Plasmonic Devices and Spatial Dispersion Effects in Graphene Technology for Terahertz Applications

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Prof. Julien Perruisseau-Carrier

- I met Prof. Perruisseau-Carrier during my undergraduate studies, in 2012.
  - He came to UPCT, Spain, to present the on-going research of his group.

- Later we started a UPCT-EPFL collaboration on graphene plasmonics.

Outline

- Reconfigurable Graphene-based Plasmonic Lowpass Filters
- Spatial Dispersion in Graphene Plasmonic Waveguides
- Conclusions

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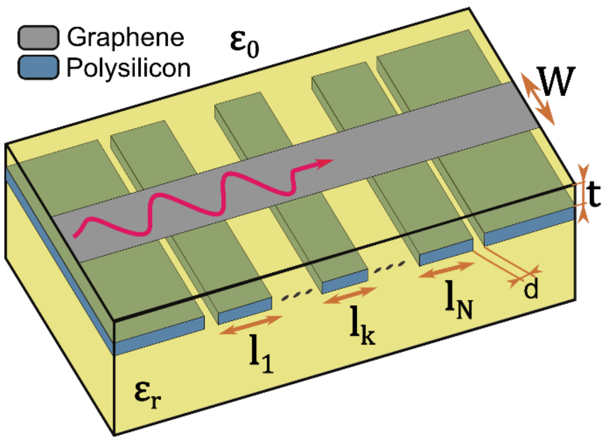
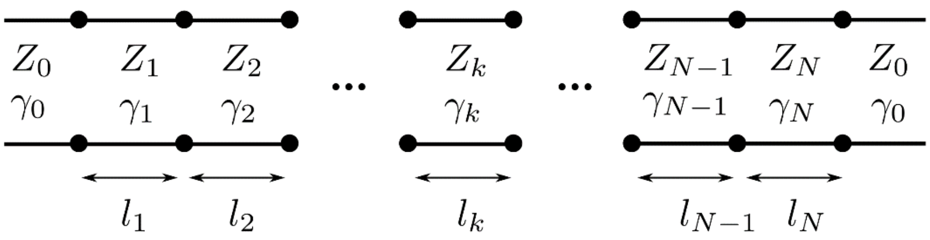
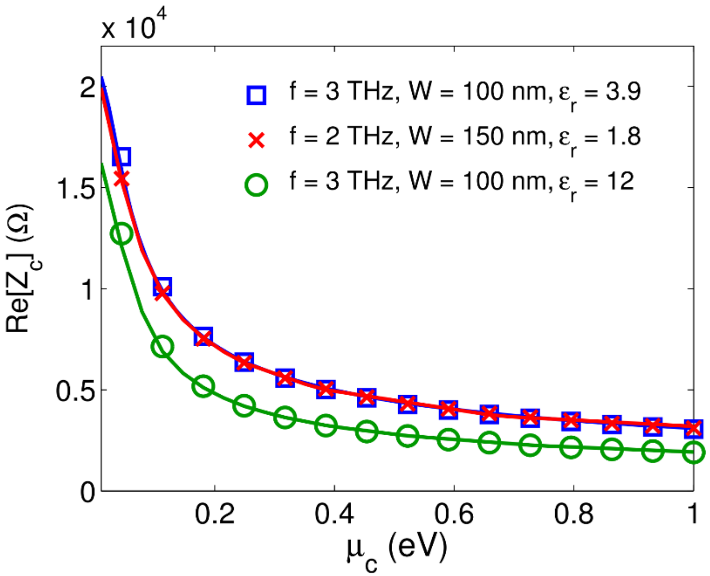
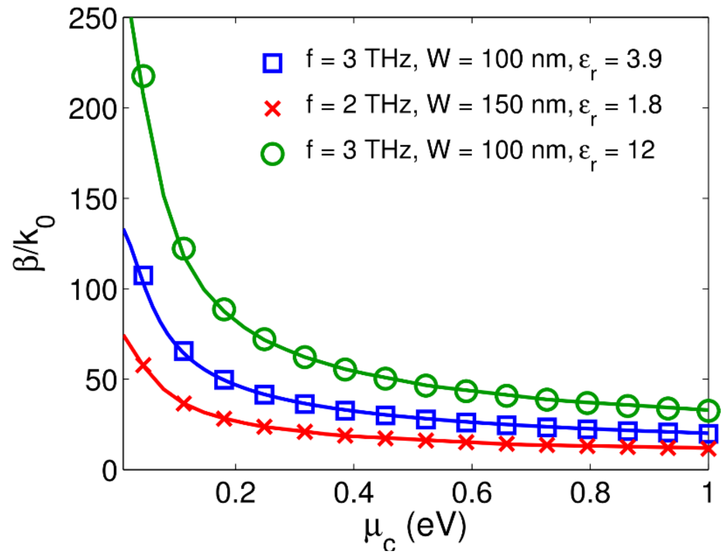
Reconfigurable LPF In Graphene Nanoribbons





$$\mu_c \approx \hbar v_F \sqrt{\frac{\pi C_{ox}(V_{DC} - V_{Dirac})}{e}}$$



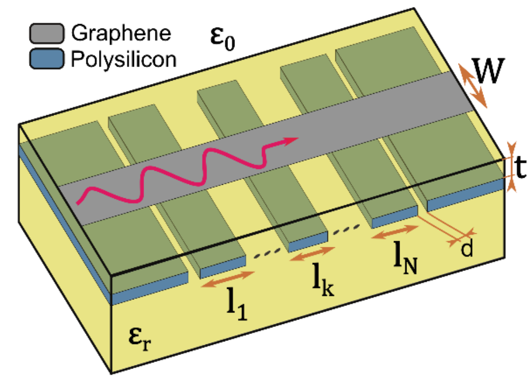


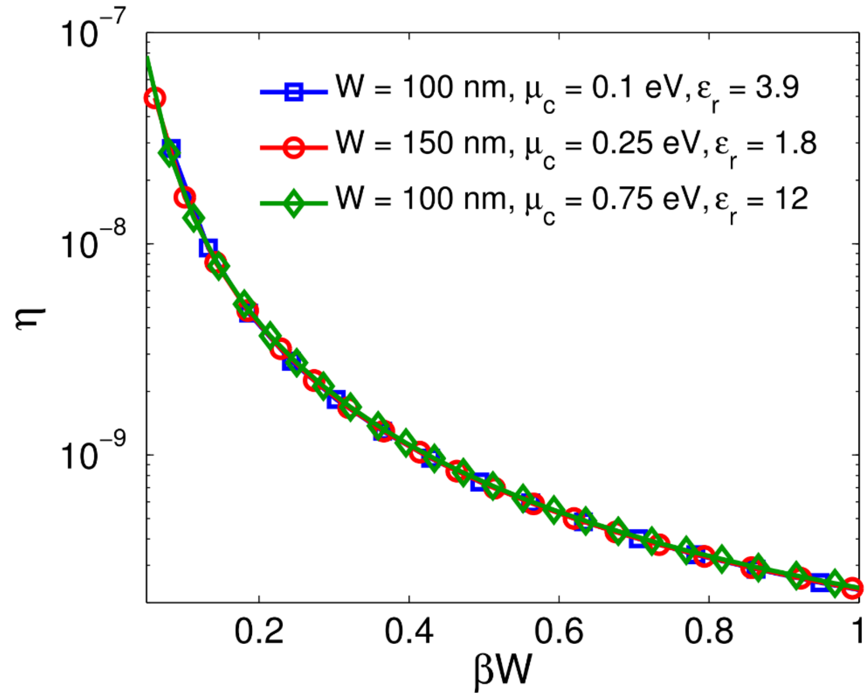
D. Correas-Serrano, J. S. Gomez-Diaz, J. Perruisseau-Carrier and A. Alvarez-Melcon, "Graphene based plasmonic tunable low pass filters in the THz band," IEEE Transactions on Nanotechnology.

Quasi-static Approximation for Modal Dispersion

- Generalization of modal dispersion from a ***single simulation***.

$$\boxed{\eta = \frac{Im[\sigma(f_\beta)]}{W f_\beta \varepsilon_{eff}}}$$





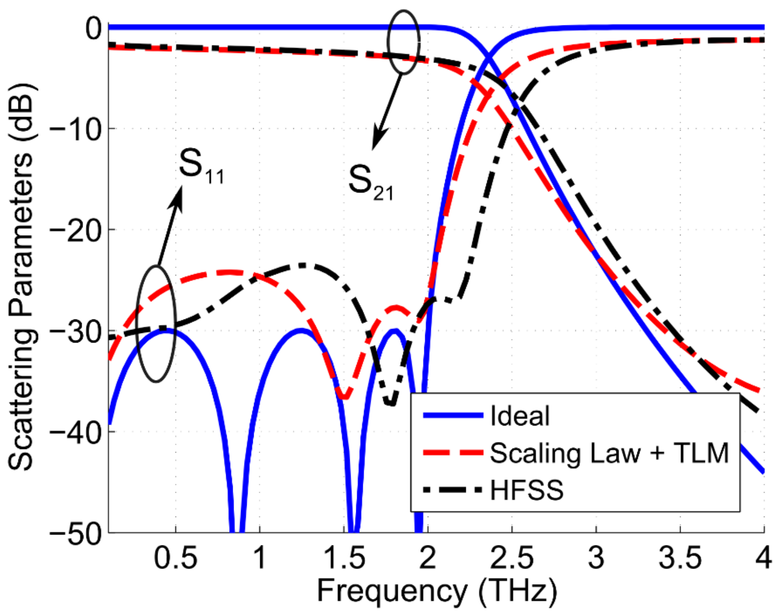
1. η *vs* βW
2. Compute η with $(\sigma, f, W, \varepsilon_r)$
3. Extract $\beta W \rightarrow \beta \rightarrow Z_c$

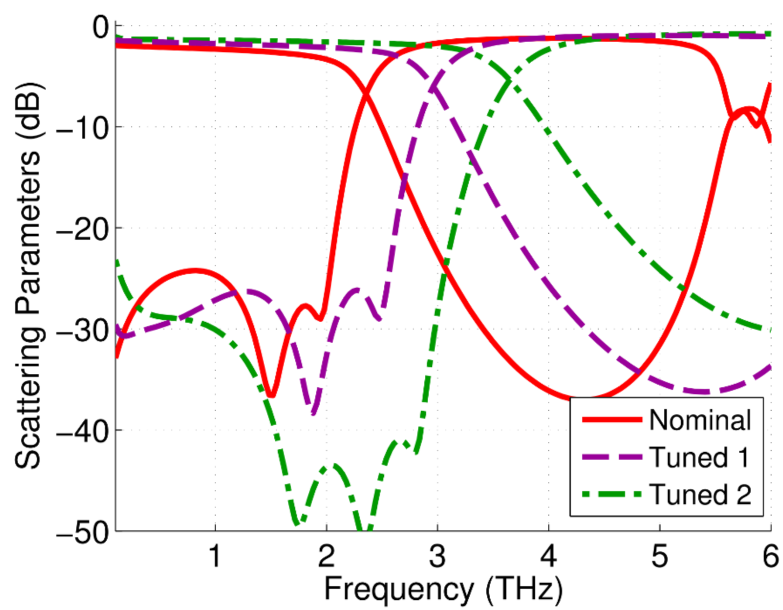
$$\boxed{\alpha = \frac{1}{2 v_g \tau}}$$

4. Transfer matrix + TL

- $N = 7, \ \theta_c = 37º, \varepsilon_r = 1.8, W = 150 \, nm, f_c = 2.3 \, THz$

Section	$\bar{Z}$	l (nm)	$\mu_{c,nominal}$ (eV)	$\mu_{c,tuned1}$ (eV)	$\mu_{c,tuned2}$ (eV)
Ports	1	500	0.17	0.27	0.41
1,7	1.37	382	0.1	0.15	0.23
2,6	0.57	929	0.51	0.74	1
3,5	2.26	232	0.026	0.06	0.1
4	0.45	1172	0.79	1	1

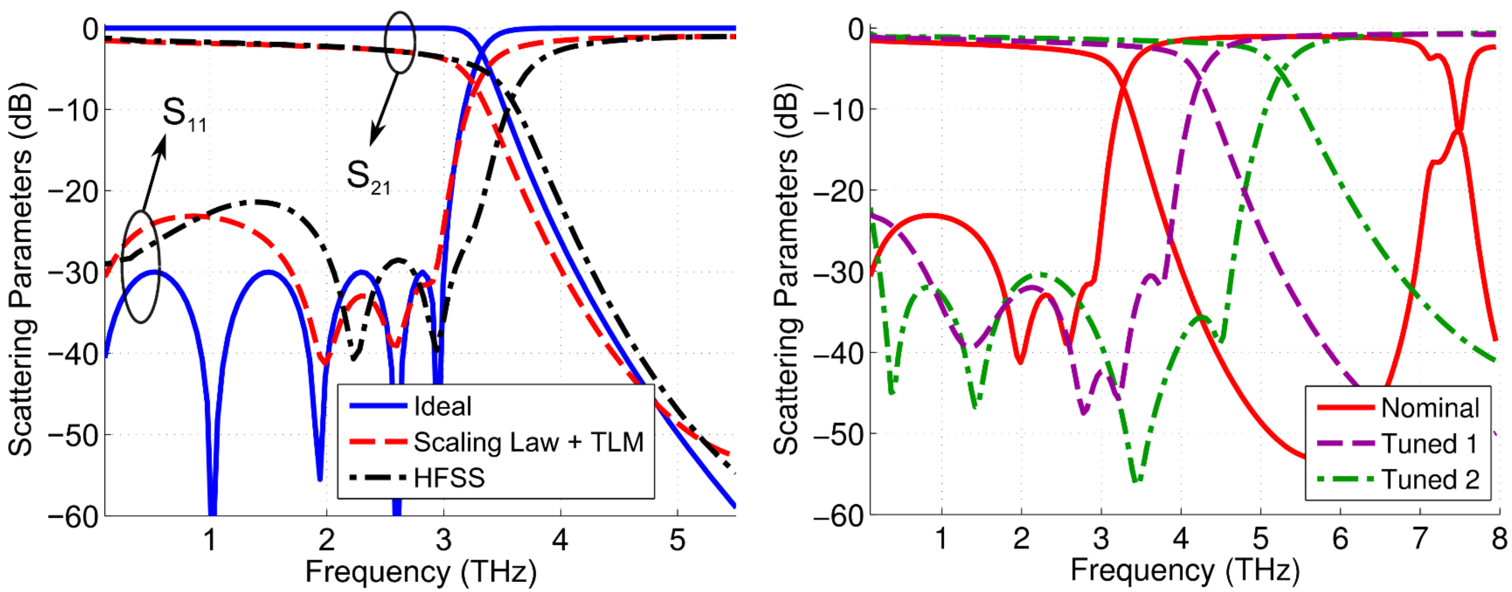




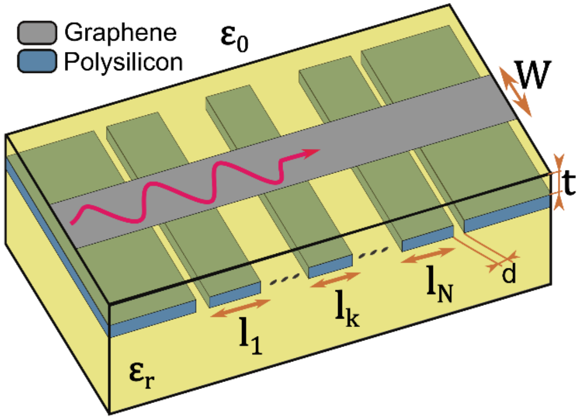
$9th$ order LPF

- $N = 9,\ \theta_c = 39º\ \varepsilon_r = 3.9, W = 100\ nm, f_c = 3.3\ THz$

Section	$\bar{Z}$	l (nm)	$\mu_{c,nominal}$ (eV)	$\mu_{c,tuned1}$ (eV)	$\mu_{c,tuned2}$ (eV)
Ports	1	200	0.17	0.35	0.46
1,9	1.36	156	0.1	0.21	0.274
2,8	0.58	367	0.43	0.93	1
3,7	2.24	94	0.035	0.01	0.12
4,6	0.44	483	0.69	1	1
5	2.48	85	0.023	0.078	0.1

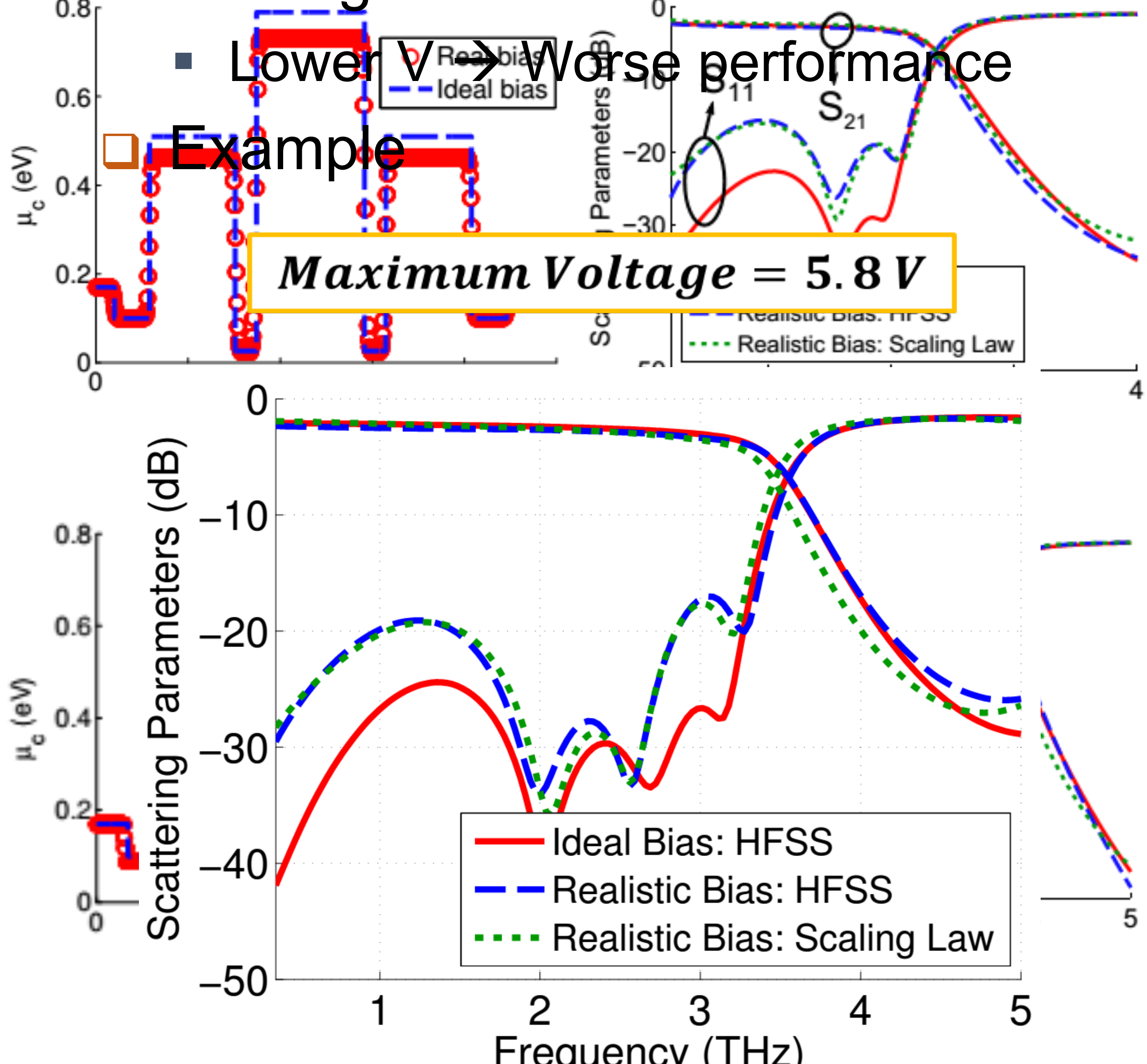


Ideal vs Realistic Electrostatic bias.



- ❑ Voltage requirements depend on the original transfer function.
  - ▪ Lower V → Worse performance
- ❑ Example

$\boldsymbol{Maximum\ Voltage = 31\ V}$



$\boldsymbol{Maximum\ Voltage = 5.8\ V}$

- ❑ $t = 25\ nm$
- ❑ $d = 35\ nm$

1. Electrostatic
2. Electromagnetic

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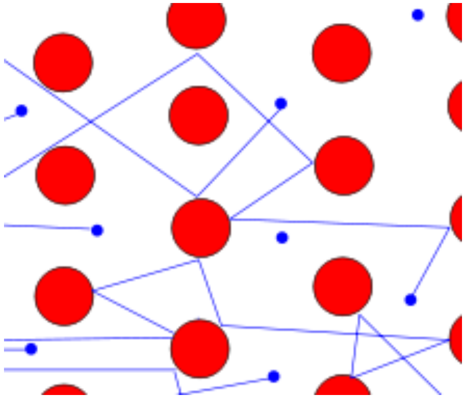
- Electrons have momentum.
- Electron movement depends of:
  - Electric field in a point
  - Wavevector



$$\boldsymbol{J}(k,\omega) = \boldsymbol{\sigma}(k,\omega)\,\boldsymbol{E}(k,\omega)$$

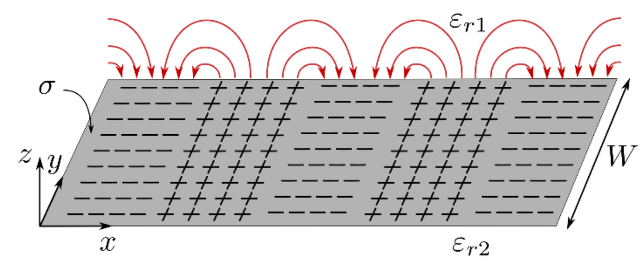
$\boxed{\boldsymbol{\sigma}(\boldsymbol{k},\boldsymbol{\omega}) \textbf{ is non-local}}$

Spatial Dispersion in Graphene Sheets

- $W \gg k_\rho$

$$k_x = k_y$$
$$\sigma_{xx} = \sigma_{yy}$$
$$\sigma_{xy} = \sigma_{yx}$$

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



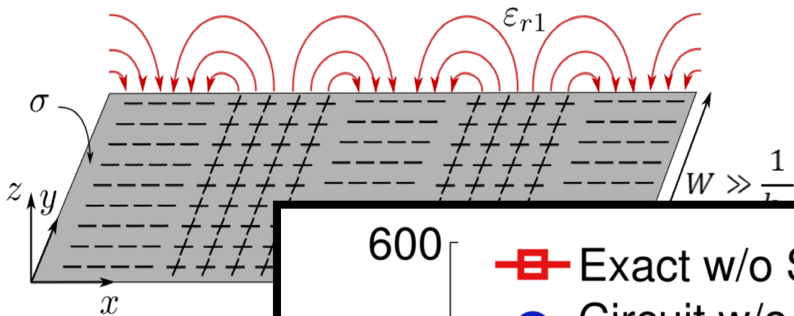
- $\sigma(k_\rho)$ & k_ρ

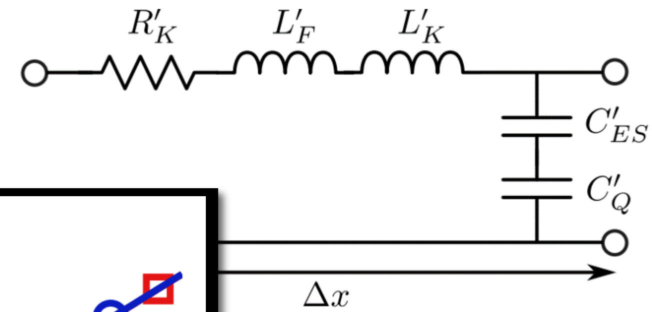
$$\sigma_{xx} = \sigma_{yy} = \gamma \frac{\pi}{\sqrt{(\omega - j\tau^{-1})^2 - v_F^2 k_\rho^2}}$$

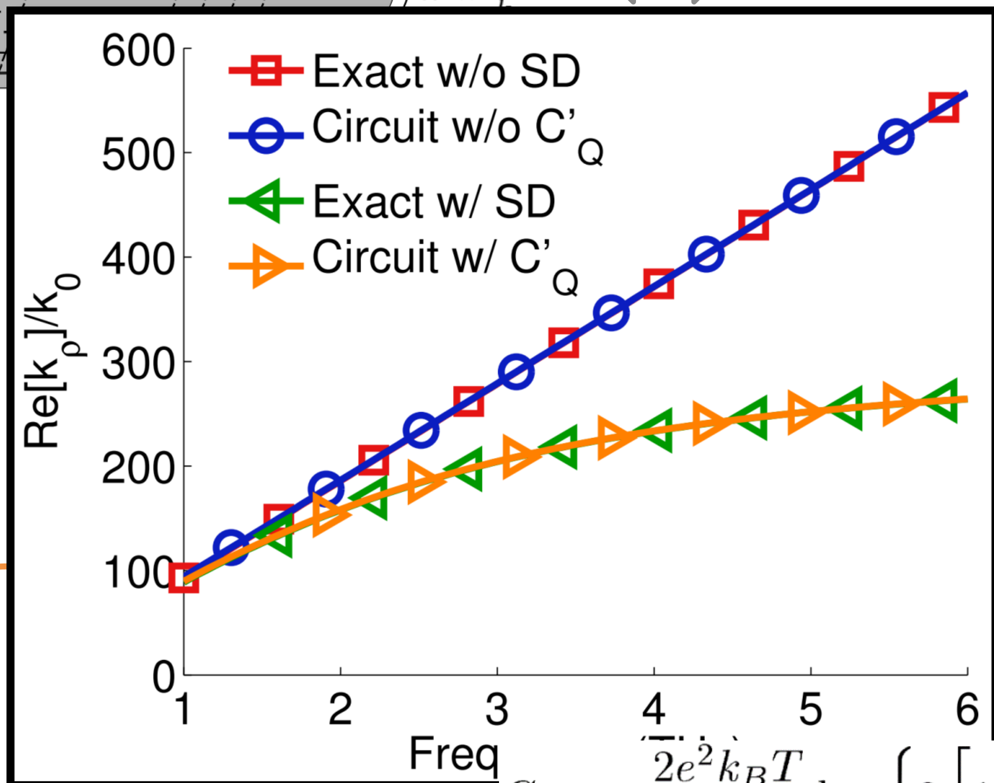
$$k_\rho = k_0\sqrt{\varepsilon_r}\sqrt{1 - \frac{4\varepsilon_r\left[(\omega - j\tau^{-1})^2 - k_0^2\varepsilon_r v_F^2\right]}{\eta_0^2\gamma^2\pi^2 - 4v_F^2 k_0^2\varepsilon_r^2}}$$

[1] Lovat, G., Hanson, G. W., Araneo, R., & Burghignoli, P. (2013). *Semiclassical spatially dispersive intraband conductivity tensor and quantum capacitance of graphene. Physical Review B.*
[2] D. Correas-Serrano, J. S. Gomez-Diaz, J. Perruisseau-Carrier and A.Alvarez-Melcon, "Spatially Dispersive Graphene Single and Parallel Plate Waveguides: Analysis and Circuit Model," IEEE MTT.

Equivalent Circuit







$\frac{e[1/\sigma]}{W}$

nce of graphene [1]

$C'_Q =$

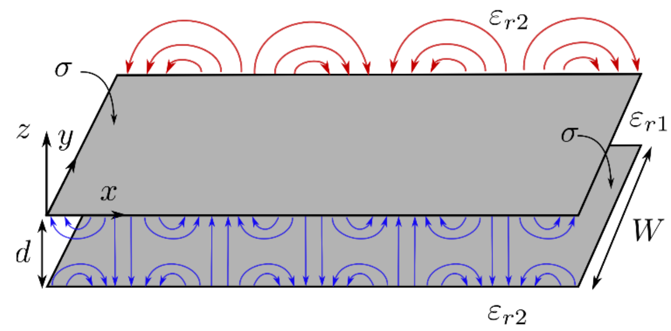
$$C_{Q_S} = \frac{2e^2 k_B T}{\pi \hbar^2 v_F^2} \log\left\{2\left[1 + \cosh\left(\frac{\mu_c}{k_B T}\right)\right]\right\}$$

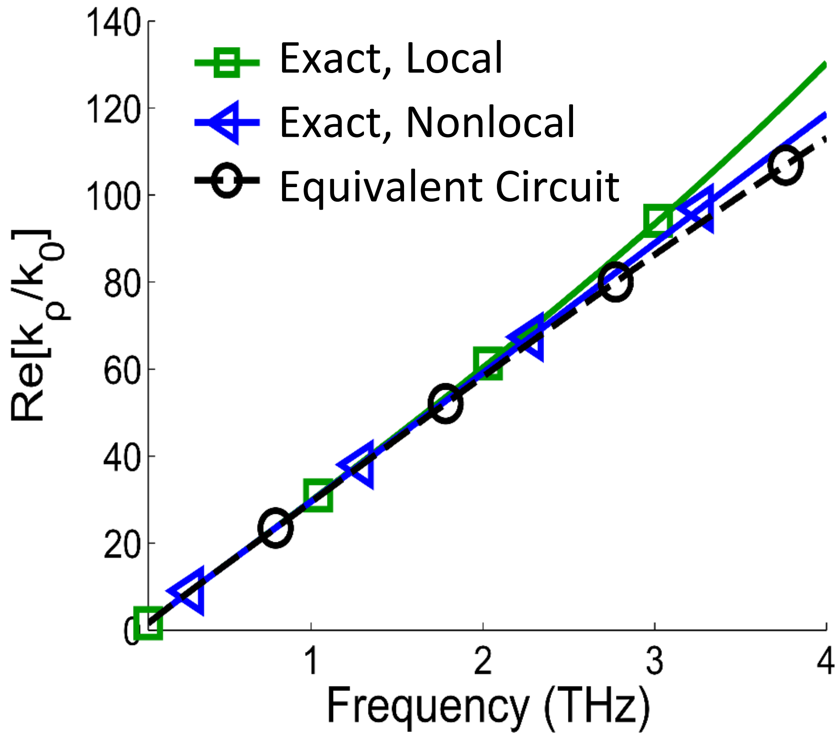
[1] D. Correas-Serrano, J. S. Gomez-Diaz, J. Perruisseau-Carrier and A.Alvarez-Melcon, "Spatially Dispersive Graphene Single and Parallel Plate Waveguides: Analysis and Circuit Model," IEEE MTT.

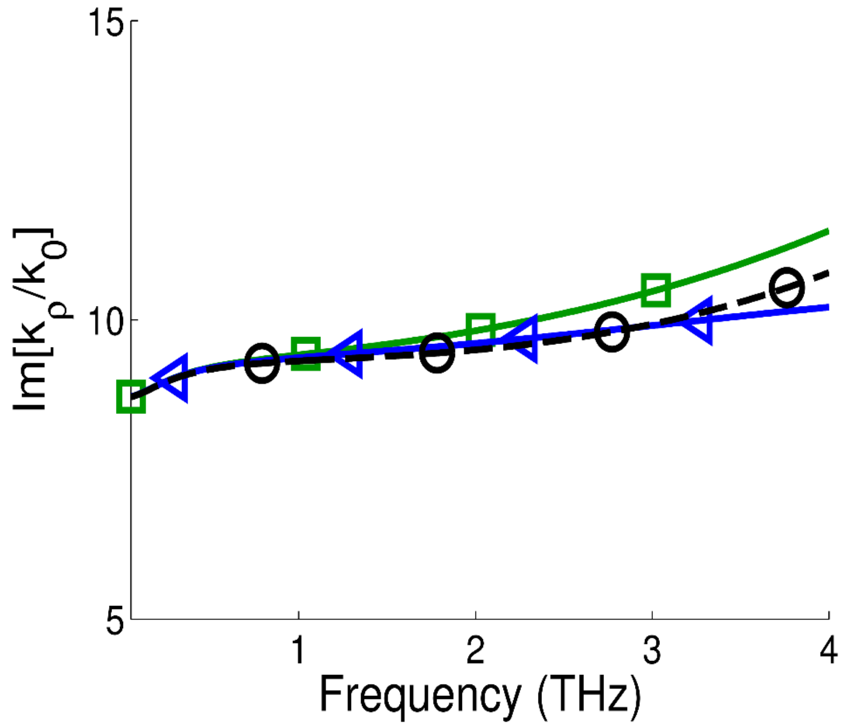
Graphene PPW. Symmetric Mode

- $d \ll \lambda_0 \rightarrow$ Equivalent sheet with:

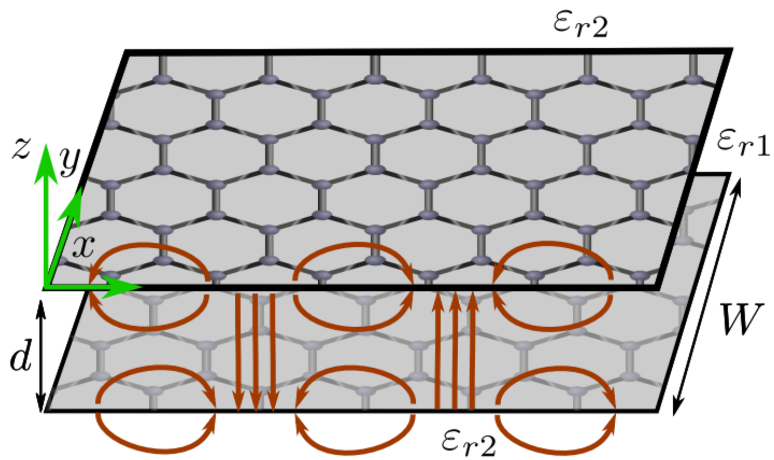
$$\boxed{\sigma_{eq} = 2\sigma_{sheet}}$$

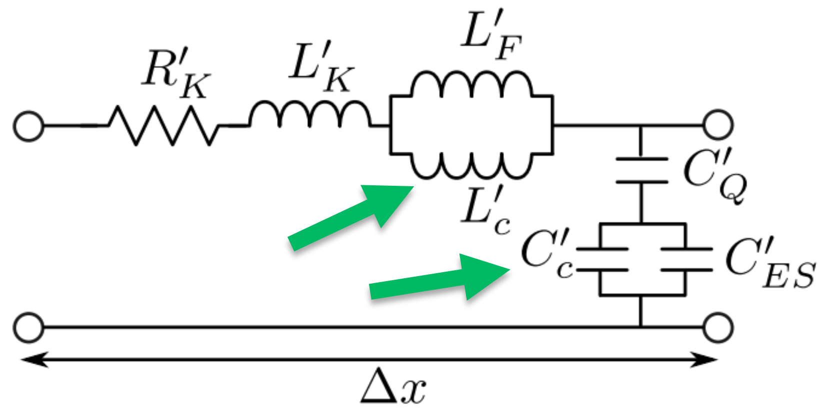






Graphene PPW. Antisymmetric mode





- Elements for each strip

$$L'_K = \boxed{2} L'_{K,sheet} \quad R'_K = \boxed{2} R'_{K,sheet} \quad L'_F = \boxed{2} L'_{F,sheet}$$

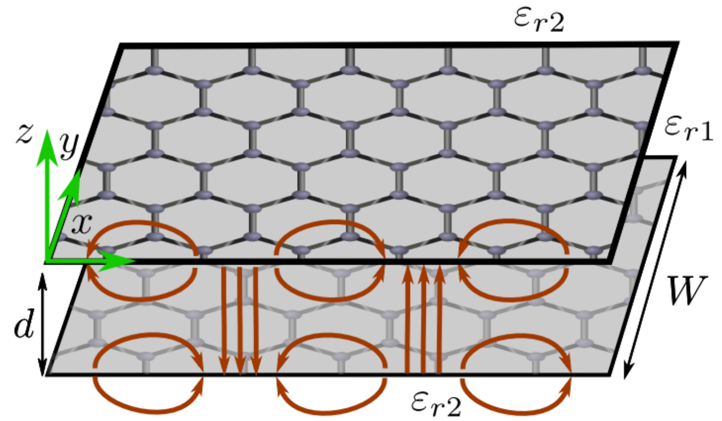
$$C'_{ES} = \boxed{\frac{1}{2}} C'_{ES,sheet} \quad C'_Q = \boxed{\frac{1}{2}} C'_{Q,sheet}$$

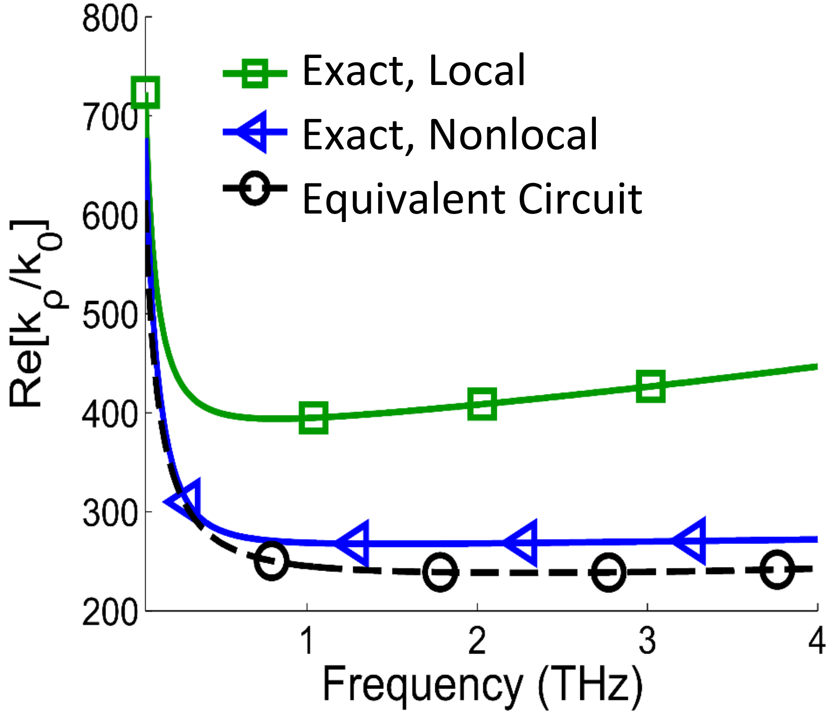
- Coupling between strips

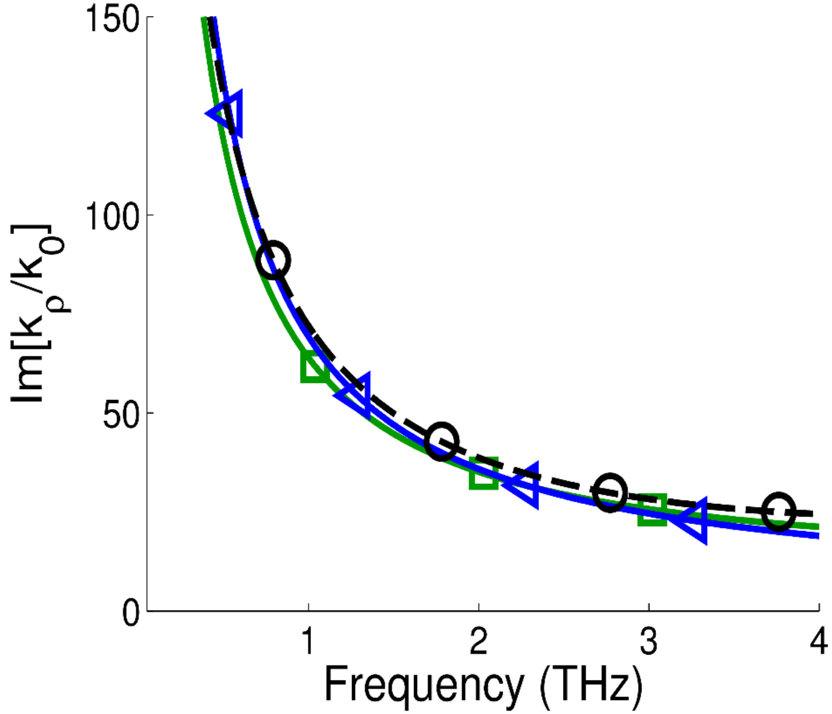
$$C'_c = \varepsilon_0 \varepsilon_{r1} \frac{W}{d} \quad L'_c = \mu_0 \frac{d}{W}$$

Graphene PPW. Antisymmetric mode

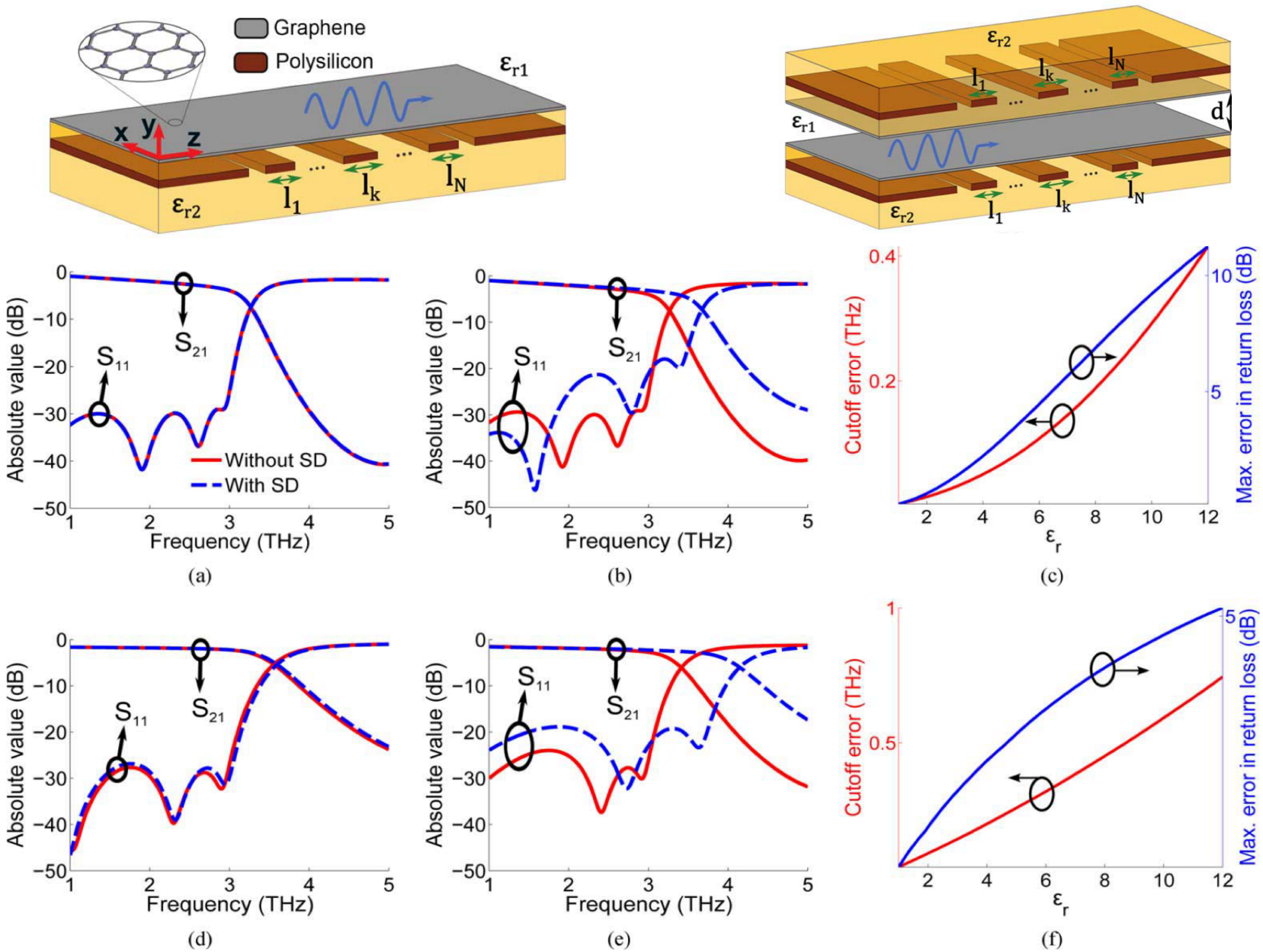
- W = 100 μm
- $\varepsilon_{r1} = \varepsilon_{r2} = 11.9$
- $\tau = 1\ ps$
- d = 100 nm







- Spatial dispersion may impact device performance



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Conclusions

- I have reviewed my collaboration with Professor Julien Perruisseau-Carrier.
  - Only a small part of his vast multidisciplinary research
- THz plasmonic filters
  - Dynamic control
  - Efficient design technique
- Spatial dispersion in graphene
  - Equivalent circuits
  - Related to quantum capacitance