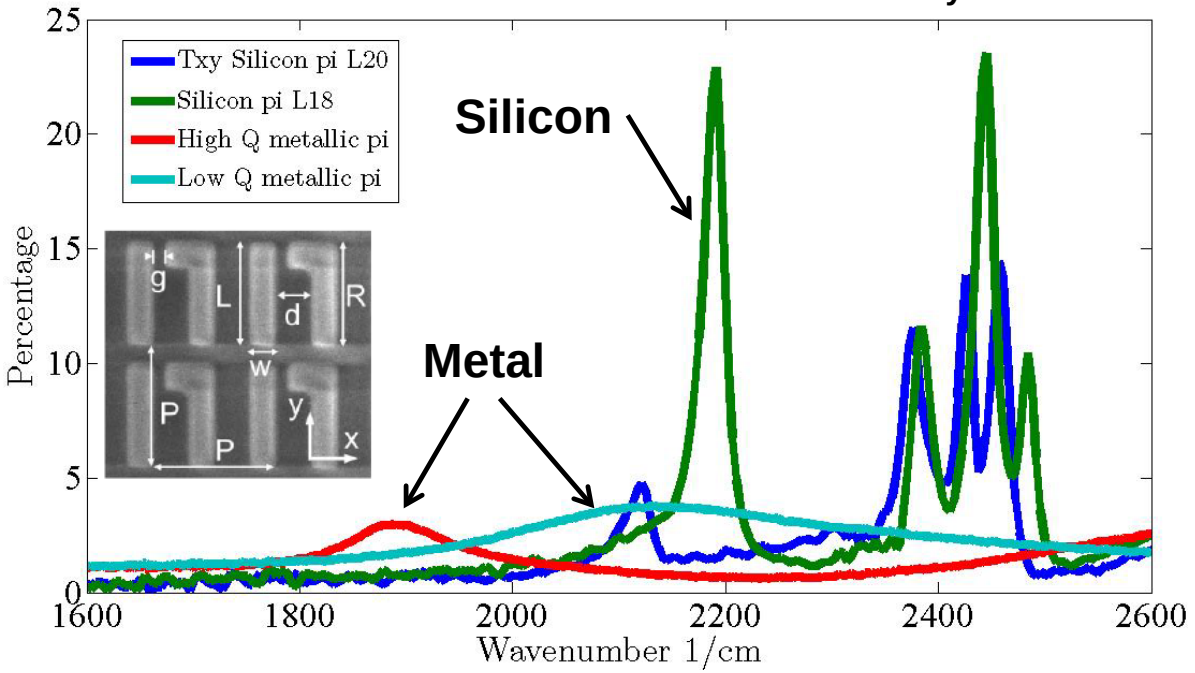
- **Either phase or amplitude can be electrically modulated**
- **Independently controlled pixels → electrically controllable IR beam steering or modulation or both**
- **This can be done either in reflection or in transmission**

All-Dielectric Fano-Resonant 2D Chiral Metasurfaces: Order of Magnitude Higher Q Than Similar Metallic Metasurfaces



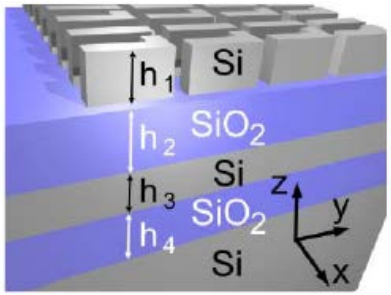


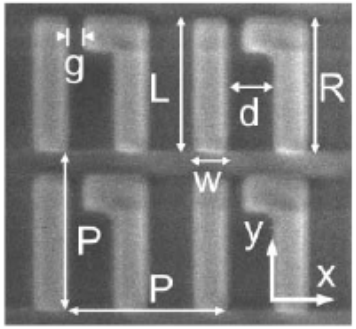
Cross-polarized transmission T_{xy}

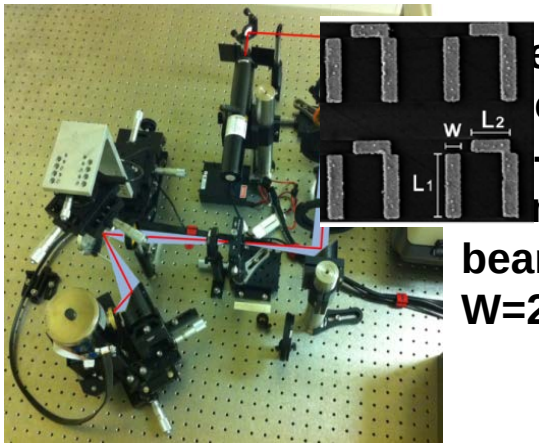


C. Wu et. al., “Spectrally Selective Chiral Silicon Metasurfaces Based on Infrared Fano Resonances”, Nature Communications (in press, 2014)

High-Q Fano Resonance in Dielectric MSs



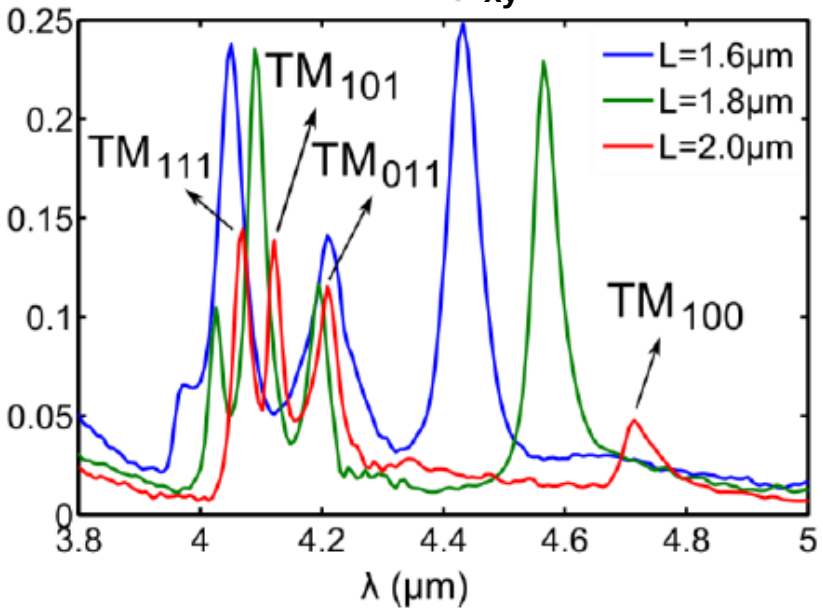




e-space FTIR
ctroscopy using
-NA (=0.14)
mally incident IR
beam focused to
W=200μm

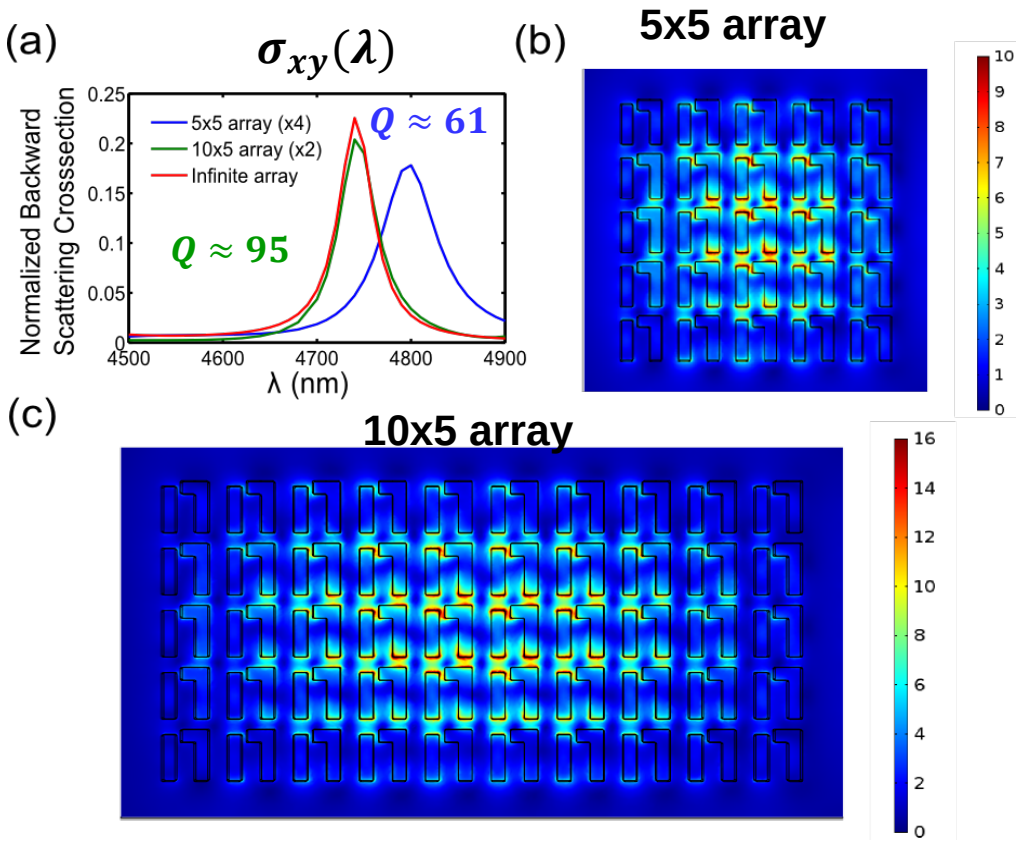
$$P = 2.4\mu m, w = 500nm,\ h_1 = h_3 = 1.2\mu m$$
$$g = 200nm, d = 700nm,\ h_2 = h_4 = 1.6\mu m$$
$$R = 2\mu m, L = 1.6 - 2\mu m$$

Experiment, T_{xy}



Dark mode	Nanorod length		
	$L = 2\ \mu m$	$L = 1.8\ \mu m$	$L = 1.6\ \mu m$
TM_{100}	$Q = 75.7$ $\lambda = 4.71\ \mu m$	$Q = 94.3$ $\lambda = 4.57\ \mu m$	$Q = 73.9$ $\lambda = 4.43\ \mu m$
TM_{011}	$Q = 113.3$ $\lambda = 4.21\ \mu m$	$Q = 100$ $\lambda = 4.2\ \mu m$	$Q = 52.9$ $\lambda = 4.21\ \mu m$
TM_{101}	$Q = 113.7$ $\lambda = 4.12\ \mu m$	$Q = 111.7$ $\lambda = 4.09\ \mu m$	$Q = 76.1$ $\lambda = 4.05\ \mu m$
TM_{111}	$Q = 116.9$ $\lambda = 4.07\ \mu m$	$Q = 127.5$ $\lambda = 4.03\ \mu m$	$Q = 98.4$ $\lambda = 3.97\ \mu m$

Collective Effects In Metasurfaces



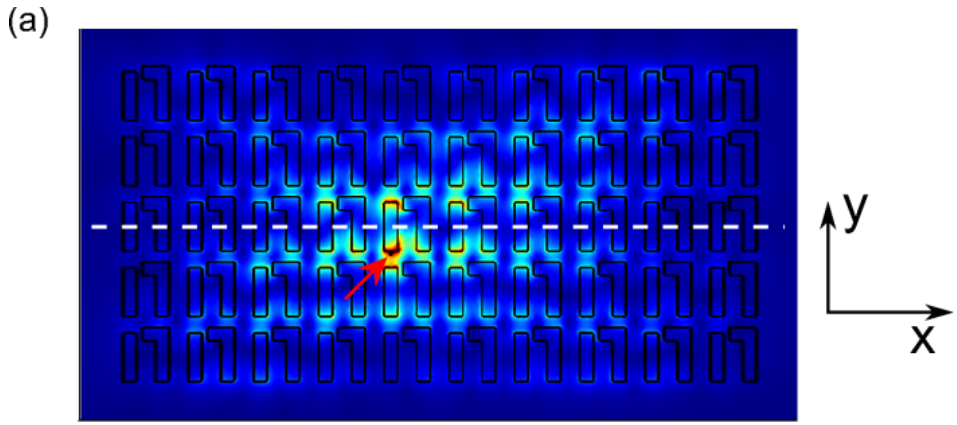
Each unit cell interacts with 2-3 neighbors on each side horizontally and about 1 cell on each side vertically → short-range interaction

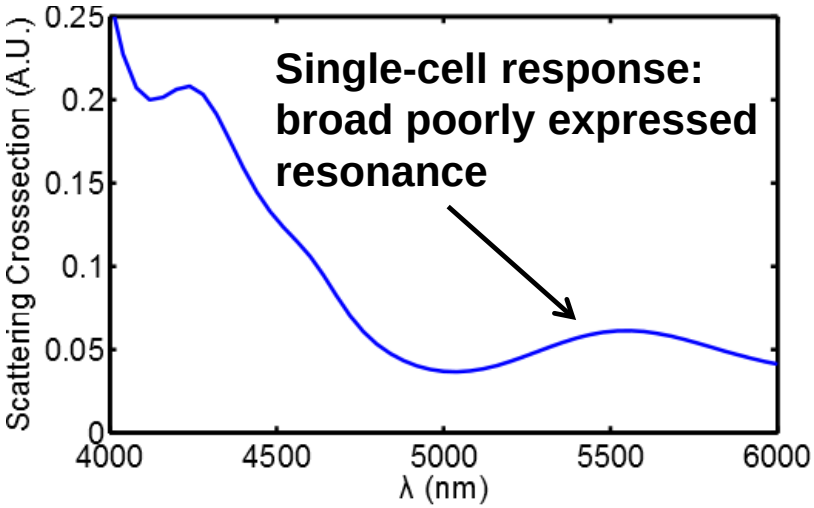
Pixels as small as $6\lambda \times 3\lambda$ have identical $Q \approx 95$ as infinite arrays

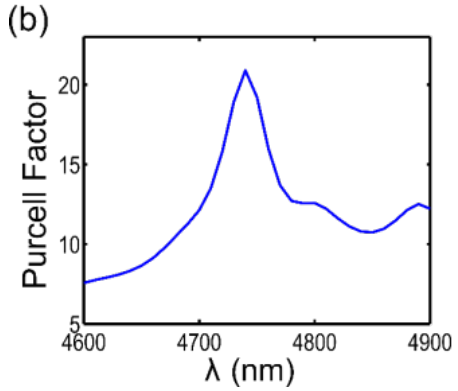
Pixels as small as $3\lambda \times 3\lambda$ have $Q \approx 61$ → number of peripheral cells exceeds the number of central cells

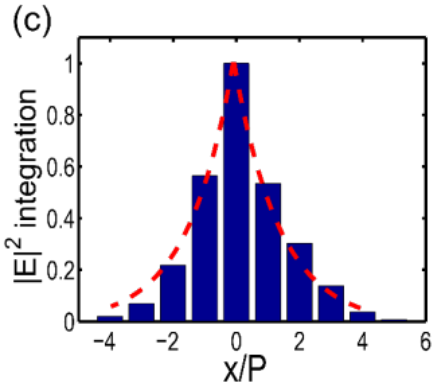
- Near-neighbor interactions are important in collective meta-surfaces, but not nearly as much as in 2D photonic crystals → distinct concept
- A 2D PhC with $Q \approx 100$ operating at $\lambda = 5\mu m$ would have to be rather large ($0.5mm \times 0.5mm$), and would require a collimated beam with $\delta\theta = 0.6°$

Importance of Close-Neighbor Interactions









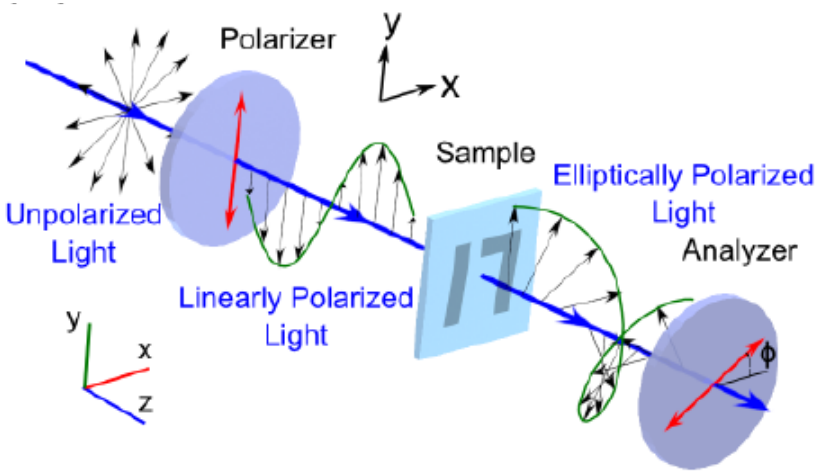
Near-field excitation reveals a narrow-band peak in the photonic density of states

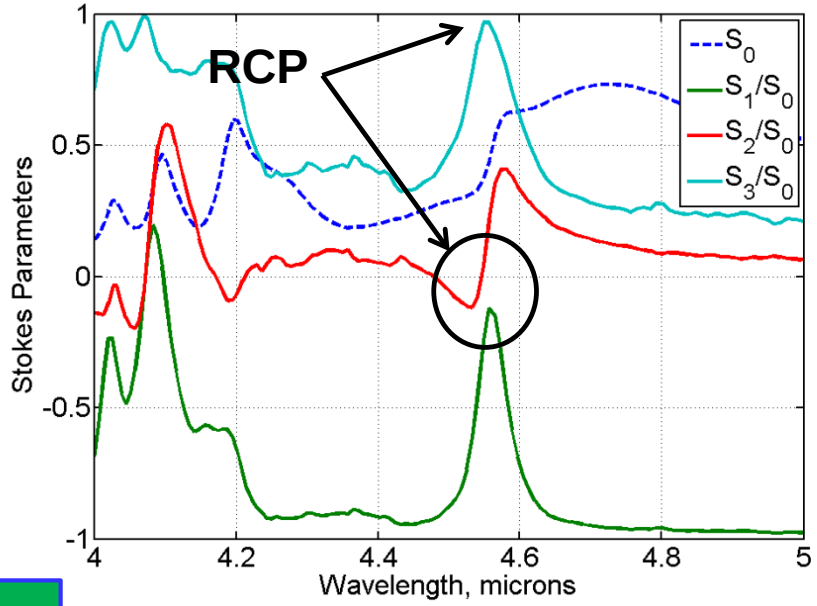
Collective close-neighbor interactions persist over periods → each unit cell must have at least 2 nearest neighbors on each side horizontally

Conceptually different from PhC → "almost-collective" metasurface

LP→ CP: Stokes Parameter Extraction

Rotating analyzer Stokes polarimetry





- **LP→CP conversion by 1 micron thick MS with high efficiency (50%) at normal incidence**
- **Experimentally measured quality factor $Q \approx 95$**
- **Close to 100% Degree of Circular Polarization**

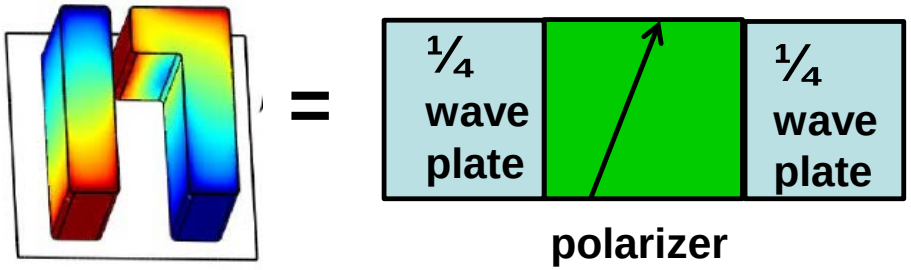
$$S_1 = I_x - I_y, S_2 = I_{45^\circ} - I_{-45^\circ}$$

$$S_0 = I_x + I_y, |S_3| = |I_{RCP} - I_{LCP}|$$

How does LP→CP conversion work?

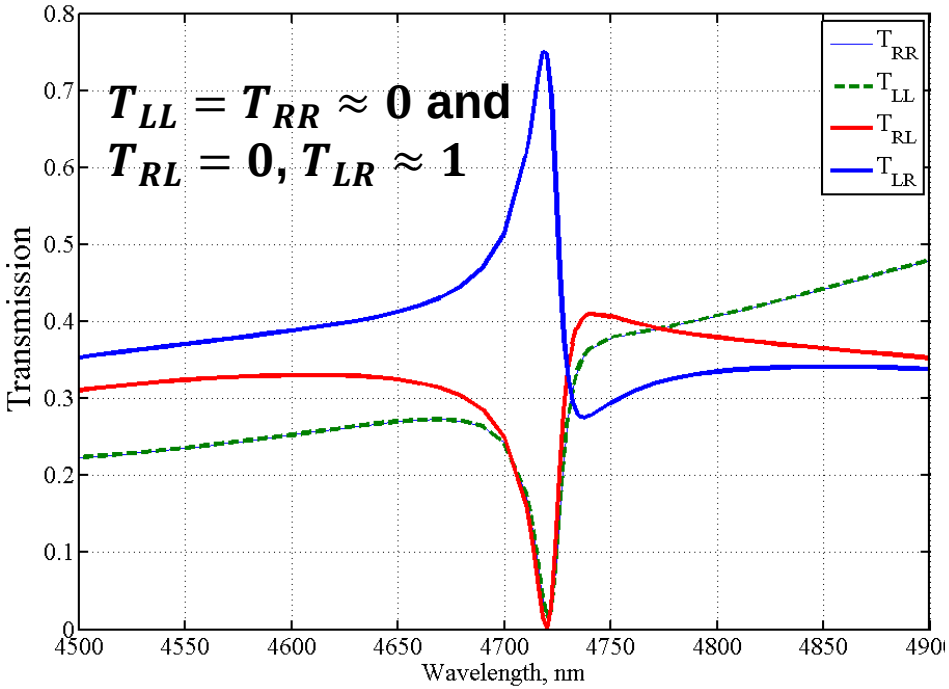
How is it different from regular birefringence or 3D chiral structures?

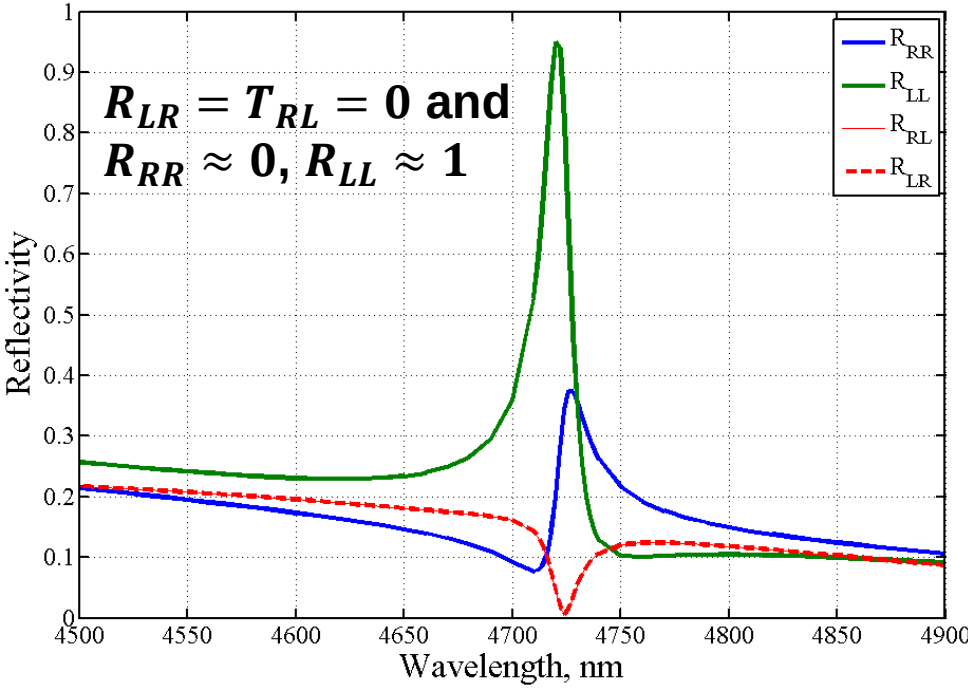
Can one use chiral MS for developing a CP thermal emitter?



Super-Chiral Metasurfaces

Objective: $T_{RR} + T_{RL} \ll T_{LL} + T_{LR}$ → high Degree of Circular Polarization



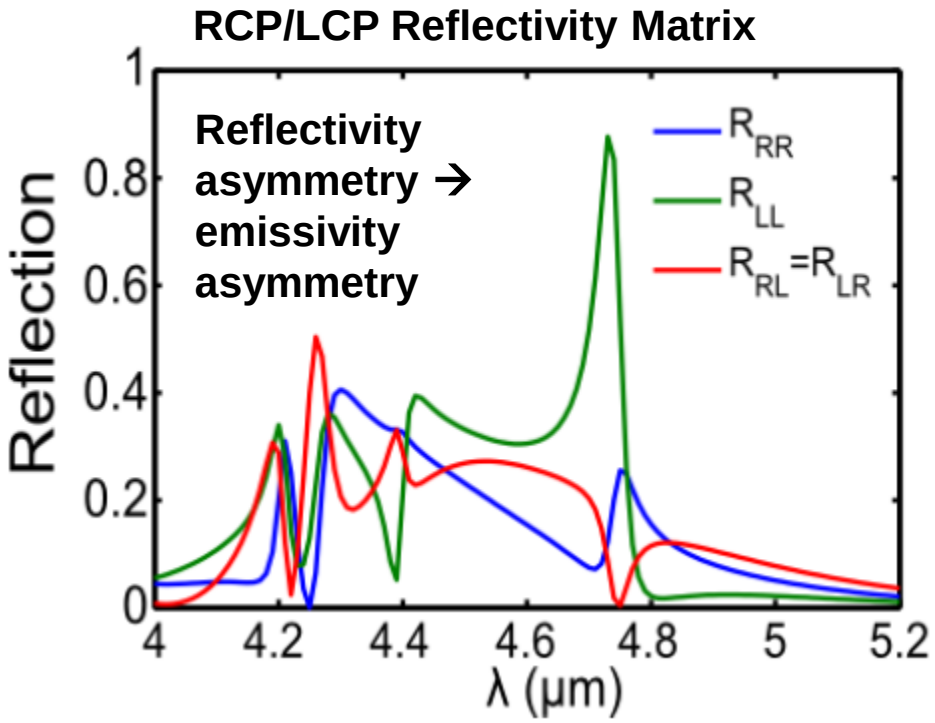


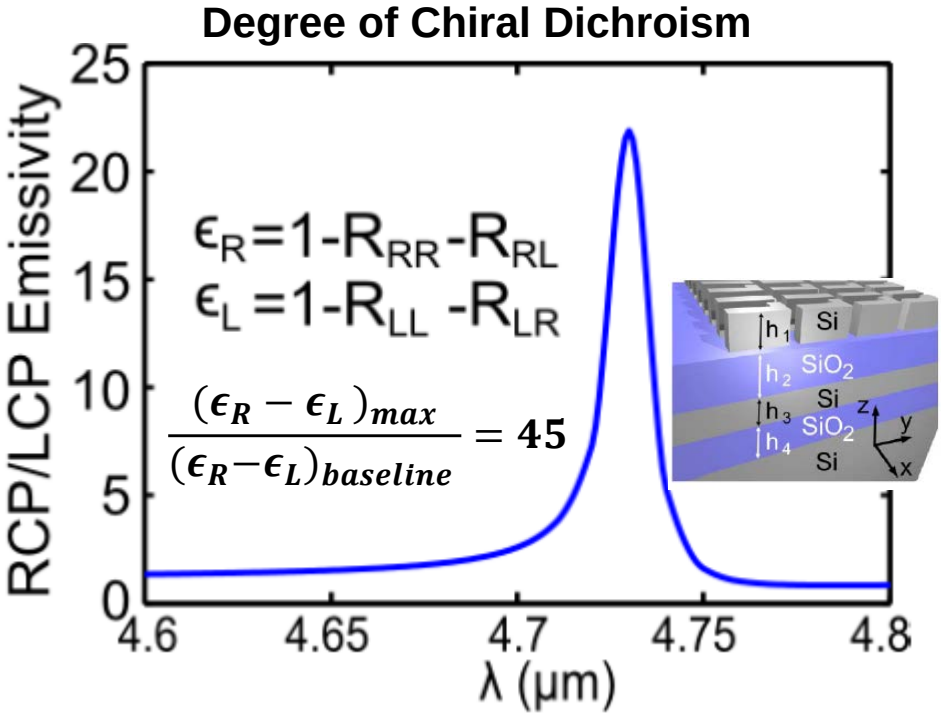
Only RCP gets transmitted. And when it does, it gets flipped into LCP!

All of LCP gets reflected…as LCP → Super-Chiral Mirror!

- **The effect does not require (a) dissipation, (b) substrate/air mismatch, (c) non-normal incidence → [¼ λplate + polarizer + ¼λplate] 1μm thick!**
- **It requires finite thickness ($h \approx \lambda/4$ → impossible with noble metals), periodicity, and bi-anisotropy ($M_z \propto \kappa E_y$)**

Spectrally Selective CP Thermal Emission

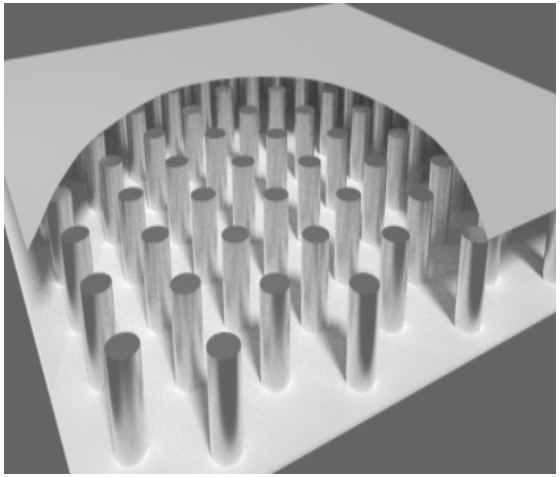


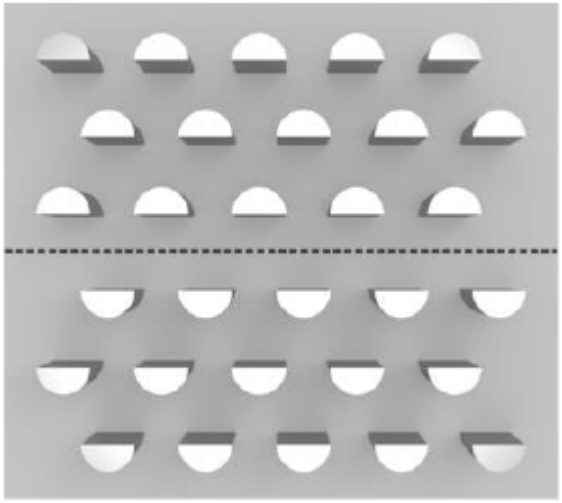


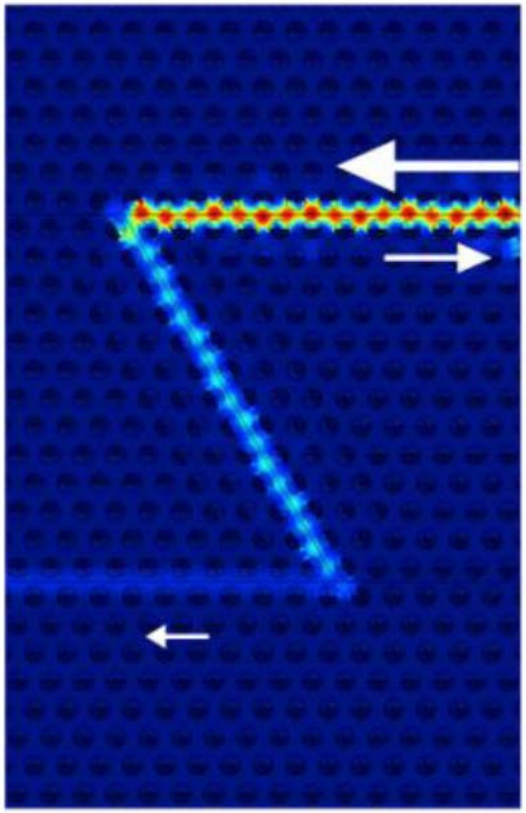
Infrared ID Tags Applications: Unique Spectral/Polarization Signatures!

- $\sigma_{FWHM} \approx 25nm$: more than 12 CP emission lines separated by 6- σ_{FWHM} inside the $\lambda = 3-5\mu m$ IR transparency window
- The entire scene emits thermal IR, but it is not circularly polarized → unique opportunities for IR Identification Tags
- Each line can be RCP, LCP, or un-polarized: $3^{12} = 530,000$ unique IR identification tags with unique spectral/polarization signatures

Avoiding Reflections Using Photonic Topological Protection







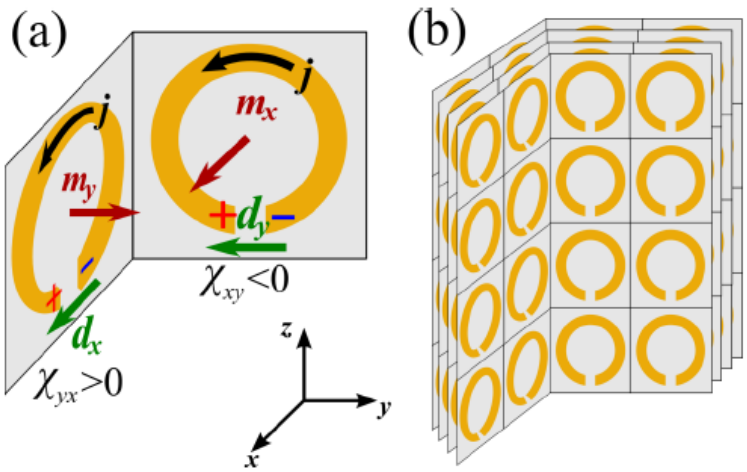
Property of a scalar wave equation: any obstacle/bend on the scale of one wavelength is going to cause reflections of the microwaves!

This is true for either bulk or surface waves

•There is a precedent of suppressed reflections in physics: an electron with spin- ½ and strong spin-orbit coupling propagates without scattering!

A. Khanikaev et. al., Nature Materials **12,** 233 (2013)

Emulating Electron Spins and Topological Insulators Using Bi-anisotropic Metamaterials



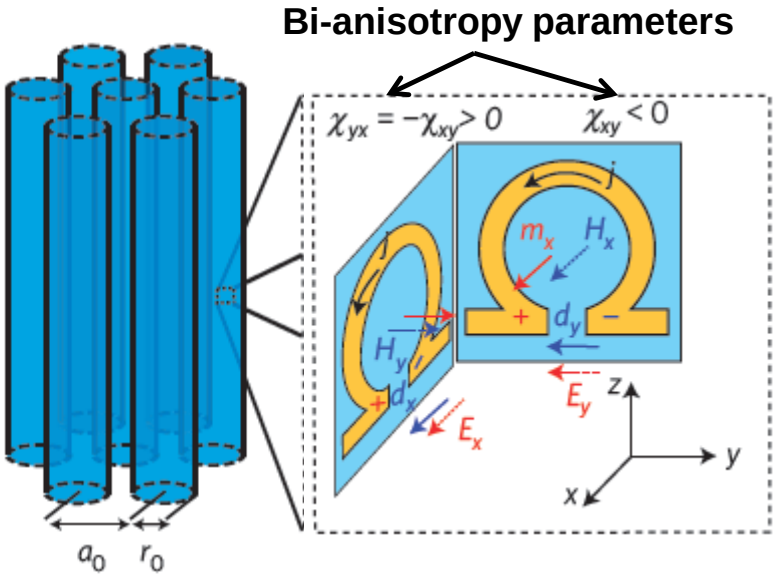
$$\vec{\nabla}\times\vec{E}=+\frac{i\omega}{c}\left(\overline{\overline{\mu}}\cdot\vec{H}+\overline{\overline{\zeta}}\cdot\vec{E}\right)$$

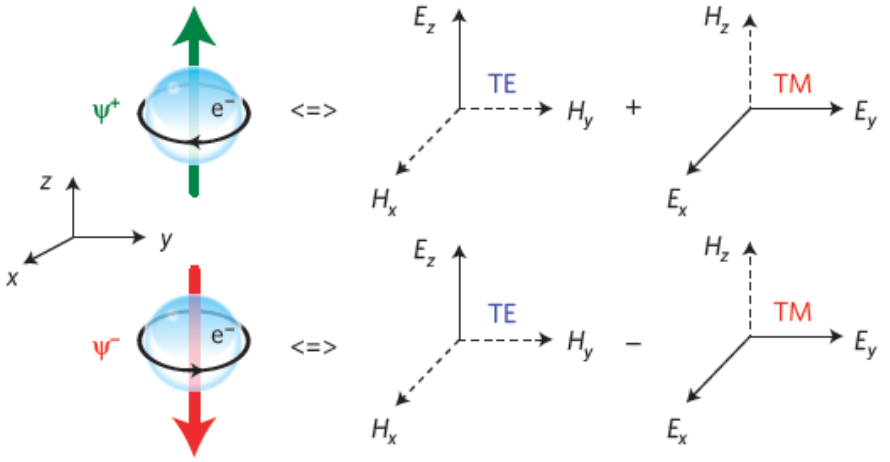
$$\vec{\nabla}\times\vec{H}=-\frac{i\omega}{c}\left(\overline{\overline{\xi}}\cdot\vec{H}+\overline{\overline{\varepsilon}}\cdot\vec{E}\right)$$

Bi-anisotropy requires breaking mirror reflection symmetry

A. Khanikaev et. al., Nature Materials **12,** 233 (2013)

From Metamaterial to Meta-Crystal





2-D PhMC: Photonic Crystal comprised of metamaterial inclusions

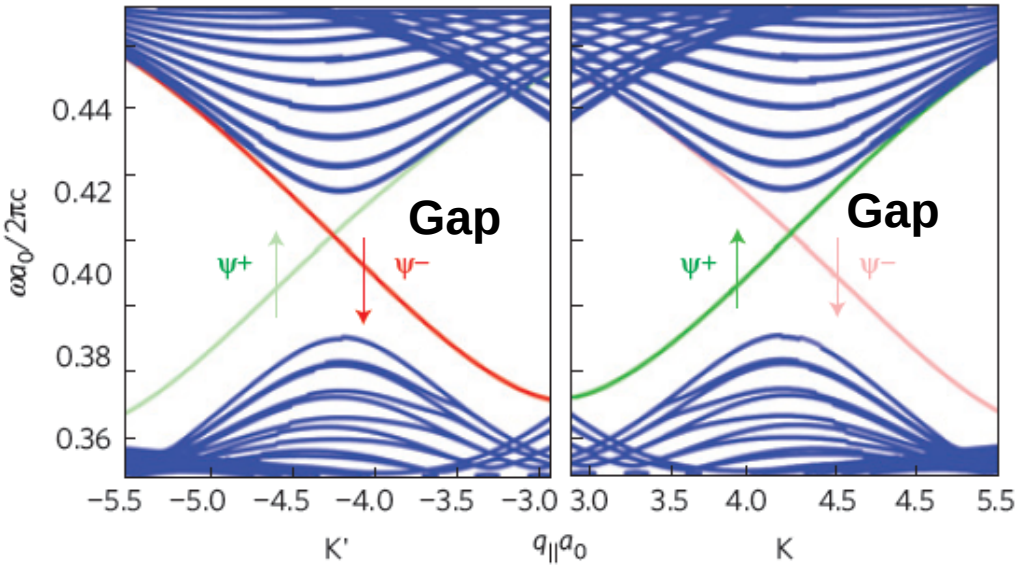
$$\psi^{\pm}(\boldsymbol{x}_{\perp};\boldsymbol{q}) = E_z(\boldsymbol{x}_{\perp};\boldsymbol{q}) \pm H_z(\boldsymbol{x}_{\perp};\boldsymbol{q})$$

$$\left(k_0^2\epsilon_{zz} + \boldsymbol{\nabla}_{\perp}\frac{1}{\mu_{\perp}}\boldsymbol{\nabla}_{\perp}\right)\psi^{\pm} = \pm\left[\boldsymbol{\nabla}_{\perp}\left(\frac{-i\chi_{xy}}{\epsilon_{\perp}\mu_{\perp}}\right)\times\boldsymbol{\nabla}_{\perp}\psi^{\pm}\right]_z$$

- **Photonic equivalents of spin-up and spin-down electron states**
- **Requires spin-degenerate metamaterials: $\epsilon_{zz} = \mu_{zz}$, $\epsilon_{\perp} = \mu_{\perp}$**
- **Exact emulation of Kane-Mele Hamiltonian of graphene TIs**

Interfaces: Edge States of PTIs

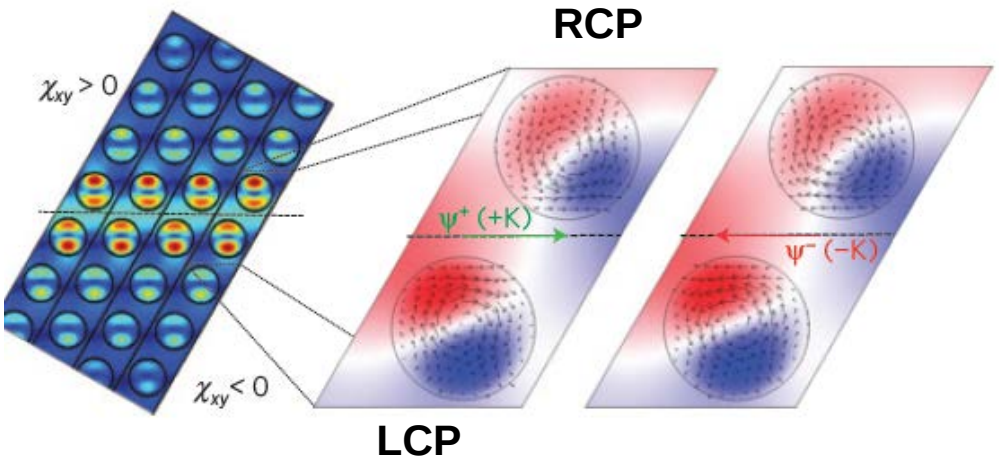
Interfaces between PTIs (e.g. between $\chi_1 > 0$ and $\chi_2 < 0$) support one-way spin-degenerate states!



"Spins" don't scatter into each other as long as the materials are spin-degenerate: $\epsilon_{zz} = \mu_{zz}$, $\epsilon_{\perp} = \mu_{\perp}$ → restricted topological protection

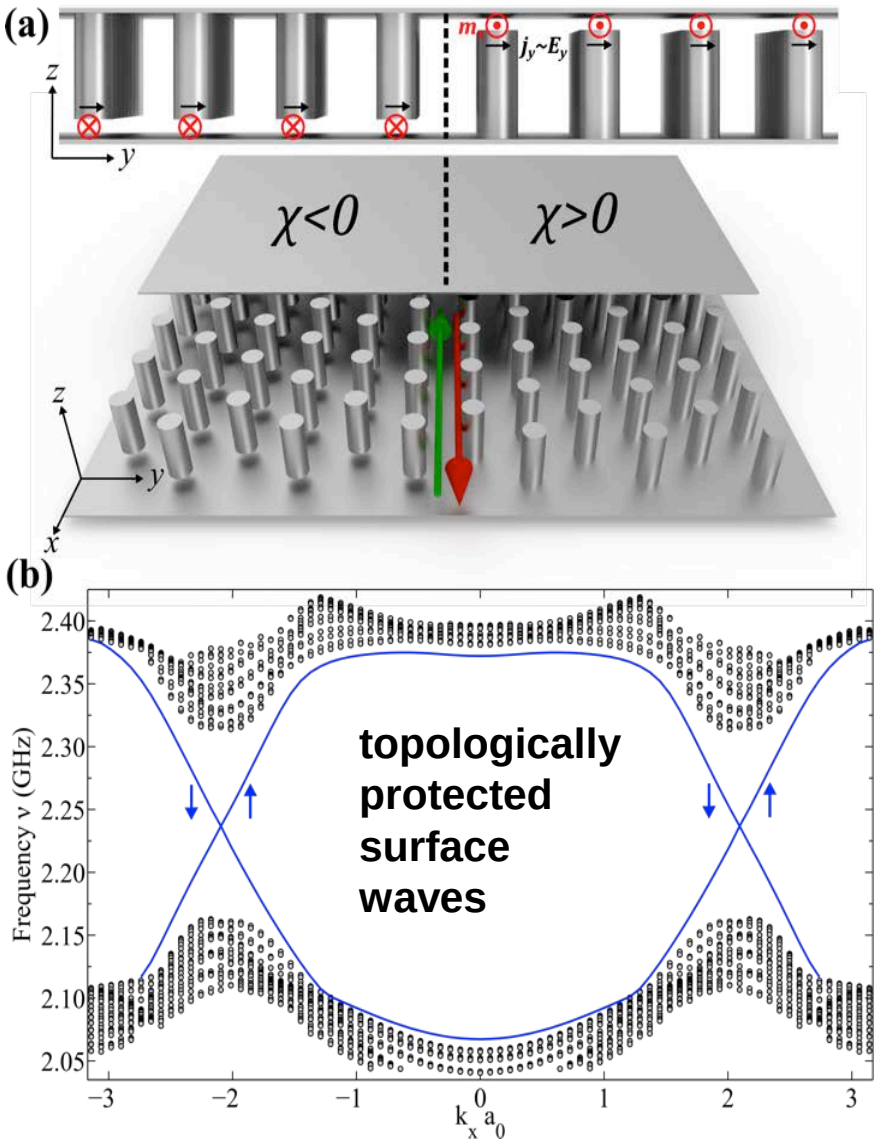
Spin degree of freedom → relative phase between E_z and H_z

Orbital degree of freedom → CP at K point of Brillouin zone

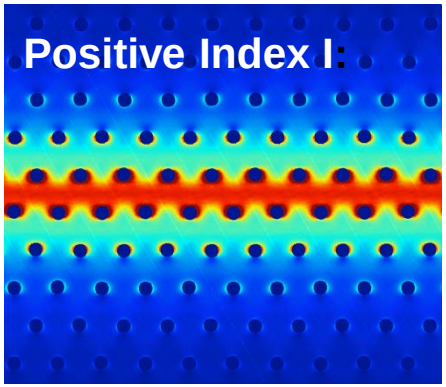


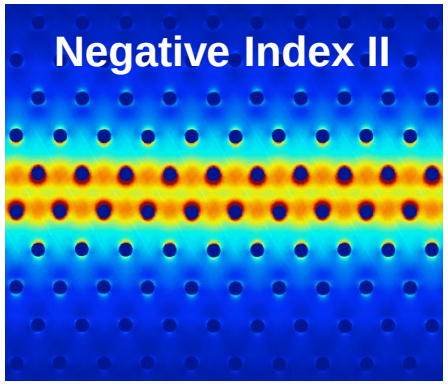
From Meta-Crystals to Meso-MMs

Topological Interface



Bi-anisotropic Meta-Waveguide (BMW) → simplified version of PTIs emulates spin-orbit coupling



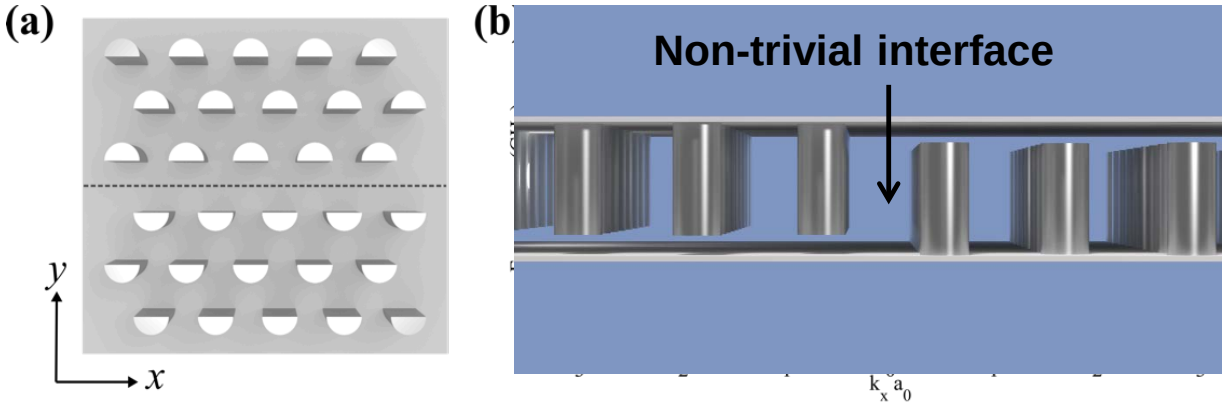


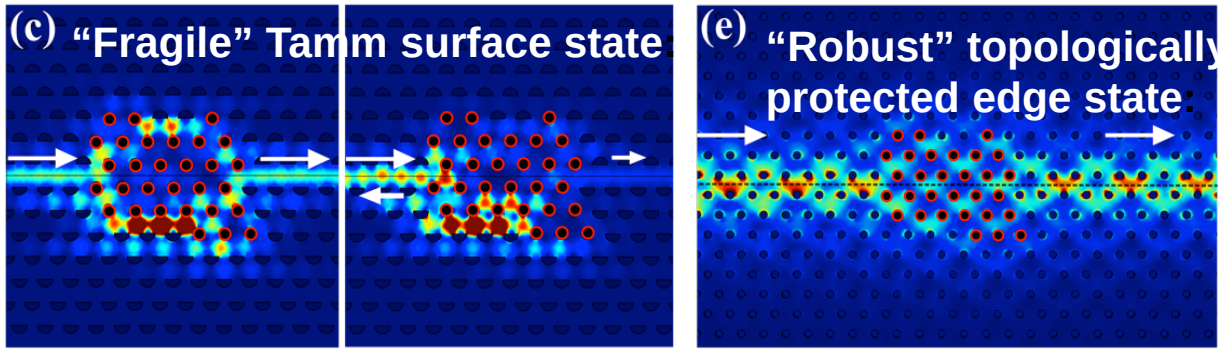
Spin-polarized photon flow: two spin-up states moving forward, two spin-down states moving backward

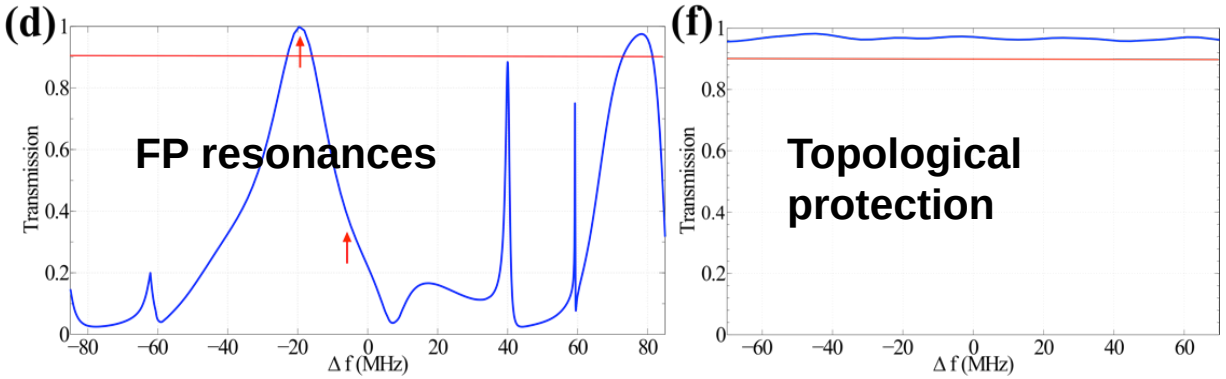
Topological protection of edge states against backscatter

Fundamentally different from Tamm states!

Tamm States vs Topologically Protected Edge States: Disorder Sensitivity



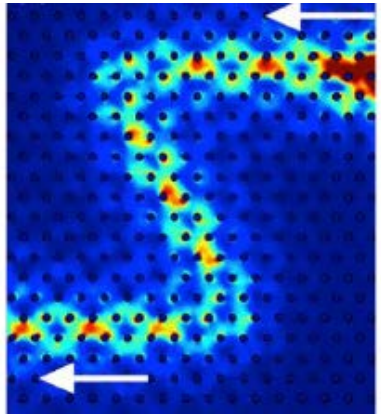




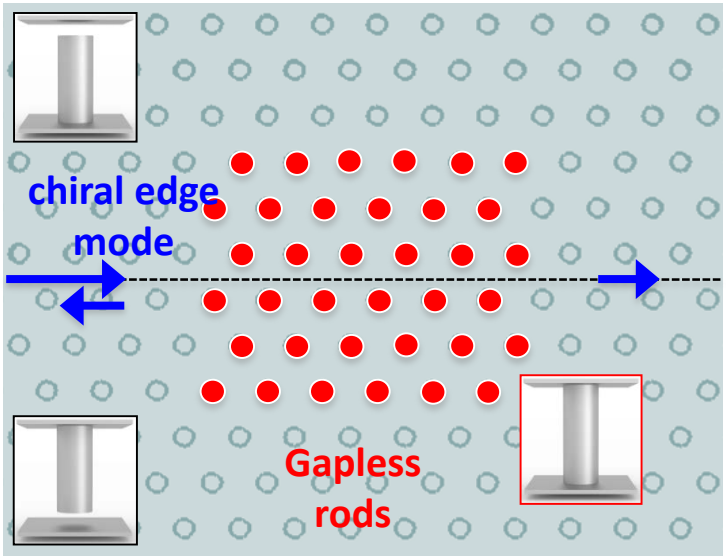
"Cavity" placed along the interface → transmission depends on the nature of edge state:

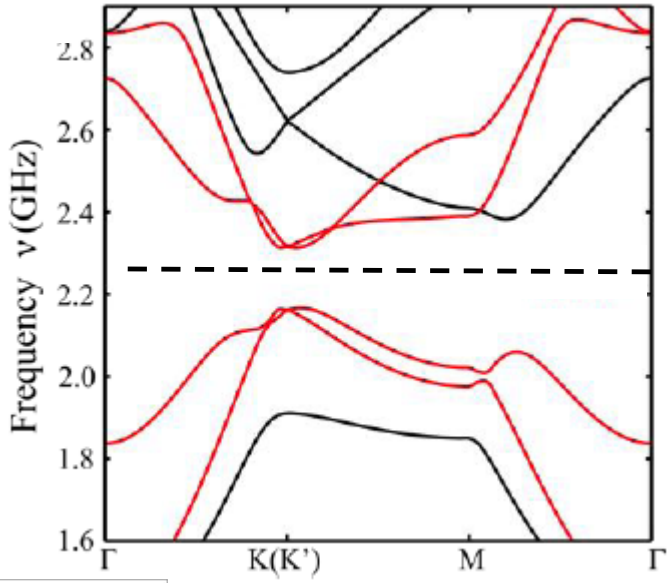
(1) Tamm state → small transmission interrupted by Fabry-Perot resonances

(2) Topologically protected edge state → nearly perfect transmission → guide waves around corners

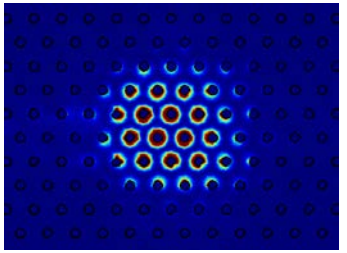


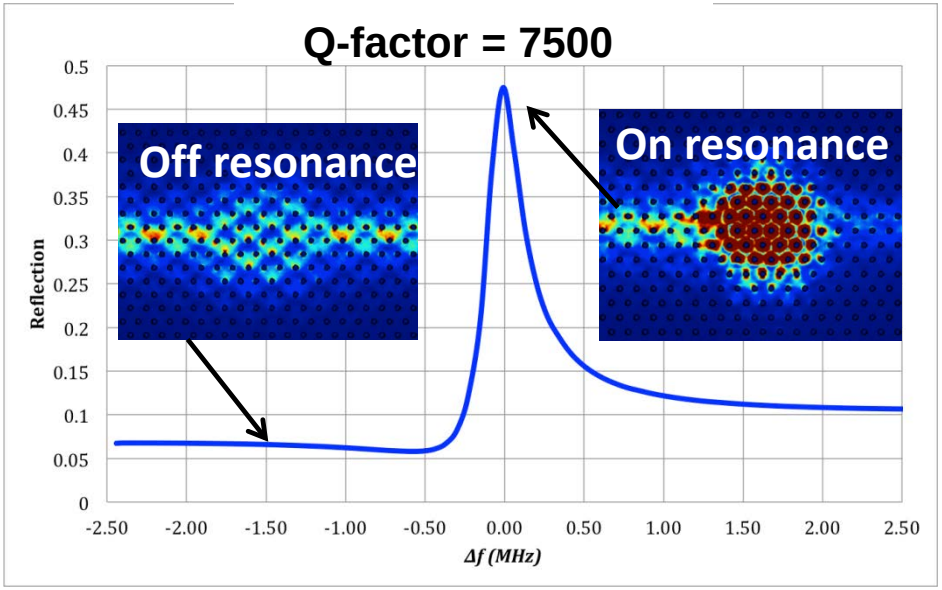
Breaking topological protection





Resonant magnetic impurity inside topological bandgap



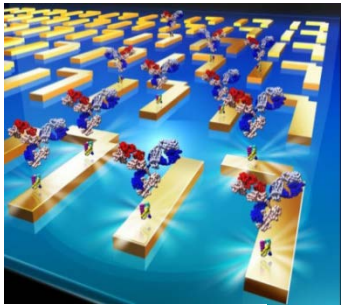


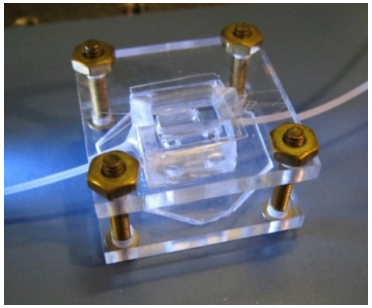
Cavity eigenmode couples ↑↓ spin states → resonant backscattering is allowed by spin-flipping!

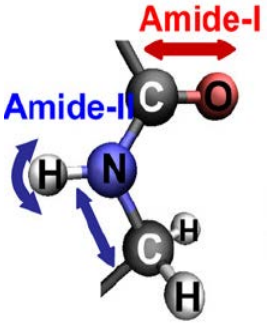
Two-mode theory collapses in the presence of third mode!

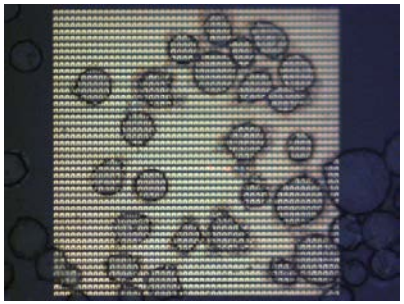
Nonlinearities also break topological protection → emulation of many-body effects in CM

What Can Metamaterials Do For You: Applications Time!



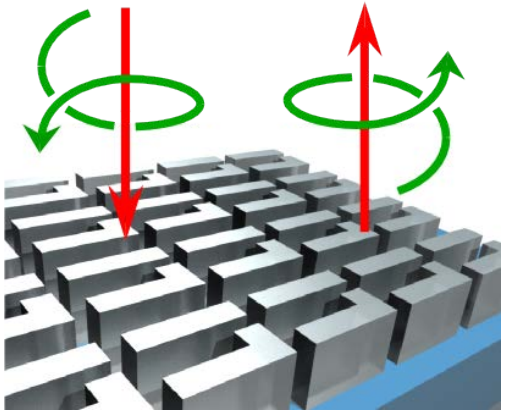




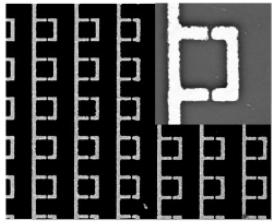


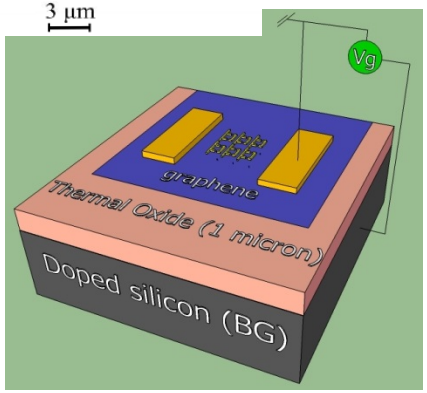
C. Wu et.al., Nature Materials **11,** 69 (2012) → surface-enhanced IR spectroscopy of protein monolayer; microfluidic integration for cell identification in blood (CTCs)

All-dielectric super-chiral metasurfaces with Q>100



C. Wu et.al., Nature Comm. (in press) → engineering of thermal/quantum emission → sources of CP radiation across EM spectrum





S. H. Mousavi et. al., NL **13,** 1111 (2013) → integration of SLG with metamaterials → agile IR modulators, beam steering.

Acknowledgements

Postdocs/Staff:

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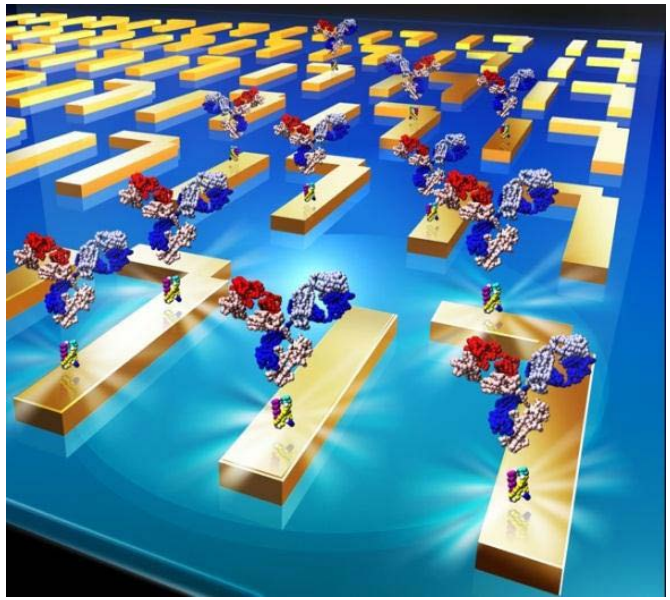
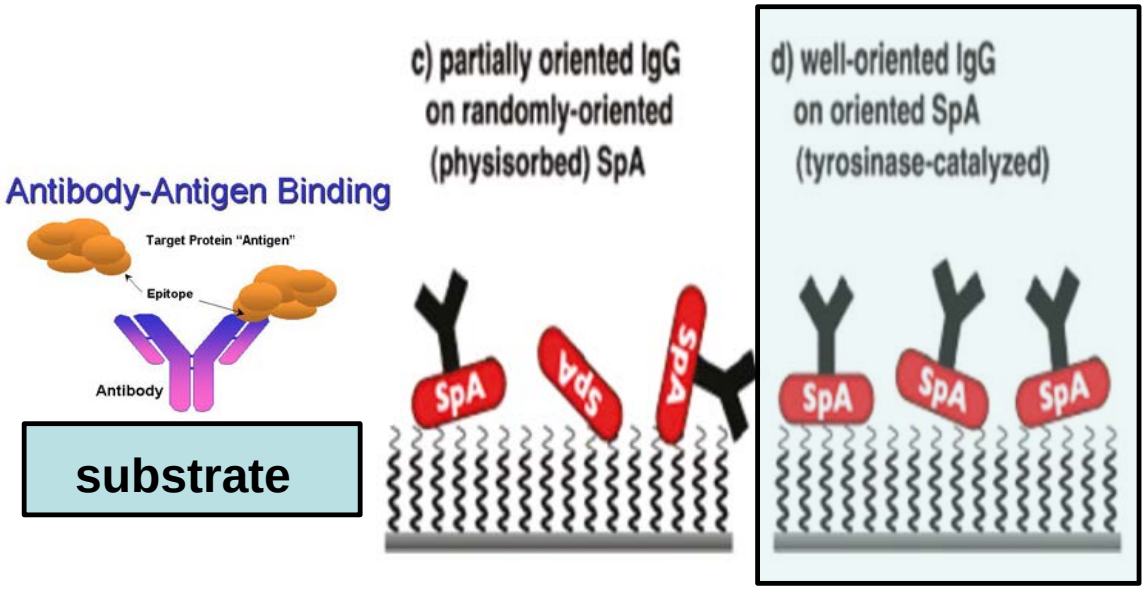
Rod Ruoff (UT)

Additional Slides

Novel platform for bio-sensing and molecular fingerprinting: Metasurface Enhanced Infrared Reflection Spectroscopy → MEIRS

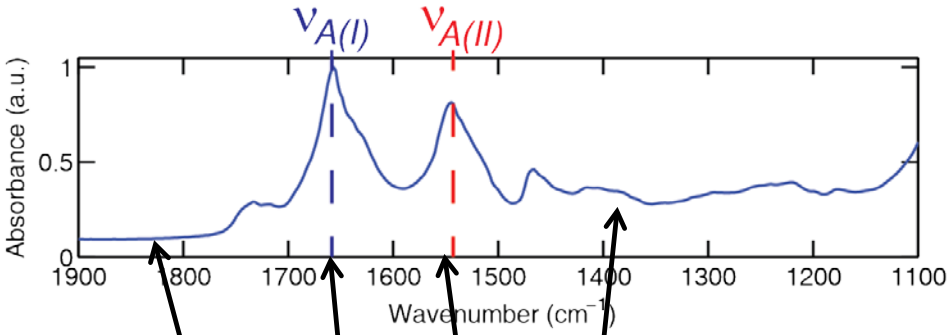


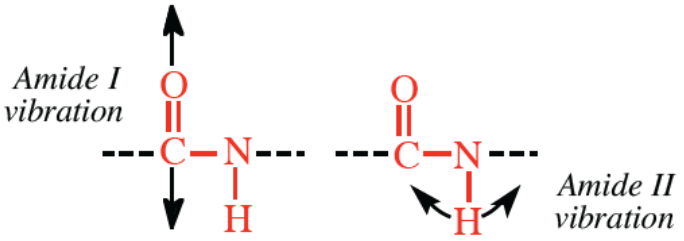


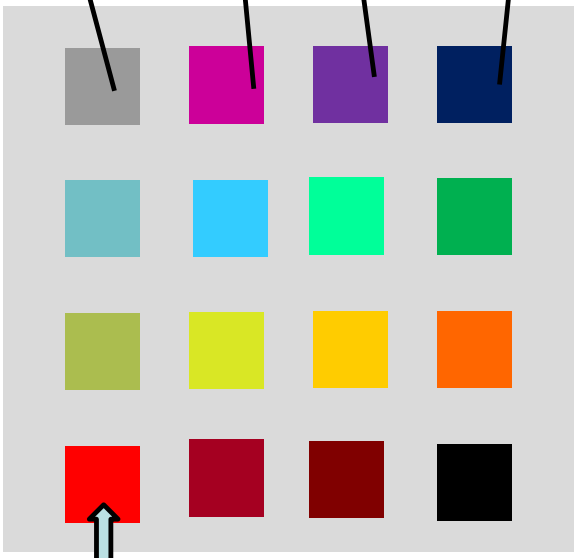
Chihhui Wu et.al., Nature Materials **11,** 69 (2012)

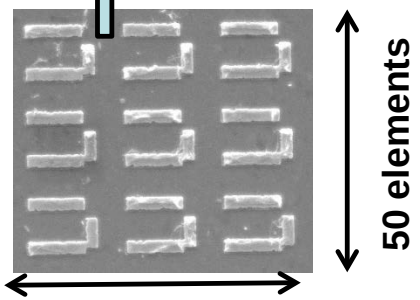
Objective: better biosensor by improving the orientation of binding proteins and antibodies → higher binding capacity

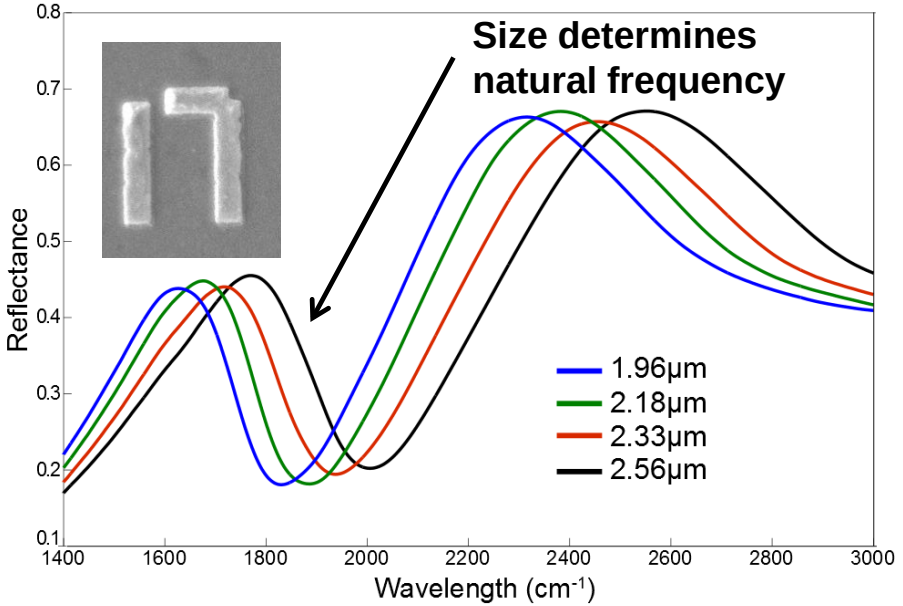
Meta-Pixels Mosaic Tuned to Fingerprints





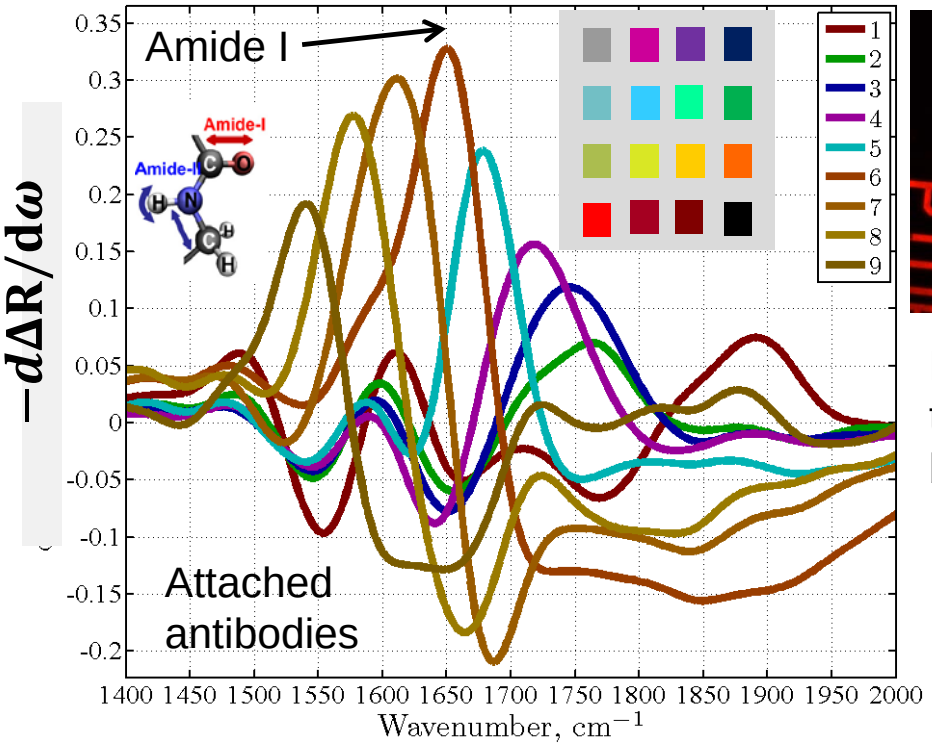






- **Pixels' resonance frequencies can be swept across vibrational resonances**
- **Resonant and non-resonant pixels → additional data points for bio-sensing**

How sensitive is MEIRS: Comparison with Fluorescence Measurements



Fluorescently tagged antibodies before washing

Attached antibodies (after washing): fluorescence not observed under microscope

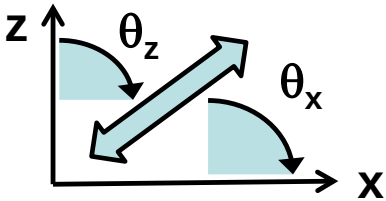
$\Delta R(\omega)$: Difference spectrum (with protein – bare) → peaks at the MM resonance

- Single monolayers of fluorescently tagged antibodies are difficult to detect using unspecialized microscopes
- Metasurface-enhanced infrared spectroscopy (MEIRS) enables the detection of antibody monolayers → strongest signal when metasurface resonance is matched to vibrational resonance of the protein (e.g., Amide I)
- **Advantageous to avoid exogenous labels for tagging**

Interaction of Anisotropic and Oriented Proteins with Metasurfaces

$$T_{ij} = N^{-1}\sum_{k=1}^{N}\cos\theta_i^{\{k\}} \times \cos\theta_j^{\{k\}}$$

orientation tensor: C=O bond with respect to Cartesian axes

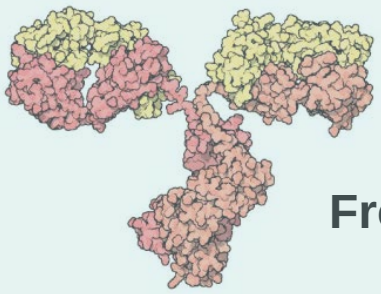


$$T_{ij} = (1/3)\delta_{ij}$$

for isotropic proteins

$$\varepsilon_p(\omega) = \varepsilon_\infty + \sum_m \frac{A_m T_{zz}}{\omega - \omega_m - i\gamma_m}$$

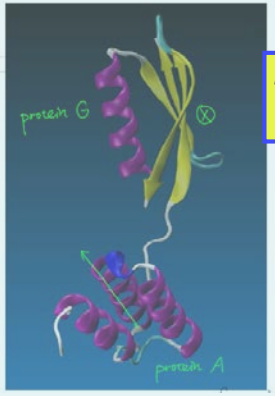
Orientation of anisotropic proteins detected by surface-enhanced spectroscopy



Isotropic IgG protein

From Protein Data Base

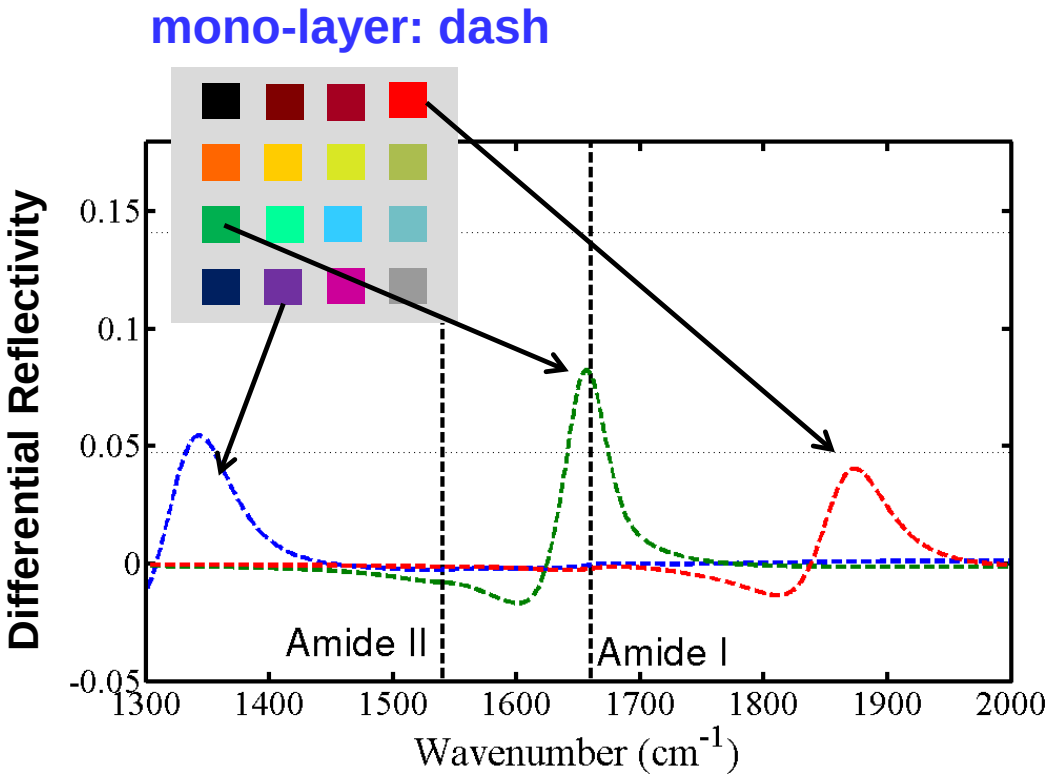
$$T_{ij}^{IgG} = (0.29;0.32;0.39)$$



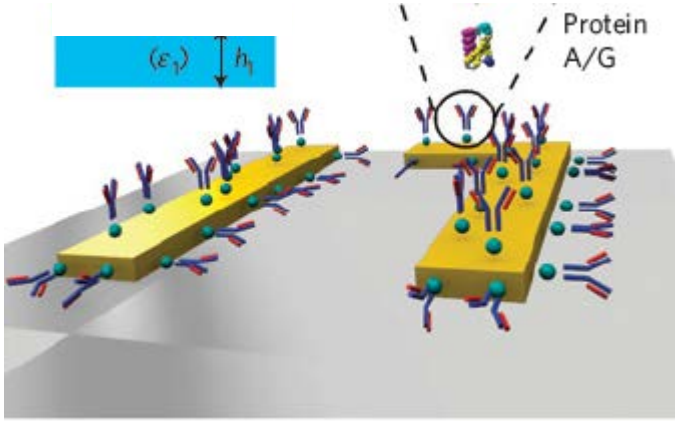
$$T_{ij}^{A/G} = (0.14;0.22;0.63)$$

Anisotropic protein A/G

MEIRS determines protein layer compositions



Binding of A/G monolayer of thickness h_1=2.7nm to three FRAMM pixels (blue, green, red)



C. Wu et.al., Nature Materials **11,** 69 (2012)

$$\varepsilon_p(\omega) = \varepsilon_\infty + \sum_m \frac{A_m T_{zz}}{\omega - \omega_m - i\gamma_m}$$

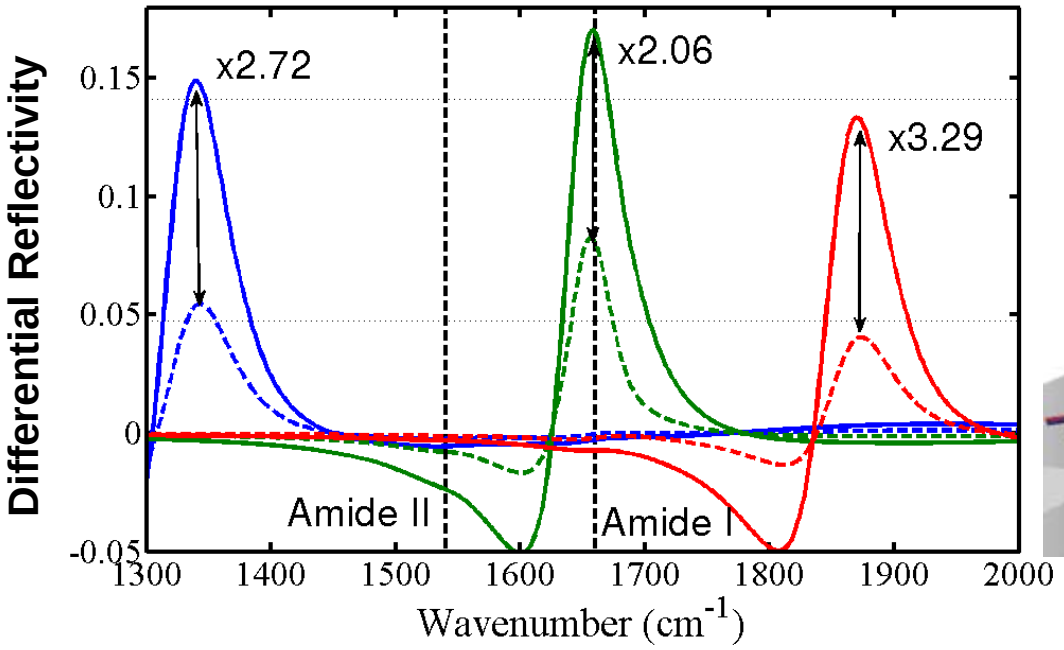
Non-resonant blue pixel is not vibration sensitive→ SPR-like thickness measurement

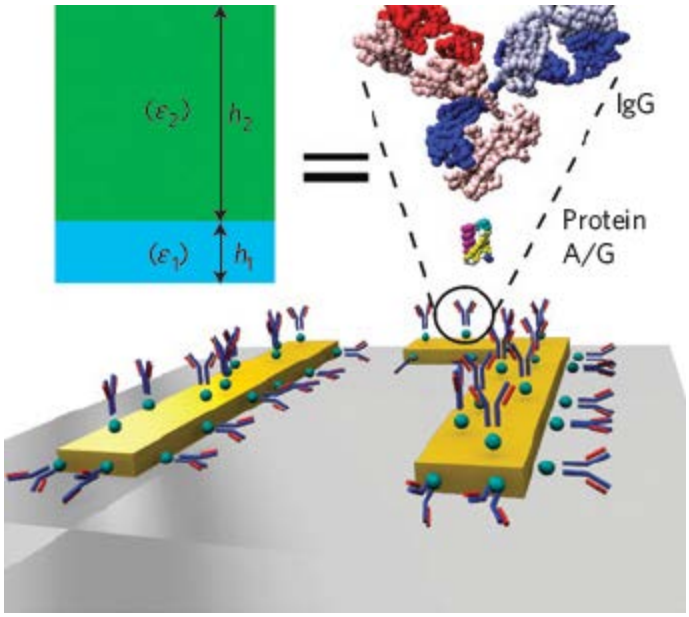
Resonant green pixel is vibration/orientation sensitive → orientation of A/G on the surface

MEIRS determine protein layer compositions

mono-layer: dash
bi-layer: solid

IgG monolayer of height h_2 = 5.1nm binds to A/G monolayer of height h_1=2.7nm → $(h_2 + h_1)/h_1$ = 2.9



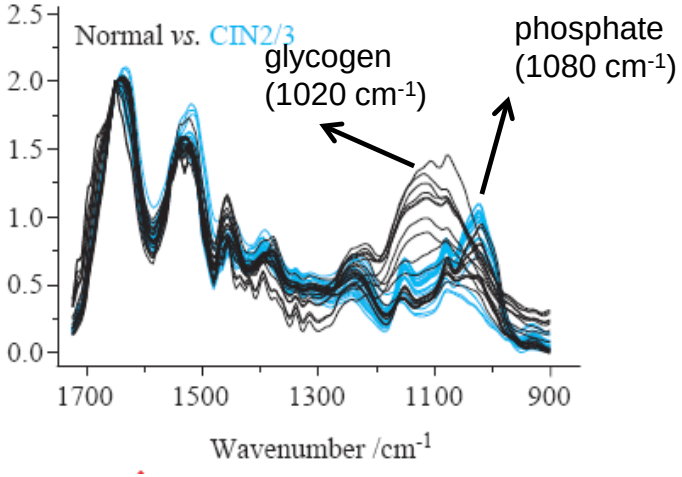


$$\varepsilon_p(\omega) = \varepsilon_\infty + \sum_m \frac{A_m T_{zz}}{\omega - \omega_m - i\gamma_m}$$

→ **Non-resonant blue pixel is not vibration sensitive→ SPR-like thickness measurement**

→ **Resonant green pixel is vibration/orientation sensitive → orientation of A/G on the surface**

Where do we go from here: From Proteins to Cells to Diagnostics

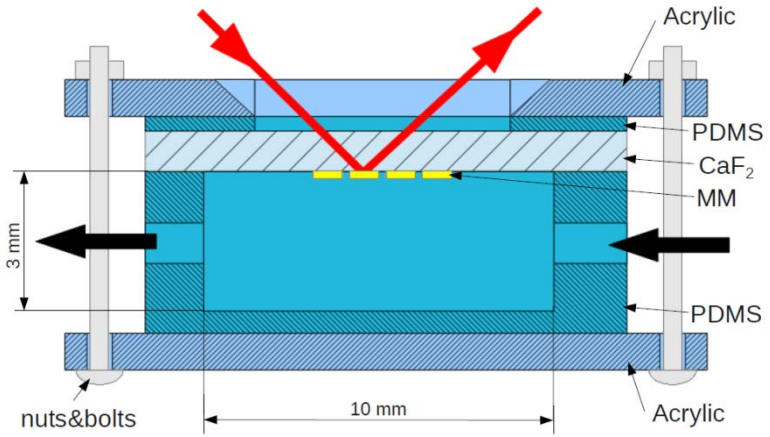


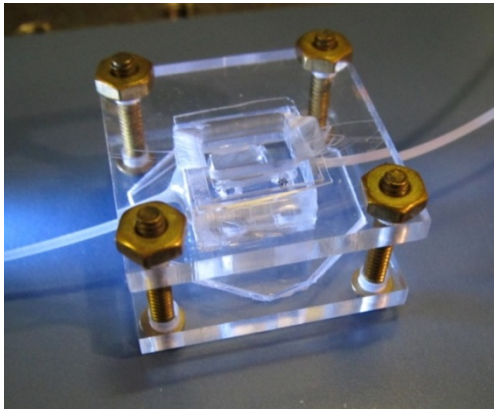
Spectral signatures of cancer cells

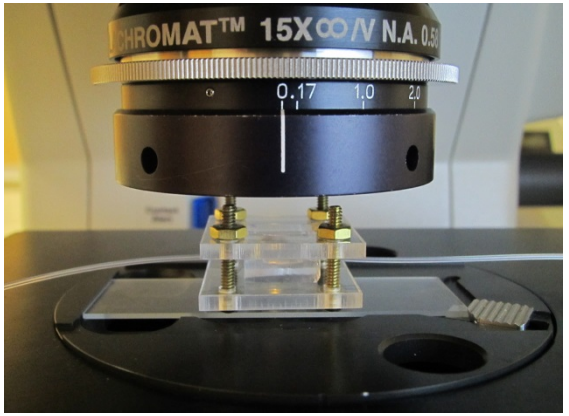
Outlook

The concept of a FRAMM enables plasmonic substrates that combine strong near-field enhancement, sharp spectral features and easy identification of the resonance frequency through polarized reflection spectroscopy. Designed to operate in the mid-infrared part of the electromagnetic spectrum, such substrates can be used for implementing structure-resolving label-free biosensing. Tremendous improvements in sensitivity, speed and time-resolution of biosensing can be achieved by parallel acquisition of the FTIR spectra from large functionalized arrays of narrow-band FRAMM pixels covering a significant portion of the fingerprint spectral region. By using infrared-transparent substrates, we can envision unlocking the mysteries of the conformational dynamics of biomolecules in their natural aqueous environment responsible for life-sustaining molecular binding processes.

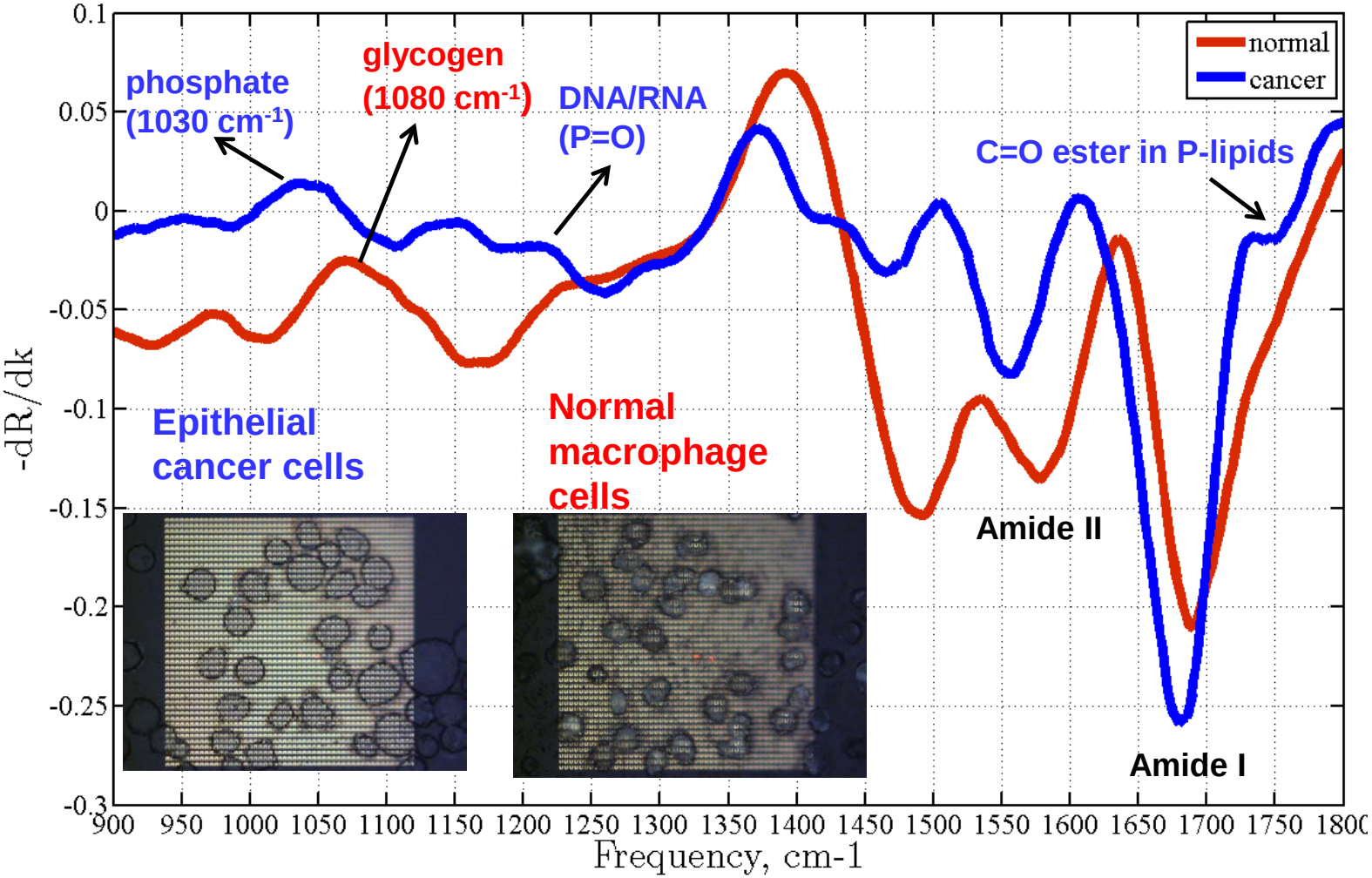
C. Wu et.al., Nature Materials **11,** 69 (2012)







Metamaterials-Based Fingerprinting of Live Cells: Macrophages vs Malignant



Future: detection and identification of circulating tumor cells (CTCs): the key cause of cancer-related mortality because of metastasis