Graphene nanophotonics methods and devices: what can we learn from the microwave field?

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Contents

Devices:

- Periodic meta-surfaces:
  - modulators, polarizer, etc. (B=0)
  - Faraday rotator, etc. (B≠0)
- Antennas
  - Resonant dipoles
  - Modulated leaky-wave antenna
- Beam deflector and reflectarray
- Plasmons waveguides/switch

Methods:

- Numerical codes for Maxwell Equations in complex setups
- Design methods for particular devices
- Simple and advanced circuit models

Measurements….

- Approach: conductivity model + Maxwell
- 2D-Periodic surfaces (metasurfaces)
  - B = 0
  - Faraday rotation
- Antennas
  - Resonant dipoles
  - Modulated leaky-wave antenna
- Beam deflection , reflectarray
- Plasmon wave-guiding
- Measurements

Approach:

- Conductivity tensor [1-3] + Maxwell

$$\bar{\bar{\sigma}}\,(q,\omega,\mu_c,\tau,T)\ \xrightarrow[\text{Analytical or numerical}]{\text{Maxwell Equations}}\ \text{Detailed EM wave fields}$$

(**thickness graphene = 0**)

- Main assumptions:
  - Spatial dispersion? Depends on the method for solving Maxwell
  - Not too small graphene geometrical feature
  - Linear conductivity

[1] G. Hanson, “Dyadic green’s functions for an anisotropic non-local model of biased graphene,” IEEE Transactions on Antennas and Propagation, vol. 56, no. 3, pp. 747–757, March 2009.
[2] L. A. Falkovsky et al, “Space-time dispersion of graphene conductivity,” European Physical Journal B, vol. 56, 2007.
[3] V. P. Gusynin, et al, “Magnetooptical conductivity in graphene,” Journal of Physics: Condensed Matter, vol. 19, no. 2, p. 026222, 2007.

- Approach: conductivity model + Maxwell
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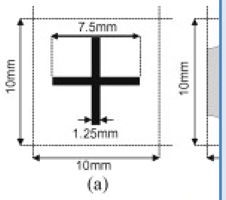
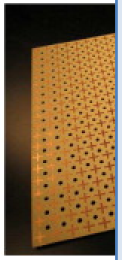
2D-Periodic surfaces (metasurfaces)

- Analyzed and used for decades at micro/mm-waves:

Abs





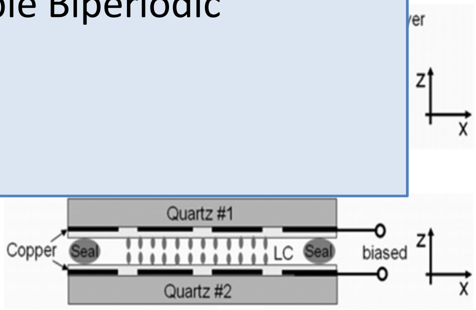
)

Reconf.

Graphene → <u>higher frequencies and especially with dynamic control (e.g. [1-5])</u>

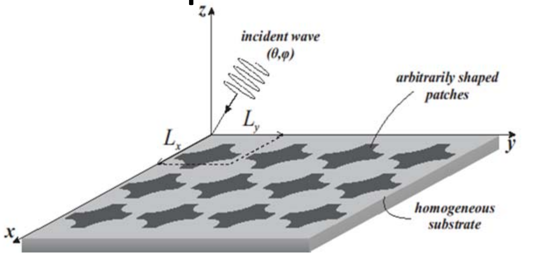
Many existing concepts and methods can be used/adapted !

[1] S. Thongrattanasiri, F. H. L. Koppens, and F. J. Garcia de Abajo, Phys. Rev. Lett. **108**, 047401 (2012).
[2] A. Y. Nikitin, F. Guinea, F. J. Garcia-Vidal, and L. Martin-Moreno, Phys. Rev. B **85**, 081405 (2012).
[3] A. Ferreira and N. M. R. Peres, arXiv:1206.3854.
[4]H. Yan, X. Li, B. Chandra, G. Tulevski, Y.Wu, M. Freitag,W. Zhu, P. Avouris, and F. Xia, Nat. Nanotechnol. **7**, 330 (2012).
[5] A. Fallahi and J. Perruisseau-Carrier, "Design of Tunable Biperiodic Graphene Metasurfaces", PRB, 2012.



2D-Periodic surfaces (metasurfaces)

- **Analysis:** very efficient Maxwell numerical techniques for 2D periodic structures can be adapted to graphene.



- E.g. Periodic Method of Moments (PMoM) [1]:
  - Very general: approaches Maxwell's exact solution for:
    - Arbitrary number of layers
    - Arbitrary shapes for the unit cell configuration
    - Full vectorial and arbitrary angles of incidence
  - Very fast:
    - Simulation of a single cell of the periodic structure (Floquet)
    - discretization of conductive layers only
  - Extended for graphene:
    - Non-diagonal conductivity for B ≠ 0
    - Spatially-dispersive conductivity
    - Metal-graphene hybrid layers (not in [1])

$$-\begin{bmatrix} E_x^i \\ E_y^i \end{bmatrix} = \sum_{m=-\infty}^{\infty} \sum_{n=-\infty}^{\infty} \left(\begin{bmatrix} \tilde{G}_{xx_{mn}} & \tilde{G}_{xy_{mn}} \\ \tilde{G}_{yx_{mn}} & \tilde{G}_{yy_{mn}} \end{bmatrix} + \begin{bmatrix} Z_s & 0 \\ 0 & Z_s \end{bmatrix} \right) \begin{bmatrix} \tilde{J}_{x_{mn}} \\ \tilde{J}_{y_{mn}} \end{bmatrix} e^{-(jk_{xm}x + jk_{yn}y)}$$

B-bias

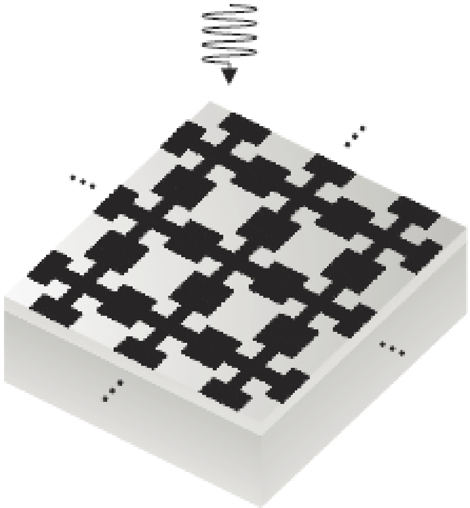
Spatial dispersion

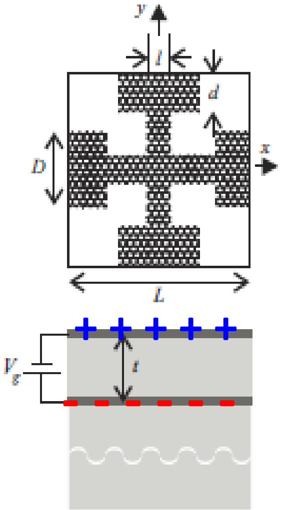
$$\mathbf{Z}_s = \begin{bmatrix} \sigma_d - \alpha \mathbf{k_x}^2 - \beta \mathbf{k_y}^2 & \sigma_o - 2\beta \mathbf{k_x} \mathbf{k_y} \\ -\sigma_o - 2\beta \mathbf{k_x} \mathbf{k_y} & \sigma_d - \beta \mathbf{k_x}^2 - \alpha \mathbf{k_y}^2 \end{bmatrix}^{-1}$$

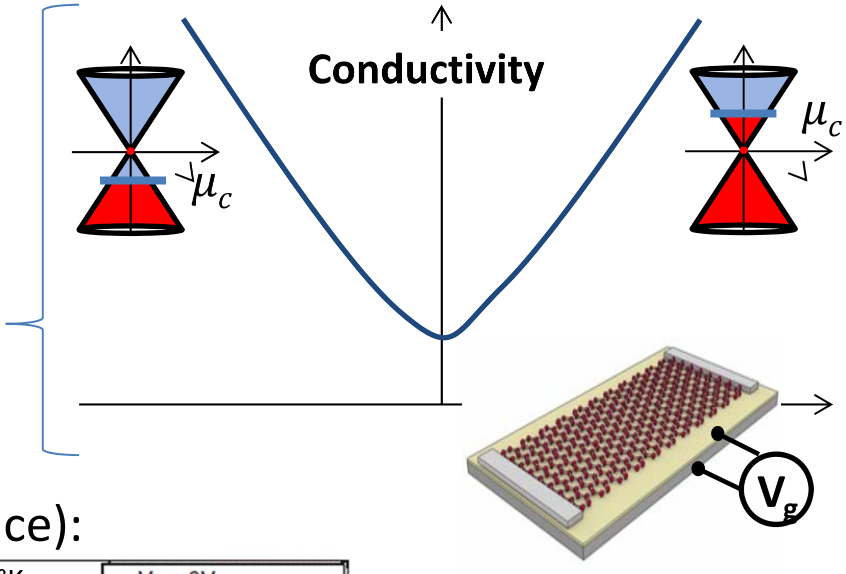
[1] A. Fallahi and J. Perruisseau-Carrier, "Design of Tunable Biperiodic Graphene Metasurfaces", PRB, 2012.

2D-Periodic surfaces (metasurfaces)

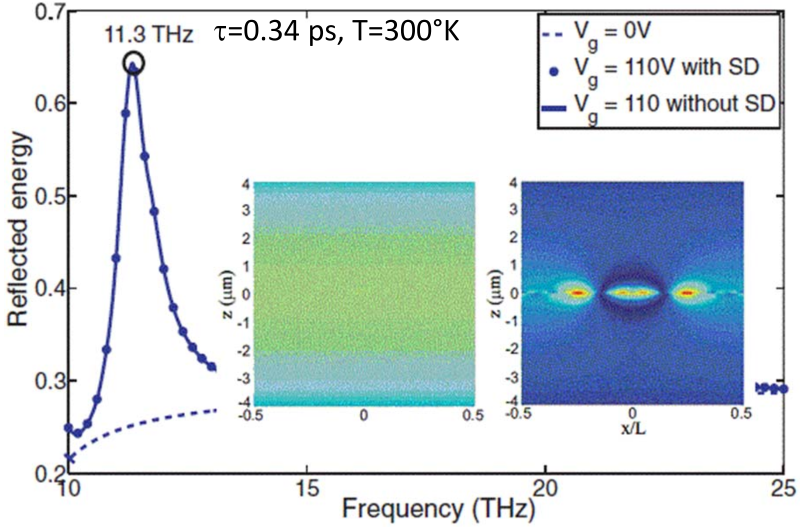
- Design of a THz controllable FSS (=modulator) [1]







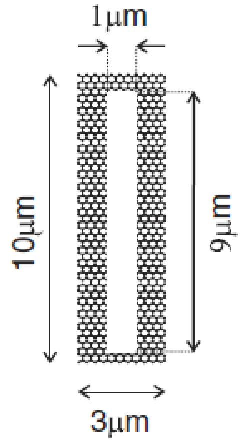
  - Simulation results (normal incidence):

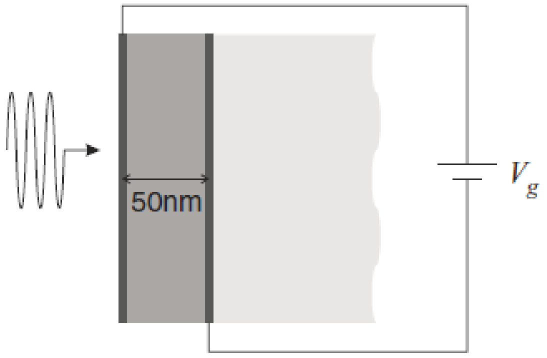


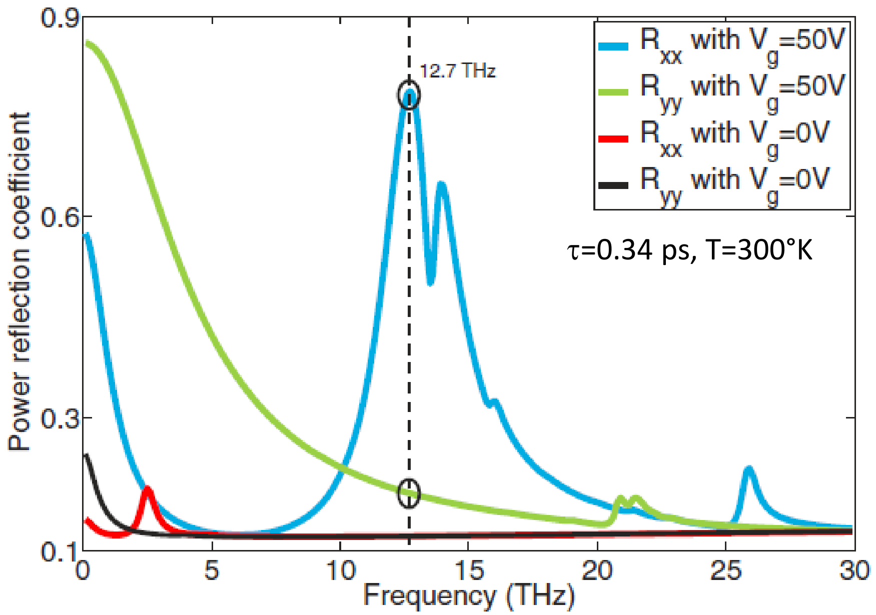
[1] A. Fallahi and J. Perruisseau-Carrier, “Design of Tunable Biperiodic Graphene Metasurfaces”, PRB, 2012.

2D-Periodic surfaces (metasurfaces)

- Switcheable reflective polarizer [1]







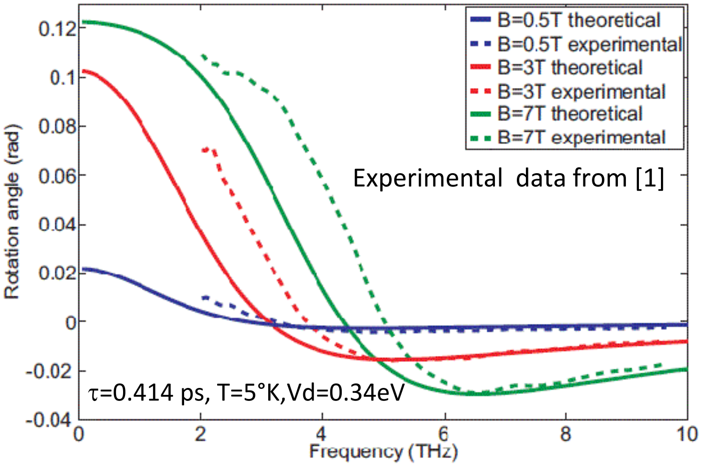
τ=0.34 ps, T=300°K

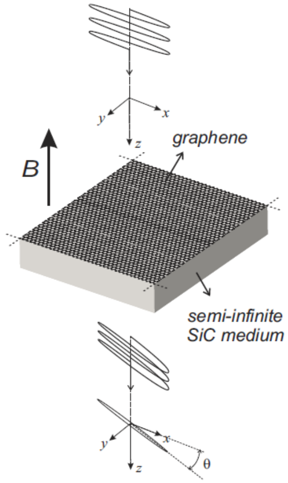
[1] A. Fallahi and J. Perruisseau-Carrier, “Design of Tunable Biperiodic Graphene Metasurfaces”, PRB, 2012.

2D-Periodic surfaces (metasurfaces)

- <u>Faraday rotation</u> in uniform graphene layers
  - H-bias → non-diagonal conductivity → Faraday rotation [1-2]

$$\bar{\bar{\sigma}} = \begin{pmatrix} \sigma_d & \sigma_0 \\ -\sigma_0 & \sigma_d \end{pmatrix}$$



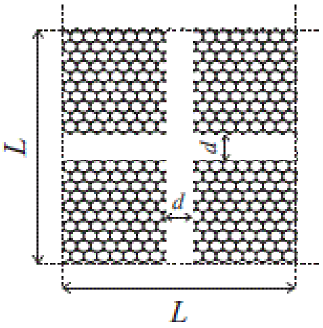


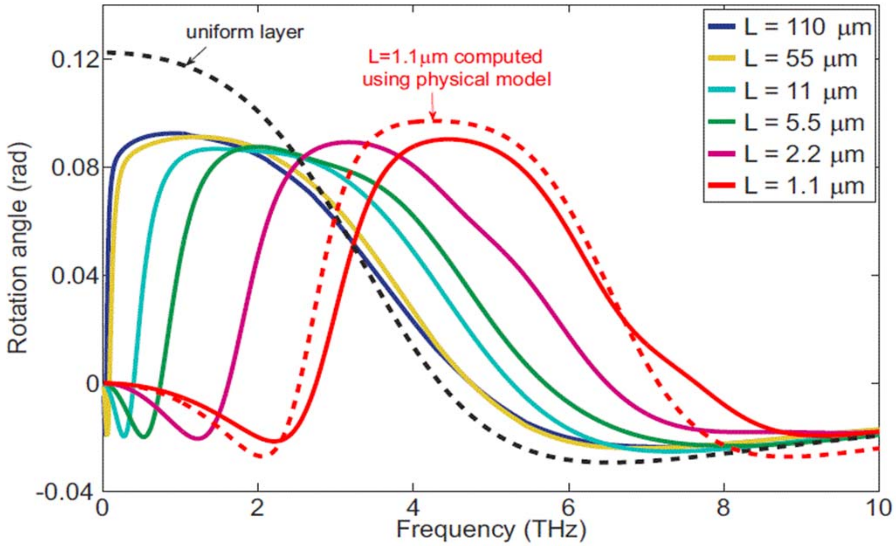
  - Our code allows studying:
    - Intentional nano-patterning for manipulating Faraday rotation [2]
    - Possible defects, different domains etc [3]
    - hybrid metal-graphene layers

[1] I. Crassee et al. “Giant Faraday rotation in single and multilayer graphene,” Nature Phys., 2010.
[2] A. Fallahi and J. Perruisseau-C. “Manipulation of Giant Faraday Rotation in Graphene Metasurfaces”, APL, 2012.
[3] I. Crassee et al. “Intrinsic Terahertz Plasmons and Magnetoplasmons in Large Scale Monolayer Graphene”, Nanoletters, 2012.

2D-Periodic surfaces (metasurfaces)

- Manipulation of Faraday rotation [1]:
  - The frequency of maxiumum Faraday rotation can be controlled via nano-patterning





  - Effect well predicited by very simple model

$$Z = \sigma^{-1} = \begin{pmatrix} Z_d & -Z_o \\ Z_o & Z_d \end{pmatrix}$$

$$Z_t = \left(\frac{L}{L-d}\right)^2 \begin{pmatrix} Z_d & -Z_o \\ Z_o & Z_d \end{pmatrix} + \begin{pmatrix} \frac{1}{j\omega C} & 0 \\ 0 & \frac{1}{j\omega C} \end{pmatrix}$$

$$C = \varepsilon_0 L \frac{\varepsilon_r + 1}{\pi} \ln(\csc \frac{\pi d}{2L})$$

[1] A. Fallahi and J. Perruisseau-C. “Manipulation of Giant Faraday Rotation in Graphene Metasurfaces”, Applied Physics Lett., 2012.

- Approach: conductivity model + Maxwell
- 2D-Periodic surfaces (metasurfaces)
  - B = 0
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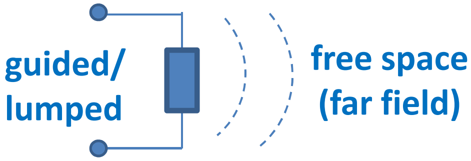
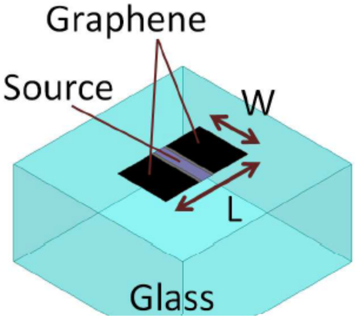
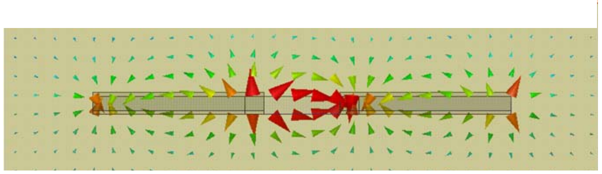
Resonant antennas

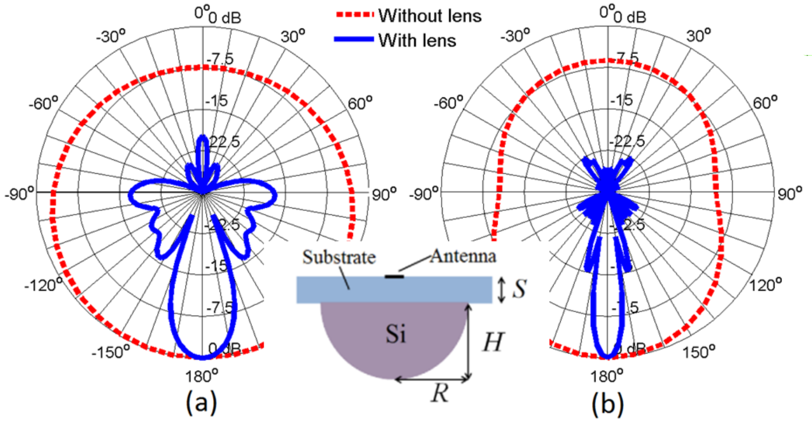
- Graphene patches as 'antenna' [1]
  - Input impedance, radiated fields, efficiency ?
- Simplest graphene 'antenna': dipole [1]:
  - Resonant behavior based on plasmonic standing waves (L =Nπ/β) [2-3]

antenna def. here →





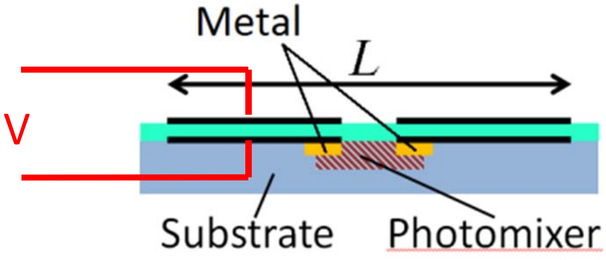




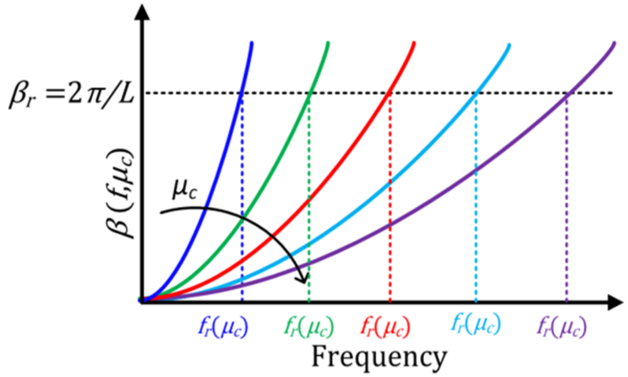
[1] M. Tamagnone, et al., "Reconfigurable terahertz plasmonic antenna concept using a graphene stack," *APL, 2012*
[2] Jornet et al. "Graphene-based Nano-antennas for EM Nanocommunications in the Terahertz Band," EuCAP 2010
[3] I. Llatser et al. "Graphene-based nano-patch antenna for terahertz radiation," *Phot .Nanostr. Fund. Appl.*, 2012.

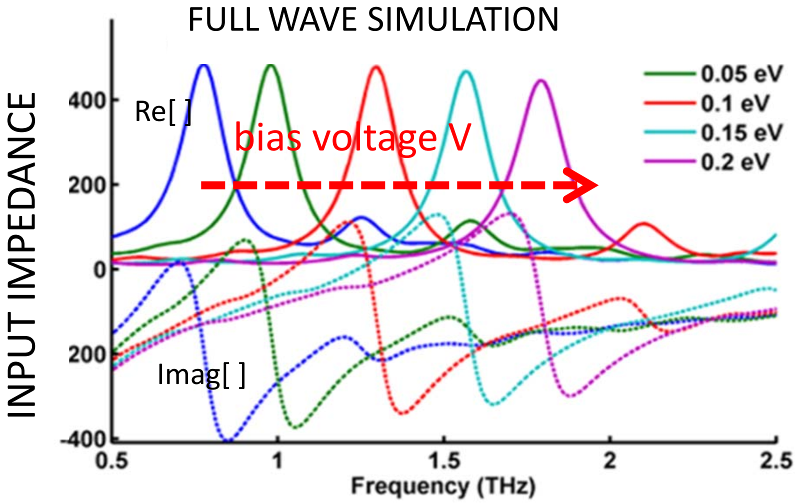
Resonant antennas

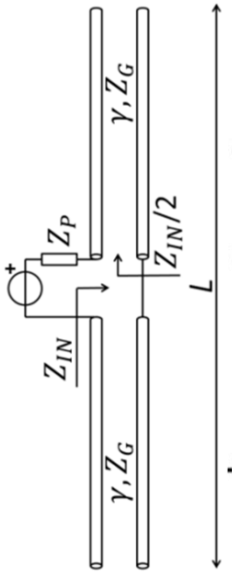
- Frequency-reconfiguration [1]:
  - Tunable plasmon phase velocity → tunable resonance

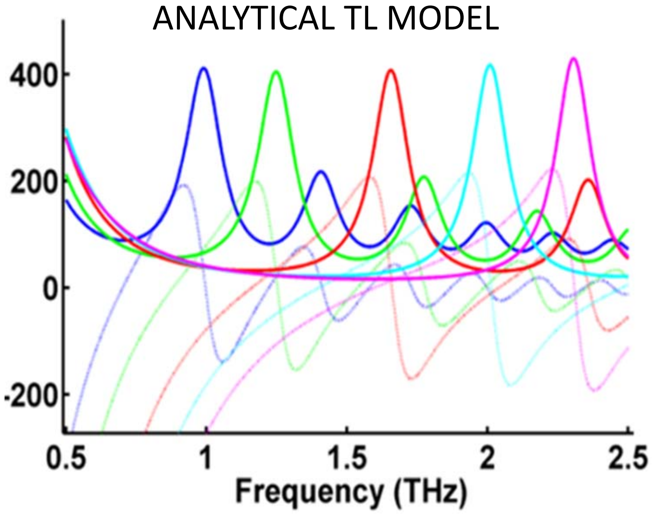


$V \rightarrow \mu_c \rightarrow Im[\sigma] \rightarrow \beta \rightarrow f_r$



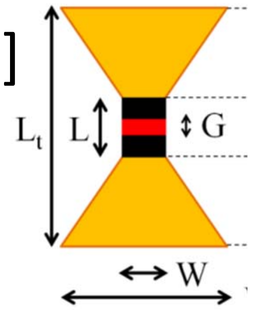






Resonant antennas

- Conclusions - dipole graphene antennas [1]
  - Integration with graphene active devices
  - Reconfigurability:
    - remarkable tuning range and performance uniformity
  - Total efficiency in the range of metal antennas
    - radiation efficiency below metal
    - Input impedance very high: better matching to high impedance source such as photomixer
    - Can be improved by metal-graphene antennas [2]
  - Behavior accurately explained by TL models



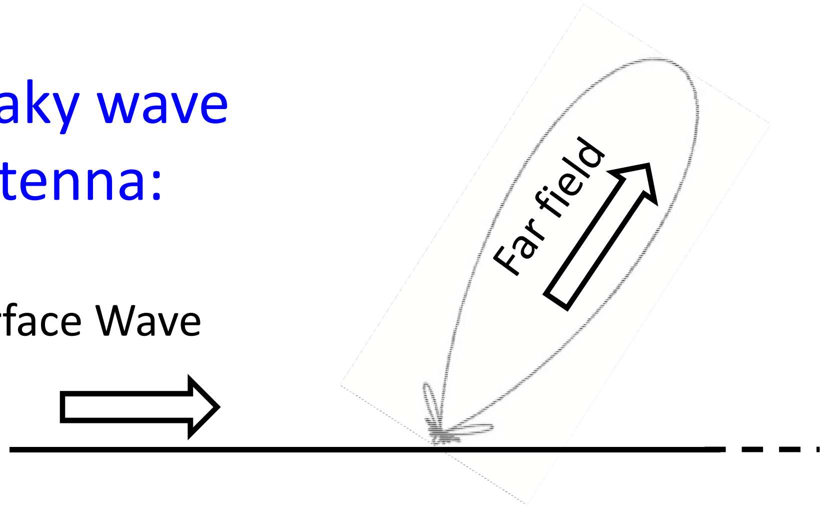
[1] M. Tamagnone, et al.. "Reconfigurable terahertz plasmonic antenna concept using a graphene stack," *APL*, 2012.

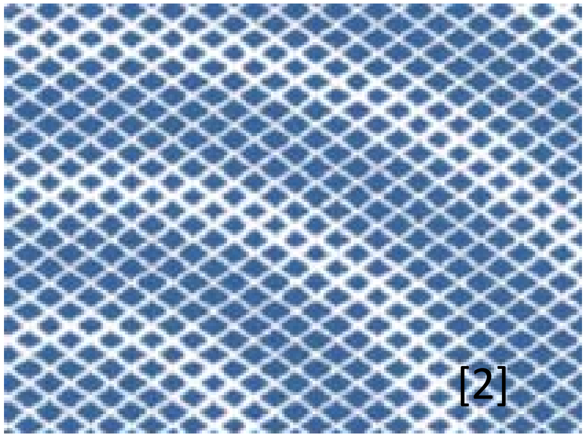
[2] M. Tamagnone, et al. "Hybrid Graphene-Metal Reconfigurable Terahertz Antenna," Int. Microwave Symposium, 2013

Leaky-wave modulated antennas

- Leaky wave antennas (LWA)
  - E.g.: sinusoidally modulating an inductive surface reactance [1-2]
  - Radiation essentially via Floquet’s n=-1 harmonic

Leaky wave antenna:



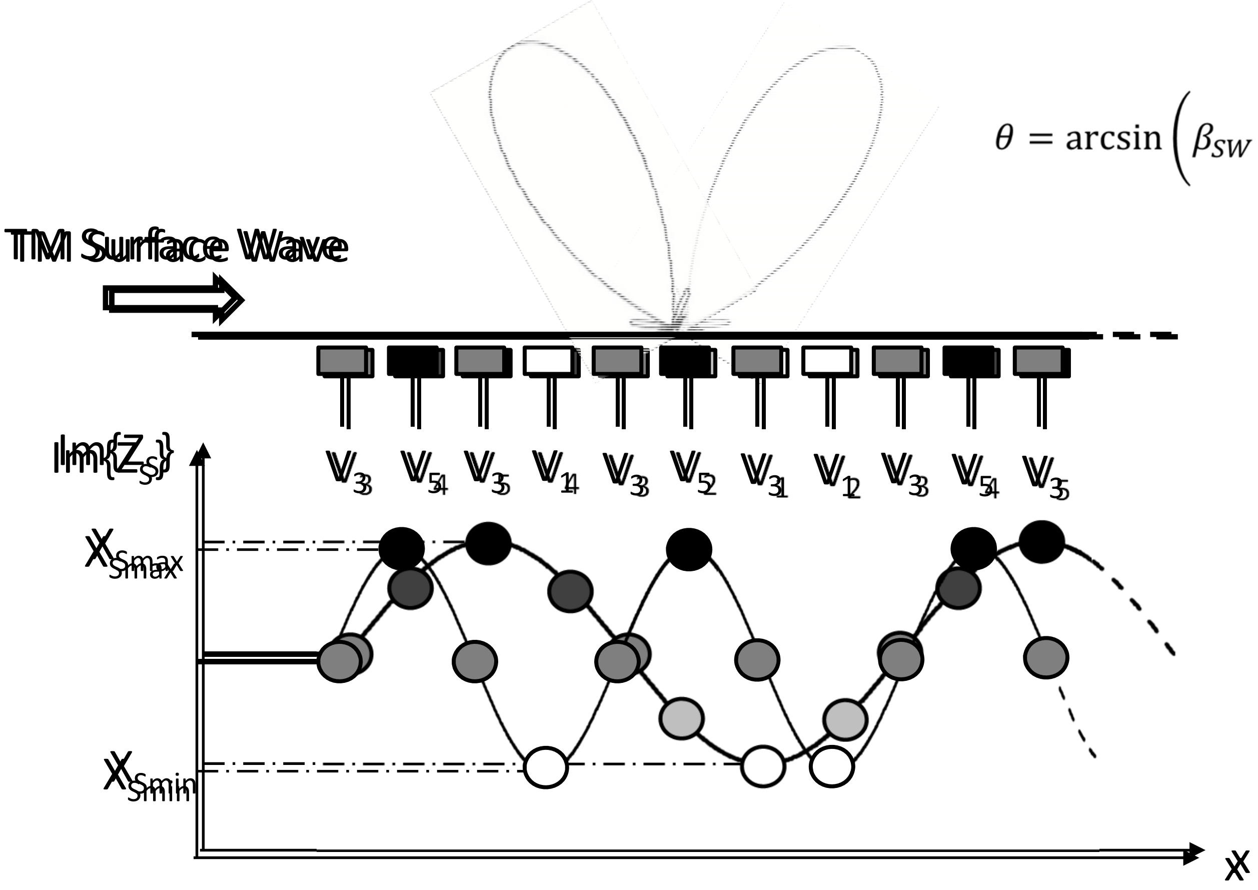


[1] A. Oliner and A. Hessel, “Guided waves on sinusoidally-modulated reactance surfaces,” *IRE Trans. Antennas Propag*., 1959.

[2] G. Minatti, F. Caminita, M. Casaletti, S. Maci, "Spiral Leaky-Wave Antennas Based on Modulated Surface Impedance," *IEEE Trans. Antennas Propag*, Dec. 2011.

Leaky-wave modulated antennas

- The radiation angle is related to the period of the modulation
- The well known graphene TM surface plasmon can be *dynamically modulated* via field effect as follows [1]:

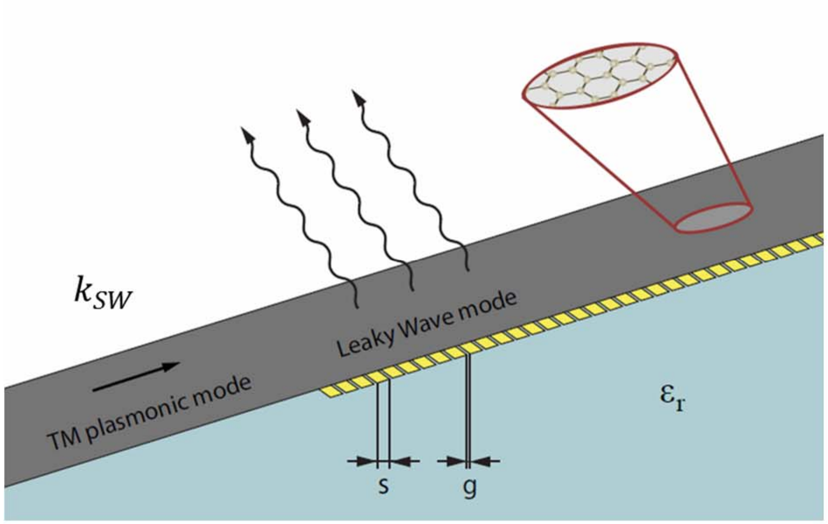


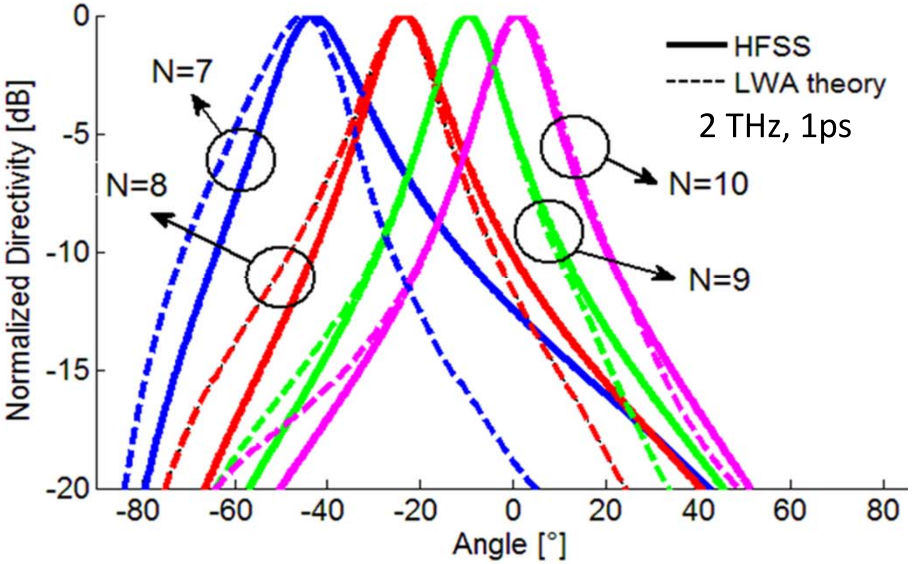
$$\theta = \arcsin\left(\beta_{SW} - \frac{\lambda_0}{N(s+g)}\right)$$

[1] J. Perruisseau-Carrier et al. "Resonant and Leaky-Wave Reconfigurable Antennas based on Graphene Plasmonics", IEEE Antenna and Prop. Symposium, 2013.

Leaky-wave modulated antennas

- Implementation in graphene:
  - Demonstration of the concept viability
  - Full-wave simulations confirm theoretical predictions





- Note: similarity with other works on periodic modulated graphene surfaces presented earlier

[1] J. Perruisseau-Carrier et al. , "Resonant and Leaky-Wave Reconfigurable Antennas based on Graphene Plasmonics", IEEE Antenna and Prop. Symposium, 2013.

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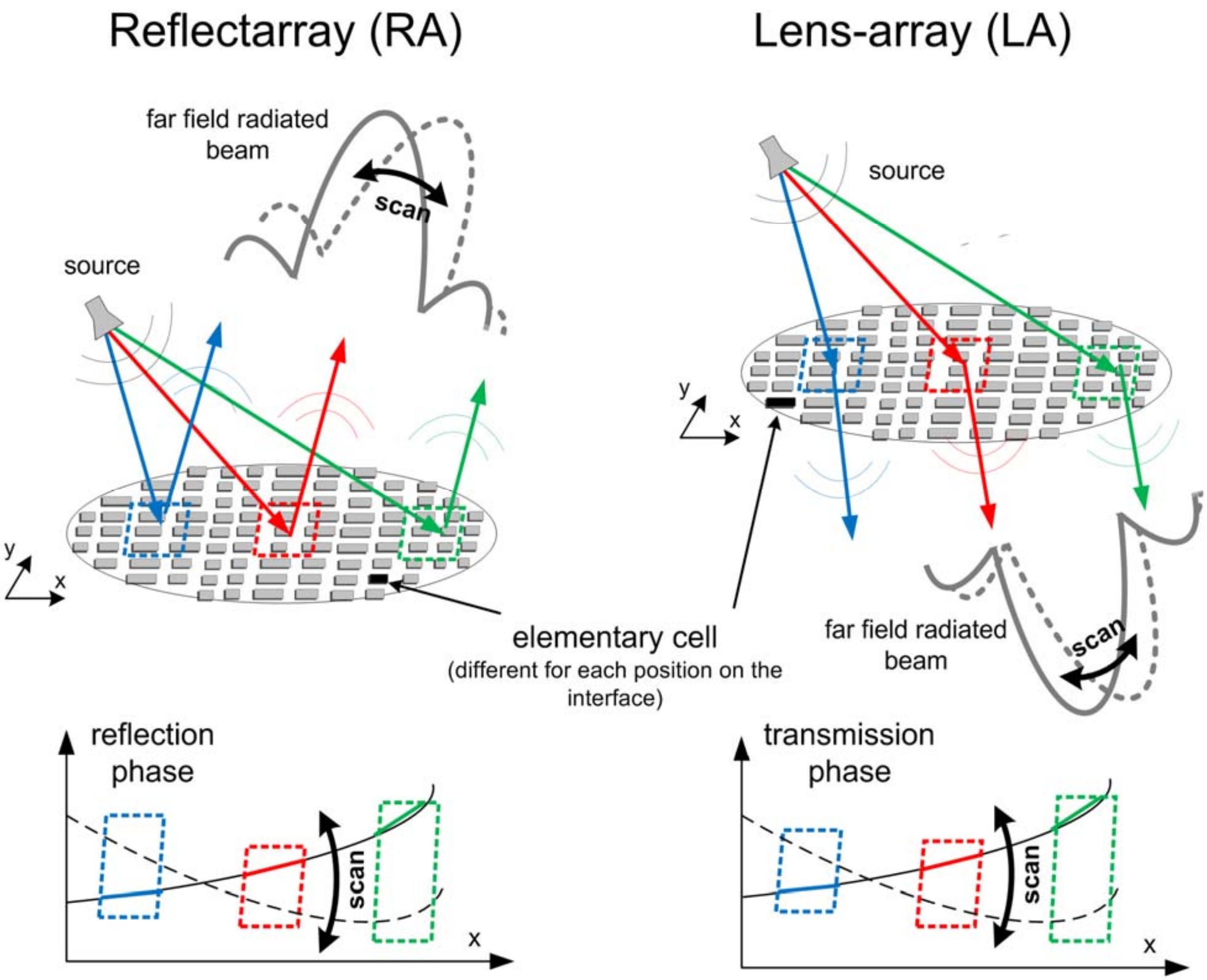
- **Beam deflection , reflectarray**
- Plasmon wave-guiding
- Measurements

Beam deflection and Reflectarrays

- Reflectarray concept: Spatially-feed (reconfigurable) antenna array
  - low loss, low cross-pol, easy manufacturing, reconfiguration



- Very intensive research in the last 10 years for satellite applications at micro and mm-wave

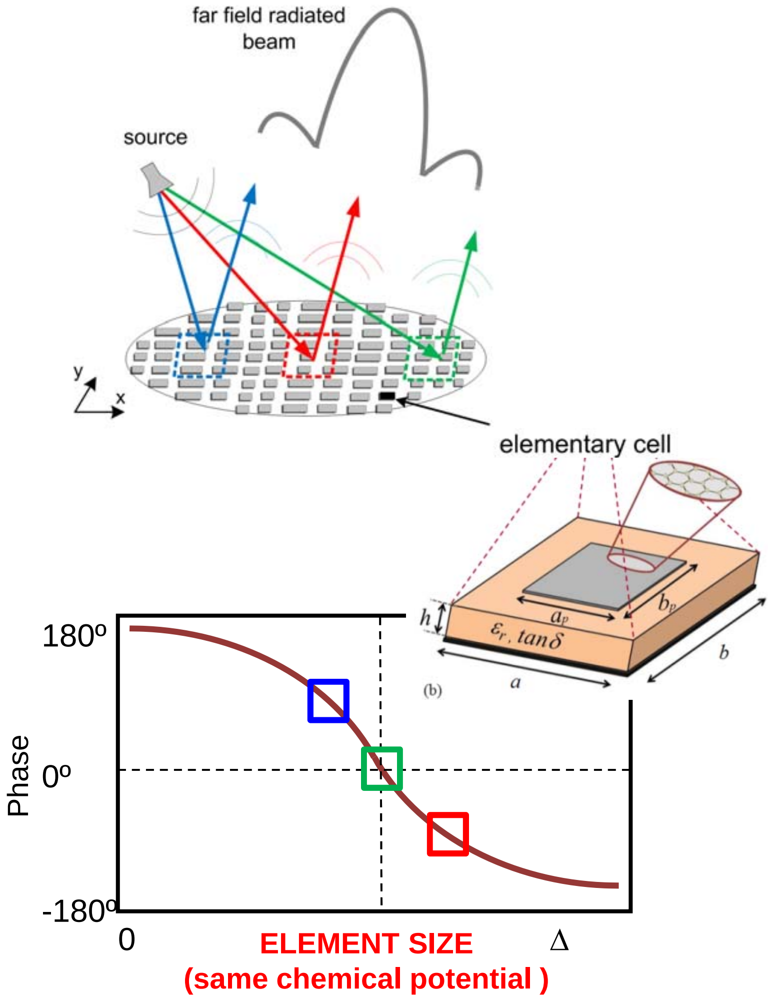
- (The recent “modified laws of reflection and refraction” at optics is the same concept)

N. Yu., et al., Science, vol. 334, pp. 333, 2011.

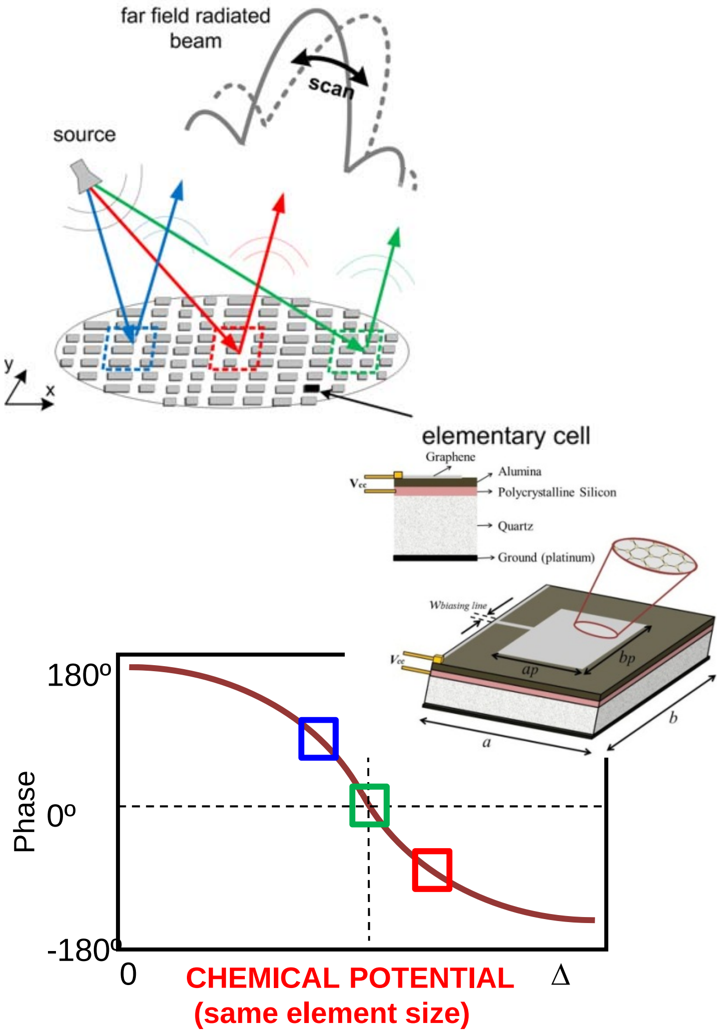
Beam deflection and Reflectarrays

- Fixed or reconfigurable implementations

Fixed-beam

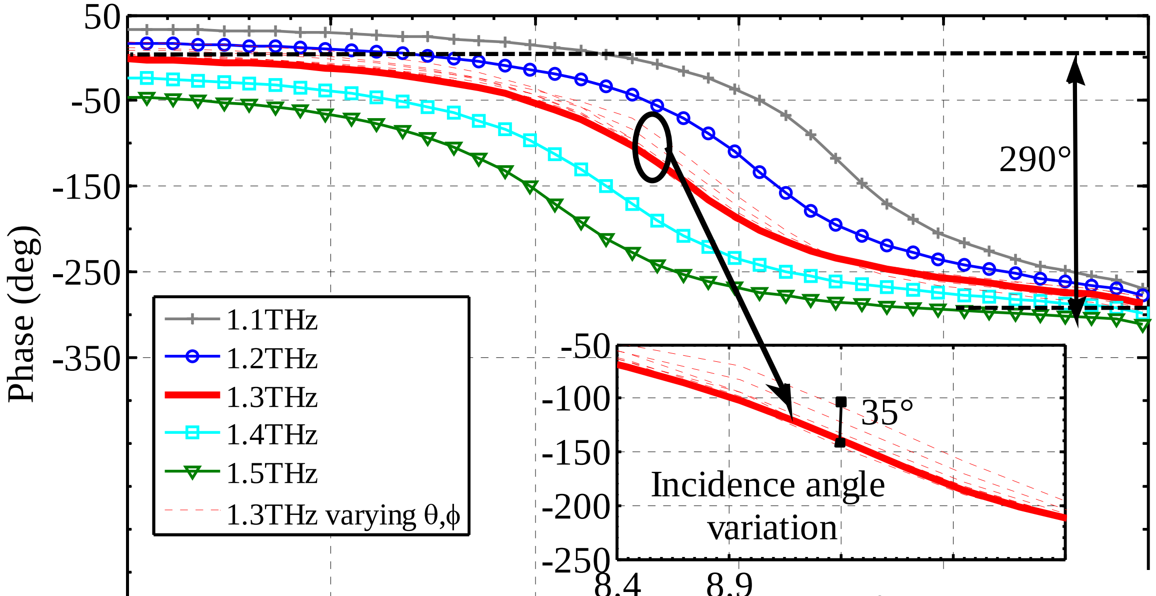


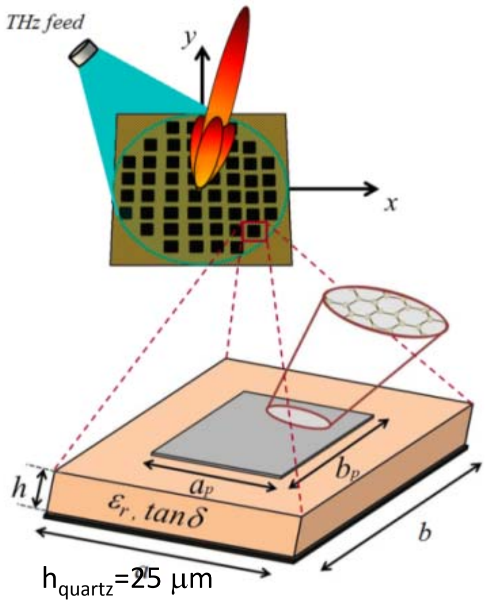
Reconfigurable-beam

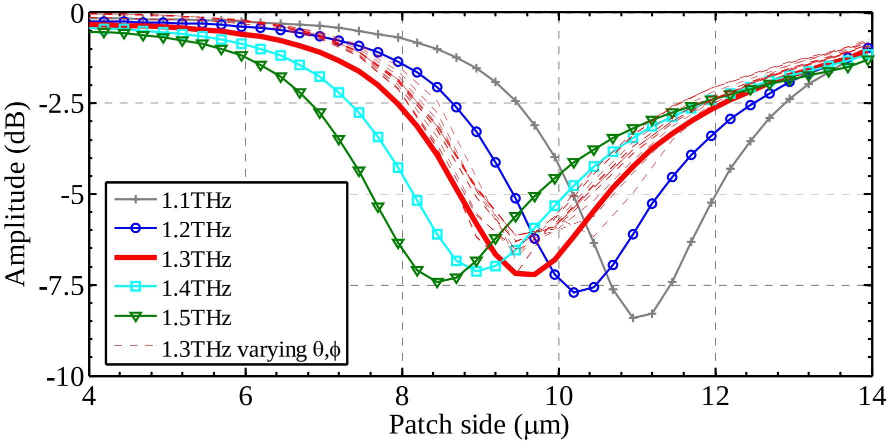


Beam deflection and Reflectarrays

- Fixed-beam reflectarray at THz using graphene: unit cell
  - Plasmonic → extremely miniaturized element
  - At least 290° of phase-shift by varying patch size



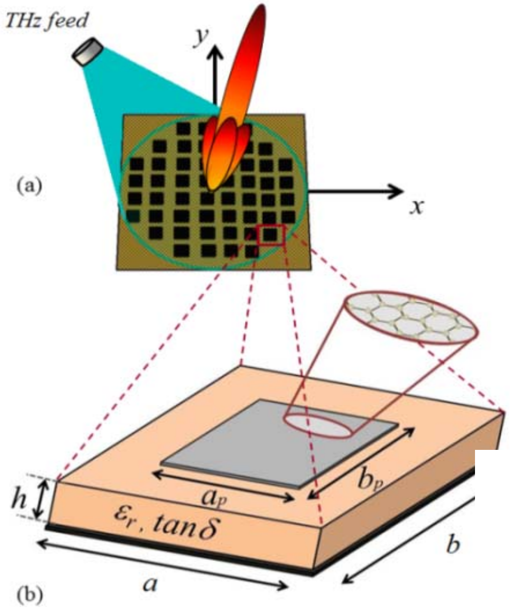




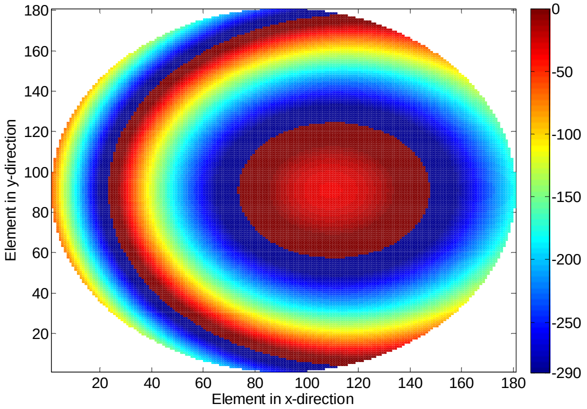
- Effects of the incidence angle practically negligible.
- Low cross-polarization.
- Moderate loss at THz.

Beam deflection and Reflectarrays

- Fixed-beam reflectarray at THz using graphene: whole array
  - Note: very accurate analysis/modelling based on a full-vectorial approach

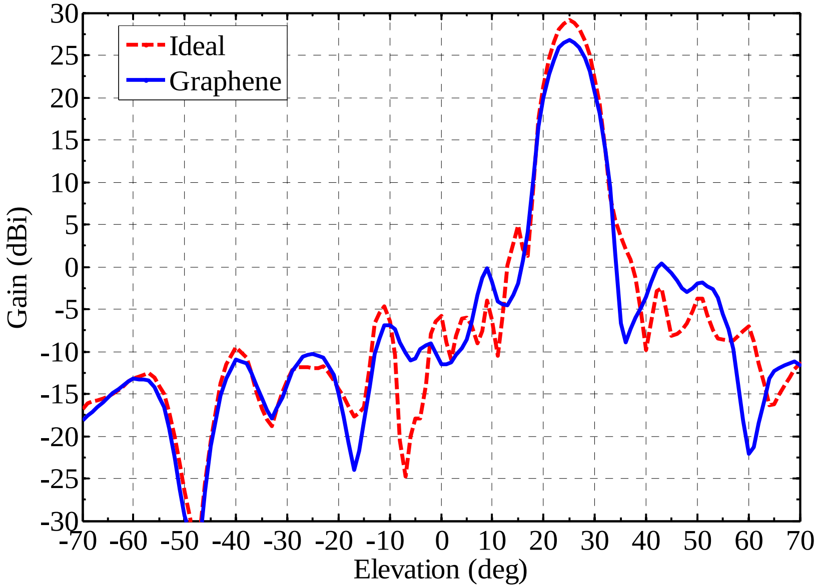


Required phase-shift at each element



MAIN FEATURES OF THE REFLECTARRAY ANTENNA

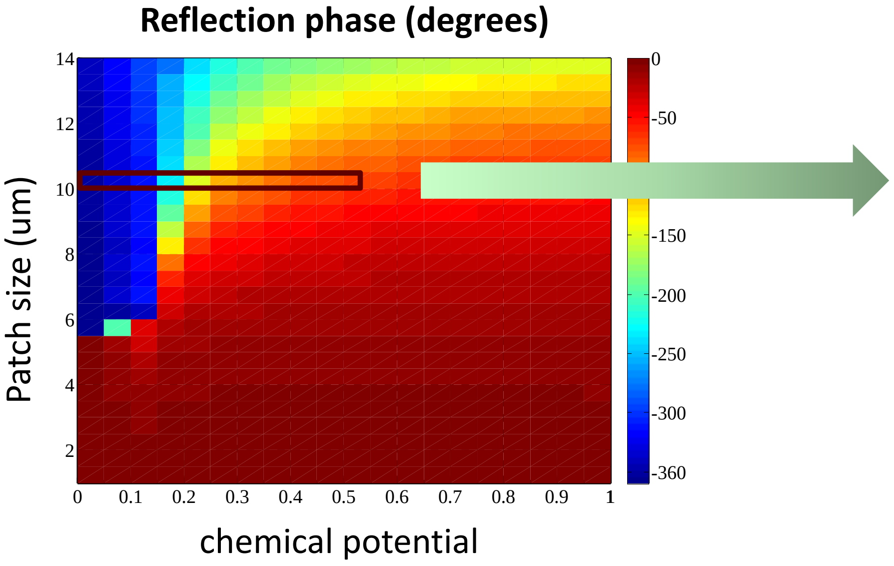
Frequency:		1.3 THz
Number of elements:		25448
Elements in the main axes:		180
Period:		14 µm (~λ/16)
Diameter:		2520 µm (~10.8λ)
Source position	X_s:	-820 µm
	Y_s:	0 µm
	Z_s:	2300 µm

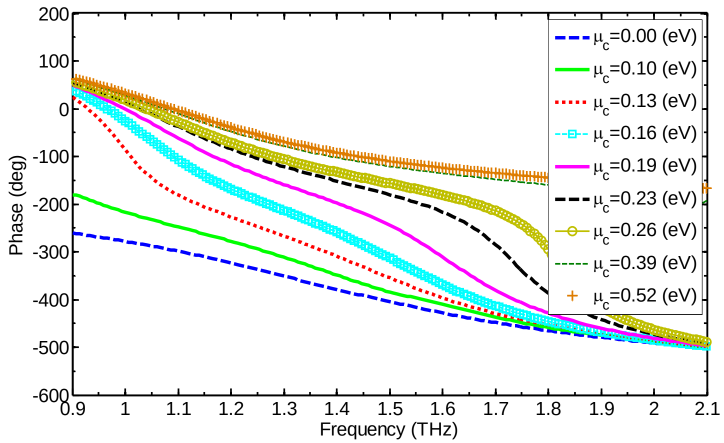


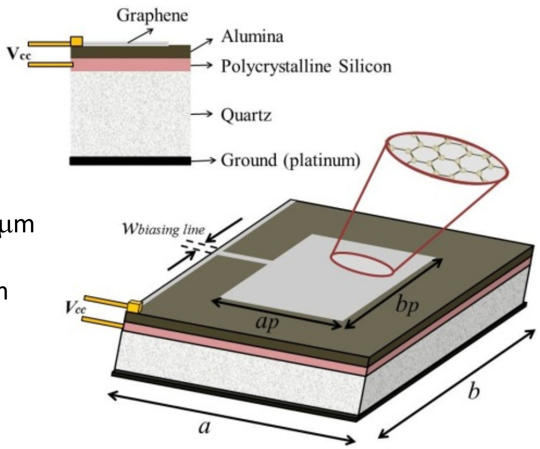
E. Carrasco et al. “Reflectarray Antenna at Terahertz Using Graphene”, IEEE Antennas and Wireless Propag. Lett., 2013.

Beam deflection and Reflectarrays

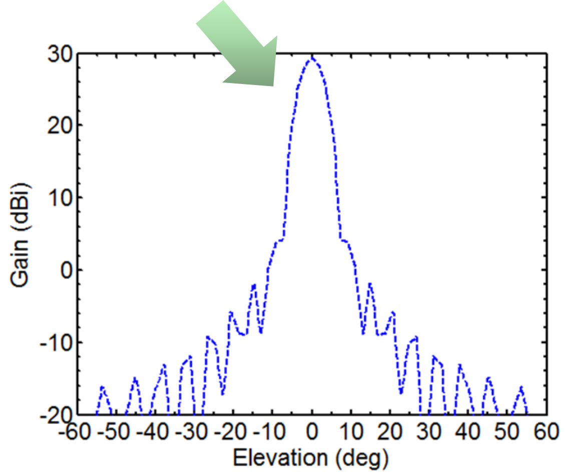
- <u>Reconfigurable-beam:</u> fixed-size elements but each cell independent control of chemical potential







a=b=14 μm
a_p=b_p=0 μm to 10 μm
h_{quartz}=30 μm
$h_{polysilicon}$=0.030 μm
$h_{alumina}$=0.010 μm



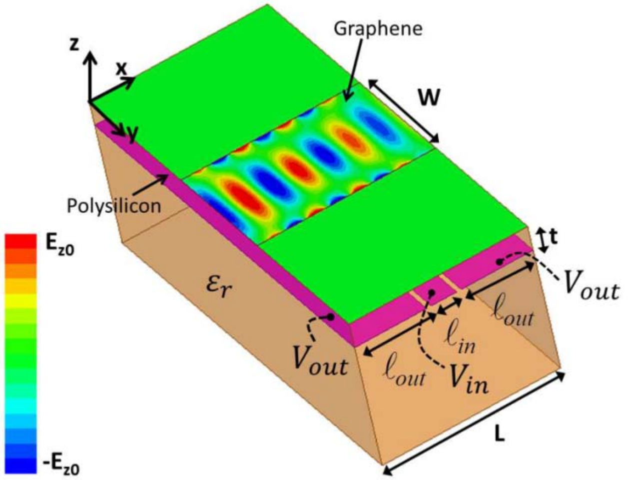
Potential excellent solution for THZ to IR highly-directive scanned beam !

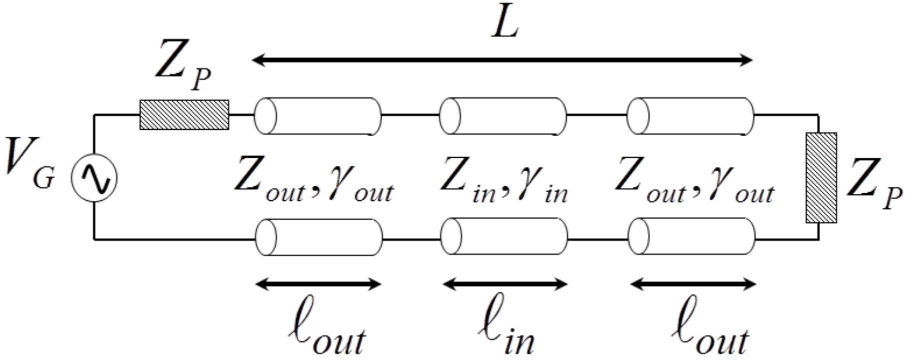
E. Carrasco et al. “Tunable Graphene Reflective Cells for THz Reflectarrays and Generalized Law of Reflection”, APL, 2013.

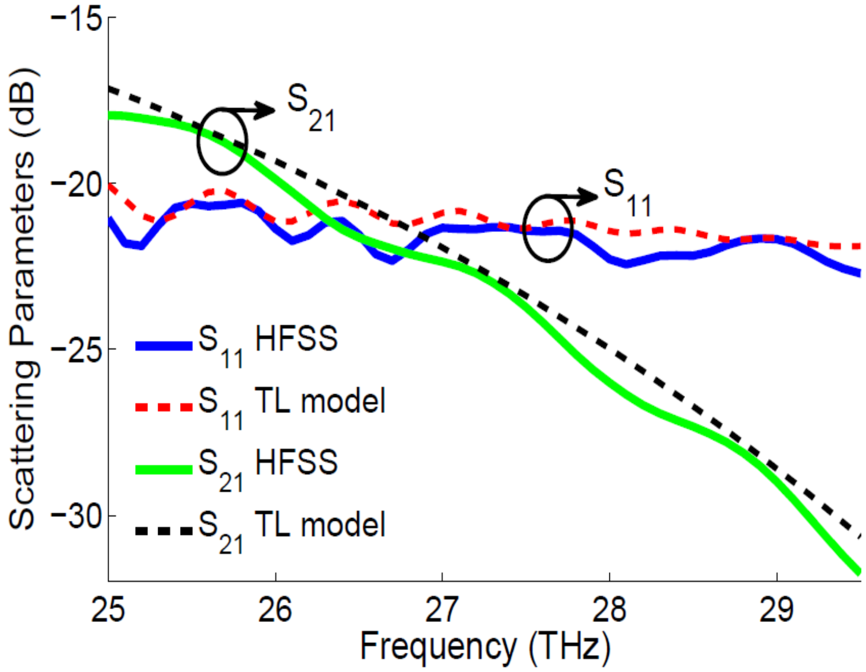
- Approach: conductivity model + Maxwell
- 2D-Periodic surfaces (metasurfaces)
  - B = 0
  - Faraday rotation
- Antennas
  - Resonant dipoles
  - Modulated leaky-wave antenna
- Beam deflection , reflectarray
- Plasmon wave-guiding
- Measurements

Plasmon waveguiding

- Transmission line model
  - Simple characterization of surface plasmon propagation on ribbons
  - Excellent agreement with FEM results







$$\mu_{cout} = 0.5\ eV\ ,\ \mu_{cin} = 0.2\ eV$$

$$\ell_{out} = \ell_{in} = 1\mu m$$

$$\tau = 0.15\ ps$$

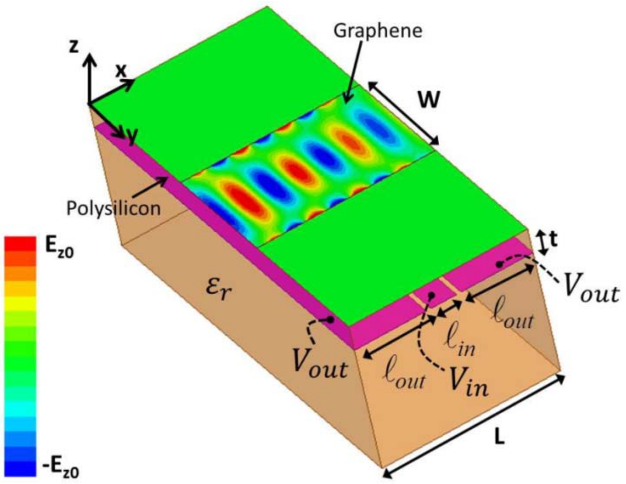
$$T = 300°\ K$$

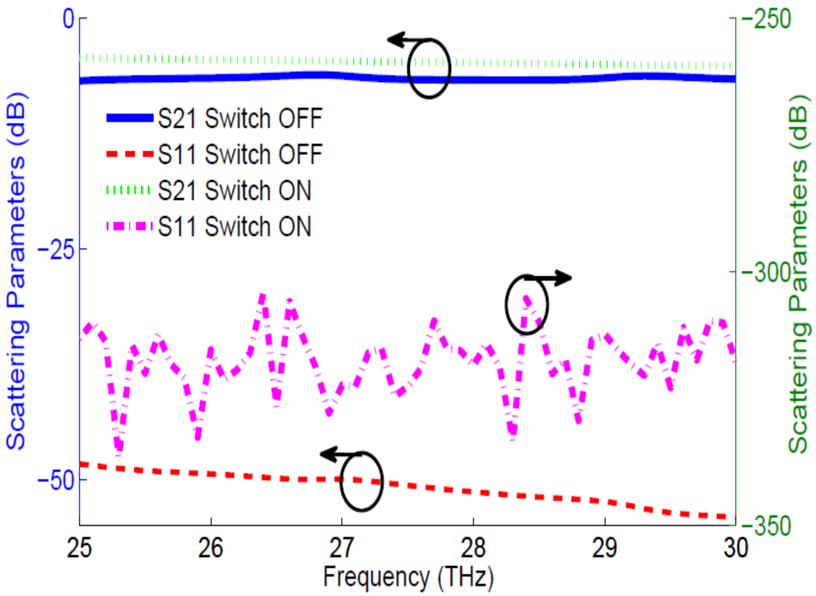
Plasmon waveguiding

- Plasmonic switch:

ON STATE

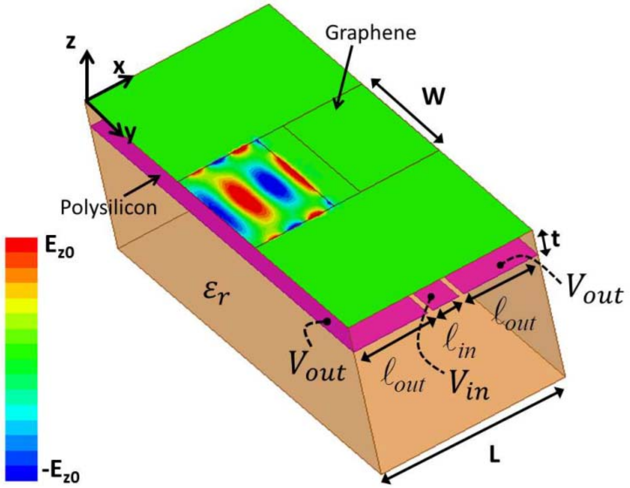
$$\mu_{cout} = 0.5\ eV$$
$$\mu_{cin} = 0.5\ eV$$





OFF STATE

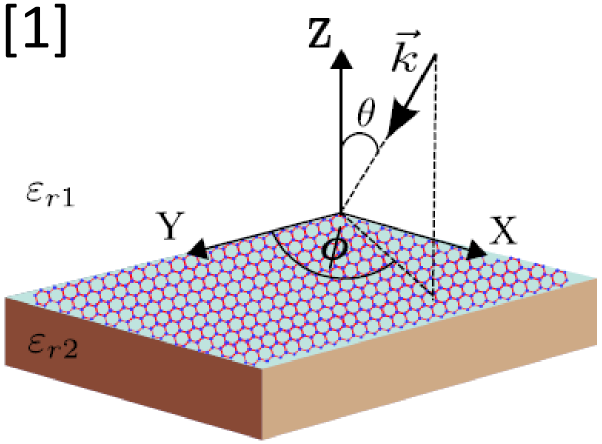
$$\mu_{cout} = 0.5\ eV$$
$$\mu_{cin} = 0.1\ eV$$



$$\ell_{out} = \ell_{in} = 0.25\ \mu m$$
$$\tau\ = 0.15\ ps$$
$$T = 300°\ K$$

Plasmon waveguiding

- Dispersion relation of SP on spatially dispersive (SD) graphene
  - Dyadic conductivity model, THz band [1]



$$\overline{\overline{\sigma}}(\omega, \mu_c, \tau, T) = \begin{pmatrix} \sigma_{x'x'} & \sigma_{x'y'} \\ \sigma_{y'x'} & \sigma_{y'y'} \end{pmatrix}$$

$$\sigma_{x'x'} = \sigma_{lo} + \alpha_{sd}\frac{\partial^2}{\partial x'^2} + \beta_{sd}\frac{\partial^2}{\partial y'^2}$$

$$\sigma_{y'y'} = \sigma_{lo} + \beta_{sd}\frac{\partial^2}{\partial x'^2} + \alpha_{sd}\frac{\partial^2}{\partial y'^2}$$

$$\sigma_{x'y'} = \sigma_{y'x'} = 2\beta_{sd}\frac{\partial^2}{\partial x'\partial y'} \qquad \beta_{sd} = \frac{\alpha_{sd}}{3}$$

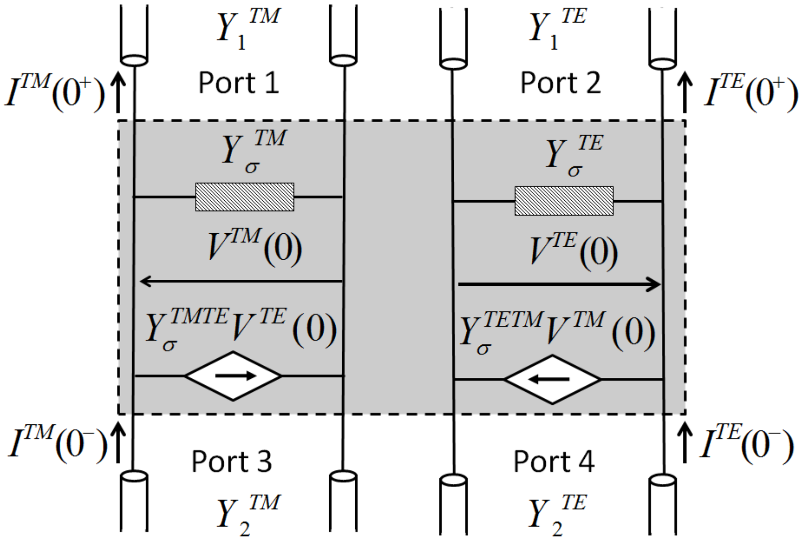
$$\alpha_{sd} = \frac{-3v_F^2\sigma_{lo}}{4(\omega - j\tau^{-1})^2} \qquad \sigma_{lo} = \frac{-jq_e^2 k_B T}{\pi\hbar(\omega - j\tau^{-1})}\ln\left[2\left(1+\cosh\left(\frac{\mu_c}{k_B T}\right)\right)\right]$$

  - Model only considers intraband contributions

[1] G. Hanson, "Dyadic green's functions for an anisotropic non-local model of biased graphene," IEEE Transactions on Antennas and Propagation, vol. 56, no. 3, pp. 747–757, March 2009.

Spatial dispersion effects on graphene sheets (II)

- Equivalent electromagnetic model
  - Transmission line model (transversal) + Transverse resonance equation (TRE)
    - Direct mapping between conductivity components and equivalent impedances



$$Y_\sigma^{TE}(k_\rho) = \sigma_{lo} + k_\rho^2[\alpha_{sd} + \beta_{sd}]$$
$$Y_\sigma^{TM}(k_\rho) = \sigma_{lo} + k_\rho^2[\alpha_{sd} + \beta_{sd}]$$
$$Y_\sigma^{TE/TM}(k_\rho) = Y_\sigma^{TM/TE}(k_\rho) = 0$$

  - Dispersion relation: TM Surface plasmon

$$\frac{\omega\varepsilon_{r1}\varepsilon_0}{\sqrt{\varepsilon_{r1}k_0^2 - k_\rho^2}} + \frac{\omega\varepsilon_{r2}\varepsilon_0}{\sqrt{\varepsilon_{r2}k_0^2 - k_\rho^2}} = -\left[\sigma_{lo} + k_\rho^2(\alpha_{sd} + \beta_{sd})\right]$$

R. E. Collin and F. J. Zucker, Antenna Theory. McGraw-Hill, 1969.

G. Lovat, “Equivalent circuit for electromagnetic interaction and transmission through graphene sheets,” IEEE Transactions on Electromagnetic Compatibility, vol. 54, pp. 101–109, February 2012.

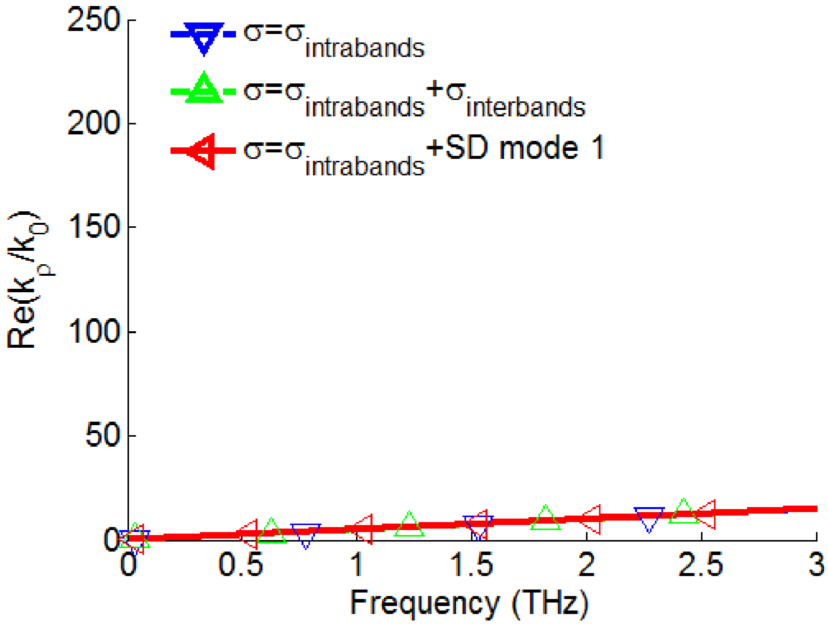
Plasmon waveguiding

- Surface plasmons on spatially dispersive graphene sheets:
  - SD usually negligible at low THz range

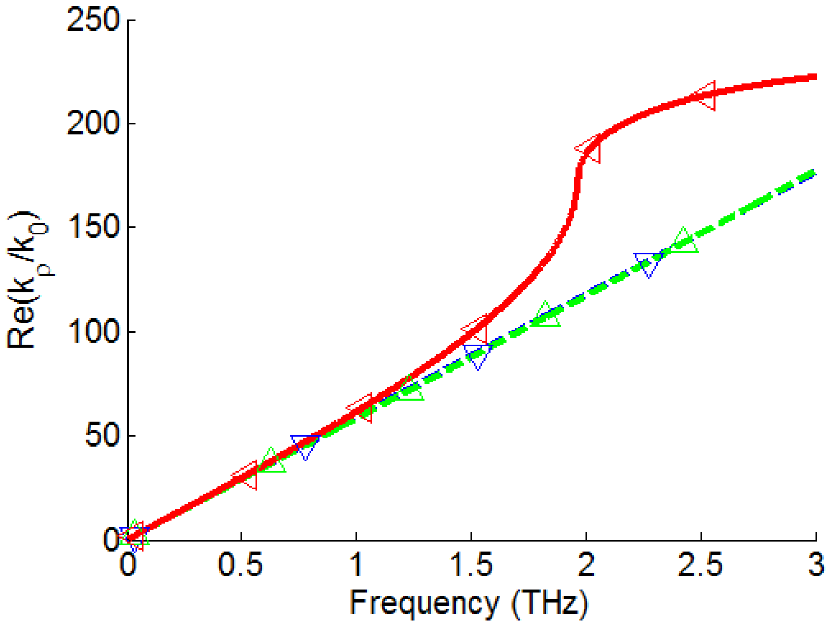
    (e.g. free-space suspended graphene)
  - SD cannot be neglected if ε_r↑↑

$$\mu_c = 0.05\ eV$$
$$\tau = 0.15\ ps$$
$$T = 300°\ K$$

Graphene in ε_r=1



Graphene in ε_r=11.9



J. S. Gómez-Díaz, J. R. Mosig, and J. Perruisseau-Carrier, "Effect of spatial dispersion on surfaces waves propagating along graphene sheets," arXiv:1301.1337, 2012.

- Approach: conductivity model + Maxwell
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  - B = 0
  - Faraday rotation
- Antennas
  - Resonant dipoles
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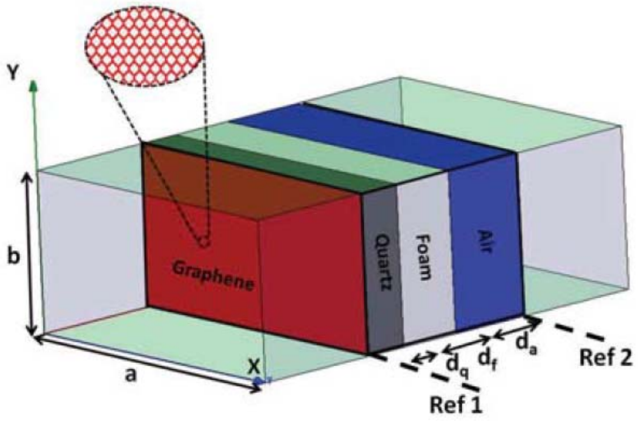
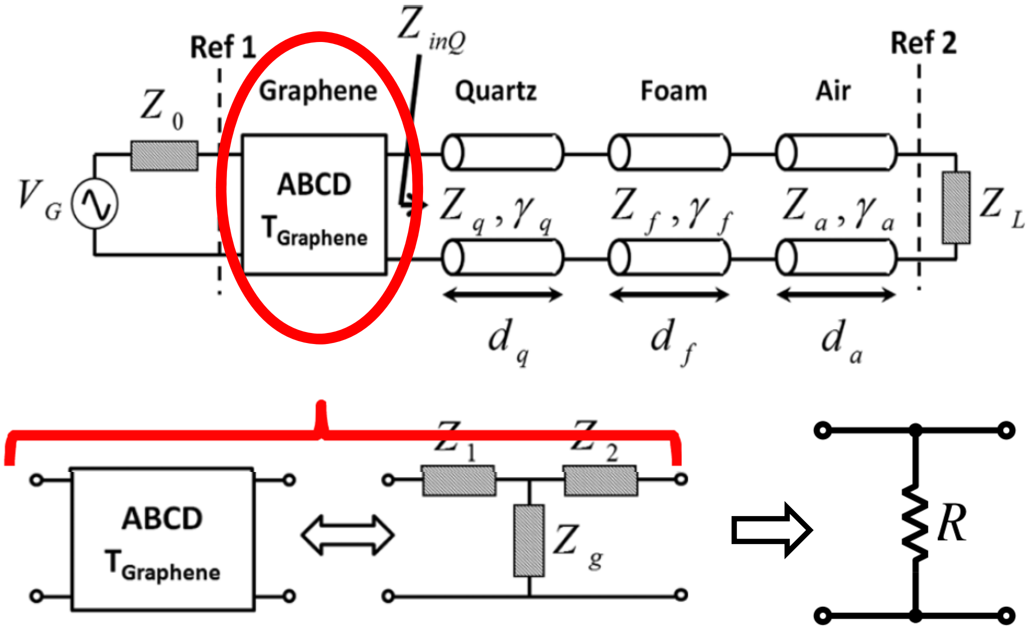
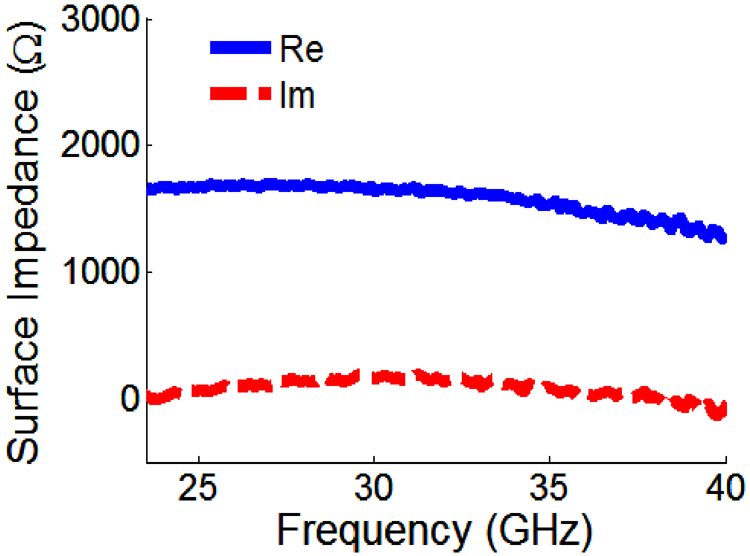
Measurements

- Micro-millimeter waves
  - Contactless RWG-based measurement.
  - Extraction with “self-calibration procedure”
  - Complex surface impedance obtained





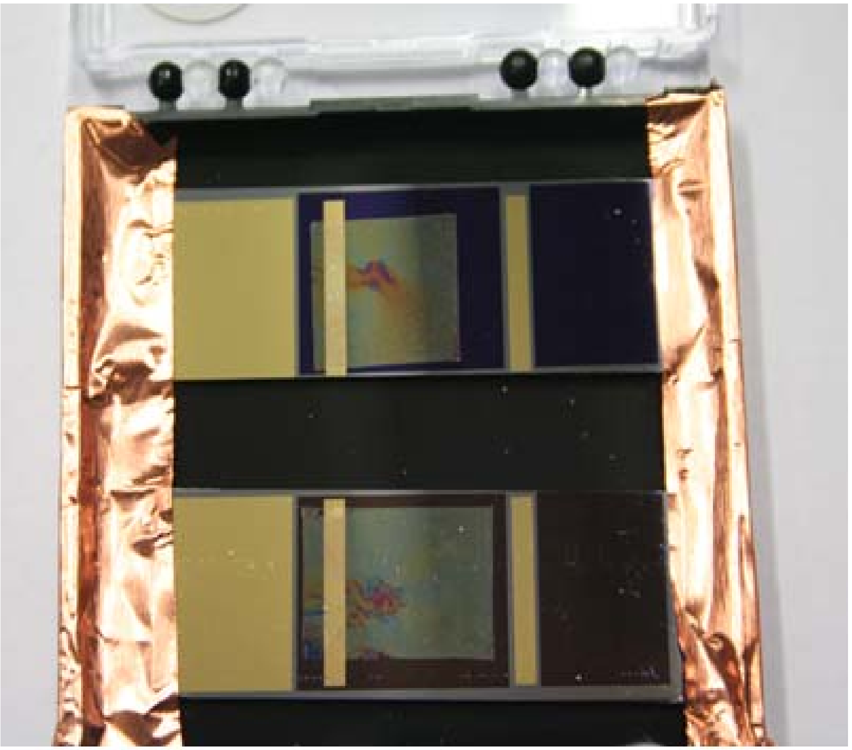


J.S. Gomez-Diaz et al “Non-Contact Characterization of Graphene Surface Impedance at Micro and Millimeter Waves” Journal of Applied Physics, 111, 114908, 2012.

Measurements

- Terahertz (under progress)
  - Multilayer graphene structures
  - THz TDS (collaboration with UPC, Spain)

Samples fabricated at EPFL



Thanks a lot for your attention !
Any questions ?

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mnwave.epfl.ch