Flatland Optics with Ultrathin Metasurfaces

J. Sebastian Gomez-Diaz

Department of Electrical and Computer Engineering
University of California, Davis
jsgomez@ucdavis.edu

UCDAVIS ELECTRICAL AND COMPUTER ENGINEERING

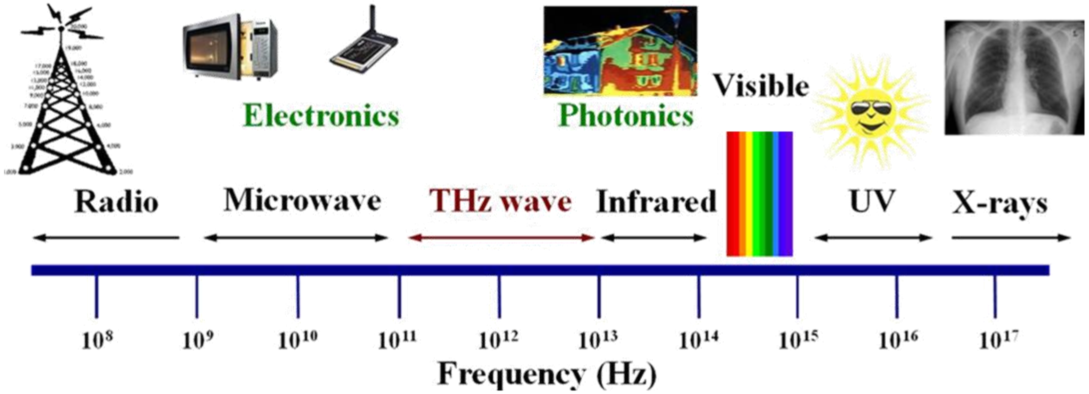
Applied Micro/Nano-Electromagnetics Research Laboratory

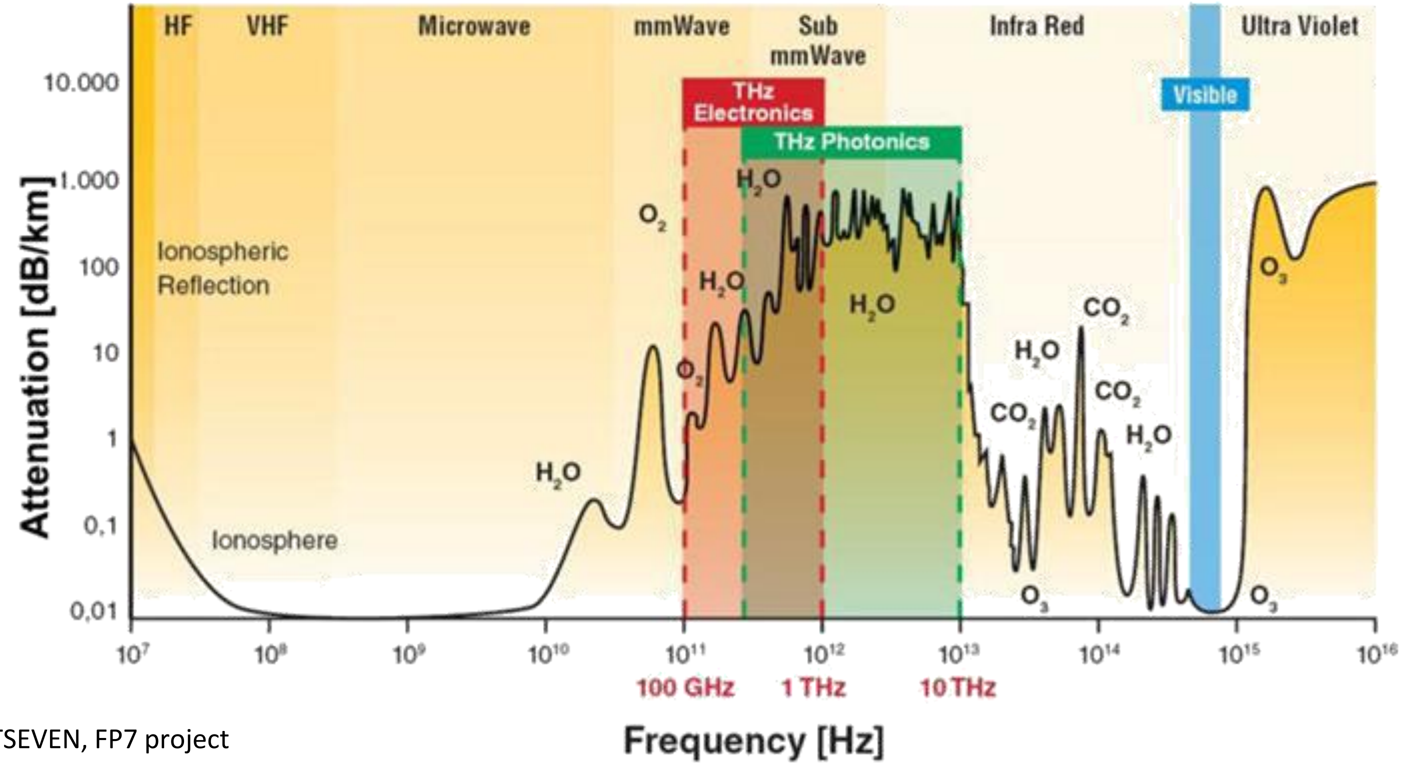
Outline

- Introduction
- Graphene plasmonics: THz devices & antennas
- Non-reciprocal metasurfaces
- Hyperbolic metasurfaces
- Non-linear metasurfaces
- Multidisciplinary
- Conclusions

Outline

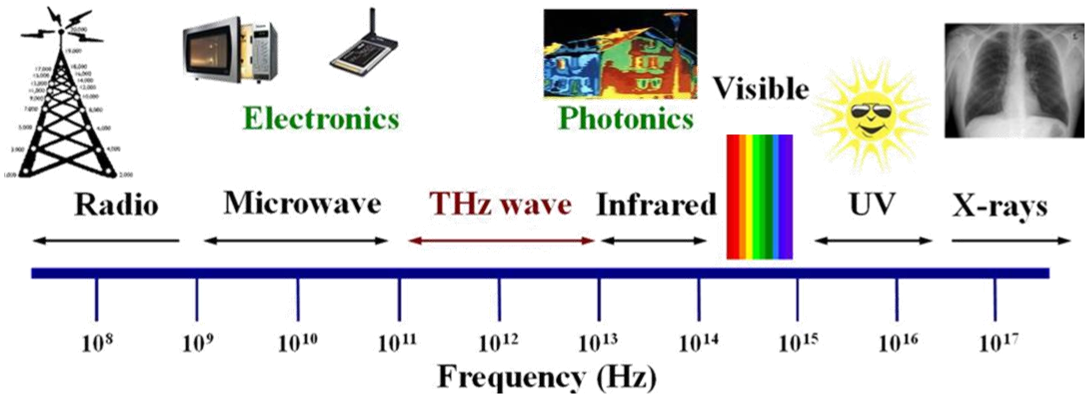
- Introduction
- Graphene plasmonics: THz devices & antennas
- Non-reciprocal metasurfaces
- Hyperbolic metasurfaces
- Non-linear metasurfaces
- Multidisciplinary
- Conclusions



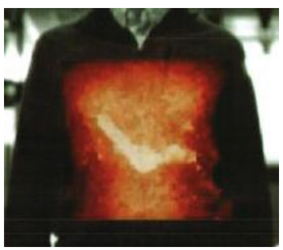


DOTSEVEN, FP7 project

Terahertz Science and Technology



Security and screening

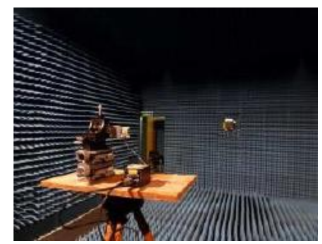


N. Llombart, et al, IEEE TAP, 2012

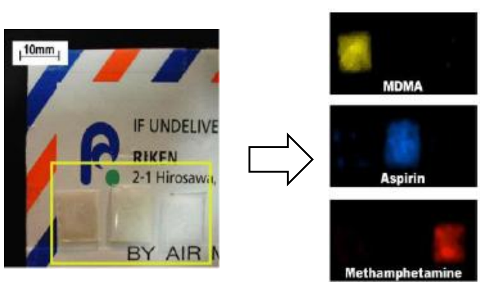
Earth observation

P. Siegel, JPL, Caltech

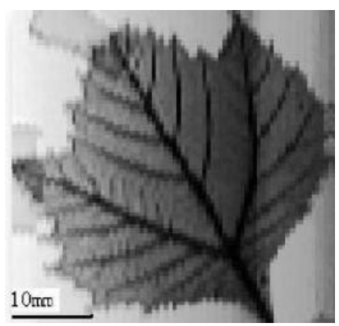
Communications



K. Kawase, Rikken

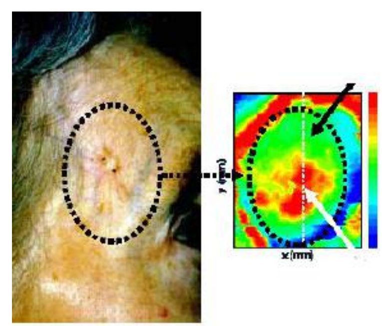


Imaging



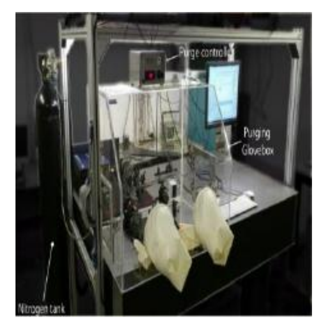
C. Zhang, et al, IRMW THz

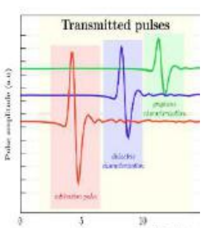
Biomedicine



Teraview

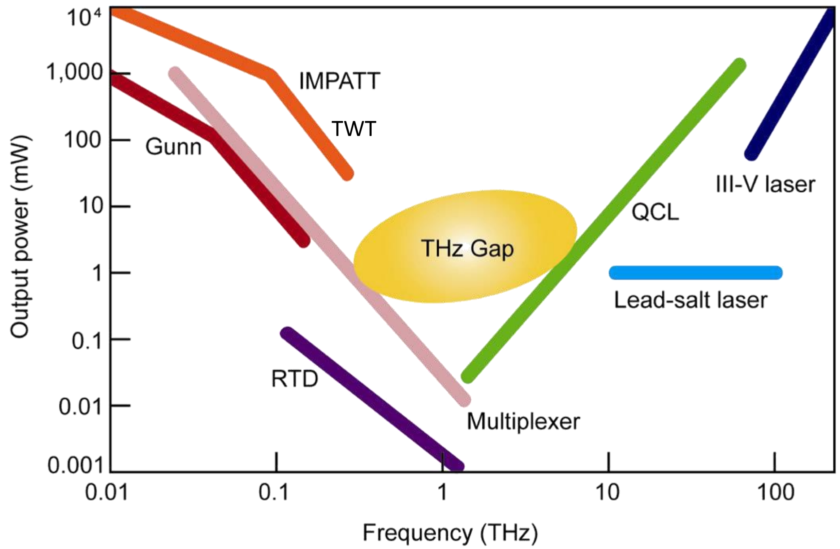
Spectroscopy



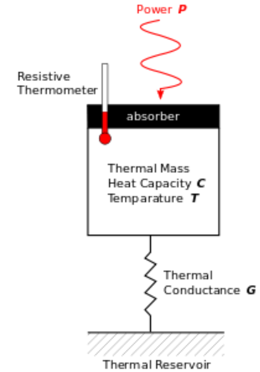


Sources

J. V. Moloney, et al, SPIE 2011.

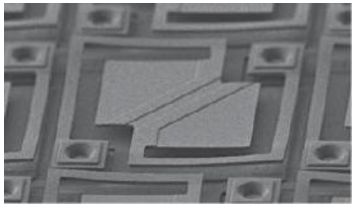


Detectors



Wikipedia

Bolometers

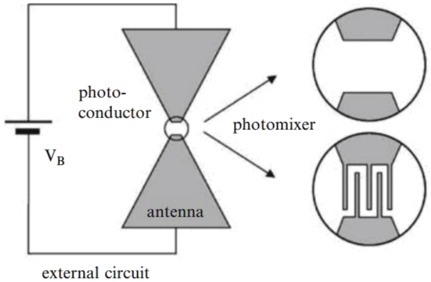


Hamamatsu, Technical resport

HEB Antenna + Mixer

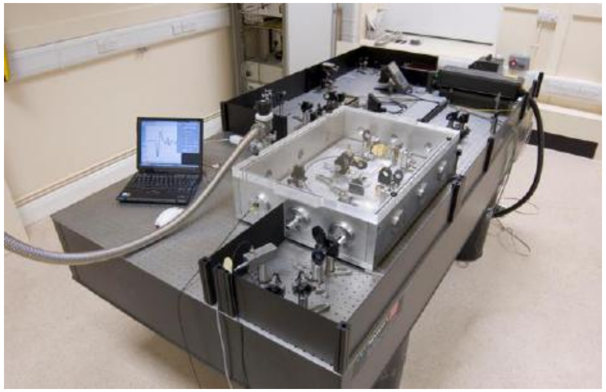
J. Bird, USAS meeting, 2011

Photomixer + Antennas



X. Yin, Springer, 2012

Manipulation of THz waves

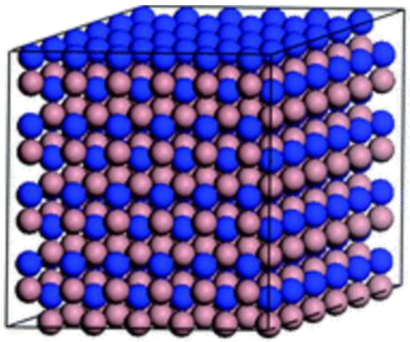


Oxford, Johnston's group

- Quasi-optical components
- Lossy
- Bulky
- Heavy
- Expensive

Electromagnetic Metamaterials

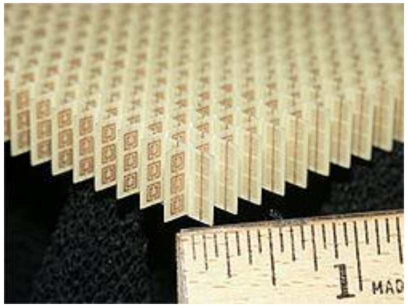
Natural material



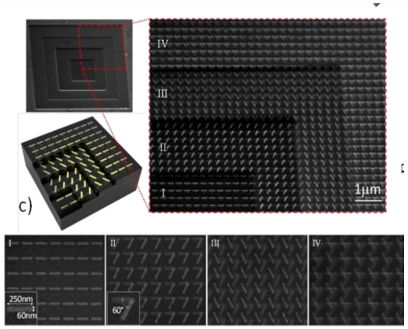
Metamaterials

Güney, Opt. Express 18, 12348

Smith's group



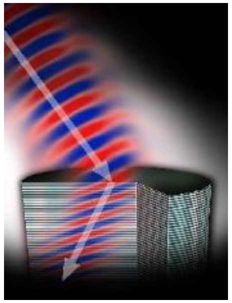
Alu's group



<u>Engineered "materials"</u> with *properties* not found in natural materials

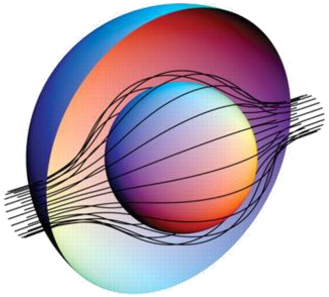
- Difficult fabrication
- High loss
- BW limitations
- 3D granularity

Negative refraction



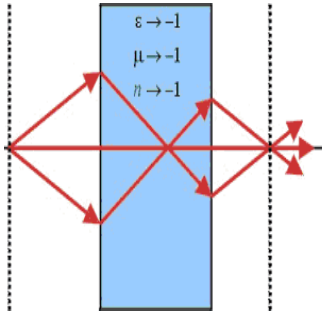
Veselago

Cloaking



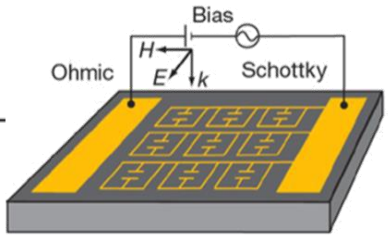
Pendry, Science

Lenses



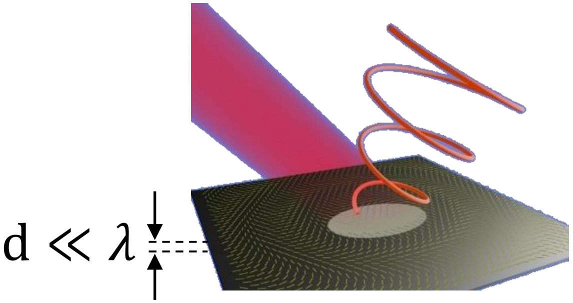
Pendry, PRL

Active devices



Chen, Nature

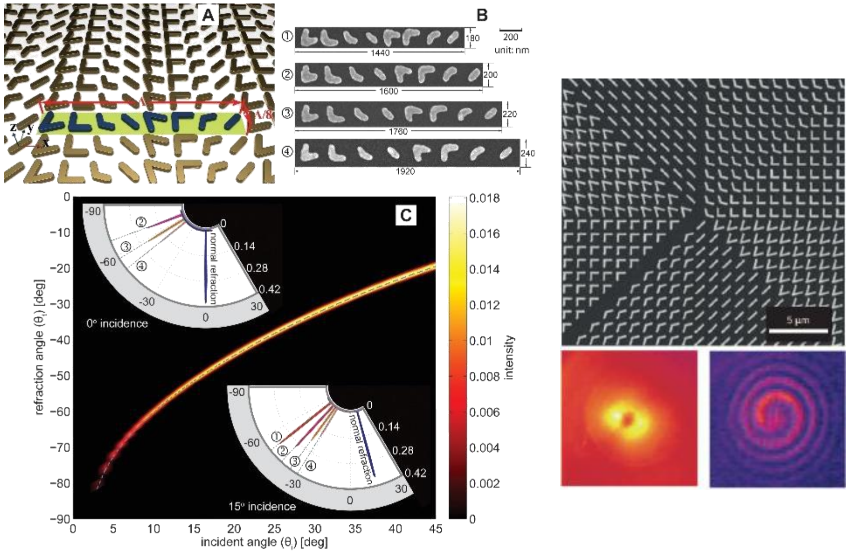
Ultrathin Metasurfaces



Metasurface: 2D version of metamaterials

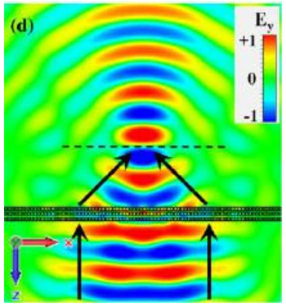
- Nanostructured surfaces
- Simple fabrication
- Reduced losses

Gradient metasurfaces



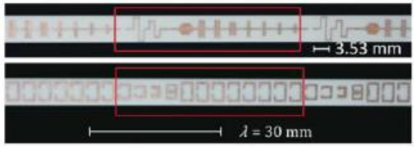
F. Capasso, V. Shalaev's groups

Meta-transmitarray



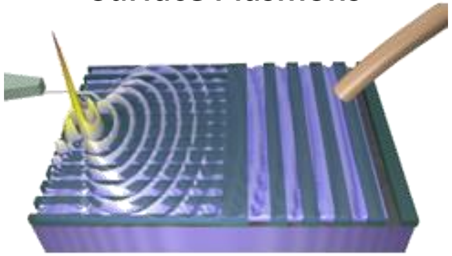
Alu's group

Huygens' metasurfaces

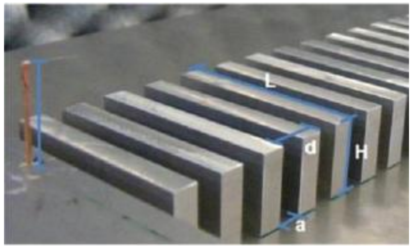


Grbic's group

Surface Plasmons



U. Levy's group



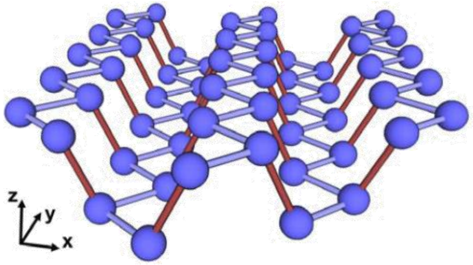
Garcia Vidal's group

Recent Advances on Material Science

Ultrathin 2D materials
Plasmonic response at THz

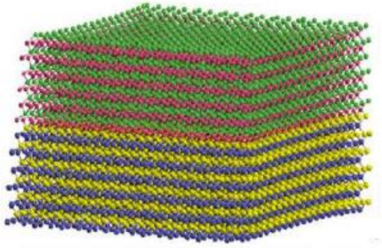
Graphene

Black Phosphorus

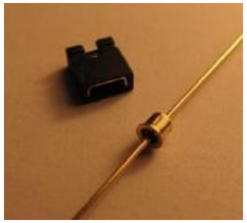


Non-linear and active responses

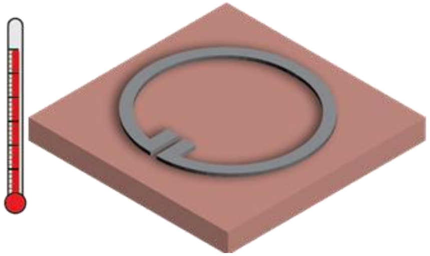
Multi quantum wells



Varactors

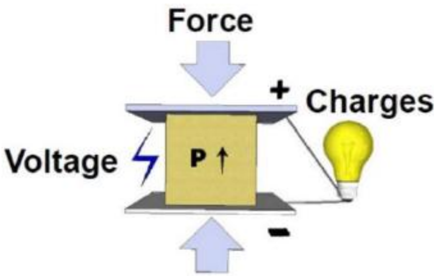


Phase change materials

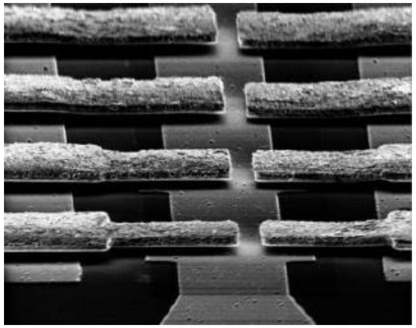


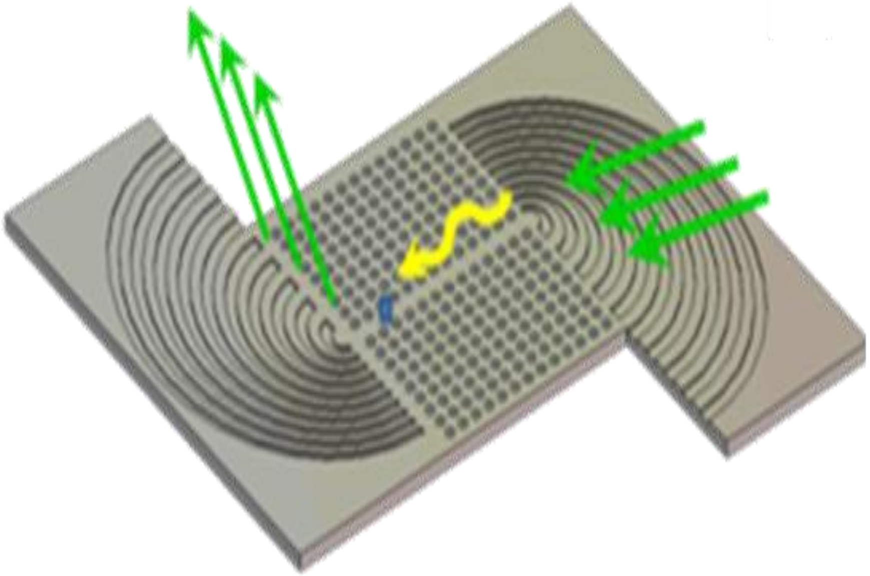
Micro/nano mechanical actuators

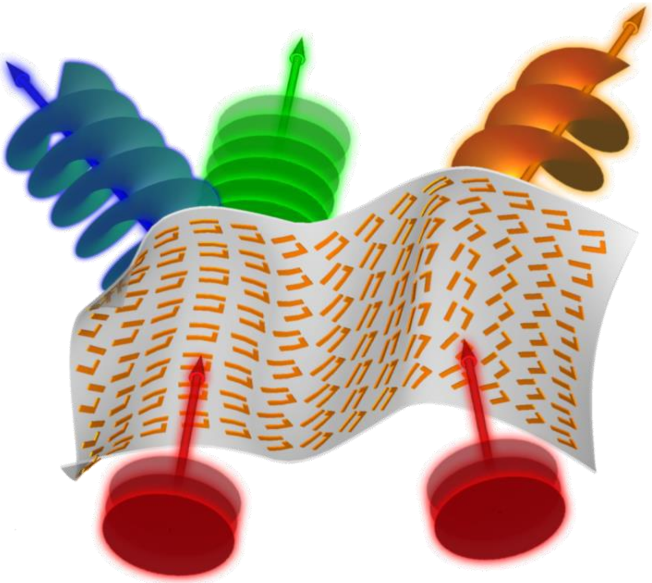
Piezoelectric materials



MEMs / NEMs







Towards a Flatland & Advanced Manipulation of EM waves

- Ultrathin artificial structures
- Strong light-matter interactions
- Suited at THz

+

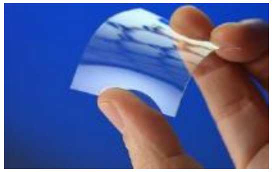
- Reconfigurability
- Non-linearity
- Non-reciprocity
- Hyperbolic

⇒

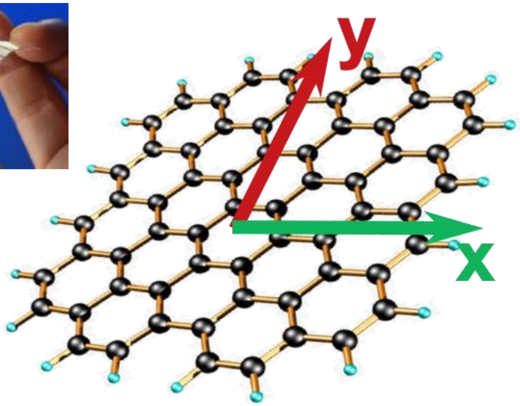
- Guided devices
- Antennas
- Sensors
- On chip systems

Outline

- ❑ Introduction
- ❑ Graphene plasmonics: THz devices & antennas
- ❑ Non-reciprocal metasurfaces
- ❑ Hyperbolic metasurfaces
- ❑ Non-linear metasurfaces
- ❑ Multidisciplinary
- ❑ Conclusions

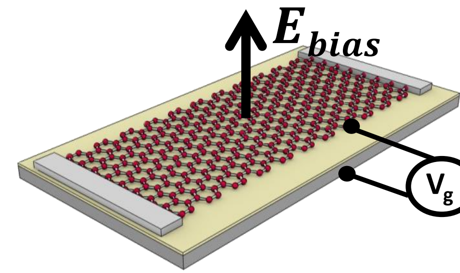


Samsung



$$\vec{J_s} = \bar{\bar{\sigma}}\vec{E} \qquad \bar{\bar{\sigma}} = \begin{pmatrix} \sigma_d & \sigma_h \\ -\sigma_h & \sigma_d \end{pmatrix}$$

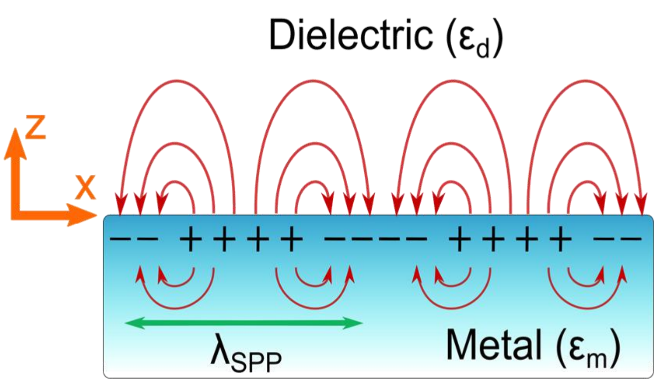
$$\bar{\bar{\sigma}}(\omega, T, \tau, \mu_c(E_{bias}, H_{bias}), k_\rho,)$$



Plasmons _on noble metals @ optics_

EM wave at the interface between a dielectric ($Re[\varepsilon_m] > 0$) and a metal ($Re[\varepsilon_m] < 0$)

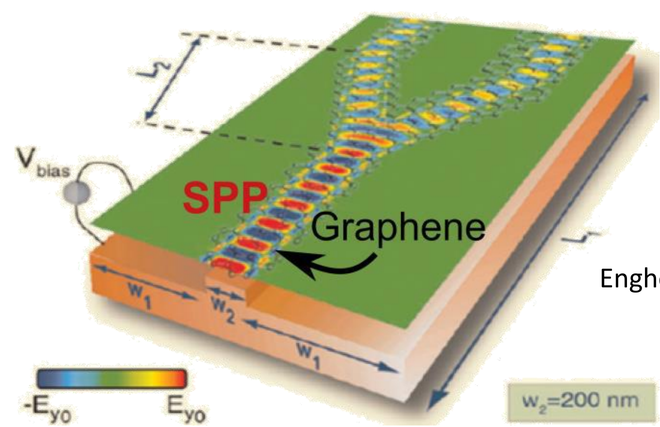
- Very confined waves
- Relatively large loss



Plasmons _on graphene @ THz_

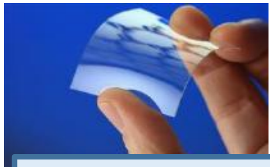
$Re[\varepsilon_m] < 0 \Longleftrightarrow Im[\sigma] < 0$ (or $Im[Z_S] > 0$)

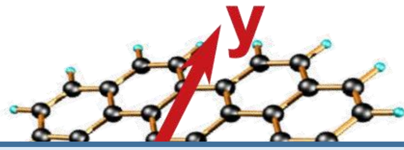
- Tunable
- Integration
- Miniaturization
- Gyroscopy



Engheta's group

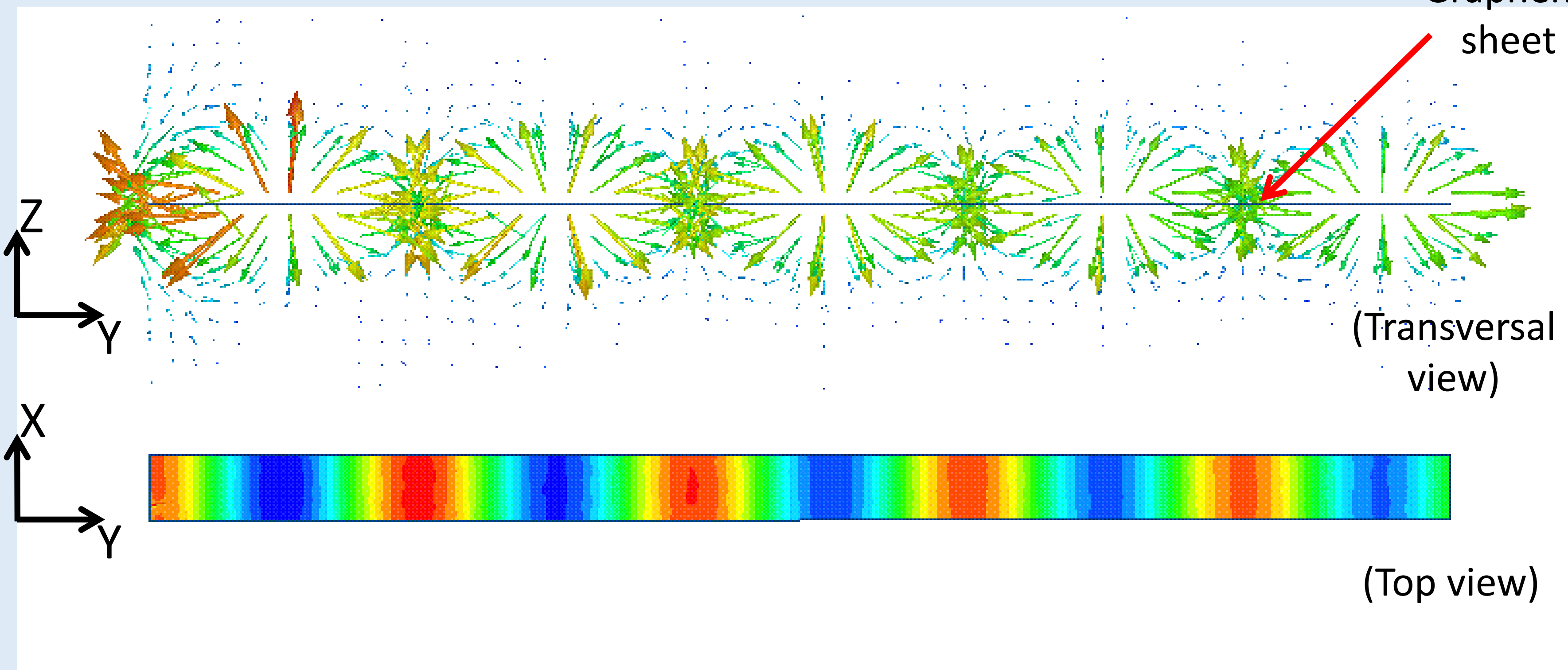
Graphene Plasmonics

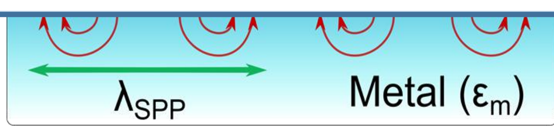


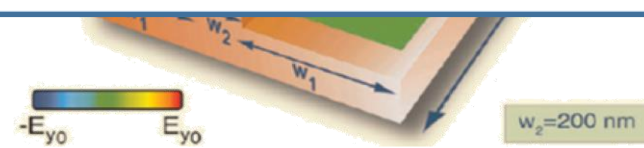


$\vec{J}_s = \bar{\bar{\sigma}}\vec{E}$ $\bar{\bar{\sigma}} = \begin{pmatrix} \sigma_d & \sigma_h \end{pmatrix}$

Example of plasmon propagation on a graphene sheet



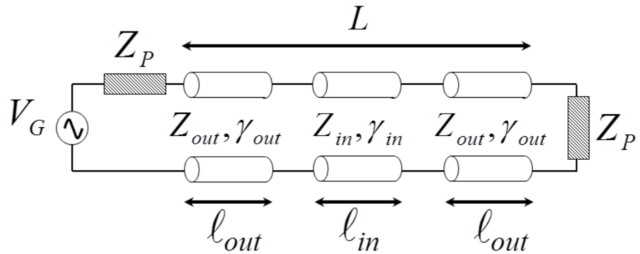


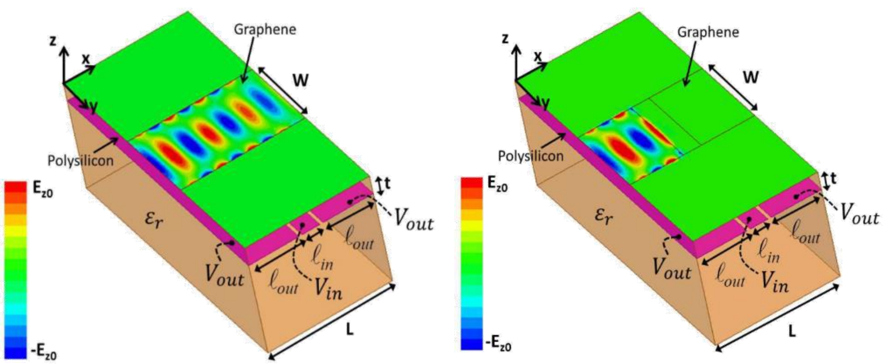


Graphene-based THz Switches & Filters

❑ Plasmonic switch

- Switching: graphene field's effect
- TL model
- Isolation > 40 dB





ON STATE

$\mu_{cout} = 0.5\ eV$
$\mu_{cin} = 0.5\ eV$

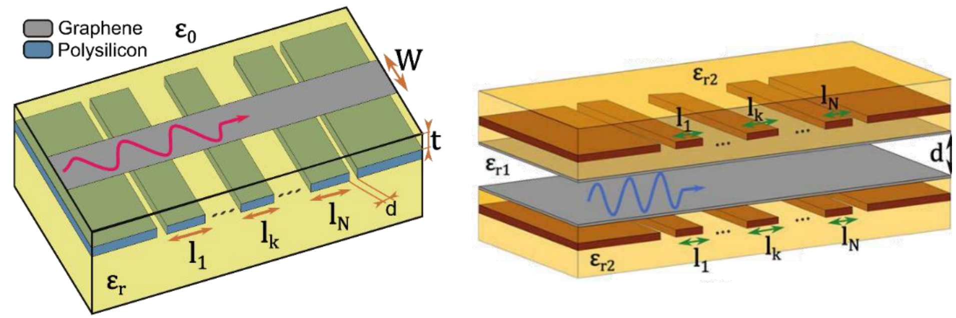
$\ell_{out} = \ell_{in} = 1\mu m$
$\tau = 0.15\ ps$
$T = 300°\ K$

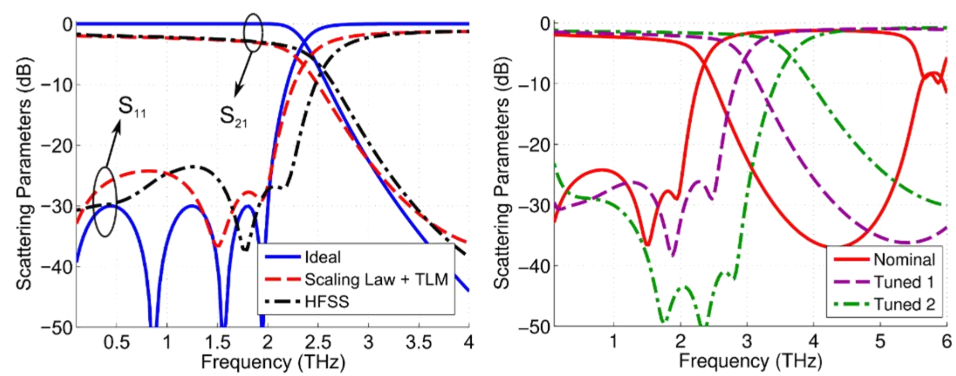
OFF STATE

$\mu_{cout} = 0.5\ eV$
$\mu_{cin} = 0.1\ eV$

❑ Plasmonic THz filters

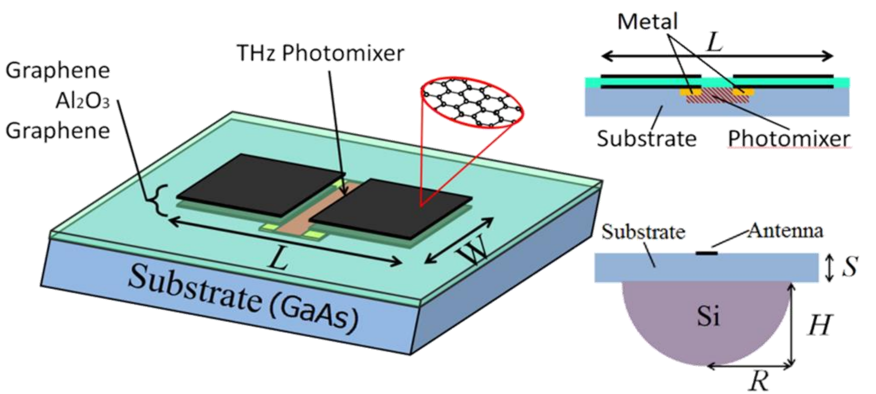
- Accurate & scalable model
- Steepped impedance filter
- Low-loss & tunable

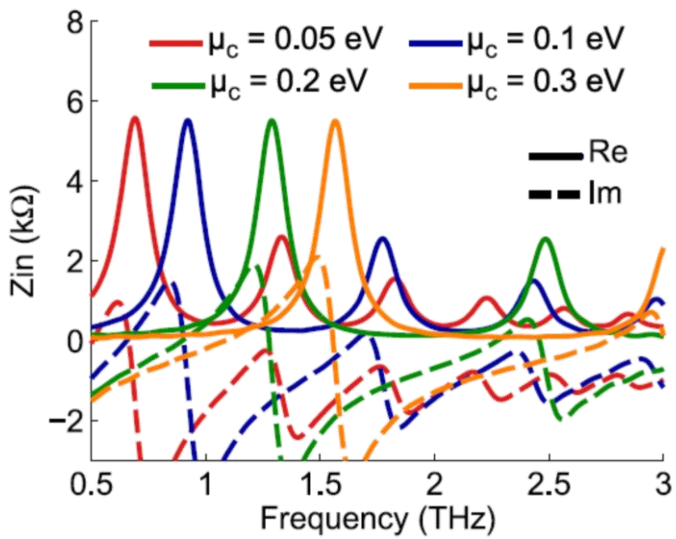




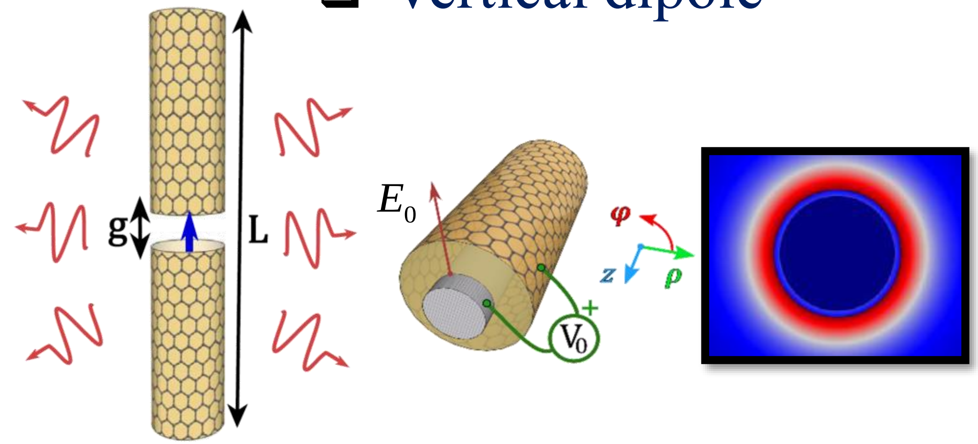
J.S. Gomez-Diaz and J. Perruisseau, "Graphene-based plasmonic switches at near infrared frequencies", Optic Express, 2013.
D. Correas-Serrano, J. S. Gomez-Diaz, et al , "Graphene based plasmonic tunable low pass filters in the THz band," IEEE Trans. on Nanotechnology, 2014.

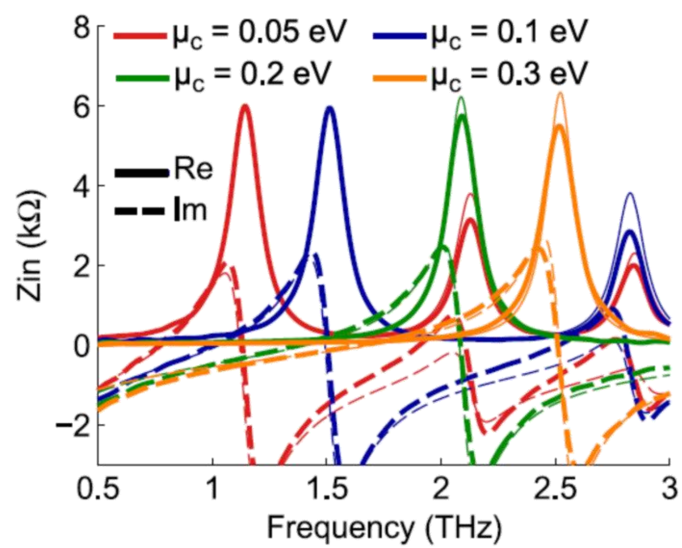
- Planar configuration





- Vertical dipole

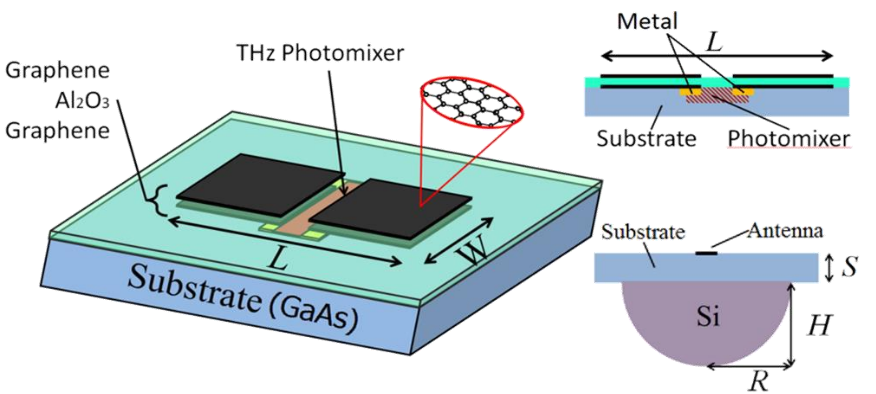




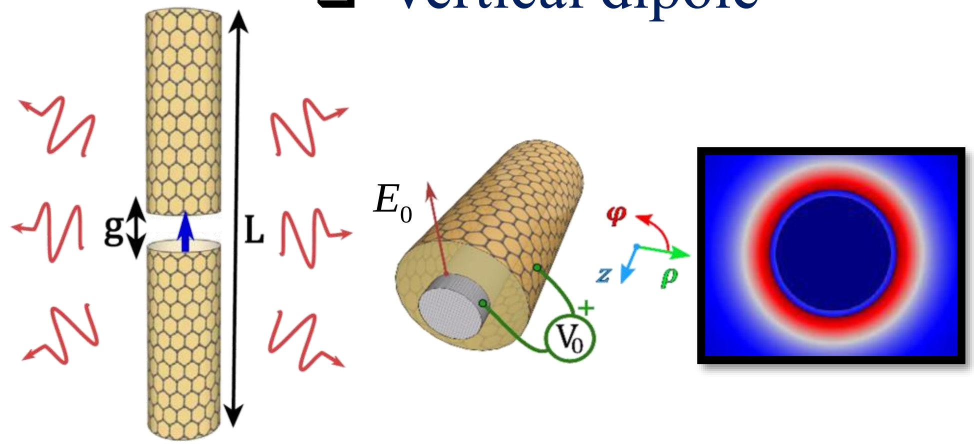
M. Tamagnone, J. S. Gomez-Diaz, et al, “Reconfigurable terahertz plasmonic antenna concept using a graphene stack,” APL , 2012.
M. Tamagnone, J. S. Gomez-Diaz, et al, “Analysis and design of terahertz antennas based on plasmonic resonant graphene sheets,” JAP , 2012.
D. Correas-Serrano, J. S. Gomez-Diaz, A. Alvarez-Melcon and A. Alù, “Electrically and Magnetically Biased Graphene-Based Cylindrical Waveguides: Analysis and Applications as Reconfigurable Antennas”, IEEE Transactions on THz Science and Technology, 2015.

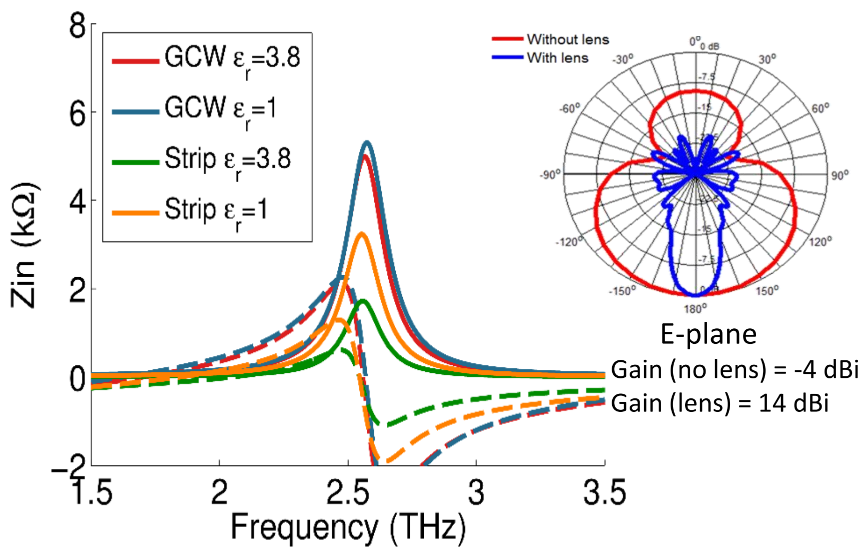
Graphene-based THz Antennas

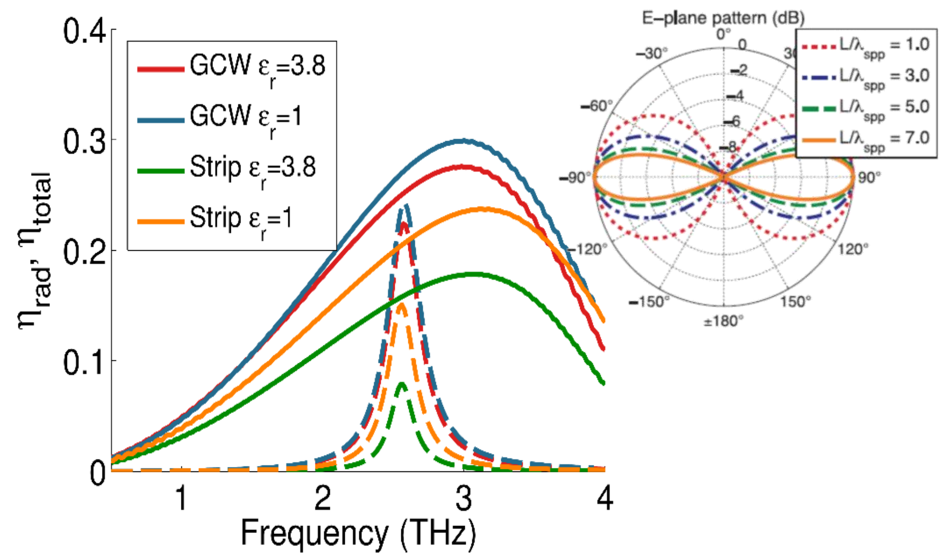
❑ Planar configuration



❑ Vertical dipole





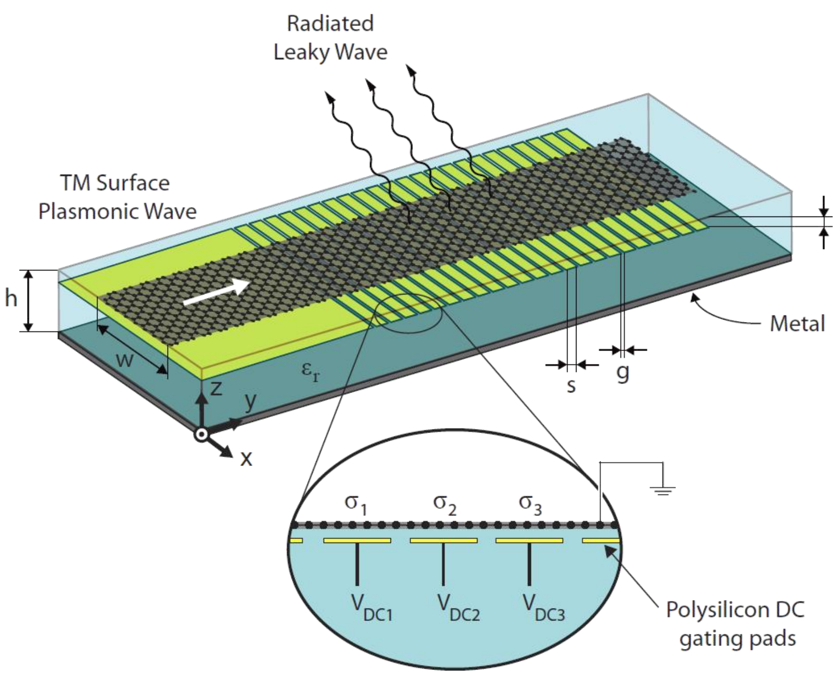


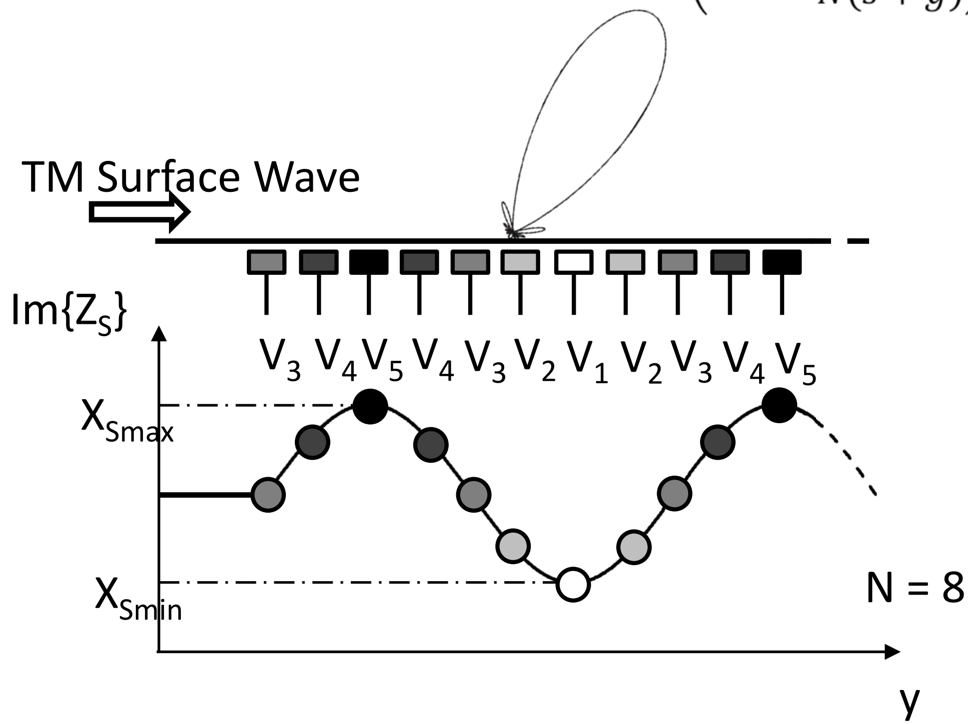
M. Tamagnone, J. S. Gomez-Diaz, et al, "Reconfigurable terahertz plasmonic antenna concept using a graphene stack," APL , 2012.
M. Tamagnone, J. S. Gomez-Diaz, et al, "Analysis and design of terahertz antennas based on plasmonic resonant graphene sheets," JAP , 2012.
D. Correas-Serrano, J. S. Gomez-Diaz, A. Alvarez-Melcon and A. Alù, "Electrically and Magnetically Biased Graphene-Based Cylindrical Waveguides: Analysis and Applications as Reconfigurable Antennas", IEEE Transactions on THz Science and Technology, 2015.

Sinusoidally modulated surfaces at THz

- Several implementations based on graphene's field effect
- Beam scanning at fixed freq

$$\theta = \arcsin\left(\beta_{SW} - \frac{\lambda_0}{N(s+g)}\right)$$

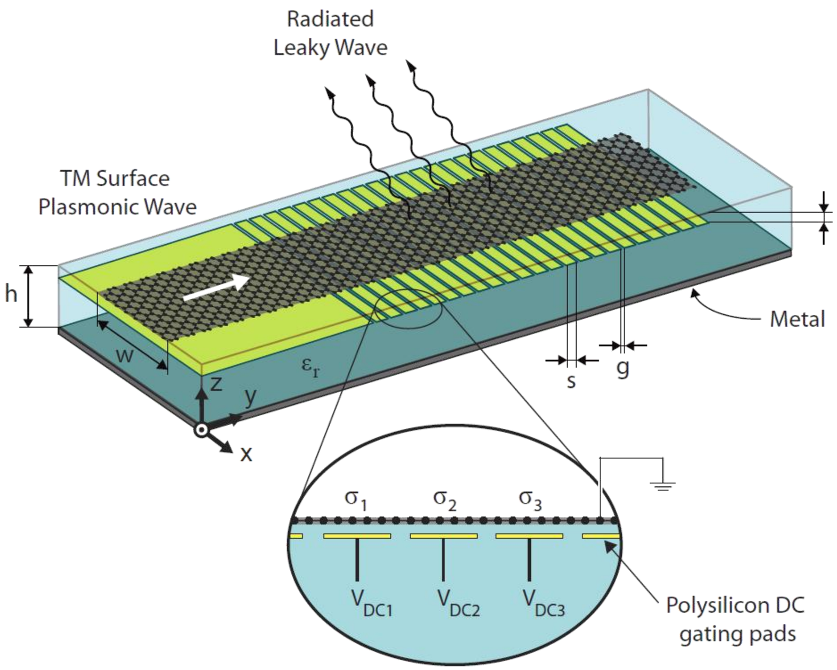


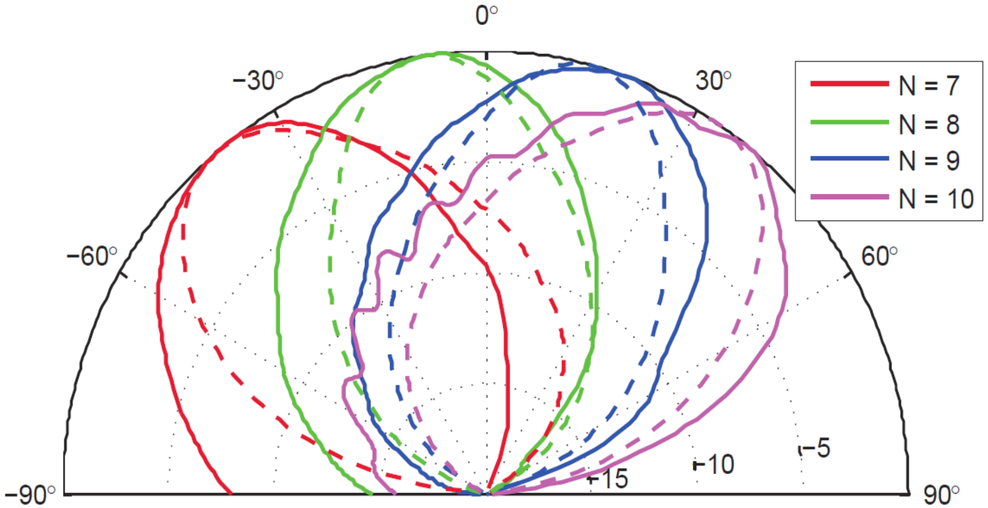


A. Oliner and A. Hessel, "Guided waves on sinusoidally-modulated reactance surfaces," IRE Transactions on Antennas and Propagation , 1959
M. Esquius-Morote, J.S. Gomez-Diaz, and J. Perruisseau-Carrier, IEEE Trans. on Terahertz Science and Technology, vol. 4, pp. 116-122, 2014
J.S. Gomez-Diaz, M. Esquius-Morote and J. Perruisseau-Carrier, Optic Express, vol. 21, pp. 24856-24872, 2013

- Sinusoidally modulated surfaces at THz
  - Several implementations based on graphene's field effect
  - Beam scanning at fixed freq

$$\theta = \arcsin\left(\beta_{SW} - \frac{\lambda_0}{N(s+g)}\right)$$



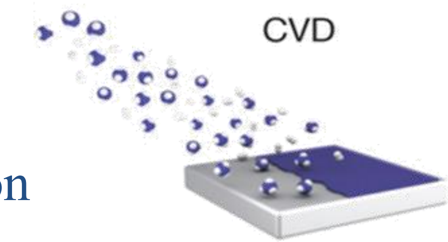


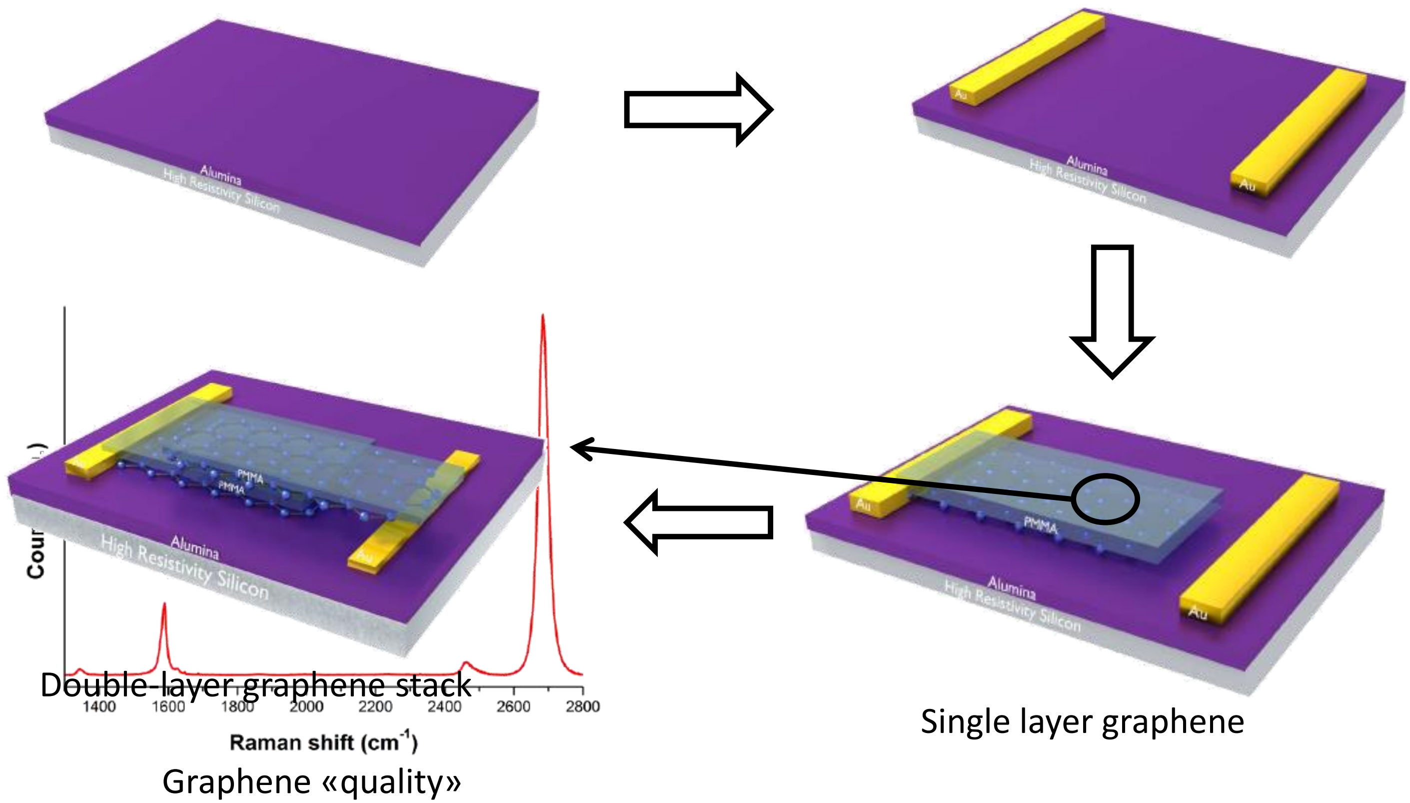
τ = 1 ps, T = 300°K, f_0 = 2 THz, V_{DC} = 6.5 − 45 V, ε_r = 3.8, s = 4.8µm and g = 0.2µm.

y

A. Oliner and A. Hessel, "Guided waves on sinusoidally-modulated reactance surfaces," IRE Transactions on Antennas and Propagation , 1959
M. Esquius-Morote, J.S. Gomez-Diaz, and J. Perruisseau-Carrier, IEEE Trans. on Terahertz Science and Technology, vol. 4, pp. 116-122, 2014
J.S. Gomez-Diaz, M. Esquius-Morote and J. Perruisseau-Carrier, Optic Express, vol. 21, pp. 24856-24872, 2013

- Fabrication of graphene stacks
  - CVD of graphene
  - Metallic contacts → DC biasing + dynamic reconfiguration

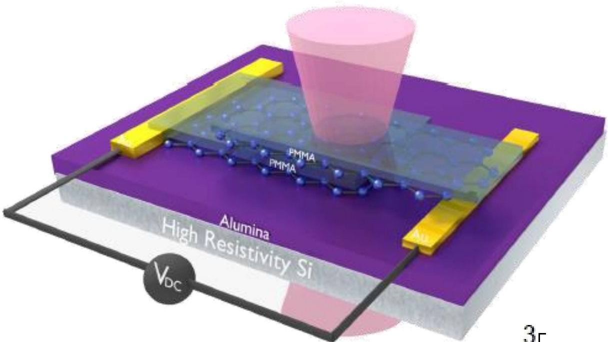


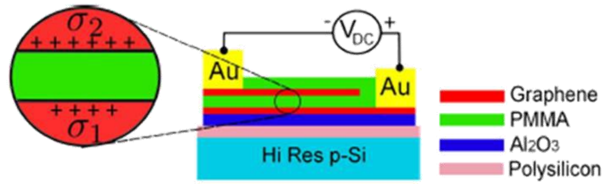


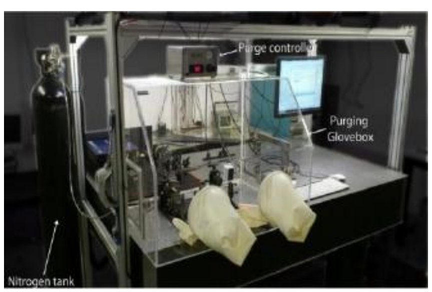
J. S. Gómez-Díaz, C. Moldovan, S. Capdevilla, L. S. Bernard, J. Romeu, A. M. Ionescu, A. Magrez, and J. Perruisseau-Carrier, "Self-biased reconfigurable graphene stacks for terahertz plasmonics", Nature Communications, 2015.

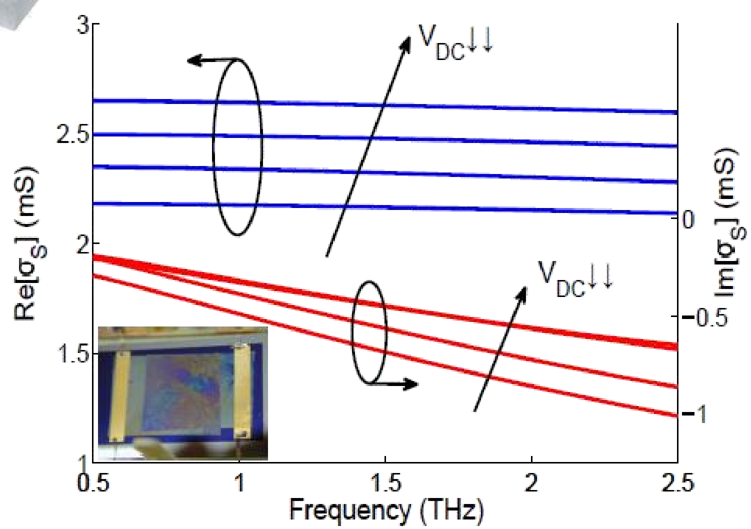
Graphene stacks

- Enhanced reconfiguration capabilities + simple fabrication avoiding metals
- Measured using THz time-domain spectroscopy → Good agreement theory

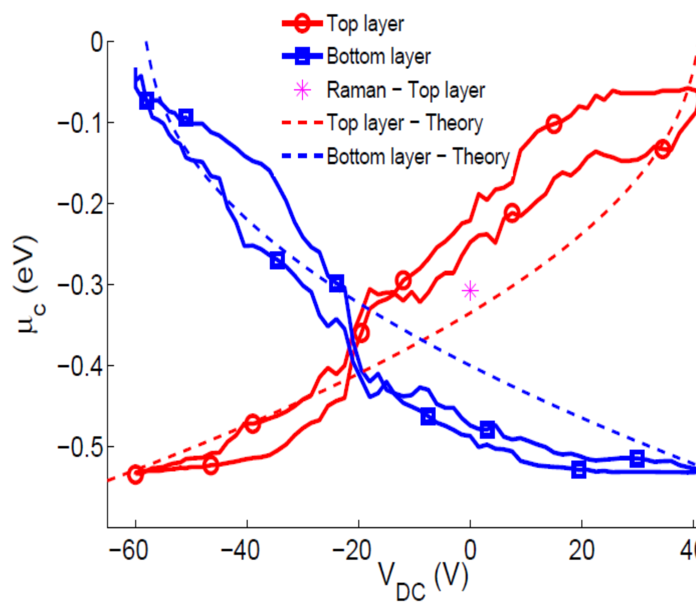








Operation frequency: 1 THz

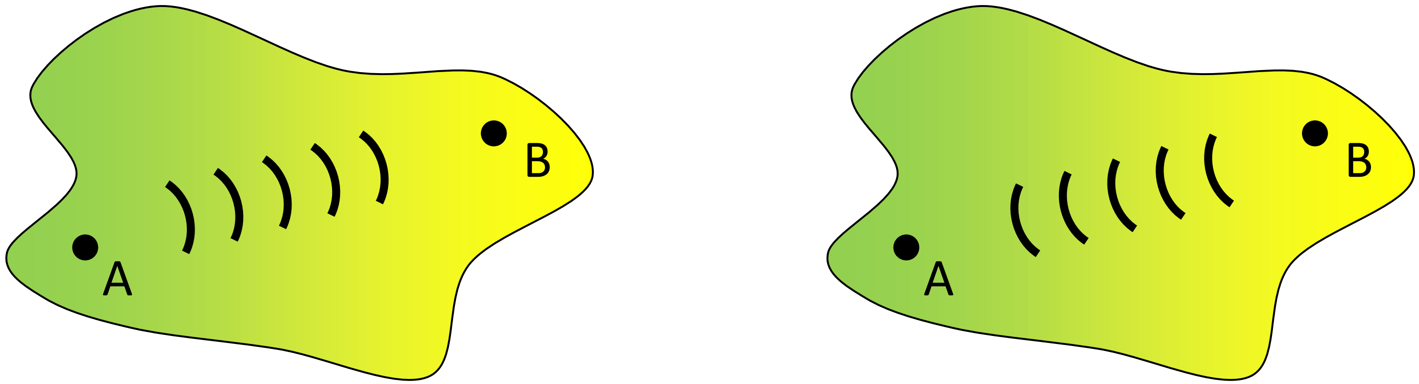


J. S. Gómez-Díaz, C. Moldovan, S. Capdevilla, L. S. Bernard, J. Romeu, A. M. Ionescu, A. Magrez, and J. Perruisseau-Carrier, "Self-biased reconfigurable graphene stacks for terahertz plasmonics", Nature Communications, 2015.

Outline

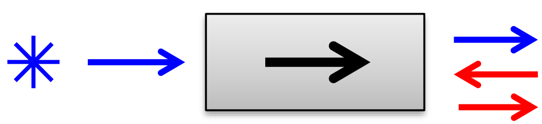
- ❑ Introduction
- ❑ Graphene plasmonics: THz devices & antennas
- ❑ Non-reciprocal metasurfaces
- ❑ Hyperbolic metasurfaces
- ❑ Non-linear metasurfaces
- ❑ Multidisciplinary
- ❑ Conclusions

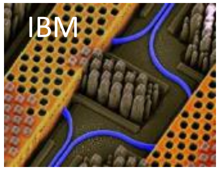
Reciprocity
symmetry in transmission for opposite propagation directions



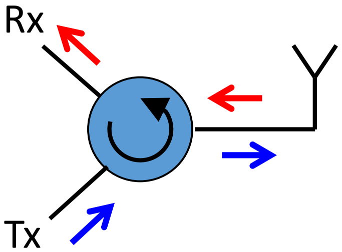
$$T_{\mathrm{BA}} = T_{\mathrm{AB}}$$

Isolators



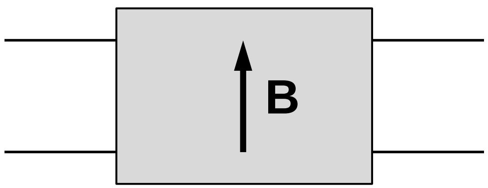


Duplexers



Slide courtesy of Dr. Dimitrious Sounas.

❑ Onsager-Casimir Principle



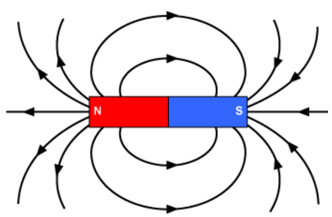
$t \rightarrow -t$

B ⇨ **–B**

Linear network

⇨ $T_{21} \neq T_{12}$

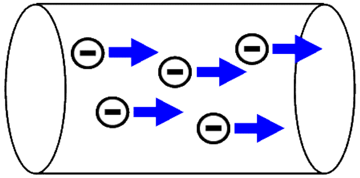
Magnetic Field



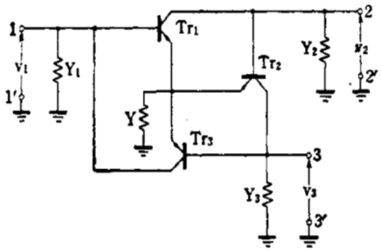
Static Magnets

Massive Devices

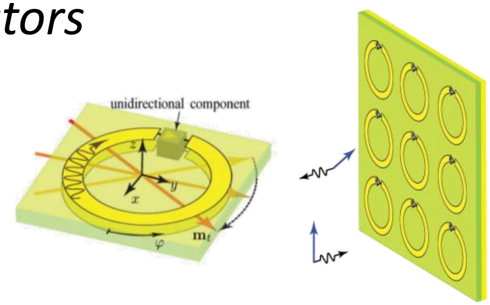
Direct current



Transistors

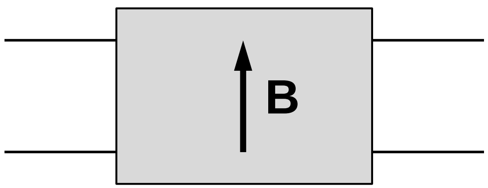


Tanaka, Proc. IEEE 53, 260 (1965)



D. L. Sounas et al, IEEE TAP (2013)

❑ Onsager-Casimir Principle



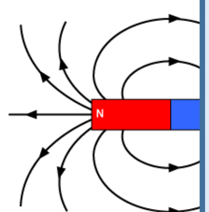
$t \rightarrow -t$

B ⇨ **–B**

Linear network

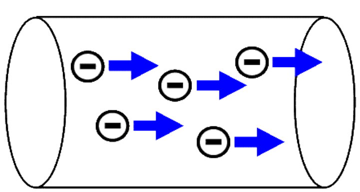
⇨ $T_{21} \neq T_{12}$

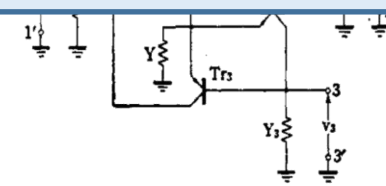
Magneti



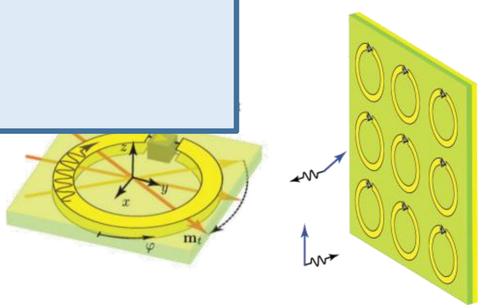
ces

Direct cu





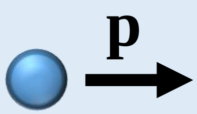
Tanaka, Proc. IEEE 53, 260 (1965)



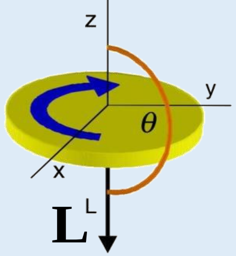
D. L. Sounas et al, IEEE TAP (2013)

Alternative approach? ***<u>Momentum</u>*** **<u>Bias</u>**

Linear Momentum



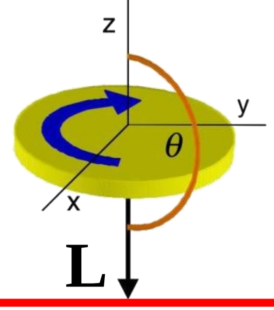
Angular Momentum

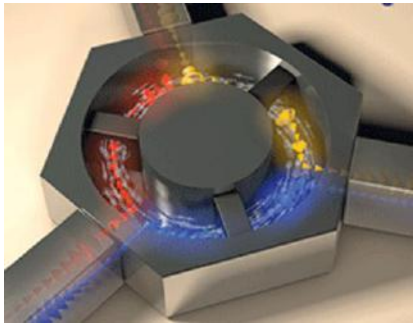


Non-Reciprocity with Momentum Bias

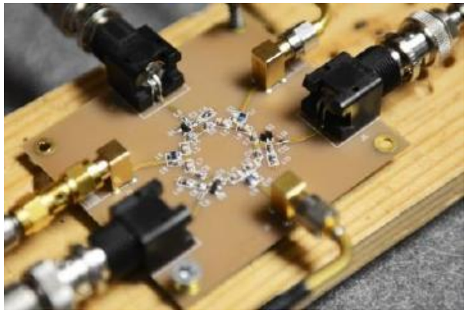
Demonstrated @ acoustics, microwaves and optics

Angular Momentum

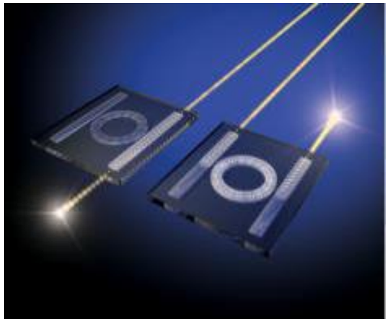




R. Fleury et al, Science (2014)



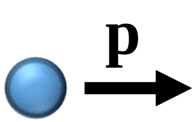
N. A. Estep et al,
Nature Phys. (2014)



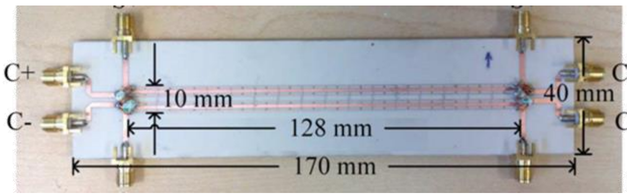
D. Sounas, et al
ACS Photonics (2014)

Demonstrated @ microwaves and optics

Linear Momentum



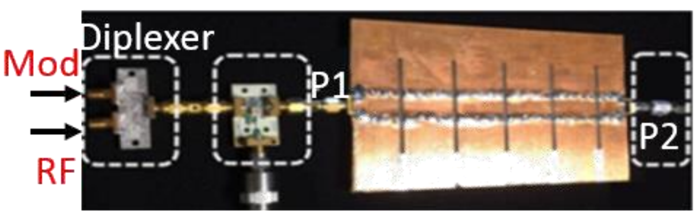
Isolators



S. Qin et al, IEEE MTT (2014)

Lira et al, PRL 109, 033901 (2012)

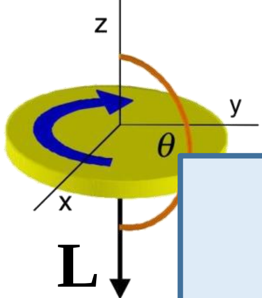
Non-reciprocal LWAs

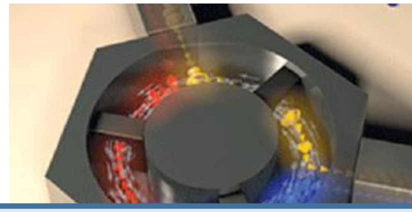


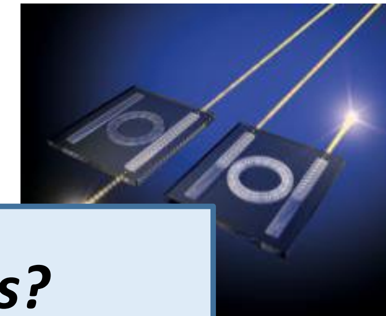
Y. Hadad et al, Proc. Nat. Acad. Sci. (2016)

Demonstrated @ acoustics, microwaves and optics

Angular Momentum





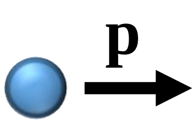


s, et al
ics (2014)

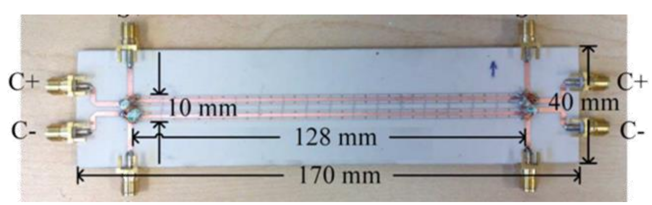
Potential application in growing areas?

- THz science and technology
- Plasmonics

Linear Momentum



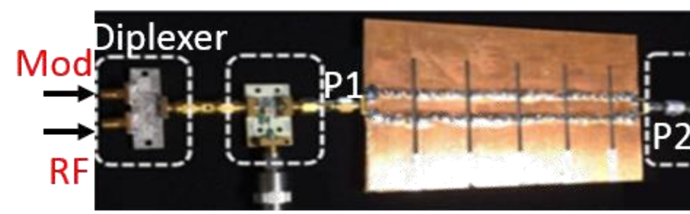
Isolators



S. Qin et al, IEEE MTT (2014)

Lira et al, PRL 109, 033901 (2012)

Non-reciprocal LWAs

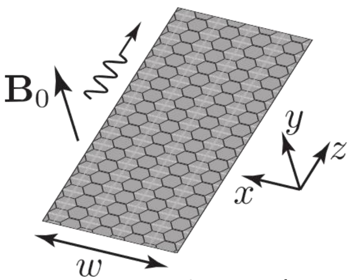


Y. Hadad et al, Proc. Nat. Acad. Sci. (2016)

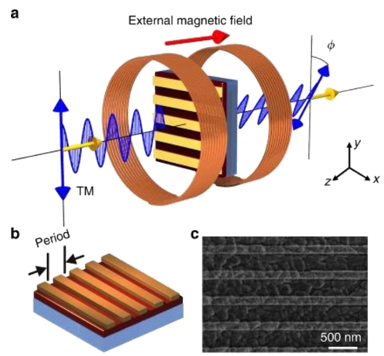
Non-Reciprocal Graphene Components

- All **non-reciprocal** graphene THz devices rely on magnetic bias…

Non-reciprocal plasmonics

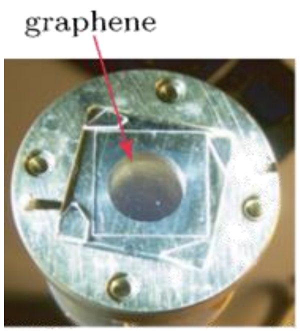


Sounas et al, APL (2011)

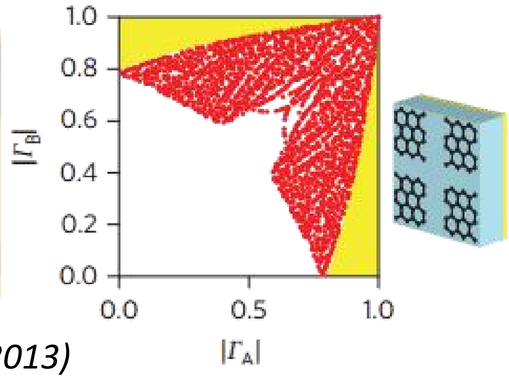


J.Yao Chin, et al. Nature Com. (2013)

Giant Faraday Rotation



D. L. Sounas et al, APL (2013)



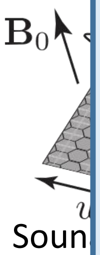
M. Tamagnone et al, Nature Phot. (2014)

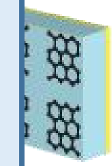
- Bulky static magnets

2D material & **highly-confined** plasmons but **massive** devices

- All **non-reciprocal** graphene THz devices rely on magnetic bias…

Non-reciprocal plasmonics *Giant Faraday Rotation*



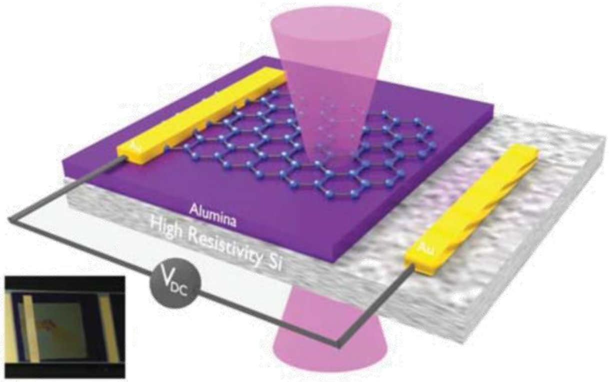


Motivation and objectives

- Magnet-free non-reciprocal graphene plasmonics
- Linear momentum through graphene's field effect
- Integrated, low-cost technology
- Relatively easy fabrication
- Potential applications

plasmons but **massive** devices

- Reconfigurability through applied bias
  - Implement static conductivity profiles



$$n_s = C_{ox}(V_{DC} - V_{Dirac})/q_e$$

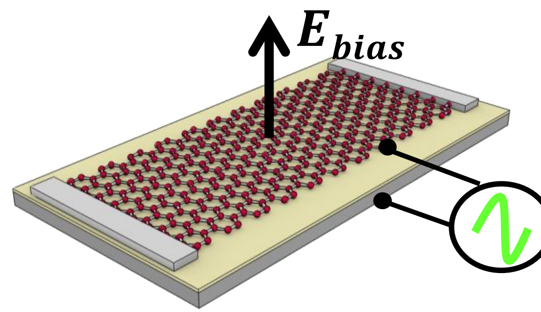
$$n_s = \frac{2}{\pi\hbar^2 v_F^2}\int_0^{\infty} \varepsilon\left[f_d(\varepsilon-\mu_c) - f_d(\varepsilon+\mu_c)\right] d\varepsilon$$

- Usual static operation
  - Moderately doped ($|\mu_c| \gg k_B T$)
  - Below interband threshold ($2|\mu_c| > \hbar\omega$)

$$\mu_c \approx \hbar v_F \sqrt{\frac{\pi C_{ox} V_{DC}}{q_e}}$$

$$\sigma \propto \sqrt{V_{DC}}$$

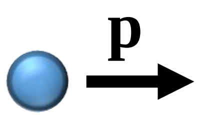
- Up to ~100 GHz
  - C. T. Phare et al, Nat. Phot. (2015)
  - V. Ginis et al, PRB Rapid Comm. (2015)



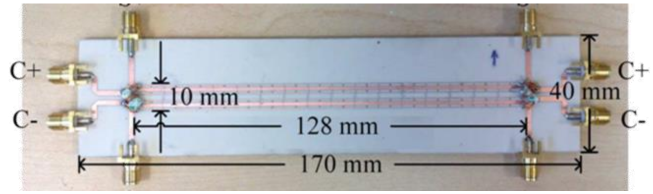
$$\sigma(t) \propto \sqrt{V(t)}$$

Spatio-Temporal Modulation in Graphene

Linear Momentum



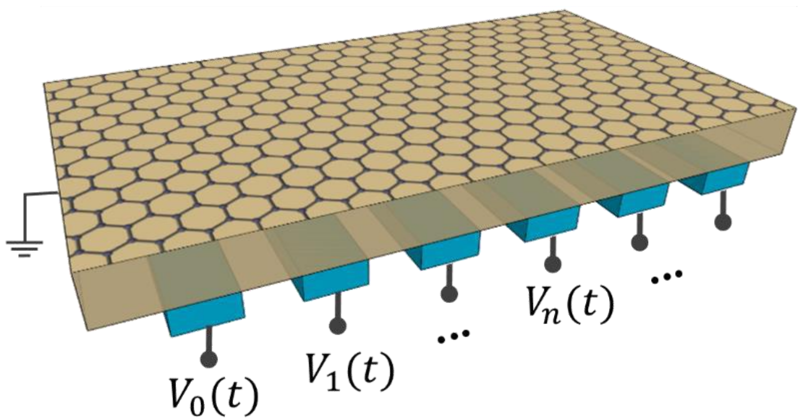
Isolators

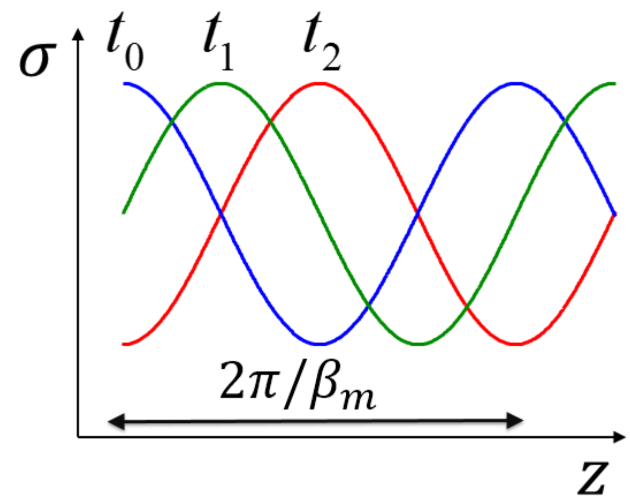


S. Qin et al, IEEE MTT (2014)

- ❑ Implemented at microwaves
- ❑ Time modulated varactors
- ❑ Can we apply this at THz?

Graphene: Ideal material to implement spatiotemporal modulation @ THz

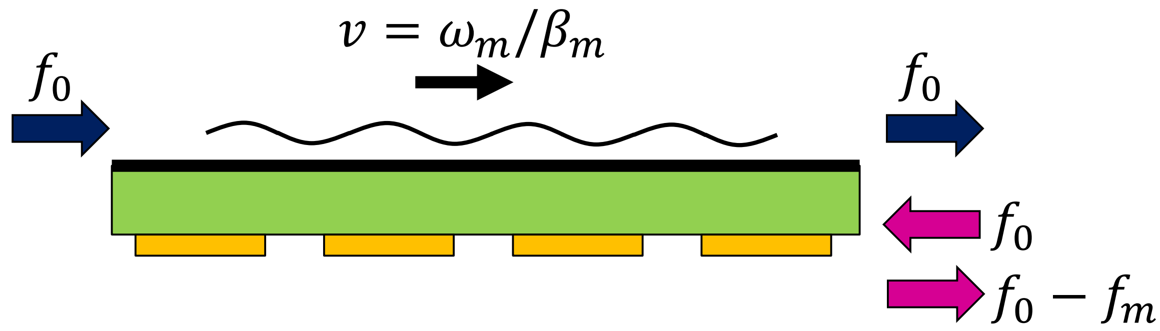




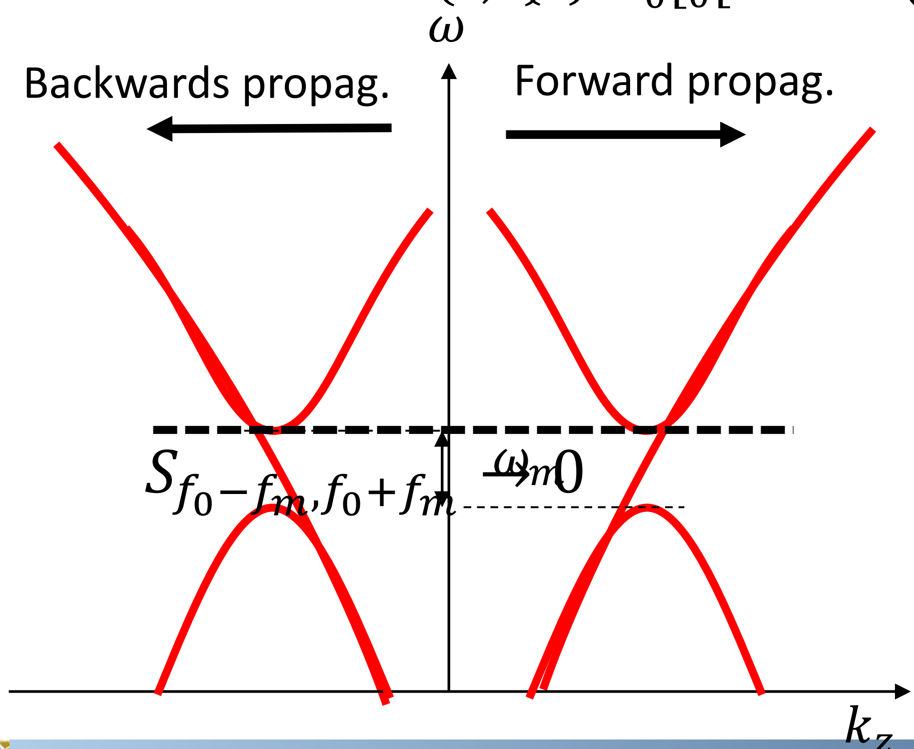
$$V_n(t) = V\cos(\omega_m t + n\phi_m) \quad \Longrightarrow \quad \sigma(z,t) \approx \sigma_0(1 + M\cos[\omega_m t - \beta_m z])$$

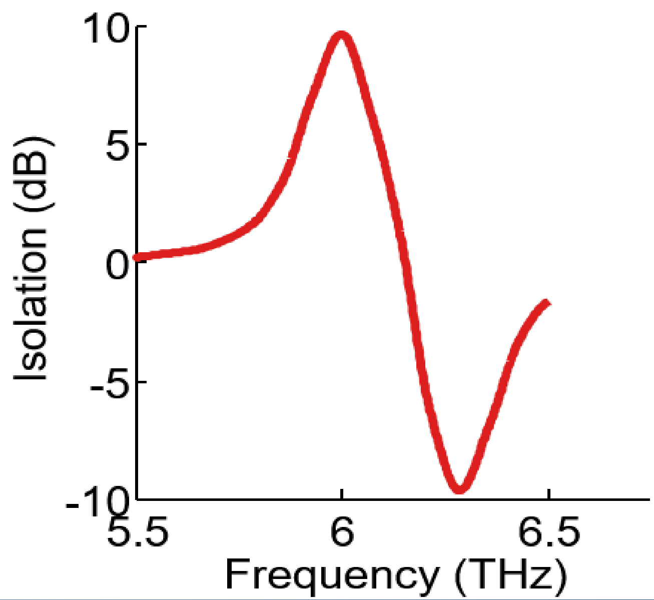
D. Correas-Serrano, J. S. Gómez-Díaz, D. Sounas, A. Alvarez-Melcon and A. Alù, "Non-reciprocal graphene devices and antennas at THz based on spatio-temporal modulation", IEEE Antennas and Wireless Propagation Letters, vol. 15, pp. 1529-1533, 2016.

- Single layer implementation



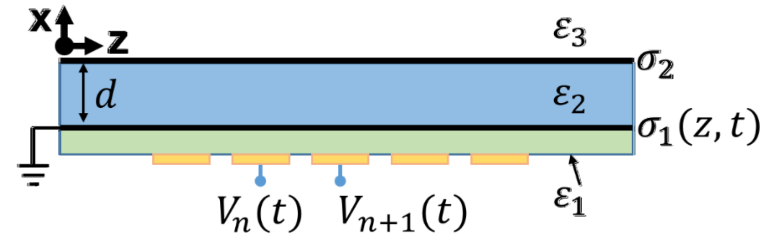
$$\sigma(z,t) = \sigma_0[1 + M\cos(\omega_m t - \beta_m z)]$$





PPW Graphene-based Isolator

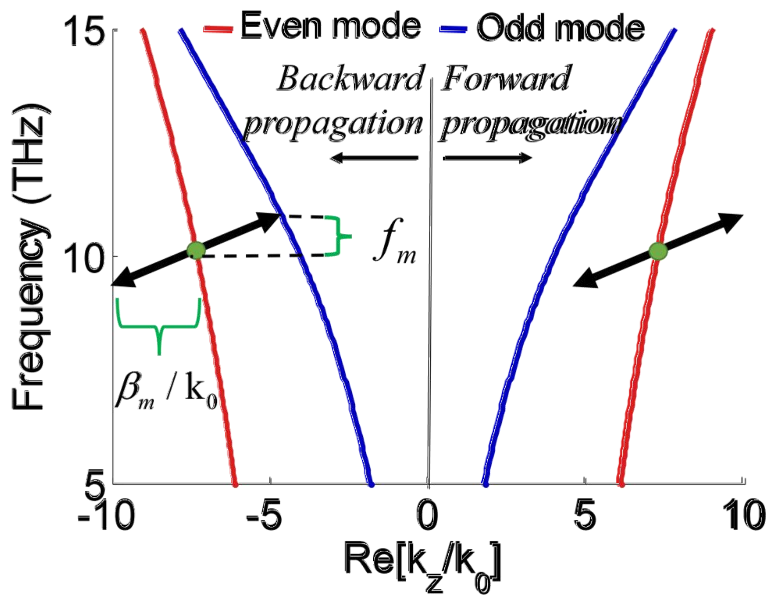
- Graphene PPW: Two orthogonal modes



- PPW + ST modulation of one layer:

$$\sigma_1(z,t) = \sigma_0(1 + M\cos[\omega_m t - \beta_m z])$$

- Isolator requirements
  - Modes are **phase-matched** @ one direction
  - Modulated length = **Coherence length** L_c



- Coupled-mode analysis

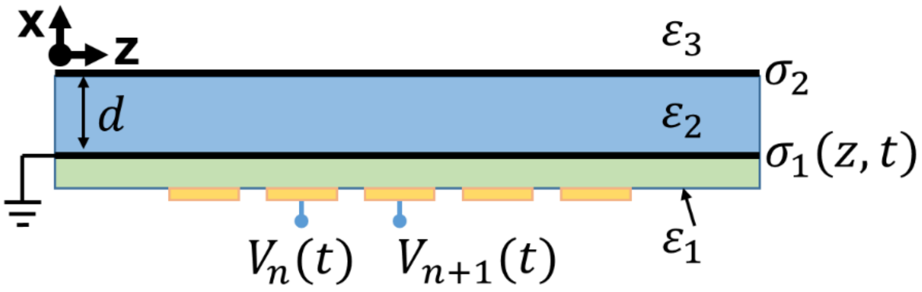
$$\frac{da_1}{dz} = -jk_{z1}a_1 + Ca_2 e^{j(k_{z1}-k_{z2}-\beta_m)z}$$
$$\frac{da_2}{dz} = -jk_{z2}a_2 + Ca_1 e^{-j(k_{z1}-k_{z2}-\beta_m)z}$$

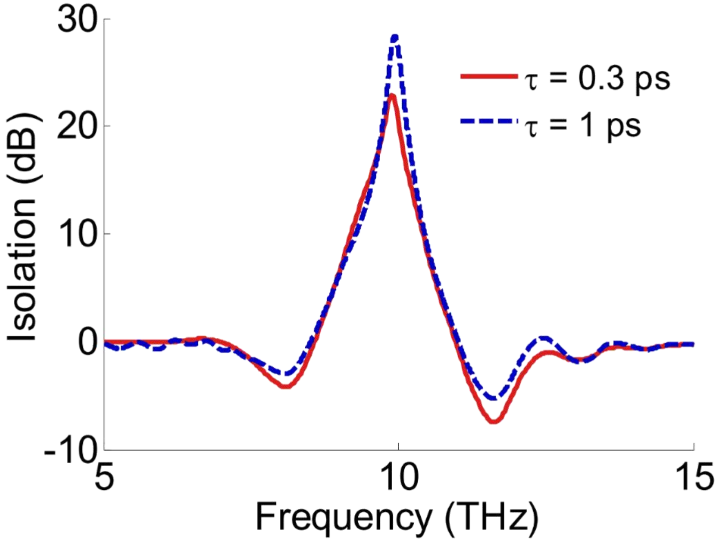
where $C = \frac{M\sigma_0}{8} E_{z1}(x_{\sigma 1})E^*_{z2}(x_{\sigma 1})$

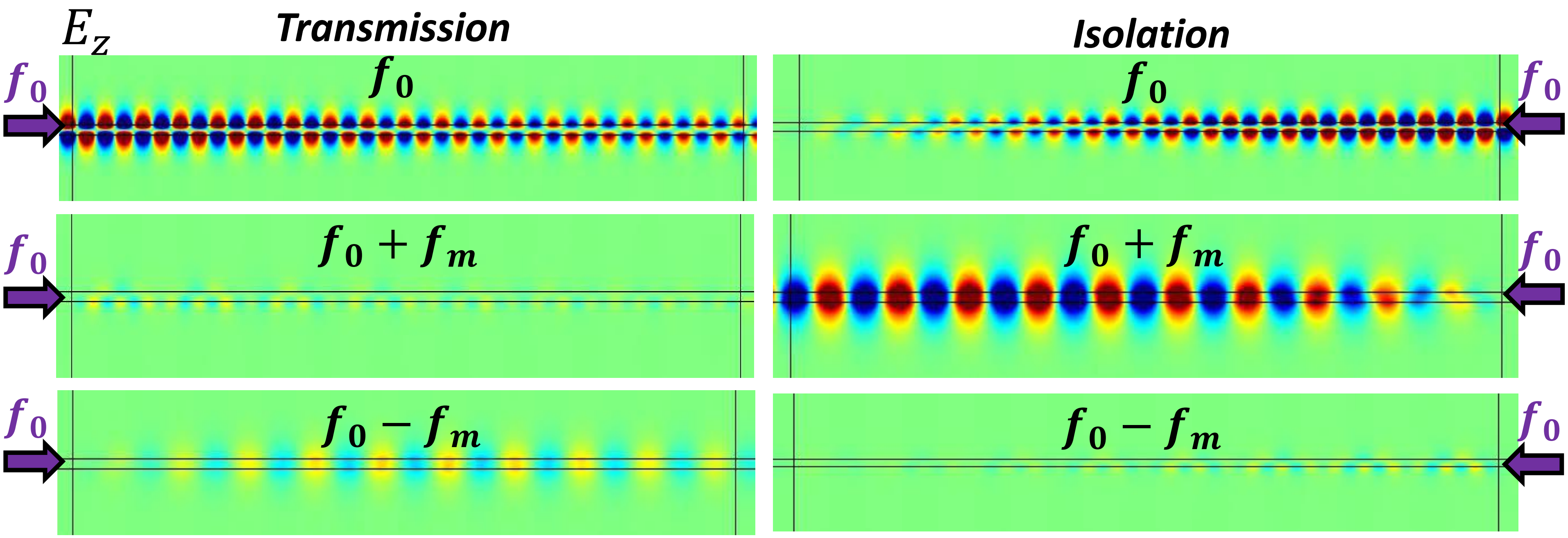
$$L_c = \pi/2|C|$$

D. Correas-Serrano, J. S. Gómez-Díaz, D. Sounas, A. Alvarez-Melcon and A. Alù, "Non-reciprocal graphene devices and antennas at THz based on spatio-temporal modulation", IEEE Antennas and Wireless Propagation Letters, vol. 15, pp. 1529-1533, 2016.

- Numerical Simulations

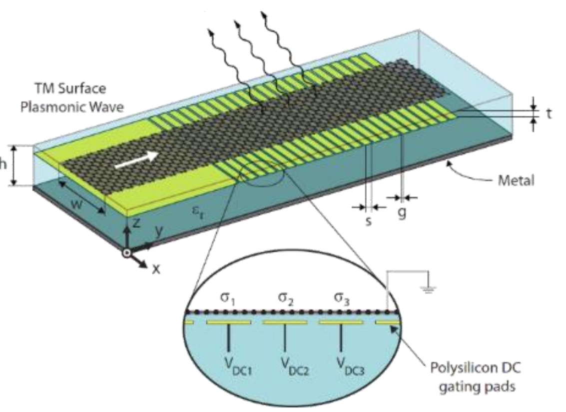


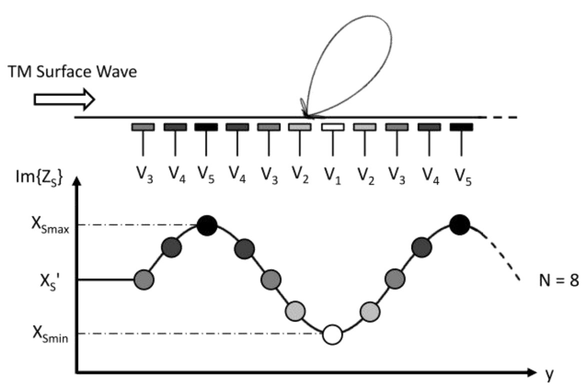




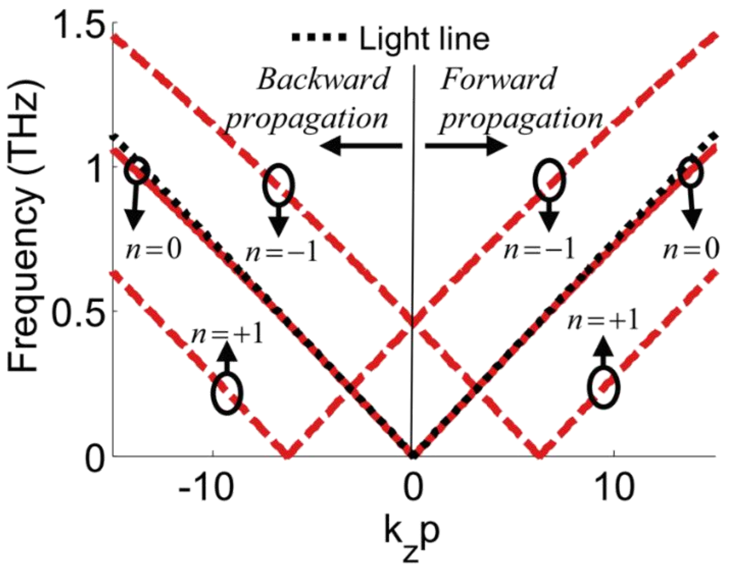
Non-Reciprocal Graphene Leaky-wave Antenna

- Sinusoidally modulated LWA

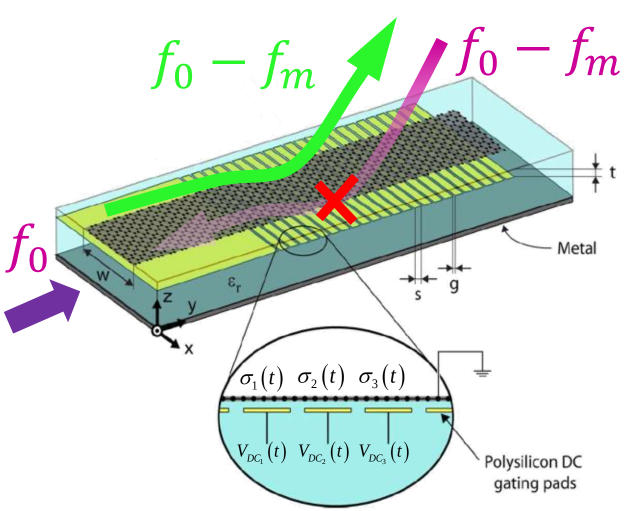


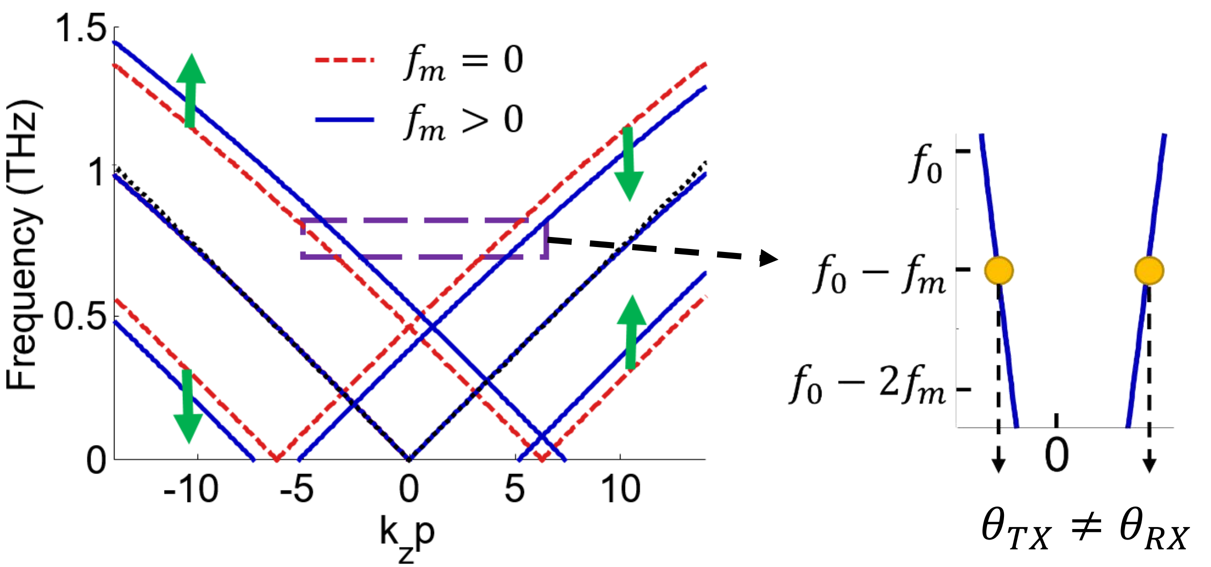


$$\sigma(z) = \sigma_0[1 + M\cos(\beta_m z)]$$



- Spatiotemporally modulated LWA

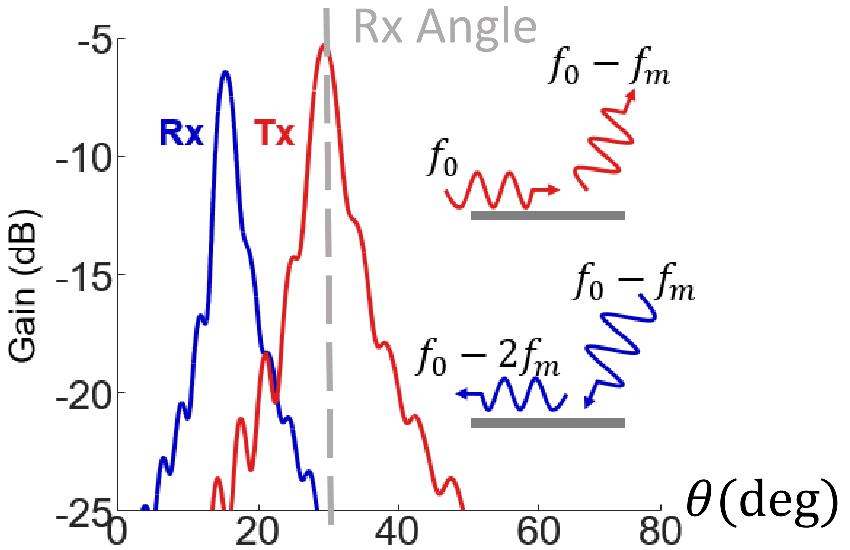


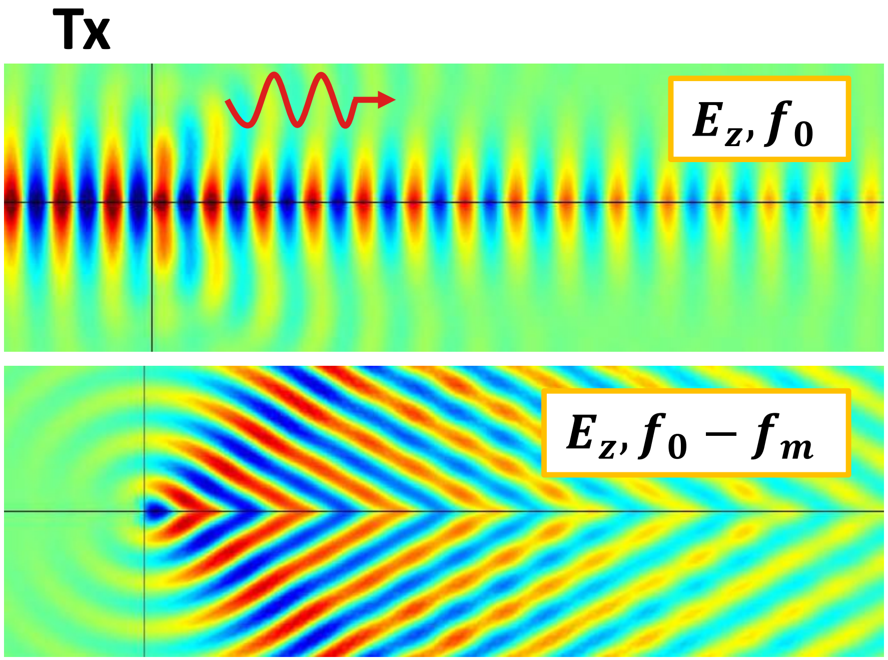


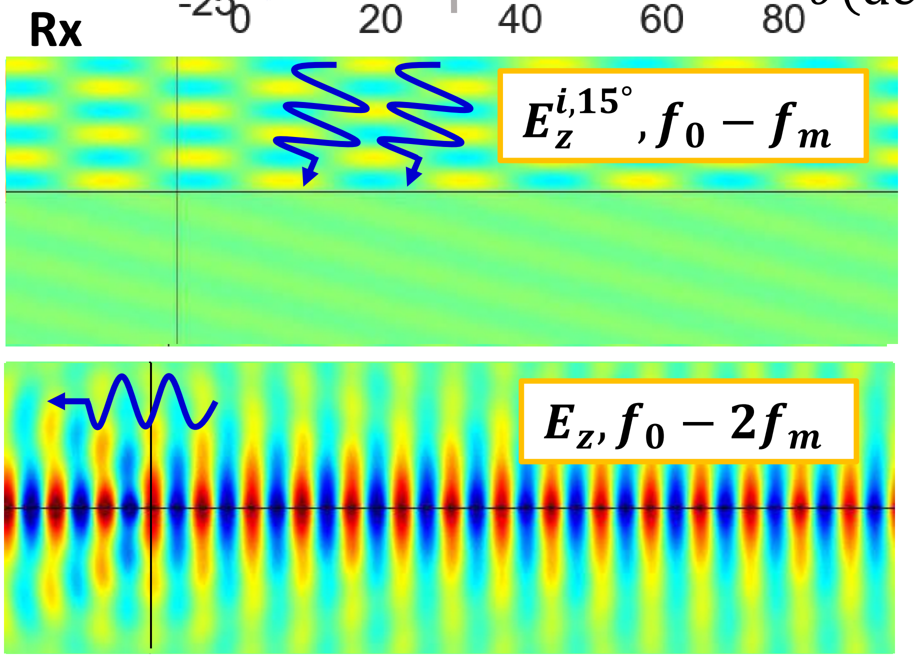
Non-Reciprocal LWA Radiation/Reception

- Non-reciprocity is two fold
  - Radiation diagram in Tx - Rx
  - Frequency conversion

D. Correas-Serrano, J. S. Gómez-Díaz, D. Sounas, A. Alvarez-Melcon and A. Alù, "Non-reciprocal graphene devices and antennas at THz based on spatio-temporal modulation", IEEE Antennas and Wireless Propagation Letters, vol. 15, pp. 1529-1533, 2016.





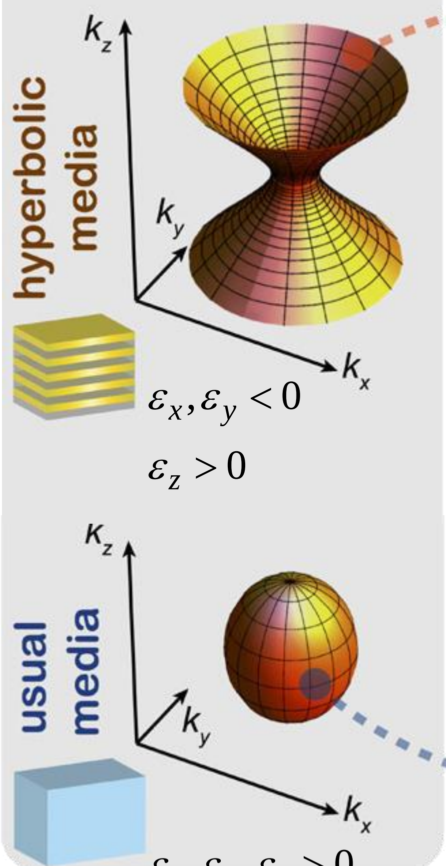


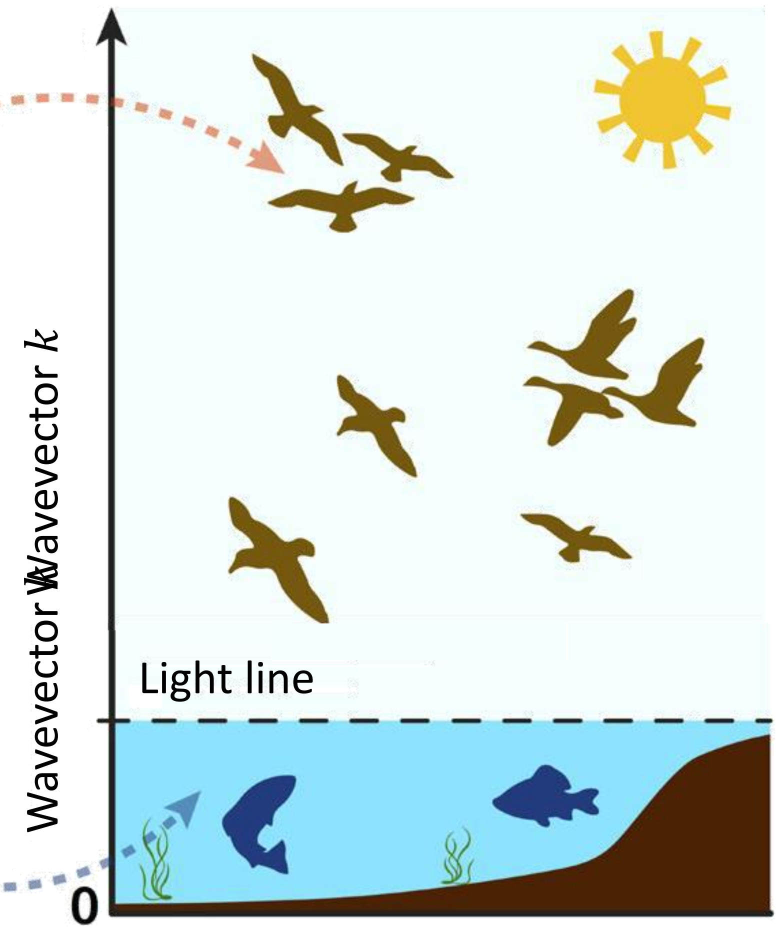
Outline

- Introduction
- Graphene plasmonics: THz devices & antennas
- Non-reciprocal metasurfaces
- Hyperbolic metasurfaces
- Non-linear metasurfaces
- Multidisciplinary
- Conclusions

Hyperbolic and Isotropic Materials

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



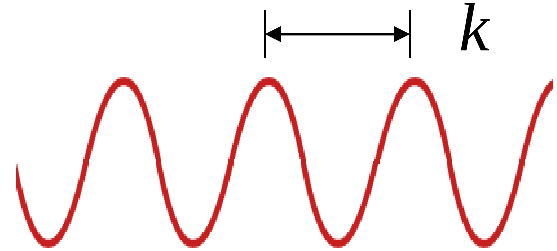


'zoo' of propagating waves

$k \to \infty$

$\lambda \to 0$

$$\lambda = \frac{2\pi}{k}$$

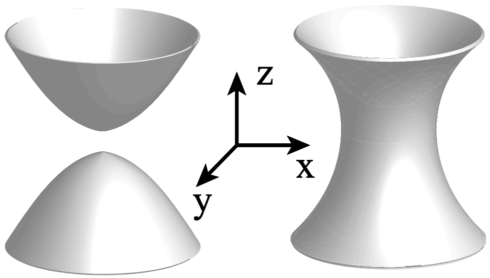


λ, k are "bounded" !

Images from Lavrinenko's group (DTU, Denmark). SPIE Newsroom. DOI: 10.1117/2.1201410.005626

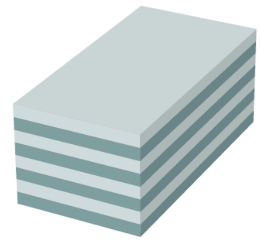
Hyperbolic Wave Propagation & Applications

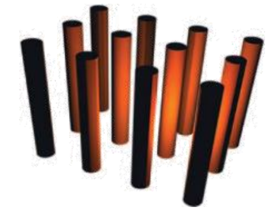
$$\pm \frac{k_\perp^{\,2}}{\varepsilon_\parallel} \mp \frac{k_\parallel^{\,2}}{|\varepsilon_\perp|} = \omega^2 / c^2$$



$\varepsilon_\perp < 0 \;\&\; \varepsilon_\parallel > 0$ $\varepsilon_\perp > 0 \;\&\; \varepsilon_\parallel < 0$

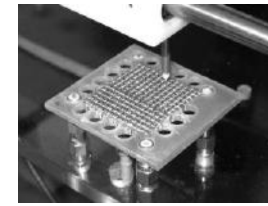
E. E. Narimanov and A. V. Kildishev Nature Photonics, 9, 214 (2015)



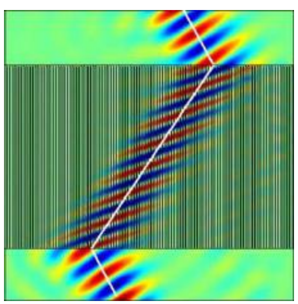


Natural and Artificial Hyperbolic media

A. Poddubny, I. Iorsh, P. Belov and Y. Kivshar Nature Photonics, **7**, 113110 (2013)

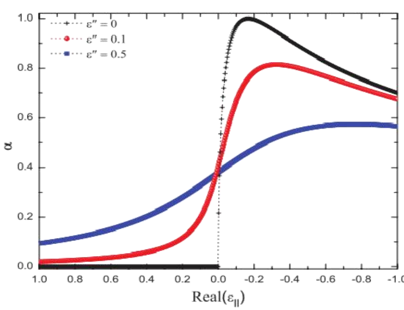


K. G. Balmain et al. IEEE TAP - AWPL 2003 – 2004



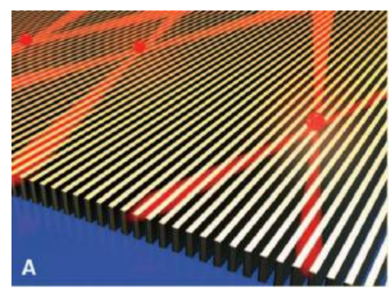
Negative refraction

A. Fang, T. Koschny, and C. M. Soukoulis, Phys. Review B, **79**, 245127, (2009)



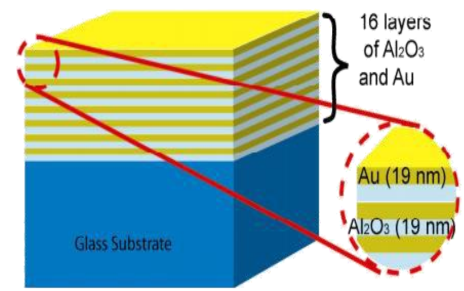
Topological transitions

H. N. S. Krishnamoorthy, Z. Jacob, E. Narimanov, I. Kretzschmar, V. M. Menon, Science , 336, (2012)



Canalization & thin structures

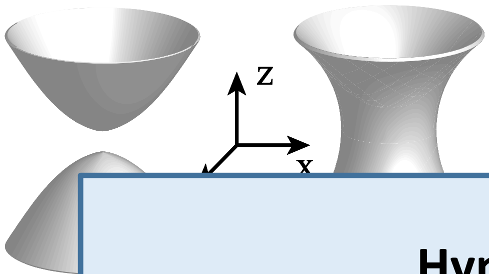
A. V. Kildishev, A. Boltasseva, V. M. Shalaev Science 339, 1232009 (2013)



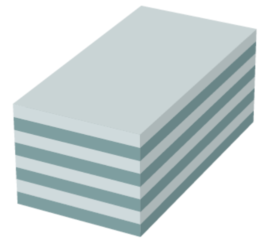
SER enhancement

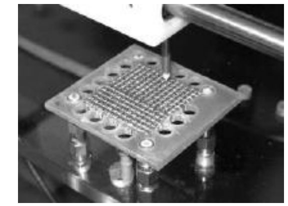
J. Kim, V. Drachev, Z. Jacob, G. V. Naik, A. Boltasseva, E. E. Narimanov, and V. M. Shalaev, Optic Express, 20, 8100, (2012)

$$\pm \frac{k_\perp^{\,2}}{\varepsilon_\parallel} \mp \frac{k_\parallel^{\,2}}{|\varepsilon_\perp|} = \omega^2 / c^2$$



$\varepsilon_\perp < 0$ &

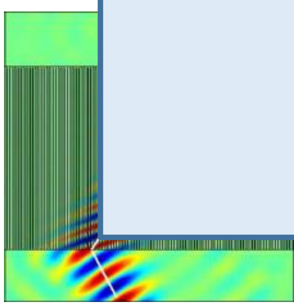




ain et al.
- AWPL
2004

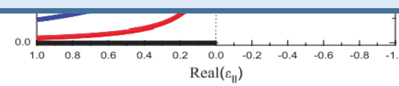
Hyperbolic Metamaterials Challenges:

→ Fabrication
→ Access to the propagating waves
→ Volumetric loss
→ Integration with other components



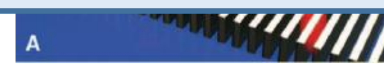
Negative refraction

A. Fang, T. Koschny, and C. M. Soukoulis, Phys. Review B, **79**, 245127, (2009)



Topological transitions

H. N. S. Krishnamoorthy, Z. Jacob, E. Narimanov, I. Kretzschmar, V. M. Menon, Science , 336, (2012)

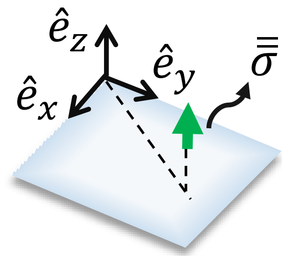


Canalization & thin structures

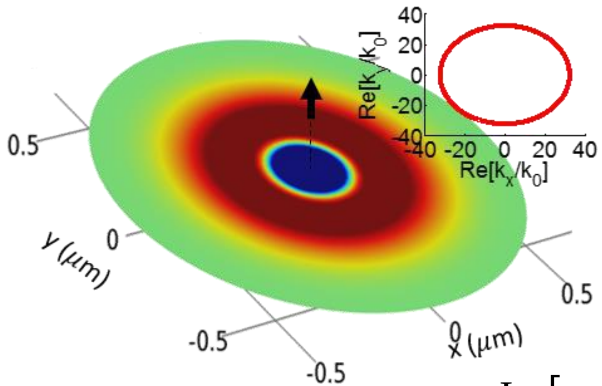
A. V. Kildishev, A. Boltasseva, V. M. Shalaev
Science 339, 1232009 (2013)

SER enhancement

J. Kim, V. Drachev, Z. Jacob, G. V. Naik, A. Boltasseva, E. E. Narimanov, and V. M. Shalaev, Optic Express, 20, 8100, (2012)



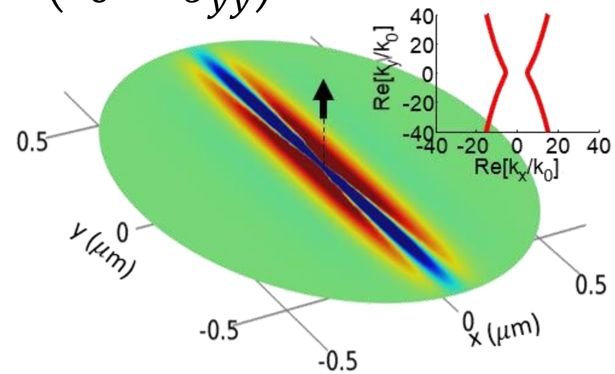
$$\bar{\bar{\sigma}} = \begin{pmatrix} \sigma_{xx} & 0 \\ 0 & \sigma_{yy} \end{pmatrix}$$



Elliptic topology

$\mathrm{Im}[\sigma_{xx}] > 0$

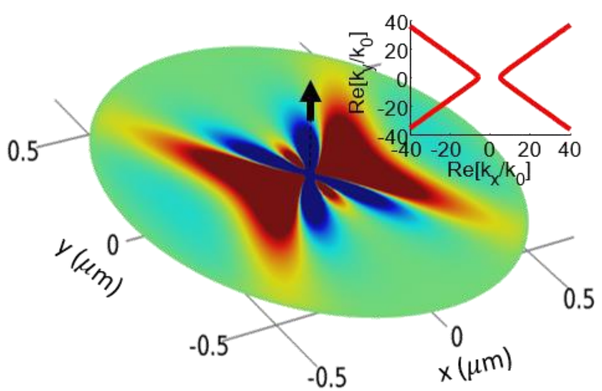
$\mathrm{Im}[\sigma_{yy}] > 0$



σ-near zero topology

$\mathrm{Im}[\sigma_{xx}] > 0$

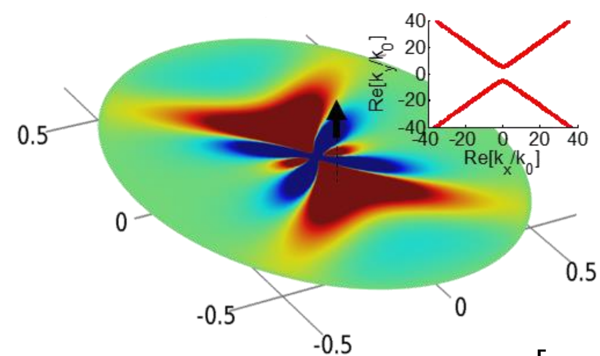
$\mathrm{Im}[\sigma_{yy}] \approx 0$



Hyperbolic topology

$\mathrm{Im}[\sigma_{xx}] < 0$

$\mathrm{Im}[\sigma_{yy}] > 0$

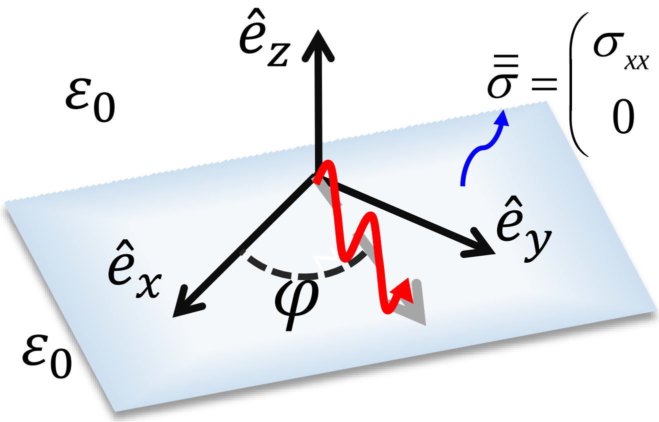


Hyperbolic topology

$\mathrm{Im}[\sigma_{xx}] > 0$

$\mathrm{Im}[\sigma_{yy}] < 0$

J. S. Gomez-Diaz, M. Tymchenko and A. Alù, Physical Review Letters , vol. 114, pp. 233901, 2015



$$\bar{\bar{\sigma}} = \begin{pmatrix} \sigma_{xx} & 0 \\ 0 & \sigma_{yy} \end{pmatrix}$$

TM mode:

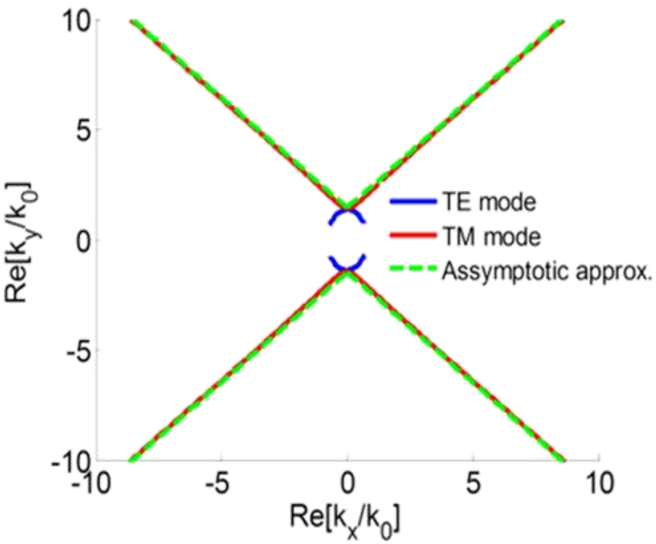
$$\eta_0^2\left(k_x^2\sigma_{xx}+k_y^2\sigma_{yy}\right)^2\left(k_x^2+k_y^2-k_0^2\right)-4k_0^2\left(k_x^2+k_y^2\right)^2=0$$

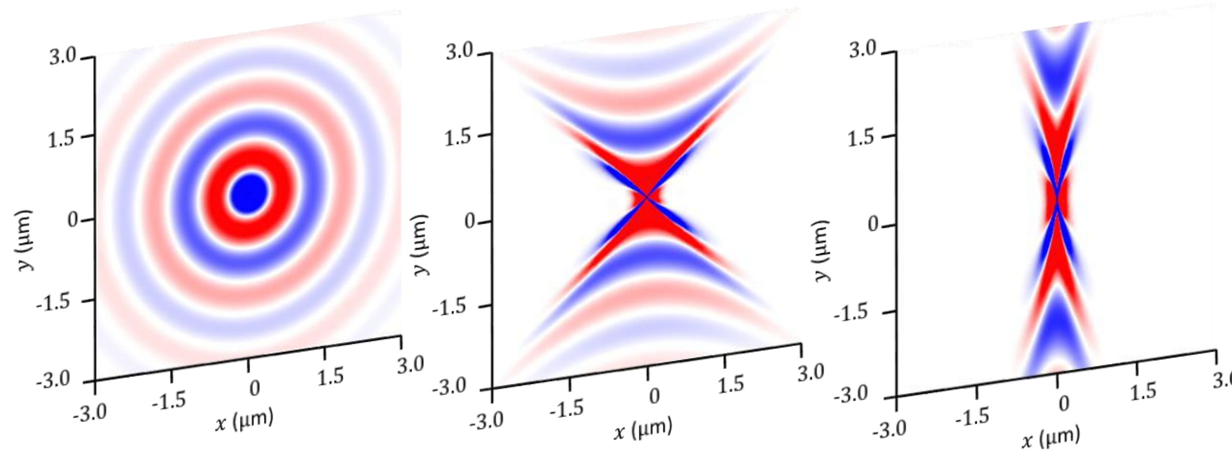
$$k_y \approx \pm m k_x \pm b \qquad m=\sqrt{-\frac{\sigma_{xx}}{\sigma_{yy}}} \qquad b=k_0\sqrt{1+\left(\frac{2}{\eta_0\sigma_{yy}}\right)^2}$$

TE mode:

$$4\left(k_x^2+k_y^2\right)^2\left(k_x^2+k_y^2-k_0^2\right)-k_0^2\eta_0^2\left(k_y^2\sigma_{xx}+k_x^2\sigma_{yy}\right)^2=0$$

TM mode - Example



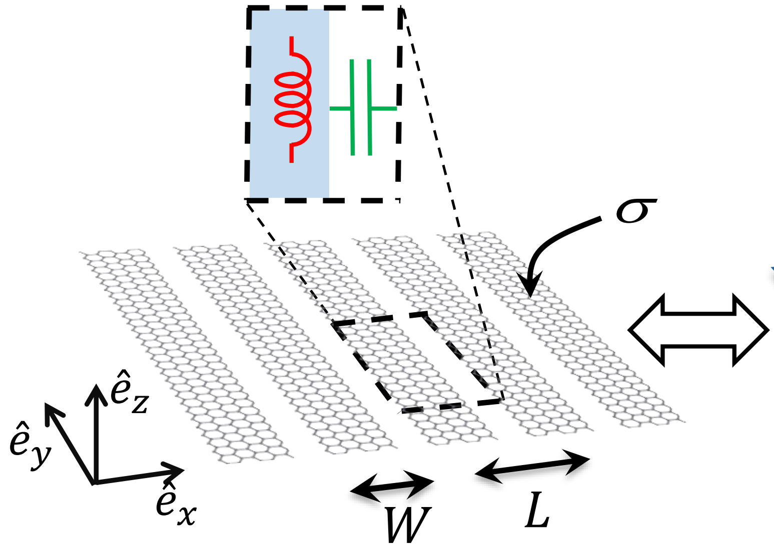


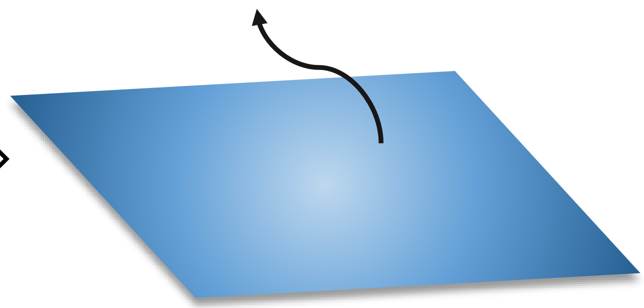
$\mathrm{Im}\left[\sigma_{xx}\right]=-i3.0mS$ | $\mathrm{Im}\left[\sigma_{xx}\right]=i0.1mS$ | $\mathrm{Im}\left[\sigma_{xx}\right]=i0.1mS$

$\mathrm{Im}\left[\sigma_{yy}\right]=i3.0mS$ | $\mathrm{Im}\left[\sigma_{yy}\right]=-i5.0mS$ | $\mathrm{Im}\left[\sigma_{yy}\right]=-i5.0mS$

H. J. Bilow, IEEE TAP 51, 2788, 2003. [2] A. M. Patel and A. Grbic, IEEE TAP. 61, 211, 2013
R. Quarfoth, and D. Sievenpiper, IEEE TAP, vol. 61, 3597, 2013
J. S. Gomez-Diaz, M. Tymchenko and A. Alù, Physical Review Letters , vol. 114, pp. 233901, 2015

Practical Implementation of Hyperbolic MTSs





$$\bar{\bar{\sigma}}^{eff} = \begin{pmatrix} \sigma_{xx}^{eff} & 0 \\ 0 & \sigma_{yy}^{eff} \end{pmatrix}$$

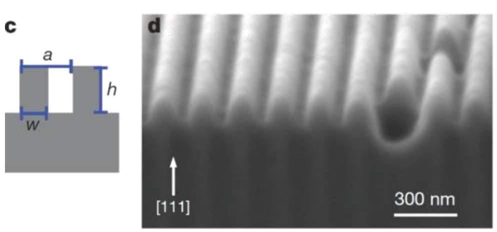
$$\sigma_{yy}^{eff} = \sigma \frac{W}{L}$$

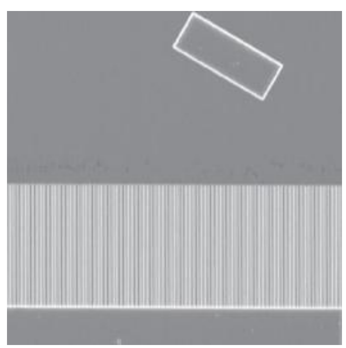
$$\sigma_{xx}^{eff} = \frac{L\sigma\sigma_C}{W\sigma_C + G\sigma}$$

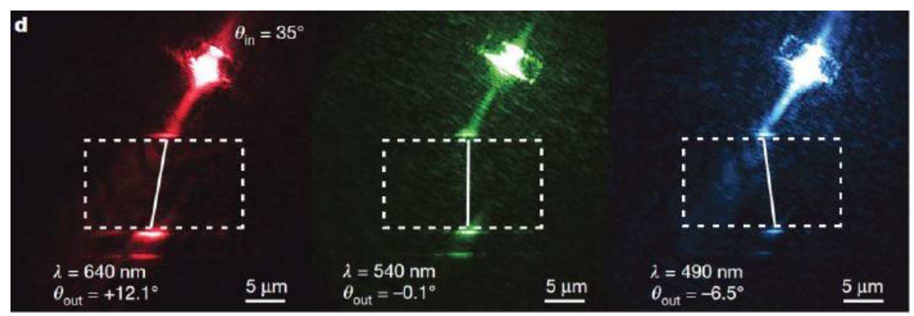
$$\sigma_C = -i\frac{\omega\varepsilon_0 L}{\pi}\ln\left[\csc\left(\frac{\pi G}{2L}\right)\right]$$

J. S. Gomez-Diaz, M. Tymchenko and A. Alù, Physical Review Letters , vol. 114, pp. 233901, 2015

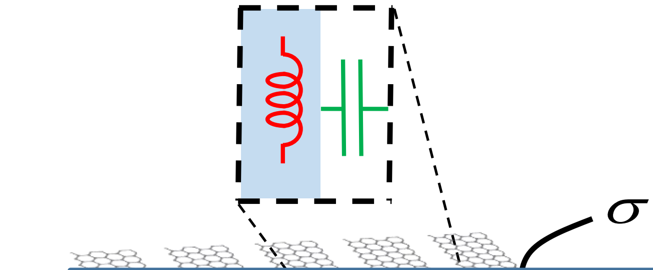
❑ Experimental verification @ optics







A. A. High, R. C. Devlin, A. Dibos, M. Polking, D. S. Wild, J. Perczel, N. P. de Leon, M. D. Lukin, and H. Park, **Nature**, vol. 522, pp. 192-196, 2015



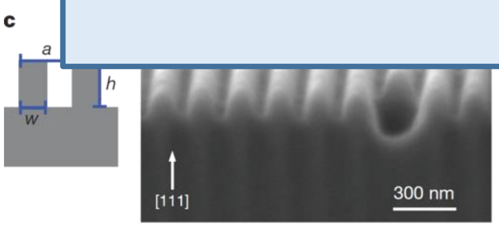
$$\bar{\bar{\sigma}}^{eff} = \begin{pmatrix} \sigma_{xx}^{eff} & 0 \\ 0 & \sigma_{yy}^{eff} \end{pmatrix}$$

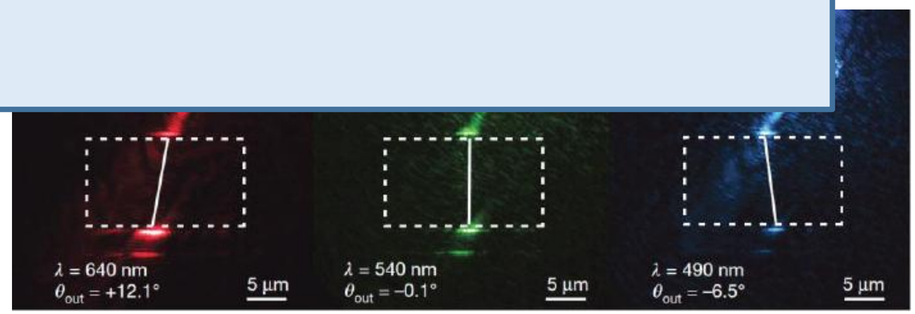
$$\sigma_{yy}^{eff} = \sigma \frac{W}{L}$$

J. S.

Graphene-based Hyperbolic Metasurfaces Benefits:

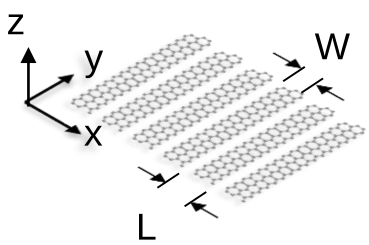
→ Easy fabrication (lithography)
→ Easy access/extraction of energy
→ Reduced loss
→ Compatible with integrated circuits / optoelectronic components
→ Tunable



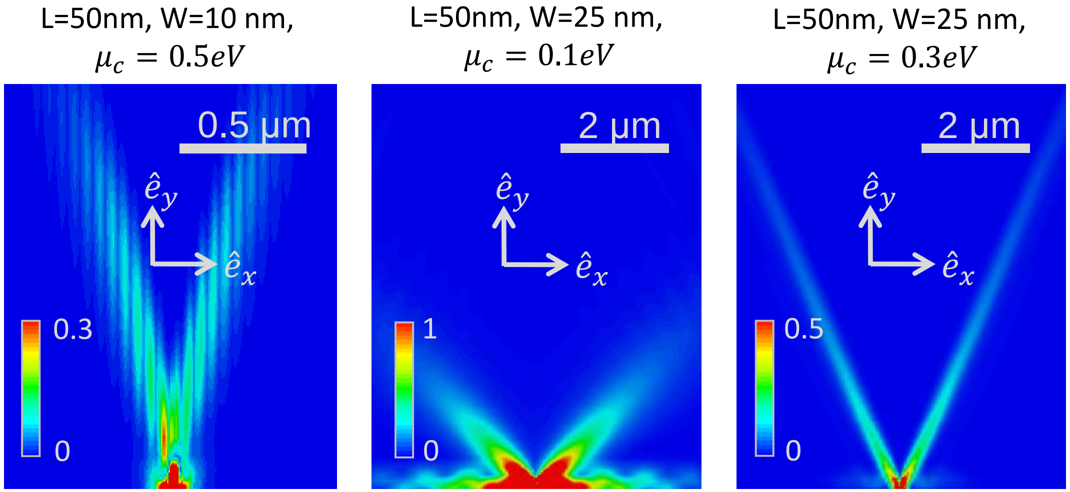


A. A. High, R. C. Devlin, A. Dibos, M. Polking, D. S. Wild, J. Perczel, N. P. de Leon, M. D. Lukin, and H. Park, **Nature**, vol. 522, pp. 192-196, 2015

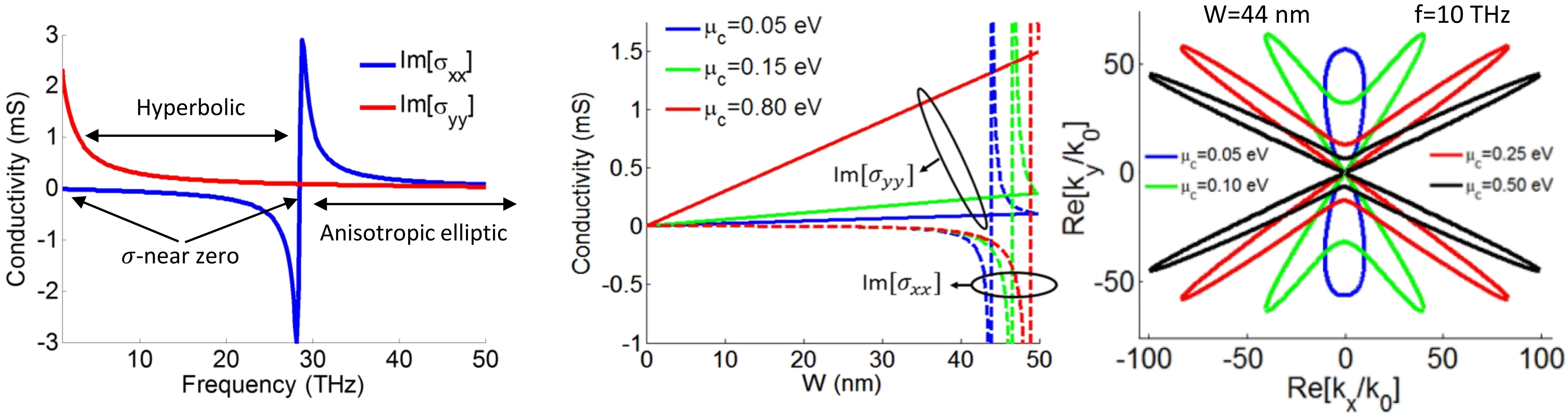
❑ Surface Plasmons @ THz



f= 5 THz

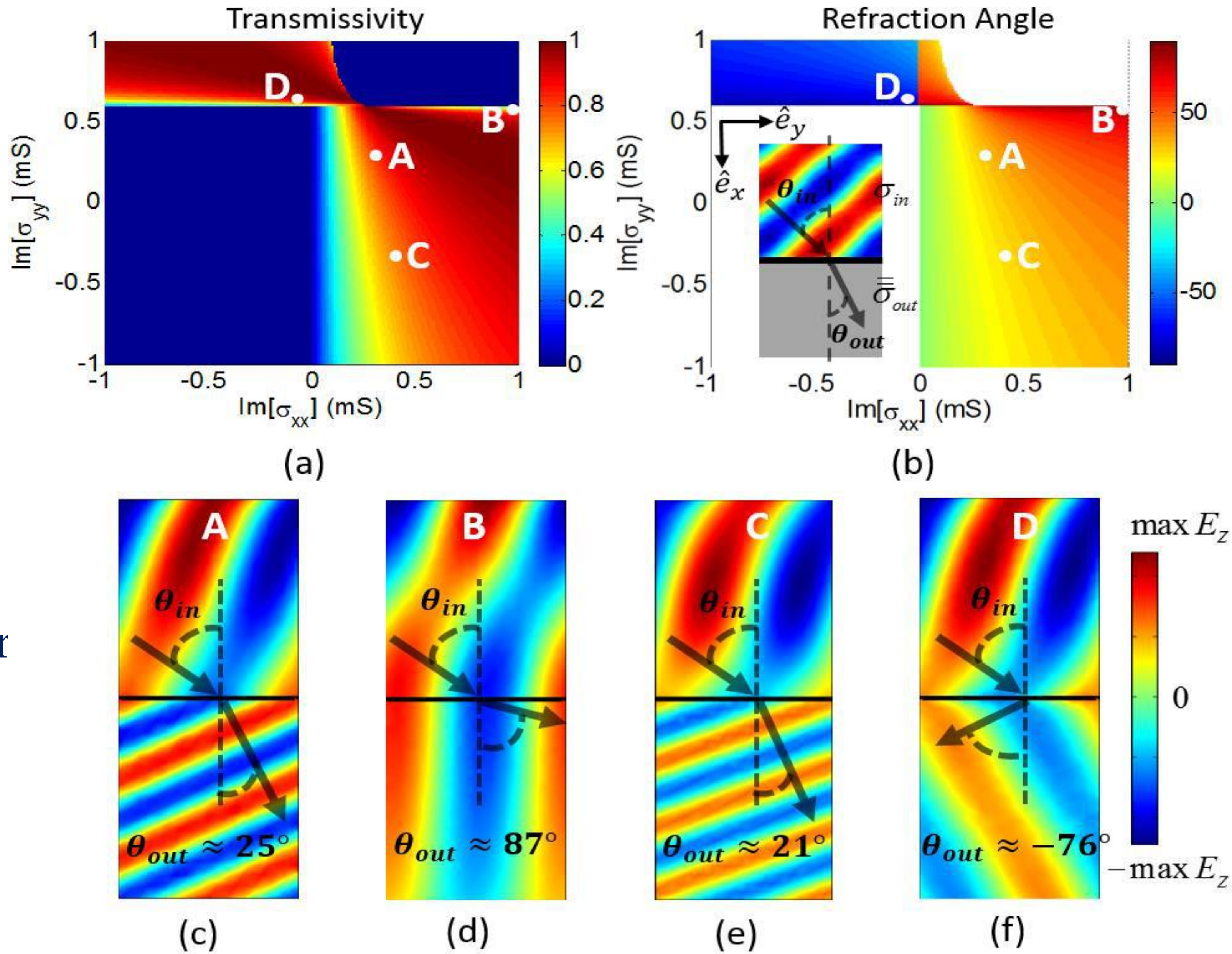


❑ Electrical reconfigurability



J. S. Gomez-Diaz, M. Tymchenko and A. Alù, Physical Review Letters , vol. 114, pp. 233901, 2015

Negative Refraction of SPPs



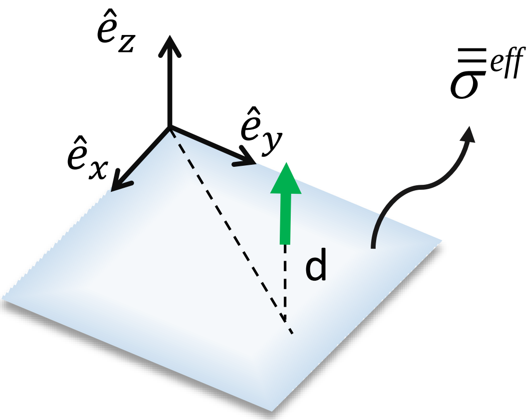
- Tr

Spontaneous Emission Rate (SER) of emitters

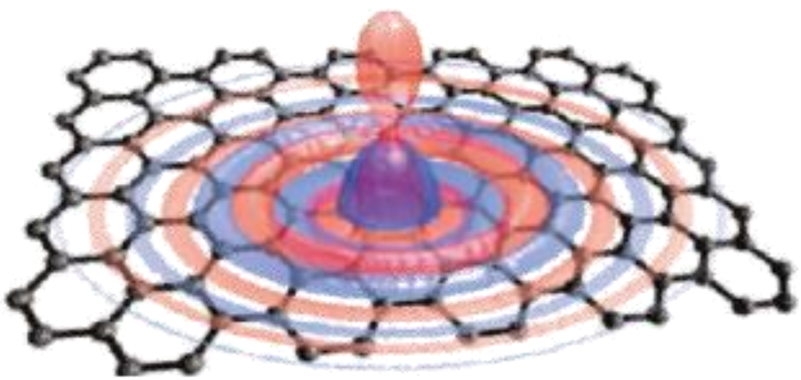
- Large enhancement expected from analogy with bulk HMTM
- Dedicated Green's function approach

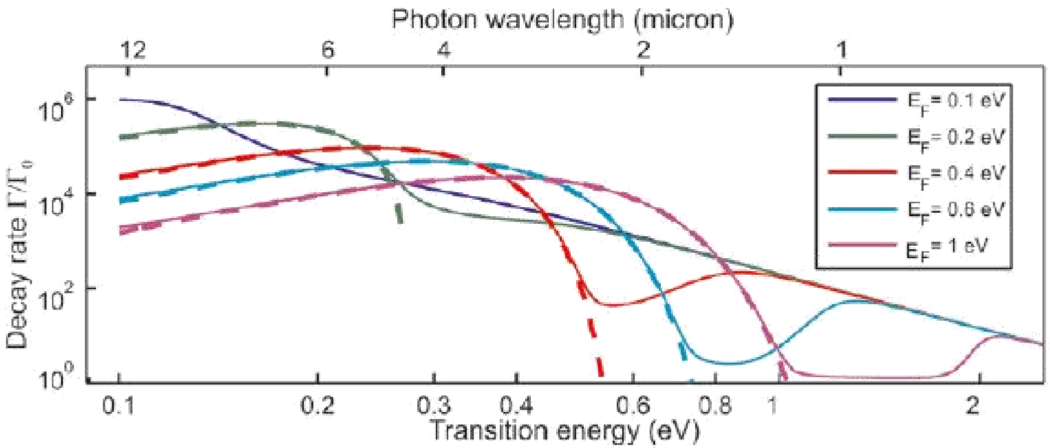
$$SER = \frac{P}{P_0} = 1 + \frac{6\pi}{|\vec{\mu}_p| k_0} \vec{\mu}_p \cdot \mathrm{Im}\left[\bar{\bar{G}}_S(\vec{r}_0, \vec{r}_0, \omega) \right] \cdot \vec{\mu}_p$$

$$\bar{\bar{G}}_S(\vec{r}_0, \vec{r}_0, \omega) = \frac{i}{8\pi^2} \int_{-\infty}^{\infty} \int_{-\infty}^{\infty} \left(\Gamma_{ss} \bar{\bar{M}}_{ss} + \Gamma_{sp} \bar{\bar{M}}_{sp} + \Gamma_{ps} \bar{\bar{M}}_{ps} + \Gamma_{pp} \bar{\bar{M}}_{pp} \right) e^{i2k_z z_0} dk_x dk_y$$



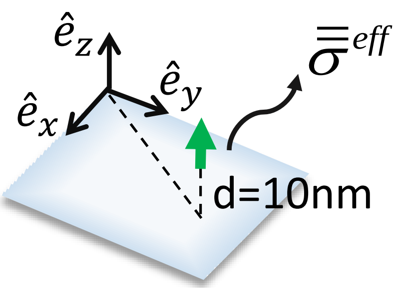
SER in graphene

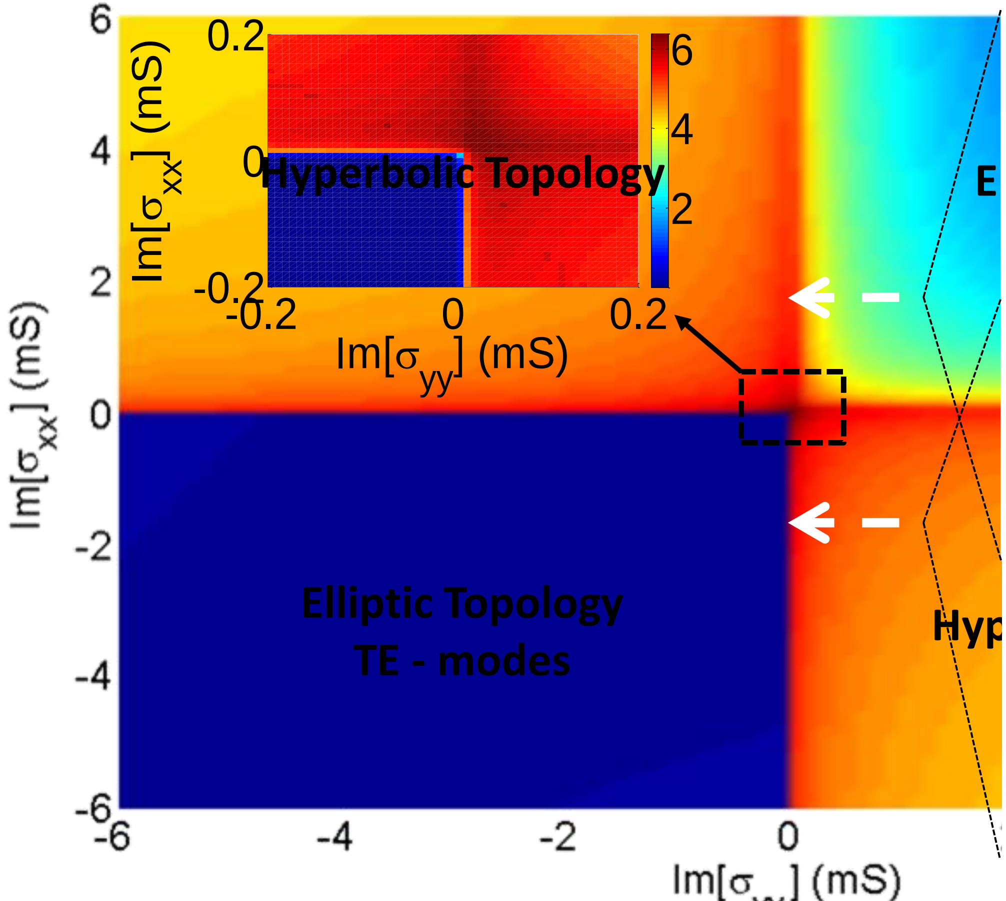


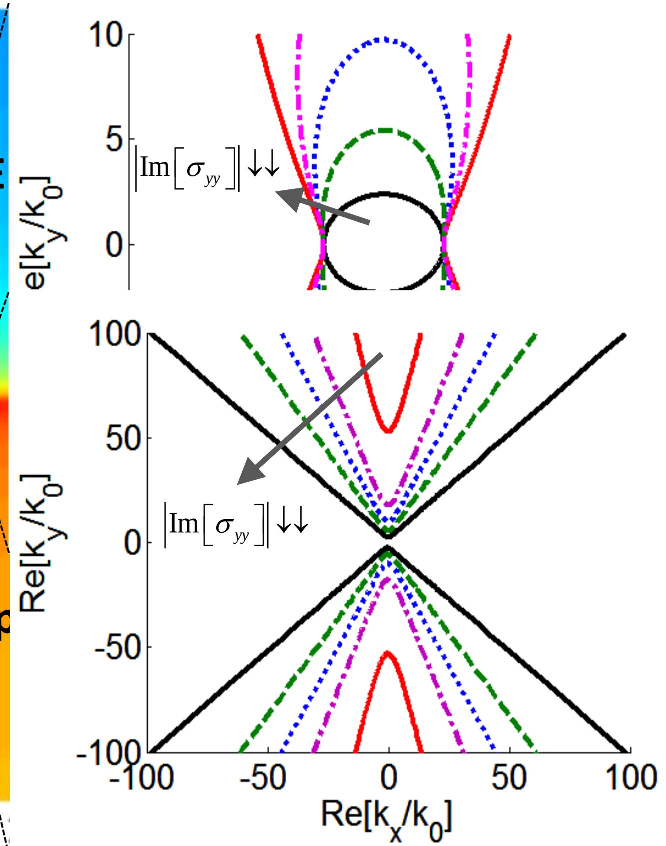


F. H. L. Koppens, D. E. Chang, and F. García de Abajo, Nanoletters, vol. 11, pp. 3370-3377, 2011

- SER of a z-oriented dipole over a uniaxial metasurface
  - Topological transitions
  - Dramatic SER enhancement



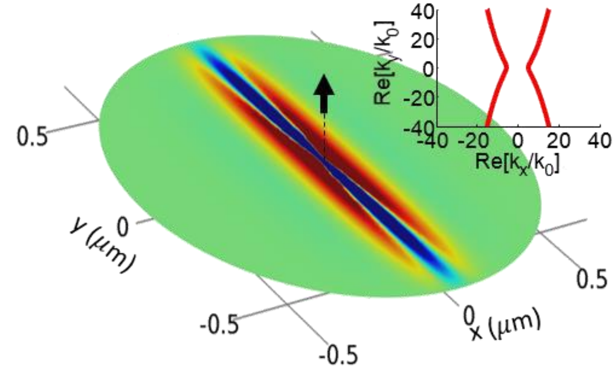




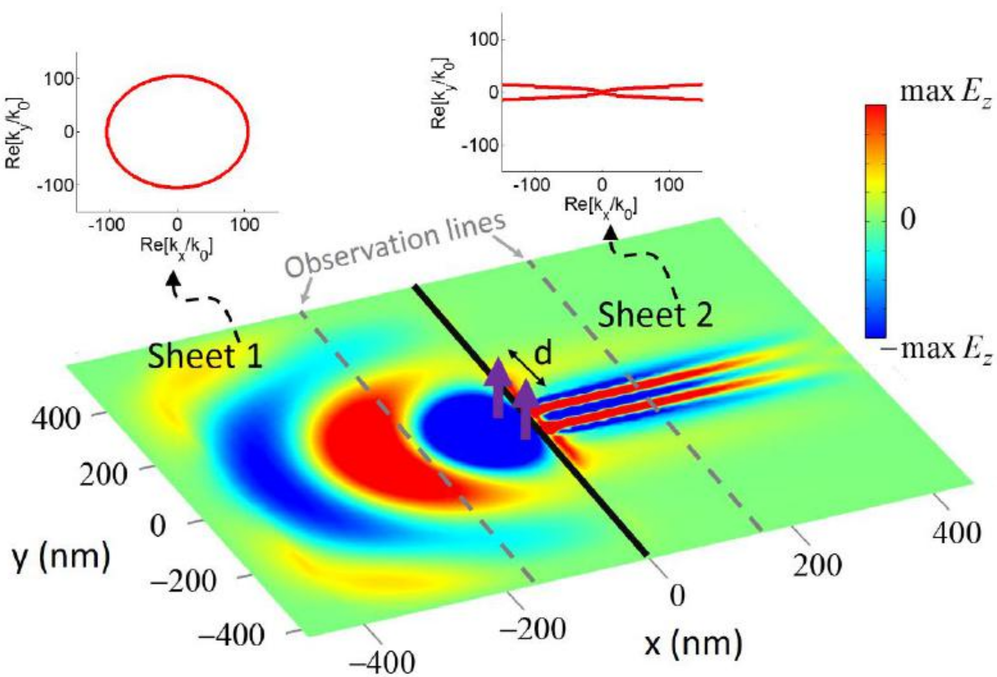
J. S. Gomez-Diaz, M. Tymchenko and A. Alù, Physical Review Letters , vol. 114, pp. 233901, 2015

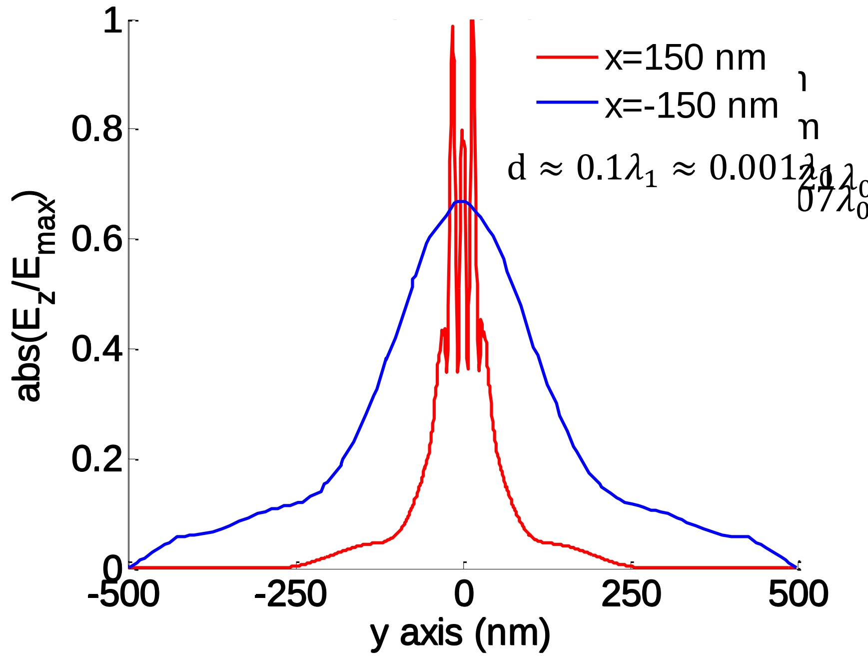
- Canalization over a surface
    - LDOS/SER enhancement
    - σ near-zero topology

$$\mathrm{Im}\left[\sigma_{xx}\right] > 0$$
$$\mathrm{Im}\left[\sigma_{yy}\right] \approx 0$$



- Application: Hyperlensing

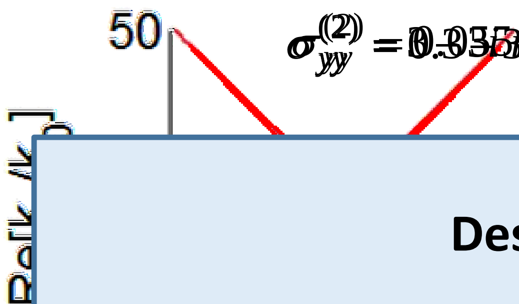


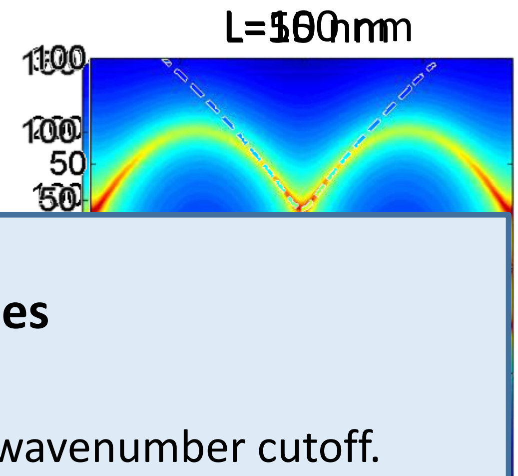


J. S. Gomez-Diaz and A. Alù, ACS Photonics, 2016

Practical Limitations

- ❑ Losses $\sigma_{xx}^{(2)} = 0.035i\ mS$ $\sigma_{yy}^{(2)} = -3i\ mS$
- ❑ Periodicity



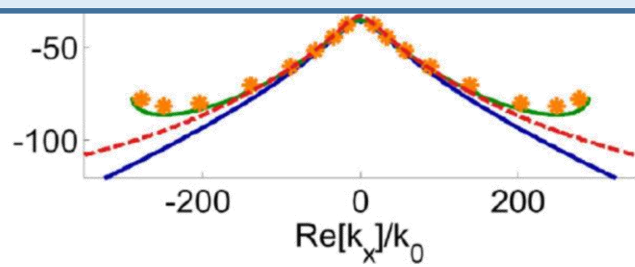


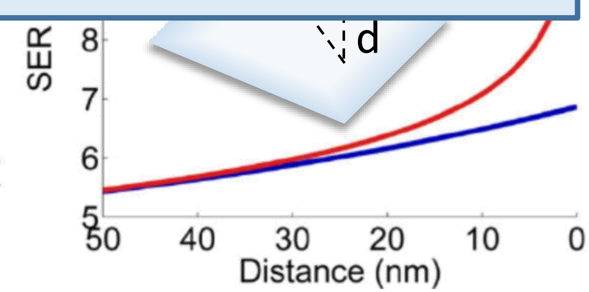
Design of Practical Hyperbolic Metasurfaces

$$L < \frac{\pi}{(c/v_f)k_0} \Rightarrow$$ Nonlocality dominates and imposes a wavenumber cutoff. Periodicity can be increased → Easier fabrication !

$$L \geq \frac{\pi}{(c/v_f)k_0} \Rightarrow$$ Periodicity dominates and imposes a wavenumber cutoff.

- Wavenumber cutoff

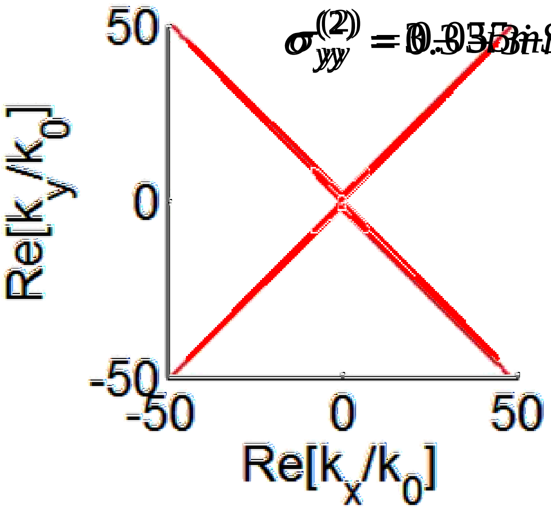




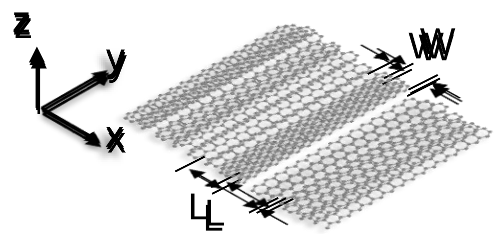
J. S. Gomez-Diaz, M. Tymchenko and A. Alù, Optic Express, vol. 5, 2313-2329, 2015
D. Correas-Serrano, J. S. Gomez-Diaz, M. Tymchenko and A. Alù, Optic Material Express, vol. 23, 29434-29448, 2015

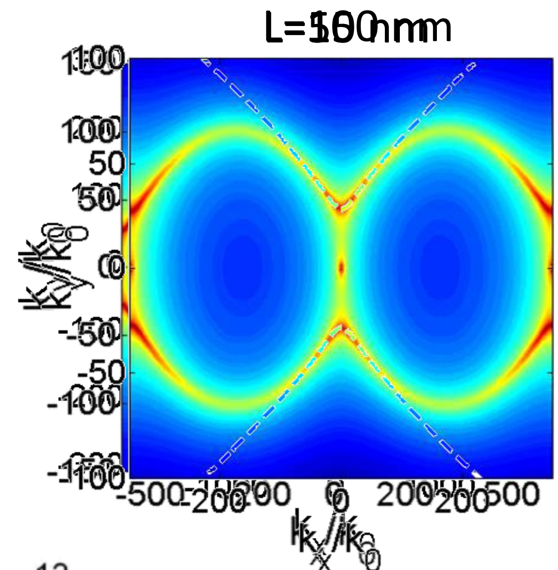
- Losses $\sigma_{xx}^{(2)} = 0.35i\,mS$, $\sigma_{yy}^{(2)} = -3i\,mS$

$\sigma_{yy}^{(2)} = 0.35i\,mS$

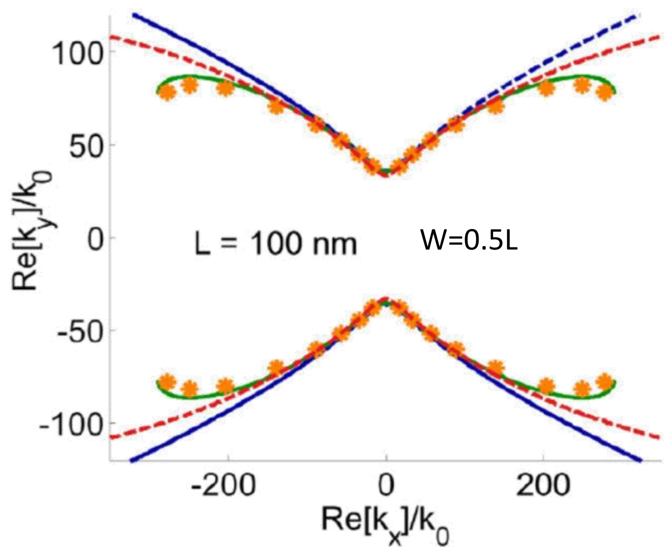


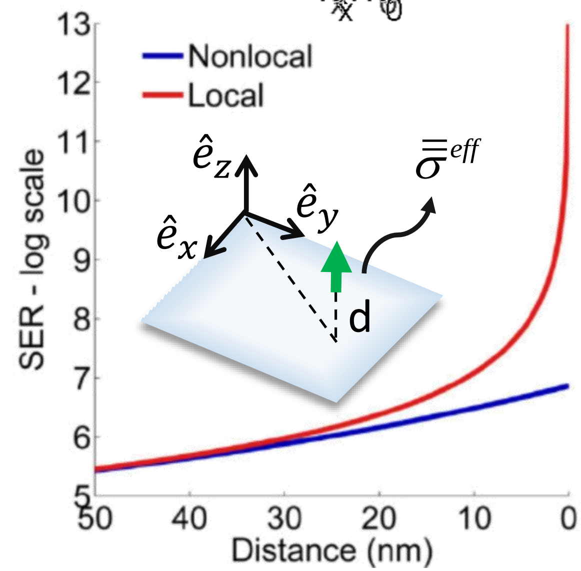
- Periodicity





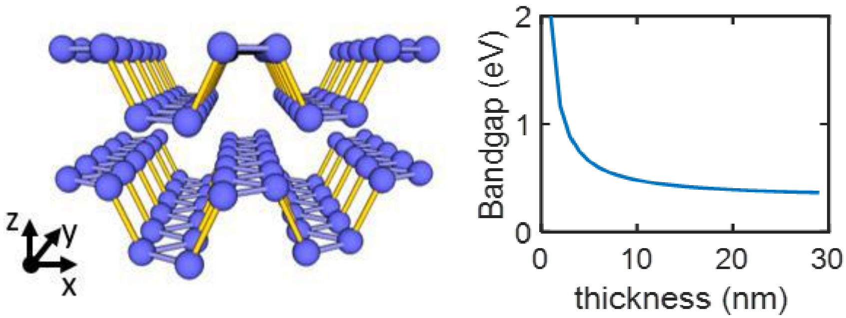
- Nonlocality
  - Limited Fermi velocity
  - Wavenumber cutoff



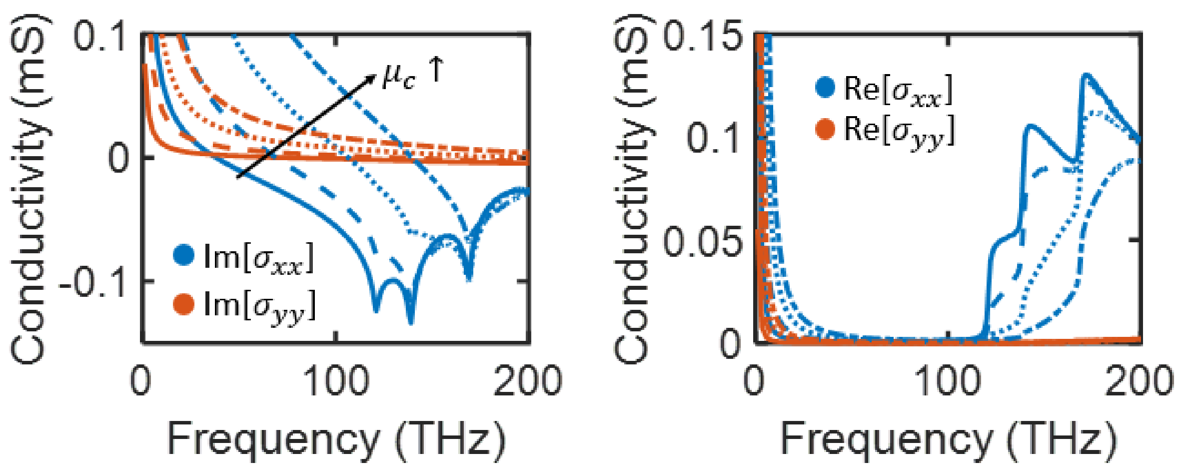


J. S. Gomez-Diaz, M. Tymchenko and A. Alù, Optic Express, vol. 5, 2313-2329, 2015
D. Correas-Serrano, J. S. Gomez-Diaz, M. Tymchenko and A. Alù, Optic Material Express, vol. 23, 29434-29448, 2015

- Black Phosphorus
  - Thickness down to few nm
  - Variable bandgap
  - Anisotropic & plasmonic material



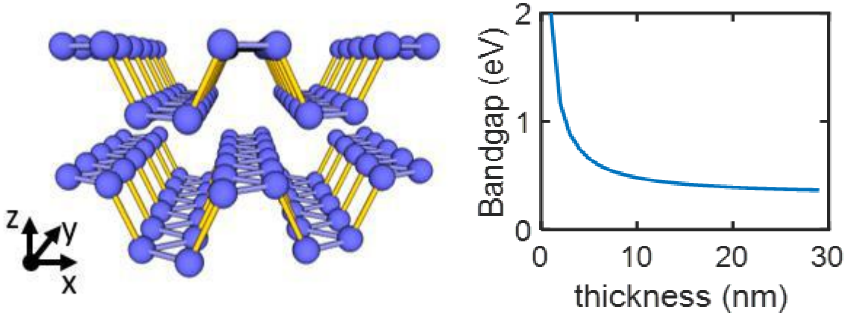
- Hyperbolic response ?
  - Local response (q→0)



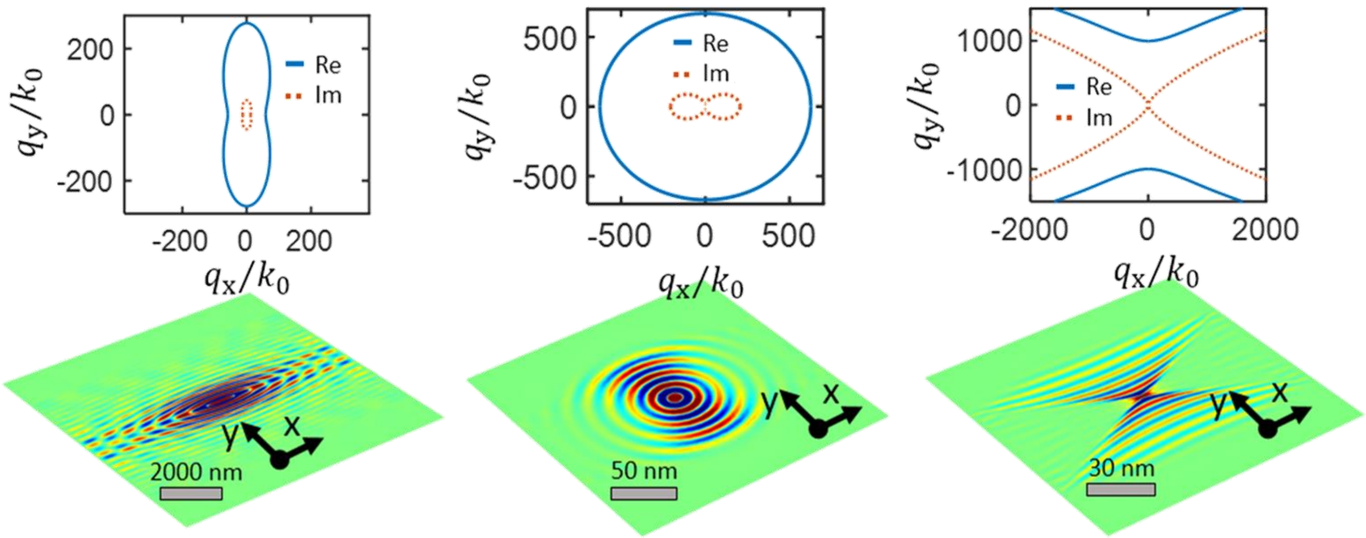
D. Correas-Serrano, J. S. Gomez-Diaz, A. Alvarez Melcon, and A. Alù, "Black Phosphorus Plasmonics: From Anisotropic Elliptical Regimes to Nonlocality-Induced Canalization", Journal of Optics, 2016.

2D Natural Hyperbolic Materials

- Black Phosphorus
  - Thickness down to few nm
  - Variable bandgap
  - Anisotropic & plasmonic material

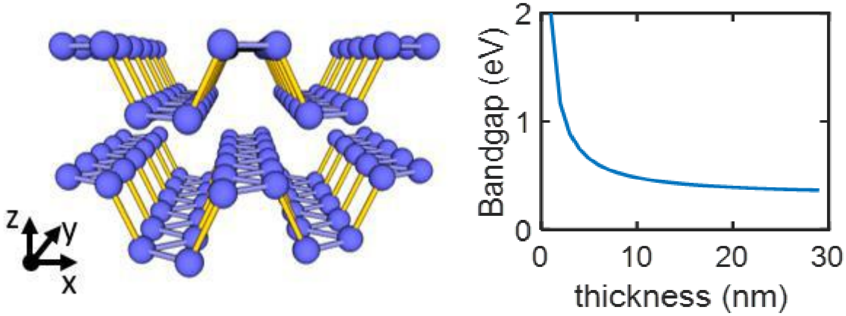


- Hyperbolic response ?
  - Local response (q→0)

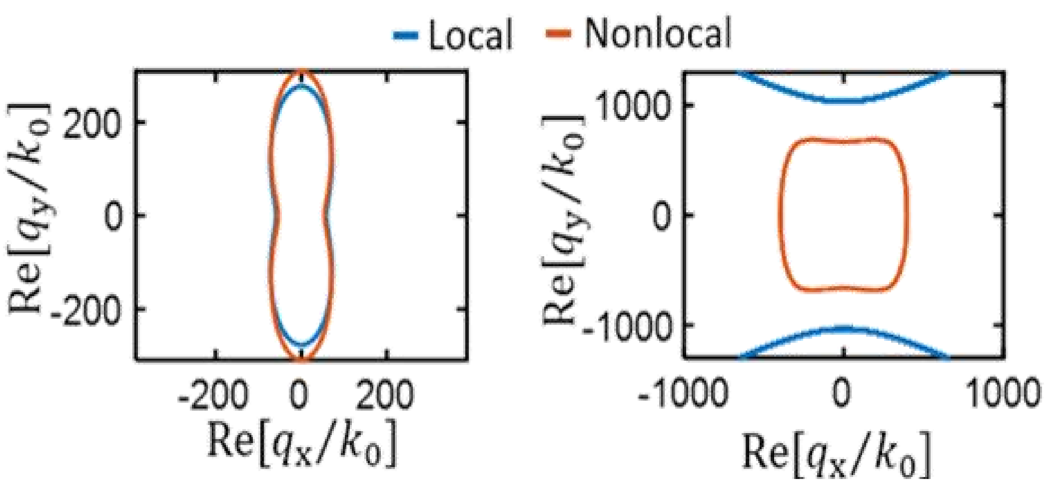


D. Correas-Serrano, J. S. Gomez-Diaz, A. Alvarez Melcon, and A. Alù, "Black Phosphorus Plasmonics: From Anisotropic Elliptical Regimes to Nonlocality-Induced Canalization", Journal of Optics, 2016.

- Black Phosphorus
  - Thickness down to few nm
  - Variable bandgap
  - Anisotropic & plasmonic material



- Hyperbolic response ?
  - Local response (q→0)
  - Nonlocality induces a wideband canalization regime

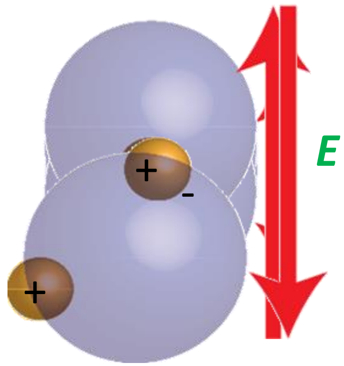


D. Correas-Serrano, J. S. Gomez-Diaz, A. Alvarez Melcon, and A. Alù, "Black Phosphorus Plasmonics: From Anisotropic Elliptical Regimes to Nonlocality-Induced Canalization", Journal of Optics, 2016.

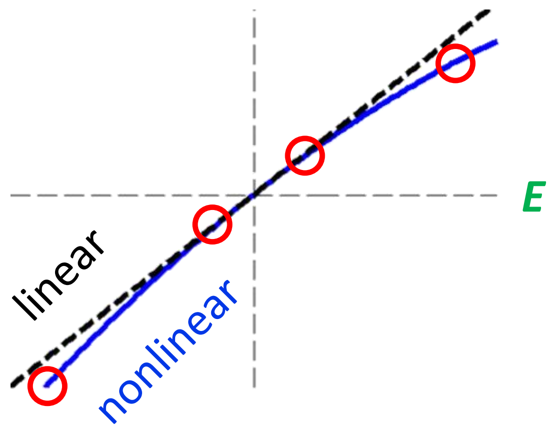
Outline

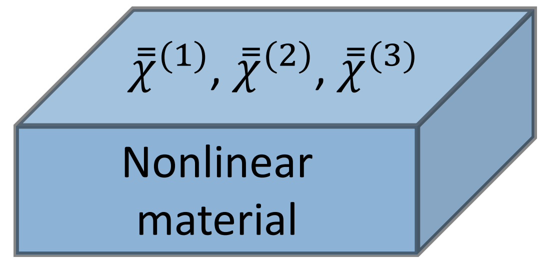
- Introduction
- Graphene plasmonics: THz devices & antennas
- Non-reciprocal metasurfaces
- Hyperbolic metasurfaces
- Non-linear metasurfaces
- Multidisciplinary
- Conclusions

Non-linear Responses



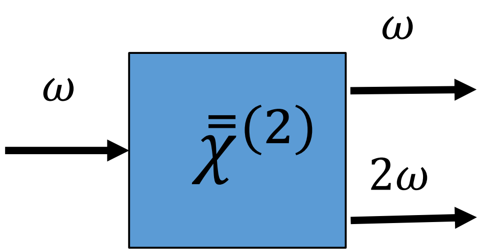
Dipole moment – Hooke's law



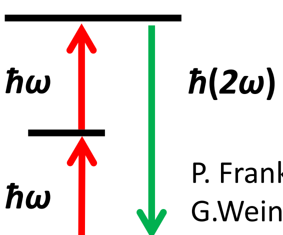


$$\frac{\boldsymbol{P}}{\epsilon_0} = \chi^{(1)}\boldsymbol{E} + \bar{\bar{\chi}}^{(2)}\boldsymbol{E}\boldsymbol{E} + \bar{\bar{\chi}}^{(3)}\boldsymbol{E}\boldsymbol{E}\boldsymbol{E} + \cdots$$

Linear   Nonlinear



Second Harmonic Generation (SHG)



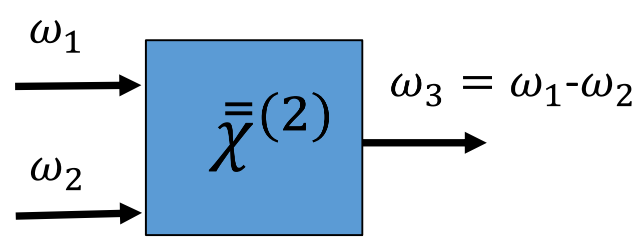
P. Franken, A. Hill, C. Peters, and G.Weinreich, Phys. Rev. Lett. **7**, 118 (1961)

Pros:

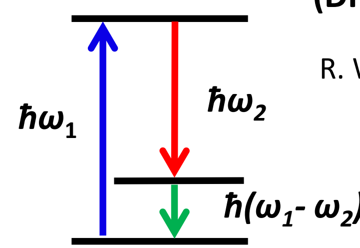
- Ultrafast response
- Coherent process

Challenges:

- Relatively *large incident intensities*
- *Weak intrinsic response*: Crystals, Metals, Diodes, Ferroelectrics, MQWs



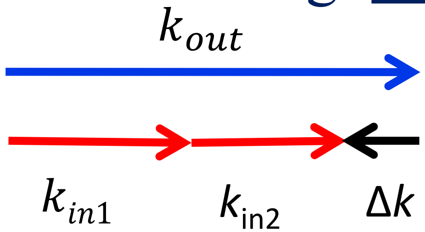
Differential Frequency Generation (DFG)



R. W. Boyd, 'Nonlinear Optics', Academic, 2008

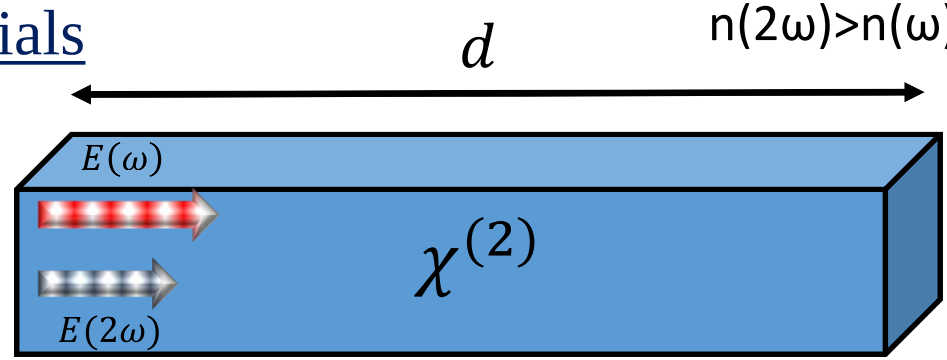
Enhancing Non-linear Responses (I)

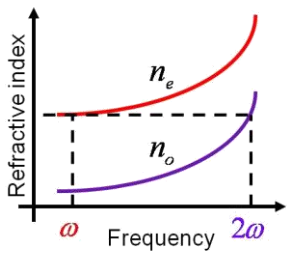
- Phase matching: Bulk materials



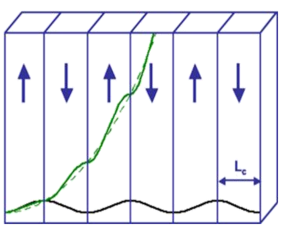
$$\vec{k}_{in1} + \vec{k}_{in2} = \vec{k}_{out}$$

n(2ω)>n(ω) !!

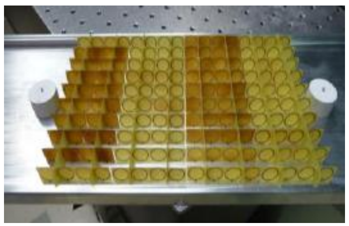




Birefringence

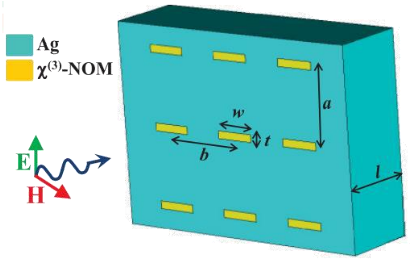


Periodically pooled material

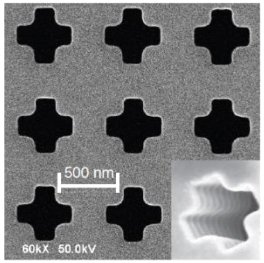


$n(\omega) = -n(2\omega)$

A. Rose, et al, PRL, 2011.



ENZ response
C. Argyropoulos,*et al*, PRB, 2012



ENZ response
Suckowski *et al*, *Science*, 2013

$$\chi^{(2)}_{eff} \approx 1 - 100 pm/V$$

$$\eta \equiv \frac{I_{2\omega}}{I_{\omega}} \propto \left(\frac{d}{\lambda_{2\omega}}\right)^2 \left|\chi^{(2)}_{eff} E_{\omega}\right|^2 \Longrightarrow \eta \uparrow\uparrow$$

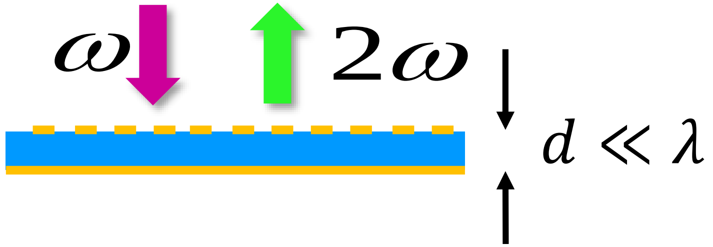
$d \uparrow\uparrow$ Bulky/heavy structures

$E_{\omega} \uparrow\uparrow$ Material damage threshold

❑ Phase matching: Ultrathin Metasurfaces (SHG)

- Relaxed conditions: in-plane

$$\vec{k}_{in1} + \vec{k}_{in2} = \vec{k}_{out}$$



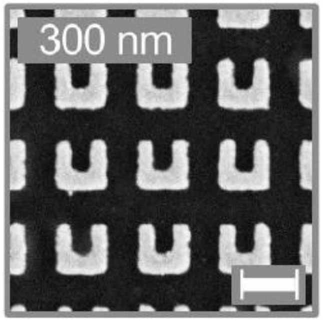
- Conversion efficiency

$$\eta \equiv \frac{I_{2\omega}}{I_\omega} \propto \left(\frac{d}{\lambda_{2\omega}}\right)^2 \left|\chi_{eff}^{(2)} E_\omega\right|^2$$

Typical non-linear materials

$$\left|\chi_{eff}^{(2)} E_\omega\right| \square 1 \Rightarrow \chi_{eff}^{(2)} \approx 10\ pm/V \Rightarrow I_\omega \approx 1\ PW/cm^2$$

Standard nonlinear metasurfaces: $\left|\chi_{eff}^{(2)} E_\omega\right| \square 1$



Linden *et al*, *PRL*, 2012


@ 57 MW/cm^2

nature COMMUNICATIONS

ARTICLE

Received 5 Aug 2013 | Accepted 3 Dec 2013 | Published 8 Jan 2014 DOI: 10.1038/ncomms4055

Broadband terahertz generation from metamaterials

Liang Luo[1], Ioannis Chatzakis[1,†], Jigang Wang[1], Fabian B.P. Niesler[2], Martin Wegener[2], Thomas Koschny[1] & Costas M. Soukoulis[1,3]


nature materials LETTERS

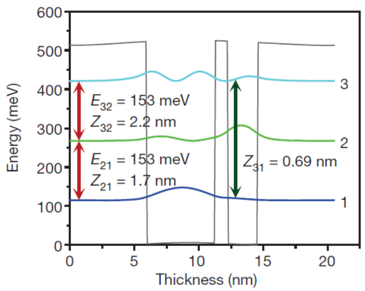
PUBLISHED ONLINE: 9 FEBRUARY 2015 | DOI: 10.1038/NMAT4214

Predicting nonlinear properties of metamaterials from the linear response

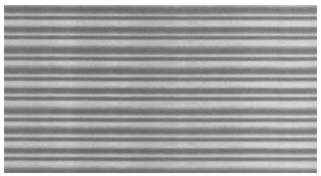
Kevin O'Brien[1†], Haim Suchowski[1,2†], Junsuk Rho[1,2], Alessandro Salandrino[1], Boubacar Kante[1], Xiaobo Yin[1,2] and Xiang Zhang[1,2,3*]

Combining Two Worlds

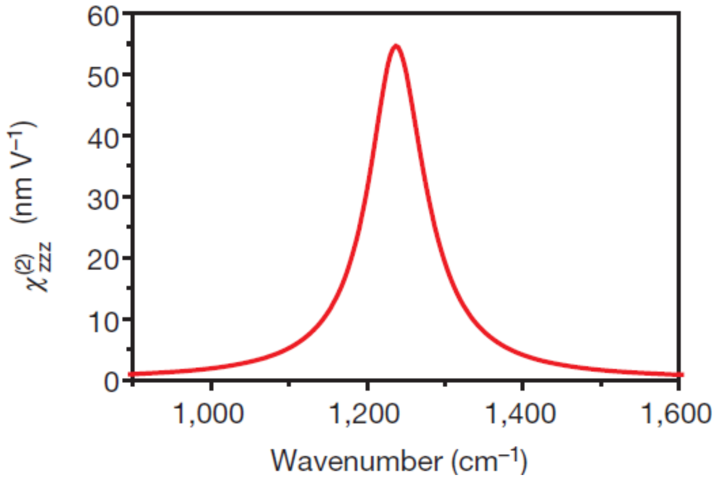
❑ Huge intrinsic NL response from MQWs



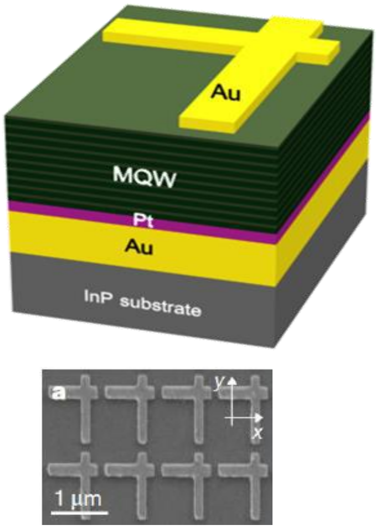
$In_{0.53}Ga_{0.47}As/Al_{0.48}In_{0.52}As$



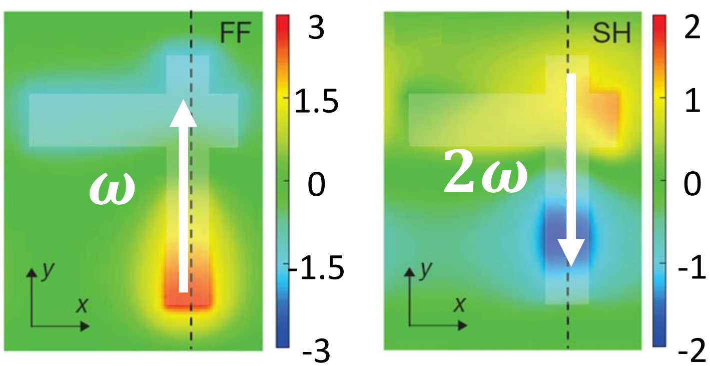
$$\bar{\bar{\chi}}^{(2)} = \chi^{(2)}_{zzz}\hat{e}_z\hat{e}_z\hat{e}_z$$

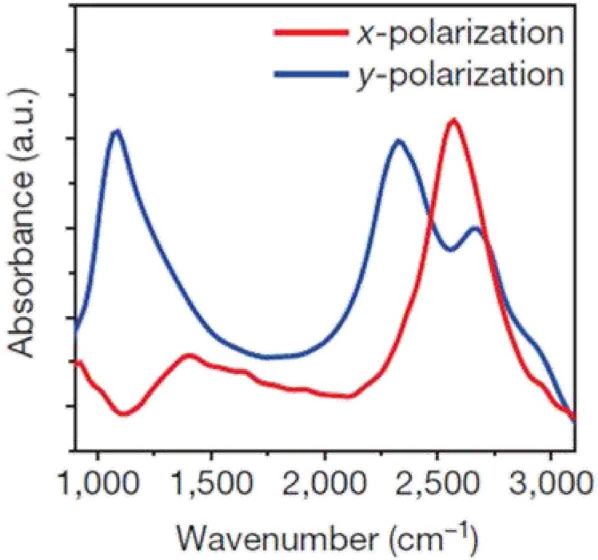


❑ Ultrathin plasmonic resonators

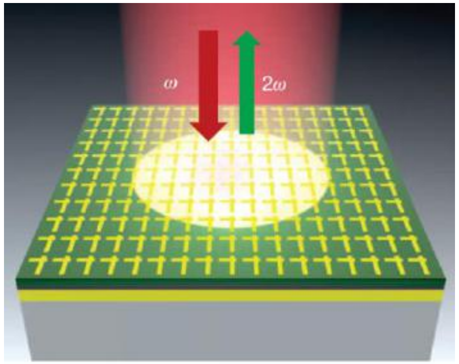


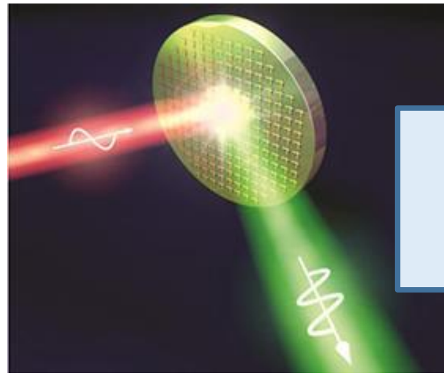
E_z/E_{pump}

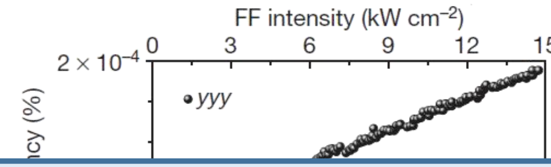




❑ Nonlinear plasmonic metasurfaces





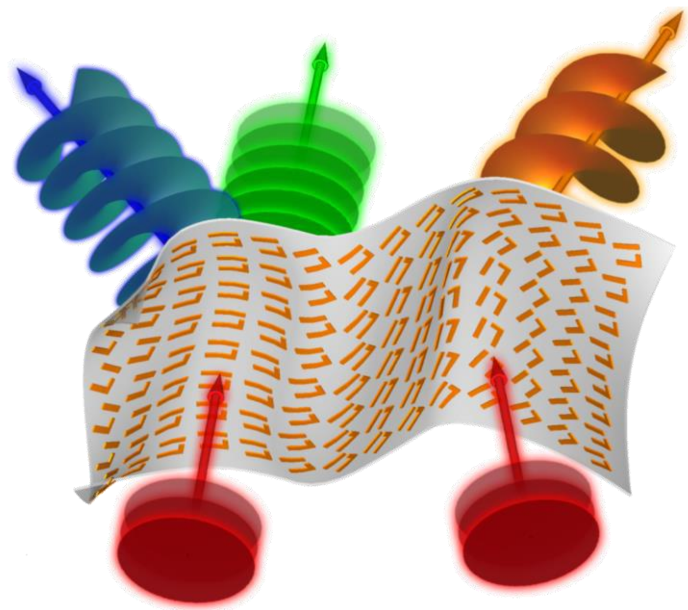


$2 \cdot 10^{-4}$% at 15 kW/cm² !!

J. Lee, M. Tymchenko, C. Argyropoulos, et al, Nature , vol. 511, pp. 65-69, 2014

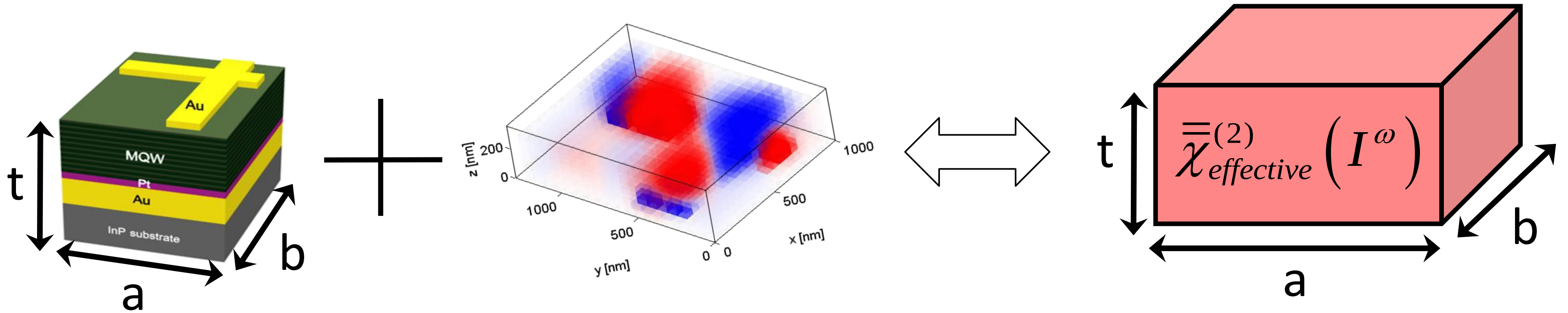
❑ Vision: Flat nonlinear paradigm

- **Enhanced conversion efficiency**
- **Manipulation of the generated beam**



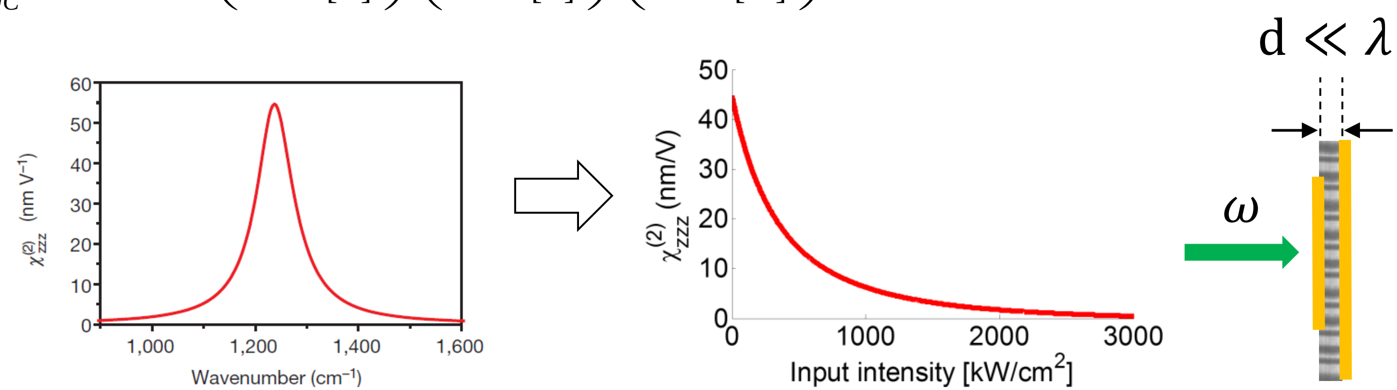
❑ Rigorous analysis of nonlinear Metasurfaces

- Effective non-linear susceptibility



$$\chi^{(2)}_{eff\,[mab]}\left(I^\omega\right)=\frac{1}{V}\int_{V_{UC}}\chi^{(2)}_{zzz}(\mathbf{r})\left(\frac{E^{\omega}_{z[a]}}{E^{\omega}_{inc[a]}}\right)\left(\frac{E^{\omega}_{z[b]}}{E^{\omega}_{inc[b]}}\right)\left(\frac{E^{2\omega}_{z[m]}}{E^{2\omega}_{inc[m]}}\right)d\mathbf{r}=\chi^{(2)}_{zzz}MI_{overlap}\left(I^\omega\right)$$

- MQWs saturation



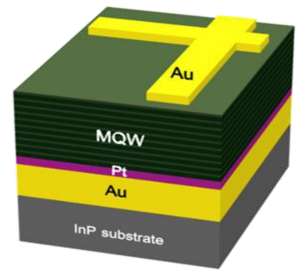
J. S. Gomez-Diaz, M Tymchenko, J Lee, M. A. Belkin, A Alù, Physical Review B, vol. 92, pp. 125429, 2015

Enhancing Efficiency: Approaches

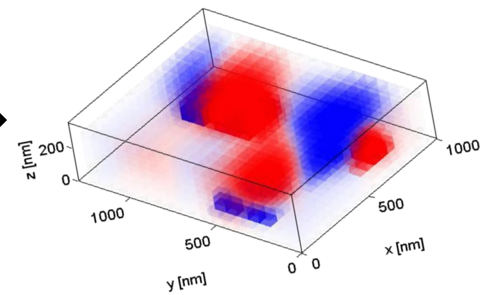
$$\eta \equiv \frac{I_{2\omega}}{I_{\omega}} \propto \left(\frac{d}{\lambda_{2\omega}}\right)^2 \left|\chi_{eff}^{(2)} E_{\omega}\right|^2 \Rightarrow \chi_{eff}^{(2)} \uparrow\uparrow$$

$$\overline{\overline{\chi}}^{(2)}_{effective}(I)$$

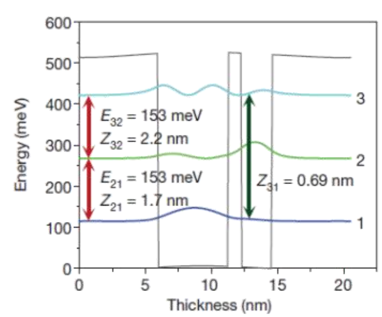
Plasmonic resonator design



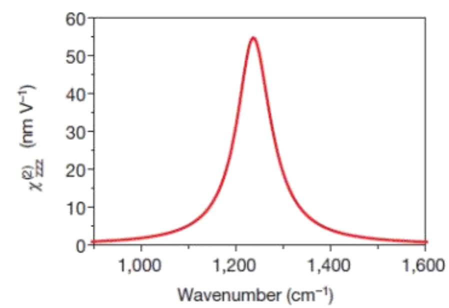
$MI_{overlap}$



MQWs design

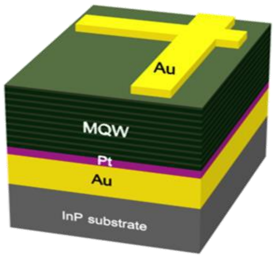


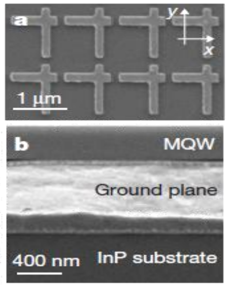
$\chi_{zzz}^{(2)}, I_{SAT}$



J. S. Gomez-Diaz, M Tymchenko, J Lee, M. A. Belkin, A Alù, Physical Review B, vol. 92, pp. 125429, 2015.

Highly-Efficient Non-Linear Metasurfaces

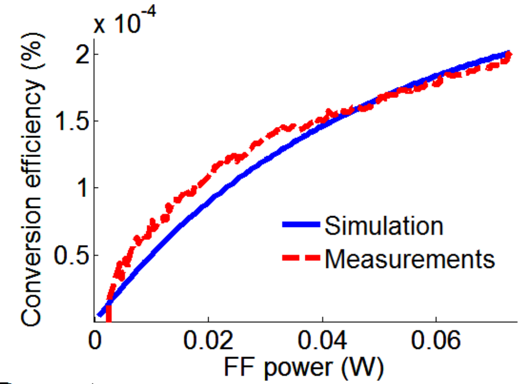


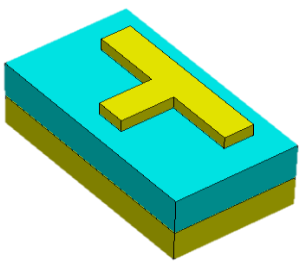


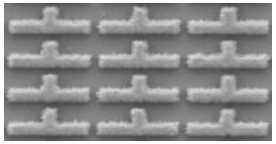
$\chi^{(2)}_{zzz} \approx 55 nm / V$

$I^{1-2}_{Sat} \approx 0.5 MW / cm^2$

$MI_{overlap} \approx 0.55$



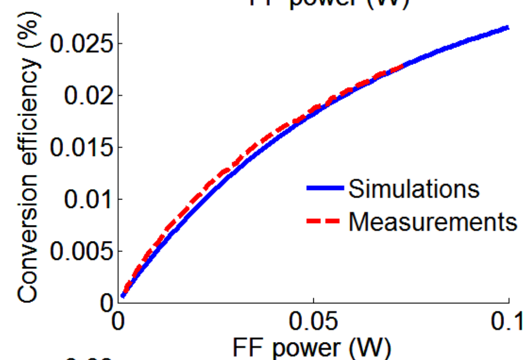


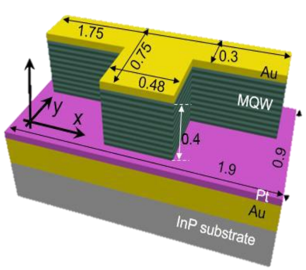


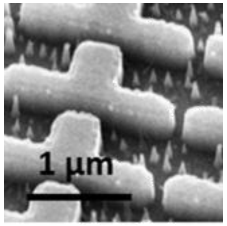
$\chi^{(2)}_{zzz} \approx 137 nm / V$

$I^{1-2}_{Sat} \approx 1.25 MW / cm^2$

$MI_{overlap} \approx 2.1$



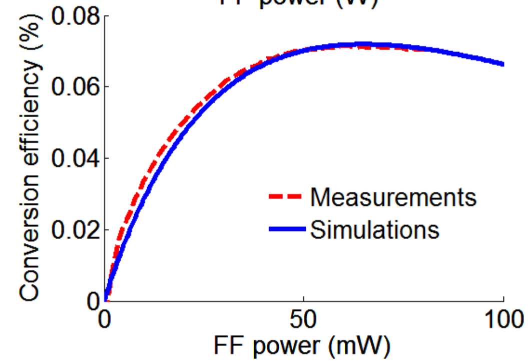




$\chi^{(2)}_{zzz} \approx 275 nm / V$

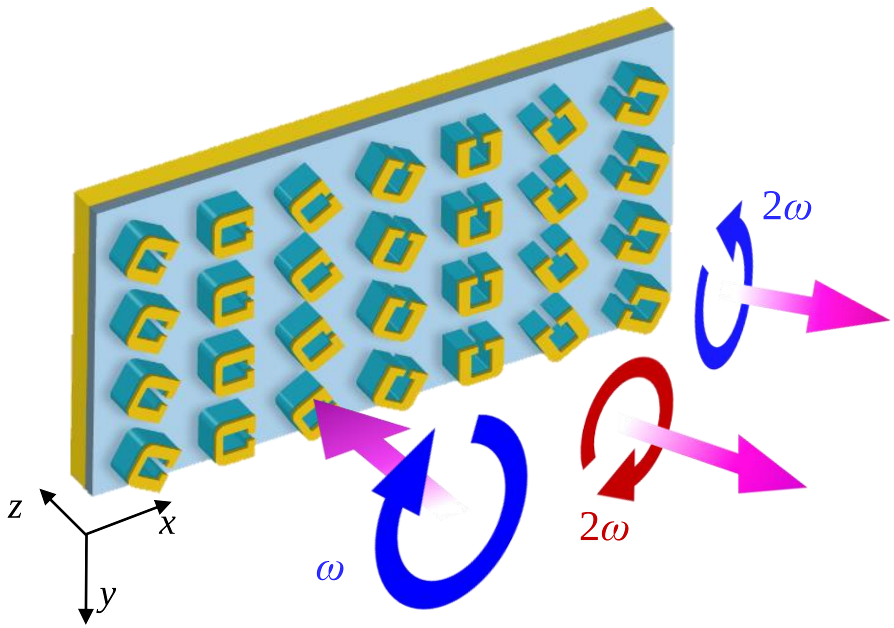
$I^{1-2}_{Sat} \approx 2 MW / cm^2$

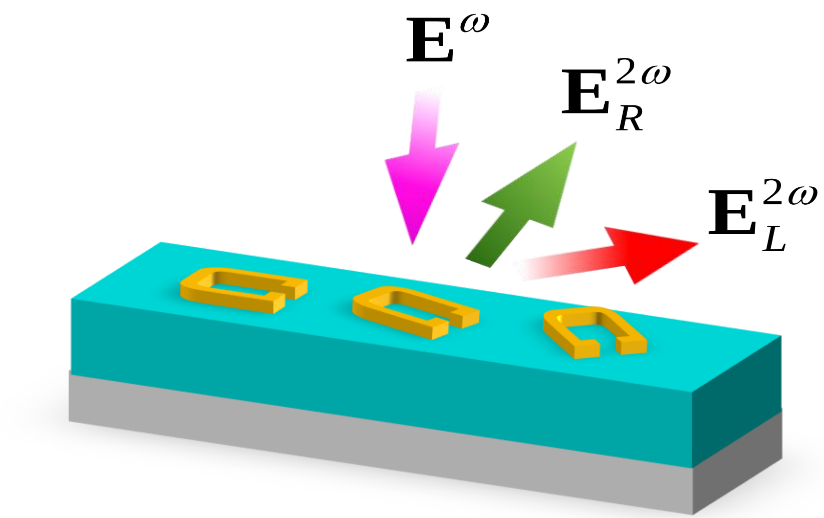
$MI_{overlap} \approx 4.25$



J. Lee, N. Nookola, J. S. Gomez-Diaz, M. Tymchenko, F. Demmerle, G. Boehm, M. Amann, A. Alu, M. Belkin, Advanced Optical Materials, doi: 10.1002/adom.201500723, 2016.

❑ Pancharatnam-Berry approach



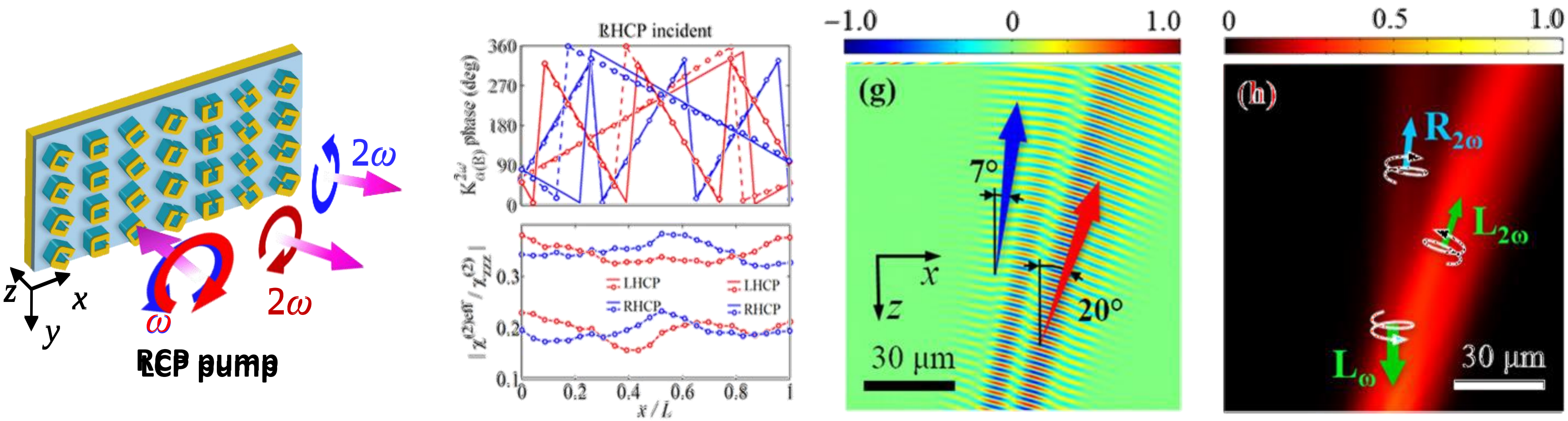


- Local control of the phase by rotation → subwavelength resolution!
- High conversion efficiency
- Enhanced functionalities for the SH beam
  - Beam steering
  - Focusing
  - Generation of vortex beam

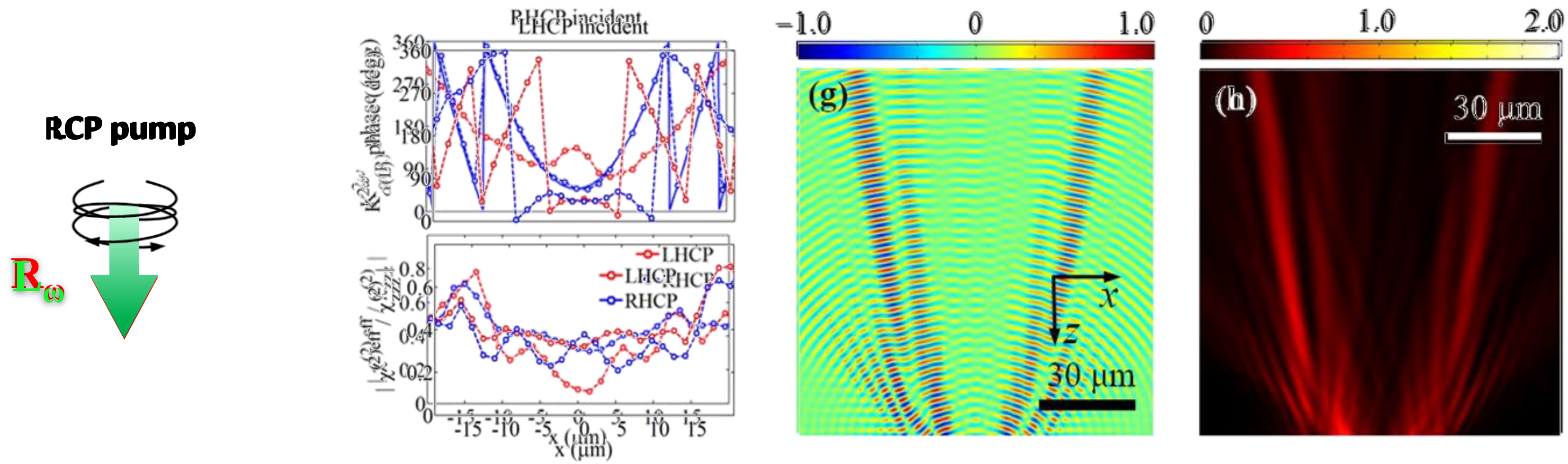
M. Tymchenko, J. S. Gomez-Diaz, J. Lee, N. Nookala, M. A. Belkin, and A. Alù, Physical Review Letters, vol. 115, pp. 207403, 2015

Advanced Functionalities (I)

❑ Steering the generated SH beam



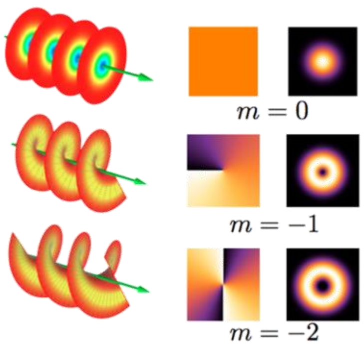
❑ Focusing the generated SH beam



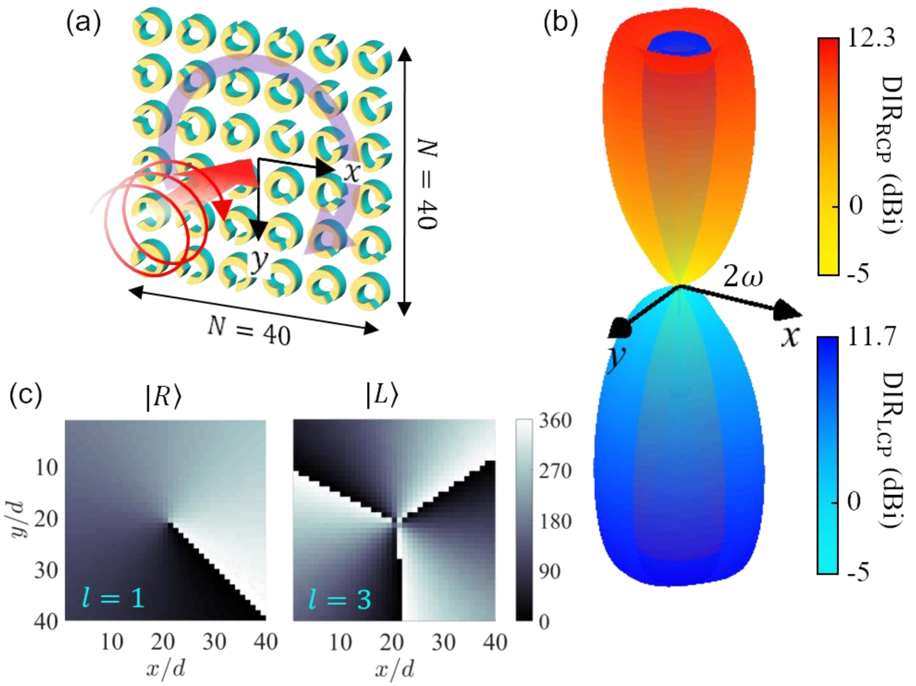
M. Tymchenko, J. S. Gomez-Diaz, J. Lee, N. Nookala, M. A. Belkin, and A. Alù, Physical Review Letters, vol. 115, pp. 207403, 2015

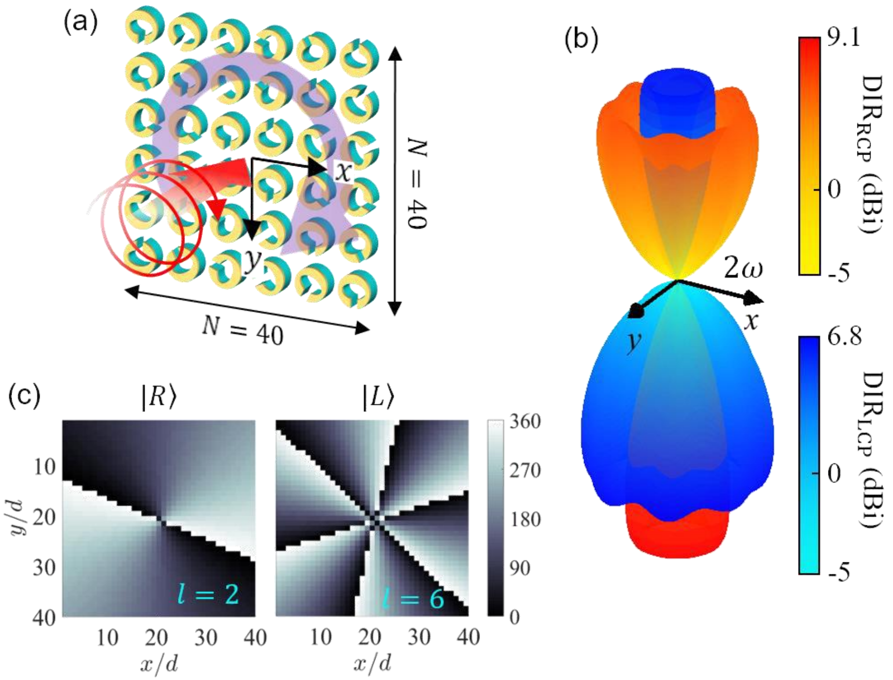
Nonlinear generation of Vortex beams

- Polarization-dependent angular momentum



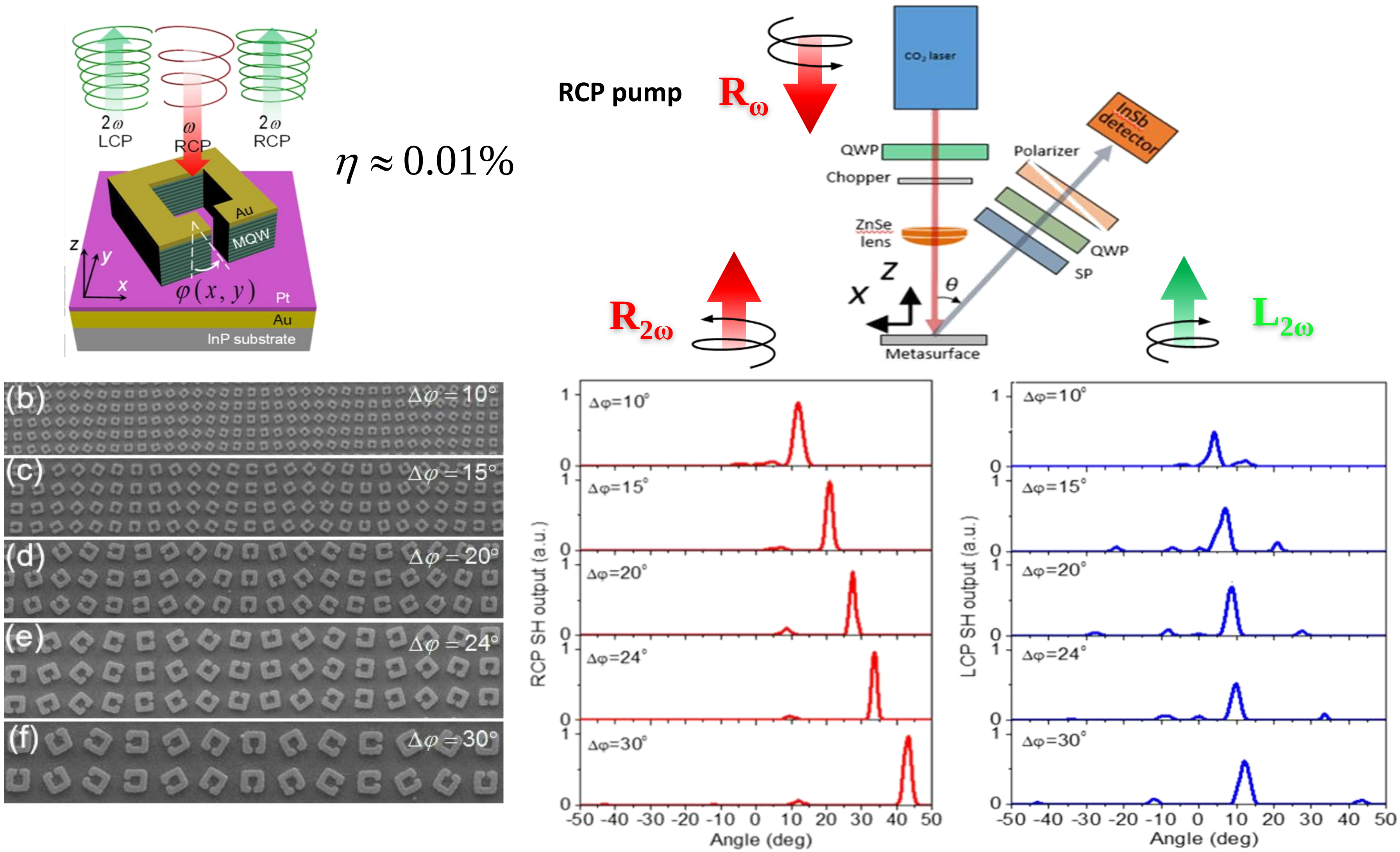
Wikipedia





M. Tymchenko, J. S. Gomez-Diaz, J. Lee, N. Nookala, M. A. Belkin, and A. Alù , “Advanced Control of Nonlinear Beams with Pancharatnam-Berry Metasurfaces”, Physical Review B, 2016.

Experimental Results



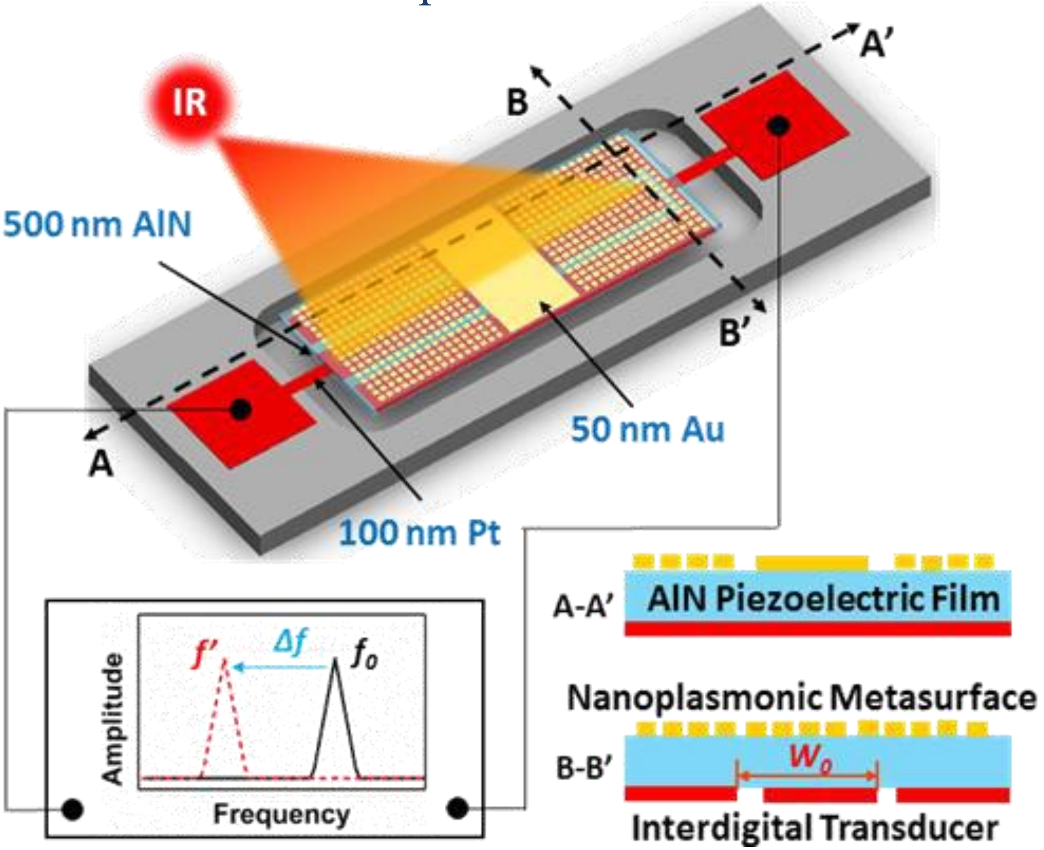
J. Lee, N. Nookola, M. Tymchenko, J. S. Gomez-Diaz, F. Demmerle, G. Boehm, M. Amann, A. Alu, M. Belkin, Optica, Vol. 3, Issue 3, pp. 283-288, 2016.

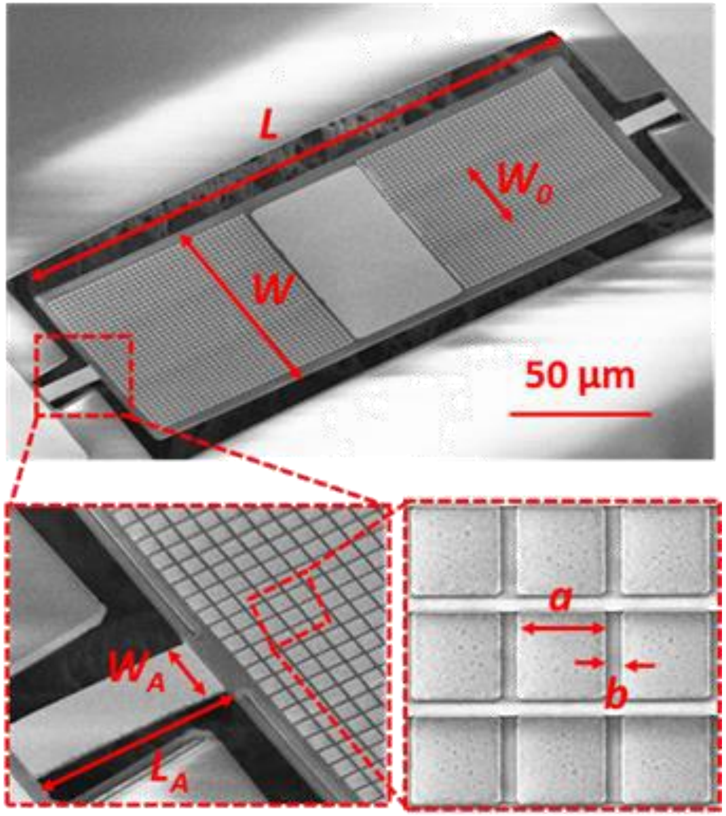
Outline

- Introduction
- Graphene plasmonics: THz devices & antennas
- Non-reciprocal metasurfaces
- Hyperbolic metasurfaces
- Non-linear metasurfaces
- Multidisciplinary
- Conclusions

❑ Infrared detector

- Ultrathin metasurface → Body of a nanomechanical resonator
- Combination of mechanical and electromagnetic resonances
- Room temperature

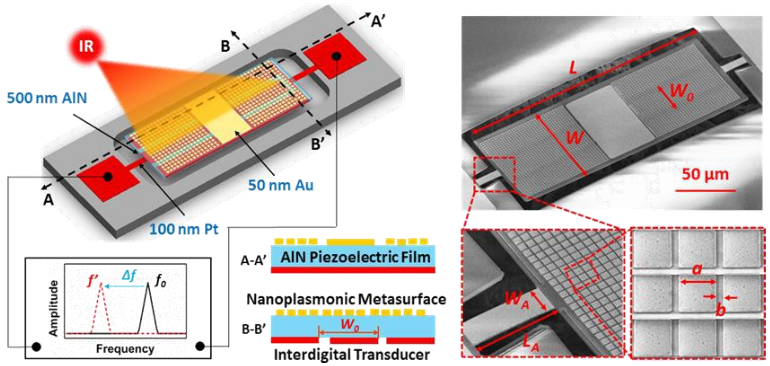


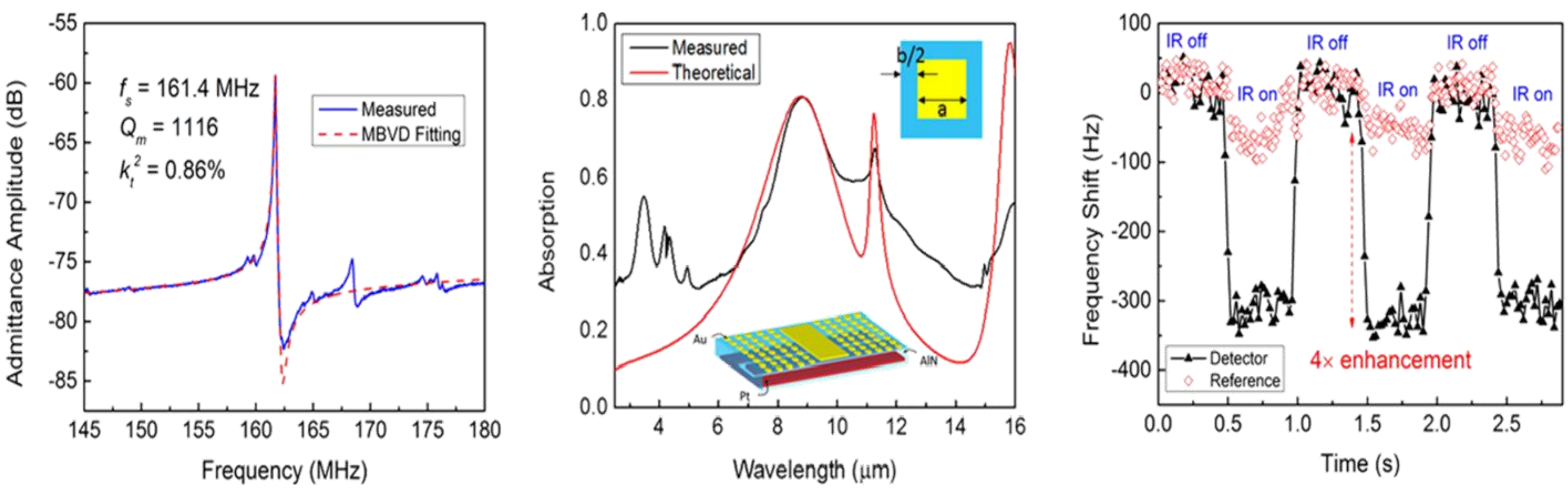


Y. Hui, J. S. Gomez-Diaz, A. Alù, and M. Rinaldi, Nature Communications, 2016.

❑ Infrared detector

- Low noise, fast response
- High electromechanical coupling coefficient



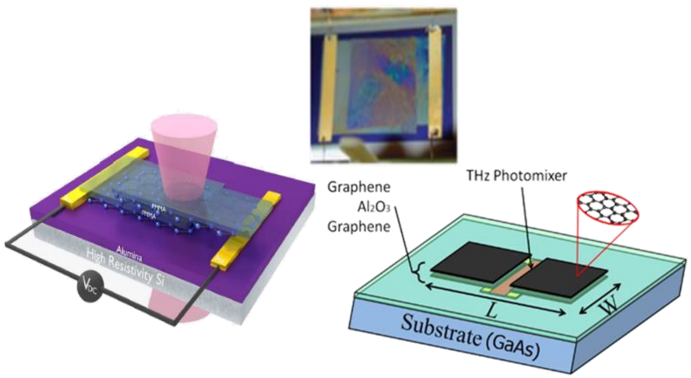


Y. Hui, J. S. Gomez-Diaz, A. Alù, and M. Rinaldi, Nature Communications, 2016.

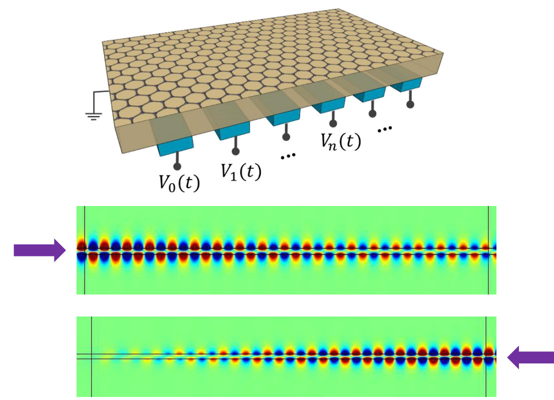
Outline

- Introduction
- Graphene plasmonics: THz devices & antennas
- Non-reciprocal metasurfaces
- Hyperbolic metasurfaces
- Non-linear metasurfaces
- Multidisciplinary
- Conclusions

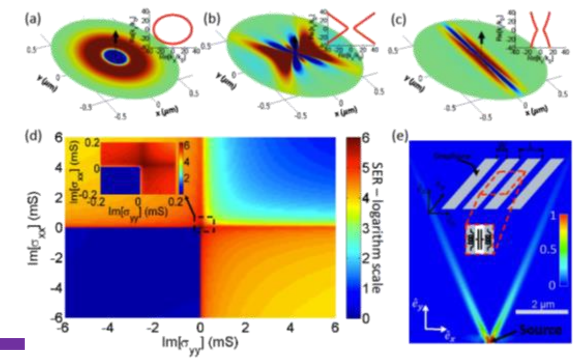
Towards a Flatland & Advanced Manipulation of EM waves



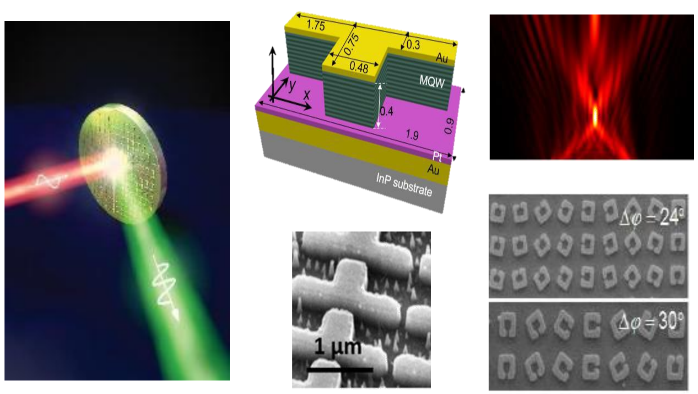
Reconfigurable THz graphene devices



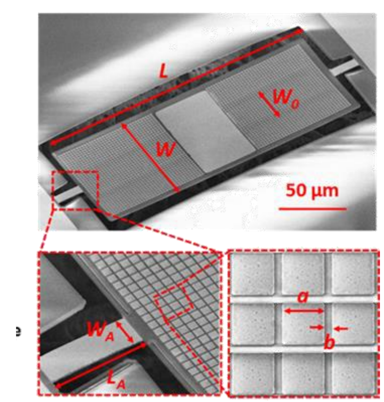
Non-reciprocal plasmonics



Hyperbolic metasurfaces



Flat **nonlinear** paradigm



NEMS

Collaborators:

- Mr. Diego Correas-Serrano – University of Califonia, Davis, USA
- Prof. Andrea Alù – The University of Texas at Austin, USA
- Prof. Mikhail Belkin – The University of Texas at Austin, USA
- Dr. Dimitrious Sounas – The University of Texas at Austin, USA
- Prof. Mateo Rinaldi – Northeastern University, USA
- Prof. Juan Mosig – École Polytechnique Fédérale de Lausanne, Switzerland
- Dr. Michele Tamagnone – École Polytechnique Fédérale de Lausanne, Switzerland
- Prof. A. Alvarez-Melcon – Technical University of Cartagena, Spain.

Thank you!

J. Sebastian Gomez-Diaz

Department of Electrical and Computer Engineering
University of California, Davis
jsgomez@ucdavis.edu

UCDAVIS ELECTRICAL AND COMPUTER ENGINEERING

Applied Micro/Nano-Electromagnetics Research Laboratory