Tunable Meta-surfaces for Active Manipulations of Electromagnetic Waves

Lei Zhou

Physics Department, Fudan University,
Shanghai 200433, China
phzhou@fudan.edu.cn

Acknowledgements

- **Key collaborators**
  Yuanbo Zhang, Qiong Wu

- **Key contributors**
  Shaojie Ma, Ziqi Miao, Xin Li, Wujiong Sun, Weijie Luo, Jiaming Hao, Shulin Sun, Qiong He

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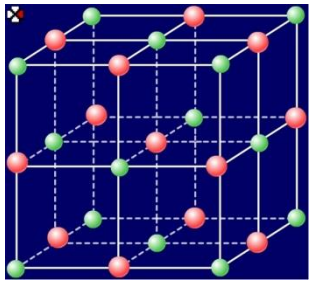
基金委员会
National Natural Science
Foundation of China

Outline

- Backgrounds and recent works in my group
- Complete phase diagram for metal/insulator/metal meta-surfaces (PRL, 2015)
- Graphene meta-surfaces for full-range phase control (PRX, 2015)
- Conclusions

What is Metamaterial?



Conventional material

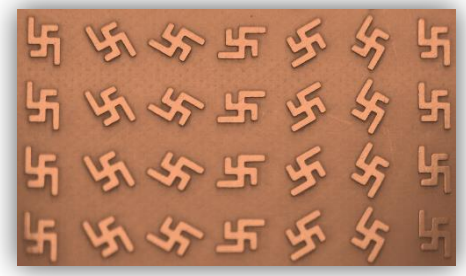
Structural unit: atom

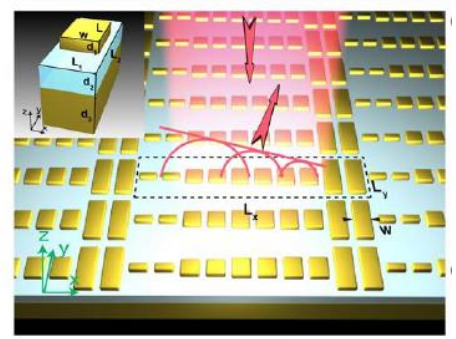
Metamaterial

Structural unit: artificial microstructure

- In principle, nothing is homogeneous except vacuum.
- However, as structural unit << wavelength, a material is homogenized with effective ε, μ; A natural material is homogeneous for visible light
- Change natural atom to subwavelength microstructure, a Metamaterial is formed

Metamaterials → Metasurfaces

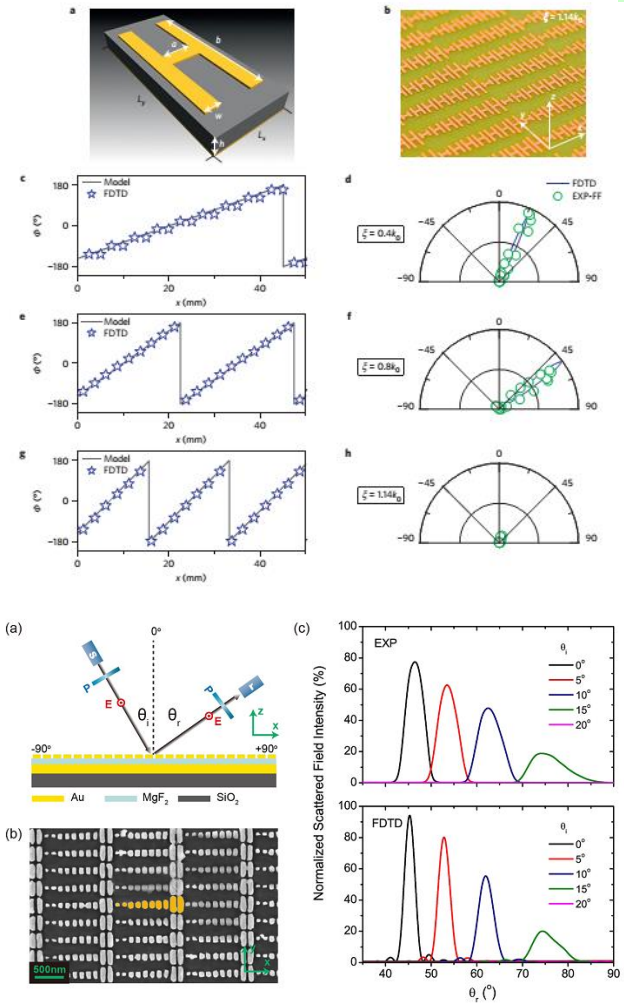




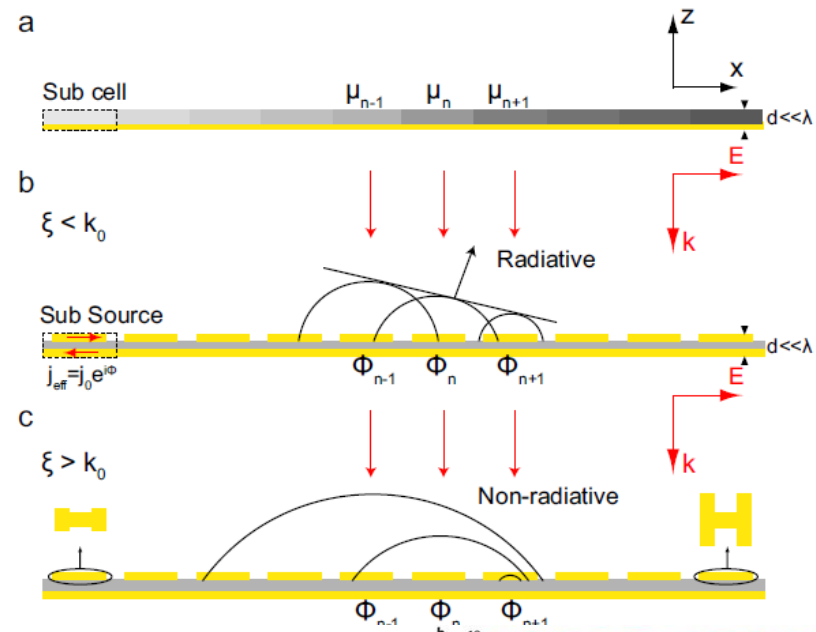
- **Bulk MTM goes to single-layer metasurface**
- **Inhomogeonity provides more freedom to control EM waves**

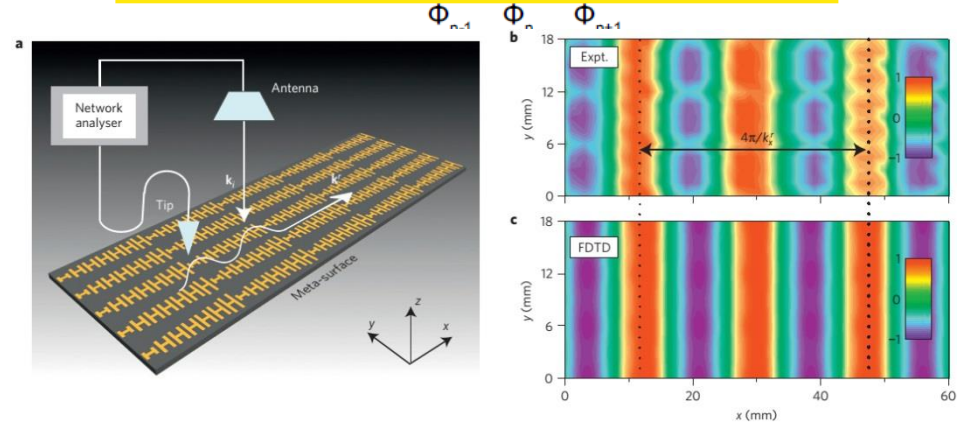
1) Gradient meta-surfaces to bridge PW and SW

Generalized Snell's law $k_{\parallel}^{r} = \xi + k_0 \sin\theta_i$



PW → SW conversion



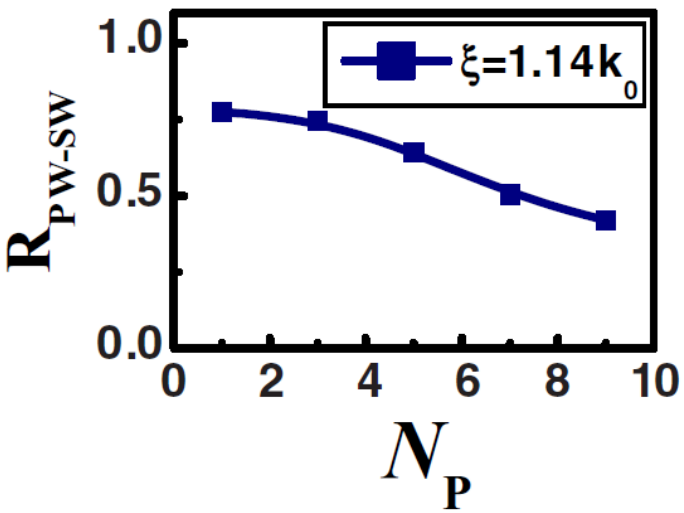


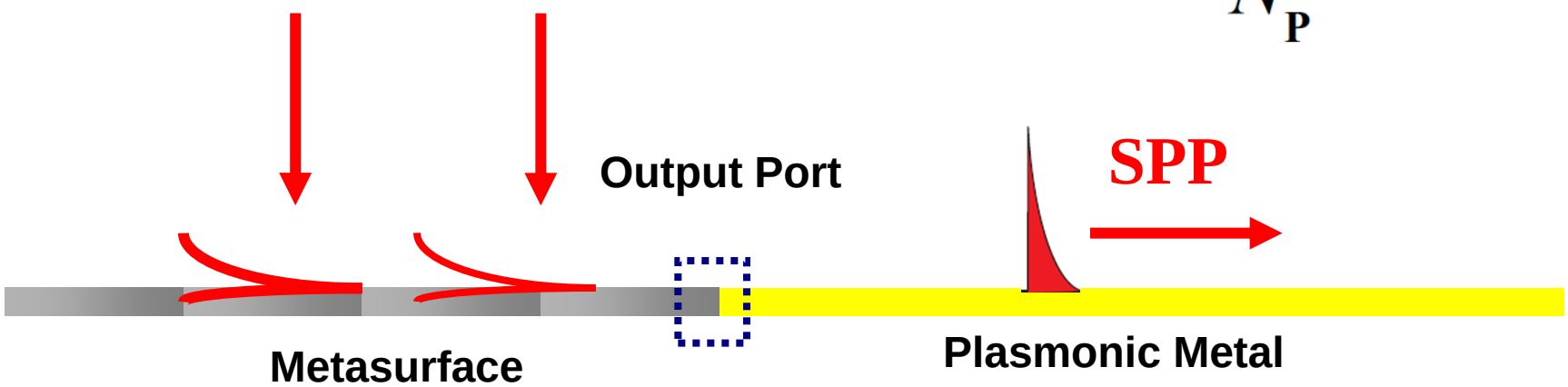
S. Sun et al., Nat. Mater. 11, 426 (2012)

S. Sun et al., Nano Lett. 12 6223 (2012)

Problems of the gradient coupler

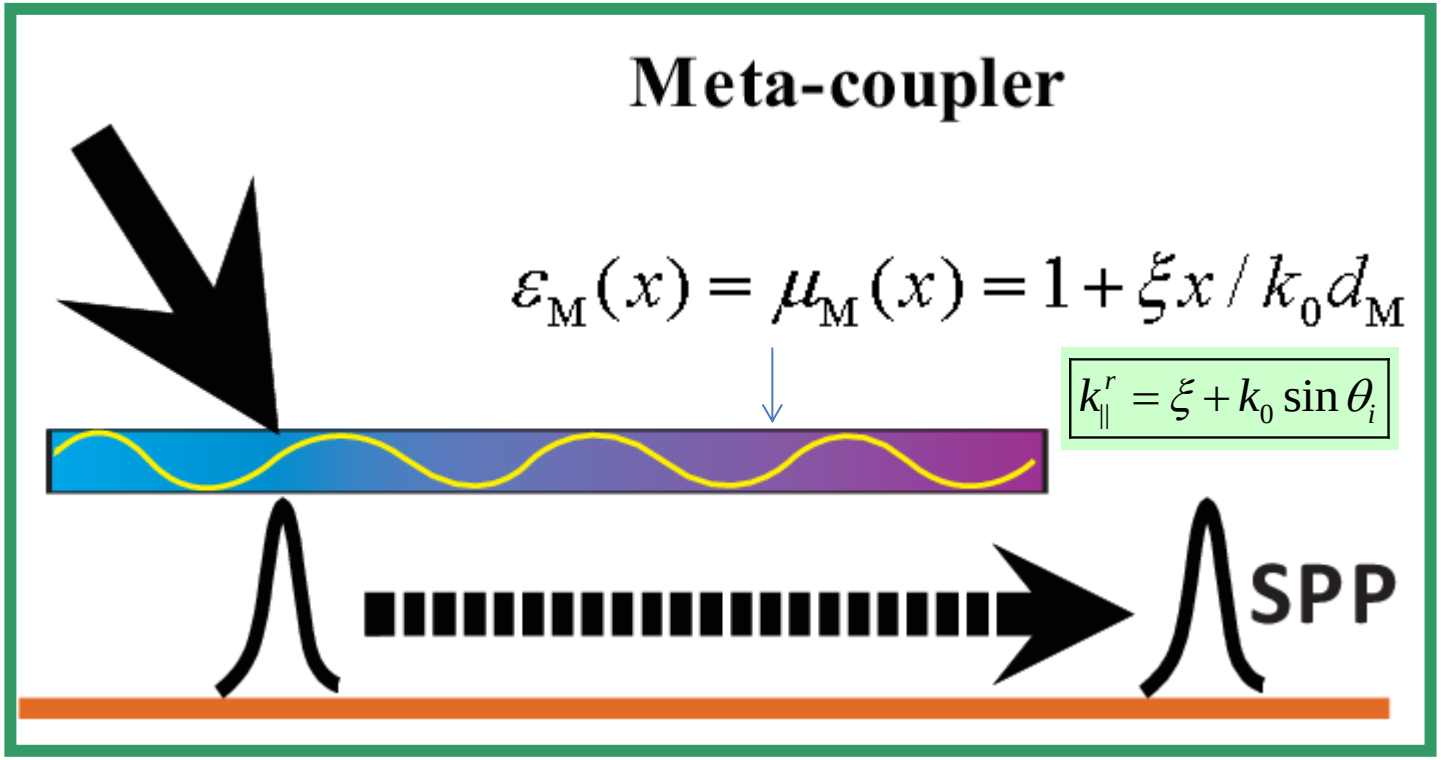
- "Driven SW" flows on the "*inhomogeneous*" meta-surface
- Decouplings due to scatterings are inevitable
- Only works for small beam width





Q. Che et. al., EPL 101, 54002 (2013)

New concept: Meta-coupler for high-efficiency SPP conversion

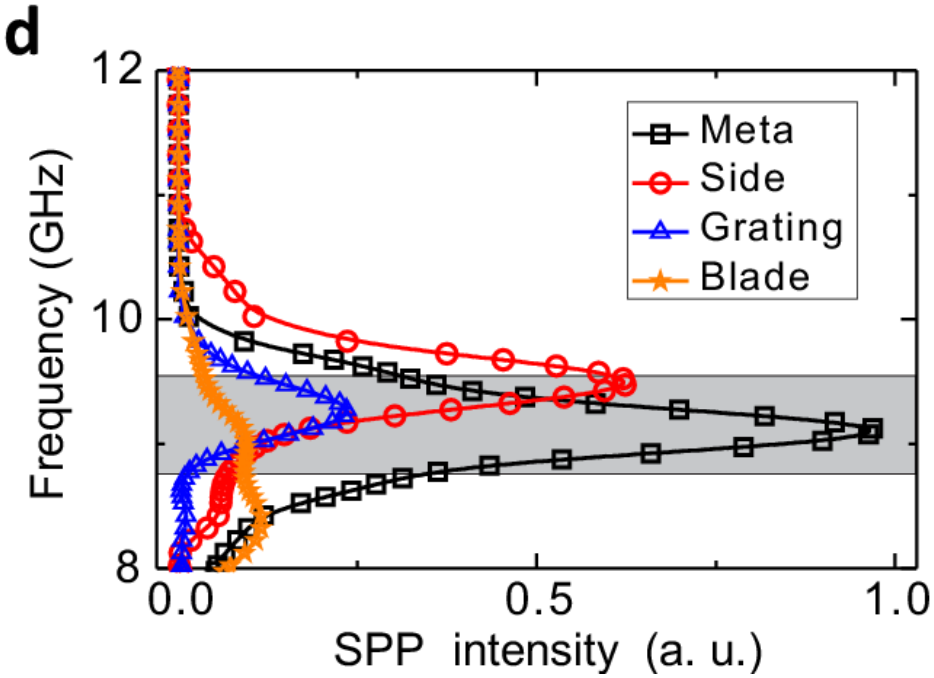


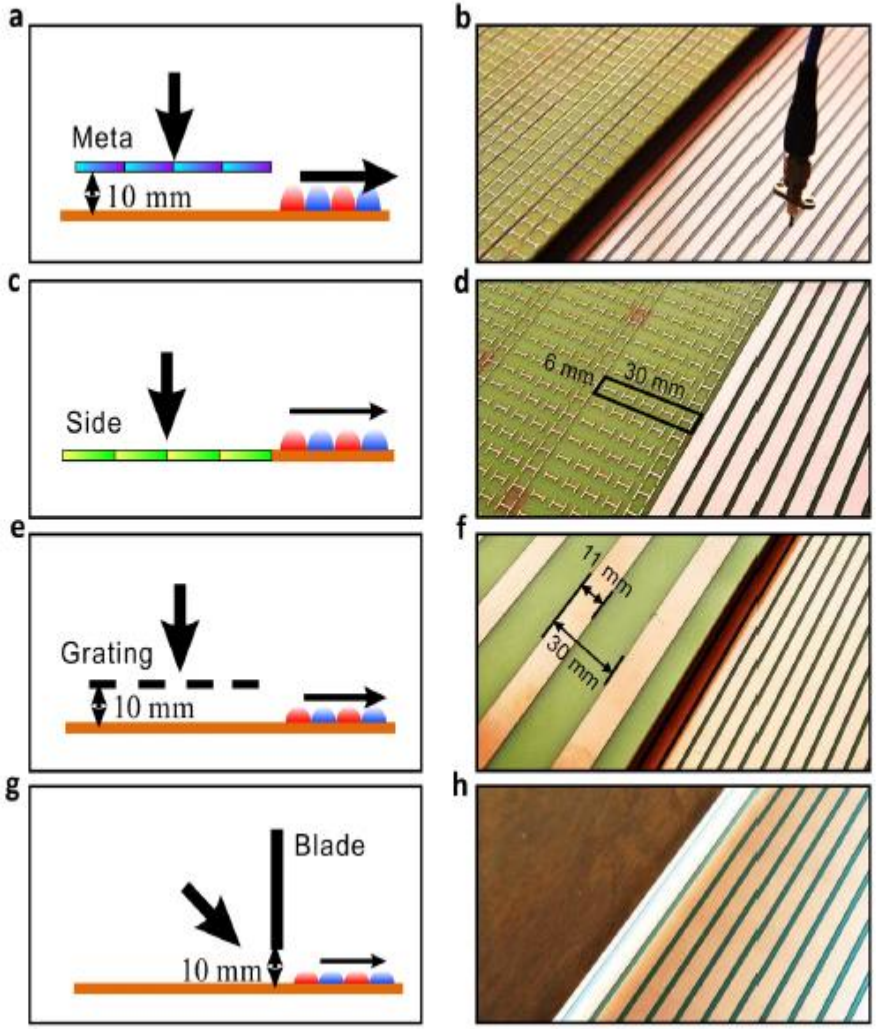
- *Transparent* gradient meta-surface: No reflection
- No x → -x symmetry, decoupling is forbidden
- More efficient to extract SPP

Realization in Microwaves

NF characterizations

- Meta-coupler is the best, several times higher than others;
- Working bandwidth: 8.8-9.5 GHz;



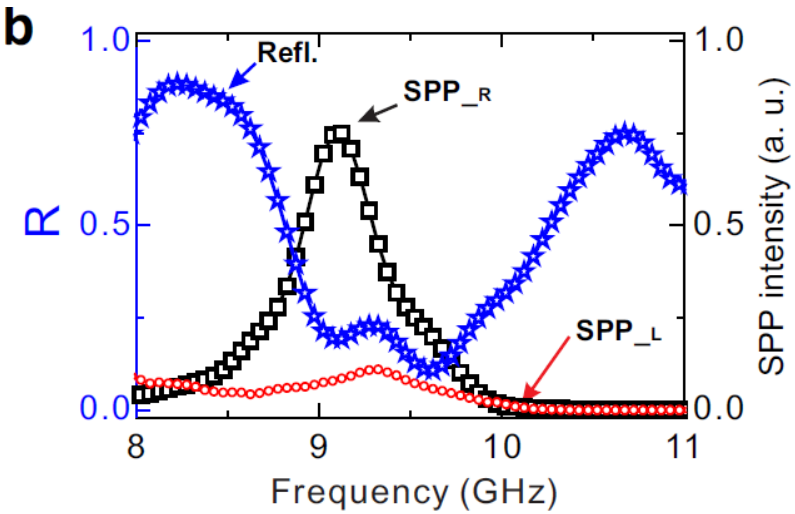


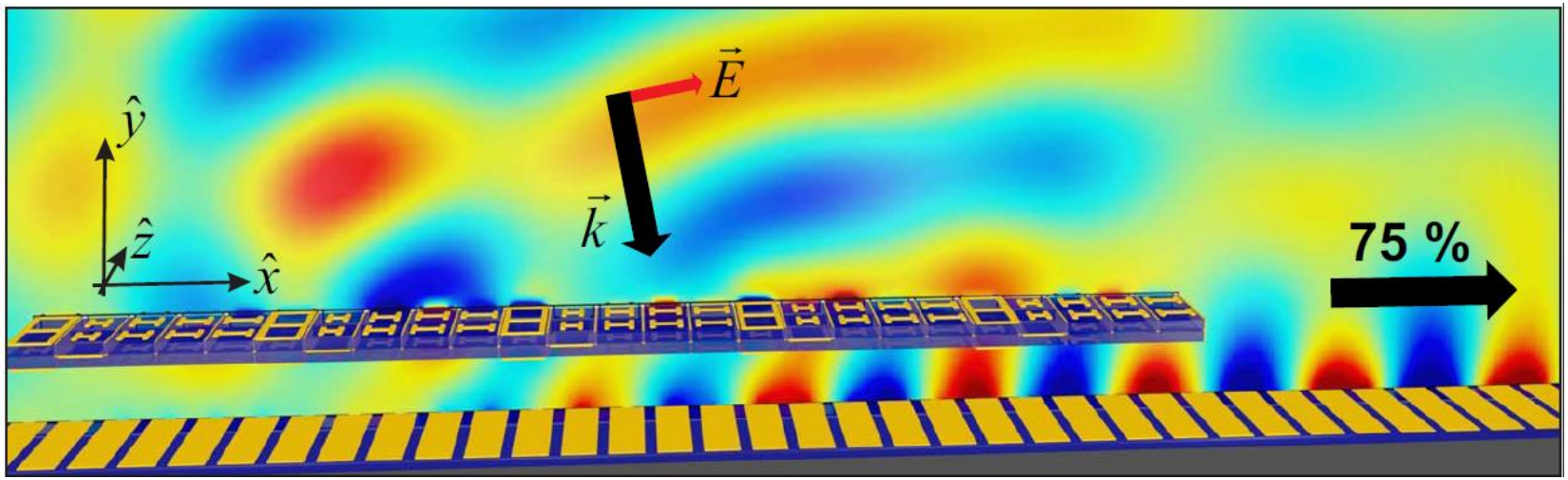
SPP excitation efficiency:

Measured vs FDTD

→ **73% efficiency (Expt.)**

→ **Match well with FDTD (75%).**



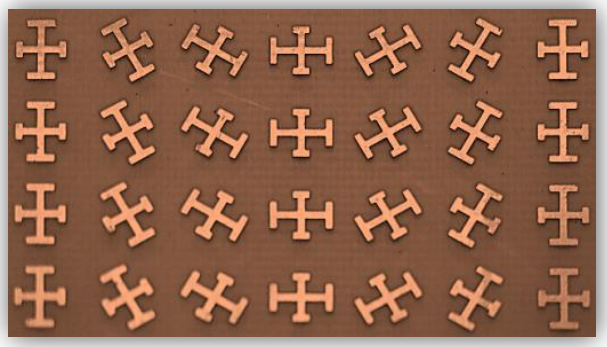


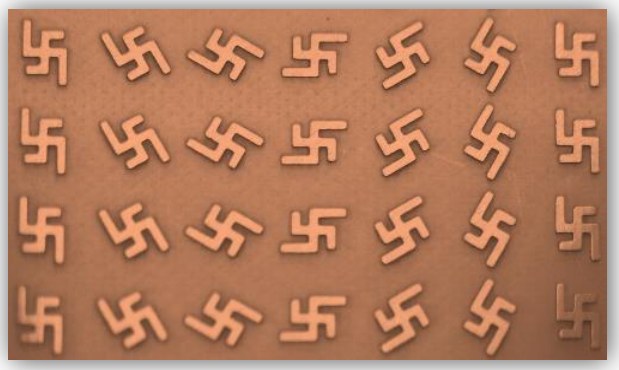
W. Sun *et al.*, *Light: Science & Applications* 5, 16003 (2016).

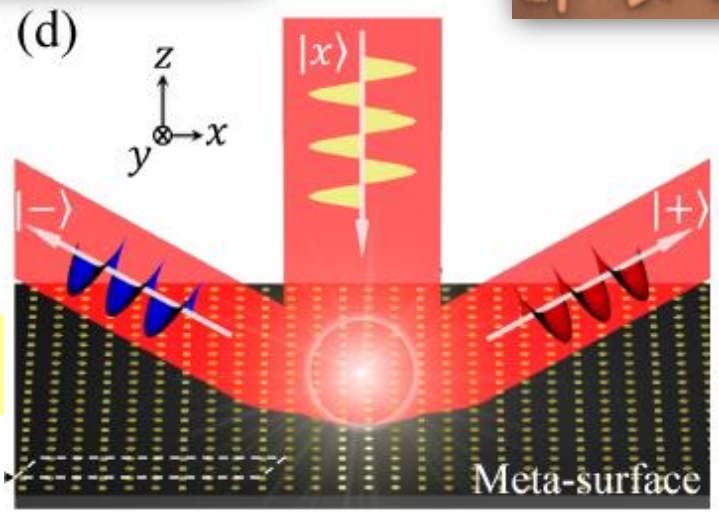
2) Spin-dependent meta-surfaces for 100%-efficiency PSHE

Case 1: Symmetrical

Case 2: Asymmetrical







$$r_{uu} + r_{vv} = r_{uv} - r_{vu} = 0$$

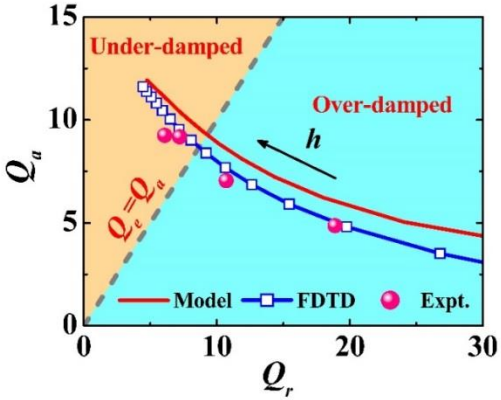
Half-wavelength plate

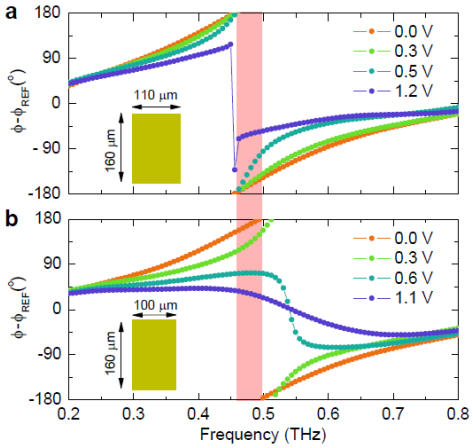
Luo *et. al.*, Adv. Opt. Mater. 3, 1102, (2015)

- **Establish a criterion to realize 100%-efficiency PSHE**
- **Experimentally demonstrated in microwaves**

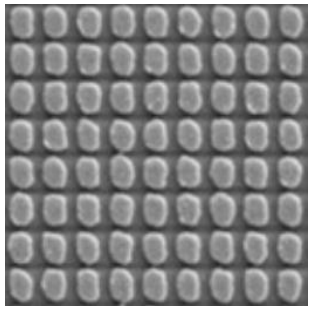
1) **Tailor the functionalities of meta-surfaces based on a complete phase diagram**

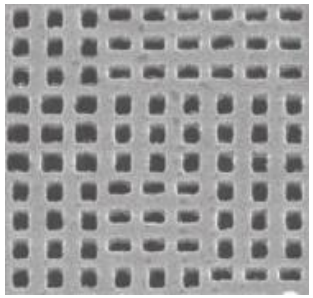
2) **Toward full-range phase modulation with gate-controlled graphene meta-surfaces**





What is Metal/Insulator/Metal Metasurface?



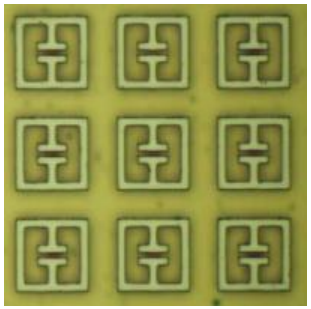


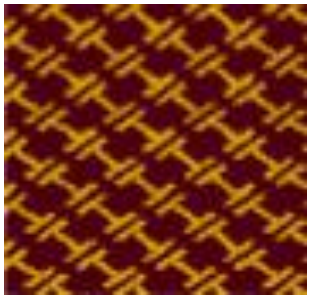
Pattern

Spacer

Metal

metal/insulator/metal

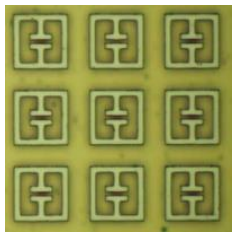


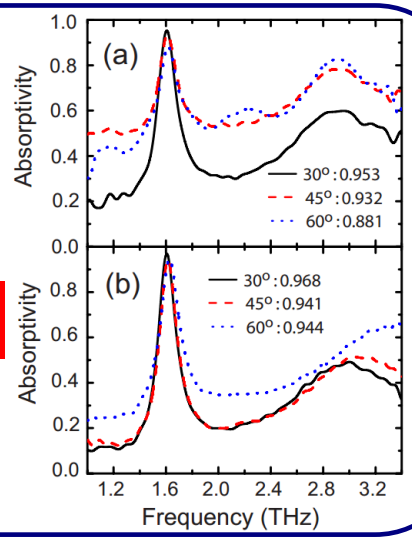


Reflectance modulation ← Change geometry/material → Phase modulation

MIM Meta-surface can control reflectance and phase on resonance

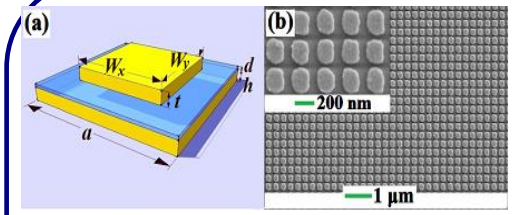
Applications 1： Reflectance Modulation

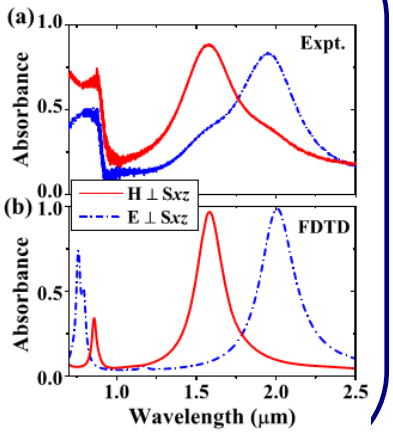




Perfect absorption

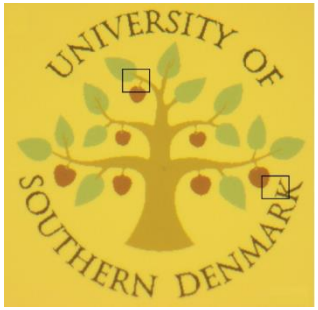
N. I. Landy, et. al.
PRB 78, 241103(2008)

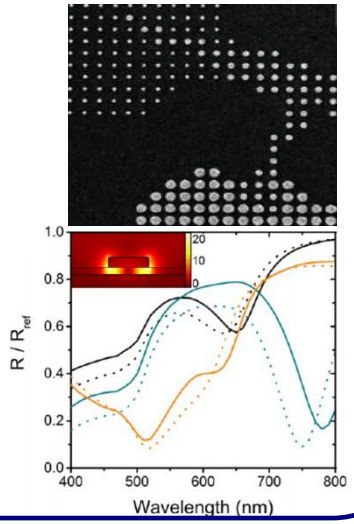




Perfect absorption

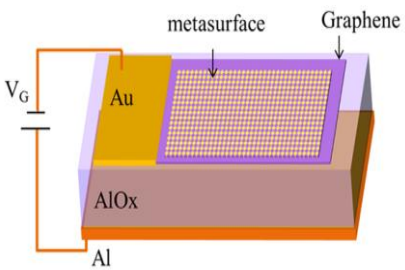
JM Hao et. al.
APL 96 251104 (2010)
Na Liu, et. al.
NL 10, 2342(2010)

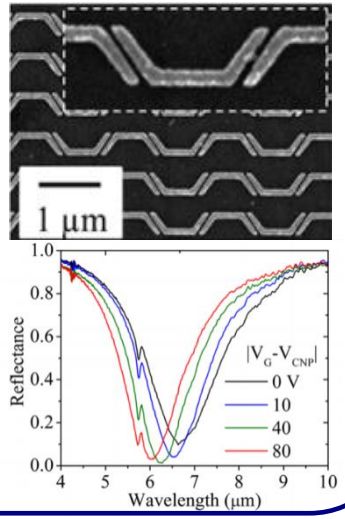




Color Printing

Alexander S. Roberts, et. al.
Nano Lett. 14, 783 (2014)



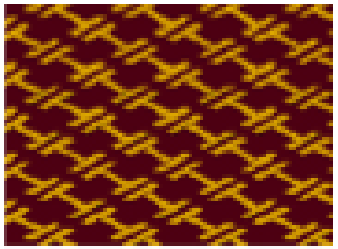


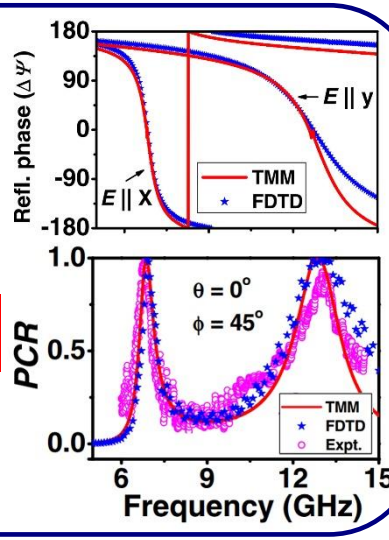
Active modulation

Yu Yao, et. al.
Nano Lett. 14, 6526 (2014)

MIM metasurface triggers many applications through reflectance modulation

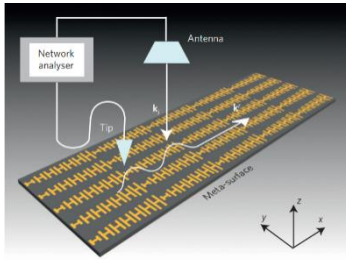
Application 2: Phase Modulation

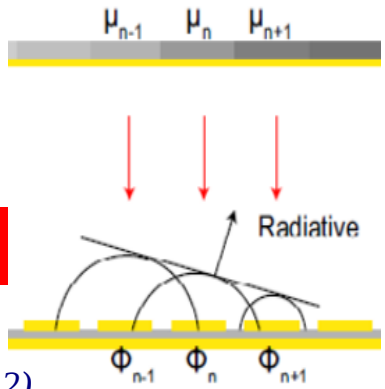




polarization control

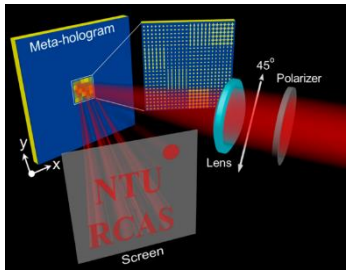
J.M. Hao, et. al.
PRL. 99, 063908 (2007)

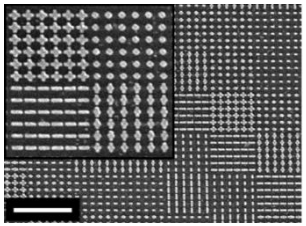


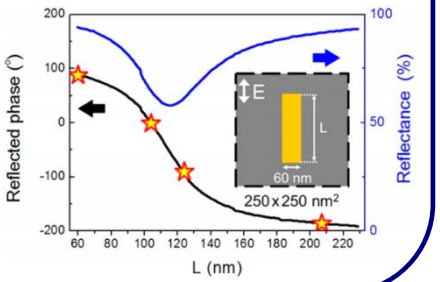


anomalous reflection

S.L. Sun, et. al.
Nat Mater 11, 426-431(2012)

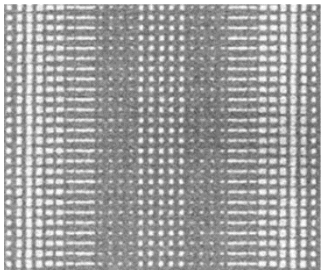


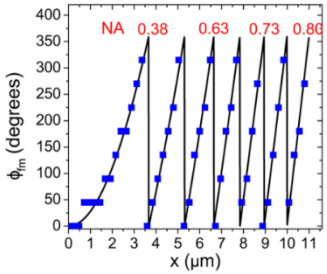


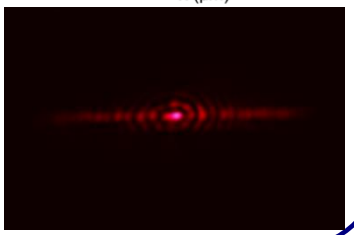


holograms

Wei Ting Chen, et. al.
Nano Lett. 14, 225 (2014)







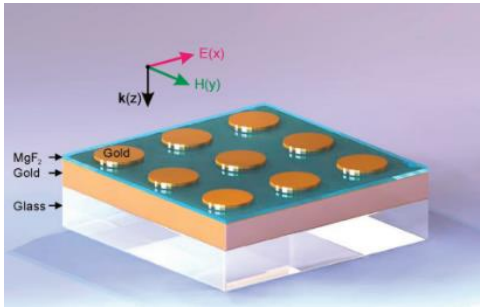
flat-lens focusing

Anders Pors, et. al.
Nano Lett. 13, 829 (2013)

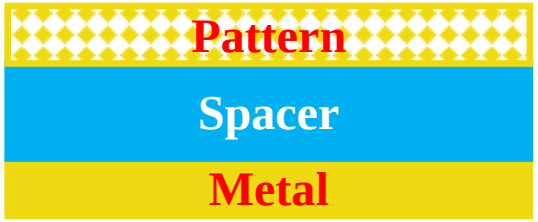
MIM metasurface triggers many applications through phase control

Motivations

Reflectance modulation

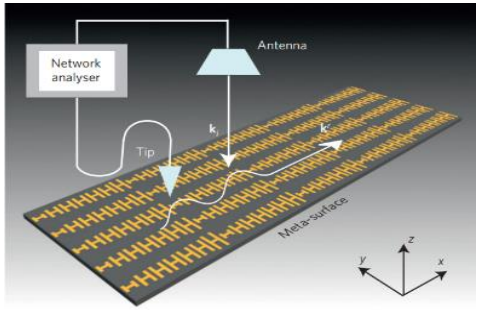


Na Liu, et. al.
Nano Lett. 10, 2342(2010)



Change geometry/material

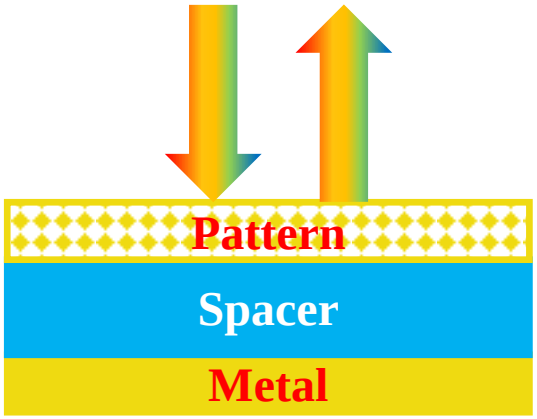
Phase modulation



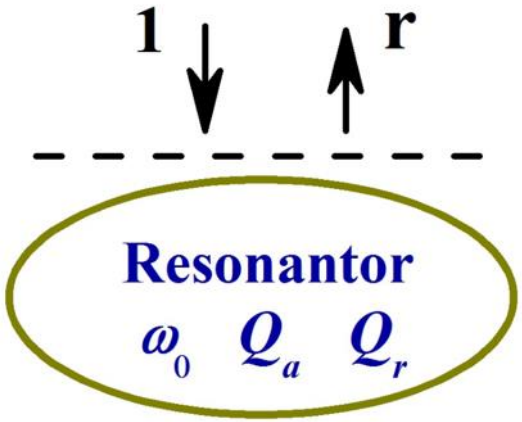
S.L. Sun, et. al.
Nat Mater 11, 426-431(2012)

- **Why and when certain functionality ?**
- **Guidelines for designing MIM metasurfaces with desired functionalities**

Coupled-mode theory for MIM metasurface



metal/insulator/metal



Coupled mode theory:

$$\begin{cases} \dfrac{\partial}{\partial t}\psi = (-i\omega_0 - \dfrac{1}{\tau_a} - \dfrac{1}{\tau_r})\psi + \sqrt{\dfrac{2}{\tau_e}} \cdot 1 \\ r = \sqrt{\dfrac{2}{\tau_e}} \cdot \psi + r_0 \cdot 1 \end{cases}$$

Response:

$$r = -1 + \frac{1/Q_r}{i(1-\omega/\omega_0) + 1/2Q_a + 1/2Q_r}$$

$$Q_i = \frac{\tau_i \omega_0}{2}$$

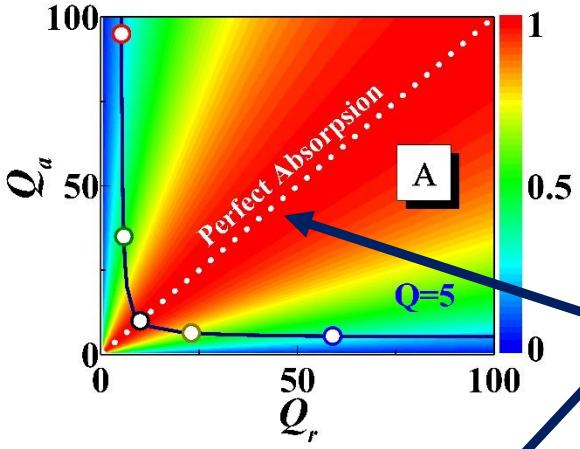
S. Fan et. al., J. Opt. Soc. Am. A 20, 569(2003)

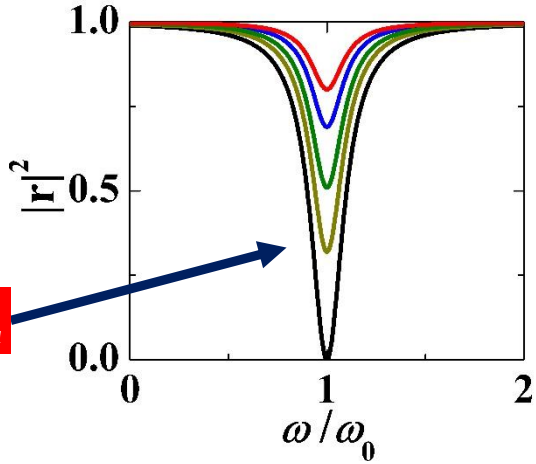
W. Suh et. al., IEEE J. Quantum Electron.,QE 40,1511(2004)

CMT model describes response through lumped Q_r and Q_a

Coupled-mode analyses: Generic phase diagram

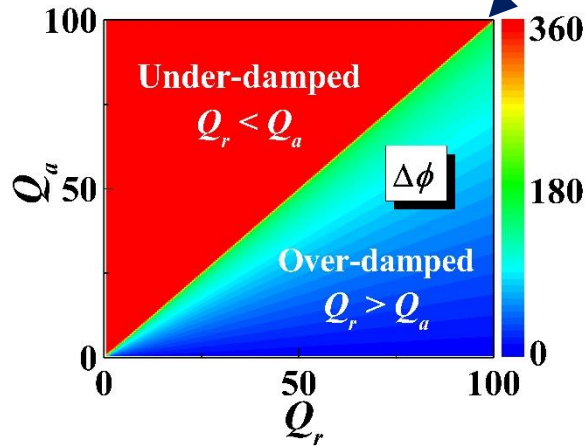
Reflectance modulation

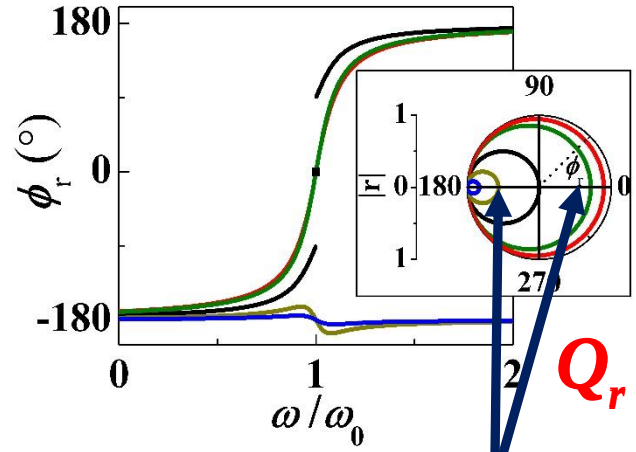




$Q_r = Q_a$

Phase modulation





$Q_r \gtrless Q_a$

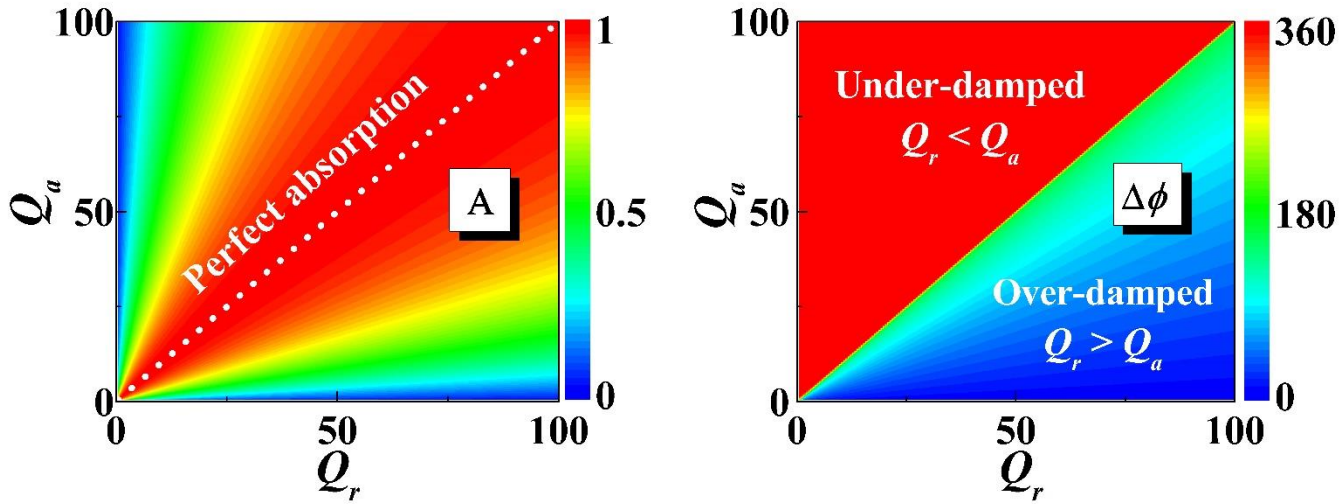
$$r = -1 + \frac{1/Q}{i(1-\omega/\omega_0) + 1/2Q_a + 1/2Q}$$

$\omega = \omega_0$

$$r_0 = \frac{1 - Q_r/Q_a}{1 + Q_r/Q_a}$$

The competitions between two Q factors generate a variety of physical effects

Coupled-mode analysis on MIM metasurface



$$r = -1 + \frac{1/Q_r}{i(1-\omega/\omega_0) + 1/2Q_a + 1/2Q_r}$$

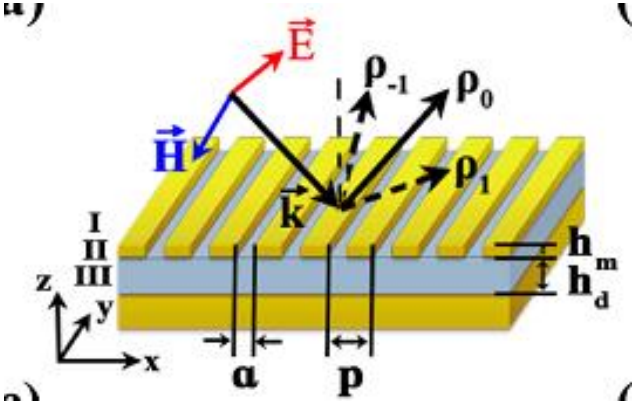
Question: what determines Q factors?

Mode-expansion theory: Analytical results

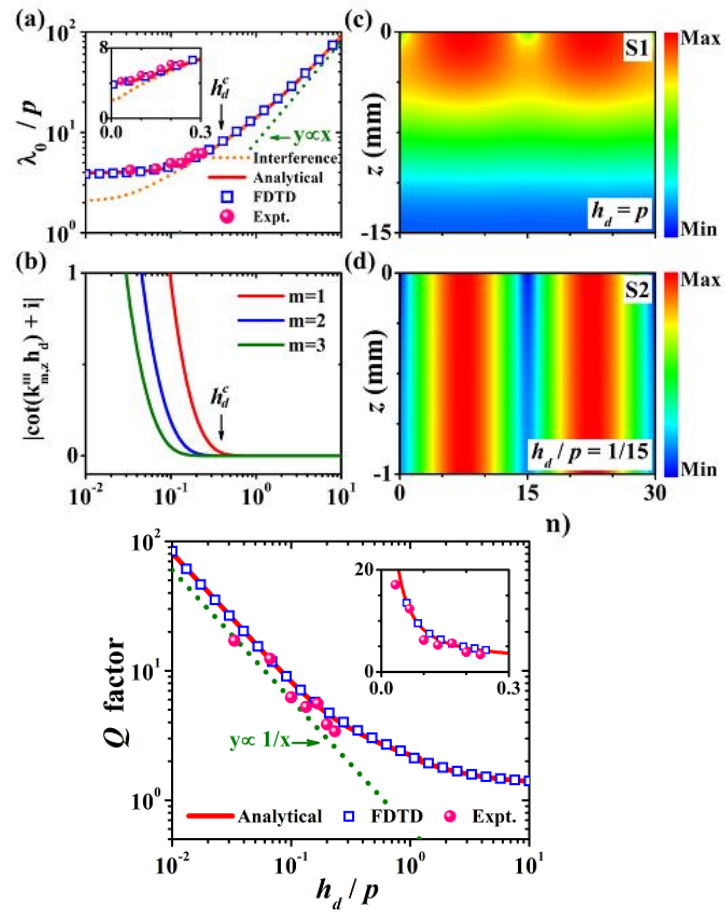
Ma *et al*, PRB (2016) to appear

Conditions:

- **Subwavelength:** $d << \lambda$
- **Thin-slit:** $a << d$



$$
\begin{cases}
\rho_0 + \delta_{0,0} = S_{00}^{(1,2)}[a_0^+ + a_0^-] \\
S_{00}^{(2,1)} Y_0^{\mathrm{I}} \left[\rho_0 - \delta_{0,0}\right] = Y_0^{\mathrm{II}}[a_0^+ - a_0^-] \\
c_m^+ + c_m^- = S_{m0}^{(3,2)}[a_0^+ + a_0^-] \\
\sum_m S_{0m}^{(2,3)} Y_m^{\mathrm{III}}[c_m^+ - c_m^-] = Y_0^{\mathrm{II}}[a_0^+ - a_0^-] \\
c_m^+ \exp(-ik_{m,z}^{\mathrm{III}} h) + c_m^- \exp(ik_{m,z}^{\mathrm{III}} h) = 0
\end{cases}
$$



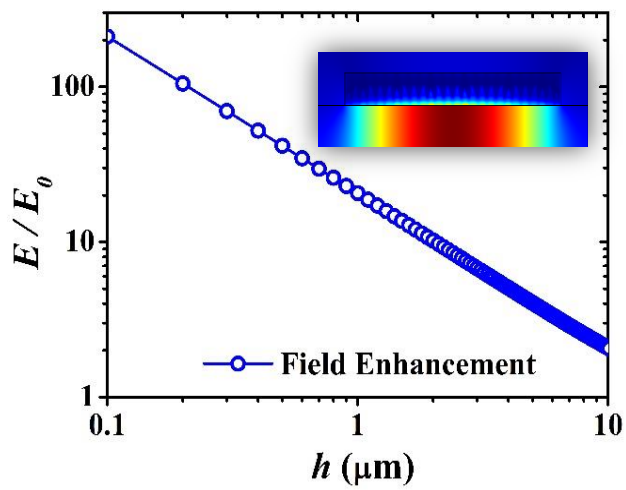
Resonance freq. & Q of MIM metasurfaces analytically obtained

Analytical expressions for Q factors

Q_r factor:

$$Q_r = \frac{2\pi\omega \cdot \langle U \rangle_{cavity}}{\langle P \rangle_{radiat}}$$

$$Q_r = \frac{1}{k_0 h} \cdot F(a,d)$$



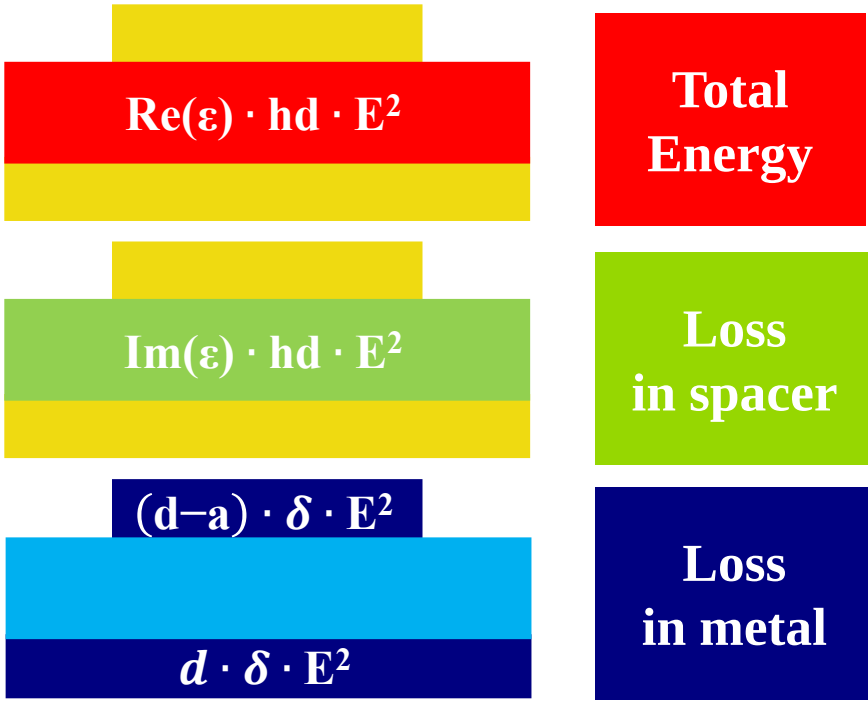
$$\vec{E},\vec{H} \sim \frac{1}{h} \quad U,Q_r \sim \left|\vec{E}\right|^2 \cdot h \quad U,Q_r \sim \frac{1}{h}$$

Ma *et al*, PRB (2016) to appear

Q_a factor: (perturbation)

$$Q_a = \frac{2\pi\omega \cdot \langle U \rangle_{cavity}}{\langle P \rangle_{absorb}}$$

$$Q_a = \frac{\mathrm{Re}(\varepsilon) hd}{\alpha\,\mathrm{Im}(\varepsilon) hd + \beta(2d-a)\cdot\delta_{eff}}$$



Concrete expressions of Q factors are obtained

Tailor MIM Metasurface Through Structural/Material Tuning

- **Response:**

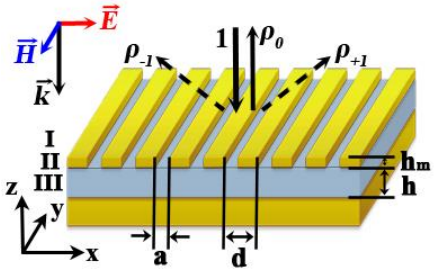
$$r = -1 + \frac{1/Q_r}{i(1-\omega/\omega_0) + 1/2Q_a + 1/2Q_r}$$

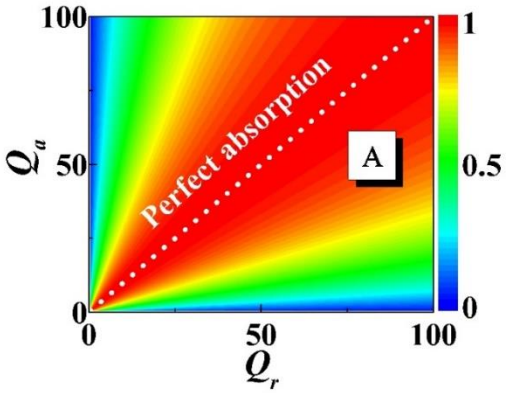
- **Q_r factor:**

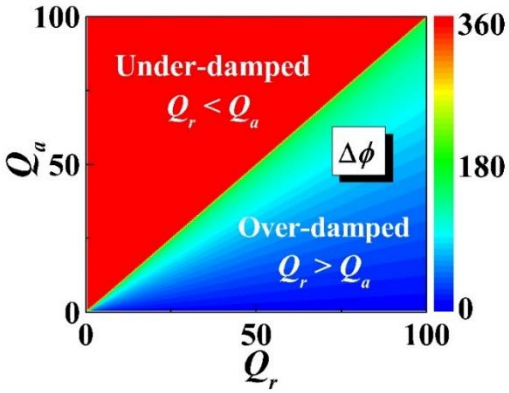
$$Q_r = \frac{1}{k_0 h} \cdot F(a,d)$$

- **Q_a factor:**

$$Q_a = \frac{\mathrm{Re}(\varepsilon) hd}{\alpha\,\mathrm{Im}(\varepsilon) hd + \beta(2d-a)\cdot\delta_{eff}}$$







MIM properties ← Two Q factors ← Structure & Materials

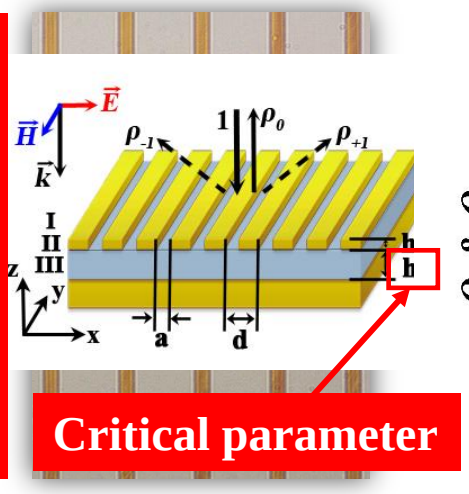
Tailor MIM Metasurfaces via tuning *h*

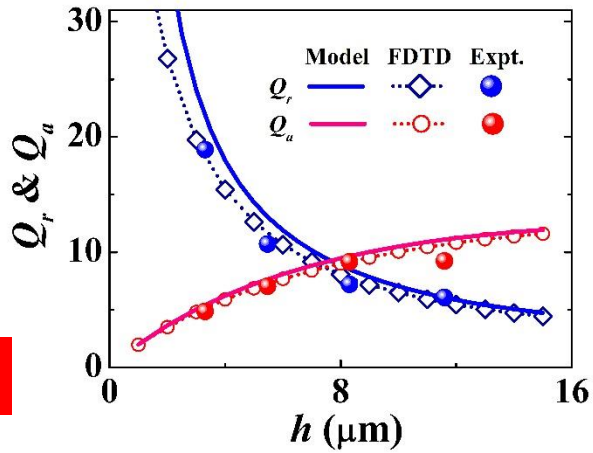
- Q_r factor:

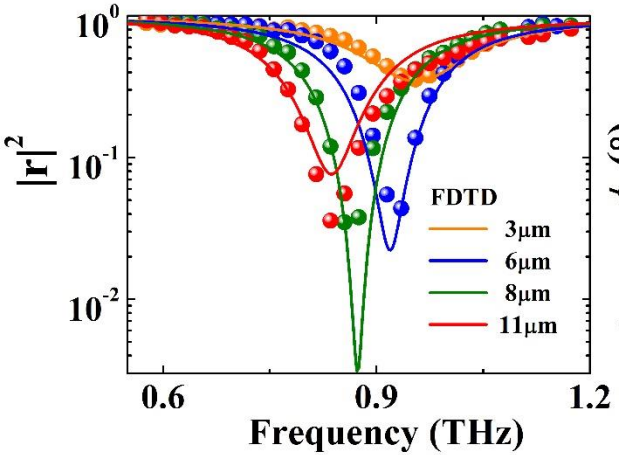
$$Q_r = \frac{1}{k_0 h} \cdot F(a,d)$$

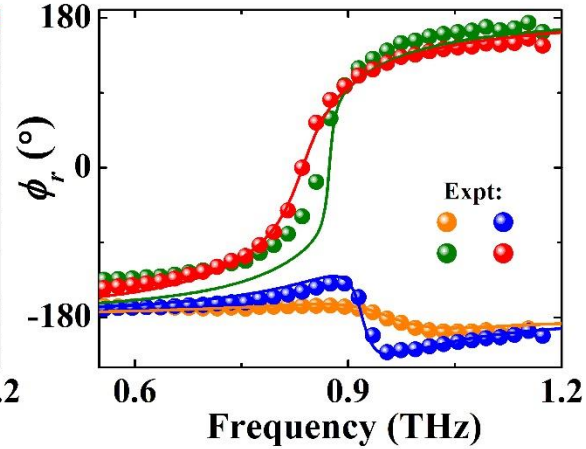
- Q_a factor:

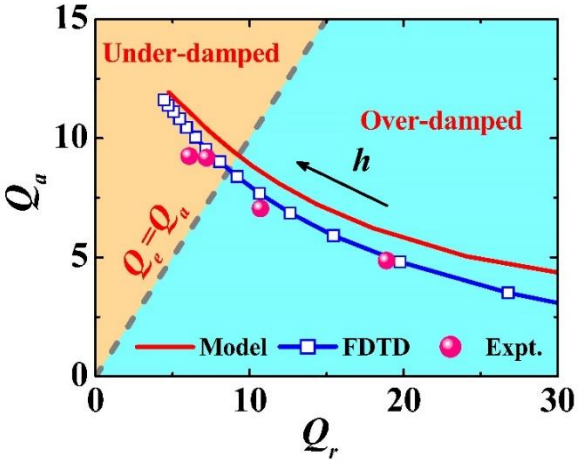
$$Q_a = \frac{\mathrm{Re}(\varepsilon) h d}{\alpha\,\mathrm{Im}(\varepsilon) h d + \beta(2d-a)\cdot\delta_{eff}}$$











Tuning *h* can dramatically change the property of a metasurface

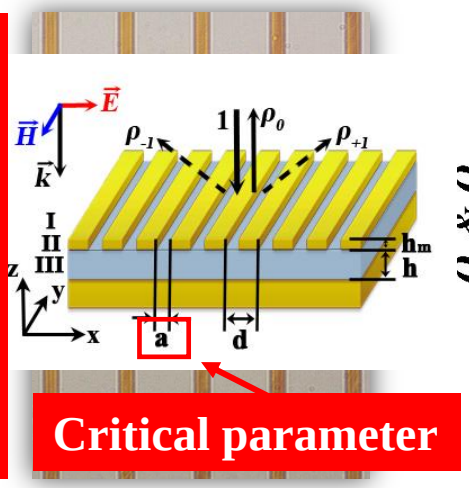
Tailor MIM metasurfaces via tuning *a*

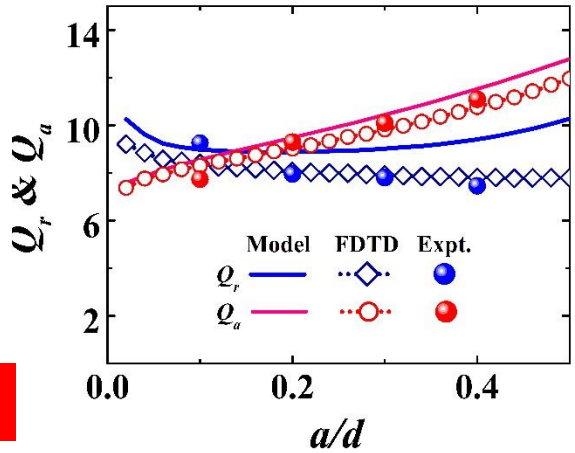
- Q_r factor:

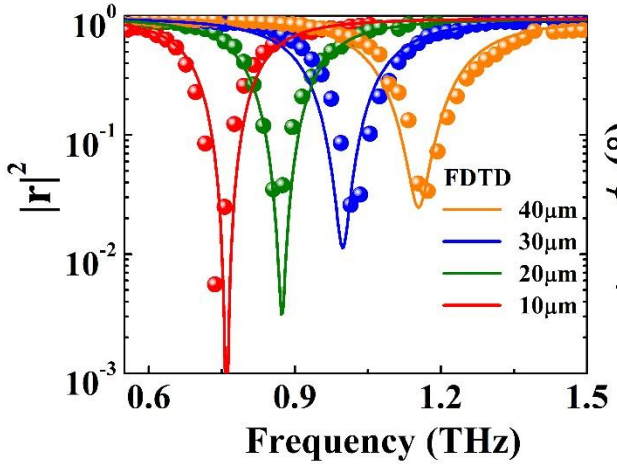
$$Q_r = \frac{1}{k_0 h} \cdot F(a, d)$$

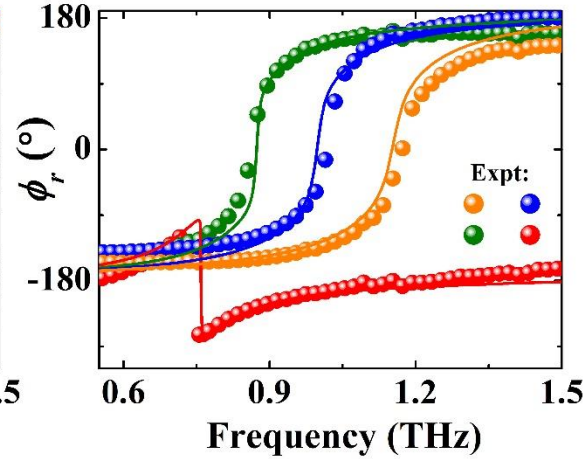
- Q_a factor:

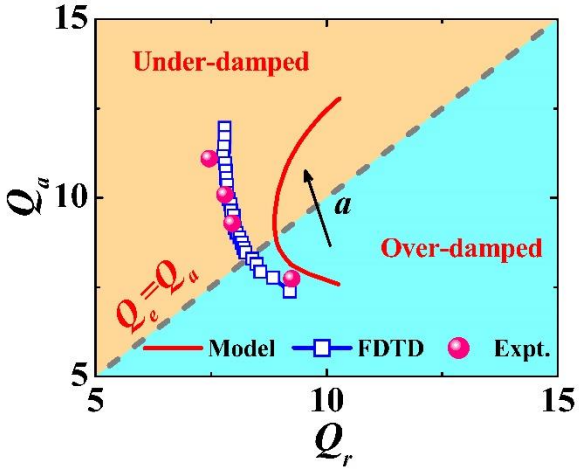
$$Q_a = \frac{\mathrm{Re}(\varepsilon) hd}{\alpha\, \mathrm{Im}(\varepsilon) hd + \beta (2d - a) \cdot \delta_{eff}}$$











Tuning *a* can change the property of a metasurface

Tailor MIM Metasurfaces via tuning material loss

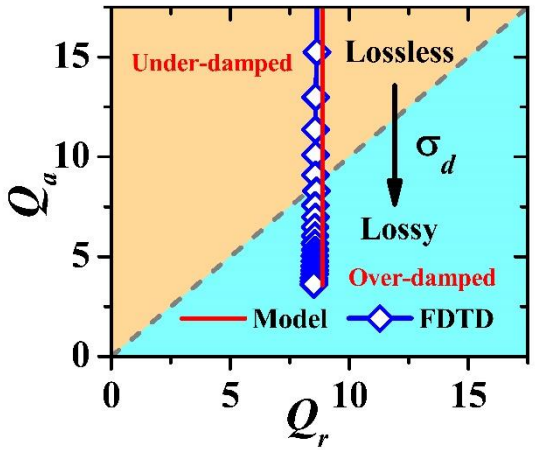
- Q_r factor:

$$Q_r = \frac{1}{k_0 h} \cdot F(a,d)$$

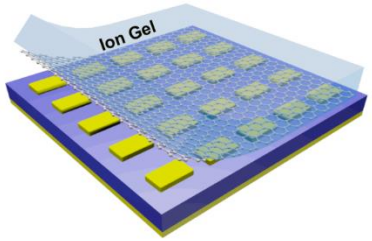
- Q_a factor:

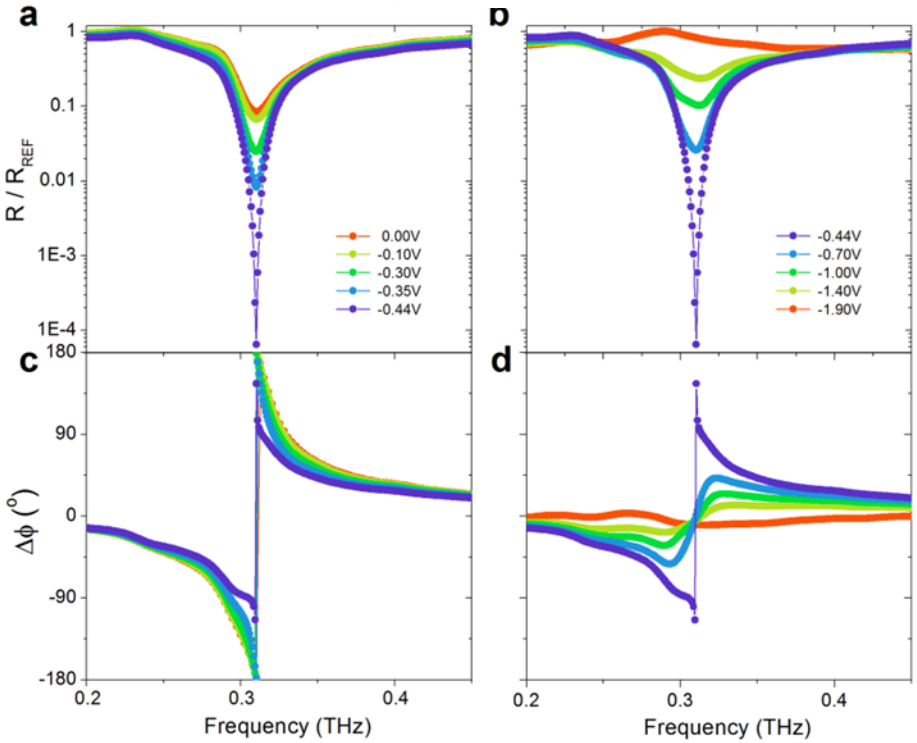
$$Q_a = \frac{\mathrm{Re}(\varepsilon) hd}{\alpha\, \mathrm{Im}(\varepsilon) hd + \beta(2d-a)\cdot \delta_{eff}}$$

Tune dielectric loss:



Gate-controlled graphene :





Tuning material can dramatically change the property of a metasurface

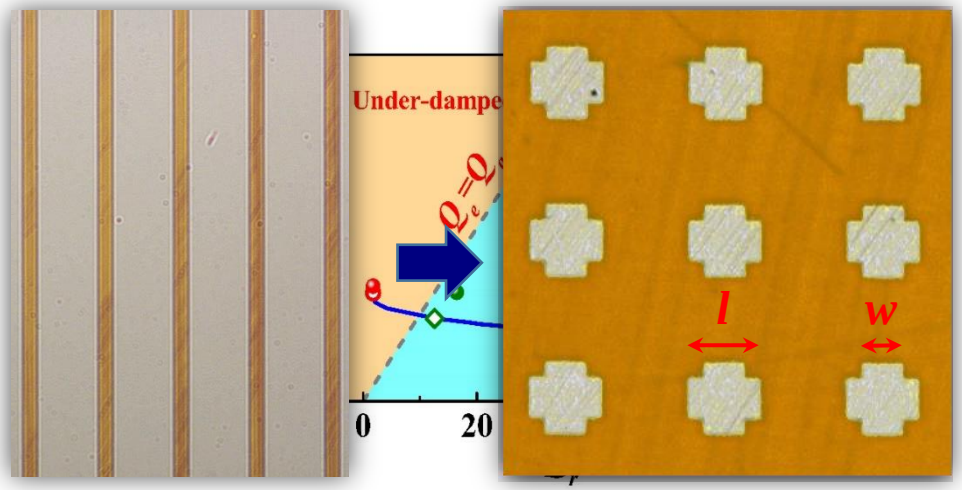
Extension to General Situations

- Q_r factor:

$$Q_r = \frac{1}{k_0 h} \cdot F(shape)$$

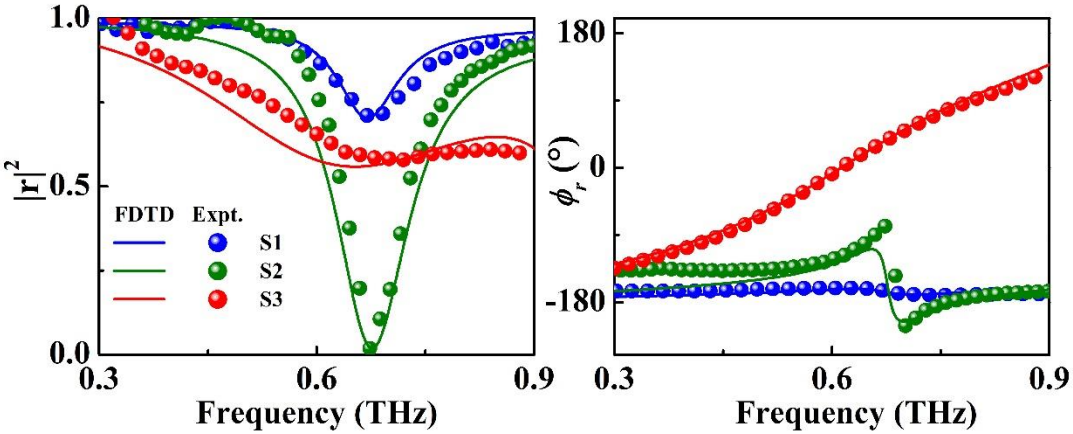
- Q_a factor:

$$Q_a = \frac{\mathrm{Re}(\varepsilon) hd}{\alpha \,\mathrm{Im}(\varepsilon) hd + \beta \cdot S_{metal} \cdot \delta_{eff}}$$



THz experiments verification:

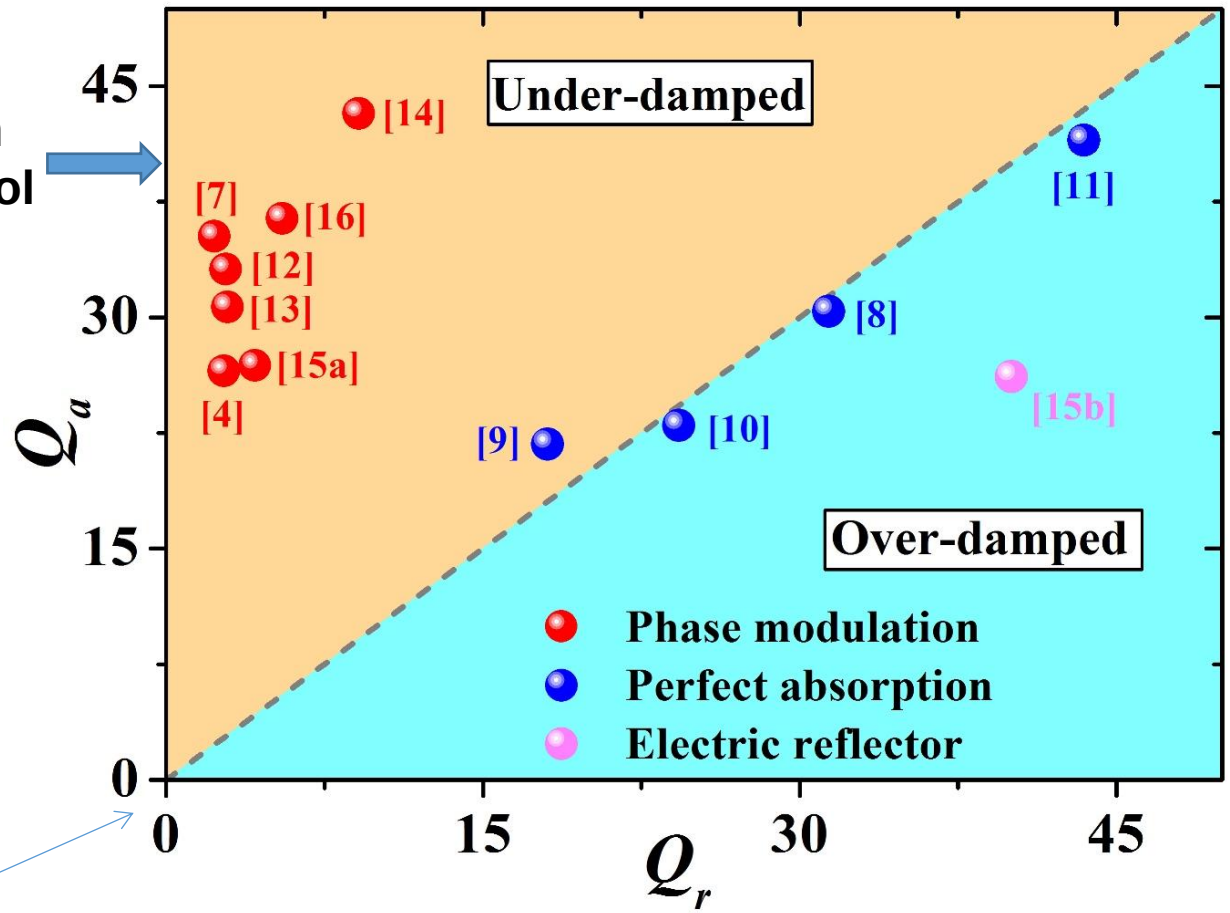
- *h increase:*
  $Q_r \downarrow, Q_a \uparrow$
- *l increase:*
  $Q_r \sim C, Q_a \downarrow$
- *w increase:*
  $Q_r \downarrow, Q_a \sim C$



Tuning can be extended to a general 2D metasurface

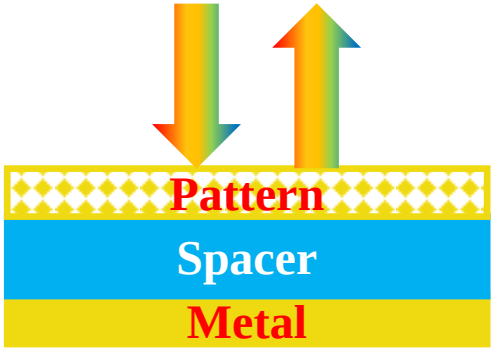
Re-interpreting previous works with our phase diagram

Phase-modulation
Polarization control
Gradient MS



Perfect absorbers

Conclusions



- **Response:**

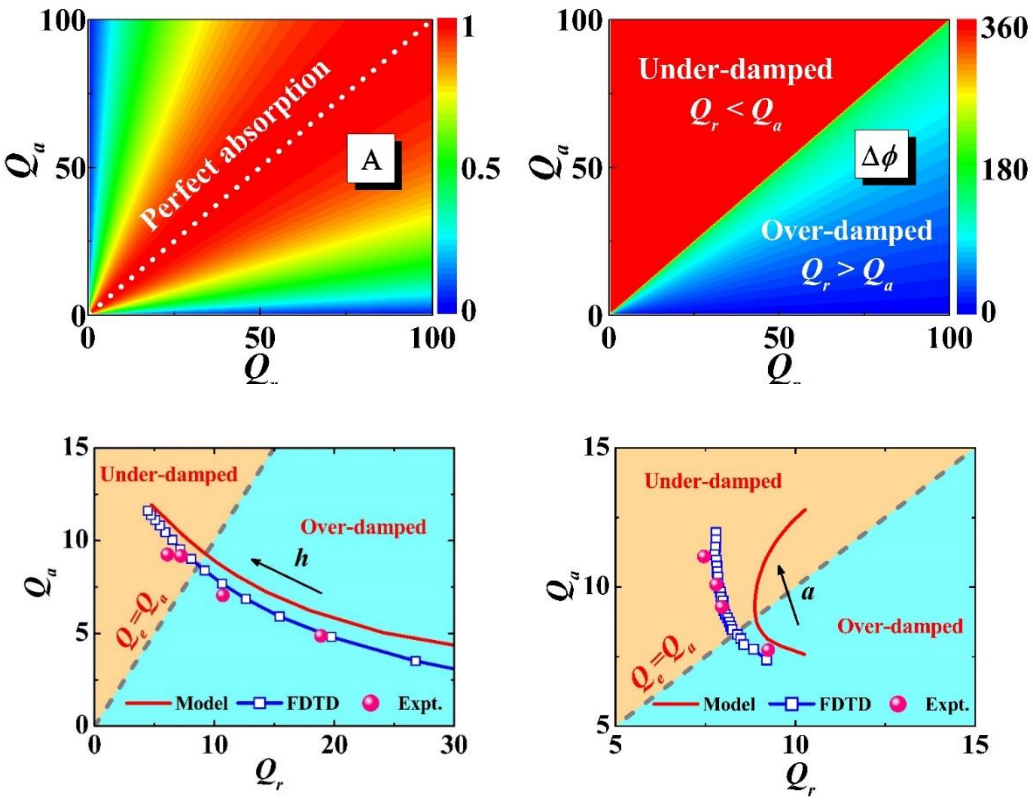
$$r = -1 + \frac{1/Q_r}{i(1-\omega/\omega_0) + 1/2Q_a + 1/2Q_r}$$

- **Q_r factor:**

$$Q_r = \frac{1}{k_0 h} \cdot F(a,d)$$

- **Q_a factor:**

$$Q_a = \frac{\mathrm{Re}(\varepsilon) hd}{\alpha\,\mathrm{Im}(\varepsilon) hd + \beta(2d-a)\cdot\delta_{eff}}$$

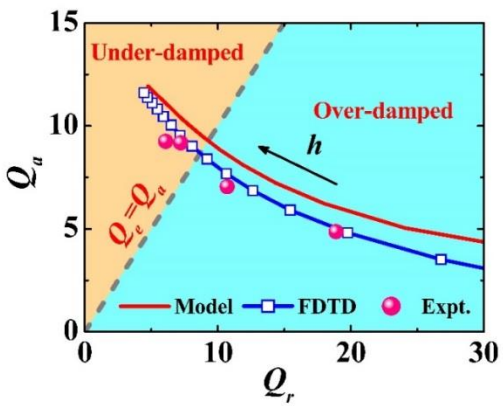


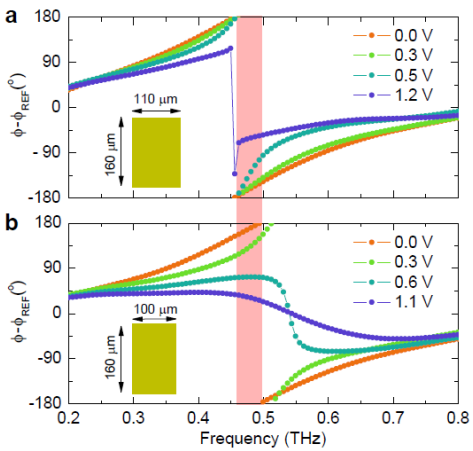
Guidelines for designing metasurfaces with desired functionalities: Perfect absorption, Phase modulation, Active control …

Qu *et. al*, Phys. Rev. Lett. 115, 235503 (2015)

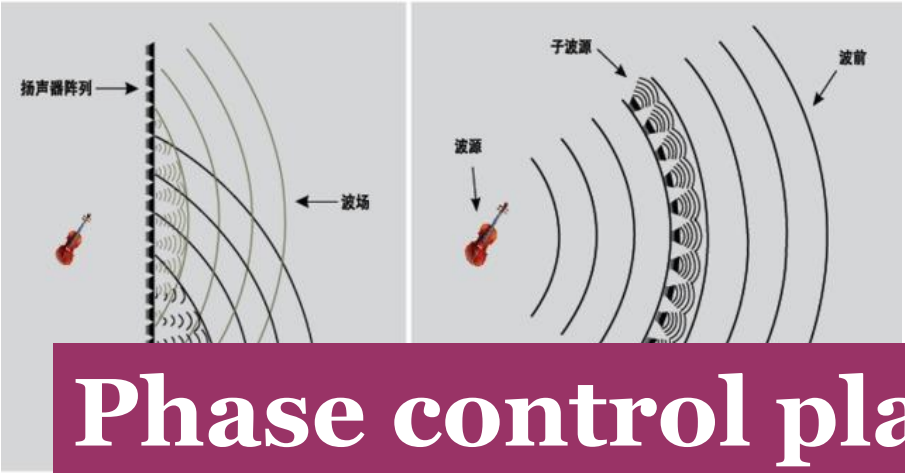
1) Tailor the functionalities of metasurfaces based on a complete phase diagram

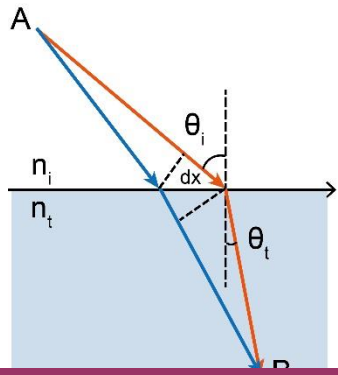
2) **Toward full-range phase modulation with gate-controlled graphene metasurfaces**

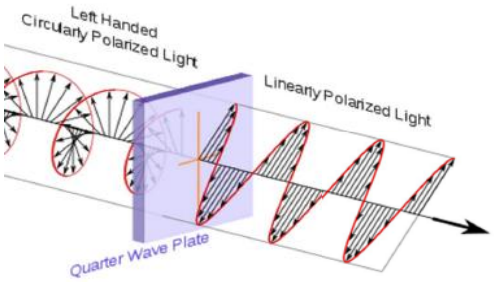




Background: Why need phase control?







Phase control plays a central role in wave optics !

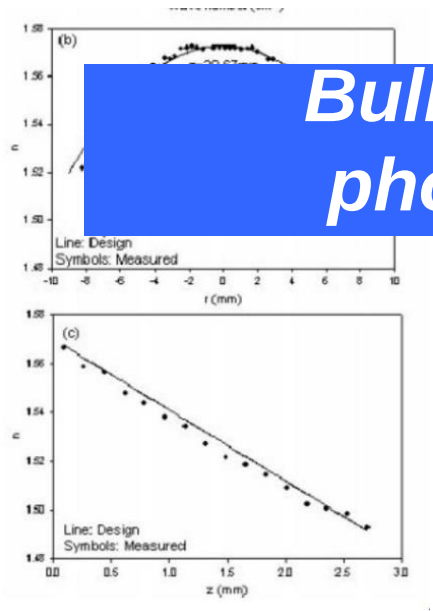
Fermat-Huygens law:

Phase distribution on a certain plane determines the far-field radiation

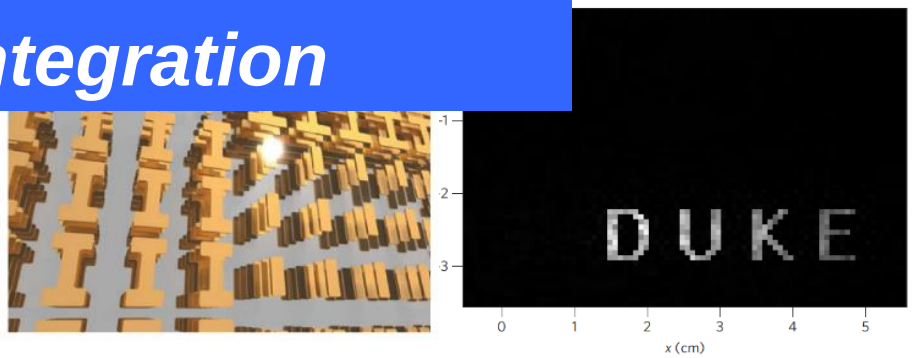
Refraction, polarization control, hologram …

How to realize phase control?

Conventional techniques:
Gradient-index natural materials or MTMs:



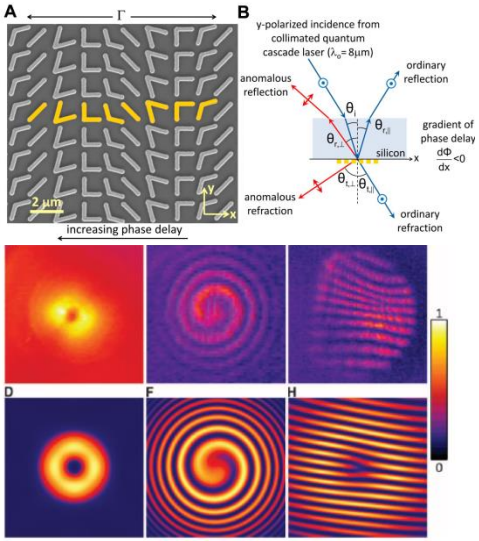
Bulk effect, difficult for photonics integration

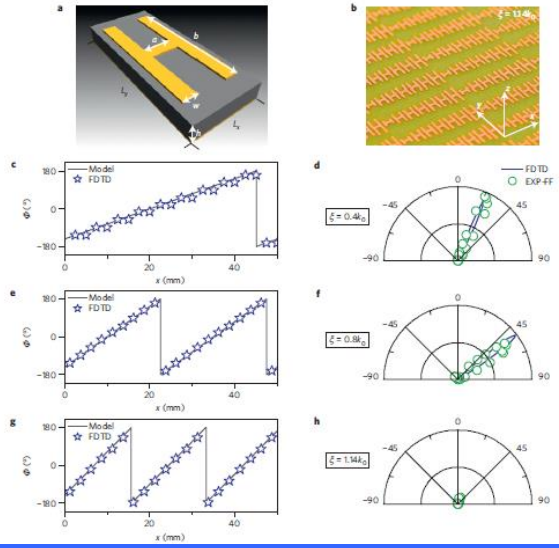


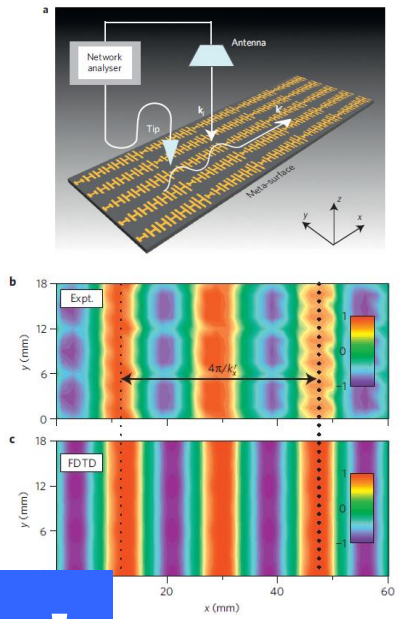
Larouche, S et al., *Nat. Mater* (2012).

Jin, Y. et al., *J Appl. Polym*. Sci. 103,1834 (2007)

Meta-surfaces: *full-range* phase control in *deep-subwavelength* regime







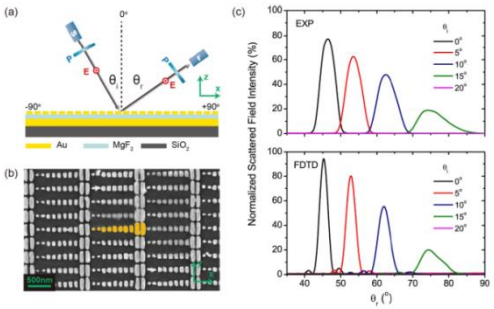
Yu, *Science* (2011).

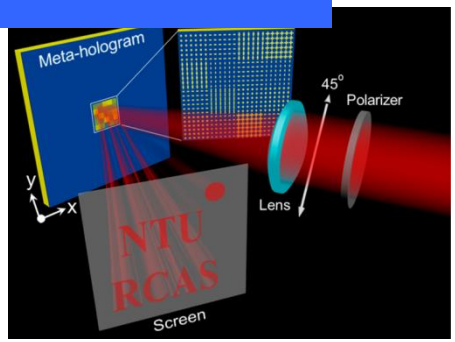
Anomalous refracti

Vortex generations,

All these are passive !

le-mode





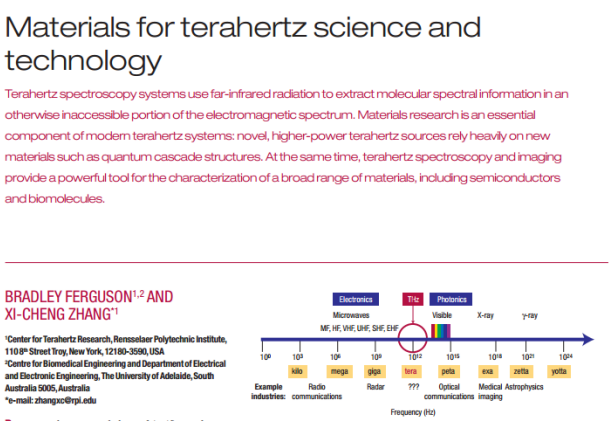
Sun, Nano Lett. (2012).

Wide-band, optical regime

Chen, *Nano. Lett.*, (2014)

High-efficiency meta-holograms

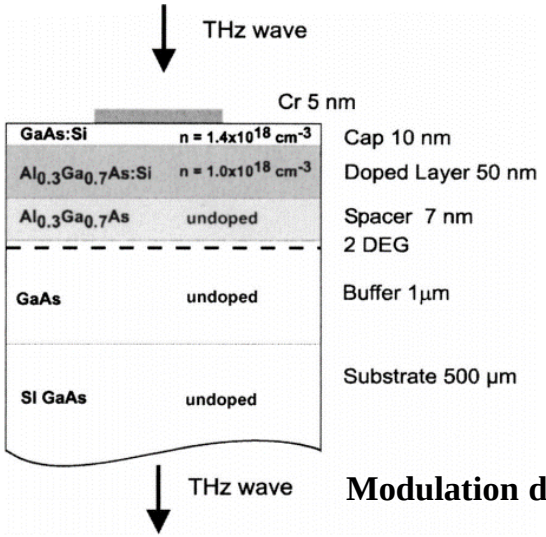
Available active phase modulations


Materials for terahertz science and technology

Terahertz spectroscopy systems use far-infrared radiation to extract molecular spectral information in an otherwise inaccessible portion of the electromagnetic spectrum. Materials research is an essential component of modern terahertz systems: novel, higher-power terahertz sources rely heavily on new materials such as quantum cascade structures. At the same time, terahertz spectroscopy and imaging provide a powerful tool for the characterization of a broad range of materials, including semiconductors and biomolecules.

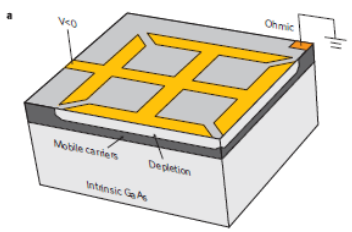
BRADLEY FERGUSON[1,2] AND XI-CHENG ZHANG[*1]

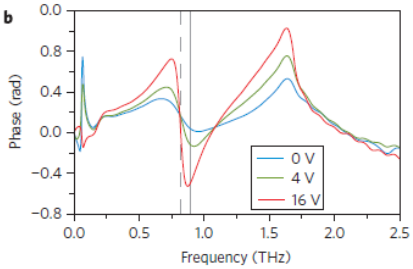
[1]Center for Terahertz Research, Rensselaer Polytechnic Institute, 1108th Street Troy, New York, 12180-3590, USA
[2]Centre for Biomedical Engineering and Department of Electrical and Electronic Engineering, The University of Adelaide, South Australia 5005, Australia
*e-mail: zhangxc@rpi.edu



Modulation depth 3%

Kleine-Ostmann, T. et al., *APL* (2004).

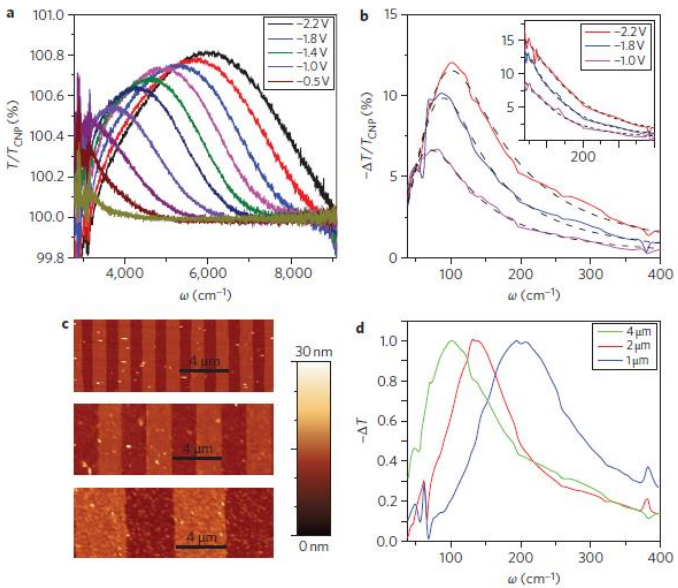




Chen et. al, *Nat. Photonics (2008)*

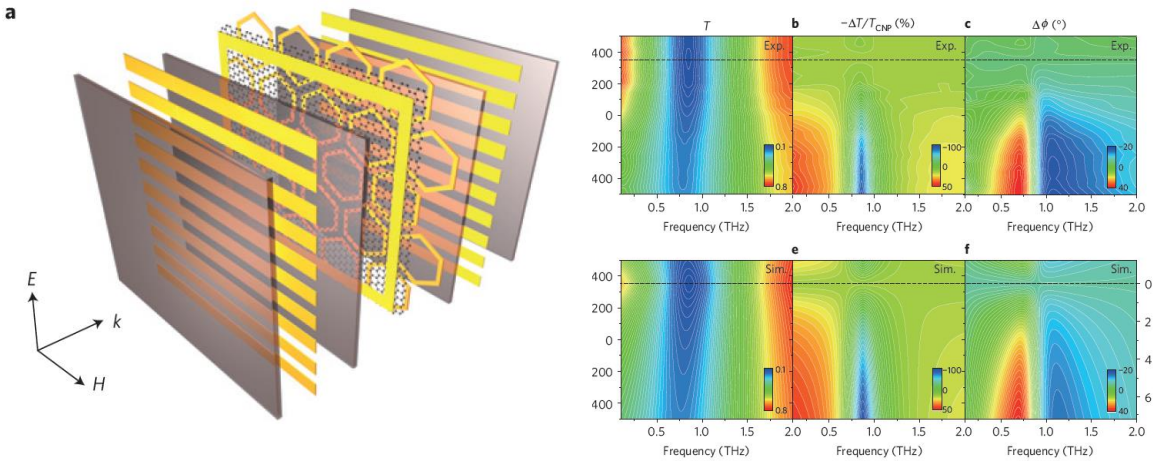
Limited phase modulations far from *full-range control*, even enhanced by MTM

Using graphene – an atomic-thin material with great tunability?



Ju, L. et al., *Nature Nano*. 6, 630-634 (2011)

Great tuning capability, loss --- low Q factor



Lee, S. et al., *Nature Mater*. 11, 936-941 (2012)

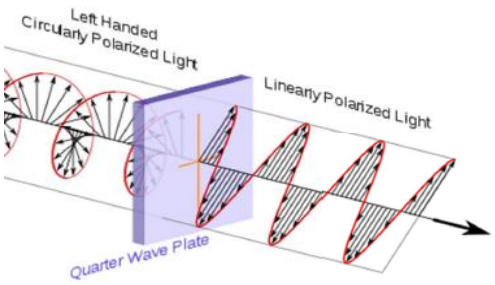
Combined with MTM: Tuning phase with 32.2 degrees

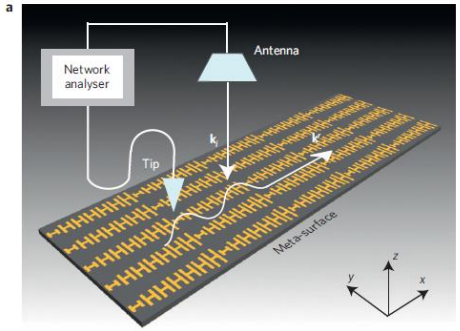
Far away from full-wave control!

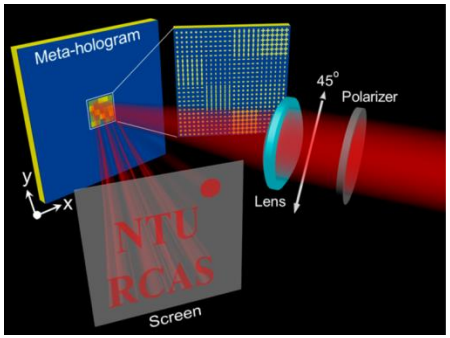
Our motivations

Realize *active* and *full-range* phase control with gate-controlled graphene *meta-surface*

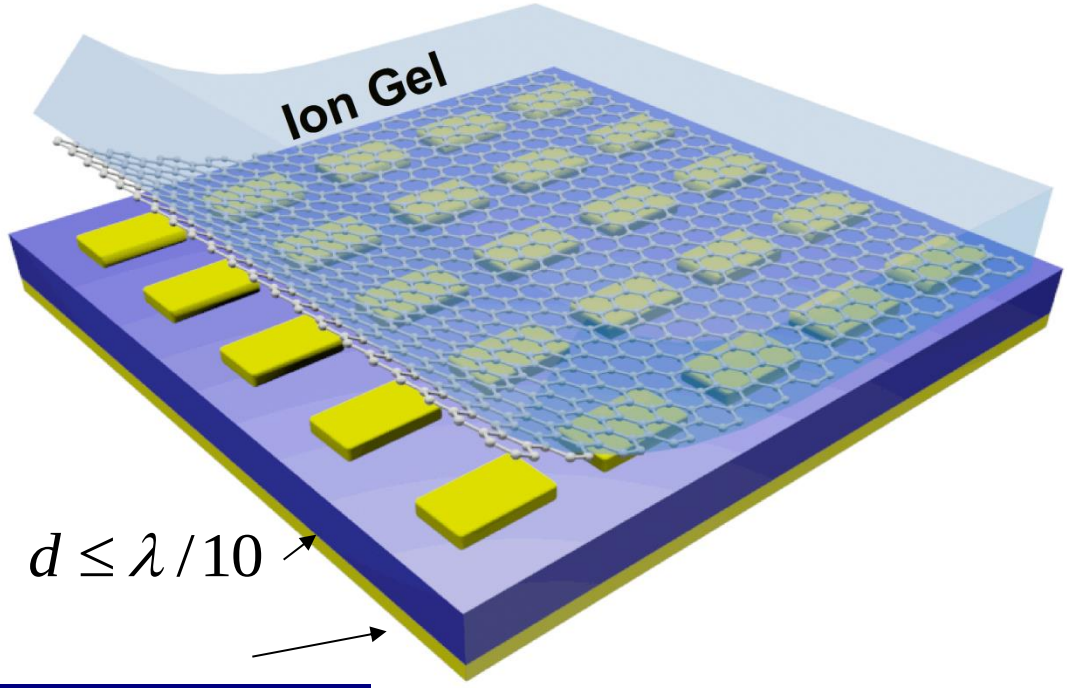
Active?

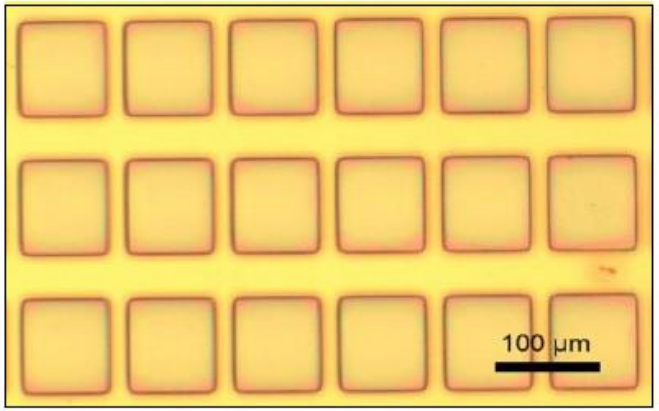






Our structure
Graphene + Meta-surface

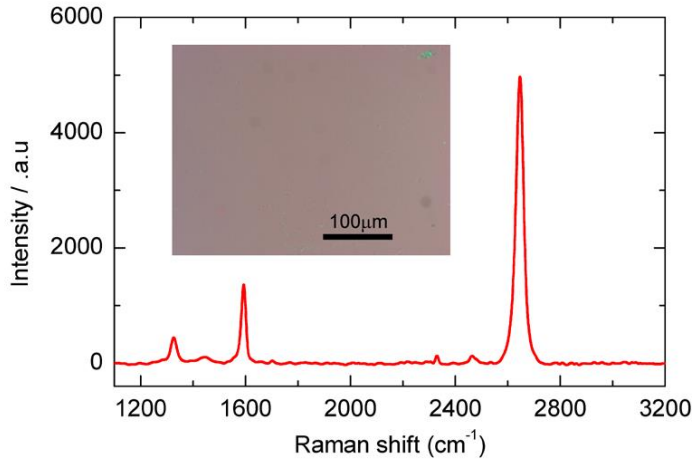


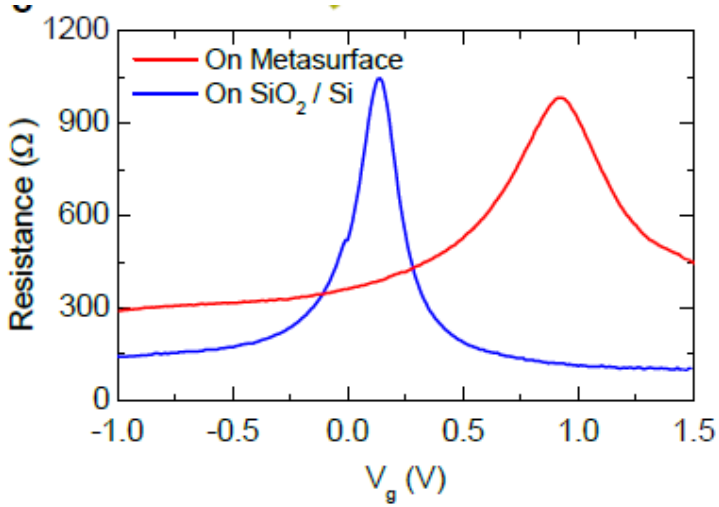


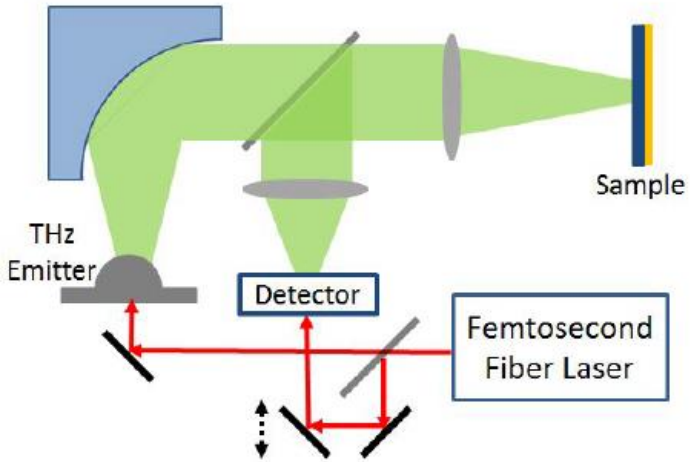
Metallic sheet

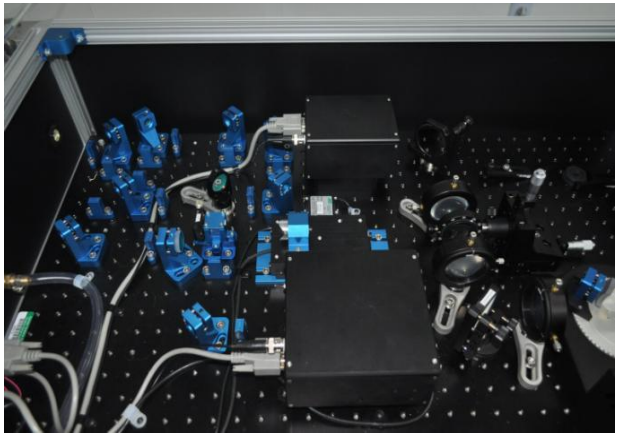
- **Combining Graphene with reflective meta-surface**
- **Working at THz domain**
- **The transmission port is blocked --- crucial !**
- **Top-gating graphene using Ion-Gel**

Graphene identification and TDS-THz measurements





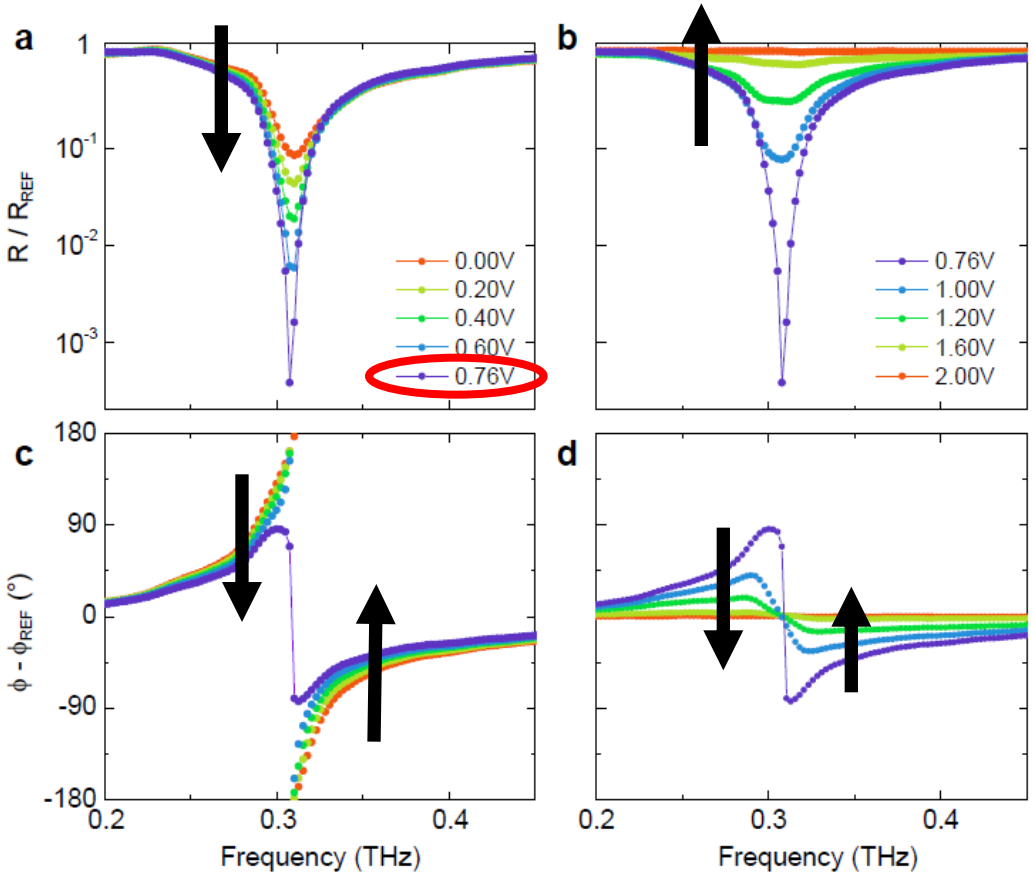




Amplitude/phase modulation (Expt.)
– e-doping

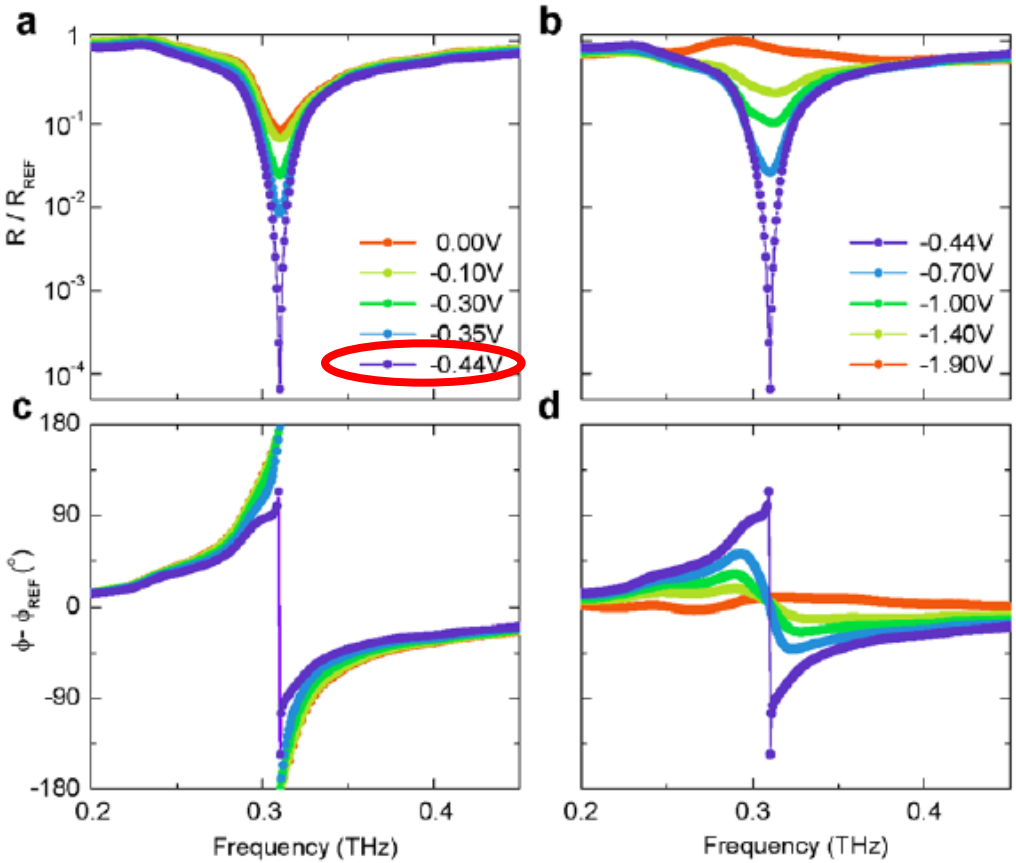
Reference:
Spectrum with highest n
Essentially featureless

±180 degrees of phase modulation



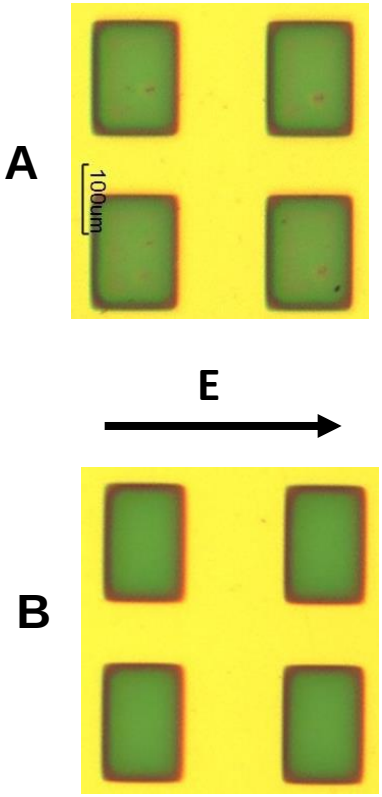
- As voltage increases, reflection amplitudes first decreases to 0, then increases to 1
- Phase behaviors change from a magnetic (~360 variation) to electric (<180) resonance
- Phase modulation covering +/- 180 degrees

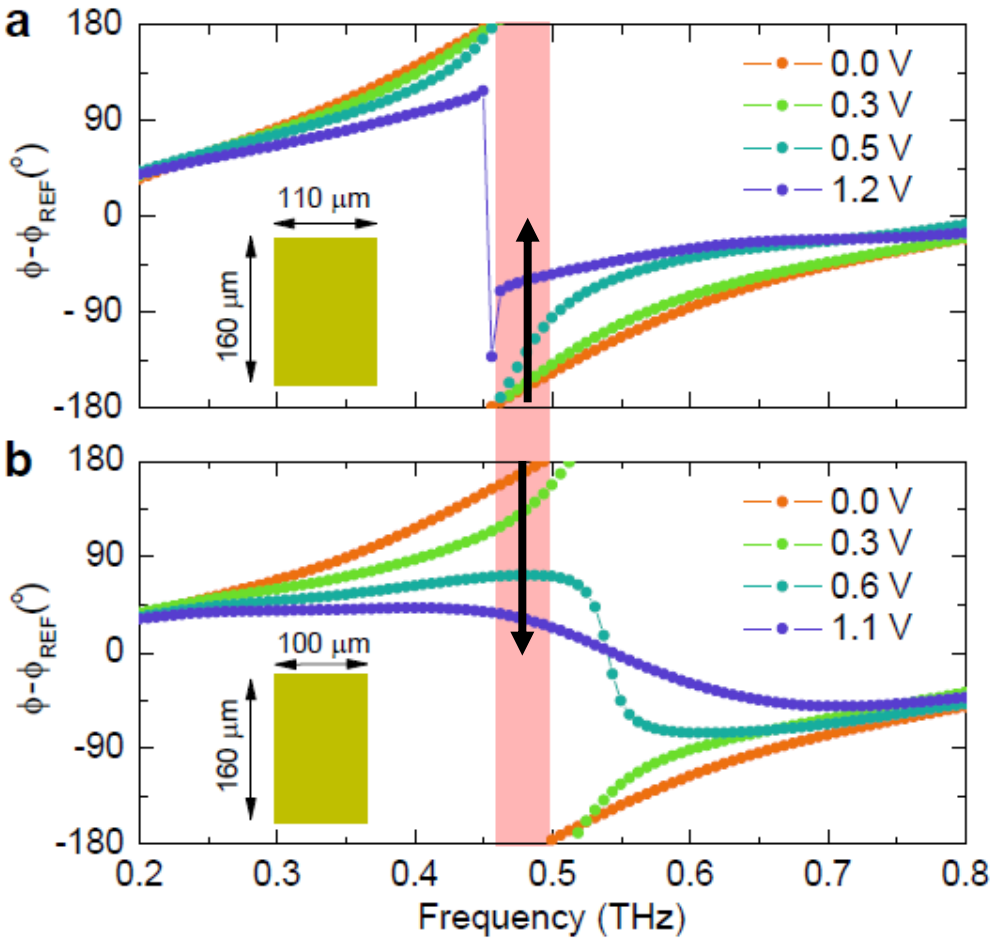
Amplitude/phase modulation (Expt.)
-- hole doping



- **Symmetrical behaviors compared to e-doping**
- **Slight asymmetry caused by band-structure deviations**

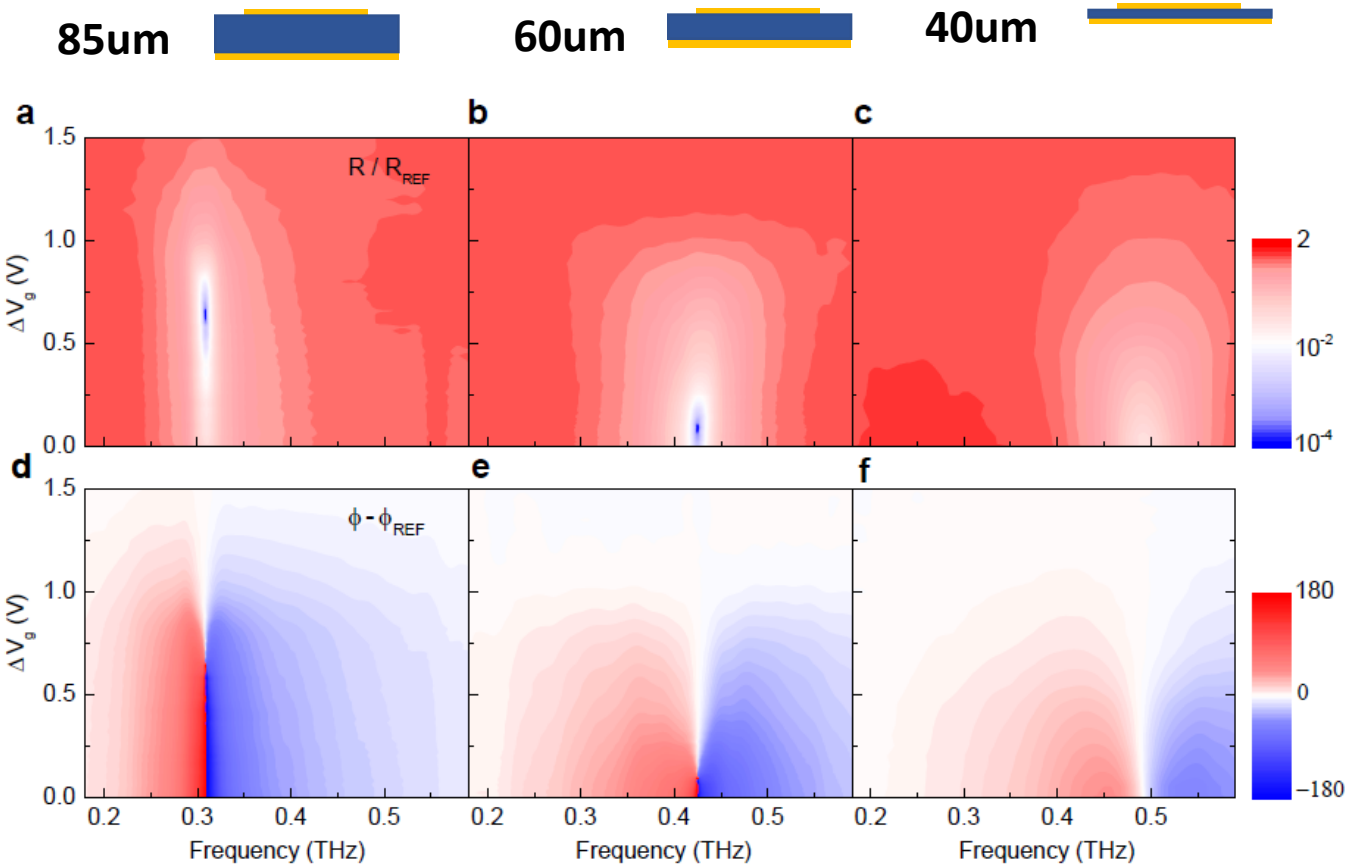
Full-range active phase control (Expt.)





- Two slightly different pixels lead to full-range phase modulation at a frequency interval
- Previous mechanism can never work, due to intrinsic limitations

Complete phase diagrams (Expt.)
--- different spacers



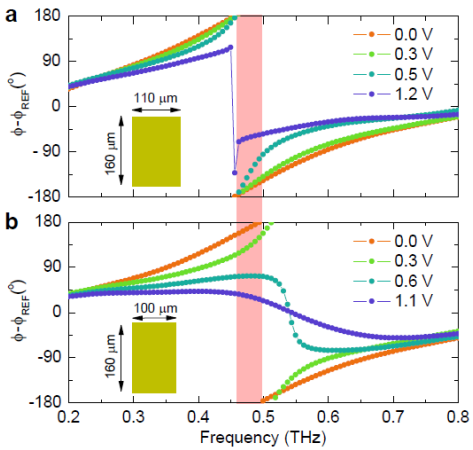
- Critical point determined by structure geometry
- Some system dose not support critical transition

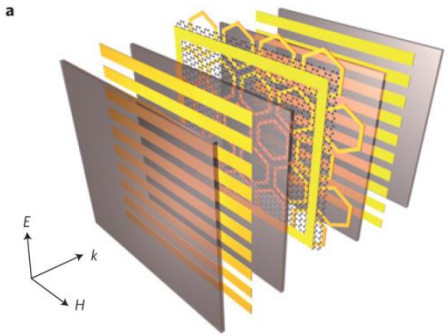
Puzzles

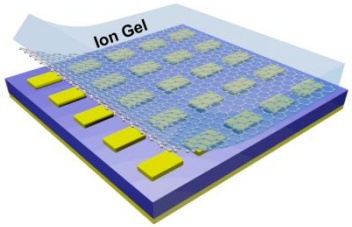
- Why can we achieve full-range phase modulation?

- Why previous system can not?

- What's the role played by graphene?







Coupled-mode theory
--- a clear & coherent picture

The temporal coupled mode theory (Fan, 2003)

$$\frac{\mathrm{d}a_{\mathrm{m}}}{\mathrm{dt}} = (-if_{0m} - \Gamma_{mi} - \Gamma_{ms})a_m + \sum_n k_{m,n} S_{m,n}^{+}$$

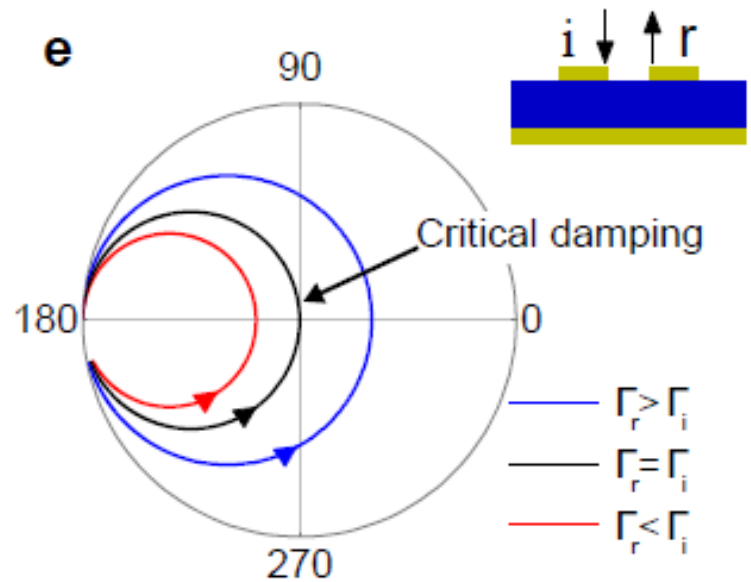
$$S_{m,n}^{-} = c_{m,n}^{s} S_{m,n}^{+} + c_{m,n}^{a} a_m$$

Single resonance

Single port

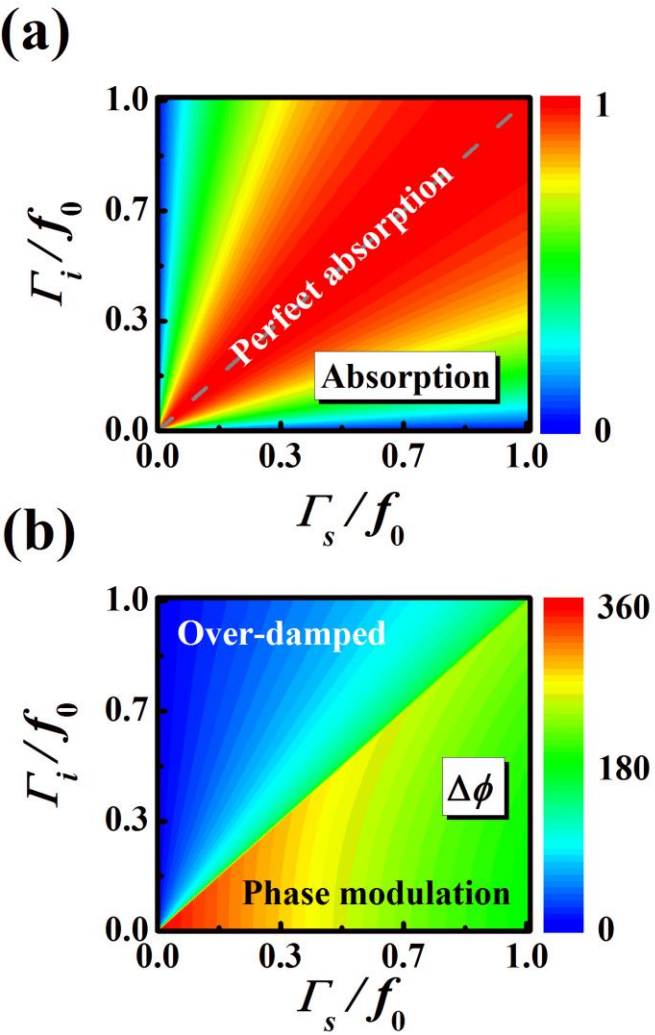
$$r = -1 + \frac{2\Gamma_r}{-i(f - f_0) + \Gamma_i + \Gamma_r}$$

$$r = (\Gamma_r - \Gamma_i)/(\Gamma_r + \Gamma_i), \quad f = f_0$$



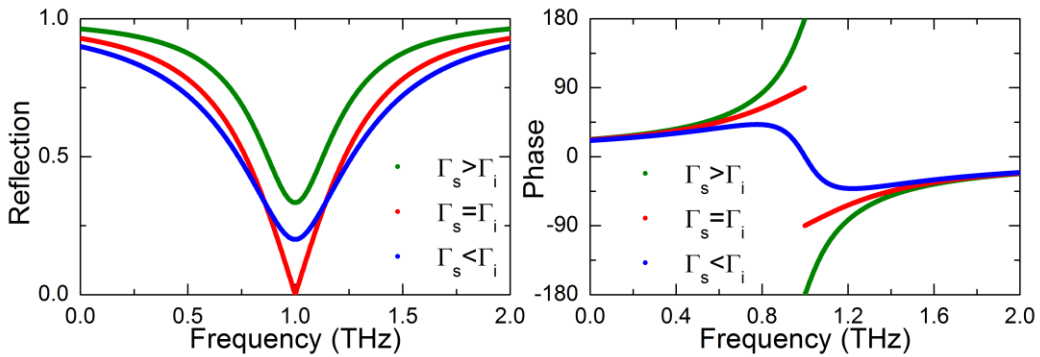
- **Different damping parameters yield different phase behaviors!**
- **Whether or not enclosing origin determines the phase variation range!**

Generic phase diagram



Qu, PRL 115 235503 (2015)

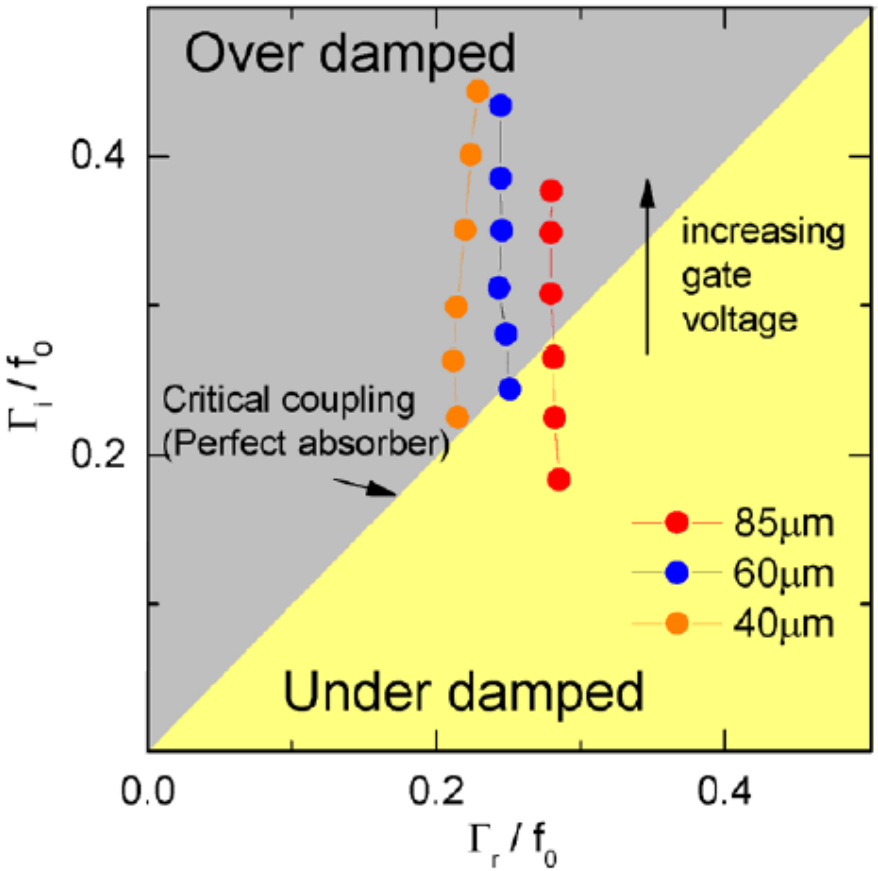
Typical behaviors in 3 regions (Reference: gold)

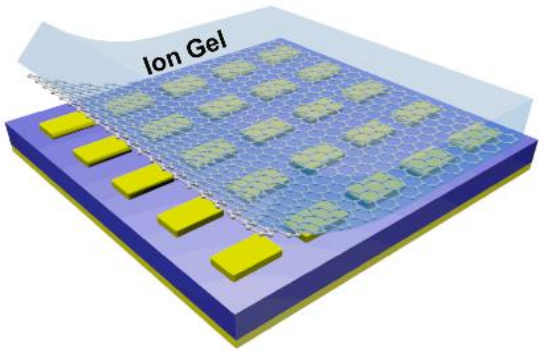


- Under-damped resonator: 360 variation
- Over-damped resonator: < 180 variation
- Critical coupling: Perfect absorber

Tuning the ratio Γ_S/Γ_i tune the system dramatically

Role of graphene upon gating
(Fitting FDTD with CMT)





Effects of gating graphene:

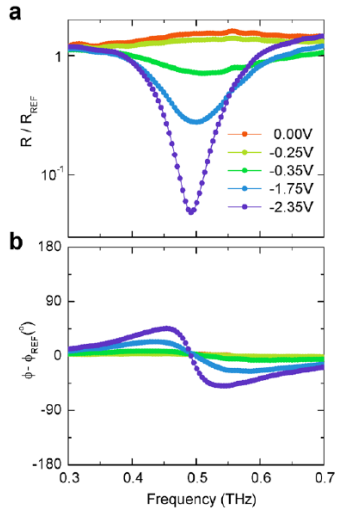
1) increasing Γ_i
2) has little effect on Γ_r
3) drives the system to transit from an under-damped to an over-damped resonator

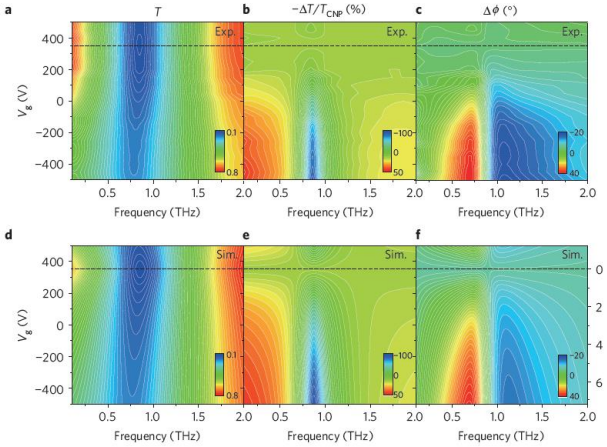
Gating graphene beaks the subtle balance between intrinsic and radiation losses!

Remaining puzzles:

1) Why some of our systems cannot?
2) Why previous systems fail?

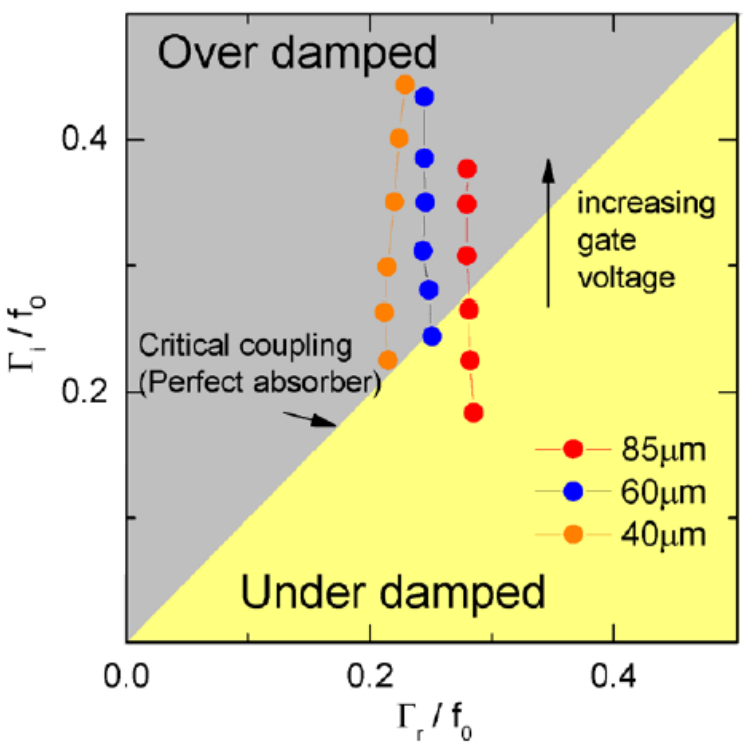
40um

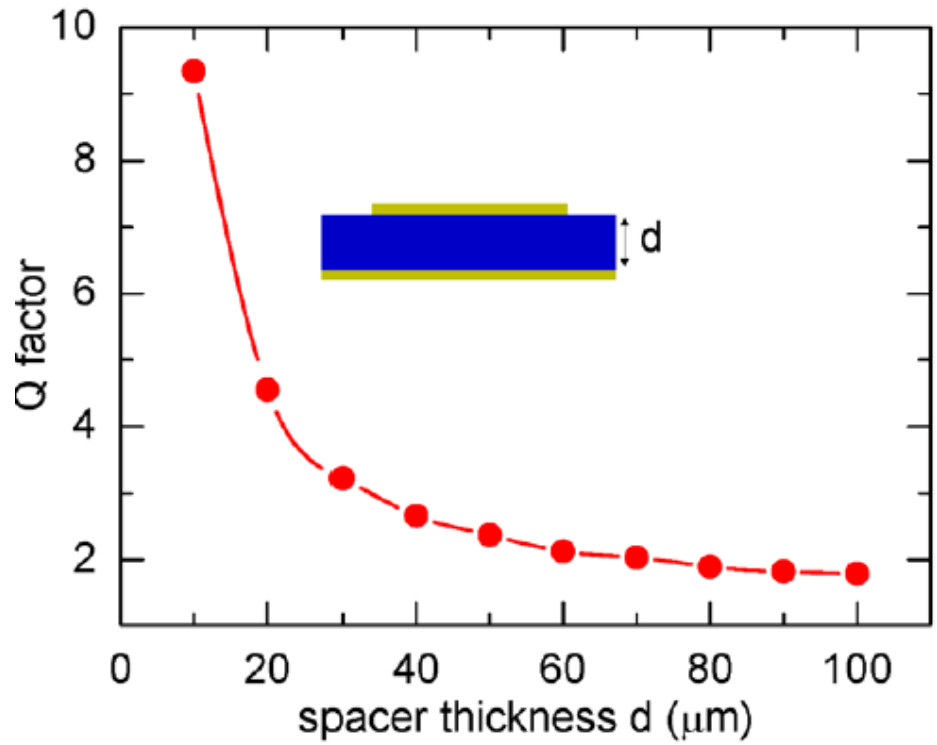




Do we have a general design guideline?

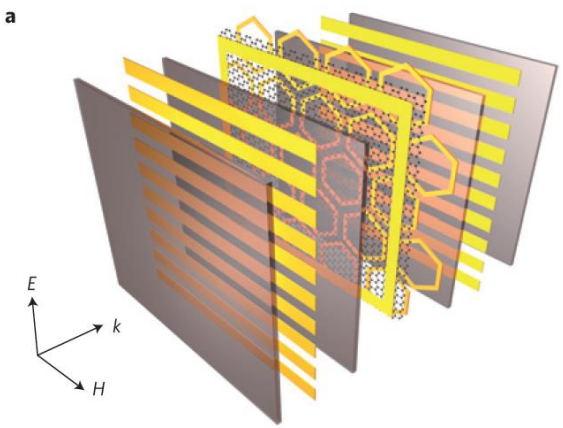
1) Why small-spacer one does not work?

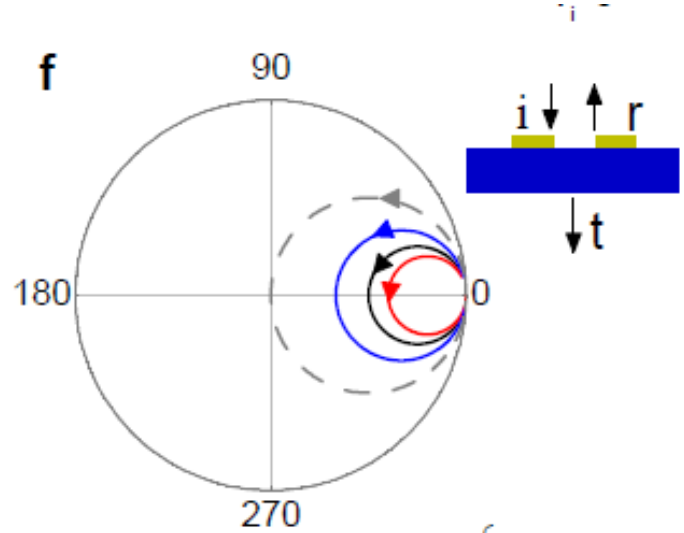




- **Smaller *d*, stronger near-field coupling, higher Q, smaller** Γ_r
- **Already in over-damped region even with graphene**
- **Graphene can only make it even more over-damped, no critical transition**

2) Why previous one cannot cover full range?

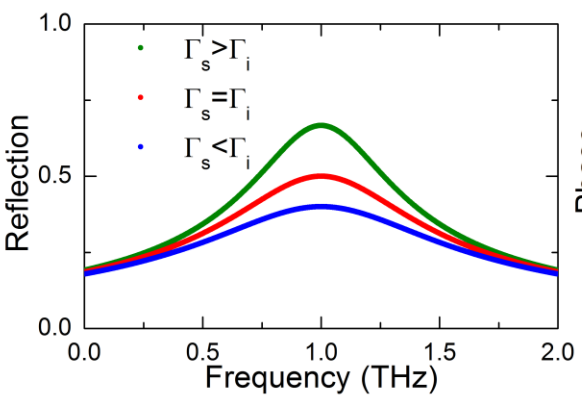


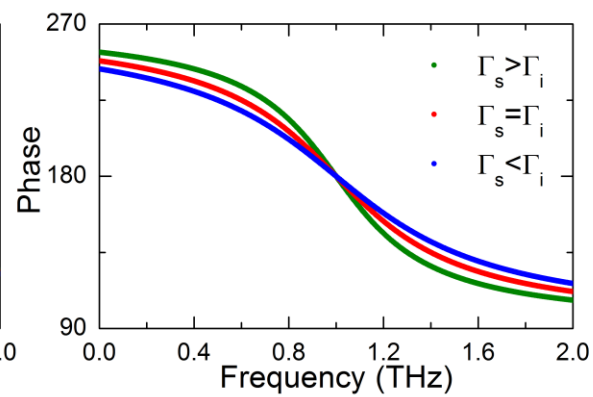


Lee, *Nature Mater*. 11, 936-941 (2012)

Double ports

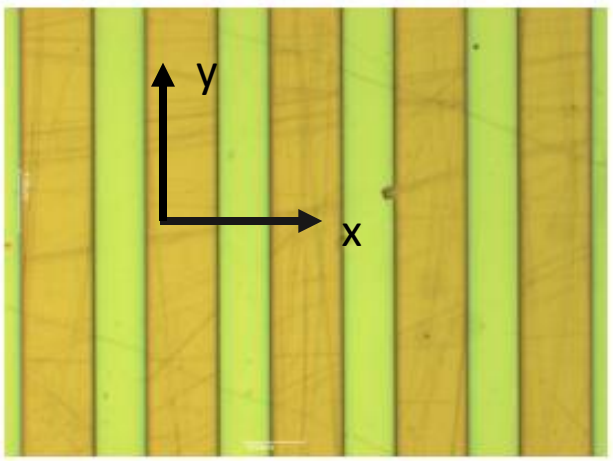
$$\begin{cases} r = \dfrac{\Gamma_e}{i(f-f_0)-\Gamma_i-\Gamma_e} \\ t = 1+\dfrac{\Gamma_e}{i(f-f_0)-\Gamma_i-\Gamma_e} \end{cases}$$

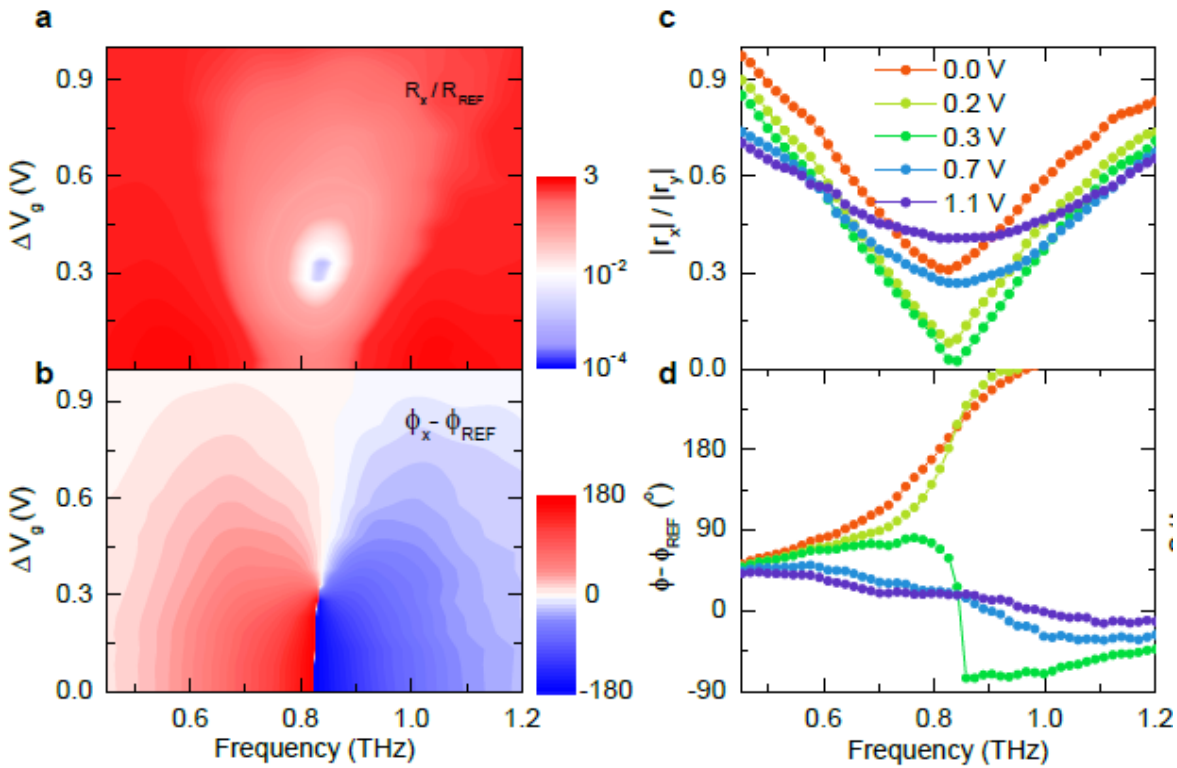




- **Two-ports system has no critical coupling**
- **Always E-resonance, can never be M-type!**

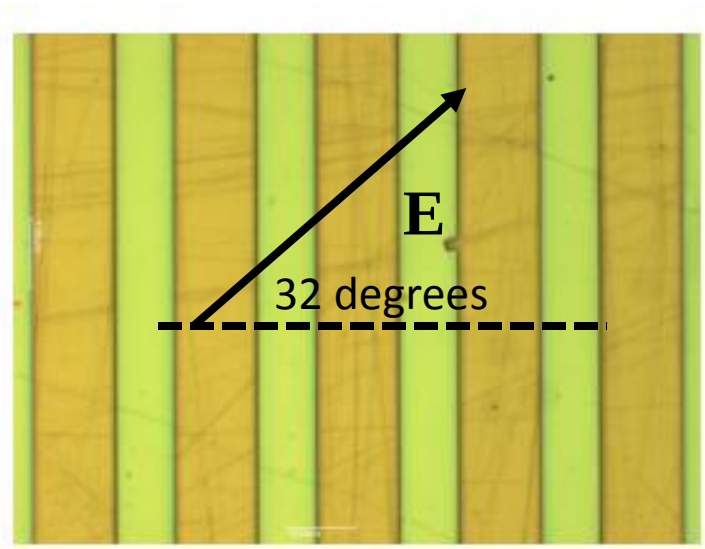
An application: an active polarizer

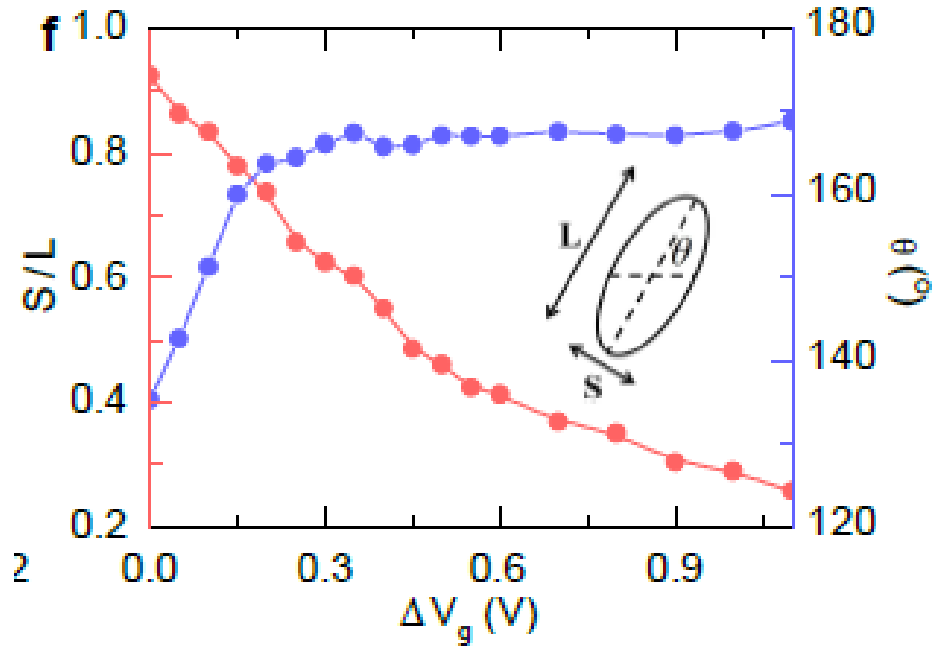




Only x polarized wave are modulated strongly

Tuning the polarization actively



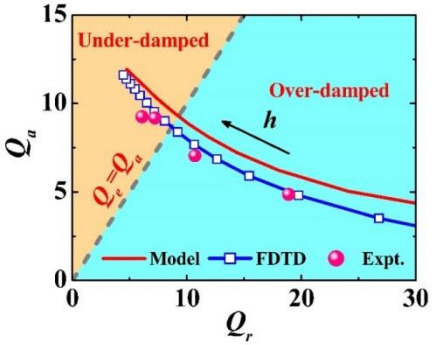


Polarization state strongly tuned by gate voltage

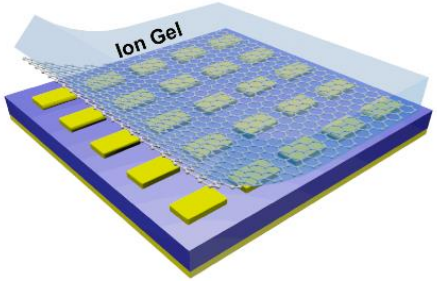
Miao *et al*., Phys. Rev. X 5, 041027 (2015).

Conclusions

- **Based on a complete phase diagram, we can easily tailor the functionalities of MIM metasurfaces.**



- **Combining graphene with meta-surface, we can realize *active full-range* phase modulation in deep-*subwavelength* regime**



Qu *et. al*, *Phys. Rev. Lett*. 115 235503 (2015)
Miao *et al*., *Phys. Rev. X* 5, 041027 (2015)
W. Sun *et al., Light: Science & Applications* 5, 16003 (2016)
W. Luo, Adv. Opt. Mater., 3 1102 (2015)

Thanks & Questions?