Pros and Cons of Patterning Graphene Layers

to the memory of Prof. Perruisseau-Carrier

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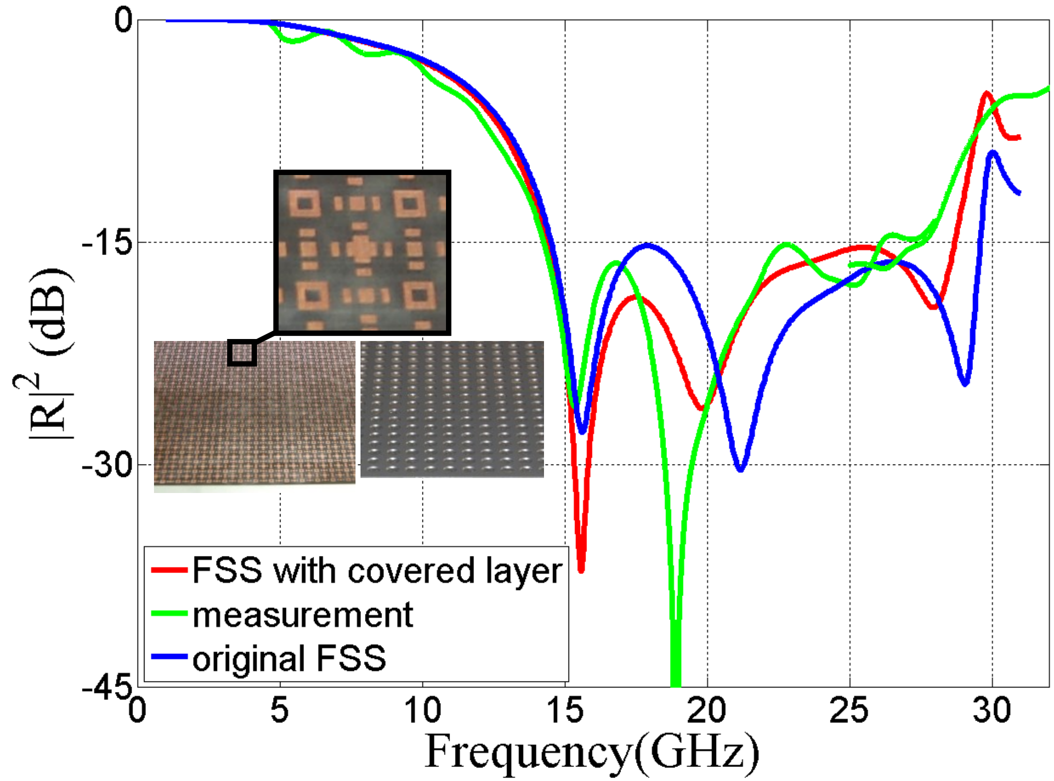
Outline

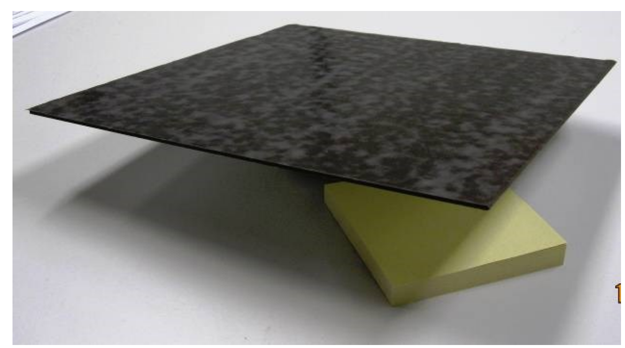
- My acquaintance with Julien
  - Metamaterial absorbers research in Zurich
  - The idea of patterning graphene layers
- Graphene metasurfaces
  - Modified PMoM
  - Tunable metasurfaces
  - Giant Faraday rotation
  - Fundamental limits
  - Nonlocal response
- Conclusion

Deutsches Elektronen Synchrotron (DESY)

Metamaterial absorbers

PhD research in ETH Zurich





A. Fallahi et al. IEEE TAP 2010

The idea of patterning graphene layers

Diffraction Analysis of FSS

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FSS with periodic substrate (MoM/TL)

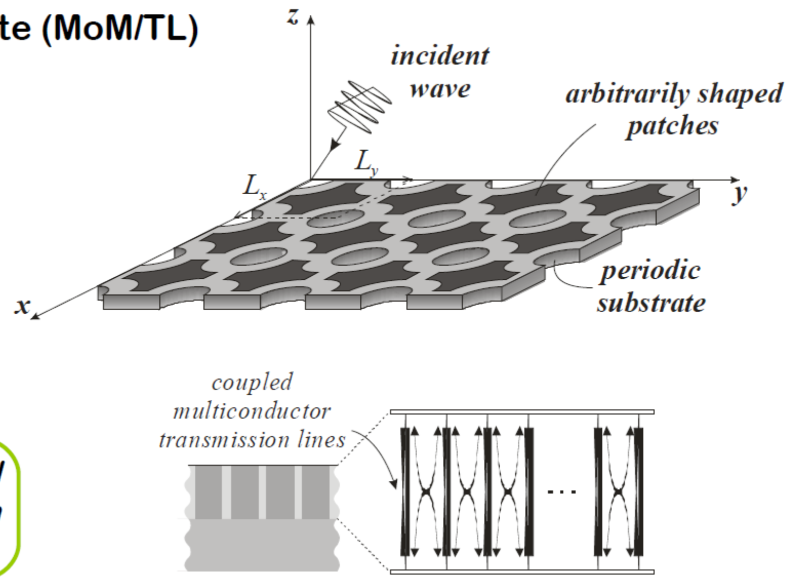
Solved using MoM

$$\mathbf{E}_t^{\mathrm{inc}} = \mathcal{L}'\mathbf{J}$$

$$\mathbf{E}_t^{\mathrm{scat}} = \mathcal{L}\mathbf{J}$$

Computed using the coupled multiconductor transmission line (TL) model

$$\mathbf{E}_t^{\mathrm{diff}} = \mathbf{E}_t^{\mathrm{scat}} + \mathbf{E}_t^{\mathrm{ref}}$$



MoM/TL method

Fallahi et al. Elsevier Metamaterials, Oct. 2009.

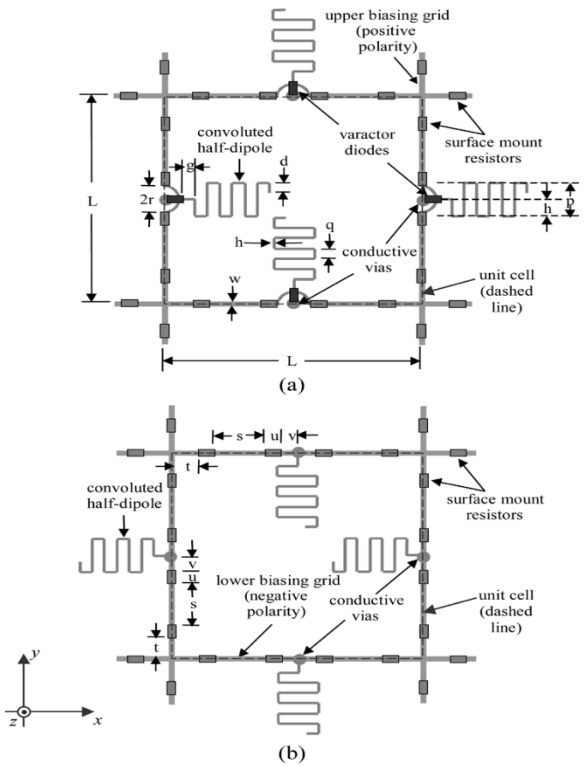
ETH Eidgenössische Technische Hochschule Zürich
Swiss Federal Institute of Technology Zurich

Laboratory for Electromagnetic Fields and Microwave Electronics (IFH)

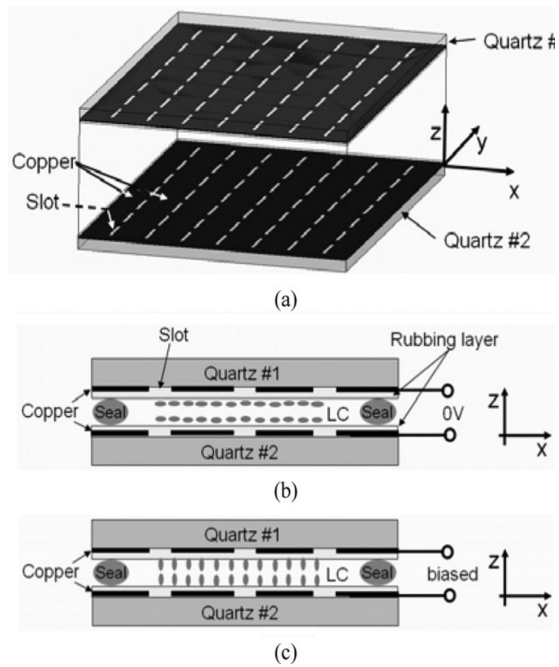
Can we consider graphene as the patches in your FSS structures?

Dynamic Frequency Selective Surface

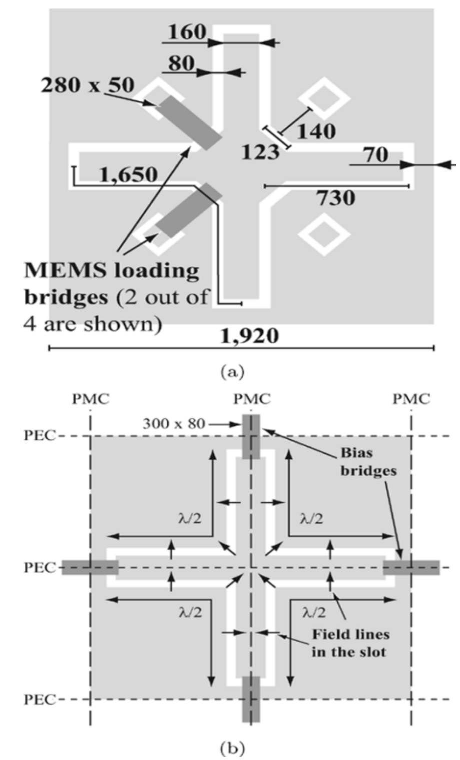
periodic arrangement of metals in a surface with a dynamic response



Varactor diodes

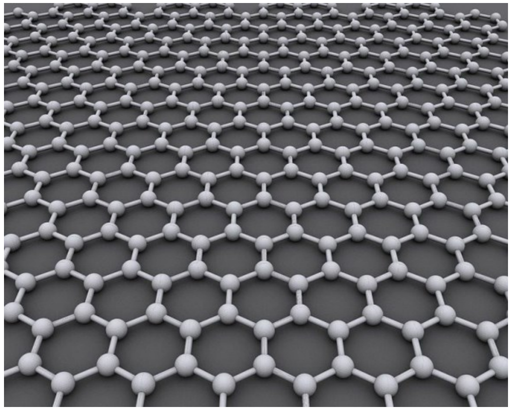


Liquid crystals



MEMS switches

A promising solution to the mentioned problems is *graphene*



A 2D honeycomb lattice made of carbon atoms

- 2D atomic lattice
- Electrons behaving as massless Dirac Fermions
- Large electron mobilities
- Transparent conductivity
- Large nonlinear Kerr effect

...

Electrically tunable conductivity

Electromagnetic properties of patterned graphene

For modeling patterned graphene surfaces, graphene conductivity is needed.

$$\mathbf{E} = Z\mathbf{J} \qquad \rightarrow \qquad \mathbf{E} = \mathbf{Z}\mathbf{J} \qquad with \qquad \mathbf{Z} = [\sigma]^{-1}$$

$$\underline{\vec{\sigma}}(\omega, \mu_c(\mathbf{E}_0), \Gamma, T, \mathbf{B}_0) = \begin{bmatrix} \sigma_{xx} & \sigma_{xy} \\ \sigma_{yx} & \sigma_{yy} \end{bmatrix}$$

$$\sigma_{xx} = \alpha\frac{\partial^2}{\partial x^2} + \beta\frac{\partial^2}{\partial y^2} + \sigma_d$$

$$\sigma_{xy} = 2\beta\frac{\partial^2}{\partial x \partial y} + \sigma_o$$

$$\sigma_{yx} = 2\beta\frac{\partial^2}{\partial x \partial y} - \sigma_o$$

$$\sigma_{yy} = \beta\frac{\partial^2}{\partial x^2} + \alpha\frac{\partial^2}{\partial y^2} + \sigma_d$$

Kubo formalism

The conductivity is dispersive, anisotropic, bias dependent and most important of all, it is an *operator*.

In the periodic Method of Moments, we work in the spectral domain:

$$f(x,y) = \frac{1}{(2\pi)^2}\int_{-\infty}^{+\infty}\int_{-\infty}^{+\infty} \tilde{f}(\alpha,\beta)e^{j\alpha x}e^{j\beta y}\mathrm{d}\alpha\,\mathrm{d}\beta$$

$$\mathbf{J}(\mathbf{r}+\mathbf{L}_{mn}) = \mathbf{J}(\mathbf{r})e^{j\mathbf{k}_{\mathrm{inc}}\cdot\mathbf{L}_{mn}} \Rightarrow \mathbf{J}(\mathbf{r}) = \sum_{m=-\infty}^{+\infty}\sum_{n=-\infty}^{+\infty}\tilde{\mathbf{J}}_{mn}e^{jk_{xmn}x}e^{jk_{ymn}y}$$

$$\boxed{\frac{\partial}{\partial x} \equiv j\mathbf{k_x} \quad \text{and} \quad \frac{\partial}{\partial y} \equiv j\mathbf{k_y}}$$

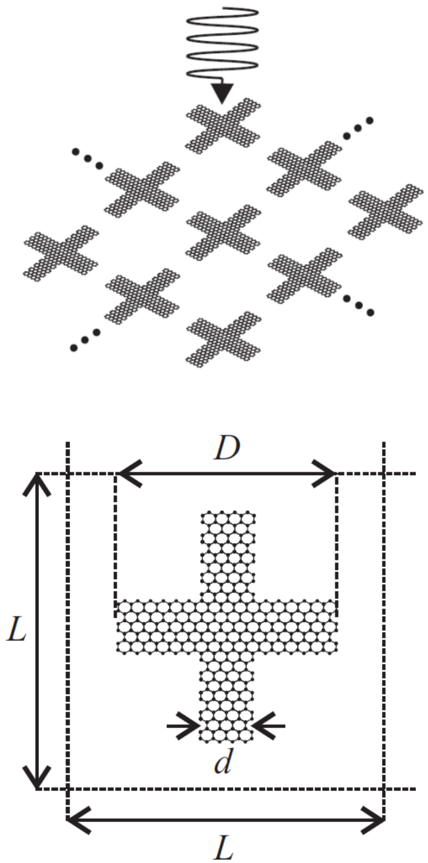
$$\Downarrow$$

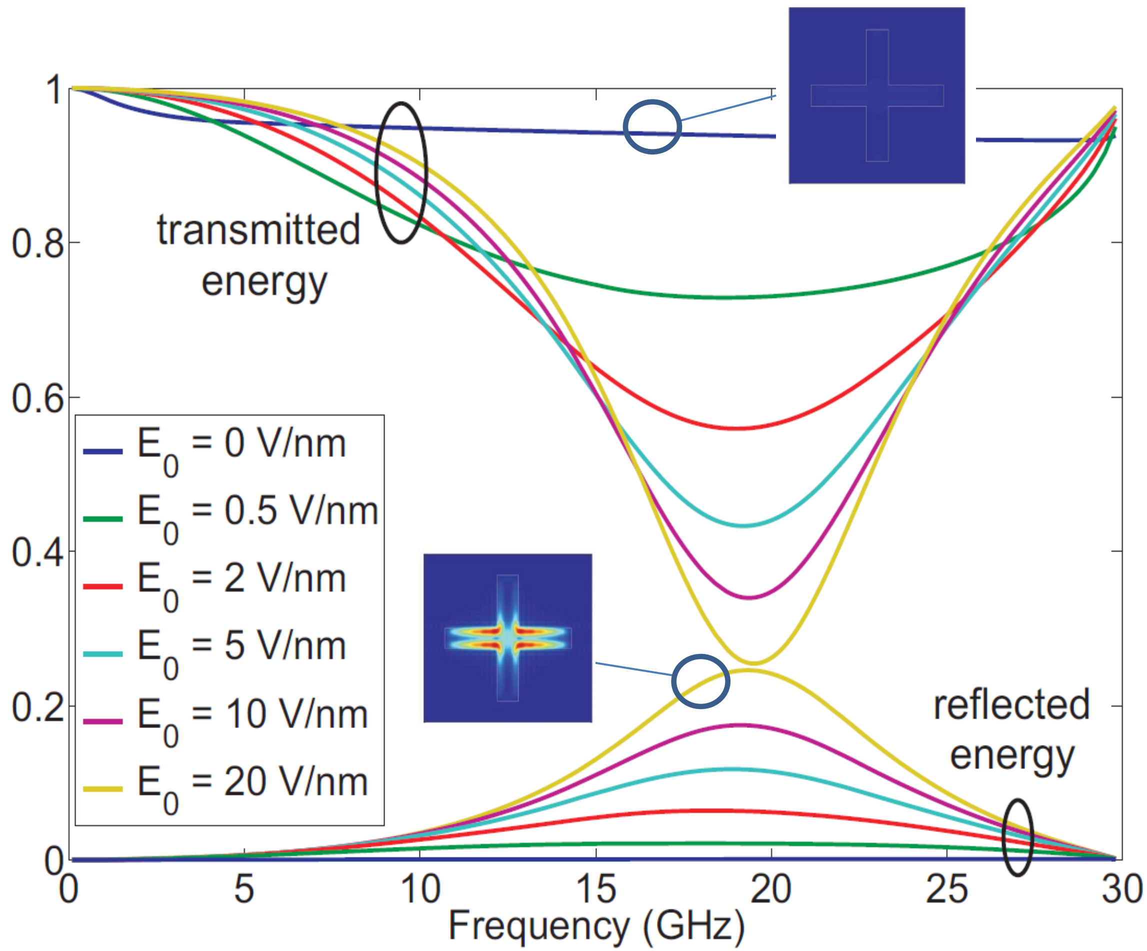
$$\begin{bmatrix} \tilde{\mathbf{J}}_x \\ \tilde{\mathbf{J}}_y \end{bmatrix} = \begin{bmatrix} \sigma_d - \alpha\mathbf{k_x}^2 - \beta\mathbf{k_y}^2 & \sigma_o - 2\beta\mathbf{k_x}\mathbf{k_y} \\ -\sigma_o - 2\beta\mathbf{k_x}\mathbf{k_y} & \sigma_d - \beta\mathbf{k_x}^2 - \alpha\mathbf{k_y}^2 \end{bmatrix} \begin{bmatrix} \tilde{\mathbf{E}}_x \\ \tilde{\mathbf{E}}_y \end{bmatrix}$$

Modified PMoM for Graphene Metasurface

PMoM is generalized for the analysis and simulation of periodic graphene metasurfaces:

- Arbitrary number of layers
- Arbitrary shapes for the unit cell configuration
- Full vectorial and arbitrary angles of incidence
- Subdomain, entire domain and largely overlappling subdomain basis functions (A. Fallahi et al, IEEE-MTT 2010)
- Simulation of a single cell of the periodic structure (Floquet)
- discretization of conductive layers only
- Both periodic and homogeneous substrates
- Non-diagonal conductivity for B ≠ 0 and spatially-dispersive conductivity
- Metal-graphene hybrid layers are recently implemented

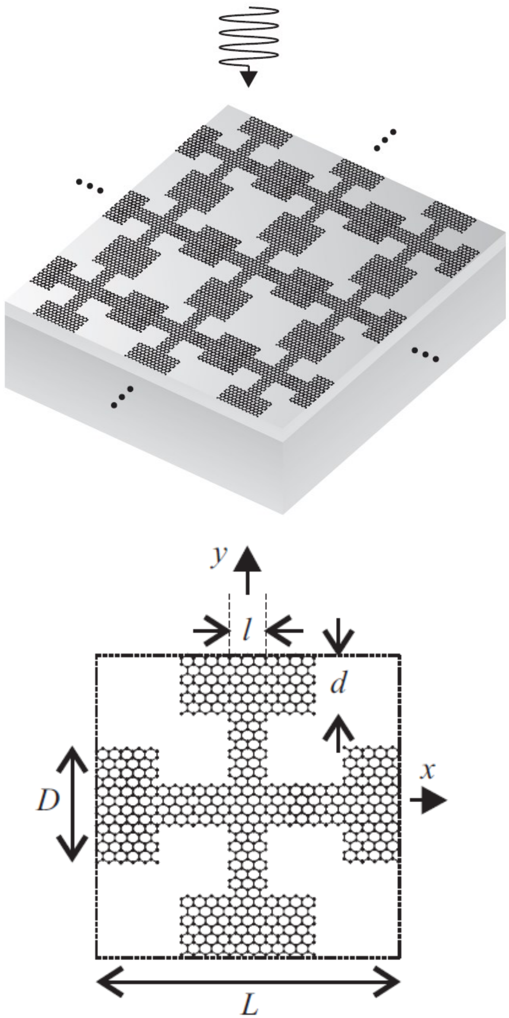


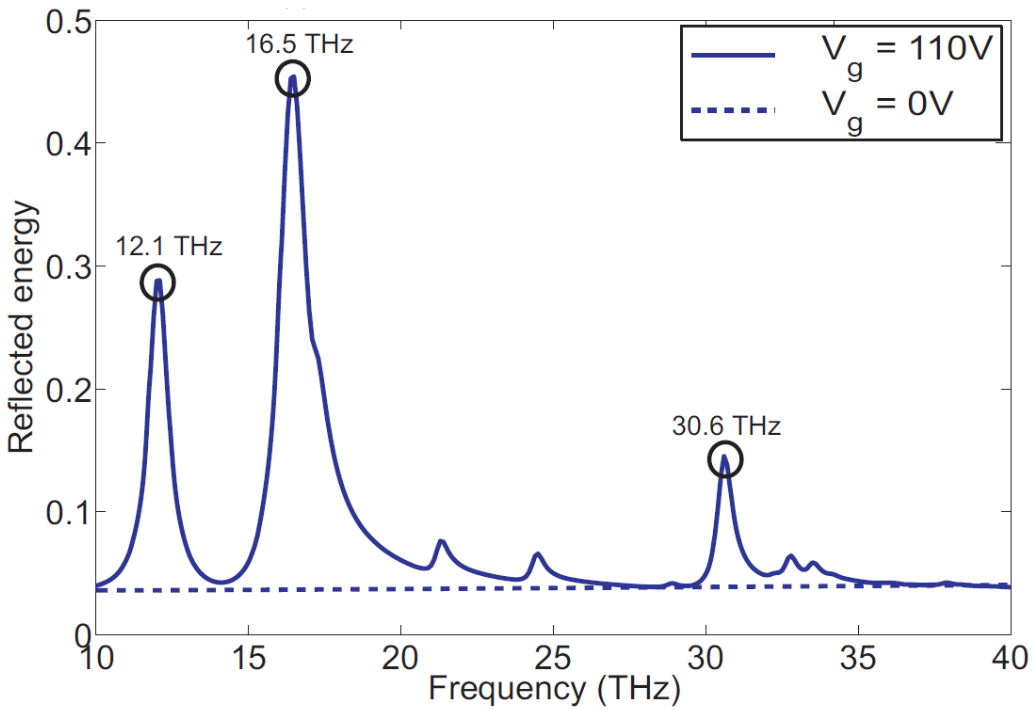


L=10mm, D=7.5mm and d=1.25mm

A. Fallahi and J. Perruisseau-Carrier, PRB, 2012.

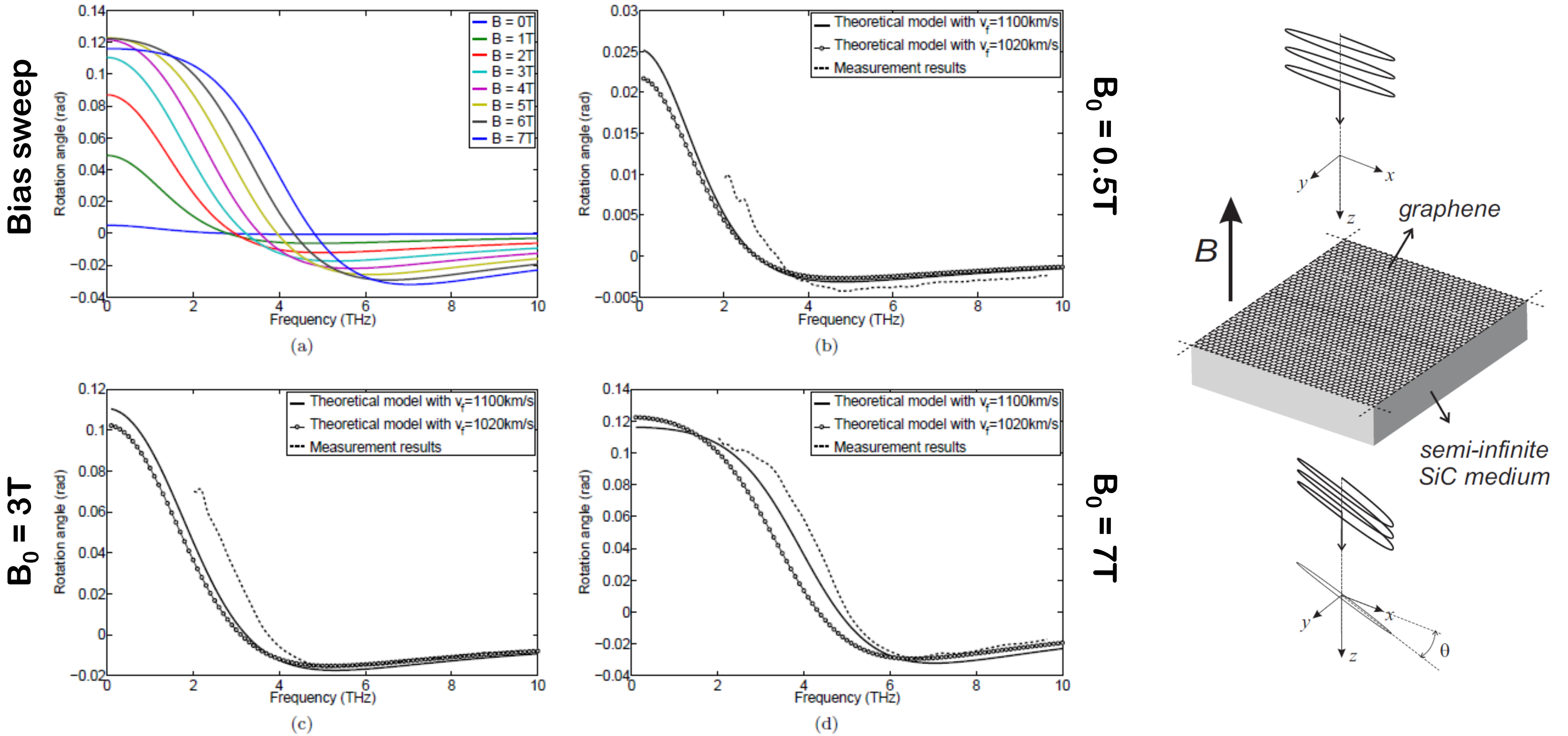
Examples of Graphene Metasurfaces





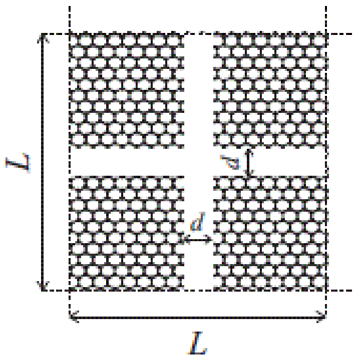
L = 5 μm, l = 0.5 μm, d = 1.25 μm, and D = 1.5 μm and the dielectric thickness is t = 50 nm.

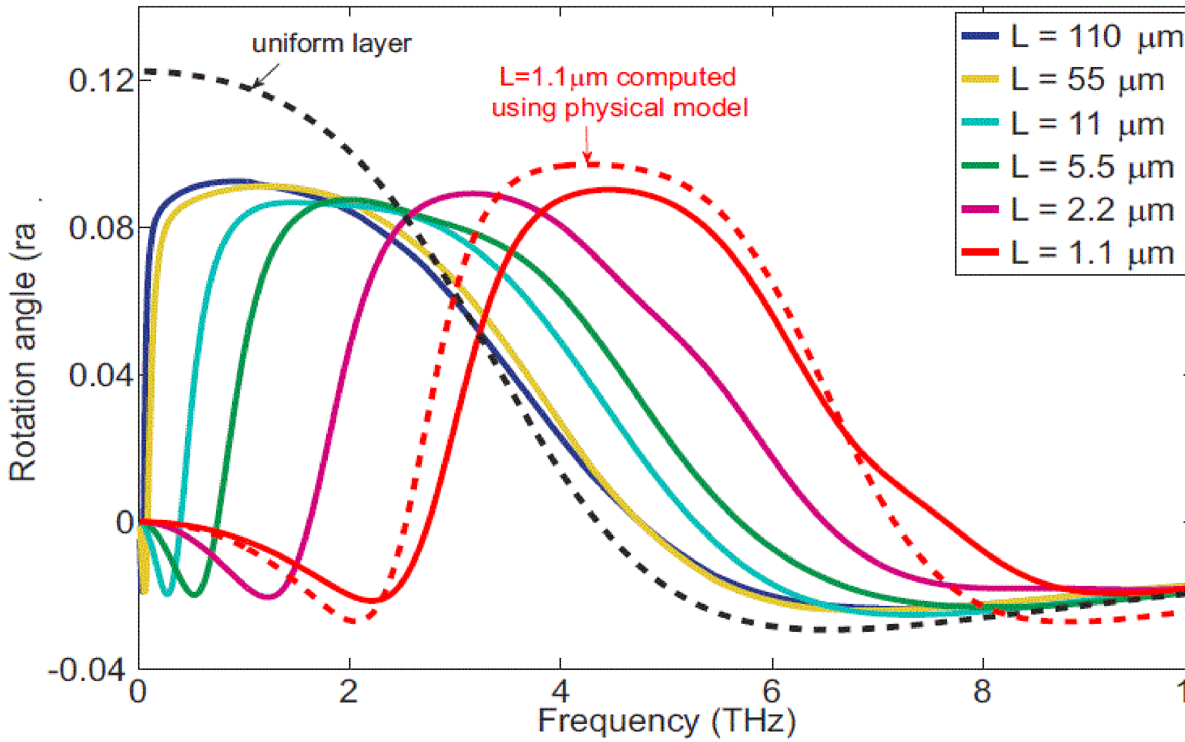
Giant Faraday rotation



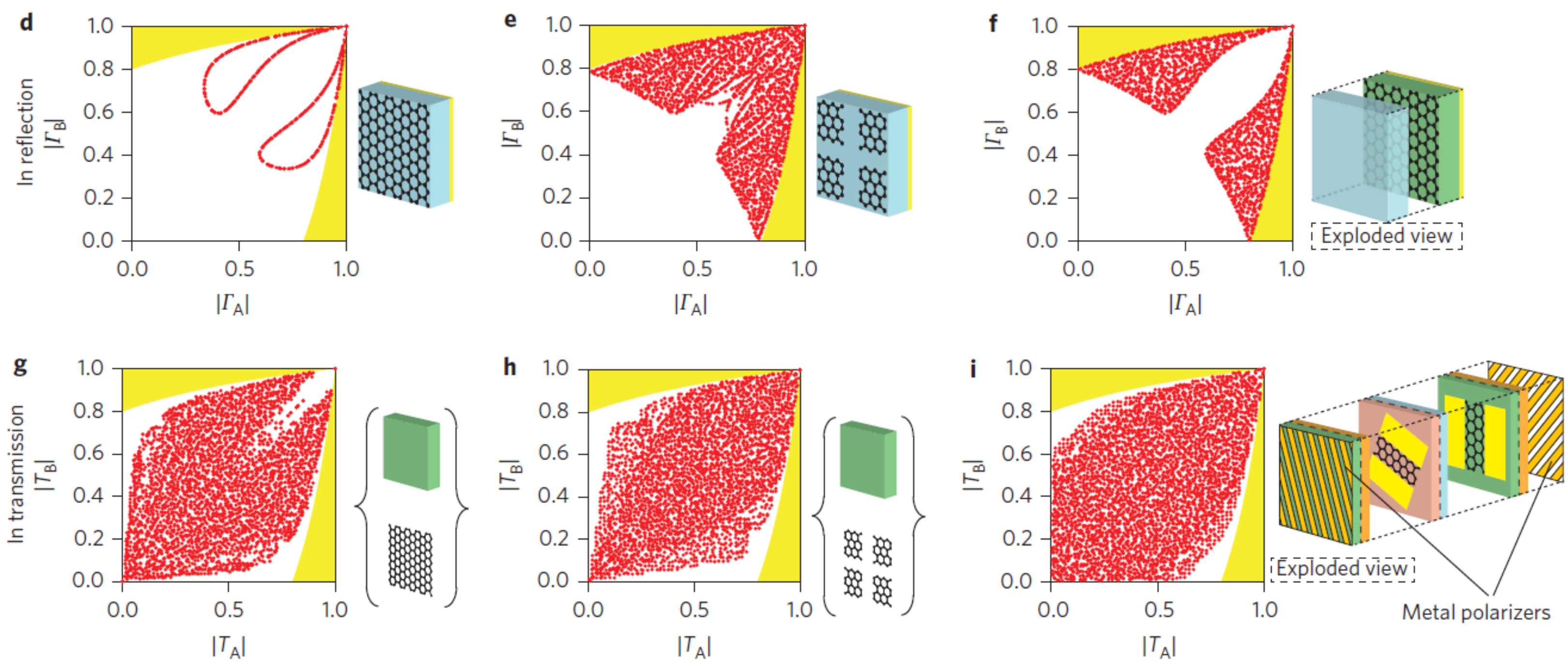
I. Crassee, et al. "Giant Faraday rotation in single- and multilayer graphene", Nature Physics 7 (2011) 48-51.

Giant Faraday rotation





A. Fallahi and J. Perruisseau-Carrier, APL, 2012.



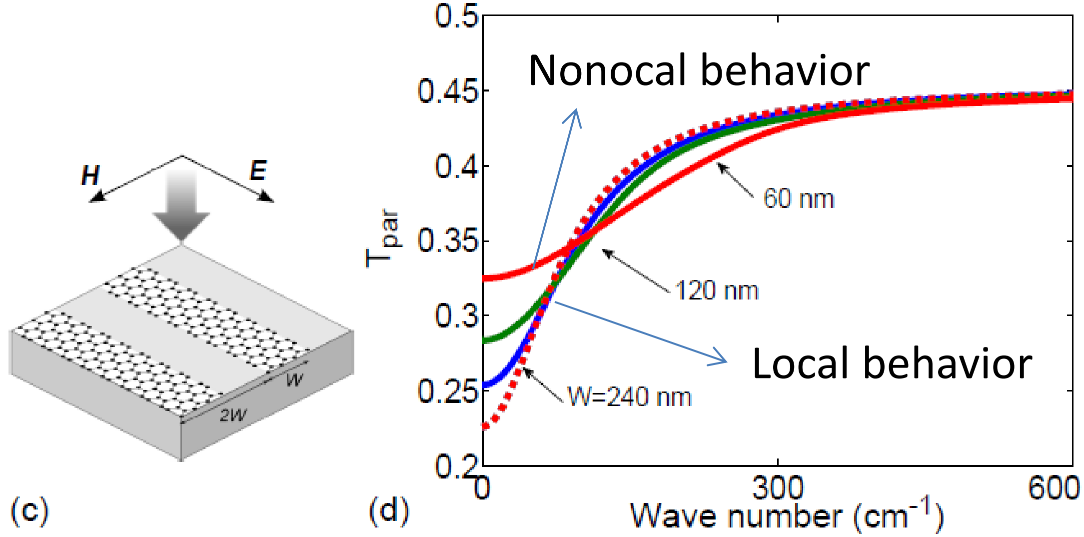
There seem to exist fundamental limits in the operation of graphene nonreciprocal structures.

$$\gamma_{\mathrm{mod}R}\left(\left|\Gamma_{\mathrm{A}}\right|, h\right) \triangleq \frac{\left(2h\left|\Gamma_{\mathrm{A}}\right|\right)^2}{\left(1-\left|\Gamma_{\mathrm{A}}\right|^2\right)\left((1+h)^2-\left|\Gamma_{\mathrm{A}}\right|^2(1-h)^2\right)} \leq \gamma_{\mathrm{M}}$$

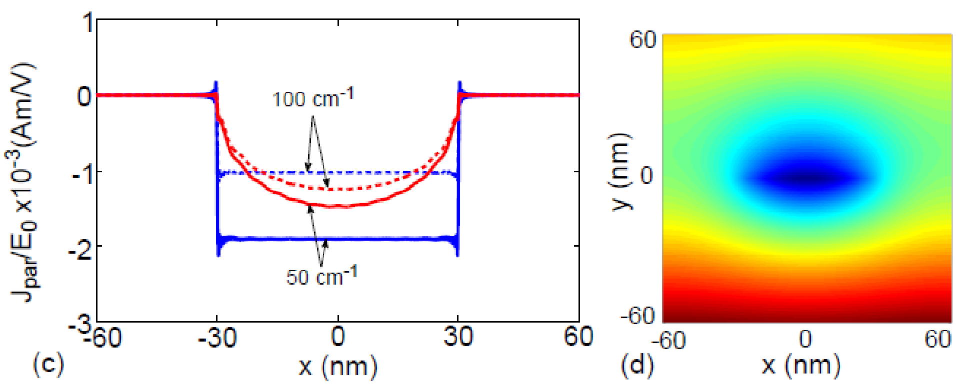
M. Tamagnone et al, Nat. Photonics, 2014. (*Today talk in graphene session*)

Nonlocal response of graphene

General form of the conductivity constitutive relation: $\boldsymbol{J}(\boldsymbol{r}) = \sigma(\boldsymbol{\nabla}, \boldsymbol{r})\boldsymbol{E}(\boldsymbol{r})$



Nonlocal effects are recently seen to be important in miniaturized structures.



A. Fallahi et al, 2015 PRB rapid communication.

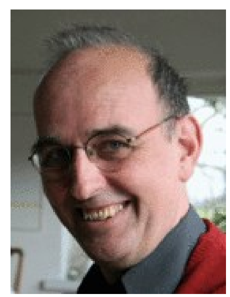
Acknowledgements

We missed him far too soon

EPFL

DESY and MIT

ETHZ



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