Dynamic Reconfiguration of Plasmonic Reflectarrays Using Graphene:

A Review of the Research Led by Prof. Perruisseau-Carrier

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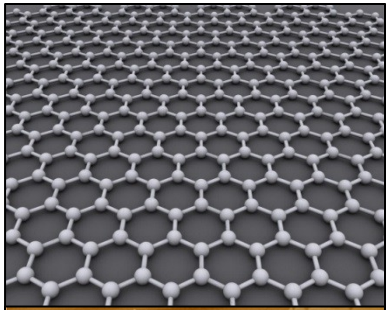
In Memoriam of Julien Perruisseau-Carrier

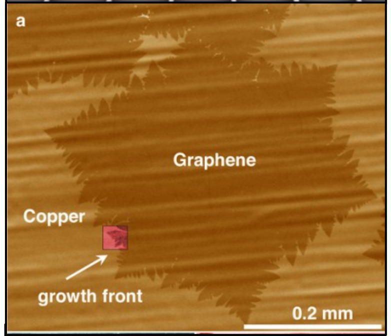
- *Julien focused his research effort on frontier and interdisciplinary studies related to electromagnetic waves, from microwave to mid-Infrared. He made significant contributions to the field of reconfigurable antennas.*
- *We would like to recognize the significant contributions of Julien to the field of reflectarray antennas, specifically with multi-reconfiguration (spatial, frequency and/or polarization), by using semiconductors, MEMS, dielectric elastometer actuators and graphene.*
- *This presentation summarizes some of the work led by Julien in the field of reflectarrays based on graphene.*

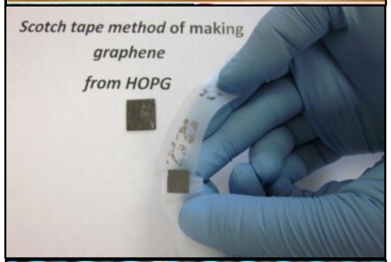
Graphene, the 2-D material

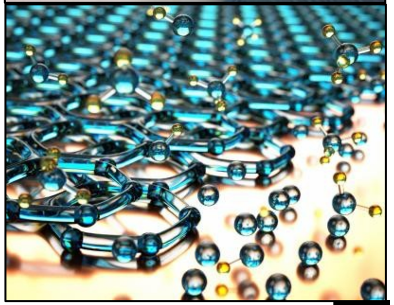
Julien was very enthusiastic about using graphene to implementing reconfiguration in reflectarray type antennas.

- Graphene is the 2D (***one-atom thick***) crystalline form of carbon, arranged in hexagons. Called “semi-metal” or zero-gap semiconductor”
- Very slow waves (plasmonic modes) → ***Extreme miniaturization***
- ***Monolithic integration*** with graphene nanoelectronics
- ***Transparent*** at optical frequencies
- ***Tunable*** via electric and magnetic field
- Fabrication:
  - Small area (mm-mm) ***exfoliation***
    - High quality
  - Larger area (> cm) ***chemical vapor deposition (CVD)***
    - Enable much larger devices:
      Solar cells, displays, transparent electrodes, ***reflectarrays!***



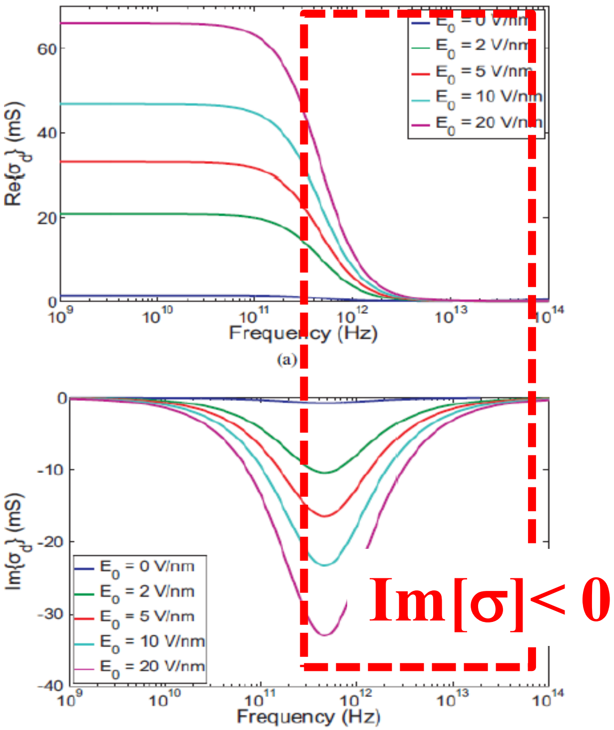




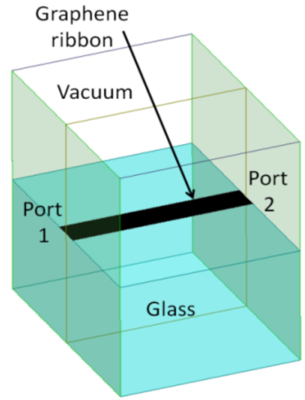


Plasmonic Modes in Graphene at THz and IR

Graphene surface conductivity:



TM plasmon on graphene strip :

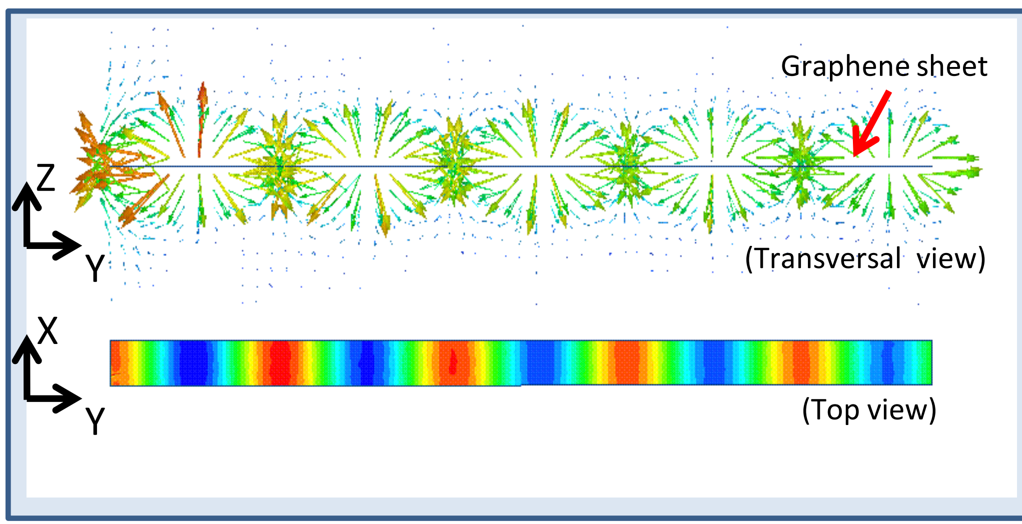


Plasmonic modes on graphene:

Im[σ]< 0 (or Im[Z_S]> 0)

→ ***plasmons!***

@ lower frequency than metals



Graphene Conductivity Modelling

❑ Kubo formula

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

B_{bias}=0 →

$$\sigma(\omega, \mu_c, \Gamma, T) = \begin{pmatrix} \sigma_d & 0 \\ 0 & \sigma_d \end{pmatrix}$$

'Direct conductivity' (σ_d)

'Hall conductivity' (σ_o)

$$\sigma(\omega, \mu_c, \Gamma, T) = \frac{jq_e^2(\omega - j2\Gamma)}{\pi\hbar^2}\left[\frac{1}{(\omega - j2\Gamma)^2}\int_0^{\infty} \epsilon\left(\frac{\partial f_d(\epsilon)}{\partial \epsilon} - \frac{\partial f_d(-\epsilon)}{\partial \epsilon}\right)\partial\epsilon - \int_0^{\infty} \frac{f_d(-\epsilon) - f_d(\epsilon)}{(\omega - j2\Gamma)^2 - 4(\epsilon/\hbar)^2}\right]\partial\epsilon,$$

Intraband term

Interband term → negigible

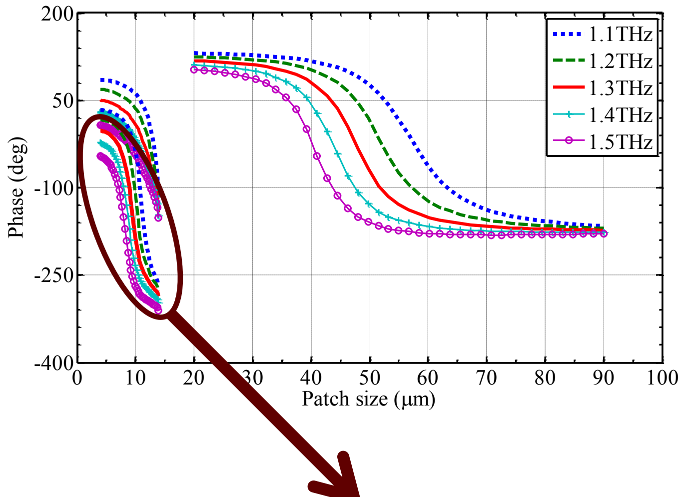
- T → Temperature
- Γ → Scattering rate, Γ=1/2τ, τ : relaxation time → ***graphene quality***
- μ_c → Chemical potential, μ_c, (E field bias) → ***applied voltage***
- ω → Angular frequency (2πf)

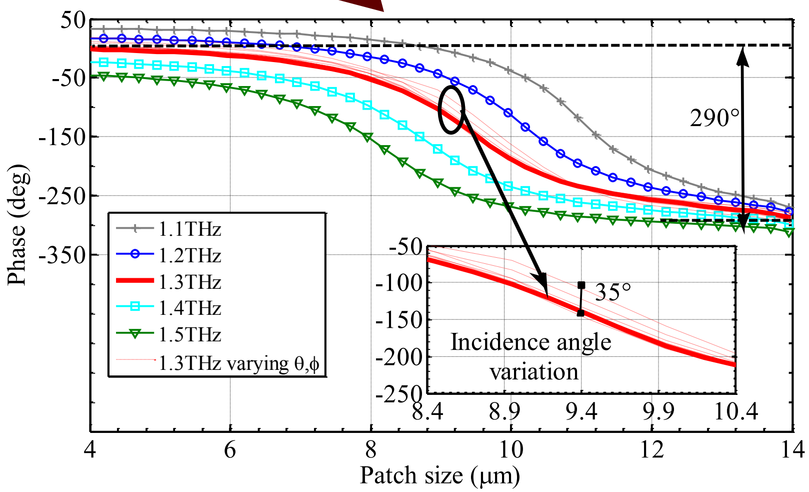
q_e :	electron charge
k_B :	Boltzmann constant
h :	reduced Planck constant
$f_d(\in)$:	Fermi distribution

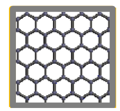
L. Falkovsky and S. Pershoguba, Phys. Rev. B76, 153410 (2007)

Plasmonic arrays (Varying size patch, fixed μ_c)

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

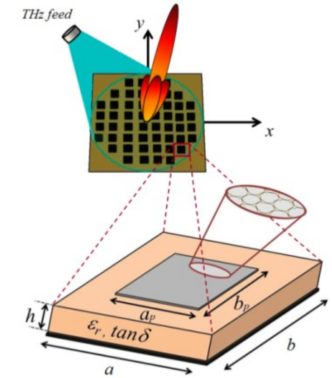






Graphene
a=b~λ/16

h_{quartz}=25 μm
(ε_r=3.75 tanδ=0.0184 @ 1.3THz)
μ_c=0.19eV



Important reduction in size!

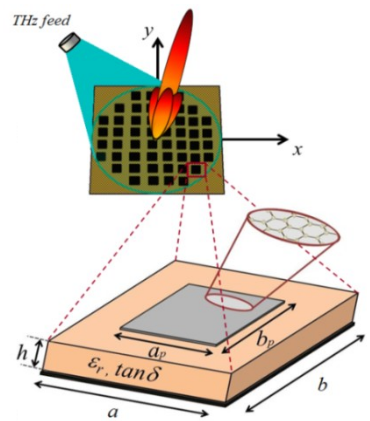
Plasmons at much lower frequencies than metal!

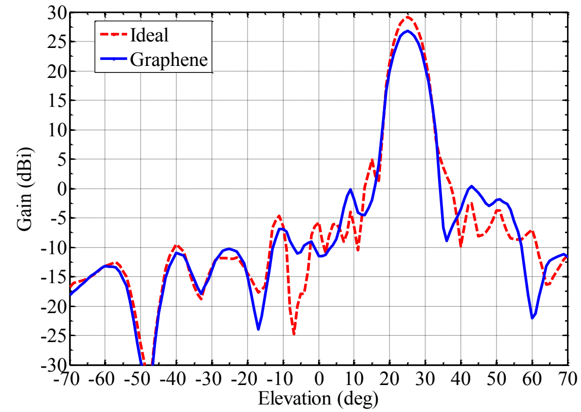
Plasmonic arrays (Varying size patch, fixed μ_c)

- Fixed-beam reflectarray at THz using graphene: whole array

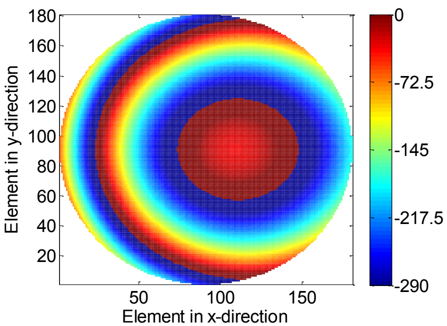
Main Features Of The Reflectarray Antenna

Frequency:		1.3 THz
Number of elements:		
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

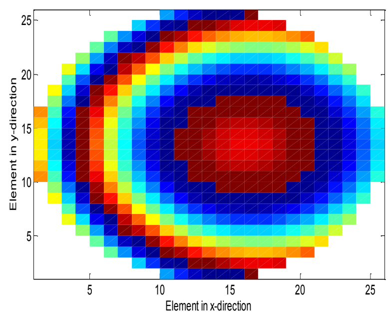


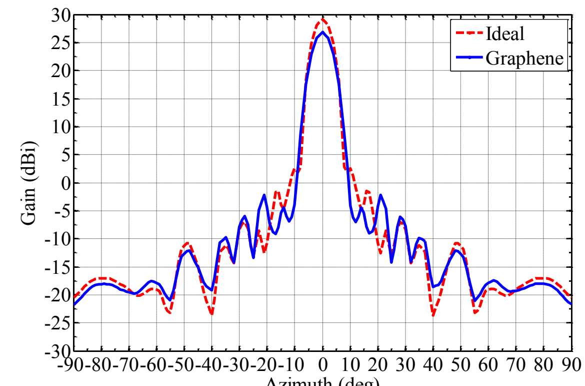


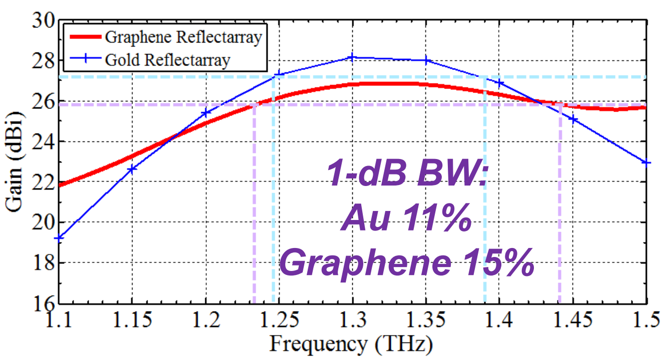
GRAPHENE

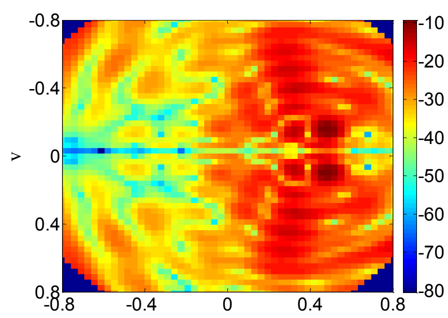


GOLD





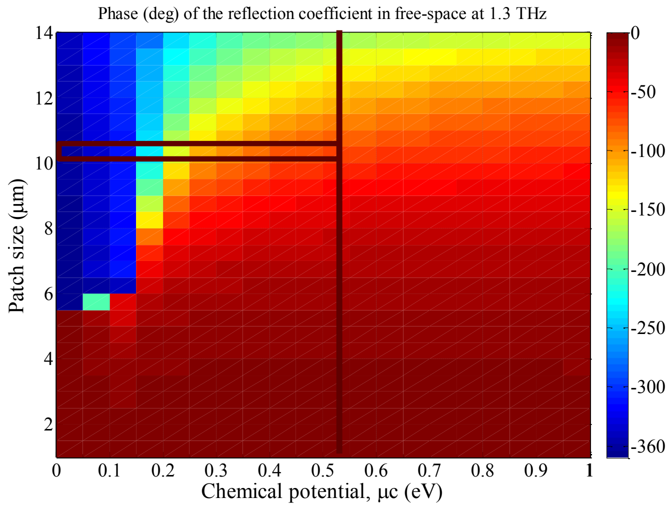




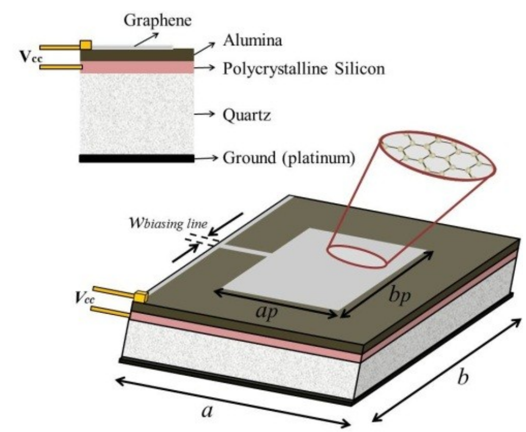
XPD>35dB

Dynamic Reconfiguration (1.3 THz)

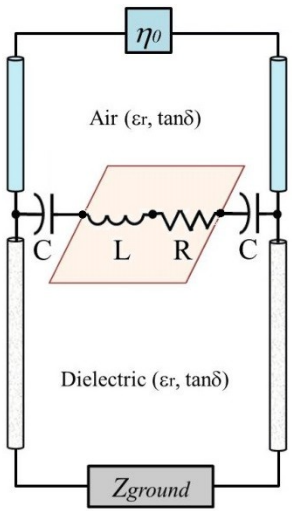
- <u>Reconfigurable-beam:</u> fixed-size elements but each cell **independent control of chemical potential**
  - Design patch for best behaviour when chemical potential is varied



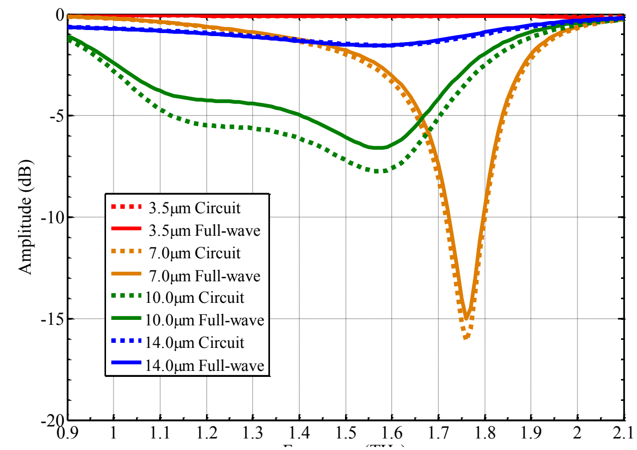
$a=b=14\ \mu m$
$a_p=b_p=0\ \mu m$ to $10\ \mu m$
$h_{quartz}=30\ \mu m$
$h_{polysilicon}=0.050\ \mu m$
$h_{alumina}=0.010\ \mu m$



Dynamic Reconfiguration (1.3 THz)

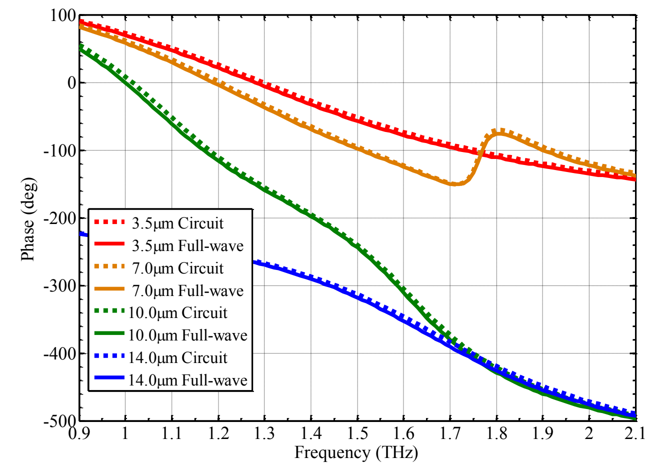


- ❑ Equivalent circuit, where the graphene patch between two stratified media (air-quartz) is represented as an RLC circuit in parallel with the grounded substrate and referred to the intrinsic impedance of air.

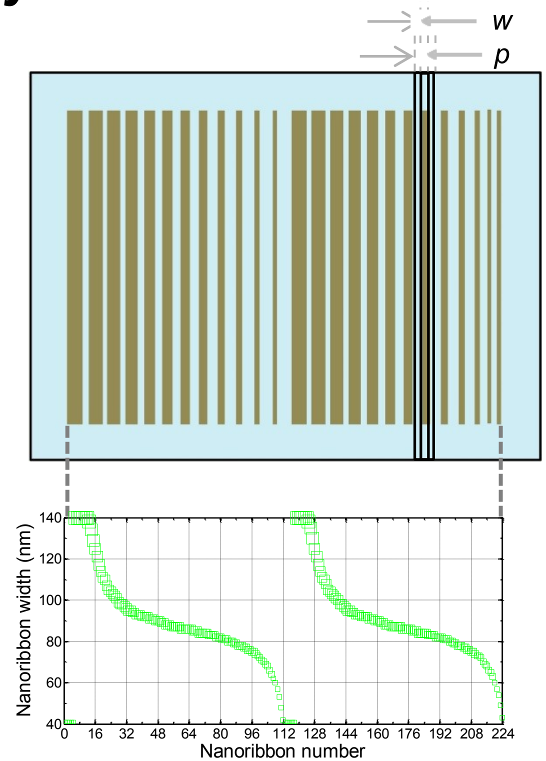


Values of the circuit elements for a graphene patch

		Chemical Potential		
Patch Size (μM)	Parameter	0.00 (eV)	0.19 (eV)	0.52 (eV)
3.5	R (Ω):	8854	799	287.5
	L (pH):	3495	803	294
	C (fF):	0.006	0.004	0.005
7.0	R (Ω):	1861	214	72.5
	L (pH):	862.1	208.9	75.07
	C (fF):	0.068	0.042	0.042
10.0	R (Ω):	861	122.5	35.4
	L (pH):	435	99.69	36.22
	C (fF):	0.148	0.137	0.133
14.0	R (Ω):	236	44.52	16.27
	L (pH):	235	44.44	16.24
	C (fF):	Very high	Very high	Very high



Dynamic Beam-Bending Array (Mid-Infrared)



Width profile along the array

Working frequency: **27 THz (900 cm^{-1})**

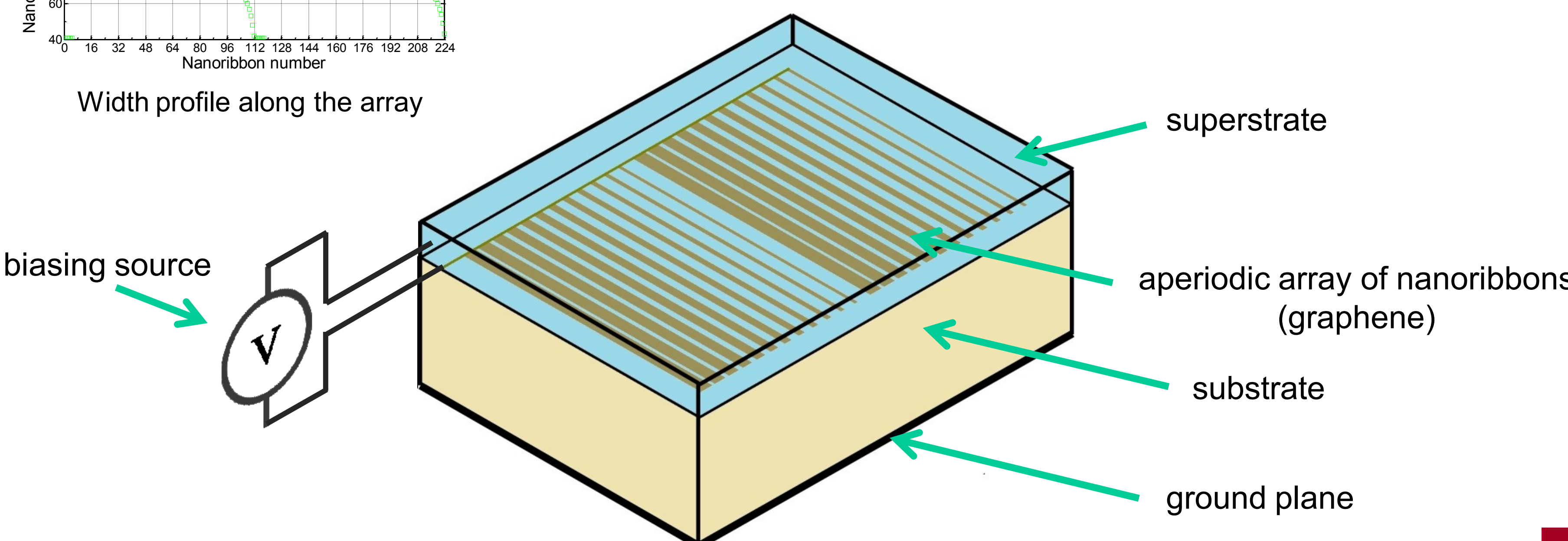
Number of elements: **224 nanoribbons**

Separation between nanoribbons: **p=140 nm**

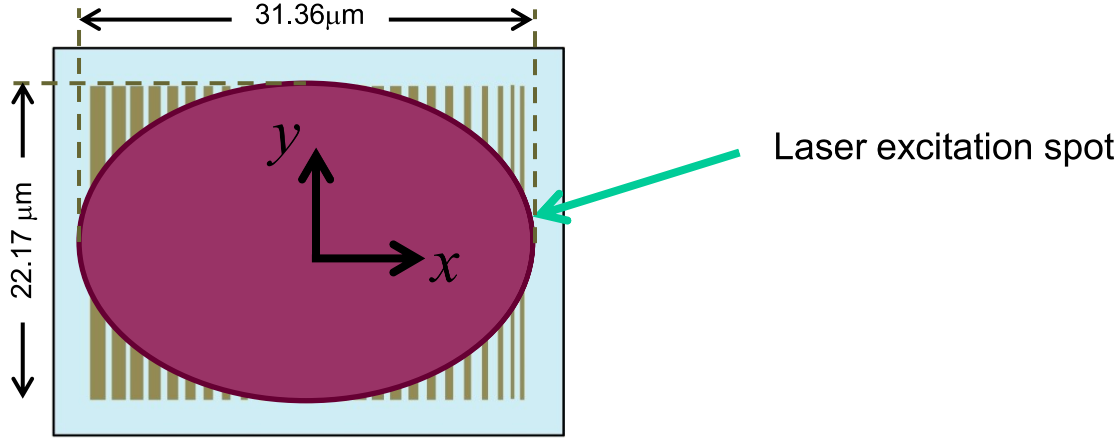
Width variation: **from w=40 nm to w=140 nm**

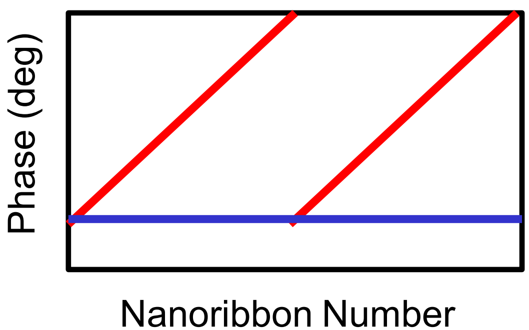
Width optimization for **μ_{c1}=1.0 eV**

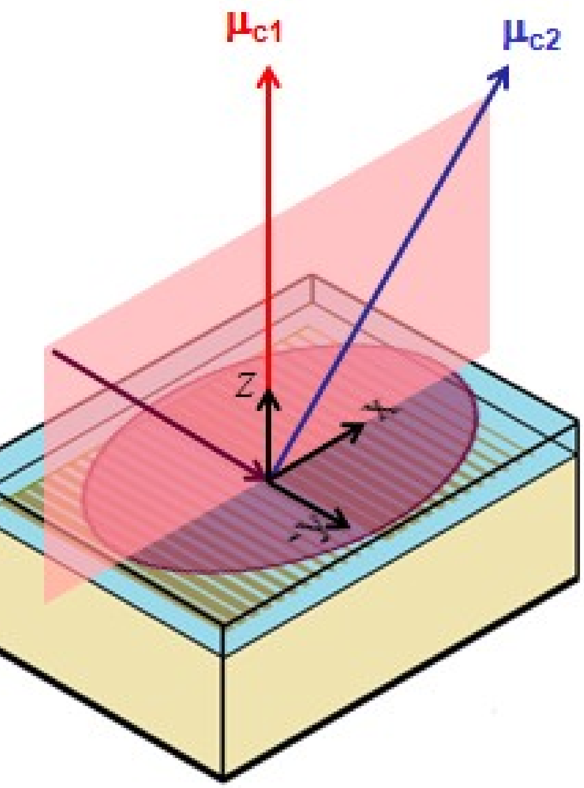
- ❑ Patches are replaced by **aperiodic nanoribbons** (bending in XZ plane)
- ❑ Biasing between graphene and a new superstrate

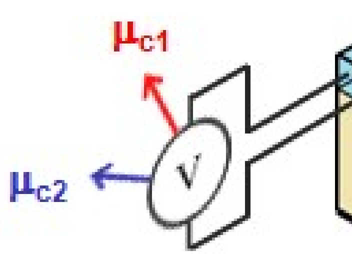


Dynamic Beam-Bending Array (Mid-Infrared)









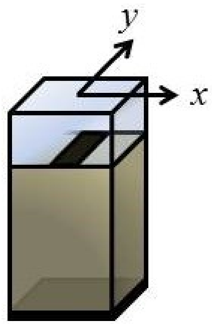
Laser beam impinging with θ_i=-45°.

Array profile optimized for bending the beam towards θ_r=0° if $\mu_c=\mu_{c1}$=1.0eV (A progressive phase-shift in reflection is produced along the array).

The progressive phase-shift disappears if chemical potential is adjusted to $\mu c=\mu_{c2}$=0.3eV. The beam is bend towards the specular direction θ_r=45° (A constant phase in reflection is produced along the whole surface of the array).

Why?

Dynamic Beam-Bending Array (Mid-Infrared)



Incident field

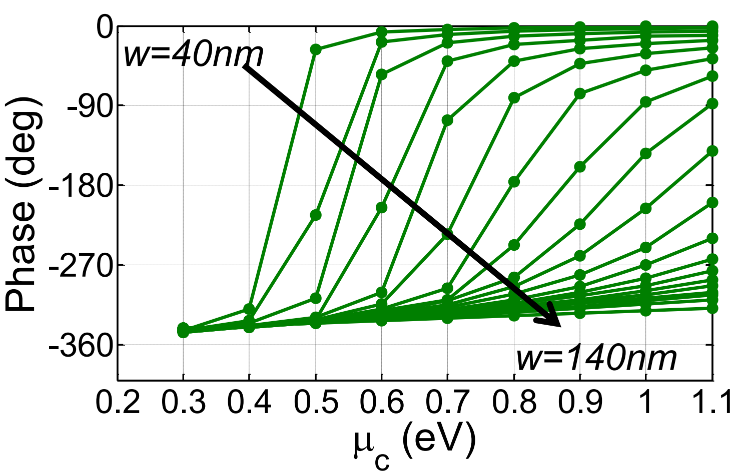
Scattering Matrix

$$\begin{bmatrix} S_{xx} & S_{xy} \\ S_{yx} & S_{yy} \end{bmatrix} \begin{bmatrix} E_{xi}(x,y) \\ E_{yi}(x,y) \end{bmatrix} = \begin{bmatrix} E_{xr}(x,y) \\ E_{yr}(x,y) \end{bmatrix}$$

Copolar
(let's focus on <u>phase</u>)

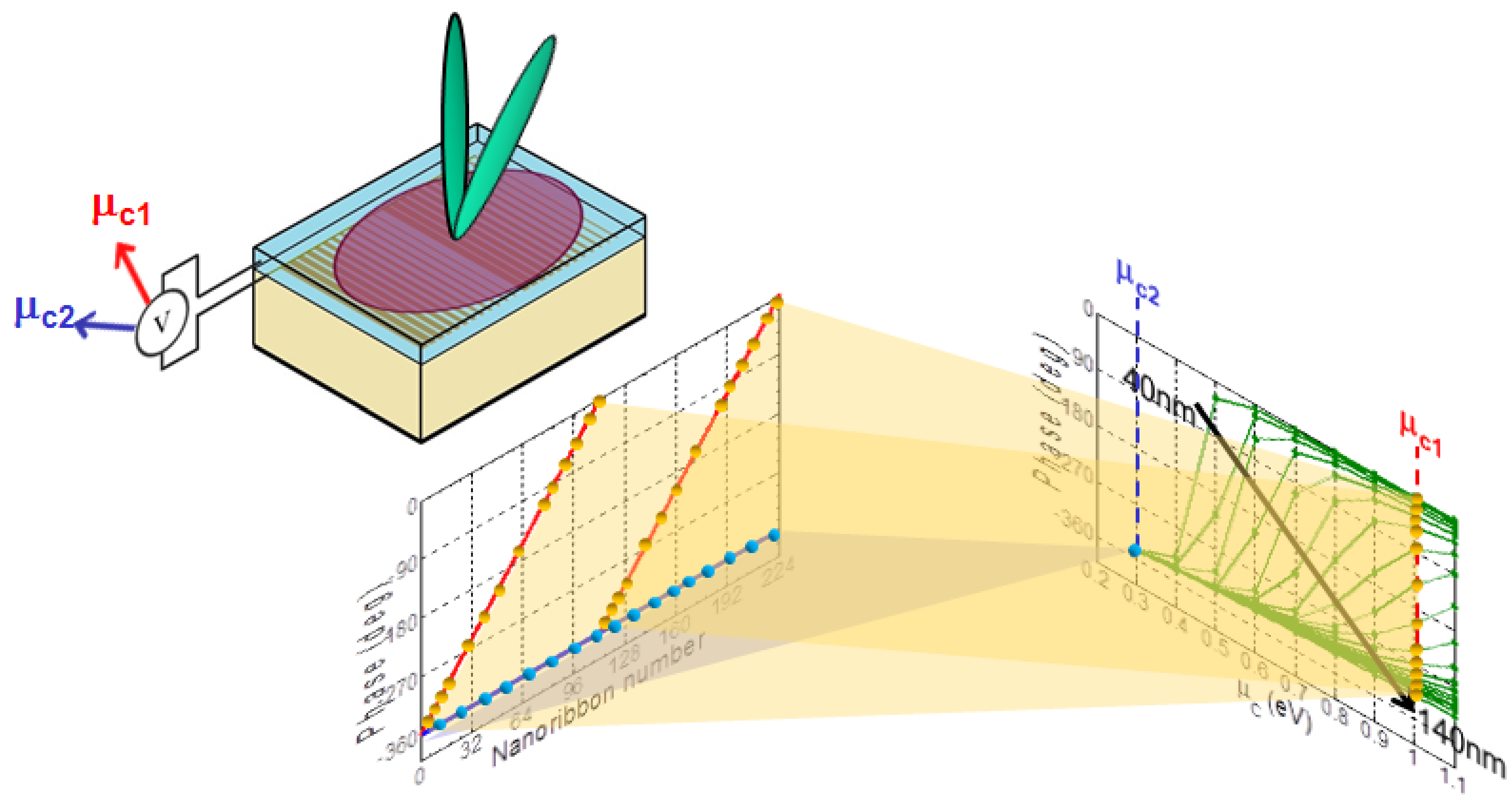
Reflected field

Far-field

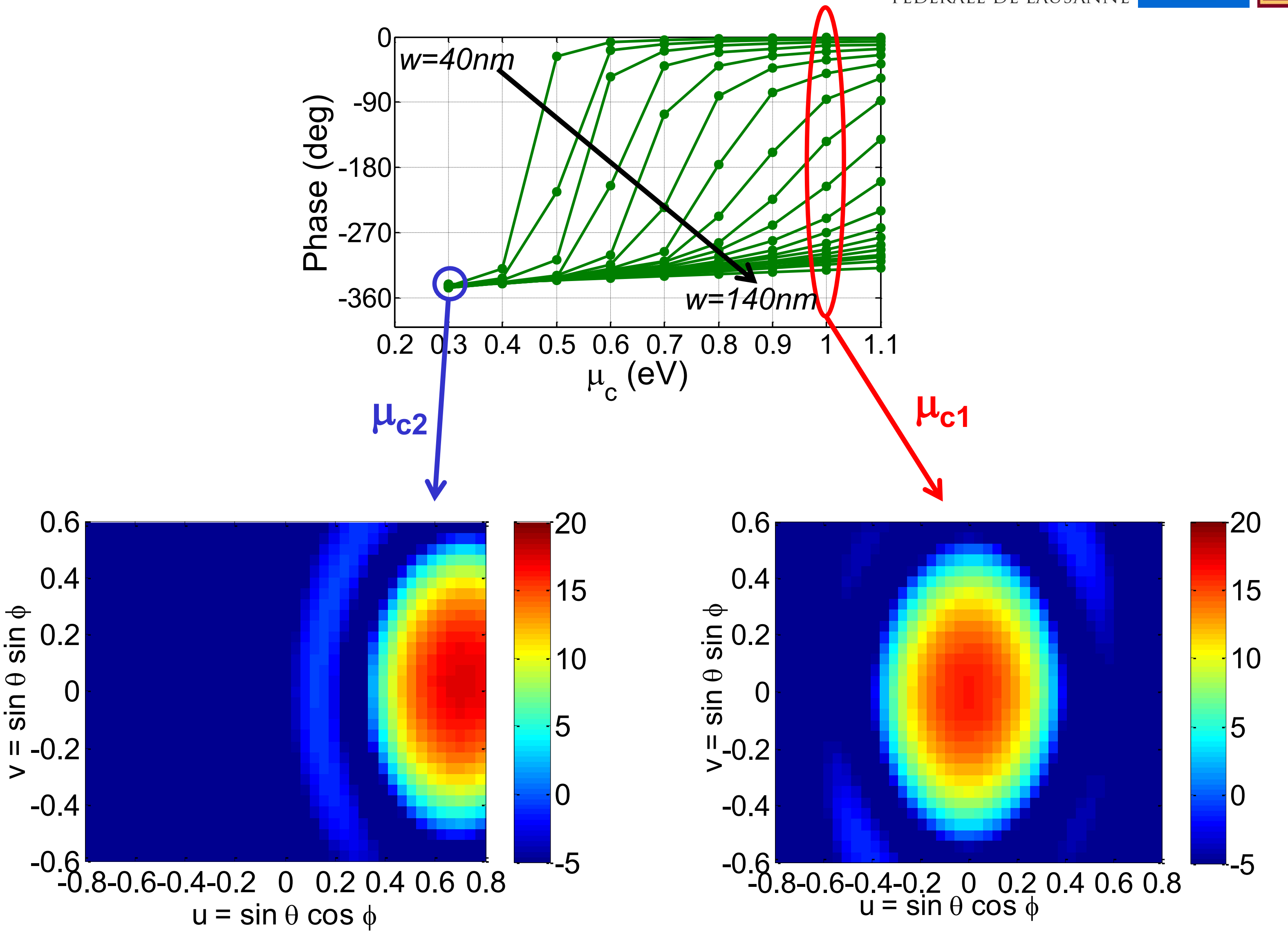


- ❑ Full vectorial scattering matrix
- ❑ Floquet's boundaries assumption
- ❑ Angle of incidence taken into account
- ❑ Gaussian beam incidence

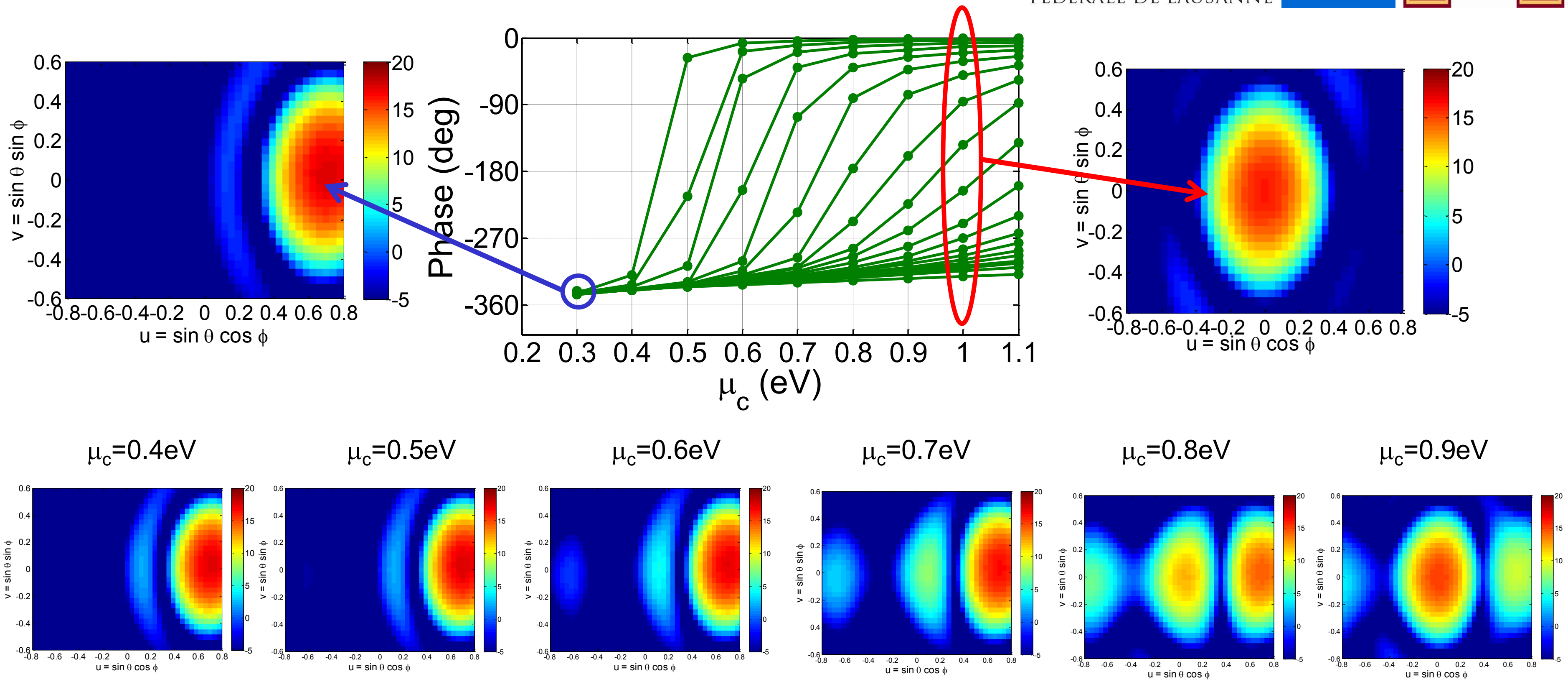
Dynamic Beam-Bending Array (Mid-Infrared)



Far-Field Bent Beams

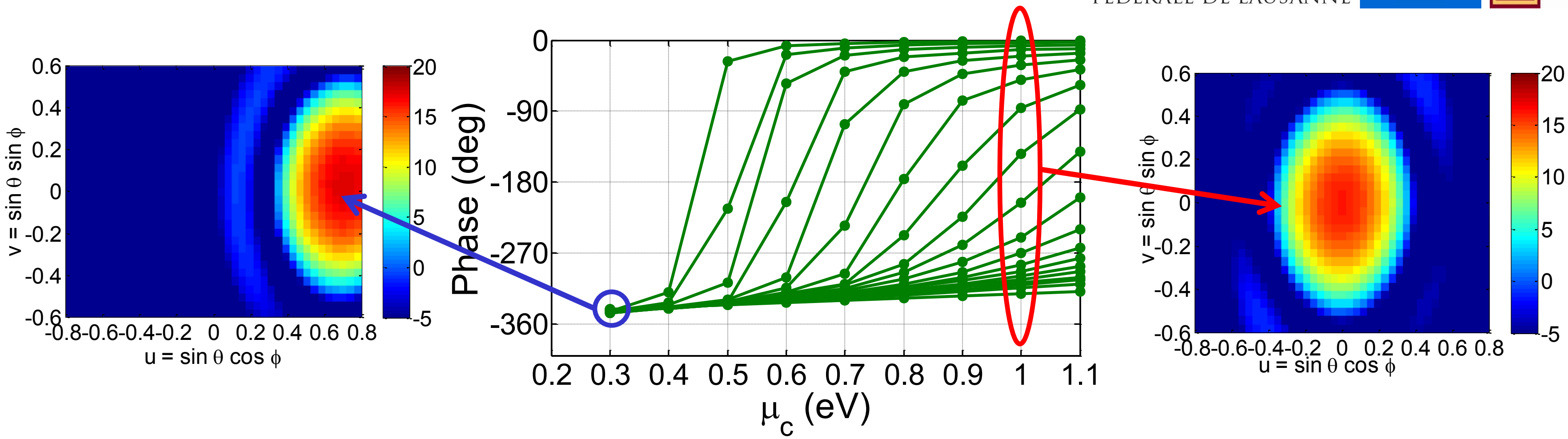


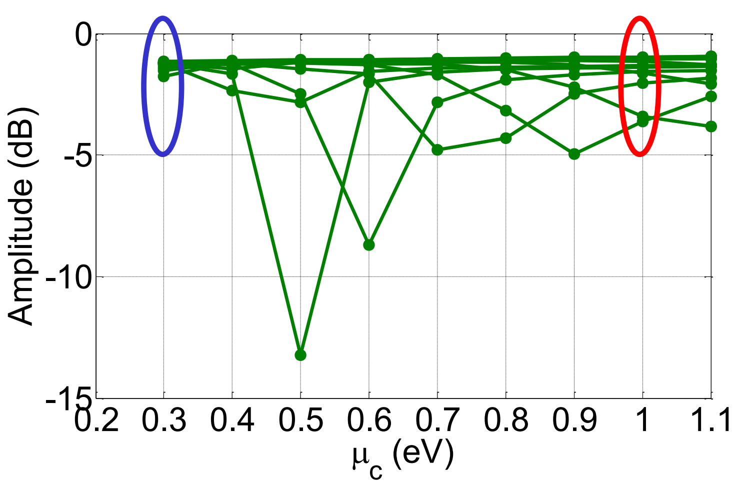
Far-Field Bent Beams (Middle states)



Continuos steering is possible using independent biasing for each nanoribbon or at least for some groups

Far-Field Bent Beams (Graphene Loss Impact)

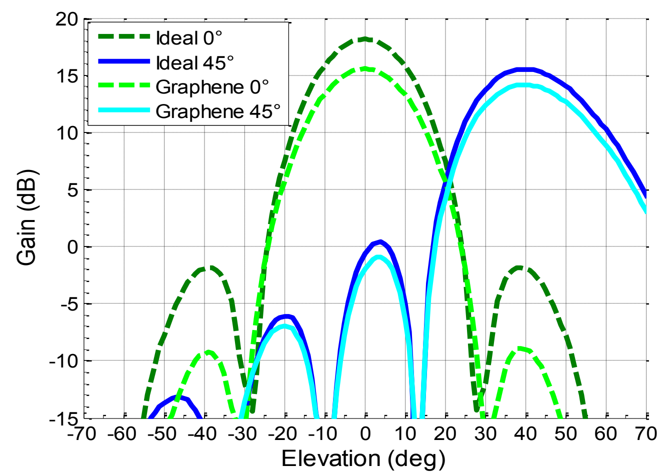




Average loss: 1.6 dB

Very moderate value at this frequency!

Impact of graphene losses?



In Memoriam of
Julien Perruisseau-Carrier

- *The work led by Julien in the field of graphene-based reflectarrays has been published in the following journal papers, one of them posthumously and dedicated to his memory :*

IEEE ANTENNAS AND WIRELESS PROPAGATION LETTERS, VOL. 12, 2013 — 253

Reflectarray Antenna at Terahertz Using Graphene

Eduardo Carrasco, *Member, IEEE*, and Julien Perruisseau-Carrier, *Member, IEEE*

APPLIED PHYSICS LETTERS **102**, 104103 (2013)

Tunable graphene reflective cells for THz reflectarrays and generalized law of reflection

Eduardo Carrasco,[a)] Michele Tamagnone, and Julien Perruisseau-Carrier[a)]
Adaptive MicroNano Wave Systems, LEMA/Nanolab, Ecole Polytechnique Fédérale de Lausanne (EPFL), 1015 Lausanne, Switzerland

IOP Publishing — Nanotechnology

Nanotechnology **26** (2015) 134002 (7pp) — doi:10.1088/0957-4484/26/13/134002

Gate-controlled mid-infrared light bending with aperiodic graphene nanoribbons array

Eduardo Carrasco[1,5], Michele Tamagnone[1,2,5], Juan R Mosig[2], Tony Low[3,4] and Julien Perruisseau-Carrier[1]

In Memoriam of
Julien Perruisseau-Carrier

- *Just a part of the contributions of Julien to the field of graphene-based devices. His wide expertise in the graphene field will be covered in other presentations:*

  ***Pros and cons of patterning graphene layers**, Arya Fallahi (Later in this session).*

  ***Theoretical Limits of Graphene Terahertz Non Reciprocal Devices**, Michele Tamagnone (Today, 17:30).*

Acknowledgment

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