13th METAMATERIALS, PHOTONIC CRYSTALS AND PLASMONICS – META 2023

18-21/07/2023 – Paris

Session 1A30: Advanced Computational Electromagnetics for the Analysis and Design of Nanophotonic Devices

A multimode quasi-normal mode framework for nonlinear harmonic generation with 2D materials

Thomas Christopoulos,[1,2] Emmanouil E. Kriezis,[1] and Odysseas Tsilipakos[2]

[1] *School of Electrical and Computer Engineering, Aristotle University of Thessaloniki, Thessaloniki, Greece*

[2] *Theoretical and Physical Chemistry Institute, National Hellenic Research Foundation, Athens, Greece*

cthomasa@eie.gr
cthomasa@ece.auth.gr

Thomas Christopoulos
cthomasa@eie.gr

Motivation and Objectives

Objectives

- ✓ Analysis and design of systems using the concept of QNMs
- ✓ Presentation of a multimode framework that incorporates **2D materials**
- ✓ Examination of **linear** and **nonlinear** responses (third-harmonic generation)
- ✓ Examination of periodic systems that support **higher diffraction orders**
- ✓ Validation of the framework with full-wave simulations

Motivation

- ✓ Physical **elegance** of modal analysis
- ✓ Rigorous capturing and better **understanding** of (modal) interference effects
- ✓ Better **intuition** on the analysis and design processes

QNMs framework with 2D materials

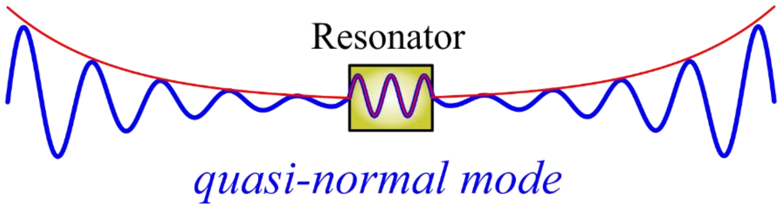
Thomas Christopoulos | cthomasa@ece.auth.gr

Thomas Christopoulos
cthomasa@eie.gr

The concept of QNMs

- ✓ **Quasi-normal modes** (QNMs) are the natural (leaky) modes of **non-Hermitian** systems

- ✓ QNMs spatially diverge → their normalization is **non-trivial**
  - [Sauvan, *et al.*, Phys. Rev. Lett. 110, 237401, 2013]
  - [Doost, *et al.*, *Phys. Rev. A* 90, 013834, 2014]
  - [Lalanne, *et al.*, Laser Photon. Rev. 12, 1700113, 2018]



- ✓ QNMs can be used as an **orthonormal basis** (strictly complete inside the cavity) to find the spectral/temporal response of a system

$$\mathbf{E}(\omega) = \sum_m a_m(\omega)\tilde{\mathbf{E}}_m$$

- ✓ $a_m(\omega)$ are **appropriate coefficients** for the expansion, depending on the **excitation** and its interaction with each QNM

The concept of QNMs

- ✓ QNMs are typically retrieved with **modal** computational **techniques**
- ✓ We use an FEM version, modified to accommodate bulk **<u>and</u>** sheet materials with dispersion
  [Raman and Fan, *Phys. Rev. B* 83, 205131, 2011]
- ✓ An additional **auxiliary field** is used to include the **Drude dispersion** of 2D materials

$$\tilde{\mathbf{J}}_m = -\frac{\bar{\bar{\sigma}}_0}{(\tilde{\omega}_m - j\gamma)}\tilde{\mathbf{E}}_m$$

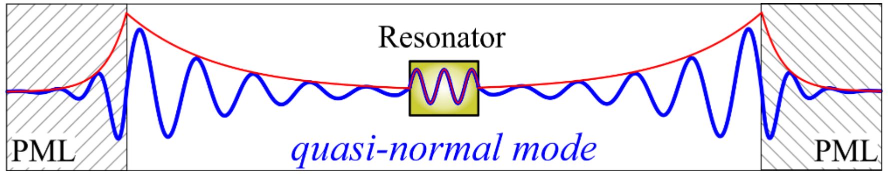
- ✓ Final system of equations to be solved through a **linearized eigenproblem** utilizing $\tilde{\mathbf{J}}_m$

$$\begin{bmatrix} 0 & j\mu^{-1}\nabla\times & 0 \\ -j\varepsilon^{-1}\nabla\times & 0 & -\varepsilon^{-1} \\ 0 & -\bar{\bar{\sigma}}_0\delta_s & j\gamma \end{bmatrix} \begin{bmatrix} \tilde{\mathbf{H}}_m \\ \tilde{\mathbf{E}}_m \\ \tilde{\mathbf{J}}_m \end{bmatrix} = \tilde{\omega}_m \boxed{\begin{bmatrix} \tilde{\mathbf{H}}_m \\ \tilde{\mathbf{E}}_m \\ \tilde{\mathbf{J}}_m \end{bmatrix}}$$

Eigenvector
(on-resonance spatial field distribution)

Eigenvalue
(QNM complex resonance frequency)

The concept of QNMs



- ✓ QNMs should be **normalized** for the expansion
- ✓ This is a non-trivial task due to **spatial field divergence**
- ✓ The normalization is known for bulk materials. Integration should be performed **inside PML** as well, to accommodate spatial divergence
  [Sauvan, et al., Phys. Rev. Lett. 110, 237401, 2013]
- ✓ We provide here the appropriate normalization for 2D materials

Traditional Version

$$\int_{V\cup V_{\mathrm{PML}}} \left(\tilde{\mathbf{E}}_m \cdot \frac{\partial\{\omega\varepsilon(\omega)\}}{\partial\omega}\bigg|_{\omega=\tilde{\omega}_m} \tilde{\mathbf{E}}_m - \tilde{\mathbf{H}}_m \cdot \frac{\partial\{\omega\mu(\omega)\}}{\partial\omega}\bigg|_{\omega=\tilde{\omega}_m} \tilde{\mathbf{H}}_m \right) \mathrm{d}V = 1$$

dispersive terms of bulk materials

Version for 2D Materials

$$\int_{V\cup V_{\mathrm{PML}}} \left(\tilde{\mathbf{E}}_m \cdot \varepsilon\tilde{\mathbf{E}}_m - \tilde{\mathbf{H}}_m \cdot \mu\tilde{\mathbf{H}}_m - \tilde{\mathbf{E}}_m \cdot \boxed{j\,\frac{\partial\bar{\bar{\sigma}}_s(\omega)}{\partial\omega}\bigg|_{\omega=\tilde{\omega}_m}} \tilde{\mathbf{E}}_m \delta_s \right) \mathrm{d}V = 1$$

dispersive (surface) conductivity

[Christopoulos, Kriezis, and Tsilipakos, *Phys. Rev. B* 107, 035413, 2023]

The concept of QNMs

- ✓ In the FEM and in the QNMs expansion framework, **respecting** the true nature of **2D materials** as **infinitesimally thin layers** is crucial
- ✓ 2D materials are typically described electromagnetically by their (complex and dispersive) **surface conductivity** tensor. A surface current is induced: $\mathbf{J}_s = \bar{\bar{\sigma}}(\omega)\mathbf{E}$
- ✓ We take care to incorporate this term in the QNMs formulation

Traditional Version

$$a_m(\omega) = -\frac{\tilde{\omega}_m}{\tilde{\omega}_m - \omega} \int_V \left[\varepsilon(\tilde{\omega}_m) - \varepsilon_b\right] \tilde{\mathbf{E}}_m \cdot \mathbf{E}_{\mathrm{inc}} \mathrm{d}V + \int_V \left[\varepsilon_b - \varepsilon_\infty\right] \tilde{\mathbf{E}}_m \cdot \mathbf{E}_{\mathrm{inc}} \mathrm{d}V$$

Version for 2D Materials

$$a_m(\omega) = -\frac{1}{\tilde{\omega}_m - \omega} \int_V \frac{\bar{\bar{\sigma}}_0}{(\tilde{\omega}_m - j\gamma)} \tilde{\mathbf{E}}_m \cdot \mathbf{E}_{\mathrm{inc}} \mathrm{d}V$$

QNMs and spurious modes

Incident field

[Christopoulos, Kriezis, and Tsilipakos, *Phys. Rev. B* 107, 035413, 2023]

The concept of QNMs

- ✓ QNMs expansion can be applied to describe **nonlinear interactions** of **2D materials**
- ✓ We focus on **third-harmonic generation**, induced by $\bar{\bar{\sigma}}_3$ of graphene
- ✓ A field @ω induces a surface current @3ω (new source) through a third-order process;
  In turn, the current produces a field @3ω which is coupled to a radiative channel (leaky mode)

$$a_m(3\omega) = -\frac{j}{\tilde{\omega}_m - 3\omega}\int_V \tilde{\mathbf{E}}_m \cdot \mathbf{J}_{s,\mathrm{NL}}^{(3\omega)}\delta_s \mathrm{d}V$$

Dominant contribution @3ω

New source term @3ω

$$\mathbf{J}_{s,\mathrm{NL}}^{(3\omega)} = \frac{\sigma_3}{4}(\mathbf{E}_{t,\parallel}^{(\omega)} \cdot \mathbf{E}_{t,\parallel}^{(\omega)})\mathbf{E}_{t,\parallel}^{(\omega)}$$

Total field @ω

[Christopoulos, Kriezis, and Tsilipakos, *Phys. Rev. B* 107, 035413, 2023]

The concept of QNMs

✓ Calculation steps

1. Find all QNMs (around ω <u>and</u> 3ω)
2. Calculate the expansion coefficients @ω: $a_m(\omega) = -\frac{1}{\tilde{\omega}_m - \omega}\int_V \frac{\bar{\bar{\sigma}}_0}{(\tilde{\omega}_m - j\gamma)}\tilde{\mathbf{E}}_m \cdot \mathbf{E}_{\text{inc}}\mathrm{d}V$
3. Calculate scattered field @ω: $\mathbf{E}_{\text{sct}}(\omega) = \sum_m a_m(\omega)\tilde{\mathbf{E}}_m$
4. Calculate total field @ω: $\boxed{\mathbf{E}_t(\omega) = \mathbf{E}_{\text{inc}} + \mathbf{E}_r + \mathbf{E}_{\text{sct}}}$
5. Calculate the induced surface current @3ω: $\mathbf{J}_{s,\text{NL}}^{(3\omega)} = \frac{\sigma_3}{4}(\mathbf{E}_{t,\|}^{(\omega)} \cdot \mathbf{E}_{t,\|}^{(\omega)})\mathbf{E}_{t,\|}^{(\omega)}$
6. Calculate the expansion coefficients @3ω: $a_m(3\omega) = -\frac{j}{\tilde{\omega}_m - 3\omega}\int_V \tilde{\mathbf{E}}_m \cdot \mathbf{J}_{s,\text{NL}}^{(3\omega)}\delta_s \mathrm{d}V$
7. Calculate scattered field @3ω: $\mathbf{E}_{\text{sct}}(3\omega) = \sum_m a_m(3\omega)\tilde{\mathbf{E}}_m$

QNMs are the same
but the expansion coefficients are not

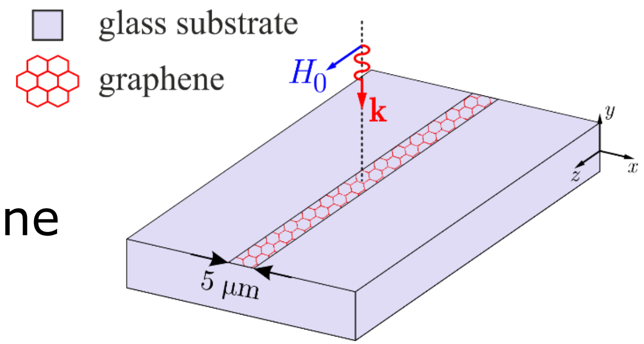
Total field consists of the incident, reflected from the background, and scattered waves!

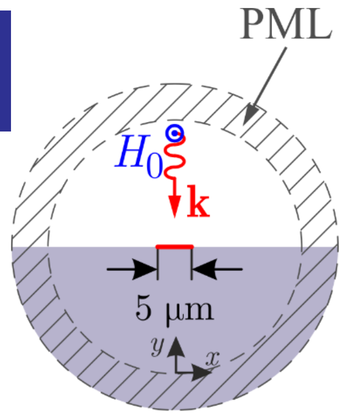
A simple system

Single graphene strip scatterer

Resonant System

- ✓ Single graphene strip on a glass substrate
- ✓ Normal illumination with a TM plane wave to excite graphene surface plasmons → Fabry-Perot resonances along *x* axis





✓ Bright modes:

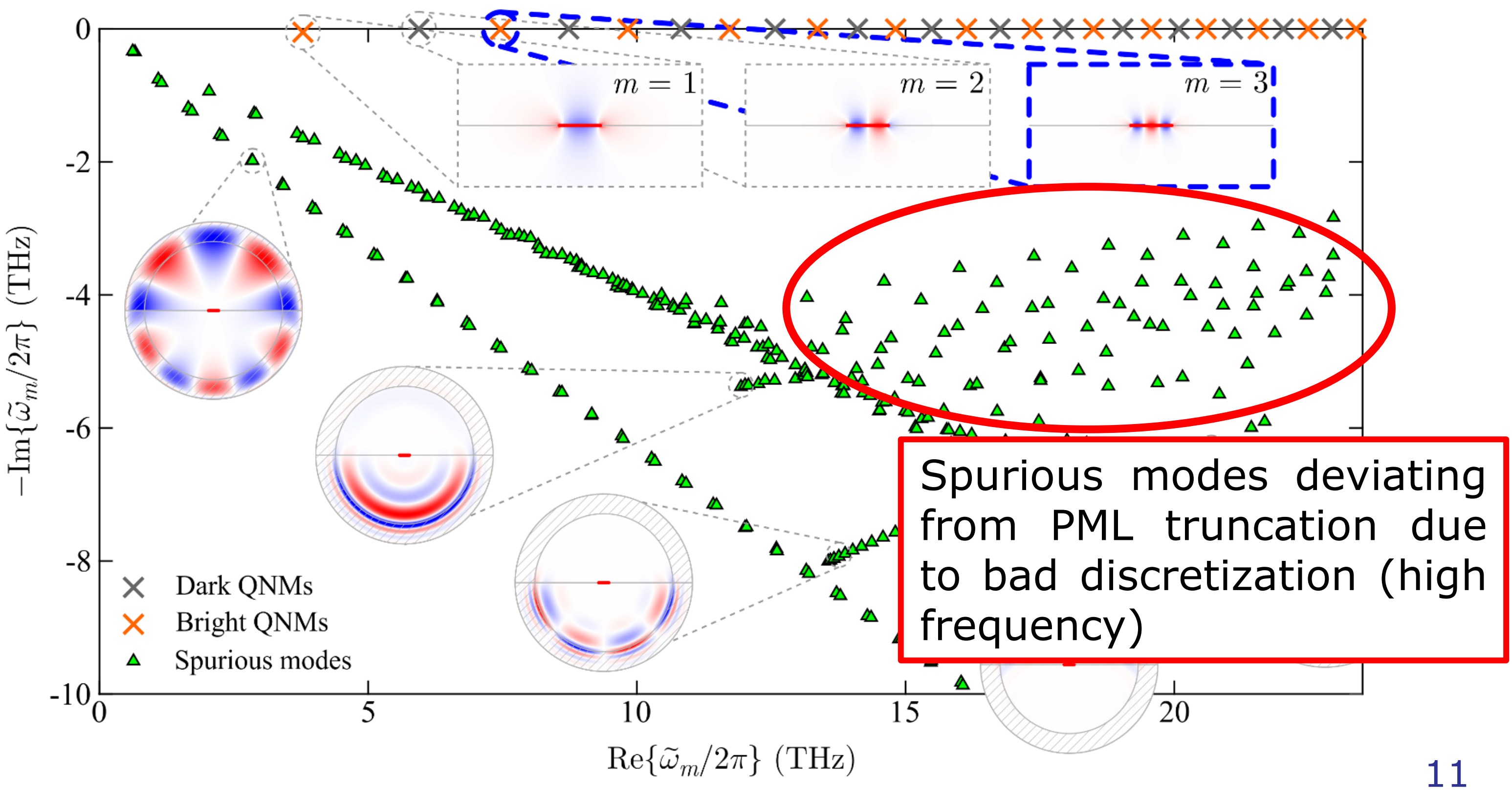
- ✓ *m* is odd (symmetric distribution)
- ✓ Q_{rad} finite
- ✓ Can be excited by a normally incident plane wave

❖ Dark modes:

- ❖ *m* is even (antisymmetric distribution)
- ❖ $Q_{rad} \rightarrow \infty$
- ❖ Cannot be excited by a normally incident plane wave

✓ Spurious (PML) modes:

- ✓ Necessary for the expansion

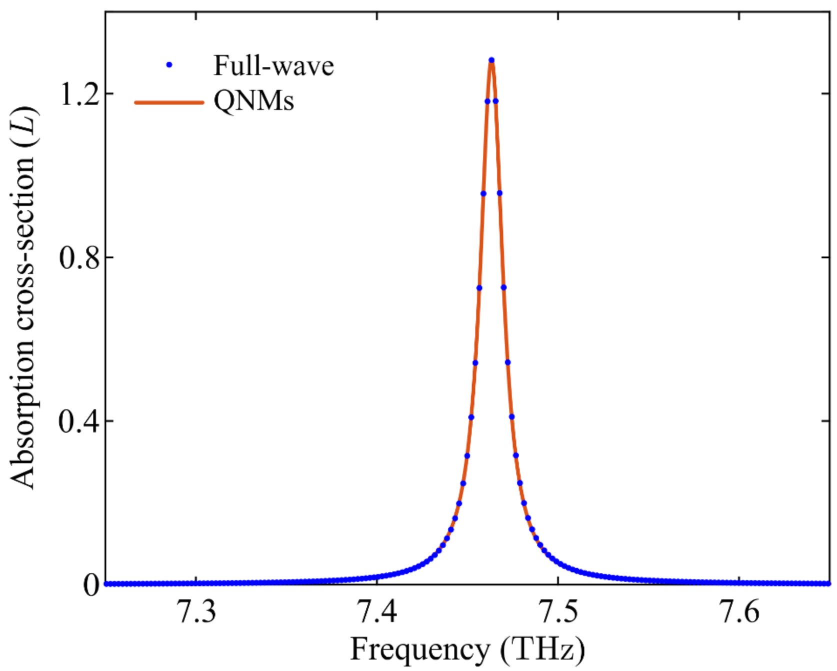


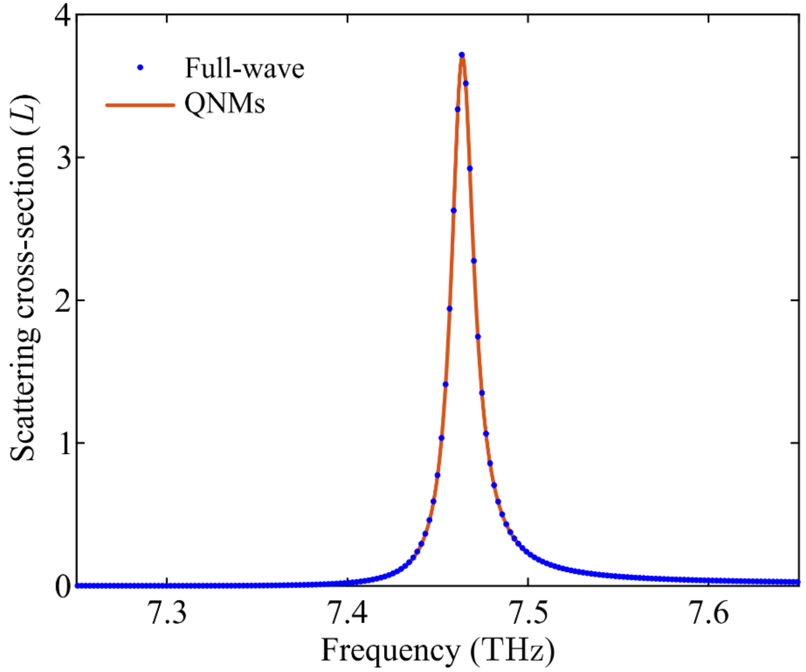
Spurious modes deviating from PML truncation due to bad discretization (high frequency)

Thomas Christopoulos
cthomasa@eie.gr

Linear Absorption and Scattering Cross-Sections

- ✓ Comparison with full-wave linear simulations (around ω) gives **excellent agreement**
- ✓ Even **asymmetries** in scattering cross-section are accurately captured
- ✓ **Correct QNMs normalization** considering **graphene's surface contribution** is crucial to get accurate results

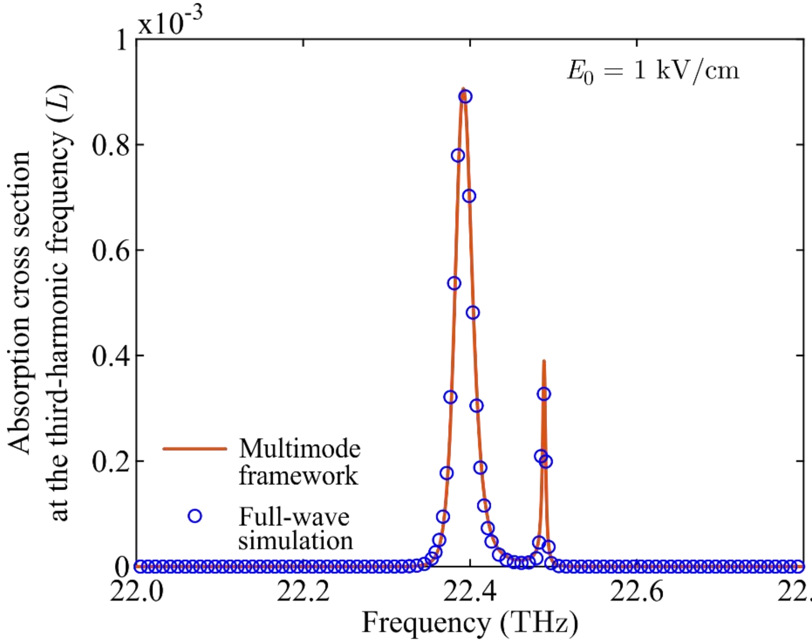


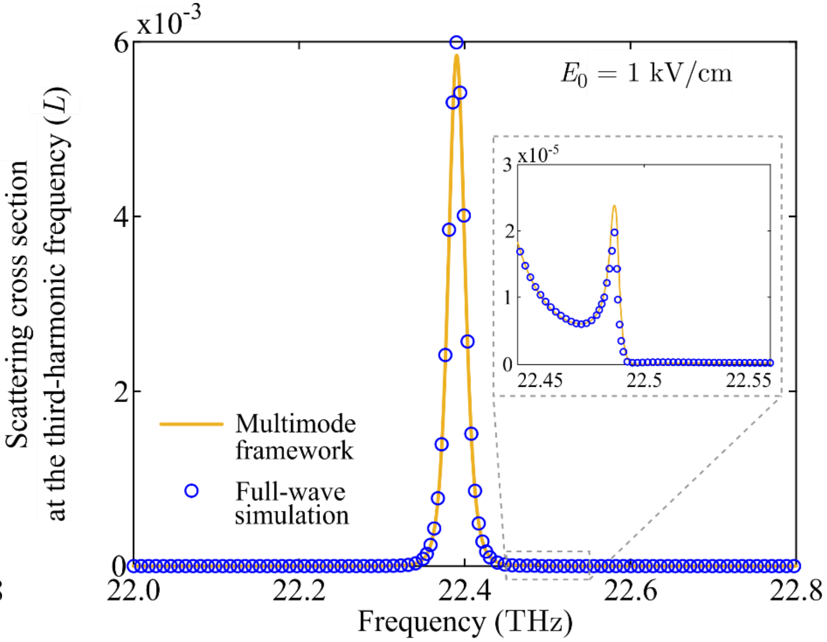


Thomas Christopoulos
cthomasa@eie.gr

Nonlinear Absorption and Scattering Cross-Sections @3ω

- ✓ Using QNMs and the **nonlinear expansion**, **third-harmonic generation** can be efficiently and accurately described
- ✓ Comparison with full-wave nonlinear simulations (around 3ω) gives **excellent agreement**
- ✓ The multimode framework can reveal **interesting physics** of the THG process (two peaks, next slide)
- ✓ Very good agreement even in **asymmetric non-Lorentzian lineshapes** or very weak peaks/interactions

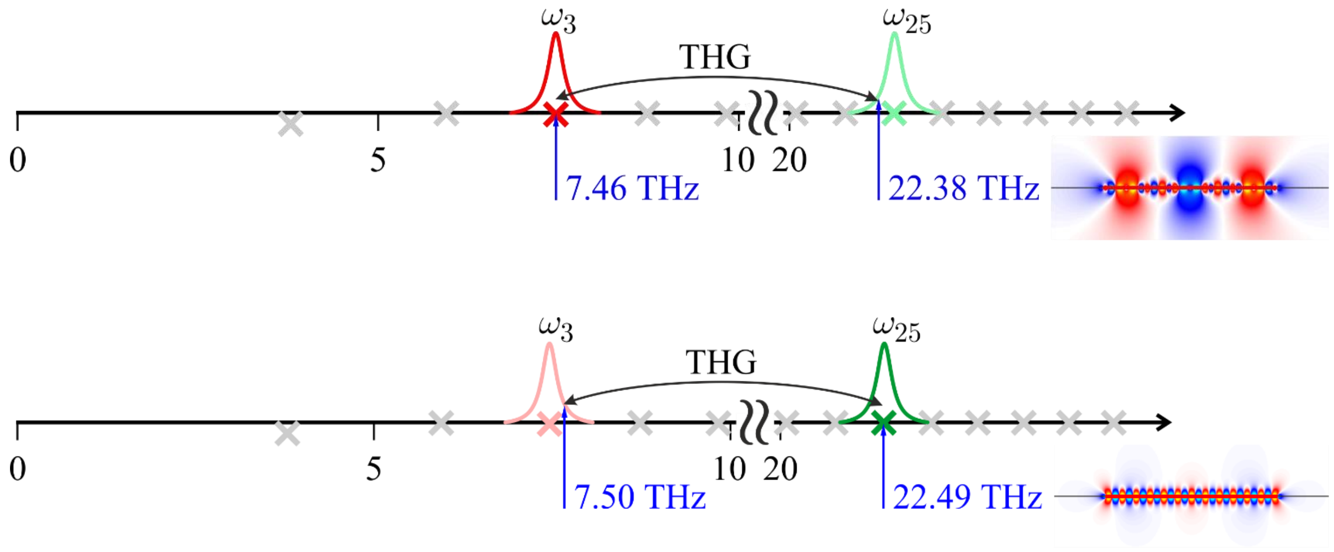


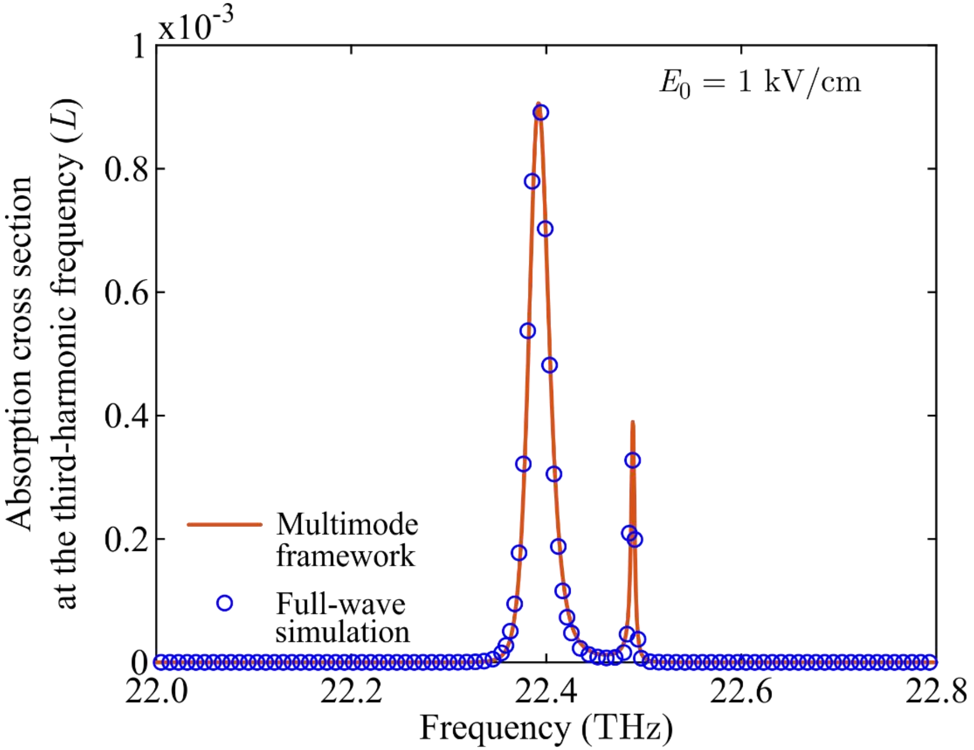


Thomas Christopoulos
cthomasa@eie.gr

Nonlinear Absorption and Scattering Cross-Sections @3ω

- ✓ The **multimode** framework can reveal **interesting physics** of the THG process (non-trivial mode interaction)
- ✓ The first peak emerges at the third harmonic of the fundamental frequency ($3\omega_3$ = 22.38 THz)
- ✓ The second peak emerges exactly at the resonance frequency of the QNM lying closest to 3ω (ω_{25} = 22.49 THz)





A more practical system

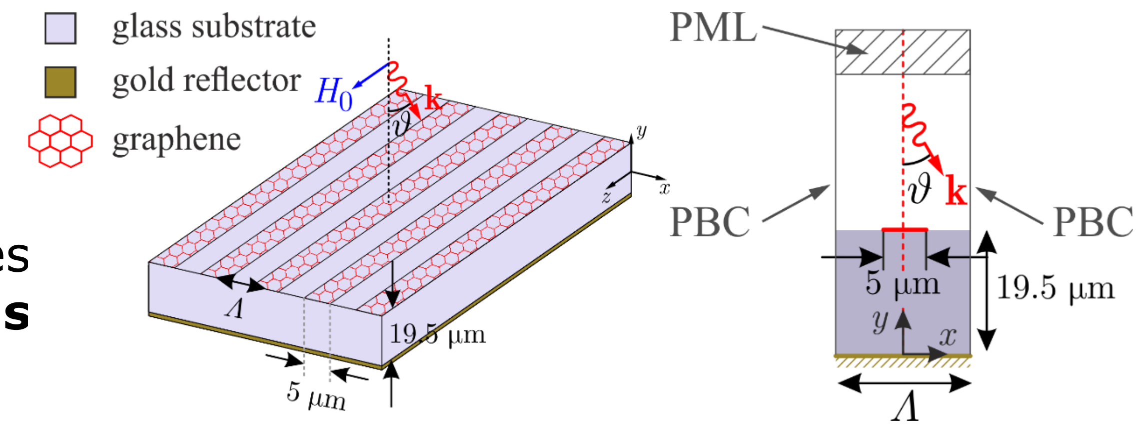
Graphene strip metasurface

Thomas Christopoulos | cthomasa@ece.auth.gr

Thomas Christopoulos
cthomasa@eie.gr

Resonant System

- ✓ Expansion of the previous graphene strip in a **reflective metasurface**
- ✓ Graphene allows for **deeply subwavelength** cavities due to tightly confined **graphene surface plasmons** (GPSs), i.e., large parallel wavevector



- ✓ Deeply subwavelength cavities → lattice remains **subwavelength** even in the **third-harmonic frequency**
- ✓ QNMs **can** also describe metasurfaces with larger periodicity (gratings) where **higher diffraction orders** are excited

QNM framework modifications for periodic systems

- ✓ **Floquet** periodic boundary condition **cannot** be used in **modal calculations** because the knowledge of the wavevector in the periodicity dimension is required and $\tilde{\mathbf{k}}_m \propto \tilde{\omega}_m$

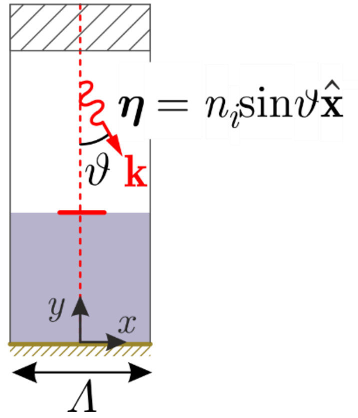
- ✓ The wave equation that is to be solved with the FEM is **modified** to account for this fact

- ✓ Fields are expressed with respect to a spatial periodic envelope $\mathbf{E} = \mathbf{e}\exp\{-j\mathbf{k}_F \cdot \mathbf{r}\} = \mathbf{e}\exp\{-jk_0 \boldsymbol{\eta} \cdot \mathbf{r}\}$

- ✓ The incorporation of $\boldsymbol{\eta}$ vector that depends only on the incident angle allows for a **new** and **correct** wave equation to calculate the QNMs

$$\nabla\times\mu^{-1}\nabla\times\tilde{\mathbf{e}}_m \boxed{-j\frac{\tilde{\omega}_m}{c_0}\nabla\times\mu^{-1}(\boldsymbol{\eta}\times\tilde{\mathbf{e}}_m)-j\frac{\tilde{\omega}_m}{c_0}\boldsymbol{\eta}\times\mu^{-1}\nabla\times\tilde{\mathbf{e}}_m-\frac{\tilde{\omega}_m^2}{c_0^2}\boldsymbol{\eta}\times\mu^{-1}\boldsymbol{\eta}\times\tilde{\mathbf{e}}_m} -\tilde{\omega}_m^2\varepsilon\tilde{\mathbf{e}}_m-\tilde{\omega}_m\tilde{\mathbf{j}}_m = 0$$

new terms disentangling the eigenvalue and the angle of incidence contributions on the wave-vector



QNM framework modifications for periodic systems

- ✓ The envelope modification introduced abode modifies the QNMs eigenvalue equation

$$\begin{bmatrix} 0 & j\mu^{-1}\nabla\times & 0 \\ -j\varepsilon^{-1}\nabla\times & 0 & -\varepsilon^{-1} \\ 0 & -\bar{\bar{\sigma}}_0\delta_s & j\gamma \end{bmatrix} \begin{bmatrix} \tilde{\mathbf{h}}_m \\ \tilde{\mathbf{e}}_m \\ \tilde{\mathbf{j}}_m \end{bmatrix} = \tilde{\omega}_m \overbrace{\boxed{\begin{bmatrix} 1 & -(c_0\mu)^{-1}\boldsymbol{\eta}\times & 0 \\ (c_0\varepsilon)^{-1}\boldsymbol{\eta}\times & 1 & 0 \\ 0 & 0 & 1 \end{bmatrix}}}^{\hat{\mathcal{M}}} \begin{bmatrix} \tilde{\mathbf{h}}_m \\ \tilde{\mathbf{e}}_m \\ \tilde{\mathbf{j}}_m \end{bmatrix}$$

- ✓ It also modifies the expansion coefficients and the QNM normalization term – only **envelope quantities** are involved

$$a_m(\omega) = -\frac{1}{\tilde{\omega}_m - \omega}\int_V \frac{\bar{\bar{\sigma}}_0}{(\tilde{\omega}_m - j\gamma)} \tilde{\mathbf{e}}_{-m} \cdot \mathbf{e}_{\text{inc}} \mathrm{d}V$$

Left eigenvectors (calculated for $-\boldsymbol{\eta}$)

$$\int_V \left[\tilde{\mathbf{e}}_{-m} \cdot \varepsilon \tilde{\mathbf{e}}_m - \tilde{\mathbf{h}}_{-m} \cdot \mu \tilde{\mathbf{h}}_m - \tilde{\mathbf{e}}_{-m} \cdot j \frac{\partial \bar{\bar{\sigma}}_s(\omega)}{\partial \omega} \tilde{\mathbf{e}}_m \delta_s - \boxed{\boldsymbol{\eta} \cdot \frac{1}{c_0} \left(\tilde{\mathbf{h}}_{-m} \times \tilde{\mathbf{e}}_m + \tilde{\mathbf{e}}_{-m} \times \tilde{\mathbf{h}}_m \right)} \right] \mathrm{d}V = 1$$

extra normalization term

QNM framework modifications for periodic systems

✓ Expansion coefficients are also modified in the nonlinear system

$$\boxed{a_m(3\omega) = -\frac{j}{\tilde{\omega}_m - 3\omega}\int_V \left[\tilde{\mathbf{e}}_{-m}\cdot\mathbf{j}_{s,\mathrm{NL}}^{(3\omega)}\delta_s - \boldsymbol{\eta}\cdot\left(\tilde{\mathbf{h}}_{-m}\times\mathbf{j}_{s,\mathrm{NL}}^{(3\omega)}\delta_s\right)\right]\mathrm{d}V}$$

Nonlinear current envelope

$$\mathbf{j}_{s,\mathrm{NL}}^{(3\omega)} = \frac{\sigma_3}{4}\left(\mathbf{e}_{t,\parallel}^{(\omega)}\cdot\mathbf{e}_{t,\parallel}^{(\omega)}\right)\mathbf{e}_{t,\parallel}^{(\omega)}$$

Expected envelope term

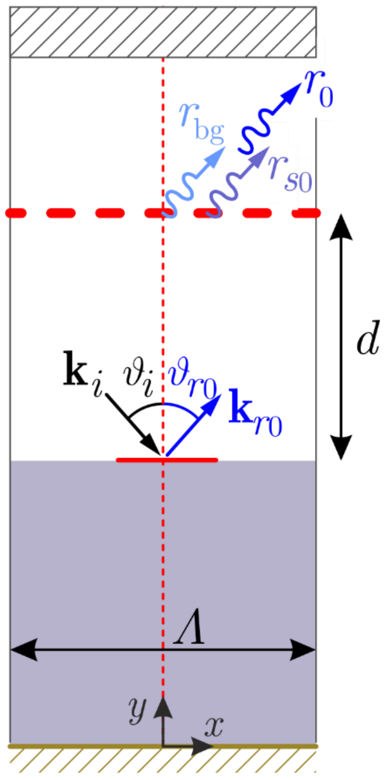
New additional term due to periodicity

$$\mathbf{e}_t^{(\omega)} = \mathbf{E}_t^{(\omega)}e^{+jk_0\boldsymbol{\eta}\cdot\mathbf{r}}$$

Non-zero when there is a surface current component perpendicular to the periodicity vector $\boldsymbol{\eta}$

Thomas Christopoulos
cthomasa@eie.gr

Linear reflection (specular)



$\Lambda = 10\ \mu m$

$\lambda_0 \sim 40\ \mu m$

✓ Specular reflection (Snell's law), $\vartheta_i = \vartheta_{r0}$ and $k_{i,y} = -k_{r0,y}$

✓ Reflection coefficient: $r_0 = r_{\mathrm{bg}} + \dfrac{1}{\Lambda H_0} e^{jk_{r0,y}d} \displaystyle\int_{-\Lambda/2}^{\Lambda/2} \mathbf{H}_{\mathrm{sct}}(x,d) e^{jk_{r0,x}x}\,\mathrm{d}x$

background reflection without graphene
(analytical calculation)

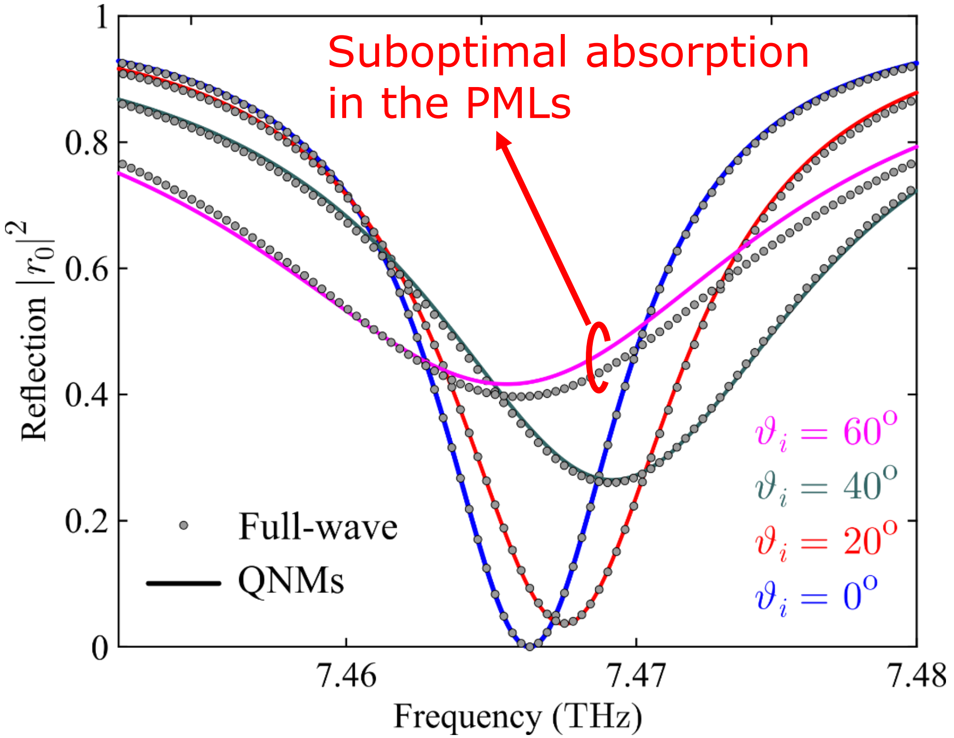
Scattered field

$$\mathbf{H}_{\mathrm{sct}}(x,d) = \sum_m a_m(\omega)\tilde{\mathbf{h}}_m(x,d)e^{-j\tilde{k}_m \sin\vartheta_i x}$$

QNM expansion coefficients

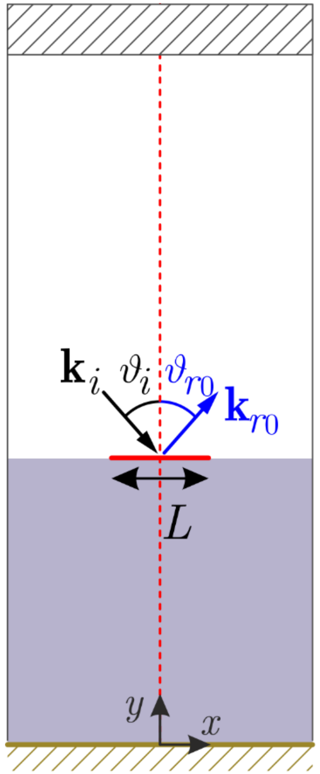
QNMs (envelopes)

Periodic phase term (different for each QNM)



Thomas Christopoulos
cthomasa@eie.gr

Linear absorption



$L = 5\ \mu\text{m}$

✓ Absorption coefficient: $$|\alpha|^2 = \frac{1}{P_\text{inc}} \int_{-L/2}^{L/2} \text{Re}\{\sigma_s(\omega)\} |\mathbf{e}_{\text{sct},\parallel}|^2 \text{d}x$$

No need for the phase term here!

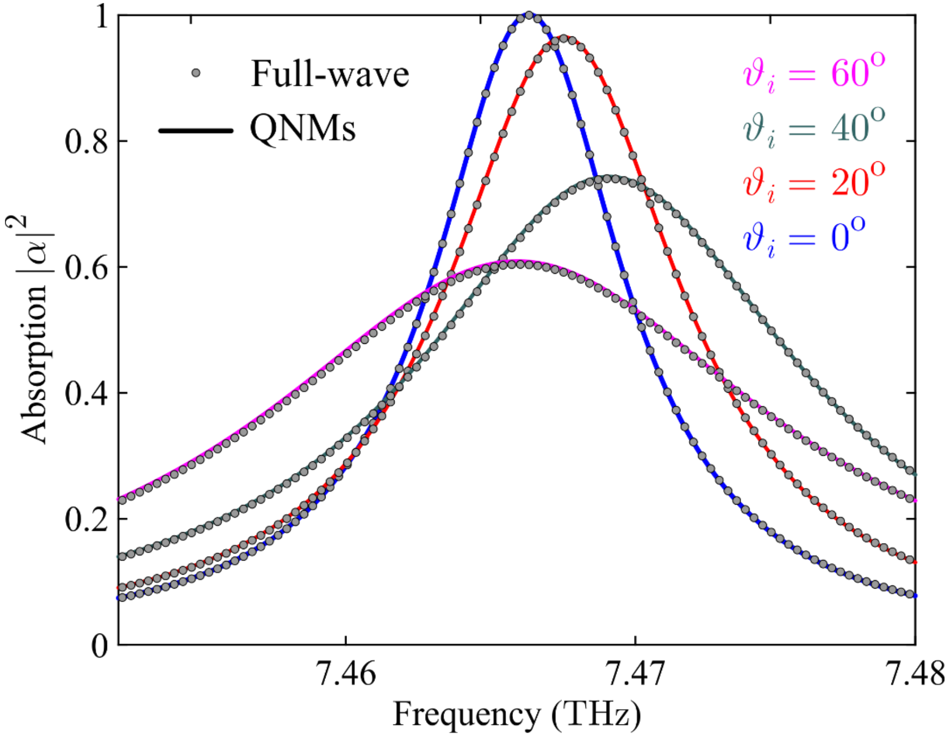
Scattered field's envelope

$$\mathbf{e}_\text{sct} = \sum_m a_m(\omega) \tilde{\mathbf{e}}_m$$

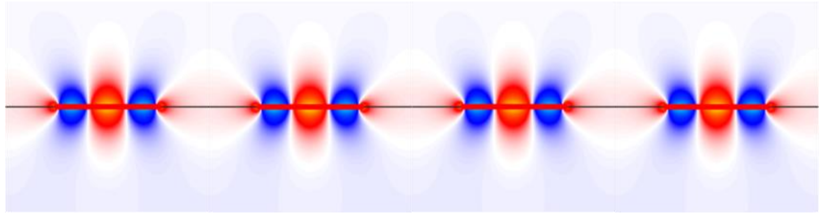
QNM expansion coefficients

QNMs (envelopes)

✓ **Perfect agreement** for **any angle of incidence** since the expansion is complete on the resonator (graphene sheet)

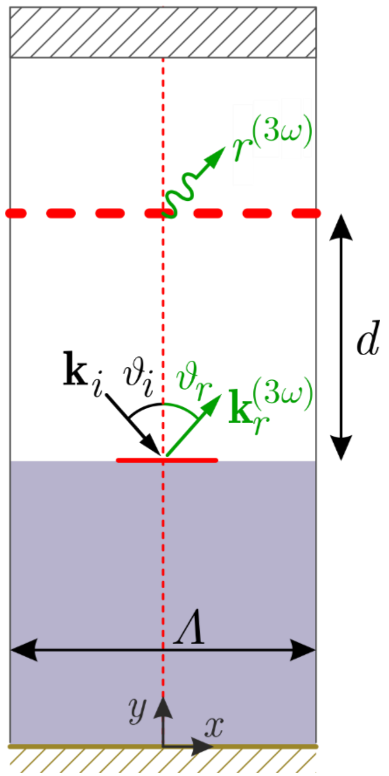


No need to consider background field (incident and reflected) due to the **high confinement** and enhancement of the GSPs



Thomas Christopoulos
cthomasa@eie.gr

Nonlinear absorption and specular reflection



$$\Lambda = 10\ \mu m$$

$$\lambda_0 \sim 40\ \mu m$$

✓ Nonlinear absorption coefficient:

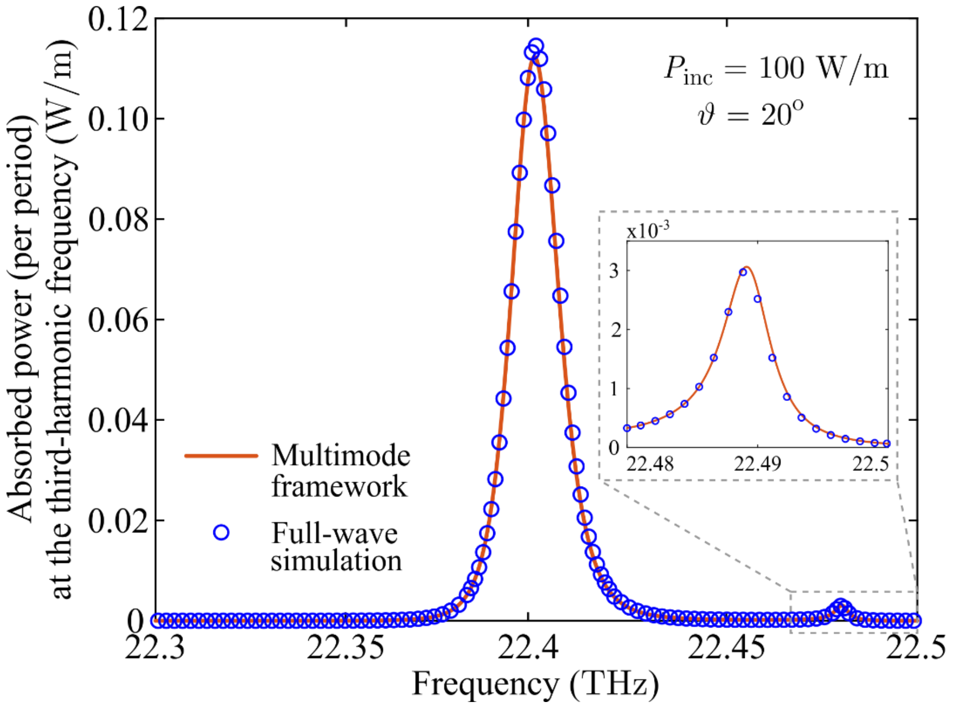
$$|\alpha|^2 = \frac{1}{P_{\text{inc}}} \int_{-L/2}^{L/2} \mathrm{Re}\{\sigma_s(\omega)\} |\mathbf{e}_{\text{sct},\parallel}^{(3\omega)}|^2 \mathrm{d}x$$

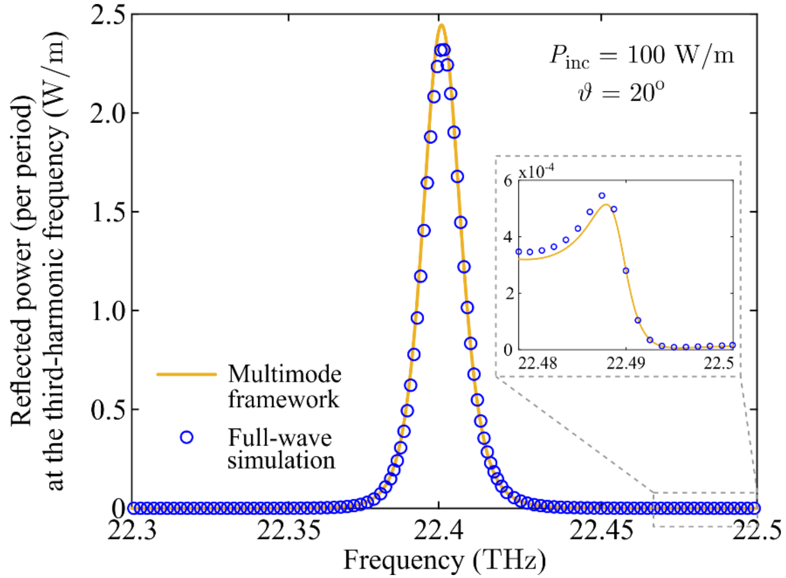
✓ Nonlinear reflection coefficient:

$$r_0 = \frac{1}{\Lambda H_0} e^{jk_{r,y}^{(3\omega)} d} \int_{-\Lambda/2}^{\Lambda/2} \mathbf{H}_{\text{sct}}^{(3\omega)}(x,d) e^{jk_{r,x}^{(3\omega)} x} \mathrm{d}x$$

Scattered field @3ω

$$\mathbf{H}_{\text{sct}}^{(3\omega)}(x,d) = \sum_m a_m(3\omega) \tilde{\mathbf{h}}_m(x,d) e^{-j\tilde{k}_m \sin\vartheta_i x}$$





A more practical system

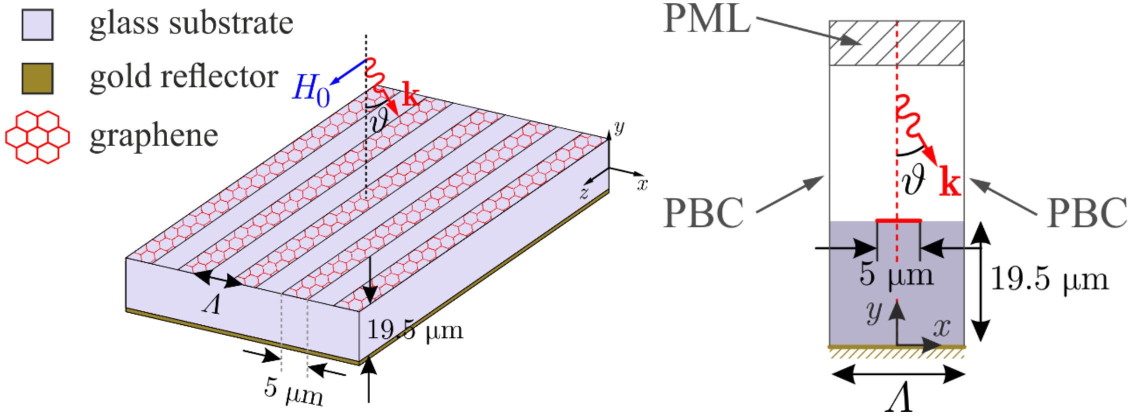
Higher diffraction orders in graphene strip metasurface

Thomas Christopoulos | cthomasa@ece.auth.gr

Thomas Christopoulos
cthomasa@eie.gr

Resonant System

- ✓ Expansion of the previous graphene strip configuration in a **reflective metasurface/grating**



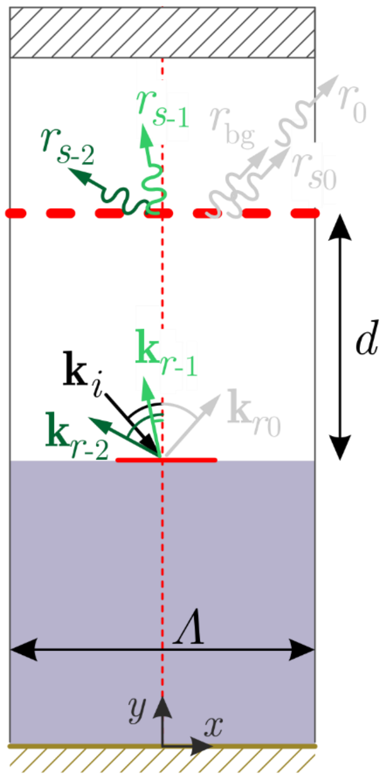
- ✓ Periodicity Λ **controls reflection** and allows:
  - only for specular reflection (subwavelength metasurface)
  - excitation of higher diffraction orders (reflective grating)

- ✓ A higher diffraction order ($\ell \neq 0$) is excited when $\dfrac{\Lambda}{\lambda_0} > -\dfrac{\ell}{n_i(\sin\vartheta \pm 1)}$

- ✓ For example, in normal incidence a higher diffraction order is excited when $\dfrac{\Lambda}{\lambda_0} > \pm|\ell|$

Thomas Christopoulos
cthomasa@eie.gr

Higher diffraction orders linear calculation



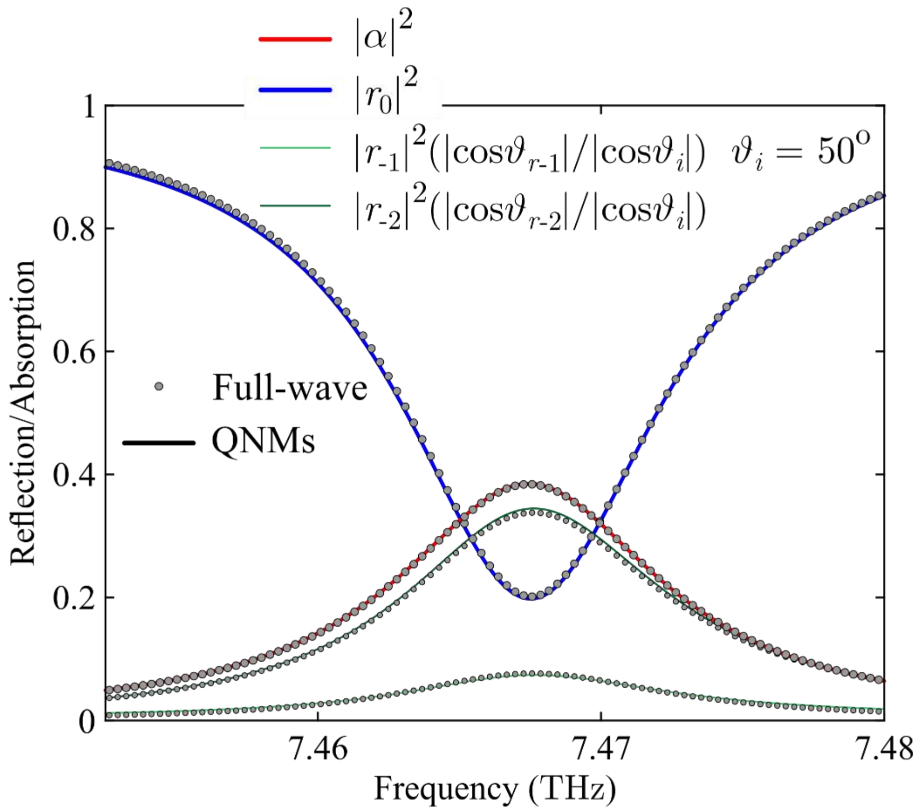
$\Lambda = 50\ \mu m$

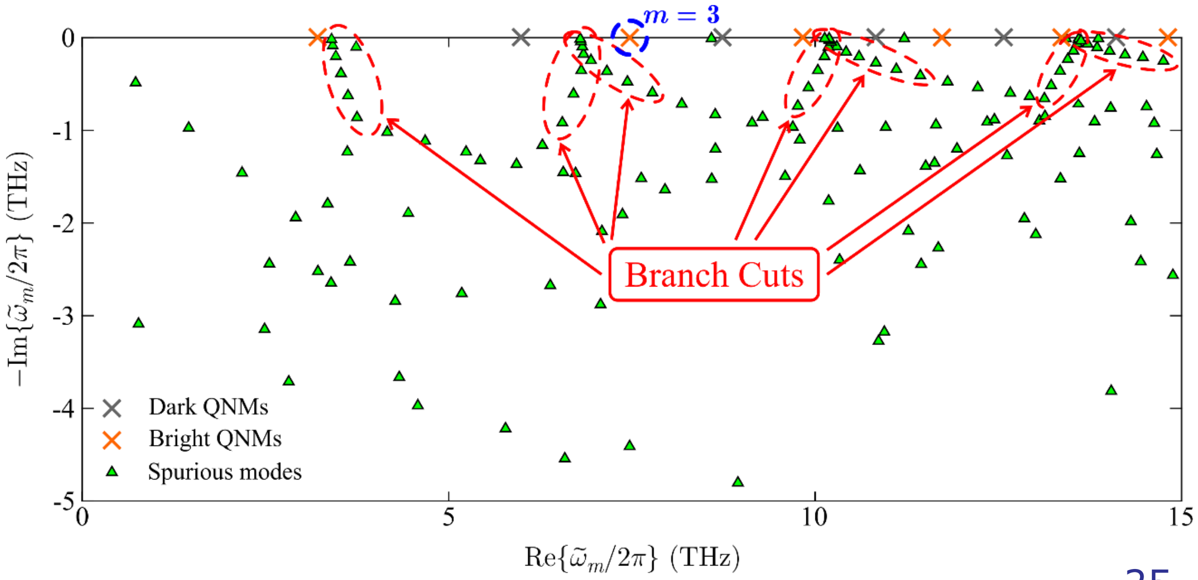
$\lambda_0 \sim 40\ \mu m$

- ✓ Higher diffraction orders: $k_{r\ell,x} = k_0 n_i \sin\vartheta_i + \ell\dfrac{2\pi}{\Lambda}$ and $k_{r\ell,y} = \sqrt{k_0^2 - k_{r\ell,x}^2}$
- ✓ Reflection coefficient: $r_\ell = \dfrac{1}{\Lambda H_0} e^{jk_{r\ell,y}d}\displaystyle\int_{-\Lambda/2}^{\Lambda/2} \mathbf{H}_{\text{sct}}(x,d)\, e^{jk_{r\ell,x}x}\,\mathrm{d}x$

Scattered field

$$\mathbf{H}_{\text{sct}}(x,d) = \sum_m a_m(\omega)\tilde{\mathbf{h}}_m(x,d)e^{-j\tilde{k}_m \sin\vartheta_i x}$$





Summary and Conclusion

Thomas Christopoulos | cthomasa@ece.auth.gr

Summary

- ✓ Presentation of a **multimode** QNMs framework, rigorously incorporating **2D materials**
- ✓ Accurate description of linear and **nonlinear effects** (third-harmonic generation) in single scatterers and periodic structures (metasurfaces)
- ✓ Excellent accuracy of the framework (validated through full-wave simulations)
- ✓ Examination of gratings with 2D materials that support **higher diffraction orders**

Outlook

- ✓ Expansion of the framework in 3D metasurfaces for additional degrees of freedom and richer mode interaction effects
- ✓ Examination of other nonlinear effects (self-phase modulation)

Publications

✓ PHYSICAL REVIEW B **107**, 035413 (2023)

Multimode non-Hermitian framework for third harmonic generation in nonlinear photonic systems comprising two-dimensional materials

Thomas Christopoulos,[1,2,*] Emmanouil E. Kriezis,[2] and Odysseas Tsilipakos[3,1,†]
[1]*Institute of Electronic Structure and Laser, Foundation for Research and Technology Hellas (FORTH), Heraklion 70013, Crete, Greece*
[2]*School of Electrical and Computer Engineering, Aristotle University of Thessaloniki (AUTH), GR-54124 Thessaloniki, Greece*
[3]*Theoretical and Physical Chemistry Institute, National Hellenic Research Foundation, GR-11635 Athens, Greece*

(Received 7 November 2022; revised 23 December 2022; accepted 23 December 2022; published 13 January 2023)

✓ **In preparation**: Higher-diffraction orders handling with QNMs

Thomas Christopoulos
cthomasa@eie.gr

Thank you!

web: photosurf.iesl.forth.gr
e-mail: cthomasa@eie.gr

This work was supported by the Hellenic Foundation for Research and Innovation (H.F.R.I.) under the "2nd Call for H.F.R.I. Research Projects to support Post-doctoral Researchers" (Project No. 916, PHOTOSURF)

H.F.R.I. Hellenic Foundation for Research & Innovation

photoSURF

ΕΘΝΙΚΟ ΙΔΡΥΜΑ ΕΡΕΥΝΩΝ
National Hellenic Research Foundation