Graphene Plasmonics: Theory and Experiments

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• Prof. Julien Perruisseau-Carrier
• Theory of Graphene plasmonics
  – Unusual electromagnetic properties of graphene
  – Guided devices and antennas @ THz
• Experimental results
  – Surface impedance @ microwaves and THz
  – Graphene stacks
• Concluding remarks
• Prof. Julien Perruisseau-Carrier

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• Concluding remarks
§ I first met Julien at APS 2008 @ San Diego
  – Julien was postdoc at CTTC, in Barcelona (Spain).
  – I was fresh PhD student @ UPCT (Spain) and Montréal (Canada).
  – We didn’t meet again in more than 3 years...
Julien Perruisseau-Carrier (II)

- Adaptive MicroNano Wave System - Research Group

- Created in June 2011 at EPFL
- Hosted at EPFL by two labs:
  - LEMA: lema.epfl.ch
  - Nanolab: nanolab.epfl.ch
- Very well funded!
- I was postdoc there from Nov. 2011 – March 2014
- Mid size group:
  - 2-3 postdocs
  - 5 PhD students
  - Many conferences together
Dynamic reconfiguration

- Update device functionality in real time
- Sense and adapt to environment
- Scan space, frequencies, polarization...

Joint antenna-coding techniques
- Higher data-rate and lower-power
- Reduced-complexity HW

artificial EM materials
- Tailor extraordinary effective EM properties

Use of micro/nano-technology:
Graphene, MEMS, Electroactive polymers...
- EM perf., higher freq., integration, low power
- Novel sensing applications (graphene)
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Introduction

- Graphene: the “famous” 2D material

- 2D material: carbon atoms in 2D honeycomb lattice
- 1 atom thick ≈ infinitesimally thin
- “Semi-metal” or “zero-gap semiconductor”
- Ambipolarity: both electrons ($E_f > 0$, n type doping) or holes ($E_f < 0$, p type doping) can conduct
- Massless electrons: $E = \sqrt{(m^2c^2) + (\hbar v_f p)^2} = \pm \hbar v_f |p|$
Graphene conductivity: *behavior and trends (I)*

- Graphene is 2D $\rightarrow$ entirely described by a surface conductivity

\[ J = \sigma E \]

\[ \sigma(\omega, \tau, T, \mu_c (E \downarrow \text{bias})) \]

\[ T = \text{temperature} \]

- $T$ relevant only when close to Dirac point (small $\mu_c$).

- $\tau = \text{relaxation time:}$
  - Rough interpretation: time between two consecutives “collisions” of an e$^{-}$ propagating on graphene
  - Large $\rightarrow$ better conductivity!
  - Highly depends on fabrication $\rightarrow$ quality of graphene

- $T = \text{temperature}$
  - $T$ relevant only when close to Dirac point (small $\mu_c$).

- Higher $T$ $\rightarrow$ higher conductivity.

- $\mu_c$: Fermi level.
Graphene conductivity: *behavior and trends (and II)*

- **Doping** or **static electric field** affect conductivity tensor:

\[ \sigma_{\downarrow d}(\omega,T,\tau,\mu_c(E_{bias})) \]

- Easy *dynamic* control of conductivity!
- Real and imaginary parts affected
Electromagnetic properties of graphene

- Absence of $B_{bias}$ and neglecting spatial dispersion

$$\sigma = (\sigma_{\downarrow d} \& 0 \& \sigma_{\downarrow d}) = \sigma_{\downarrow d}$$

$$Z_S = \frac{1}{\sigma_d}$$

- @ microwaves: mostly a resistive sheet
- @ THz: large inductive behavior ($\rightarrow$ plasmon propagation)

- $\mu_c$: 
  - Significant tuning effect
  - Losses decrease
Surface plasmons on graphene

- Plasmonic modes *on metals* at optics:
  - EM wave propagating at the interface between a dielectric (e.g. $\varepsilon_d = 1$) and a metal ($\Re\varepsilon_m < 0$)
  - Fields on both sides are evanescent
  - Slow wave: $v_g \ll c$

- Plasmonic modes on graphene:
  - $\Re\varepsilon_m < 0$ (or $\Im\sigma > 0$)
  - Interest:
    - At THz (much lower frequency than metals)
    - Very slow waves $\Rightarrow$ miniaturization
    - Tunable (easy + suitable to THz)
    - Integration with graphene accessible
    - Possibility of gyroscopy and non-reciprocity using $H$ static field

Plasmon waveguiding

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

Graphene-based patch antennas at THz

- **Graphene frequency-reconfigurable THz plasmonic dipole**
  - Exploit plasmonic resonances: miniaturized ($\approx \lambda_0/20$)
  - Powerful and simple reconfiguration
  - Good radiation efficiency


Beamscanning THz leaky-wave antennas

- Based on sinusoidally-modulated surfaces:
  - Demonstration of the concept viability. Theoretical analysis.
  - Full-wave simulations confirm theoretical predictions

$\tau = 1 \text{ ps}$

$T = 300^\circ K$

$\mu_c = 0.7 \text{ eV}$

$V_{DC} = 6.5 - 45 \text{ V}$

$\varepsilon_r = 3.8$

$s = 4.8 \mu m$ and $g = 0.2 \mu m$

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Measurements @ microwaves

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

Measurements @ THz

- Single-layer graphene structures: Measurements
  - CVD fabrication of graphene on several substrates
  - Measurements based on THz Time-domain Spectroscopy
  - Good agreement with theory
  - Unbiased graphene: $\tau = 0.025$ ps and $\mu_{\downarrow} = 0.45$ eV
Graphene stacks

Graphene stacks: Advanced reconfigurable capabilities
- One graphene layer bias the other one and vice-versa
- Boost reconfiguration range
- Analysis, design, fabrication and measurement at THz

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Concluding Remarks

Prof. Julien Perruisseau Carrier

1979-2014

- We have reviewed some of Julien’s most significant contributions to Graphene plasmonics:
  - Surface plasmons @ THz + reconfiguration
  - Novel devices: Waveguides, Antennas, etc.
  - Graphene stacks at THz: boosted reconfigurable capabilities

- His research activities were even broader:
  - Reflectarrays, MIMO technology, signal processing, MEMS, etc.
Thanks a lot for your attention!

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