High-efficiency, multifunctional, and tunable metasurfaces

Lei Zhou

Physics Department, Fudan University,
Shanghai 200433, China

phzhou@fudan.edu.cn

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Acknowledgements

- **Key contributors**
  Weijie Luo, Shaojie Ma, Ziqi Miao, He-Xiu Xu, Tong Cai, Shiwei Tang, Shiyi Xiao, Shulin Sun, Qiong He

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SHANGHAI SCIENCE & TECHNOLOGY

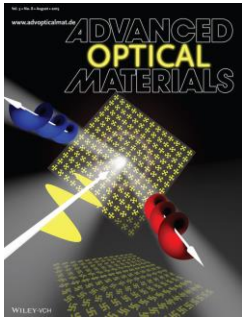
1) **Backgrounds**

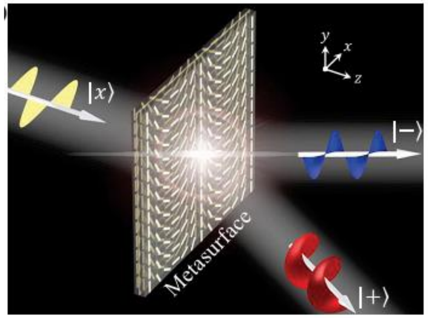
2) **High-efficiency metasurfaces for spin-polarized light**

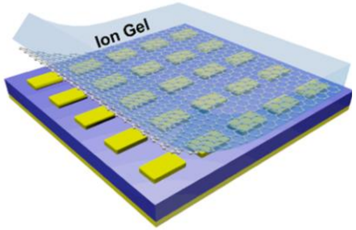
3) **Tunable metasurfaces (THz & GHz)**

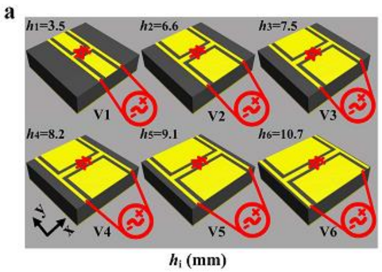
4) **Multifunctional metasurfaces**

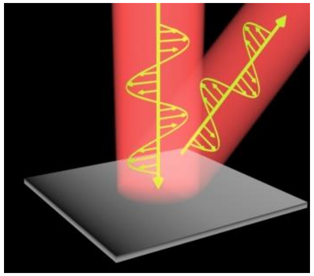
5) **Conclusions**

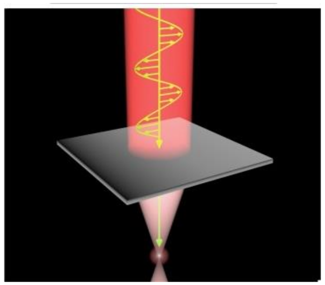




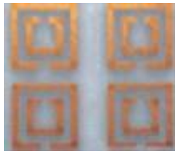


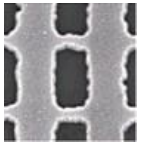




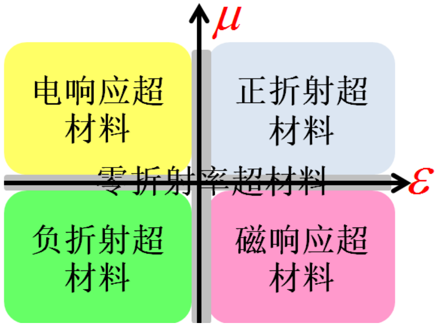


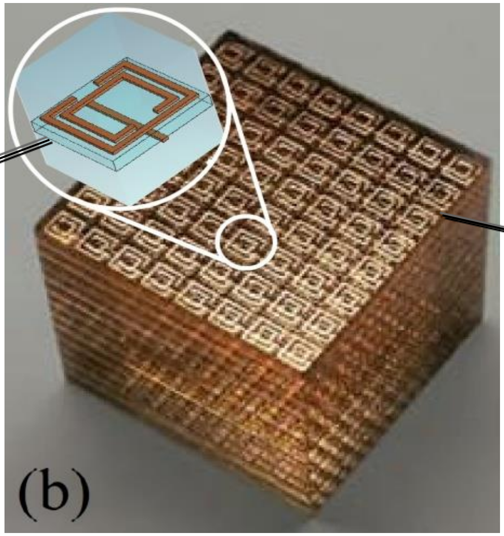
What's Metamaterial (MTM)?



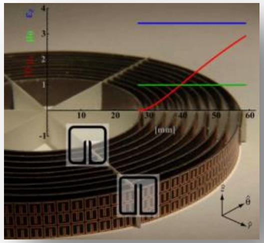


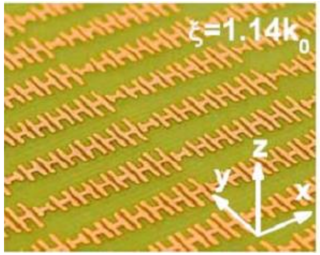
"Meta-atoms"
Subwavelength resonant units





Designable order

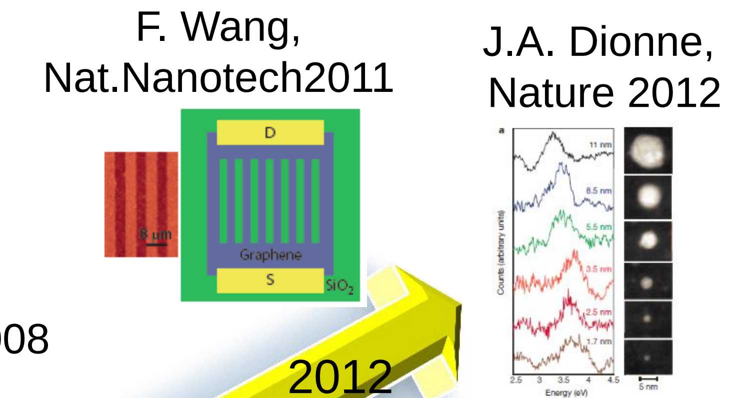


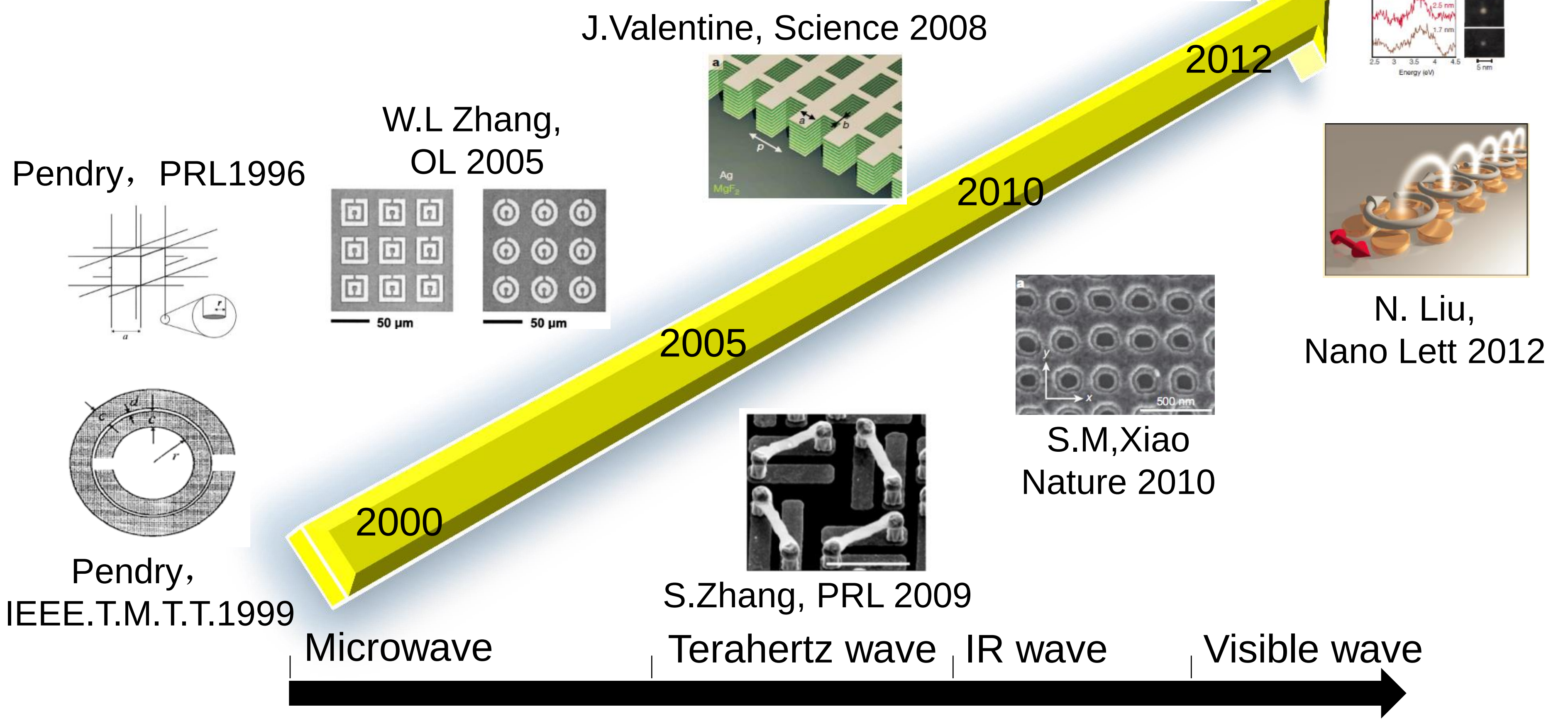


Designable meta-atoms and macro-order offer MTMs great controllability on EM waves

Development along "Meta-atoms"

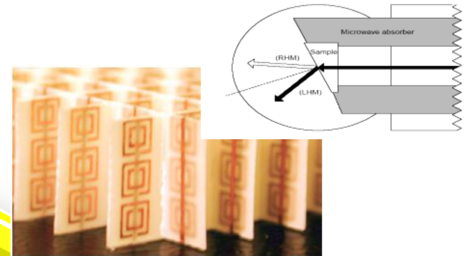
1. Minimization in dimension
2. Diversity of functionality
3. Pluralistic Materials



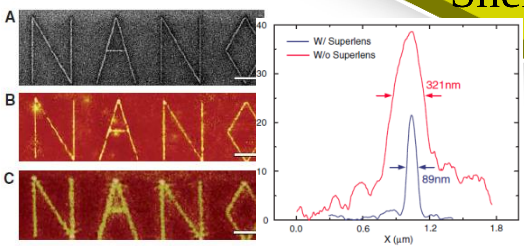


Development along "Order"

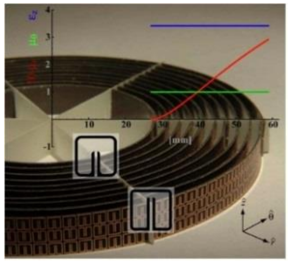
Periodic or homogeneous Marco-order



Shelby, Science (2001)

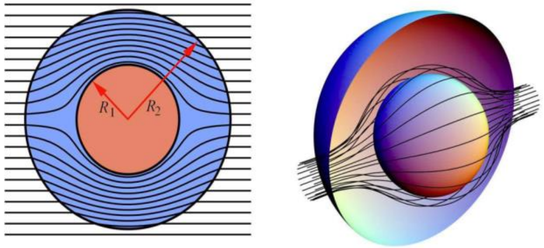


N.Fang, Science (2005)

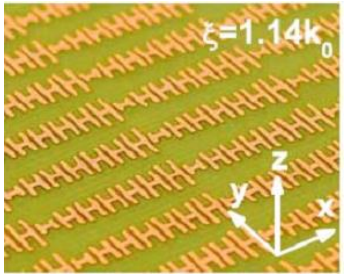


D. Schurig，Science (2006)

Slowly varying Marco-order

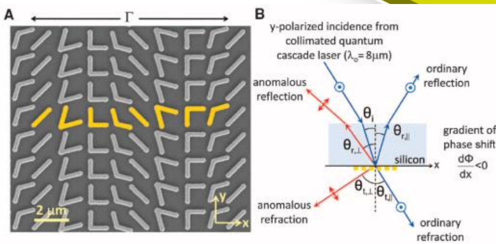


J.B. Pendry, Science (2006)
U. Leohardt, Science (2006)



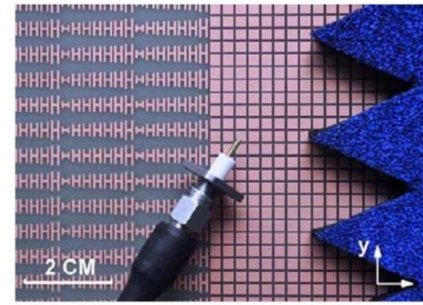
S.L. Sun et al., Nature Materials (2012)

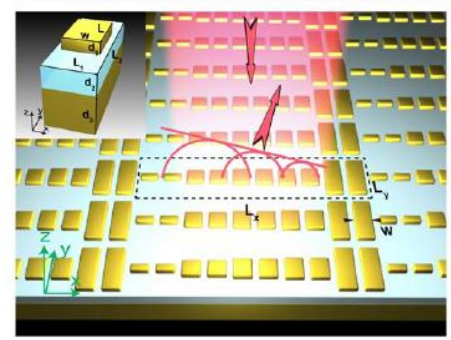
Gradient Meta-surface



N.F. Yu, Science (2011)
X. Ni, Science (2012)

Metamaterials → Metasurfaces

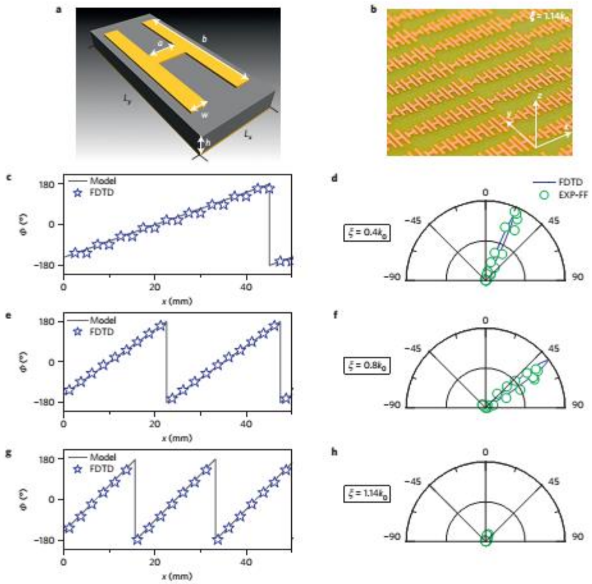


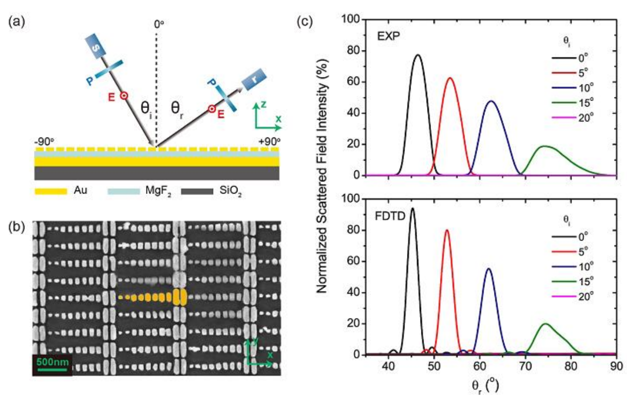


- **Bulk MTM goes to single-layer metasurface**
- **Avoid propagation losses**
- **Inhomogeonity provides more freedom to control EM waves**

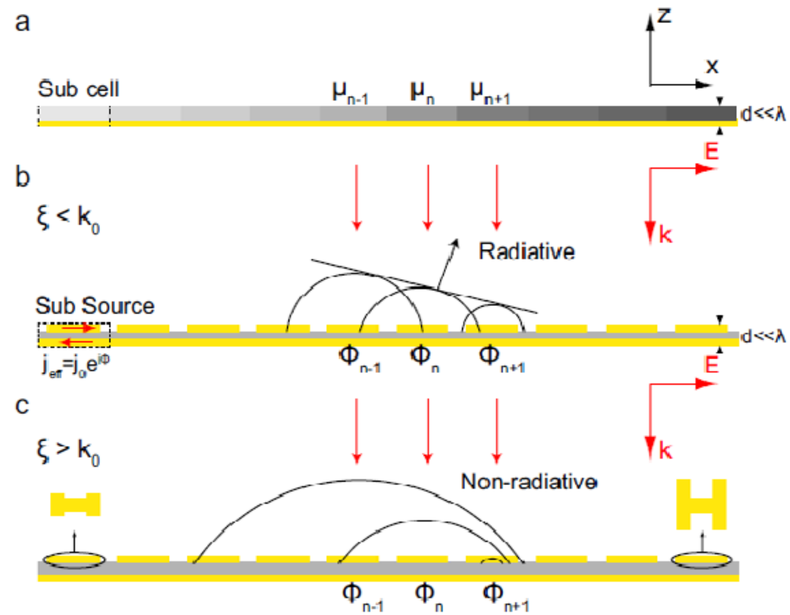
1) Gradient meta-surfaces to bridge PW and SW

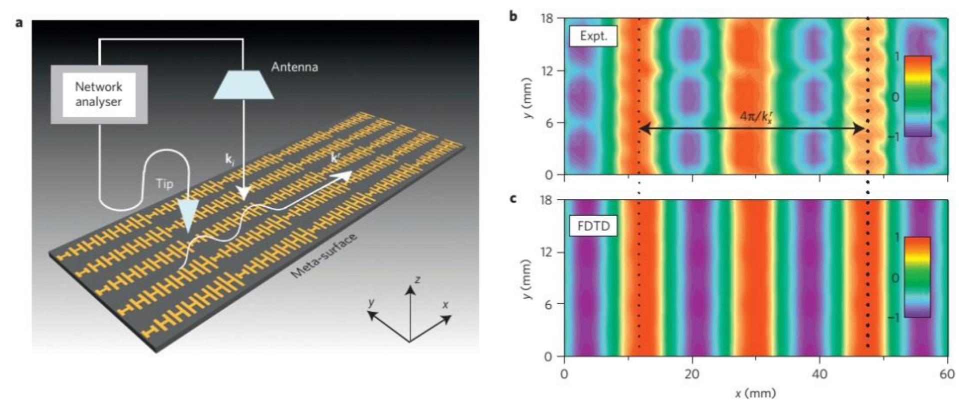
Generalized Snell's law $k_{\parallel}^{r} = \xi + k_0 \sin\theta_i$





PW → SW conversion





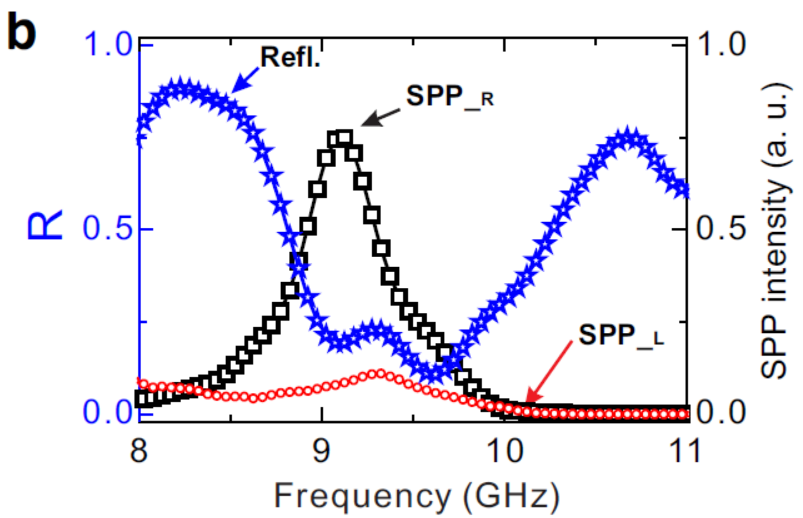
S. Sun et al., Nat. Mater. 11, 426 (2012)

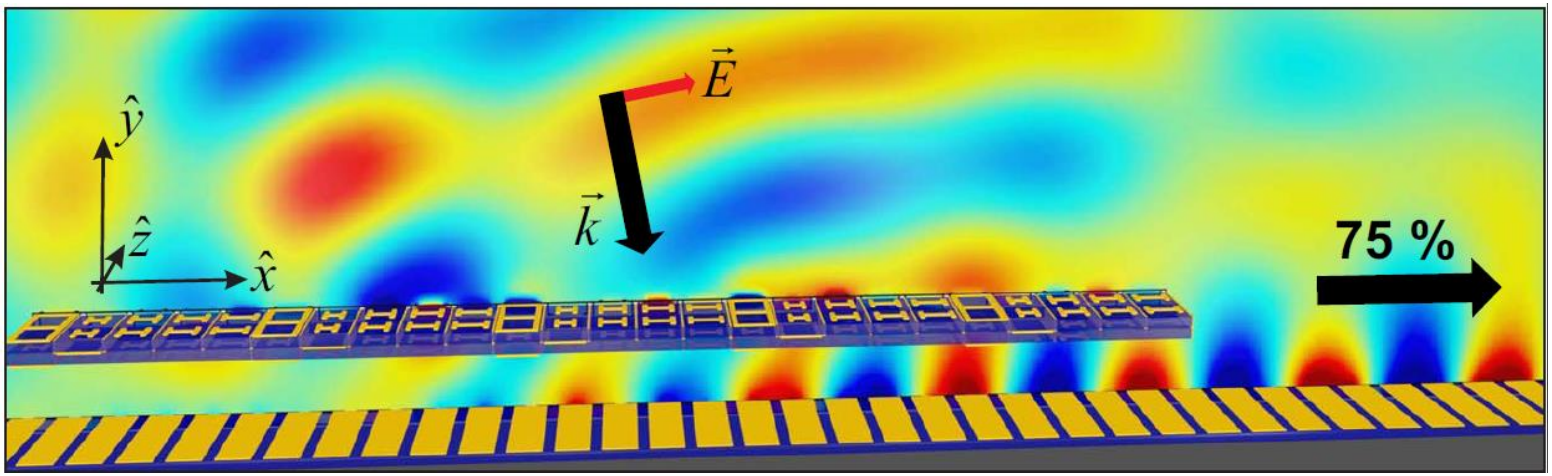
S. Sun et al., Nano Lett. 12 6223 (2012)

2) SPP meta-coupler with high efficiency

→ 73% efficiency (Expt.)

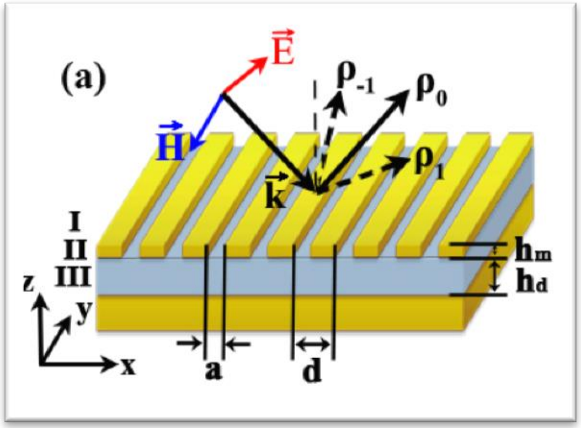
→ Match well with FDTD (75%).

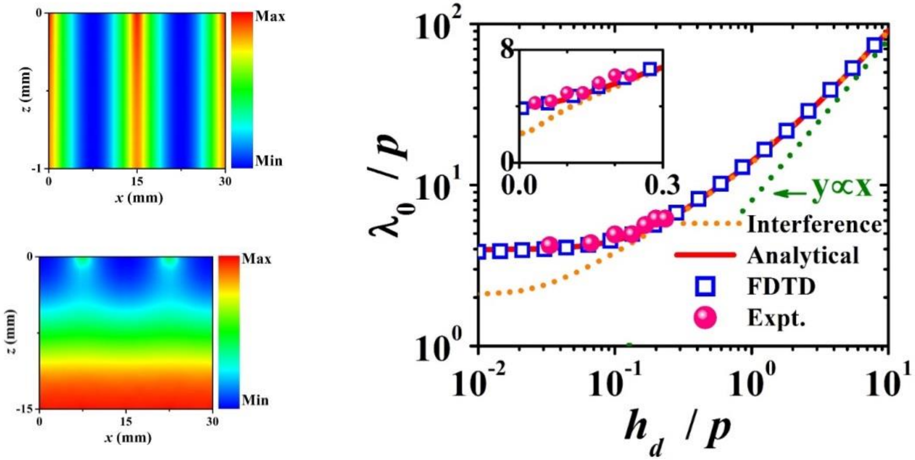




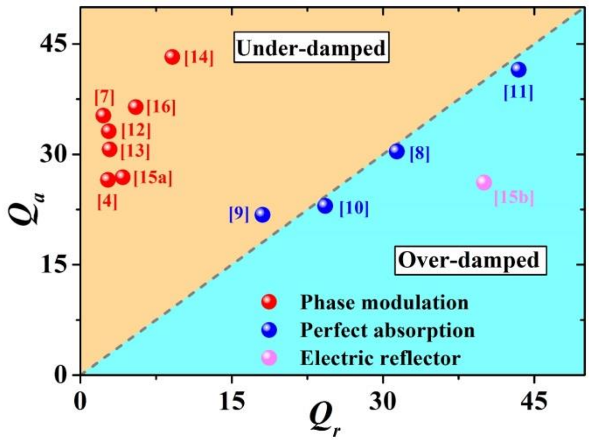
W. Sun *et al.*, *Light: Science & Applications* 5, 16003 (2016).
Jingwen Duan, *et al.*, 7 1354 (2017).

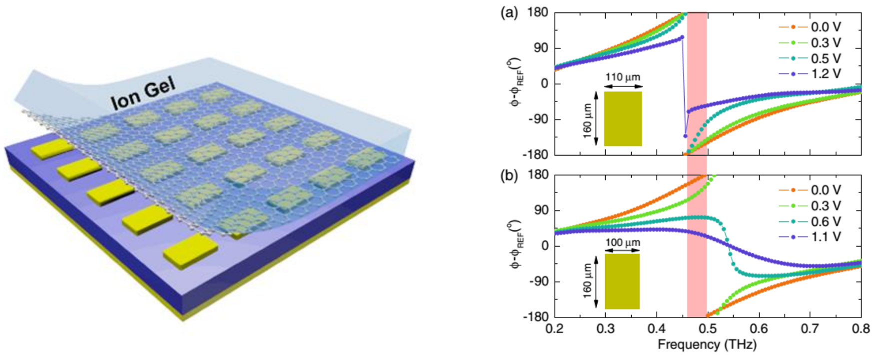
3) Physics of MIM metasurfaces





Eigen resonant modes in MIM (PRB 2016)

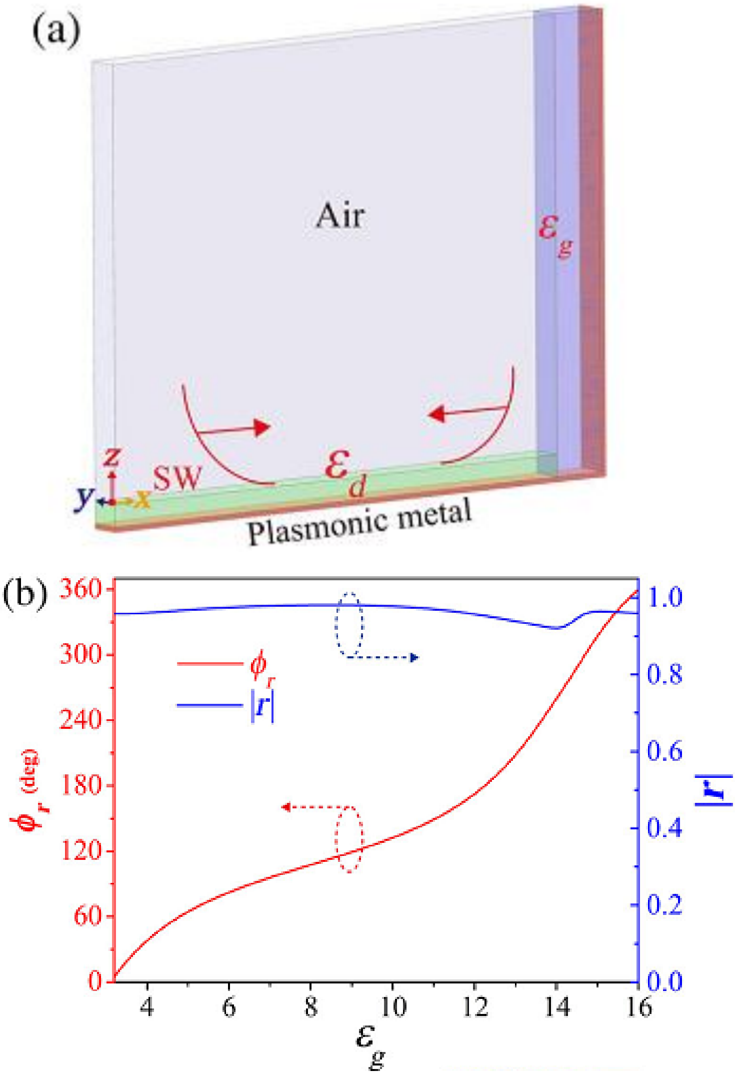


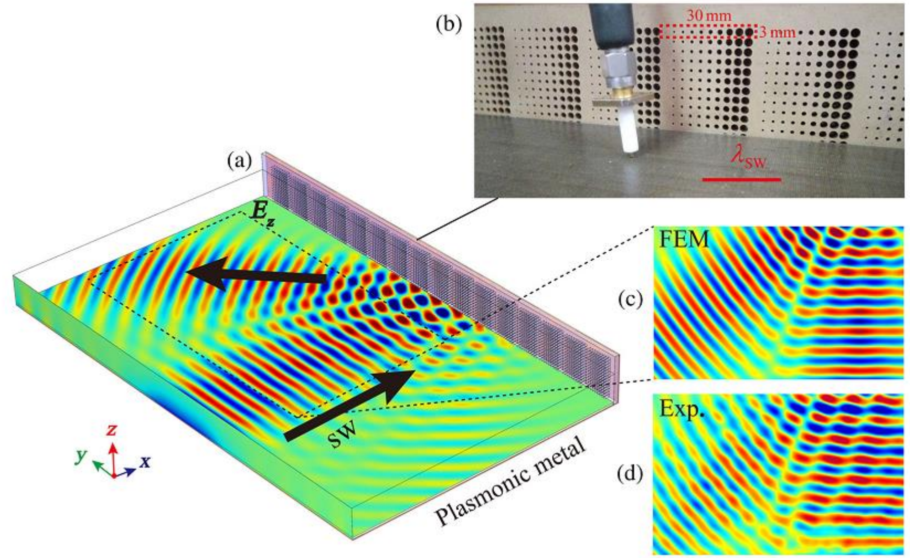


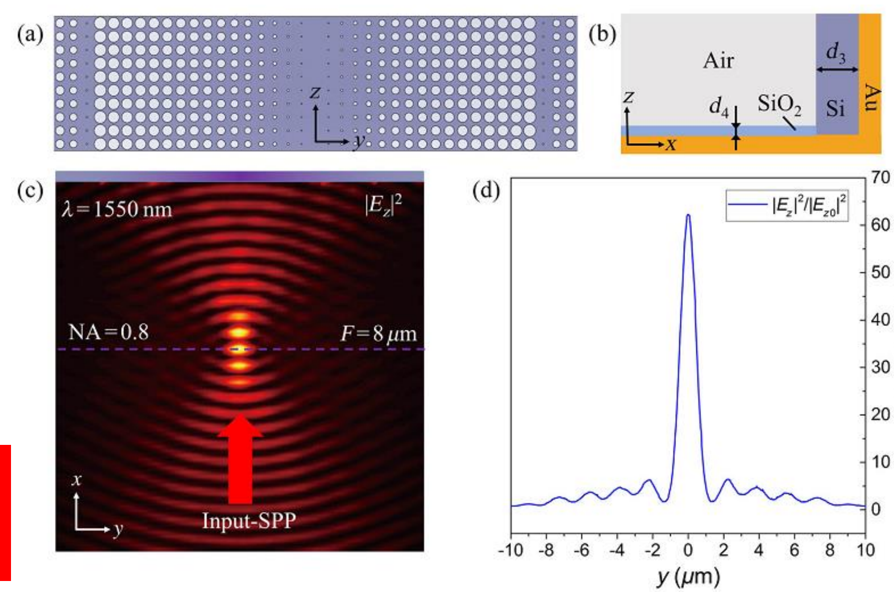
Complete functionality phase diagram for MIM (PRL 2015)

Graphene MIM for wide-range phase modulation (PRX 2015)

4) SPP manipulation with meta-walls

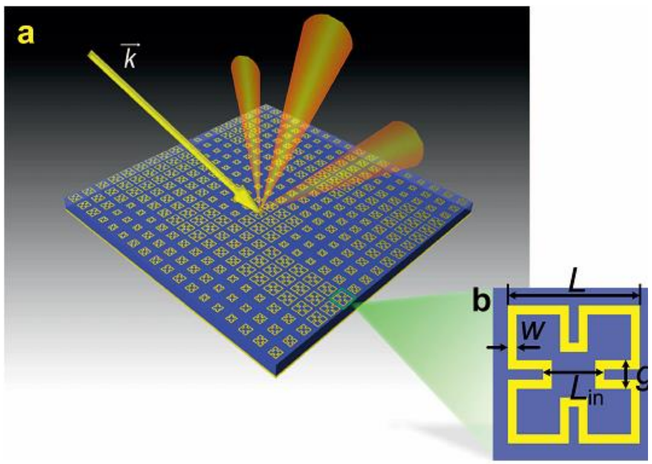






S. Ma, **et. al.,** ***Phys. Rev. Appl*****.**
9 014032 (2018)

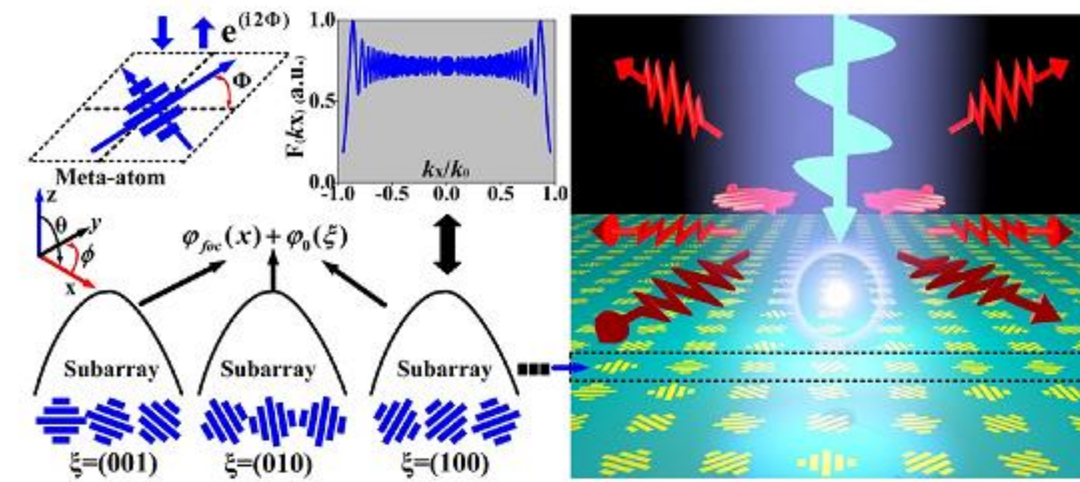
5) Deterministic approach to design polarization-independent diffusive-scattering metasurfaces



Tiejun Cui, LSA (2016)

Coding-metasurface:

requires complicated optimization to determine the "coding sequence"



Xu, ACS Photonics 10.1021/acsphotonics.7b01036, 2017

Our approach:
1) PB meta-atom independent of polarization
2) Subarray exhibits parabolic phase profile
3) Coding sequences with moderate randomness

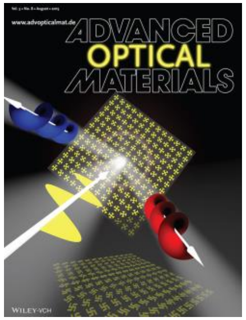
1) Backgrounds

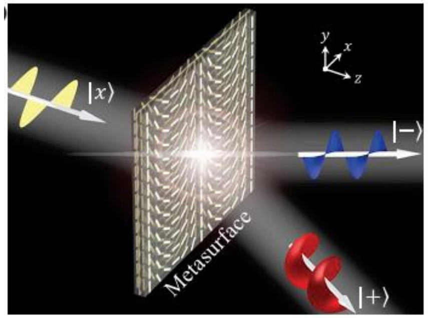
2) **High-efficiency metasurfaces for spin-polarized light**

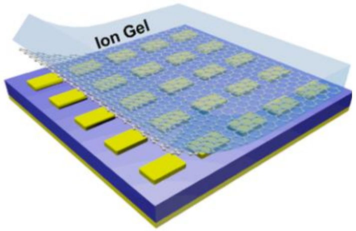
3) Tunable metasurfaces (THz & GHz)

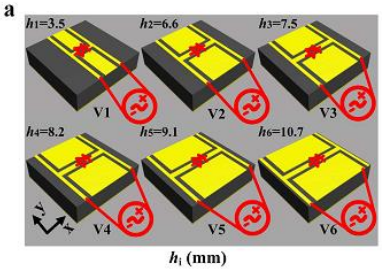
4) Multifunctional metasurfaces

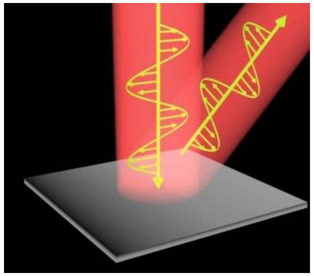
5) Conclusions

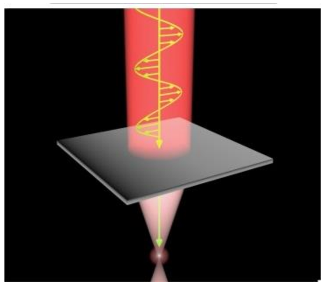






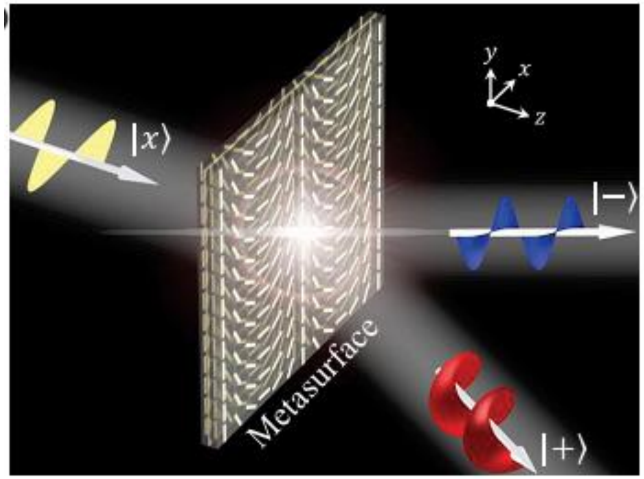




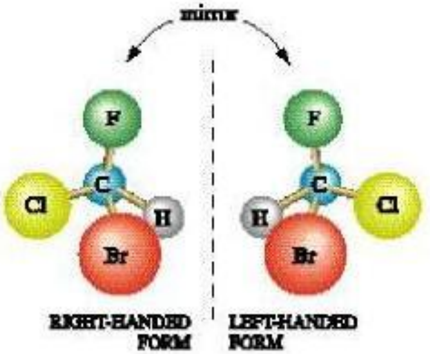


Circularly polarized light: Spin momentum

- **Circularly polarized light carries spin angular moment**



- **Spin-polarized light has important applications in manipulating chiral objects (e.g., chiral molecules)**



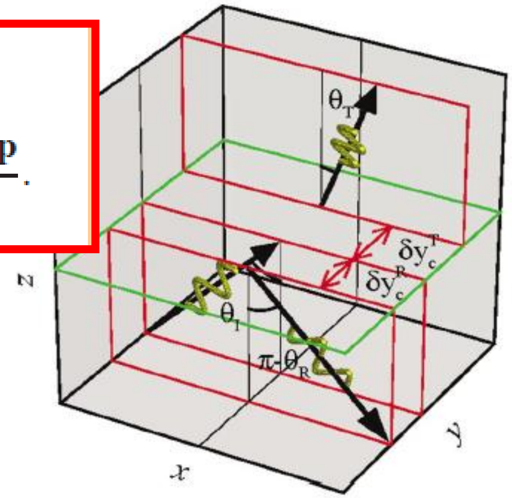
Can we use metasurfaces to control spin-polarized lights at will?

PSEH: Controlling spin-polarized light
1. Intrinsic photonic spin-Hall effect (PSHE)

- A direct analogy of electron SHE
- SOC term is crucial
- Effect very weak

$$\dot{\mathbf{p}} = \nabla n,$$

$$\dot{\mathbf{r}} = \frac{\mathbf{p}}{p} + \lambdabar_0 s \dot{\mathbf{p}} \times \mathbf{F} = \frac{\mathbf{p}}{p} + \lambdabar_0 s \frac{\dot{\mathbf{p}} \times \mathbf{p}}{p^3}.$$



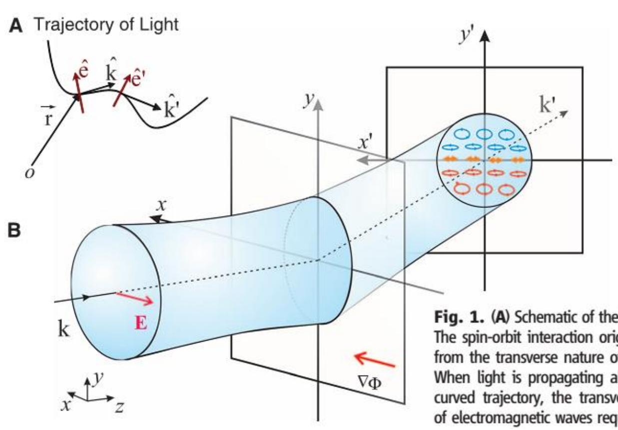
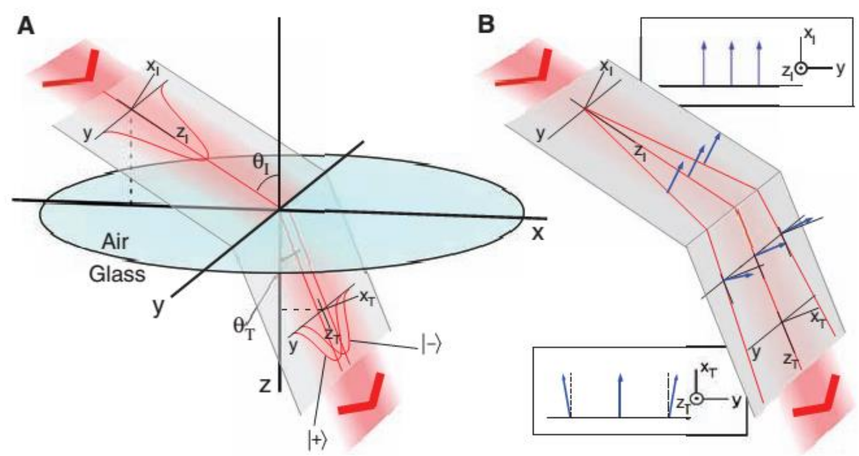


Fig. 1. (A) Schematic of the PSHE. The spin-orbit interaction originates from the transverse nature of light. When light is propagating along a curved trajectory, the transversality of electromagnetic waves requires a

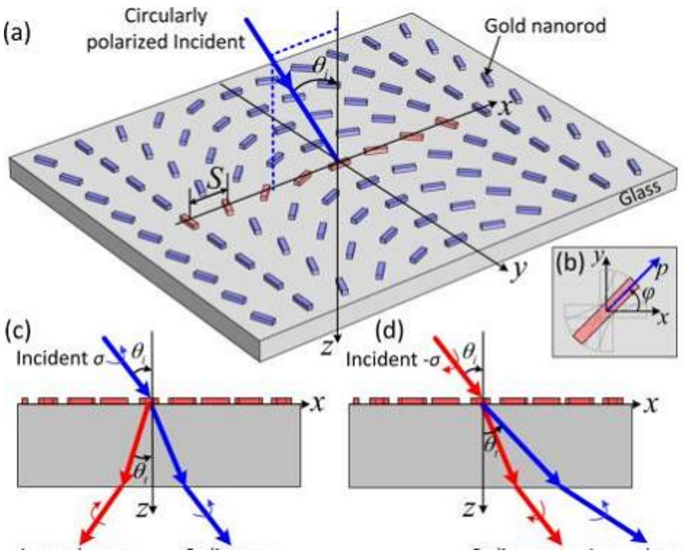


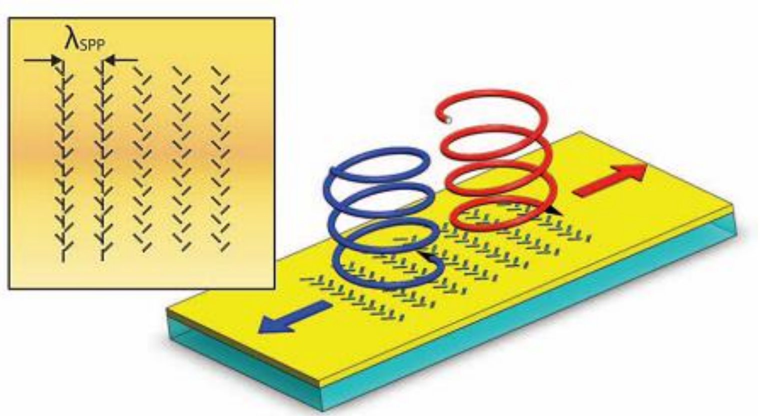
Nagaosa PRL (04); Bliokh PRL (06); O. Hosten, Science (08): Xiang Zhang, Science (13)

2. Extrinsic PSHE
Spin-dependent scatterings at meta-surfaces

- ☐ Effect very significant, can even lead to PW-SPP conversion

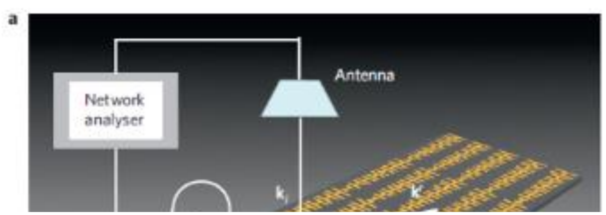
- ☐ Efficiency is low (3-5 %) !
  - --- multi-mode generation;
  - --- normal modes exist

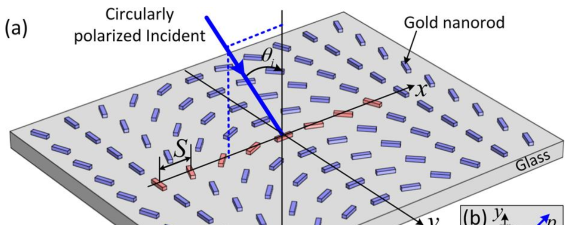




Hasman (2011); Shuang Zhang (2012), Capasso (2013) …

Our motivation





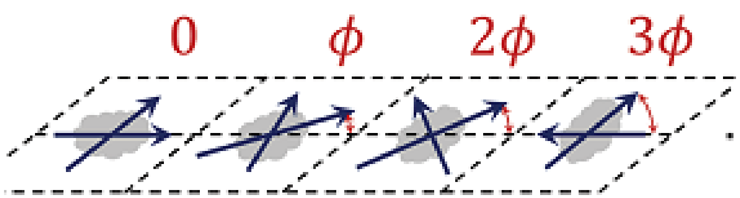
Can we realize a giant photonic SHE with almost 100% efficiency?

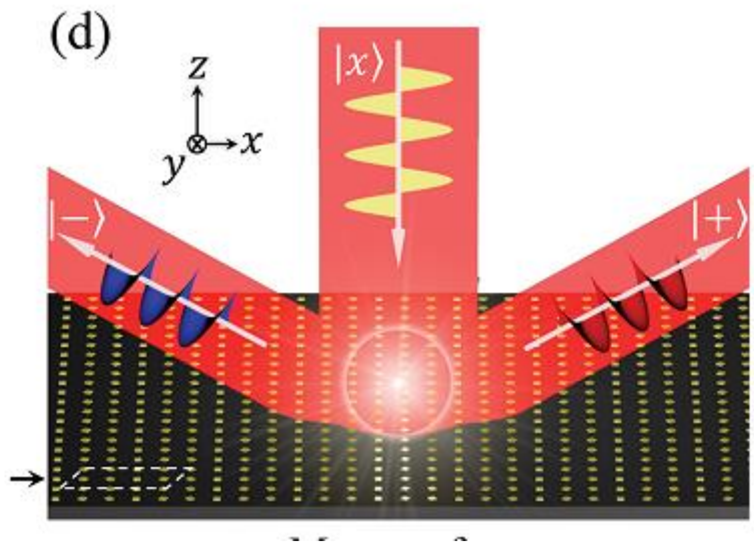
Efficiency≈100%

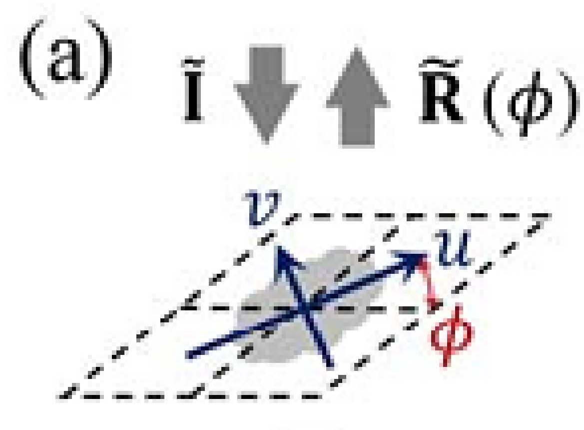
Spin Dependent

How to realize PSHE with 100% efficiency ?

Generic structure of a Berry Slab







To realize PSHE with 100% efficiency
→ the Jones' matrix of a "meta-atom"?

Criterion to realized 100% efficiency PSHE

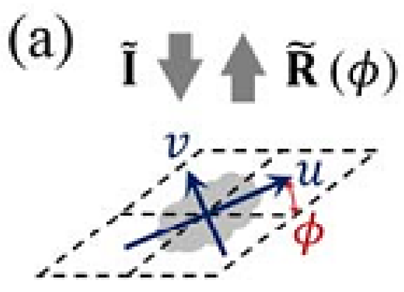
Consider R-matrix (in CP basis) only

$$\tilde{\mathbf{R}}(\phi)=\frac{1}{2}\left(r_{uu}+r_{vv}\right)\hat{I}+\frac{i}{2}\left(r_{uv}-r_{vu}\right)\hat{\sigma}_3$$

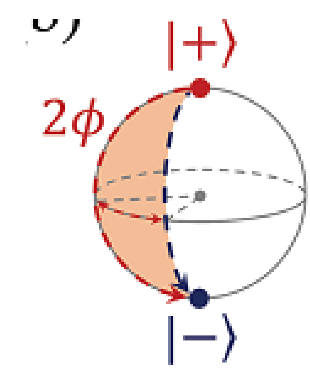
← Normal modes

$$+\frac{1}{2}\left(r_{uu}-r_{vv}\right)\left(e^{-i2\phi}\hat{\sigma}_{+}+e^{i2\phi}\hat{\sigma}_{-}\right)+\frac{i}{2}\left(r_{uv}+r_{vu}\right)\left(-e^{-i2\phi}\hat{\sigma}_{+}+e^{i2\phi}\hat{\sigma}_{-}\right)$$

Anomalous modes



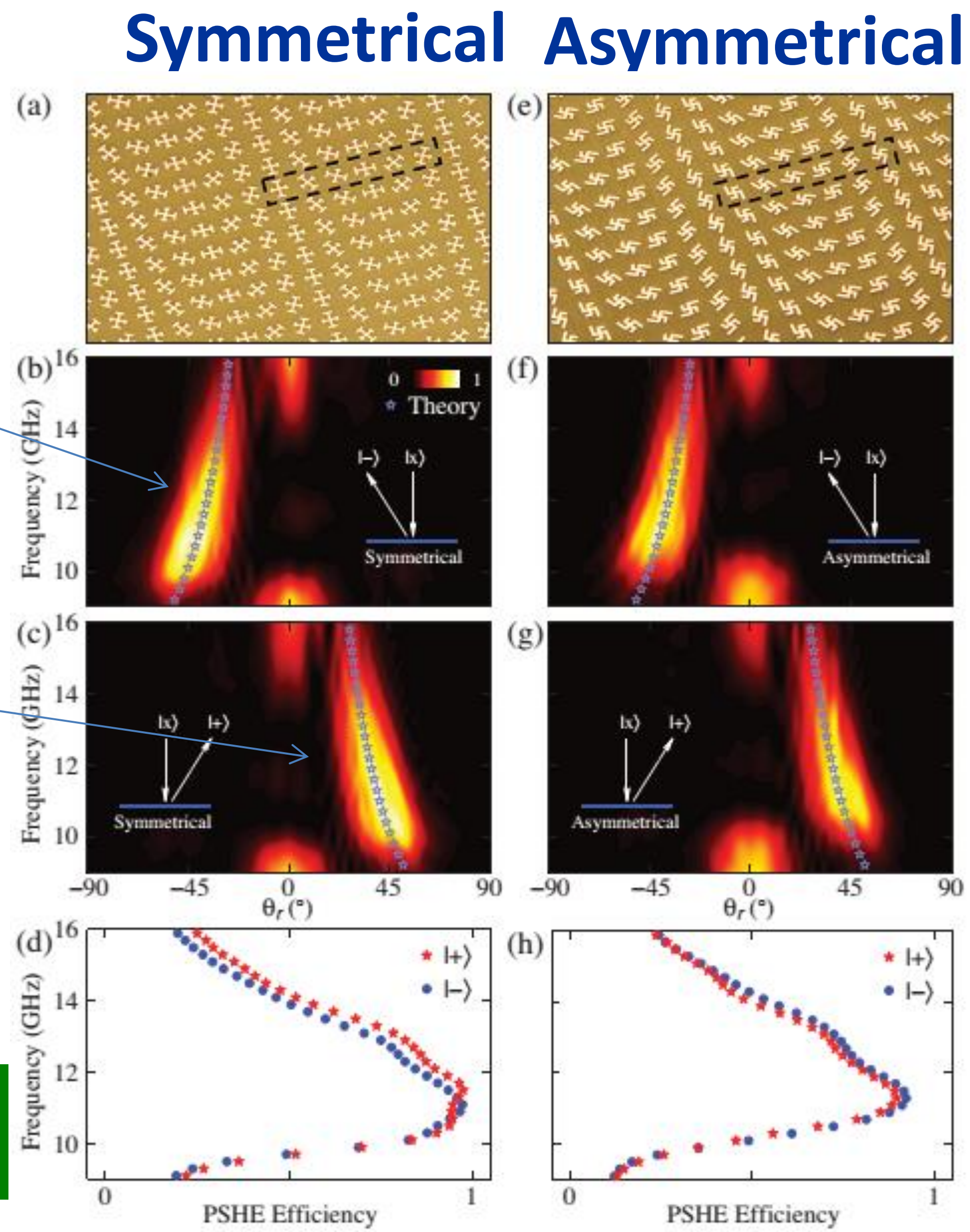
$$r_{uu}+r_{vv}=r_{uv}-r_{vu}=0$$



→ Half-wavelength wave-plate

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

Broad-band and high-efficiency SHE of Light (experiments)



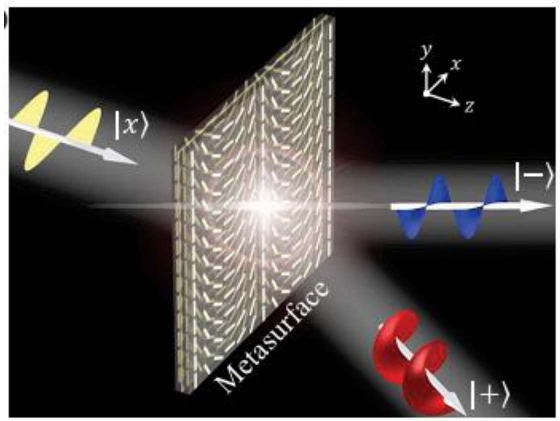
Single anomalous mode

Almost NO normal mode

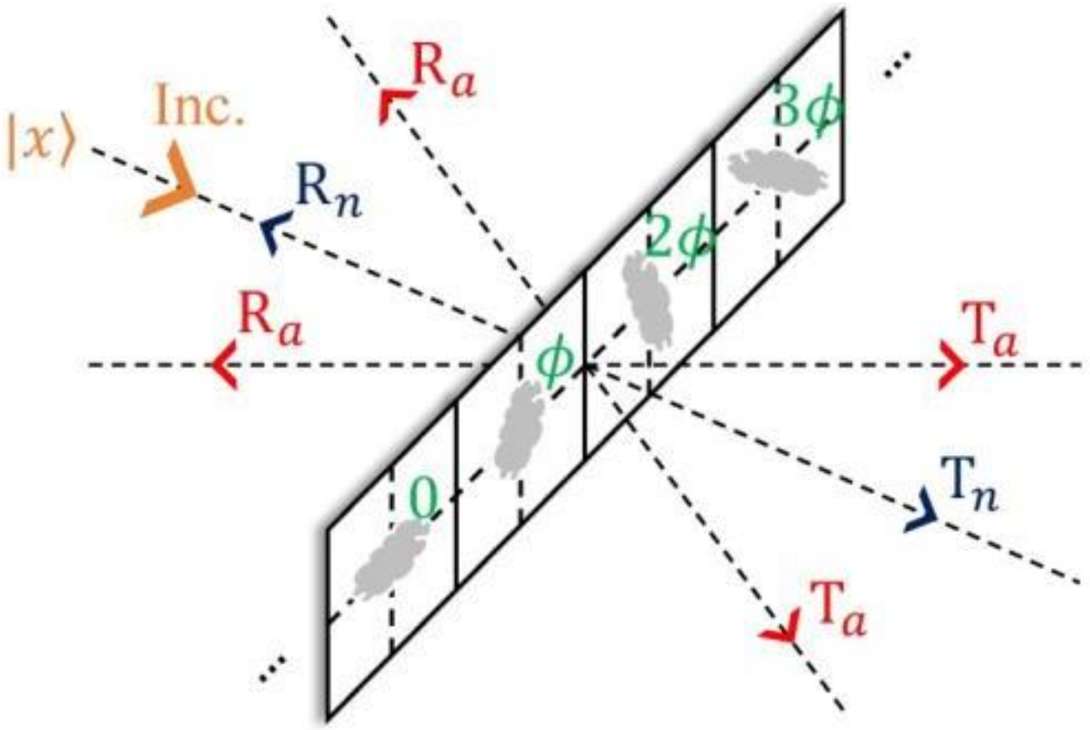
Luo et. al., Adv. Opt. Mater. 3,1102 (2015)

Question

Can we realize 100%-efficiency PSHE in transmission mode?



Challenges in transmissive PB metasurface



- Extension to transmission case is highly nontrivial
- 4 modes exist generally
- New physics and new design

Criterion in transmission geometry

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

Symmetrical case, Interchange *r* and *t*

$$r_{uu} = r_{vv} = 0, \quad t_{uu} + t_{vv} = 0$$

Ideal half wave-plate in transmission geometry

25% efficiency limit in ultrathin metasurfaces

Fundamental Limits of Ultrathin Metasurfaces

Amir Arbabi and Andrei Faraon*
T. J. Watson Laboratory of Applied Physics, California Institute of Technology, 1200 E California Blvd., Pasadena, CA 91125, USA

We present universal theoretical limits on the operation and performance of non-magnetic passive ultrathin metasurfaces. In particular, we prove that their local transmission, reflection, and polarization conversion coefficients are confined to limited regions of the complex plane. As a result, full control over the phase of the light transmitted through such metasurfaces cannot be achieved if the polarization of the light is not to be affected at the same time. We also establish fundamental limits on the maximum polarization conversion efficiency of these metasurfaces, and show that they cannot achieve more than 25% polarization conversion efficiency in transmission.

Materials Views
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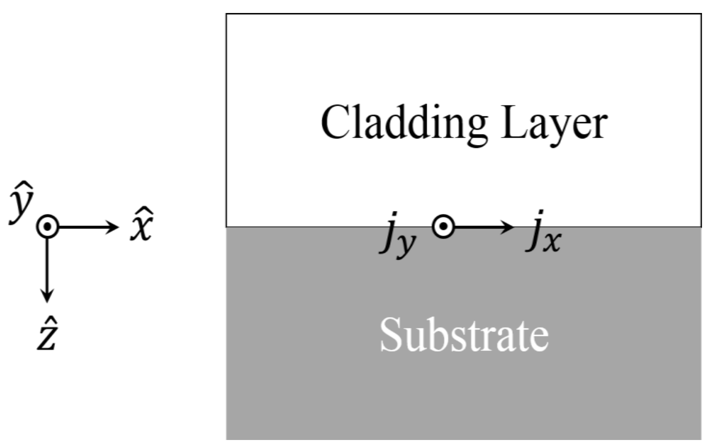
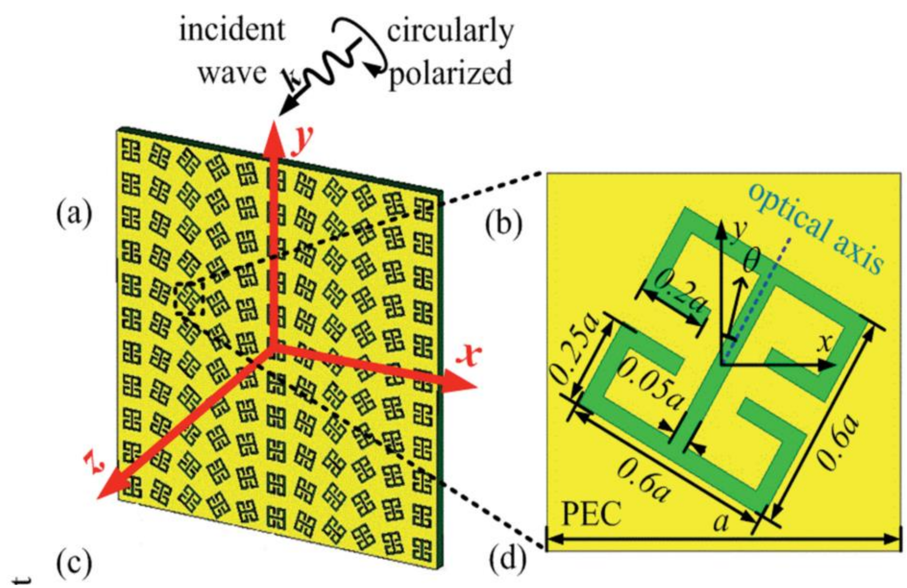
Ultrathin Pancharatnam–Berry Metasurface with Maximal Cross-Polarization Efficiency

Xumin Ding, Francesco Monticone, Kuang Zhang, Lei Zhang, Dongliang Gao, Shah Nawaz Burokur, Andre de Lustrac, Qun Wu, Cheng-Wei Qiu,* and Andrea Alù**



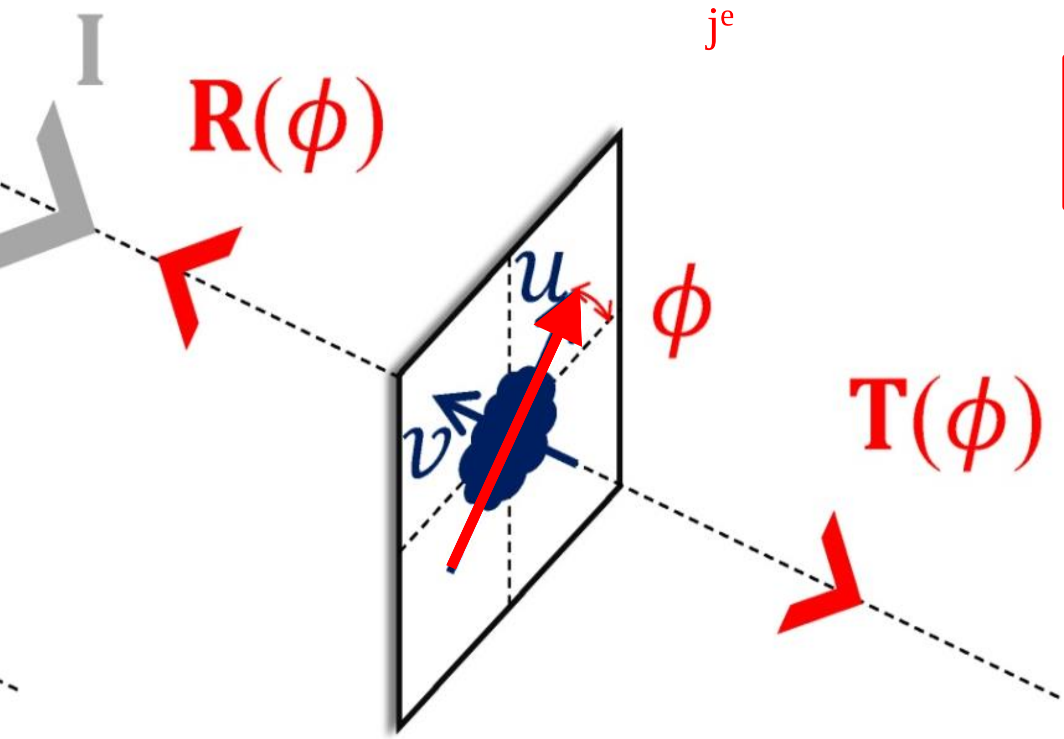


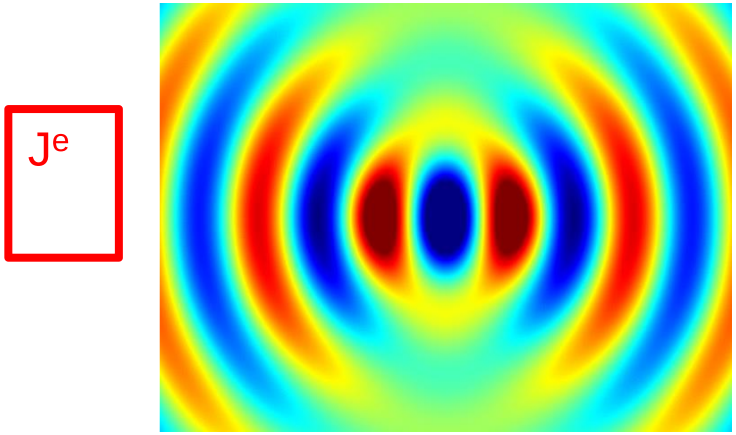
Theory, arXiv:1411.2537

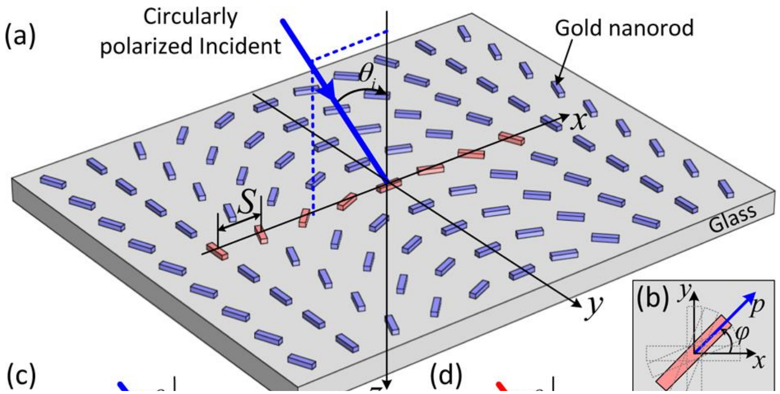
Experiment

Why 25% limit in transmissive PB metasurface?

Only electric response → both R and T



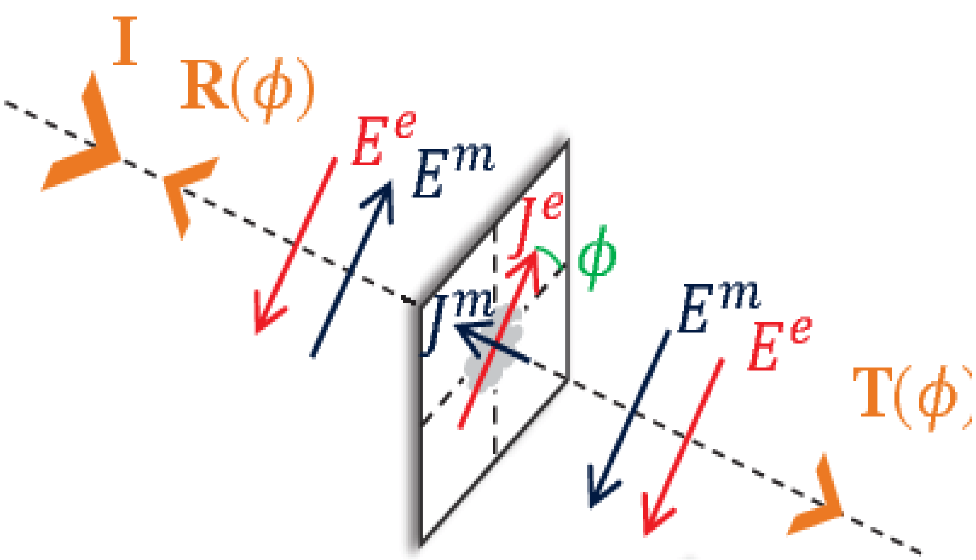




Solution: Electric + magnetic responses

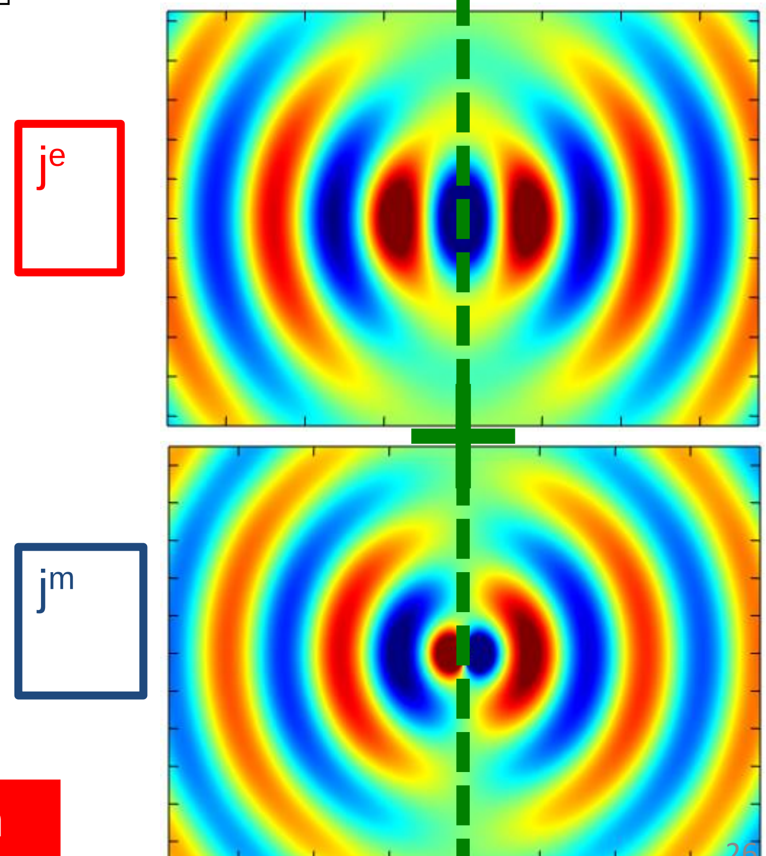
$$t_{uu} = 1 - \frac{1}{2}\chi_u^e - \frac{1}{2}\chi_v^m, \qquad t_{vv} = 1 - \frac{1}{2}\chi_v^e - \frac{1}{2}\chi_u^m,$$
$$r_{uu} = -\frac{1}{2}\chi_u^e + \frac{1}{2}\chi_v^m, \qquad r_{vv} = -\frac{1}{2}\chi_v^e + \frac{1}{2}\chi_u^m.$$

Cut off R → T=1



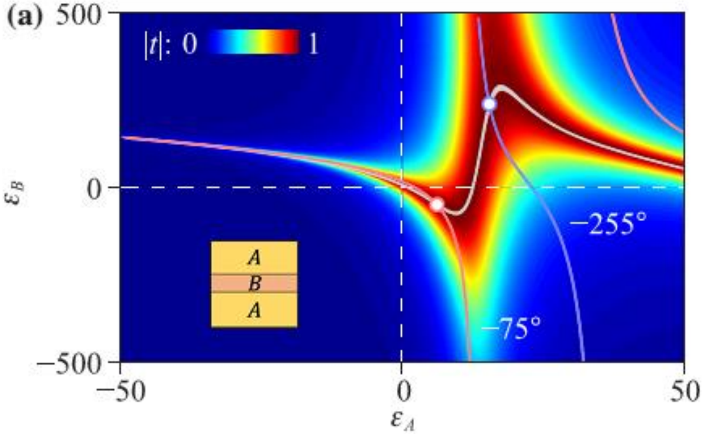
Out-phase

In-phase



choosing appropriate e/m responses, we can realize the desired 100-efficiency meta-atom

Design of the 100%-efficiency PB meta-atom

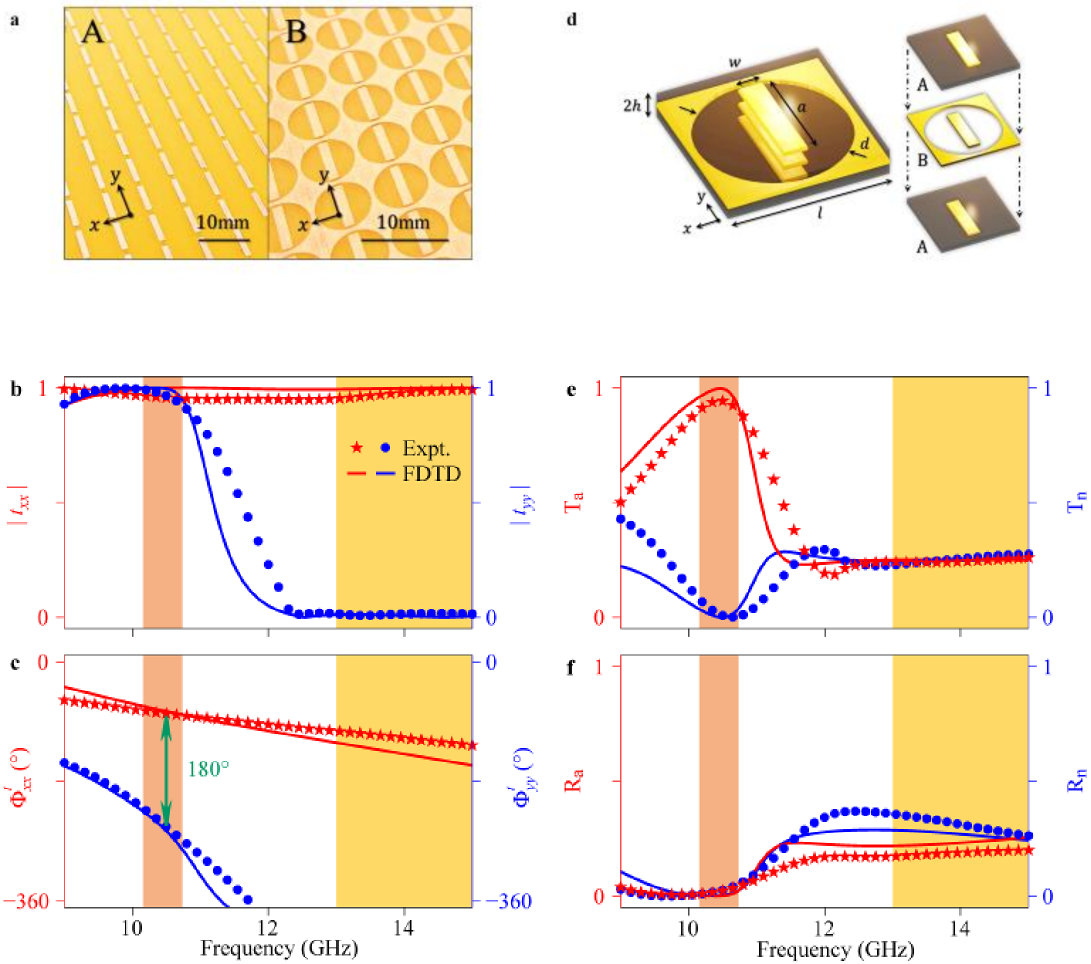


ABA structure -- PRL (2005)

PRL **94**, 243905 (2005) PHYSICAL REVIEW LETTERS week ending 24 JUNE 2005

Electromagnetic-Wave Tunneling Through Negative-Permittivity Media with High Magnetic Fields

Lei Zhou,[1,2,*] Weijia Wen,[1] C. T. Chan,[1] and Ping Sheng[1]

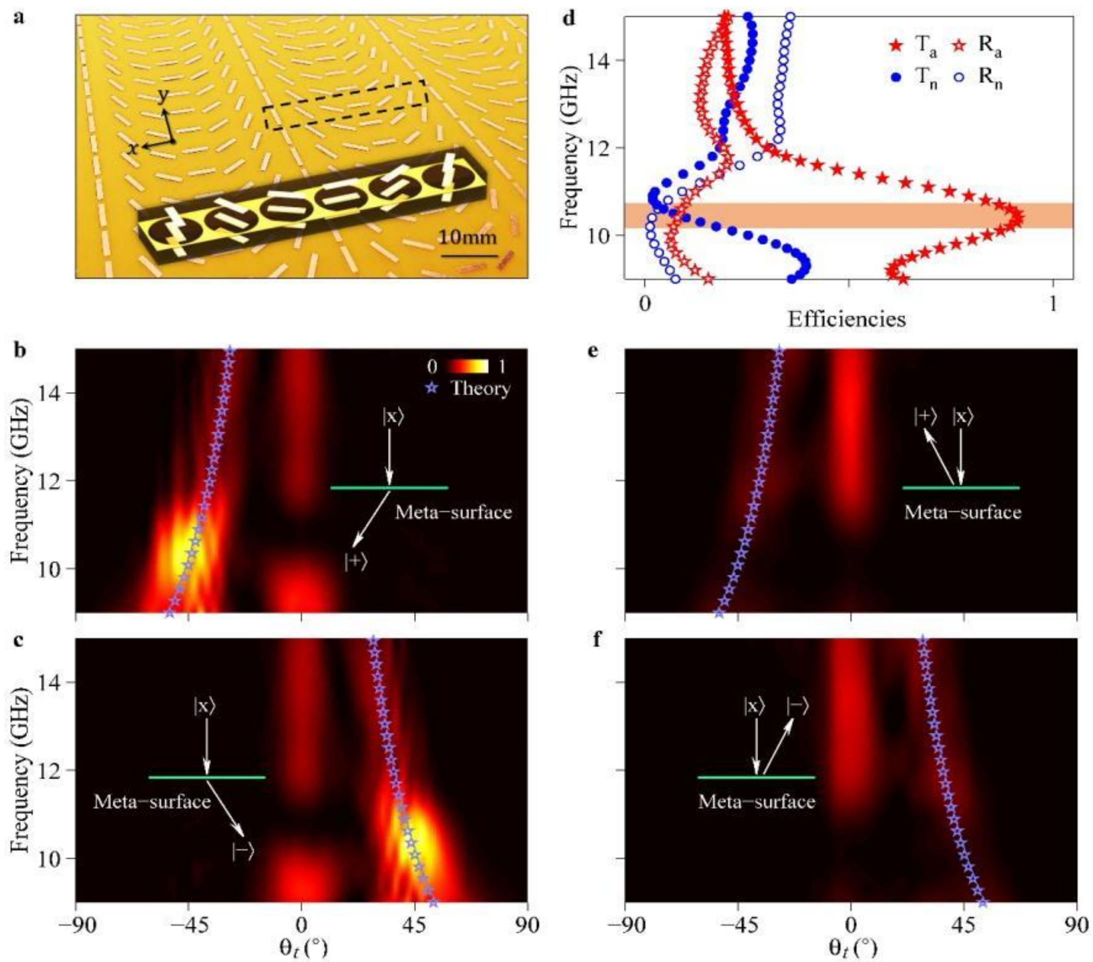


- **Still deeply subwavelength in thickness ($\lambda/8$)**
- **Magnetic responses introduced through couplings between adjacent layers**

Experimental characterization on PSHE

- **Three undesired modes Ra, Rn, Tn are suppressed**
- **Measured PSHE efficiency: 91%**

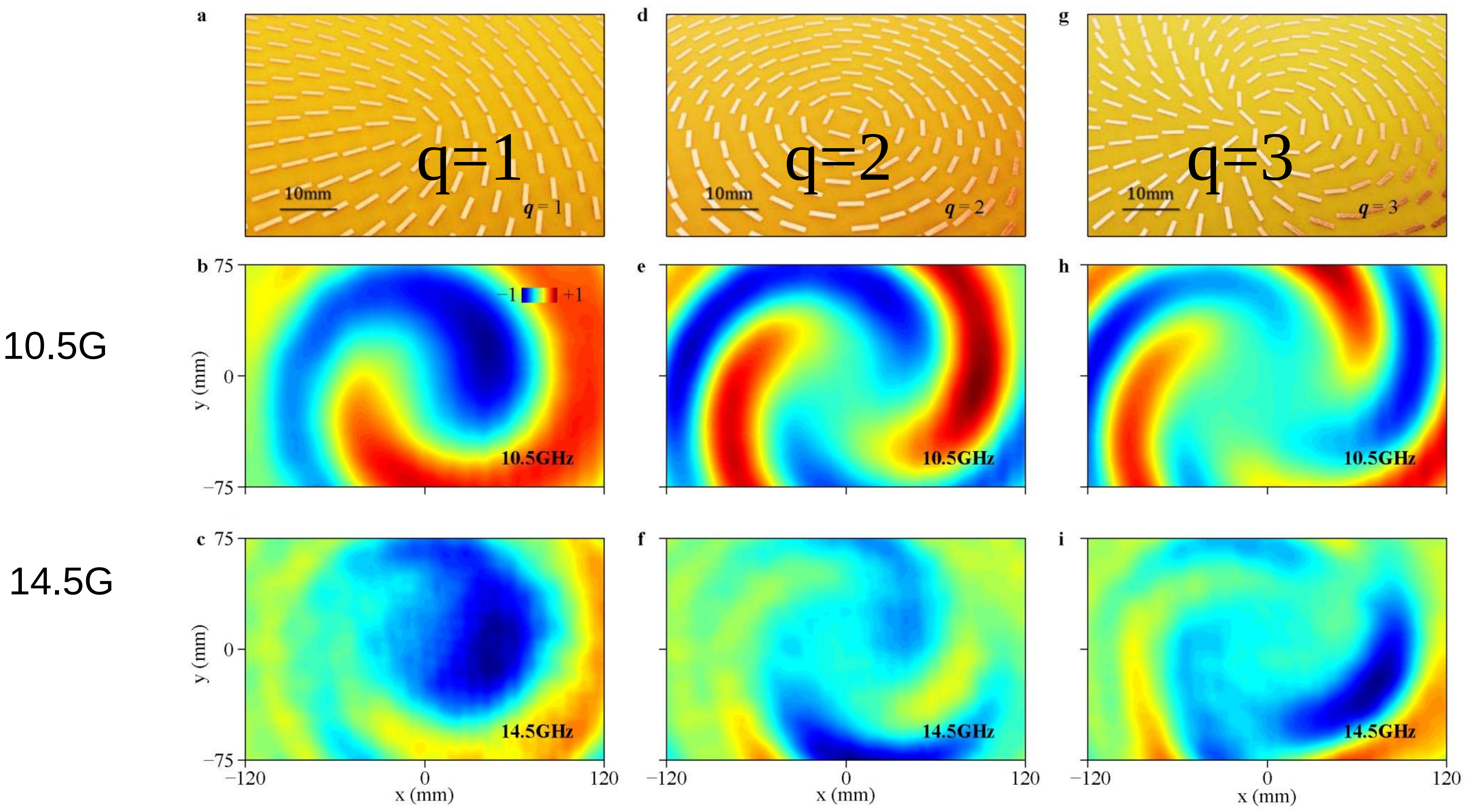
Transmission side



Reflection side

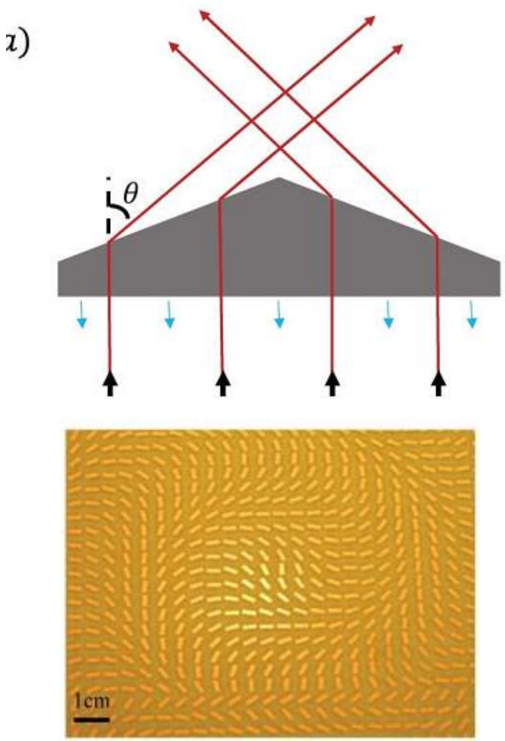
Luo *et. al., Phys. Rev. Appl.* 7, 044033 (2017)

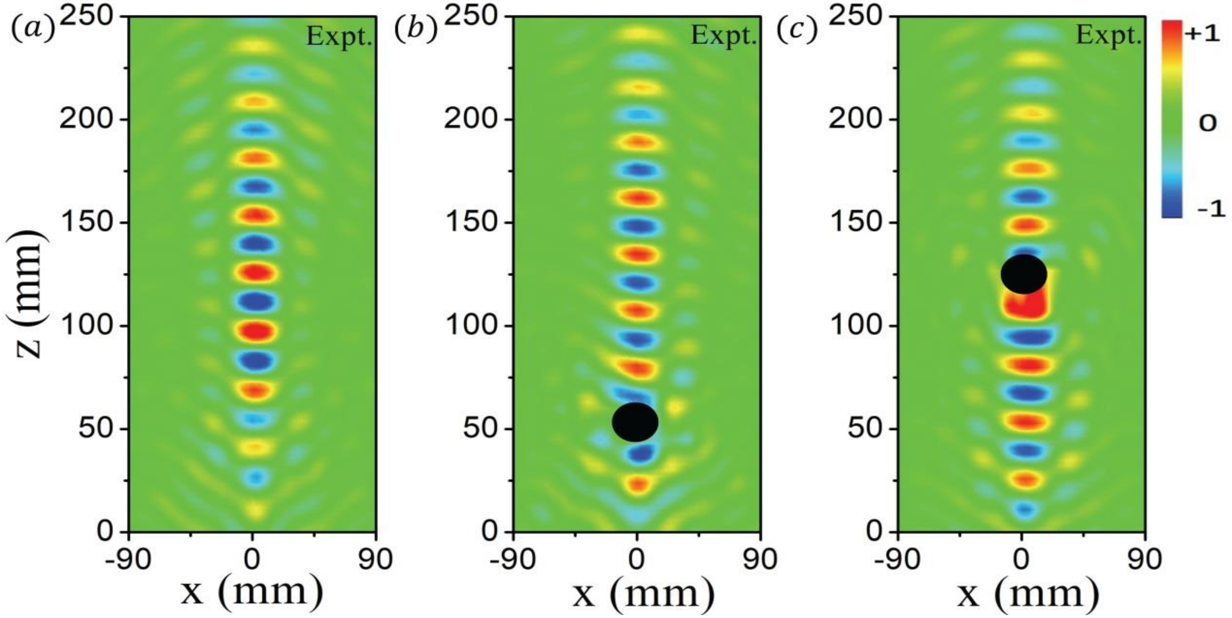
Applications I: vortex generation



- At the working band, vortex beam is of high efficiency and pure.
- Otherwise, vortex beam is of low efficiency and blurred

Applications II: Bessel beam generation



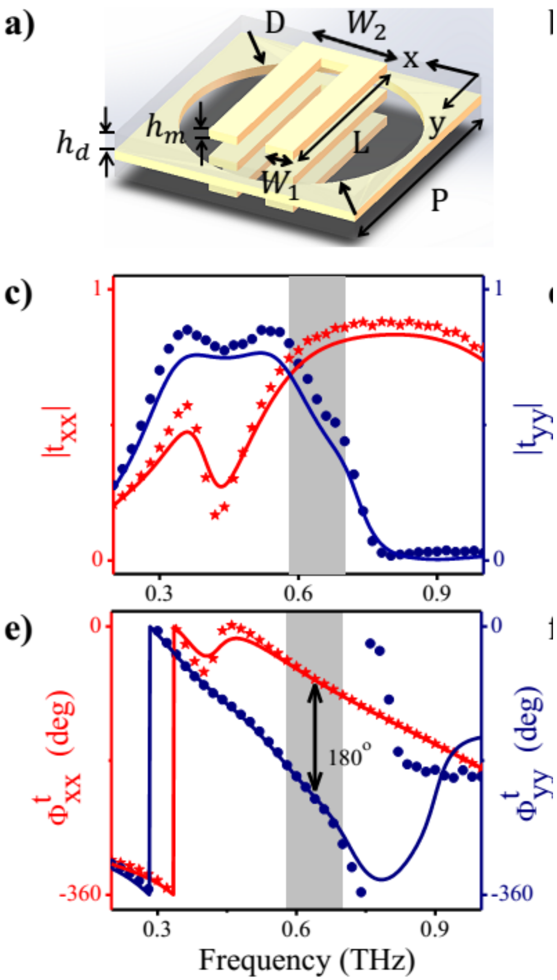


Wang, Appl. Phys. Lett, (accepted)

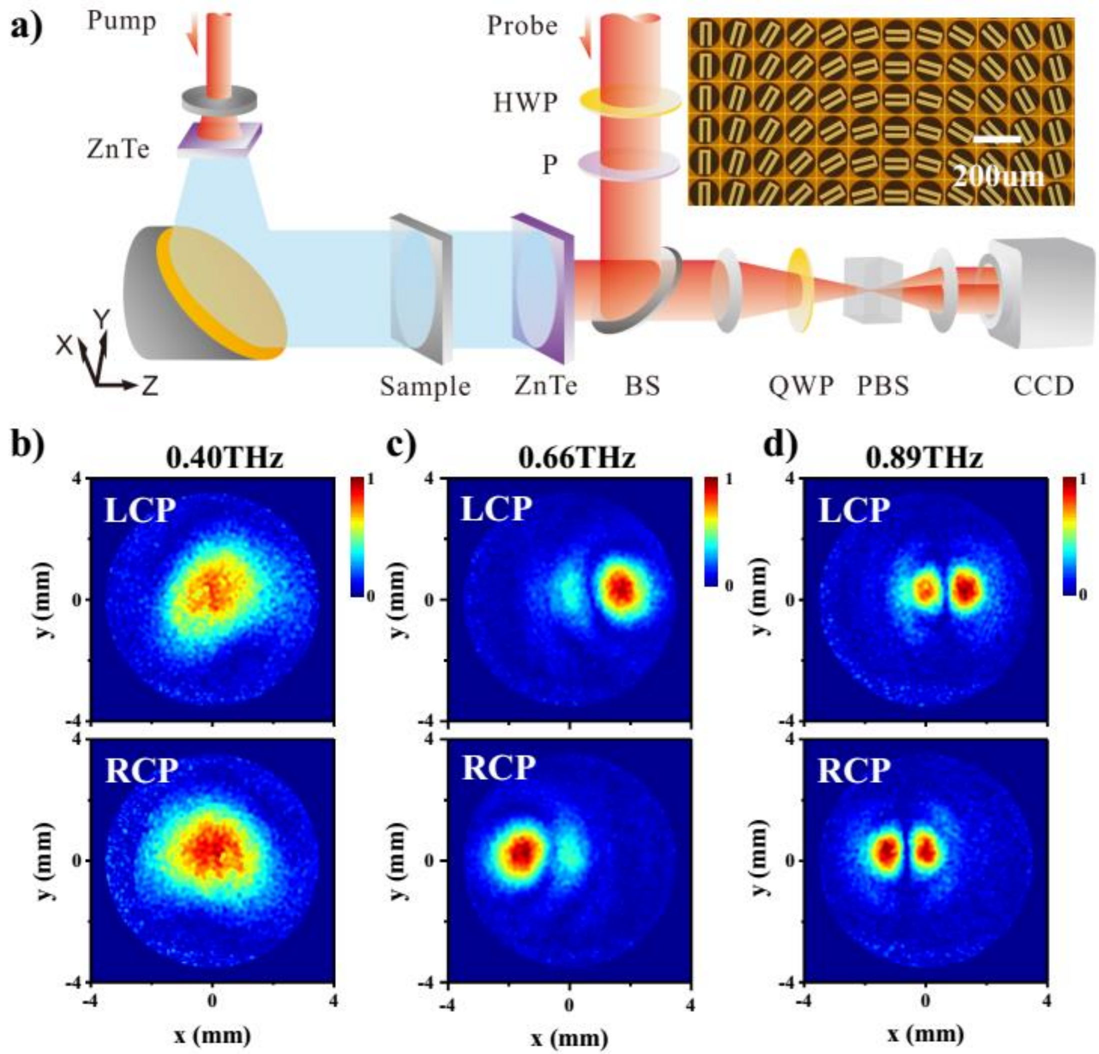
- **Very high efficiencies, without normal-mode interference**
- **Self-healing after being scattered**

Ongoing project: High-efficiency PSHE in THz

In collaboration with Yan Zhang

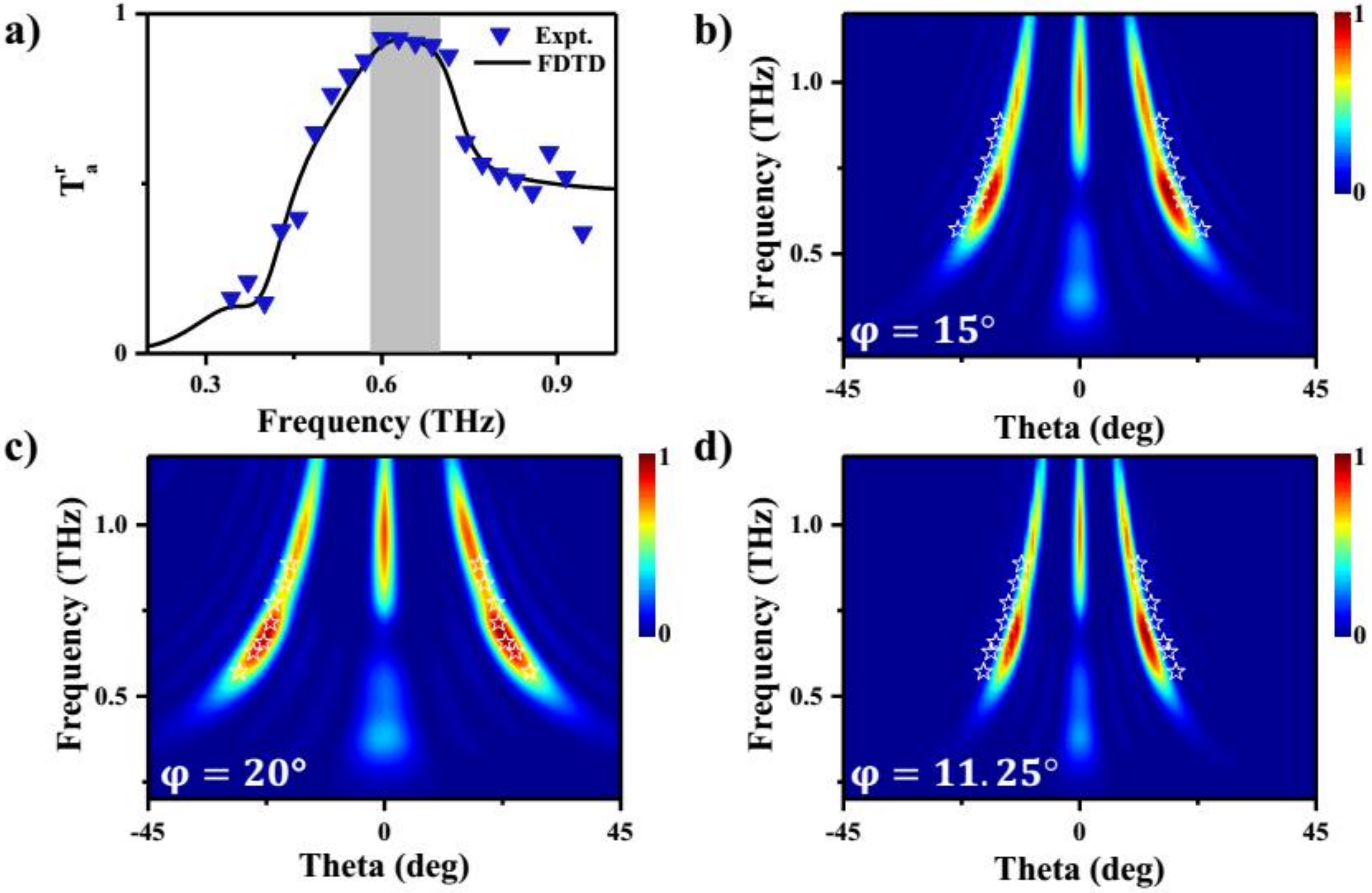


Unit-cell



Measurements on PB MS

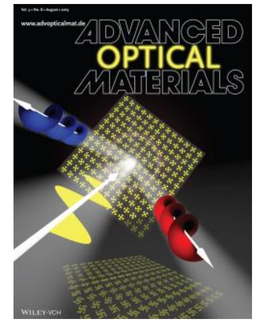
PSHE Efficiency & Generalized Snell's law

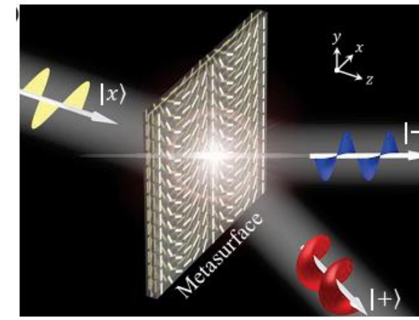


- Relative efficiency reaches 92%
- Satisfying generalized Snell's law

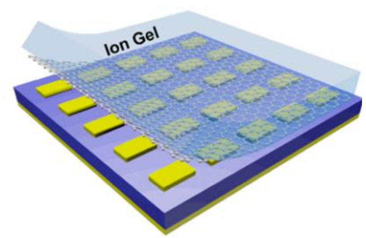
1) Backgrounds

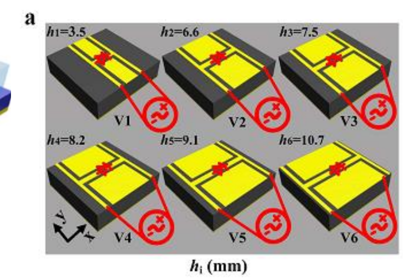
2) High-efficiency metasurfaces for spin-polarized light



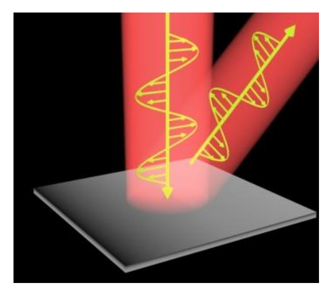


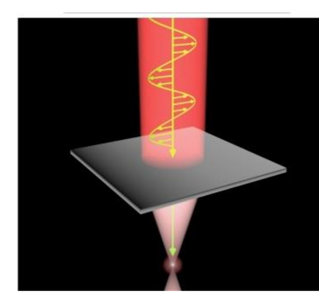
3) Tunable metasurfaces (THz & GHz)





4) Multifunctional metasurfaces

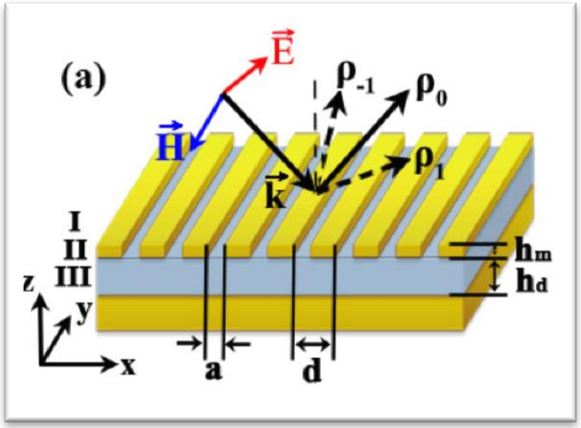


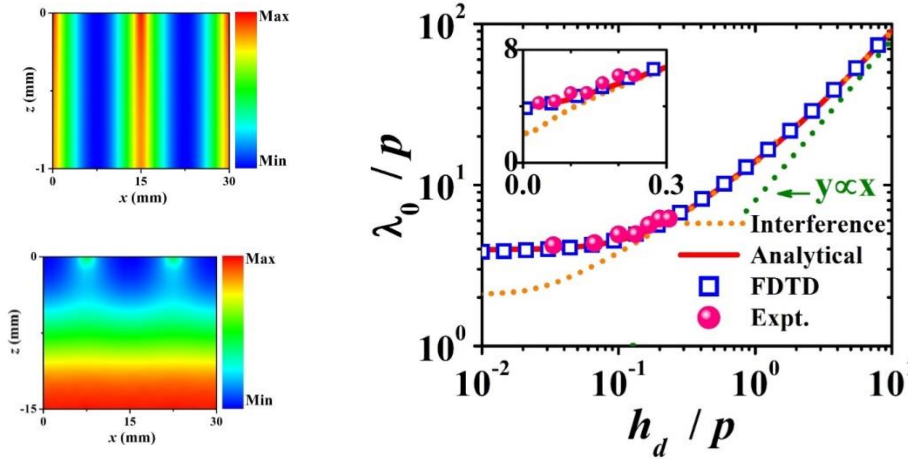


5) Conclusions

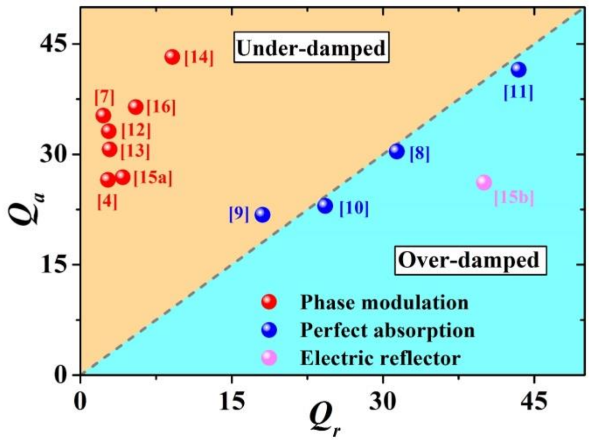
THz part

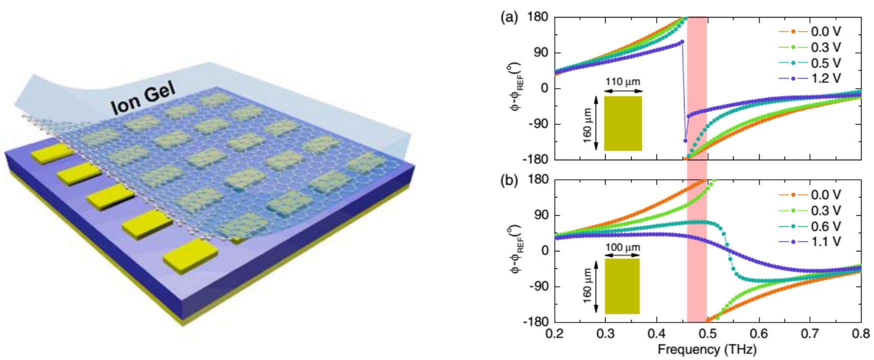
Physics of MIM metasurfaces





Eigen resonant modes in MIM (PRB 2016)

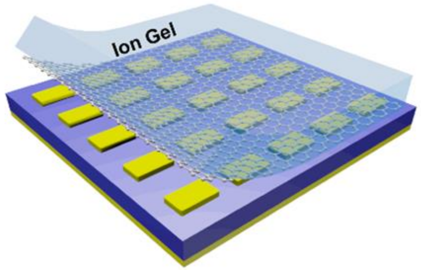




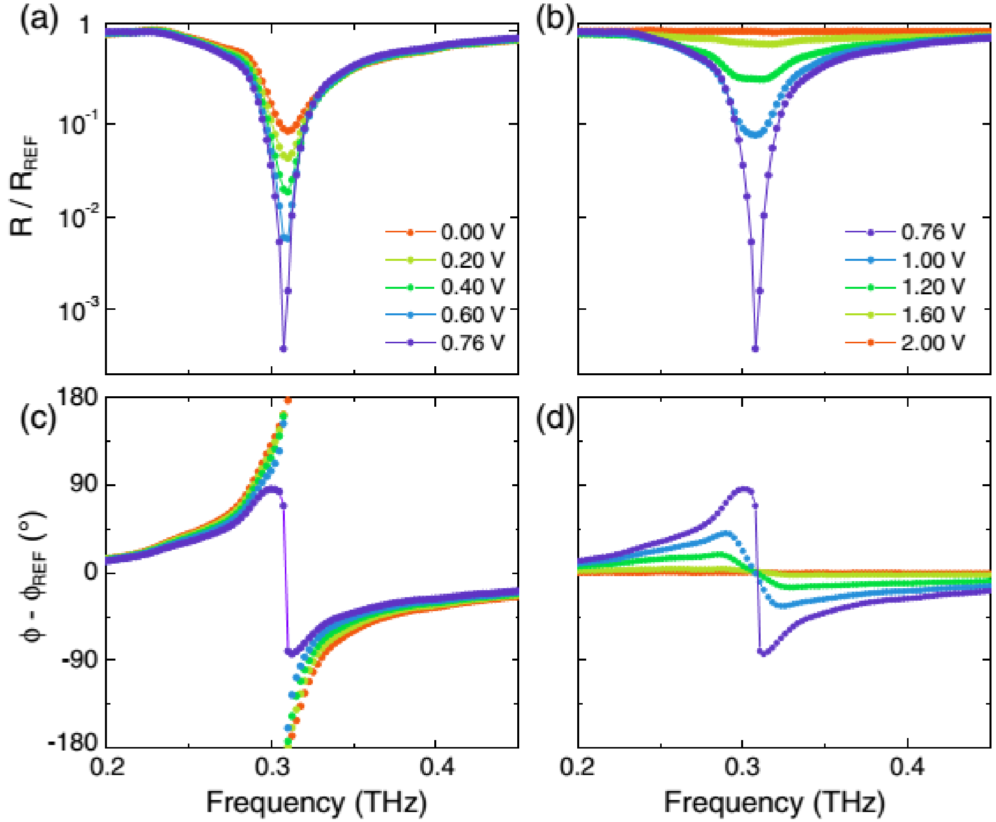
Complete functionality phase diagram for MIM (PRL 2015)

Graphene MIM for wide-range phase modulation (PRX 2015)

Amplitude/phase modulation in graphene metasurface (Expt.)

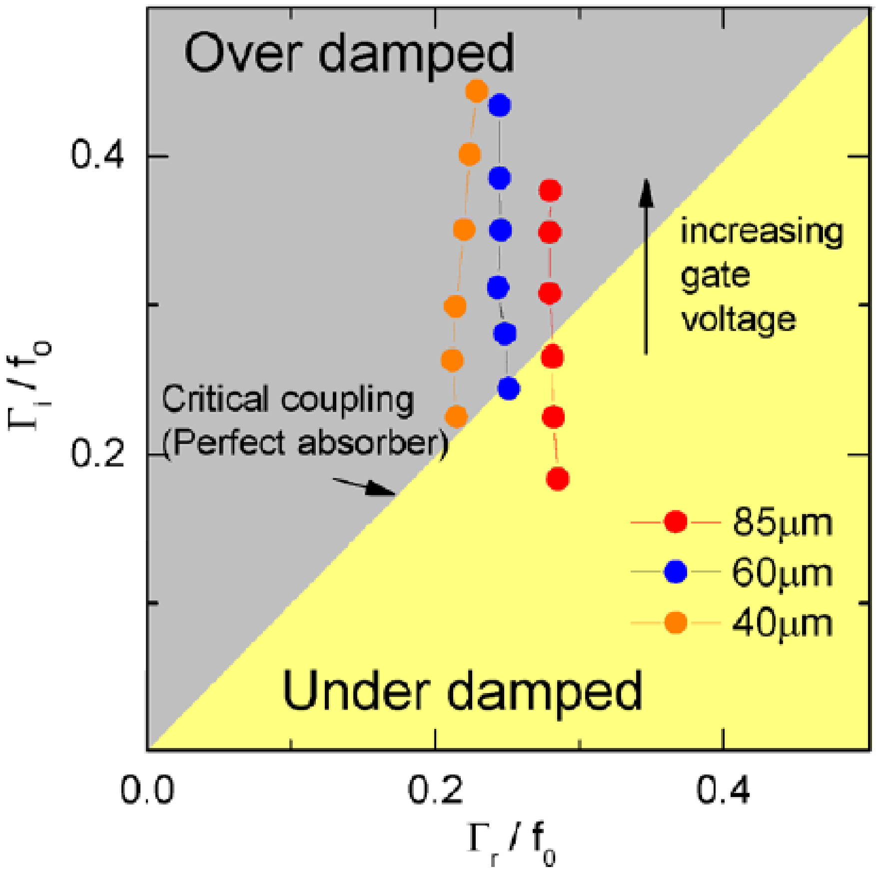


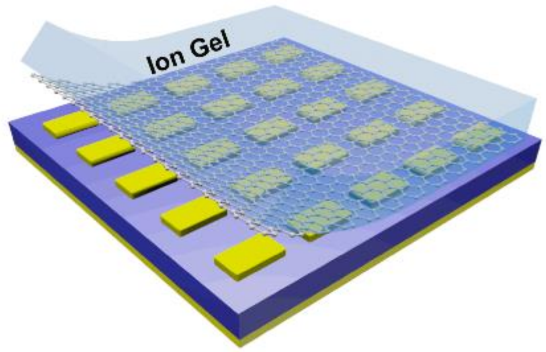
±180 degrees of phase modulation



- 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

Role of graphene upon gating



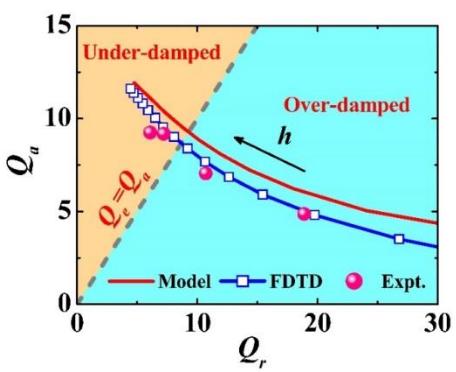


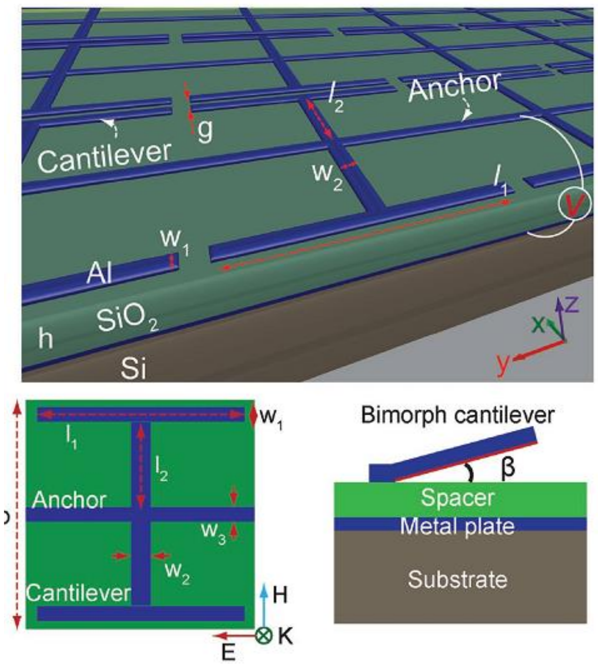
Effects of gating graphene:

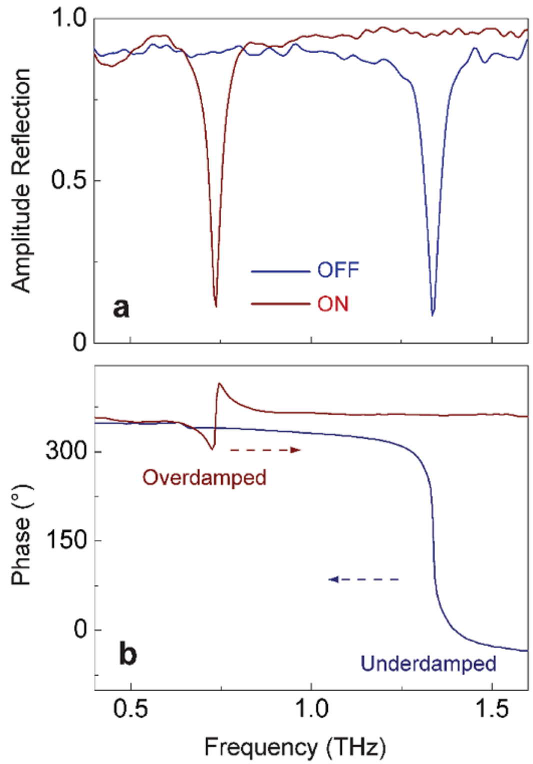
1) increasing Γ_i
2) has little effect on Γ_r
3) drives the system to transit from an under-damped to an over-damped resonator

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

MEMS-based active metasurface







Gap thickness can be another key parameter to drive the phase transition

COMMUNICATION

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Metamaterials

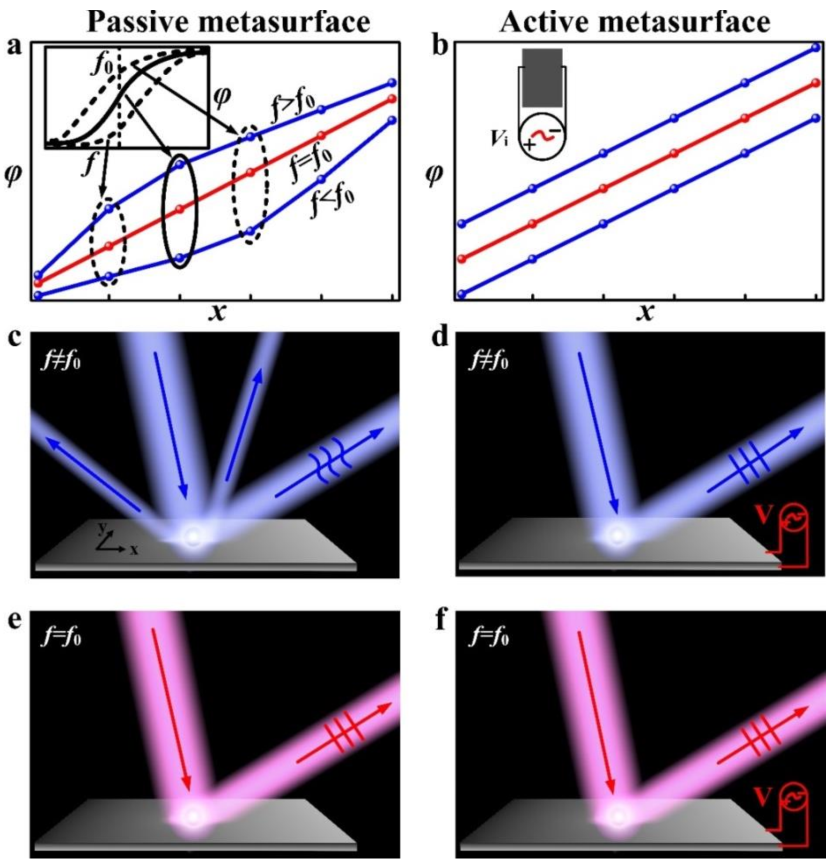
www.advmat.de

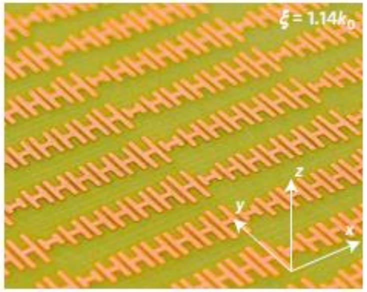
Active Phase Transition via Loss Engineering in a Terahertz MEMS Metamaterial

*Longqing Cong, Prakash Pitchappa, Chengkuo Lee, and Ranjan Singh**

GHz part

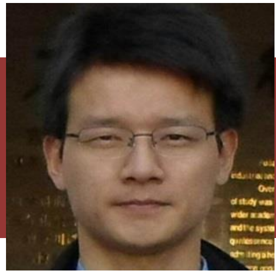
Issues with passive metasurfaces



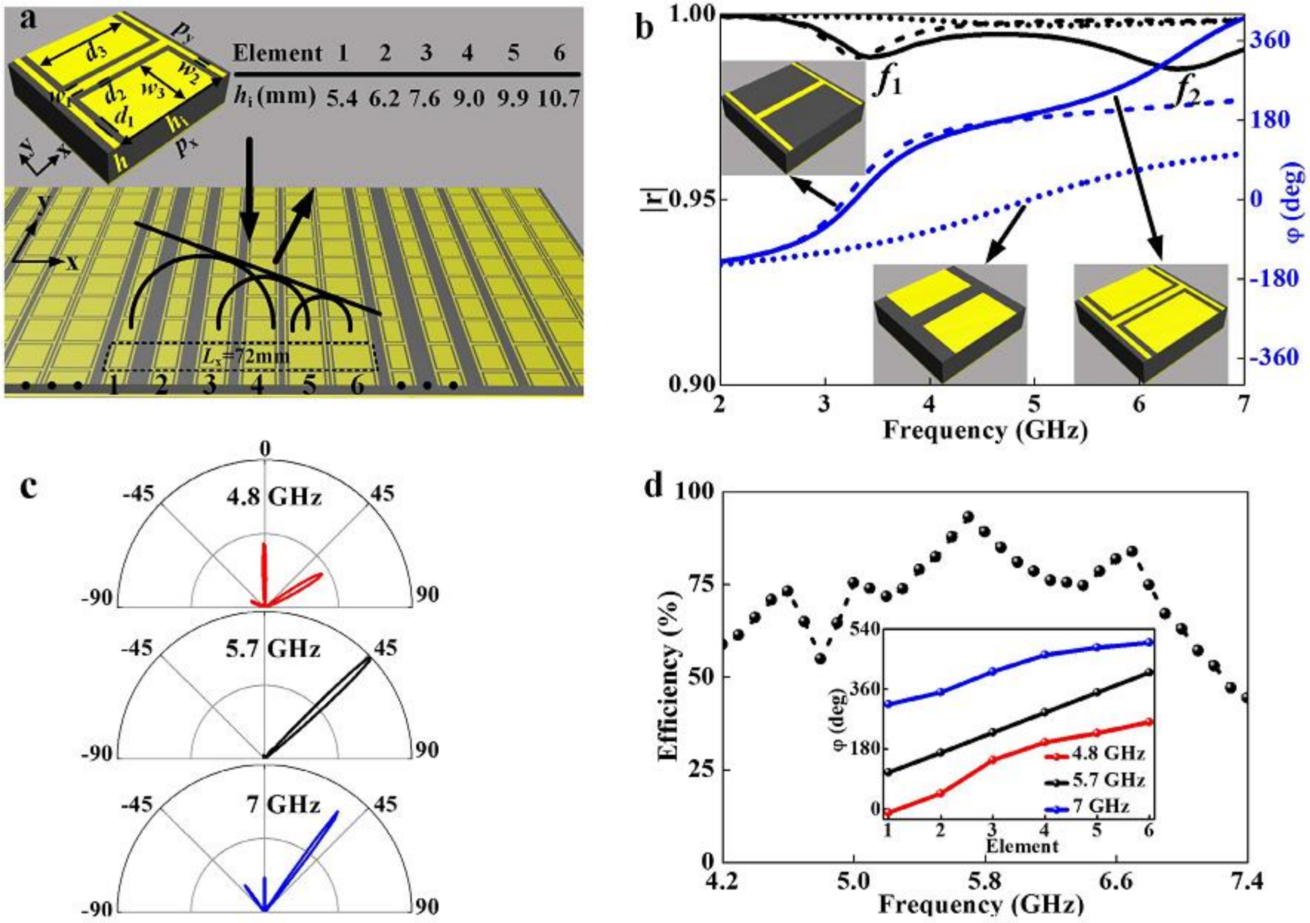


- Distorted phase gradient
- Undesired reflection modes
- Limited efficiency and bandwidth

- Functionality locked in passive metasurface
- Dispersion issue limits the performance and bandwidth

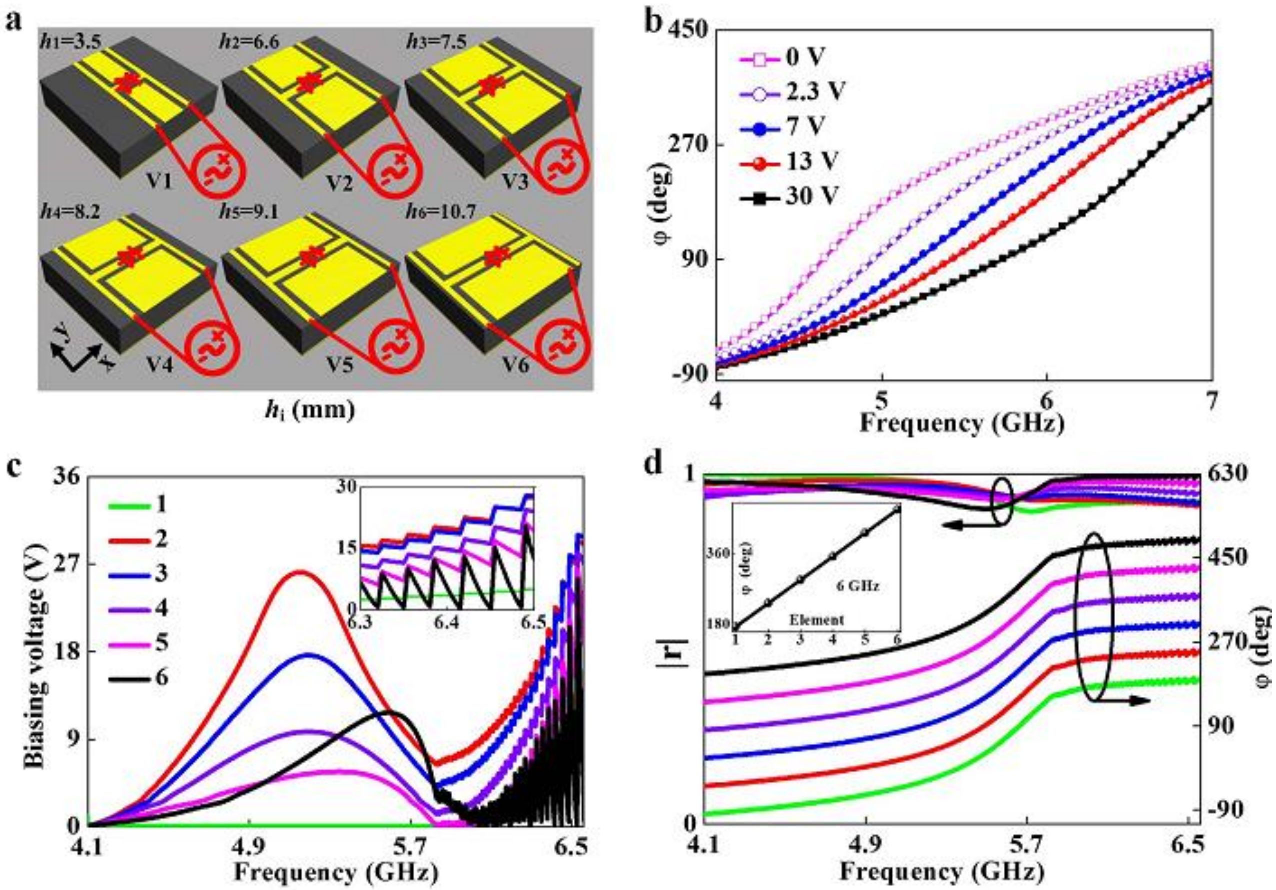


Passive metasurface has narrow bandwidth



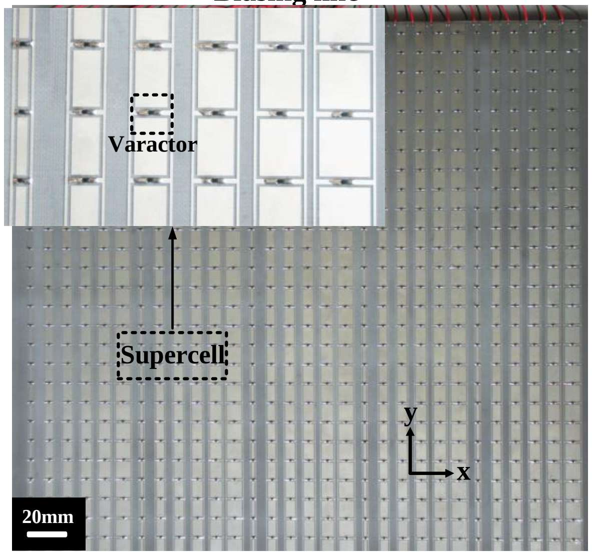
- Why performance always deteriorated even in "broad-band" sample?
- Phase distribution cannot maintain at other frequencies

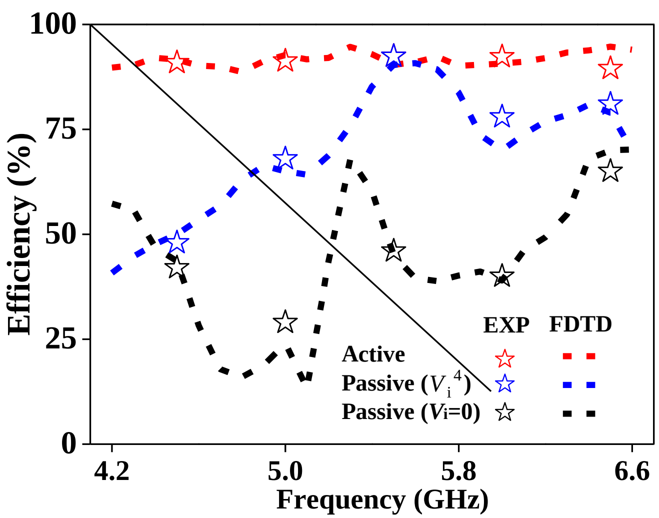
Tunable meta-atoms can help

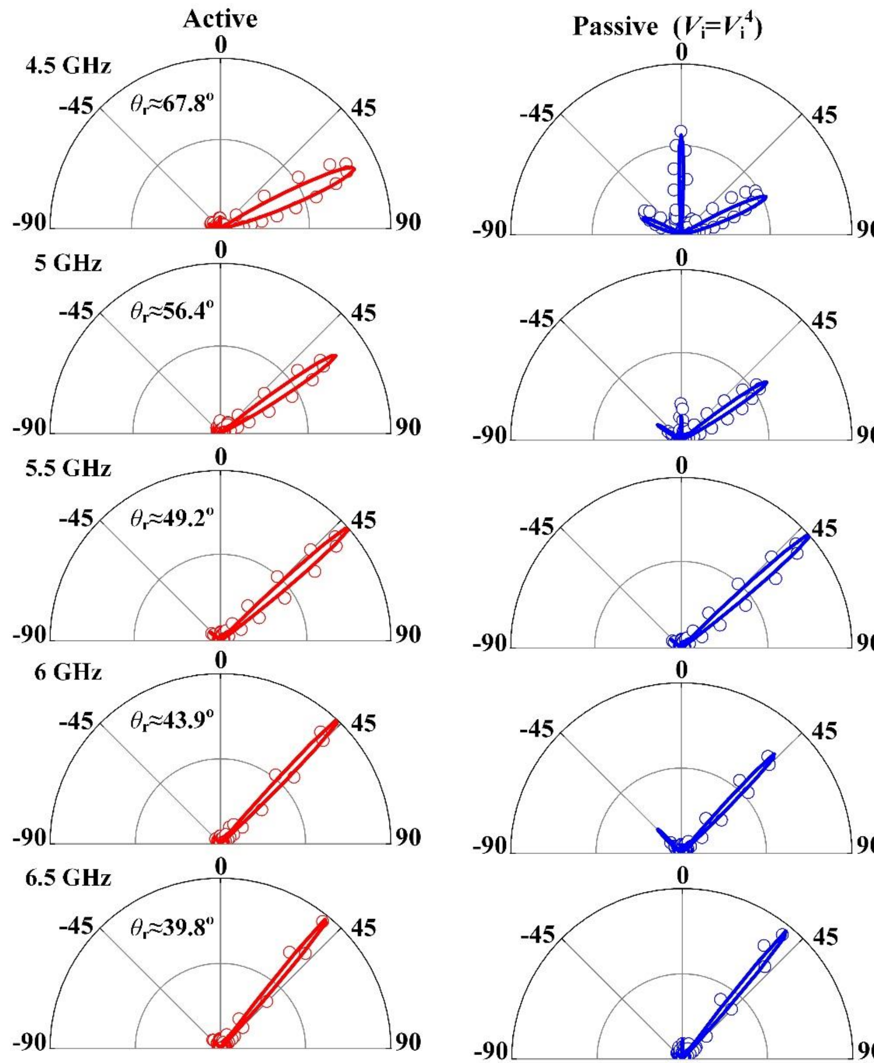


- With varactor diode incorporated, phase of our meta-atom can be controlled precisely by external biasing voltage
- Can realize any phase distribution controlled by external voltages

Active metasurface with dispersion compensated







$f \neq f_0$

$f = f_0$

$f \neq f_0$

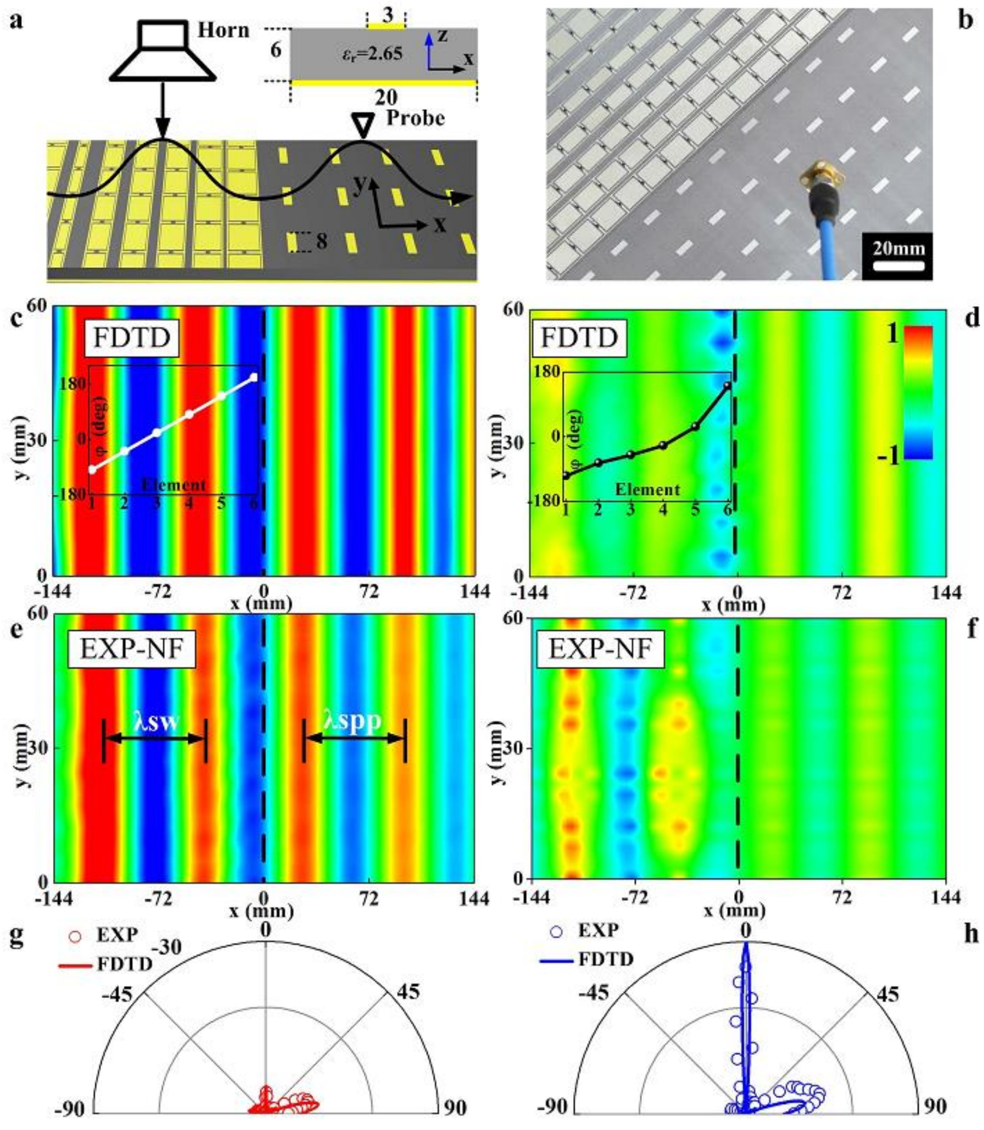
Xu, Sci. Rep. 6: 38255 (2016)

Single-mode reflection; Very high efficiency; Truly broad band

Active metasurface for functionality switching

On-state: A SPP coupler

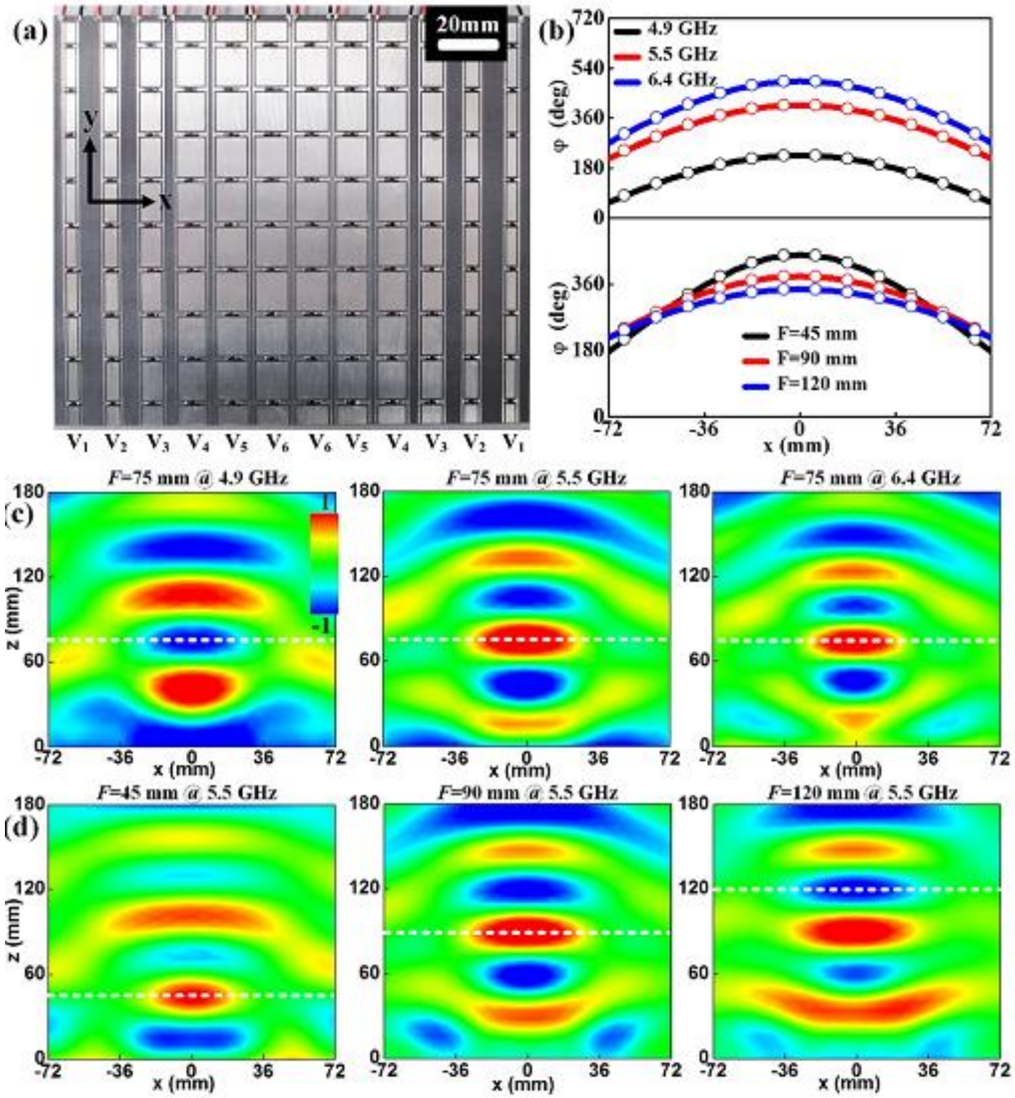
Off-state: A specular reflector



Xu, **Sci. Rep. 6: 38255 (2016)**

Active meta-lenses

- **Precisely control the local phase of each "meta-atom"**
- **Make the dispersion-induced aberrations corrected; make focal length the same for different frequencies.**
- **Make the focal point actively tunable at a single frequency**



H.X. Xu *et. al*, **Appl. Phys. Lett. 109** 193506 (2016)

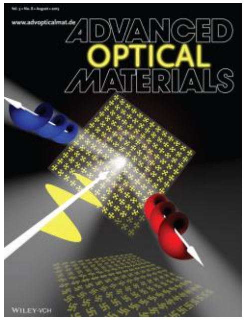
1) Backgrounds

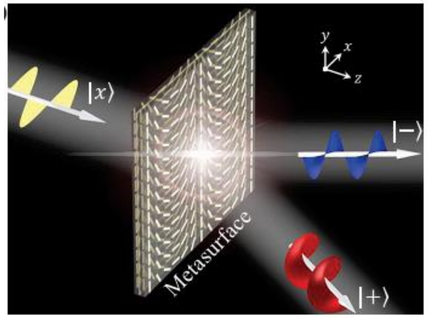
2) High-efficiency metasurfaces for spin-polarized light

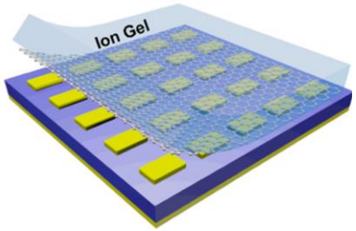
3) Tunable metasurfaces (THz & GHz)

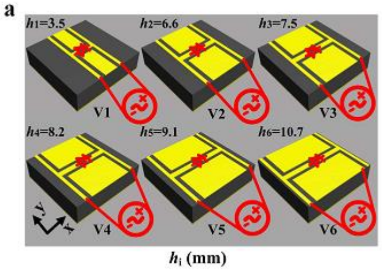
4) **Multifunctional metasurfaces**

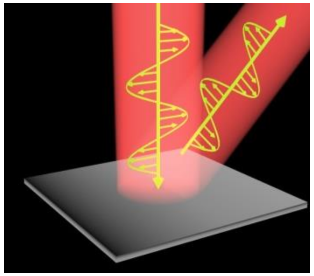
5) Conclusions

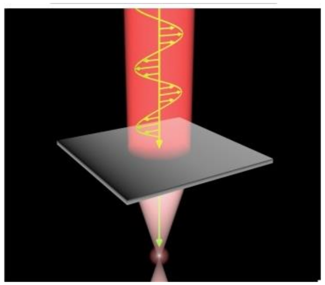








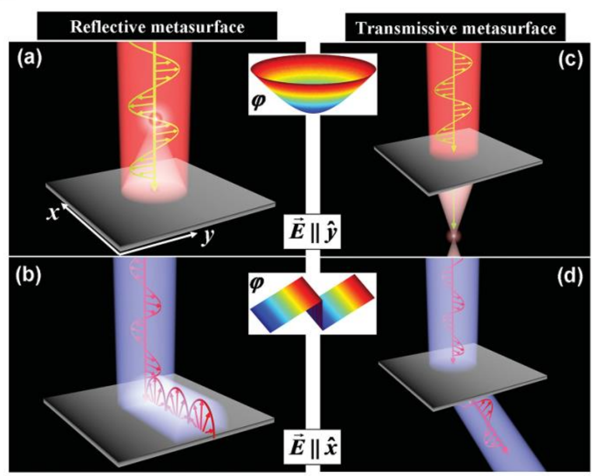




Why multifunctional metasurfaces ?

Metasurfaces

Multifunctional meta-devices

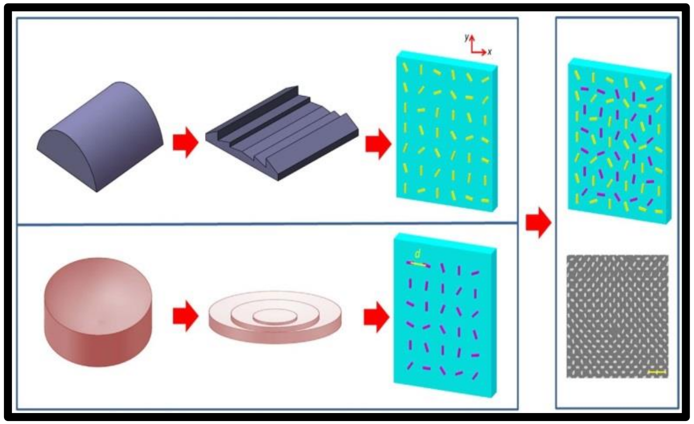


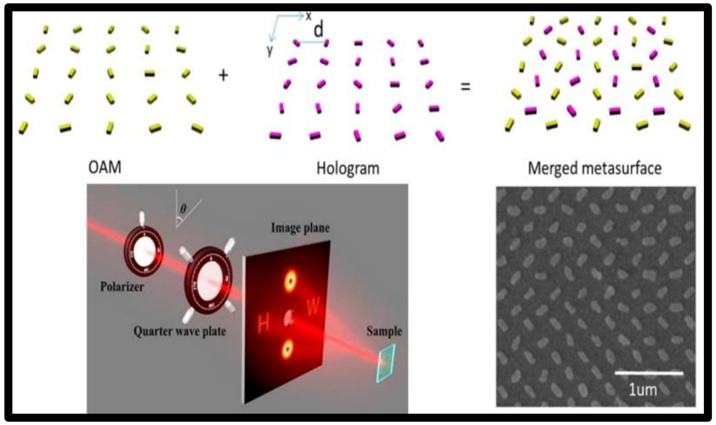
Integration systems

- **Device miniaturization**
- **Functionality diversified**

Issues with existing approaches

1. Merge two structures

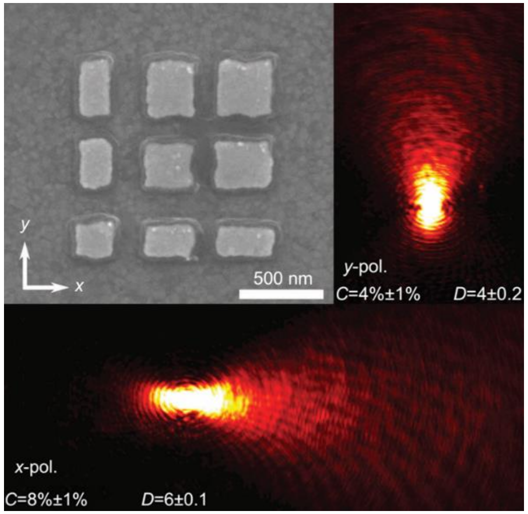




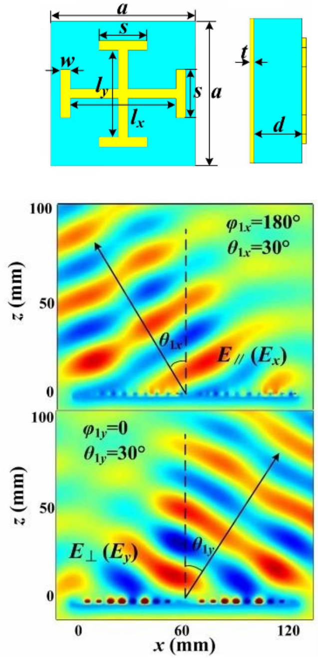
ACS Photonics 4, 1906 (2017)
SR 6, 27628 (2016) (X. Chen)

1) Functionality cross-talking
2) Low efficiencies

2. Single anisotropic meta-atom



LSA 3, e197 (2014) (Bolzhevolni)



SR 5,9605 (2015) (T. J. Cui)

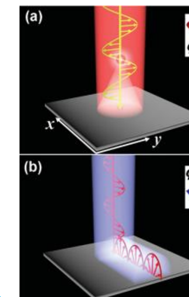
Exhibiting similar functionalities

Our motivations

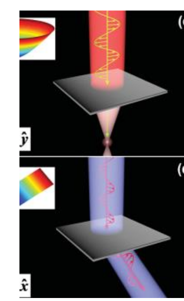
Meta-devices with *distinct* functionalities with *high efficiency* and *low cross-talking*

Meta-atoms with *polarization*-controlled responses

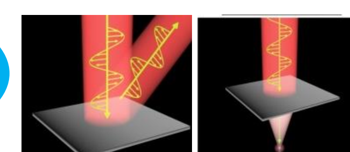
Reflection-type



Transmission-type



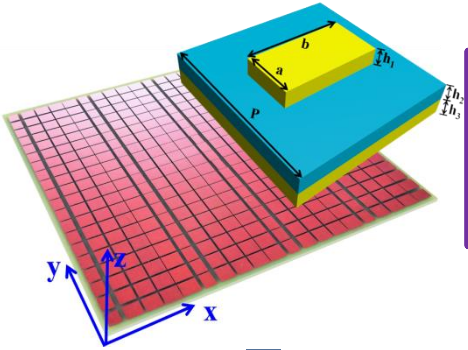
Full-space



1) Reflective multifunctional metasurfaces

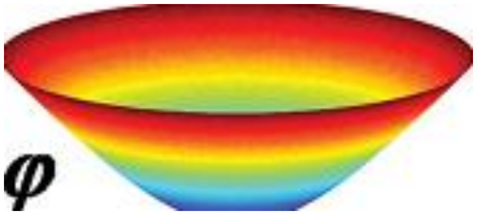
$$T \equiv 0, \quad |r_{xx}| = |r_{yy}| = 1$$

Adv. Optical Mater. 5, 1600506 (2017)



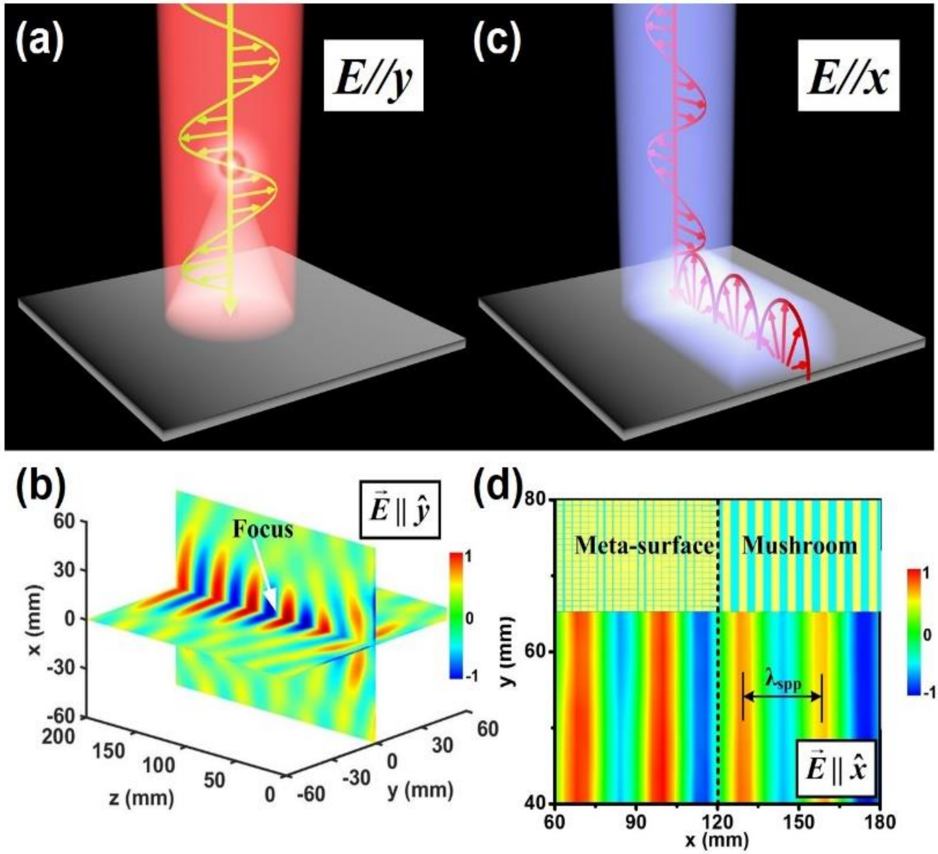
High-efficiency reflective meta-atom

Structural tuning



$\varphi_{yy}(x, y)$

$\varphi_{xx}(x, y)$



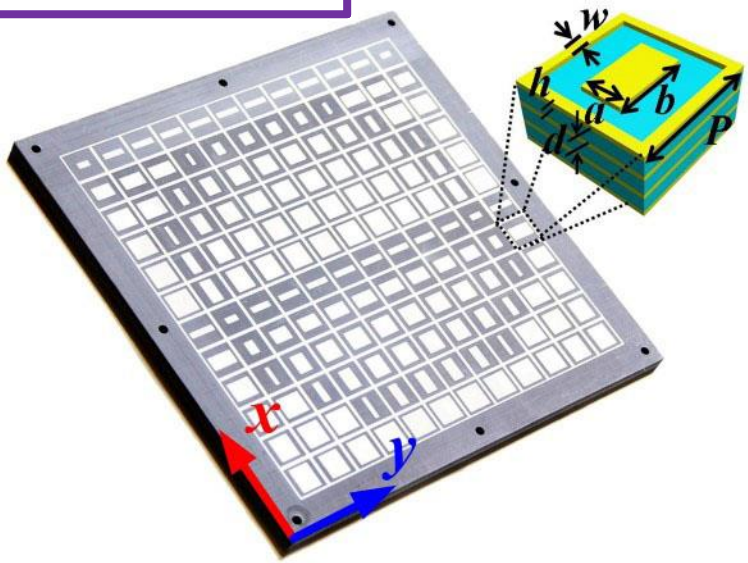
- Focusing lens for E || y
- PW-SW convertor E || x

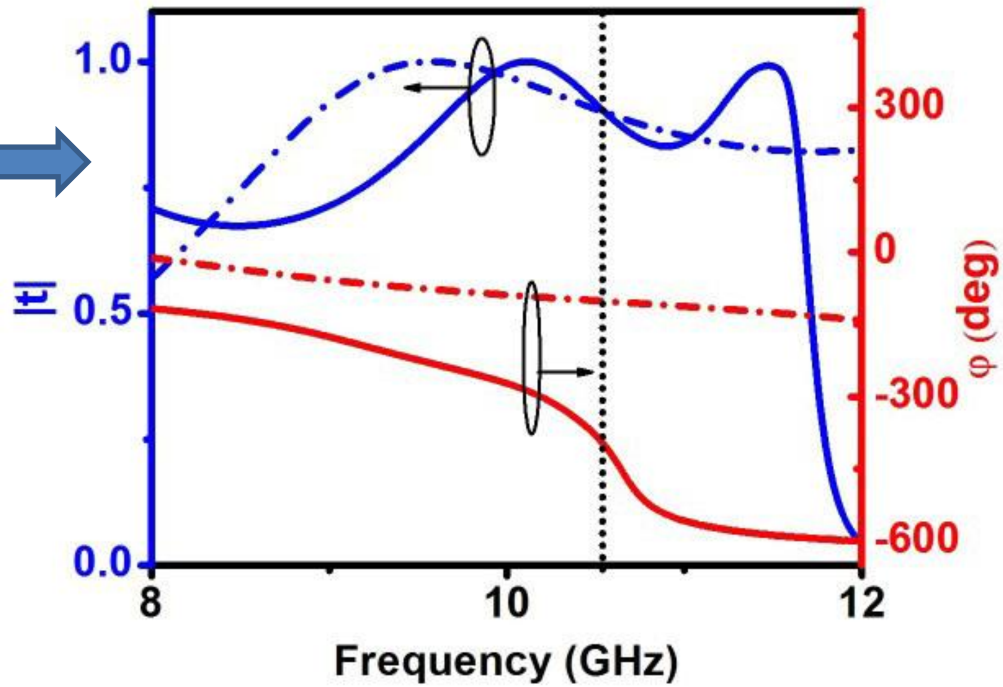
2) Transmissive multifunctional metasurfaces

$$R \approx 0, \quad |t_{xx}| = |t_{yy}| = 1$$

Adv. Optical Mater. 5, 1600506 (2017)

High-efficiency transmissive meta-atom

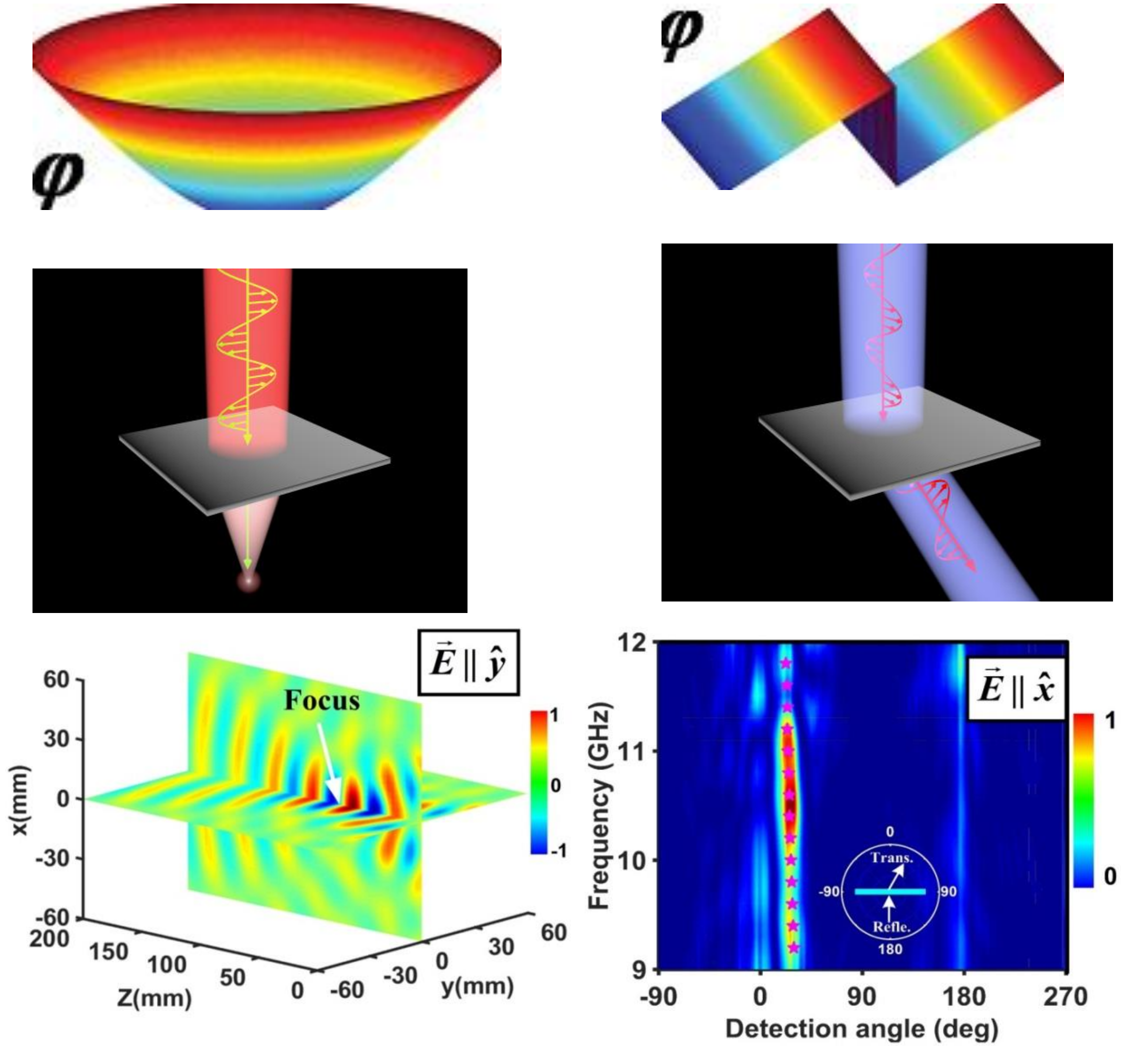




4-layer meta-atom

- Coupling between different layers forms a wide transparency band
- Transmission-phase covers 360° range

Transmissive bifunctional meta-device



Focusing lens for E || y; Beam deflector for E || x

- Working efficiency (72%)

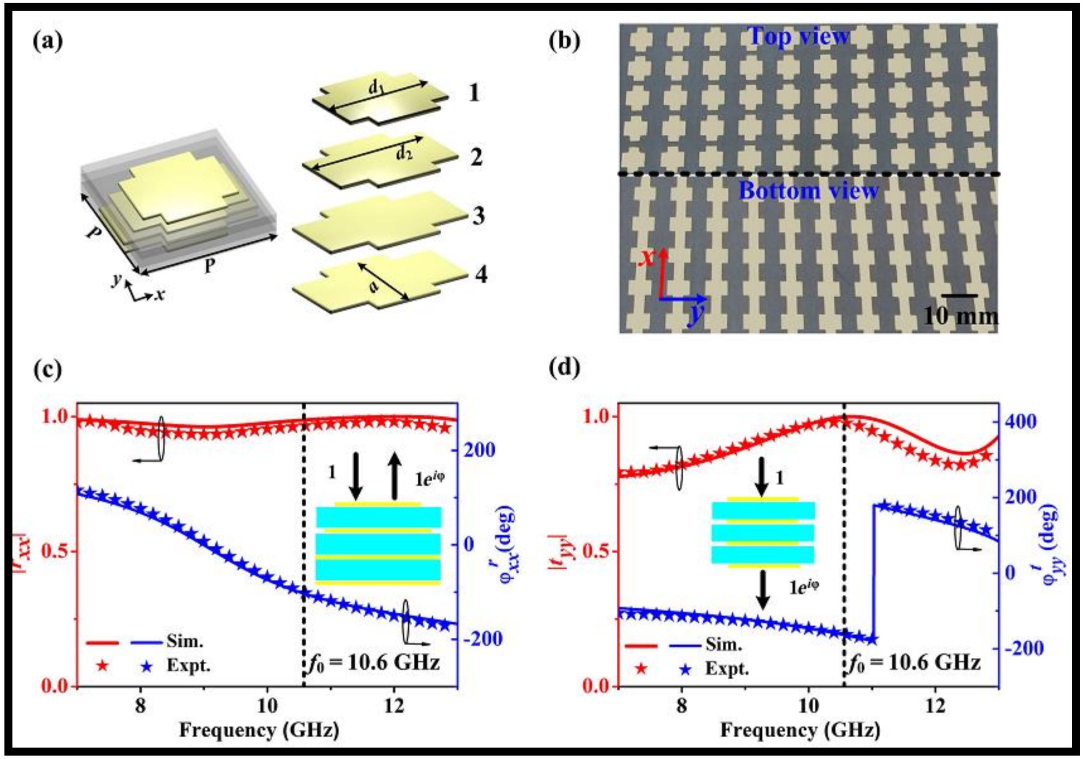
Adv. Optical Mater. 5, 1600506 (2017)

3) Full-space multifunctional devices

$$|r_{xx}| = 1; \qquad |t_{yy}| = 1$$

$$\varphi^{r}_{xx}(x, y); \qquad \varphi^{t}_{yy}(x, y)$$

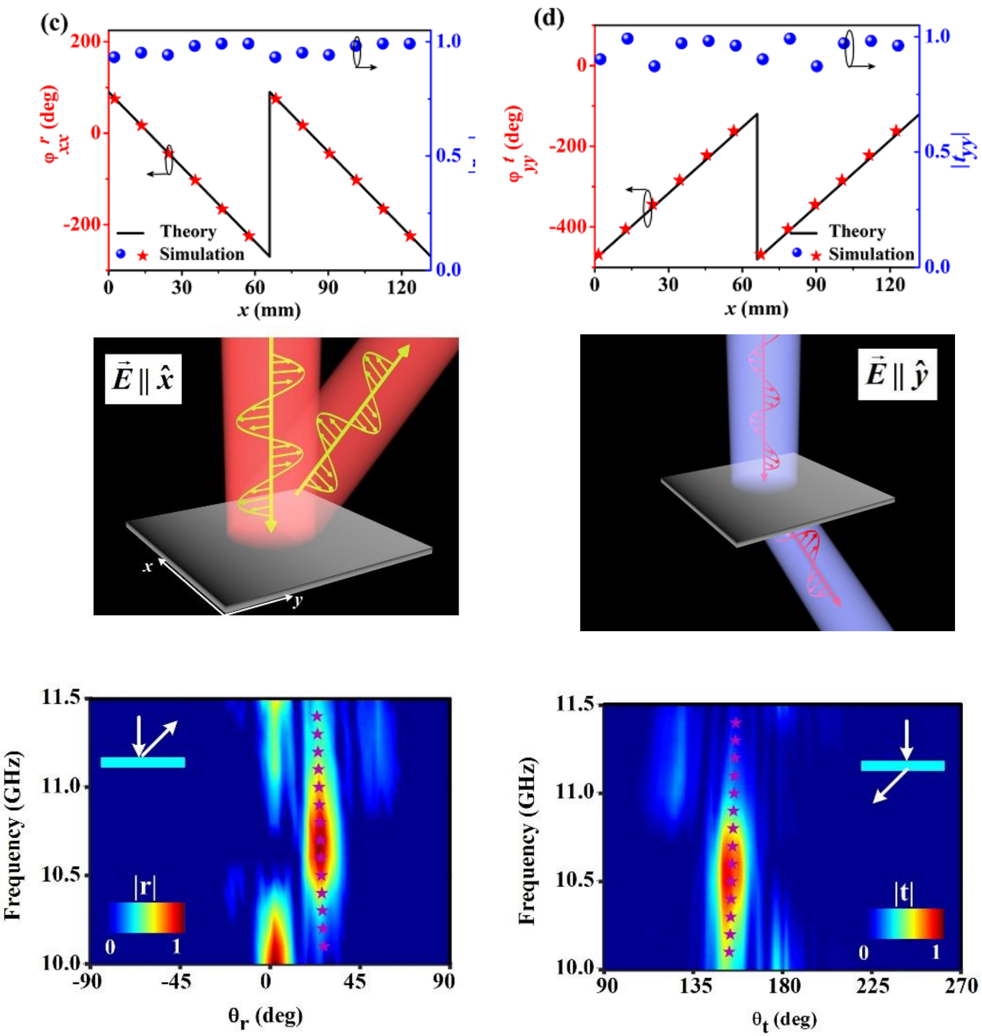
Special meta-atom

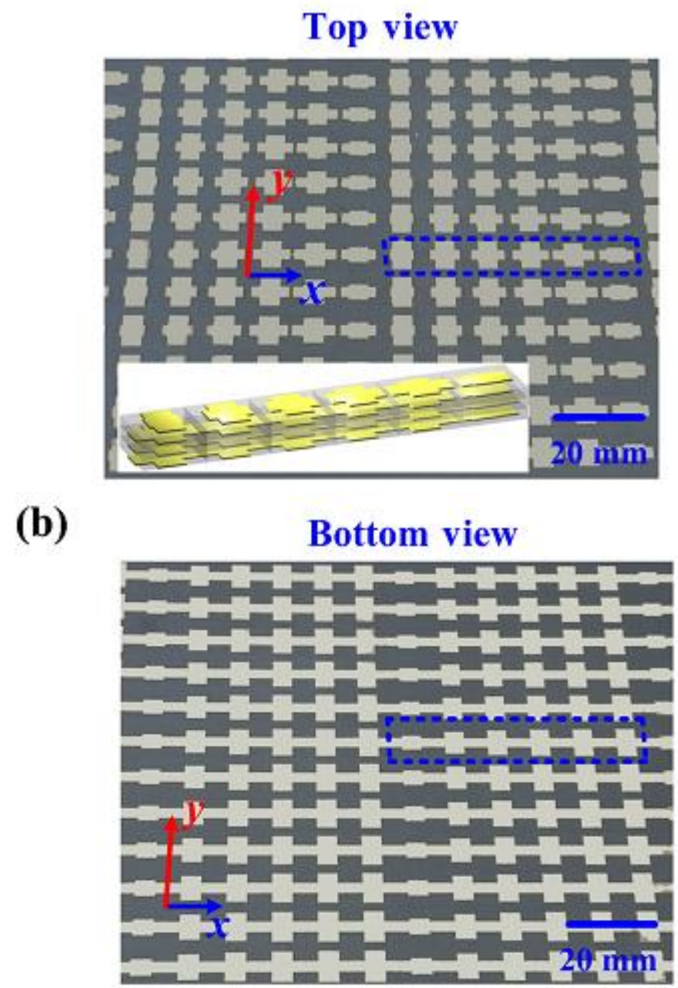


- **Continuous stripes on bottom block x-polarized wave**
- **FP-resonance enhances transmission of y-polarized wave**

Phys. Rev. Applied 8, 034033 (2017) (Editor's suggestion)

Meta-device 1: Deflector



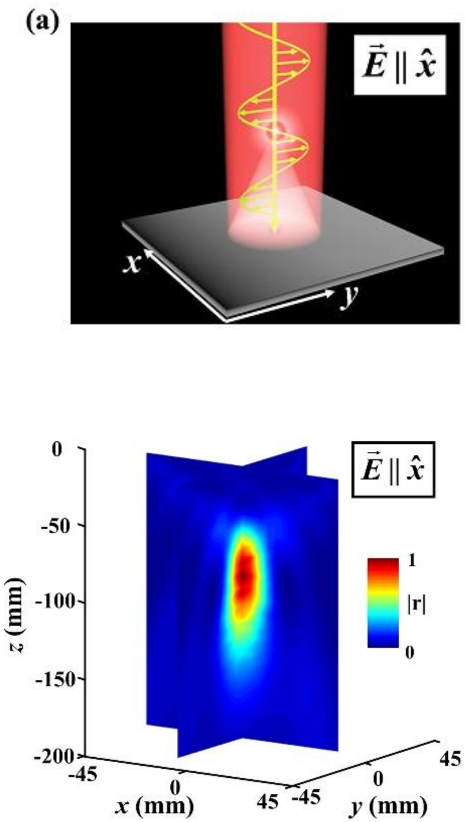


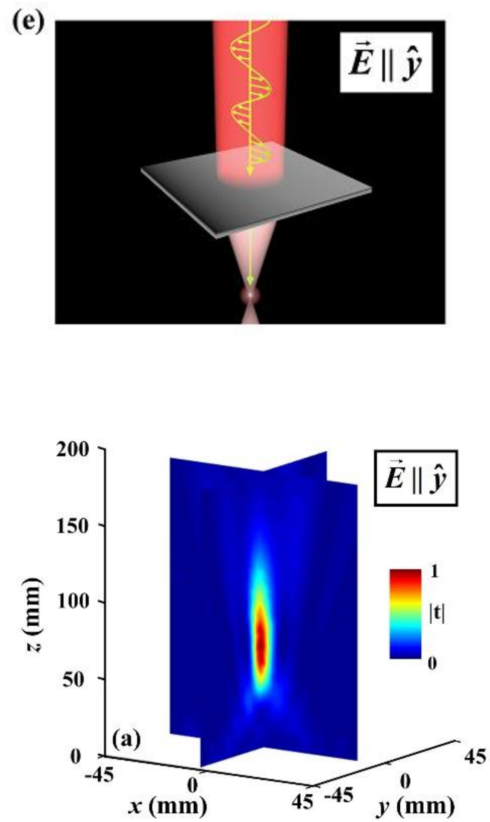
Anomalous reflector

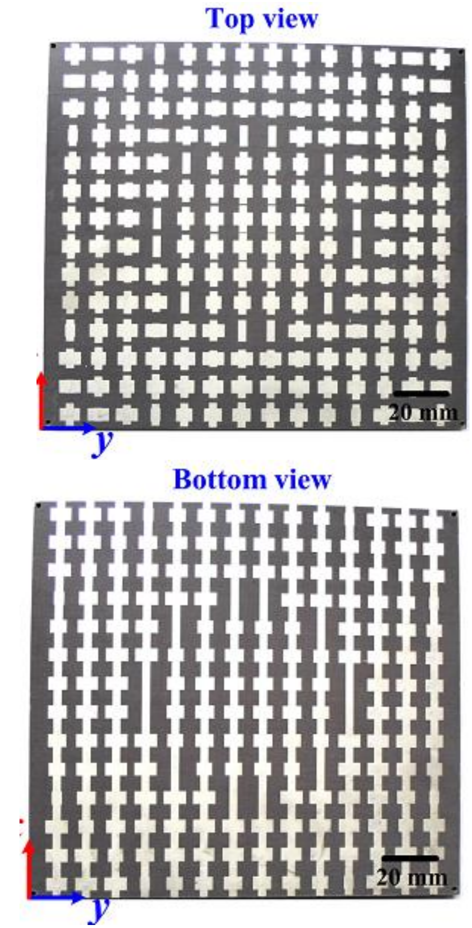
Anomalous refractor

Phys. Rev. Applied 8, 034033 (2017) (Editor's suggestion)

Meta-device 2: Lens





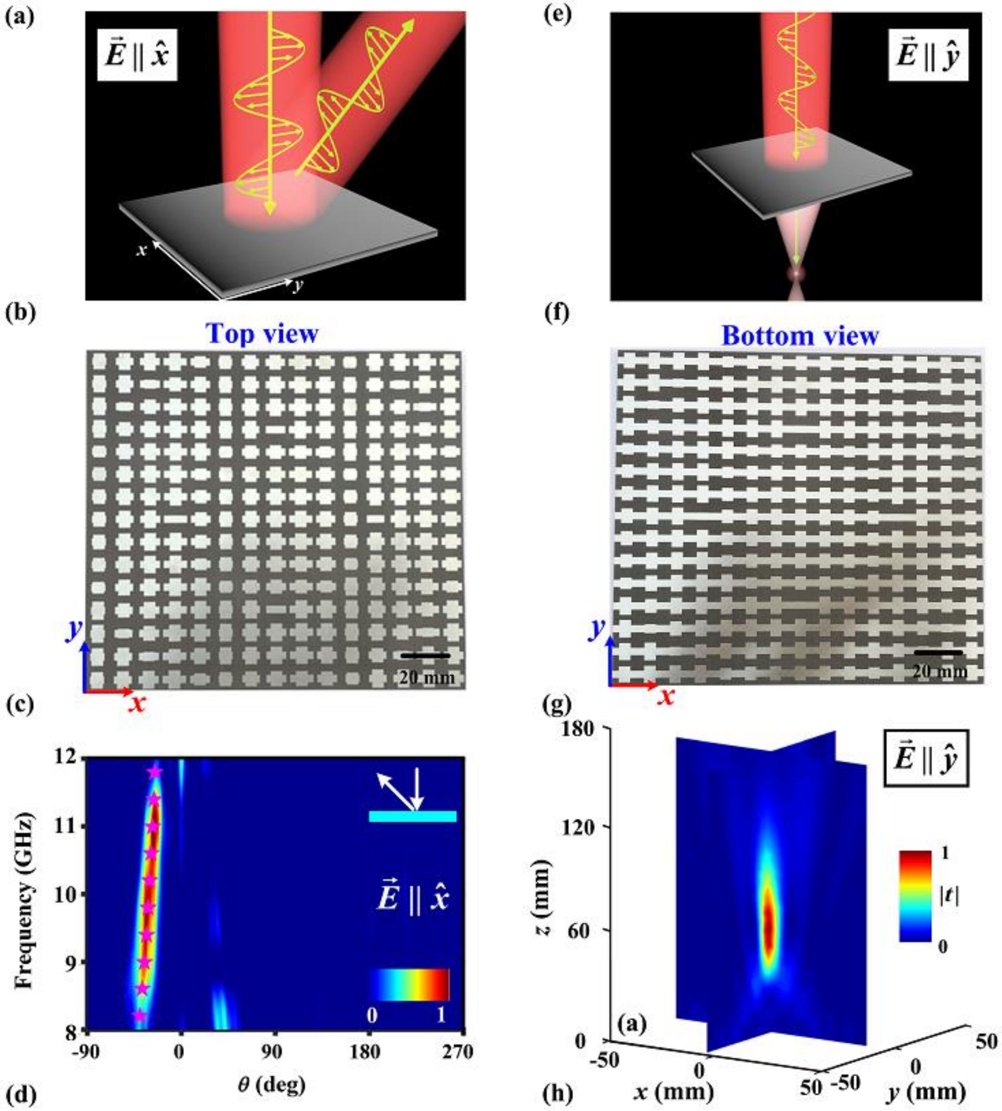


Reflective lens

Transmissive lens

Phys. Rev. Applied 8, 034033 (2017)
(Editor's suggestion)

Meta-device 3: A bifunctional device



- **Arbitrary *full-space* devices realizable via designing appropriate phases**

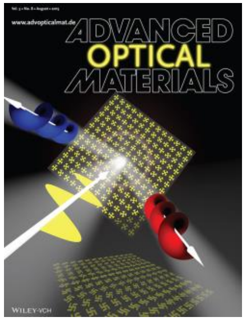
Anomalous reflector

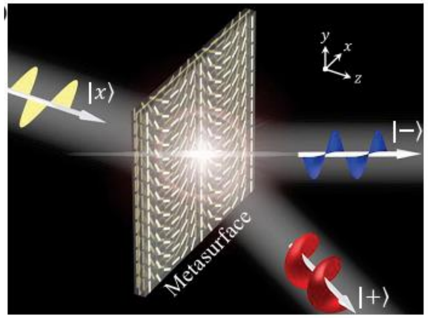
Transmissive lens

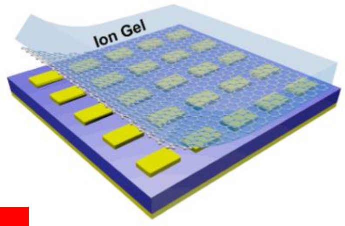
Phys. Rev. Applied 8, 034033 (2017) (Editor's suggestion)

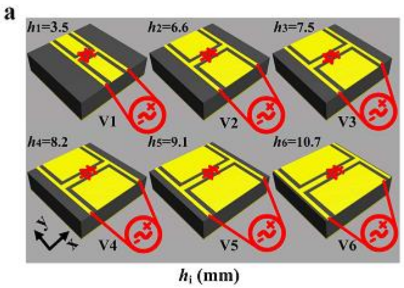
Conclusions

- **Derived a criterion to design 100%-efficiency PB metasurfaces, and realized in both reflection and transmission geometries.**
- **Making tunable metasurfaces in both THz and GHz regimes**
- **High-efficiency multifunctional meta-devices**









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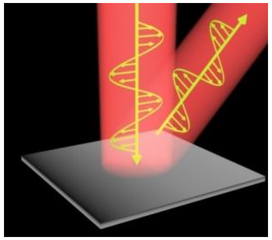

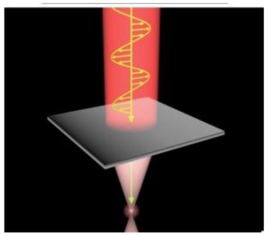

Thanks & Questions?