Thermal Radiative Properties of Micro/Nanostructured Plasmonic Metamaterials Including Two-Dimensional Materials

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Ph.D. Defense Presentation

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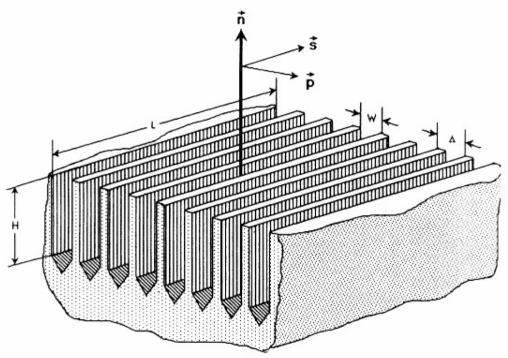
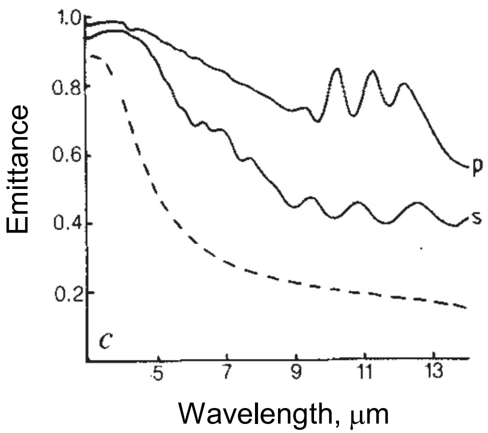
Outline

- Introduction
- Objectives
- Results
- Contributions & Outlook

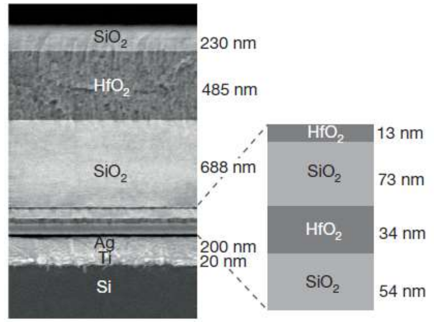
Coherent Nature of Thermal Radiation



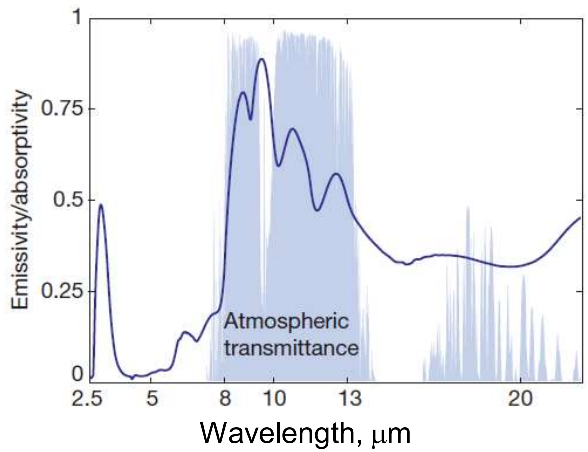
Doped-Si grating at 400°C



Hesketh et al. (1986) Nature.

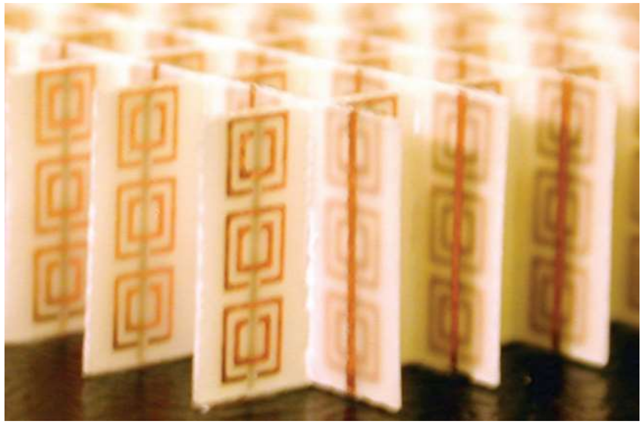


Multilayer structure

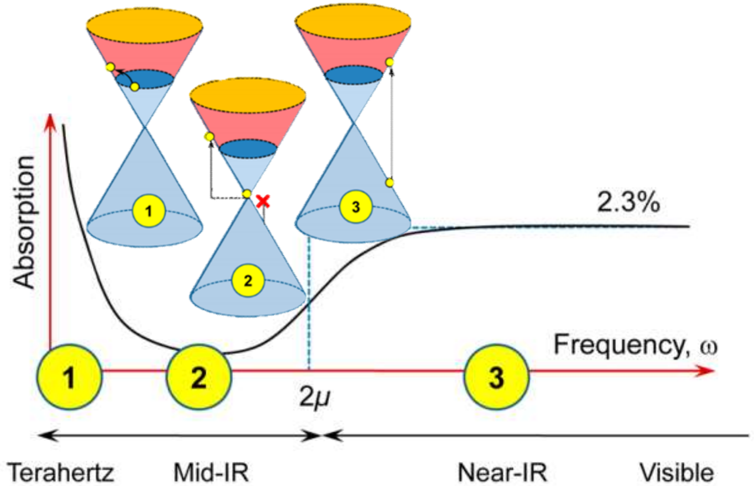


Aaswath et al. (2014) Nature.

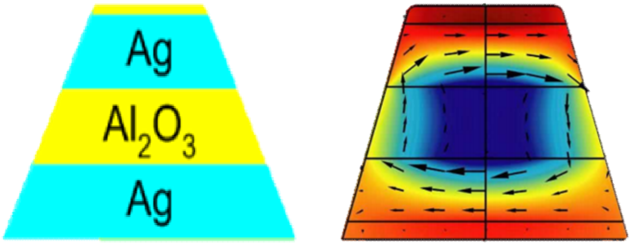
Plasmonic Metamaterials and 2D Materials



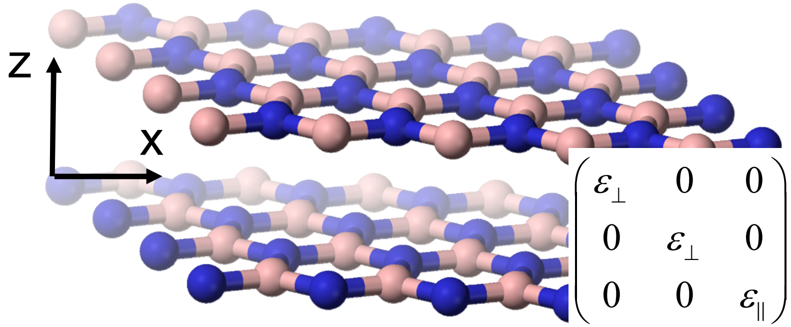
Shelby et al. (2001) Science



Low and Avouris (2014) ACS Nano



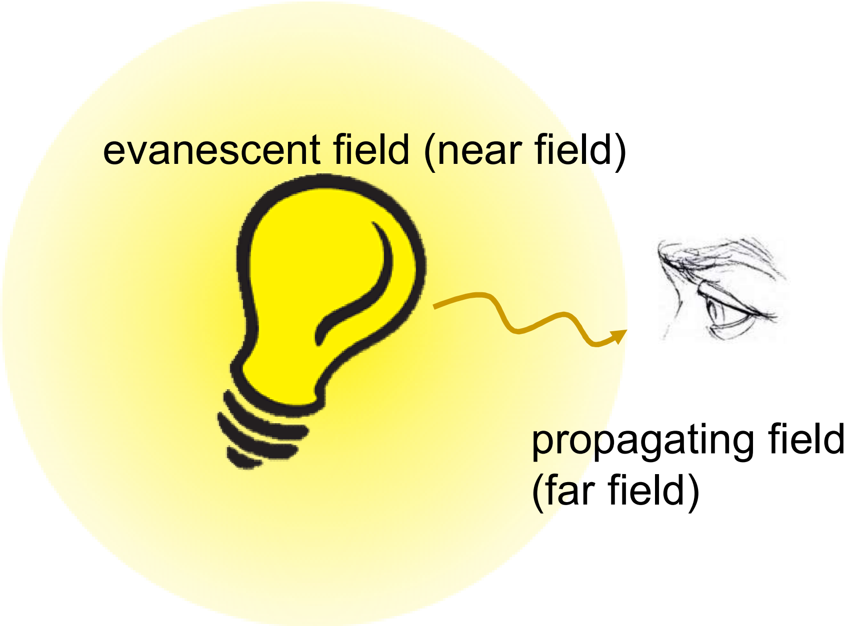
Cai et al. (2007) Opt. Express



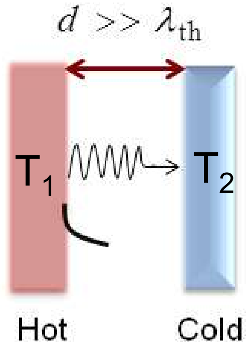
$$\begin{pmatrix} \varepsilon_\perp & 0 & 0 \\ 0 & \varepsilon_\perp & 0 \\ 0 & 0 & \varepsilon_\parallel \end{pmatrix}$$

$$\frac{k_x^2}{\varepsilon_\parallel} + \frac{k_z^2}{\varepsilon_\perp} = \frac{\omega^2}{c_0^2}$$

Near-Field Radiation

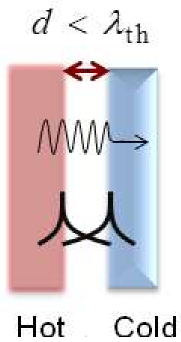


- Far Field: Only propagating modes contribute



$$q''_{BB} = \sigma\left(T_1^4 - T_2^4\right)$$

- Near Field: Evanescent waves can tunnel



Objectives

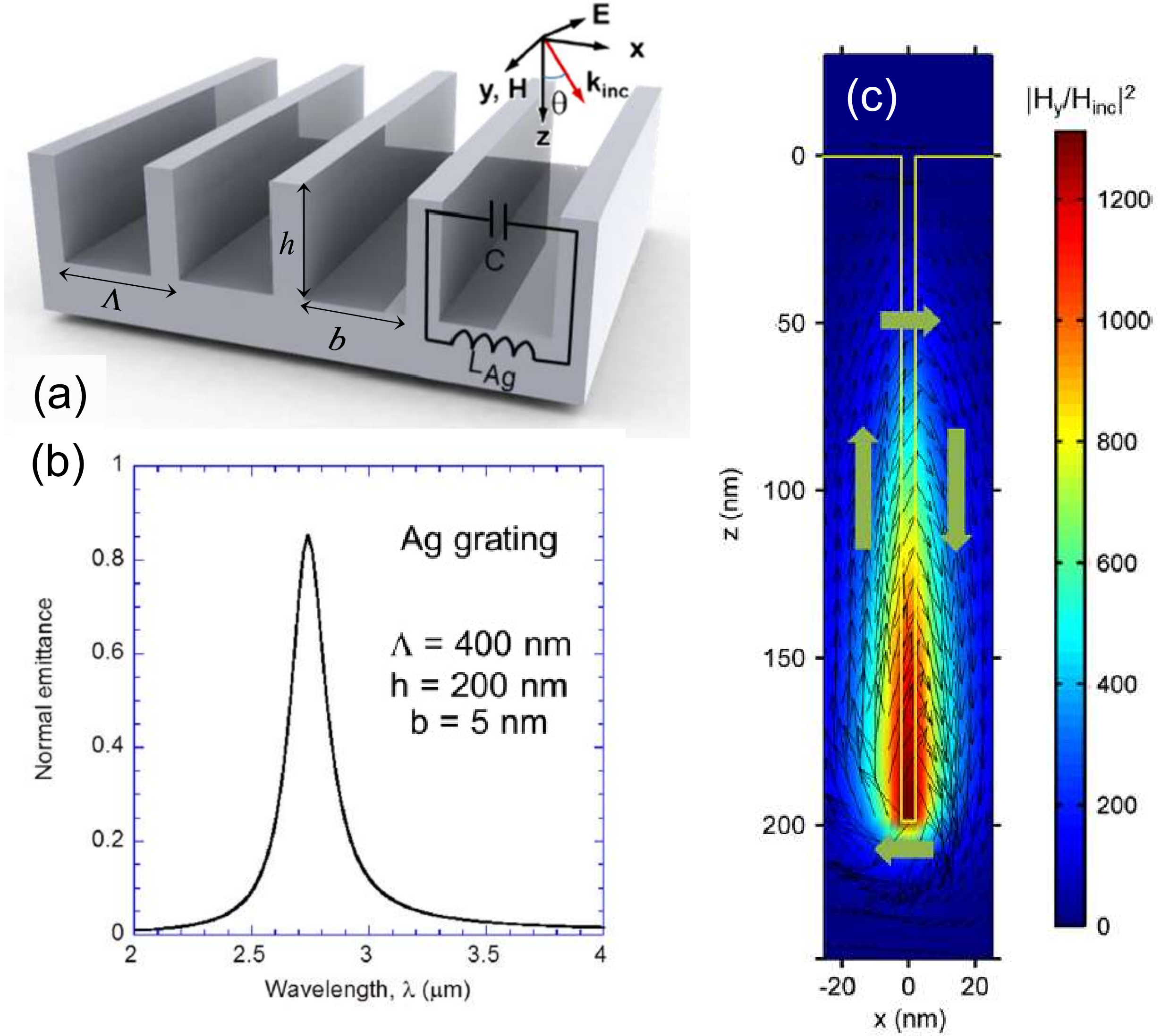
Study the thermal radiative properties of micro/nanostructured plasmonic metamaterials and different 2D materials in both far and near fields.

- Task 1: Radiative Properties of Micro/Nanostructured Plasmonic Metamaterials
- Task 2: Radiative Properties of 2D Materials and the Coupling with Metamaterials
- Task 3: Near-Field Heat Transfer Between 2D Materials

Task 1

- Task 1: Radiative Properties from Micro/Nanostructured Plasmonic Metamaterials
  - Deep Metal Grating Structures
  - Two-Dimensional Grating/Thin-Film Periodic Nanostructure
  - Anisotropic Metamaterials

Magnetic Polaritons (MPs) in Metal Gratings



$$L_{\mathrm{Ag}} = L_{\mathrm{k}} + L_{\mathrm{m}}$$

$$L_{\mathrm{k}} = -\frac{2h+b}{\varepsilon_0 \omega^2 l \delta} \frac{\varepsilon'}{\left(\varepsilon'^2 + \varepsilon''^2\right)}$$

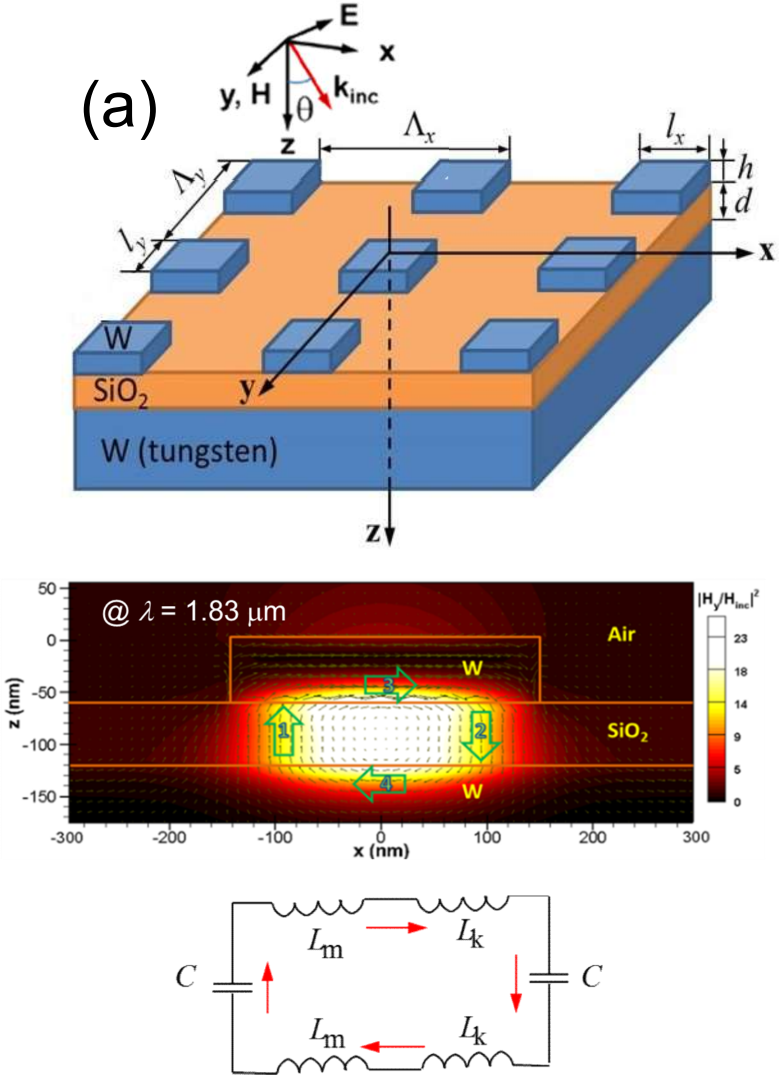
$$L_{\mathrm{m}} = \mu_0\, hb/l$$

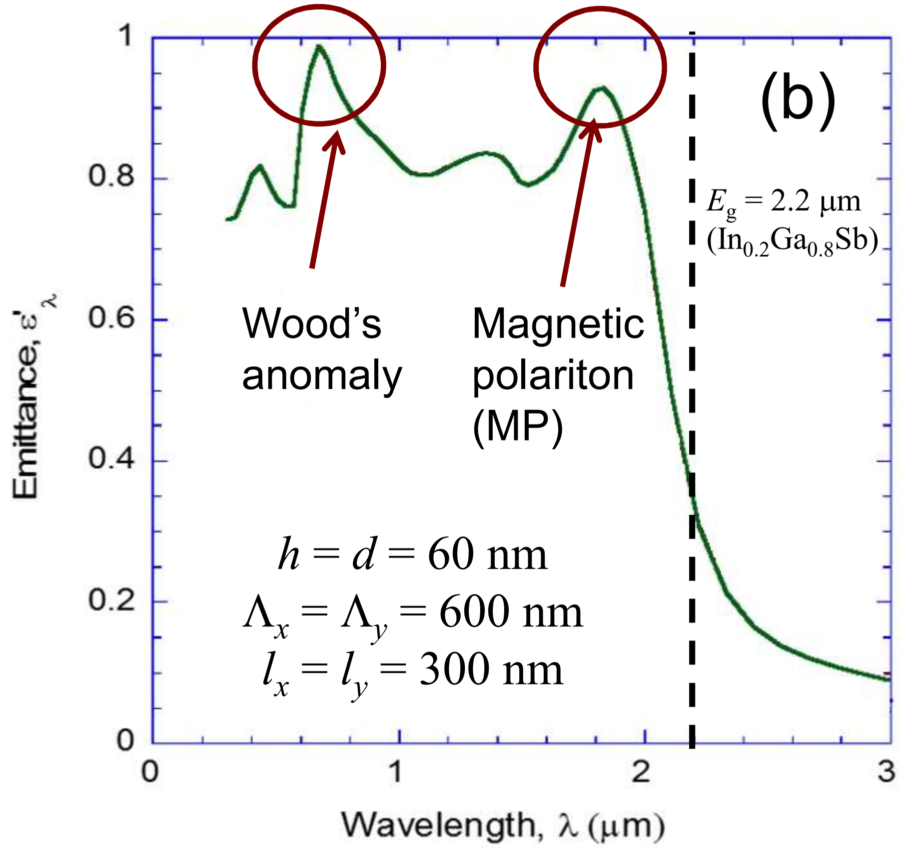
$$C = c'\varepsilon_0\, hl/b$$

$$\lambda_{\mathrm{R}} = 2\pi c_0 \sqrt{\left(L_{\mathrm{k}} + L_{\mathrm{m}}\right) C}$$

Zhao&Zhang (2014) JQSRT.

Wavelength-Selective Emitters

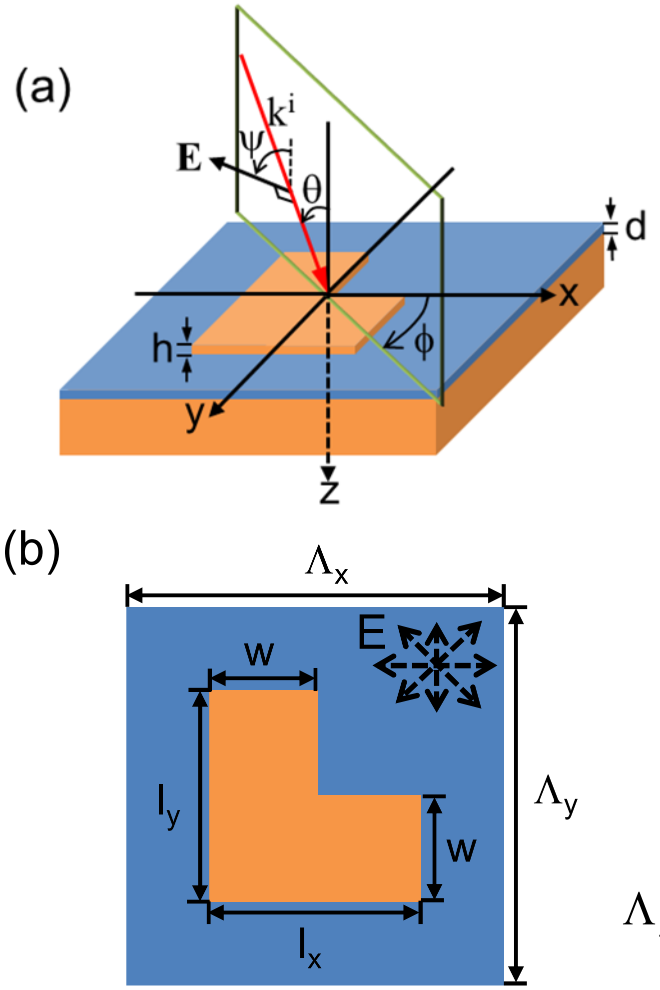


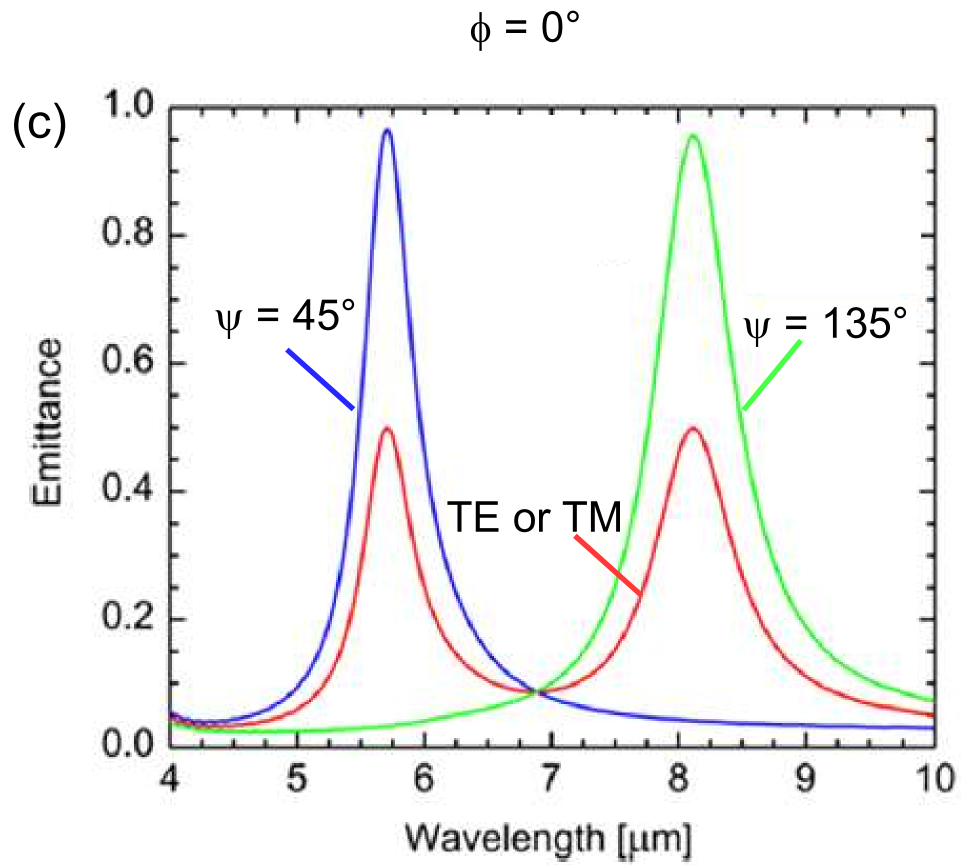


Normal direction

Zhao et al. (2013) IJHMT.

Anisotropic Metamaterials





$$\Lambda_x = \Lambda_y = 3.2\ \mu\text{m}$$

$$l_x = l_y = 1.7\ \mu\text{m}$$

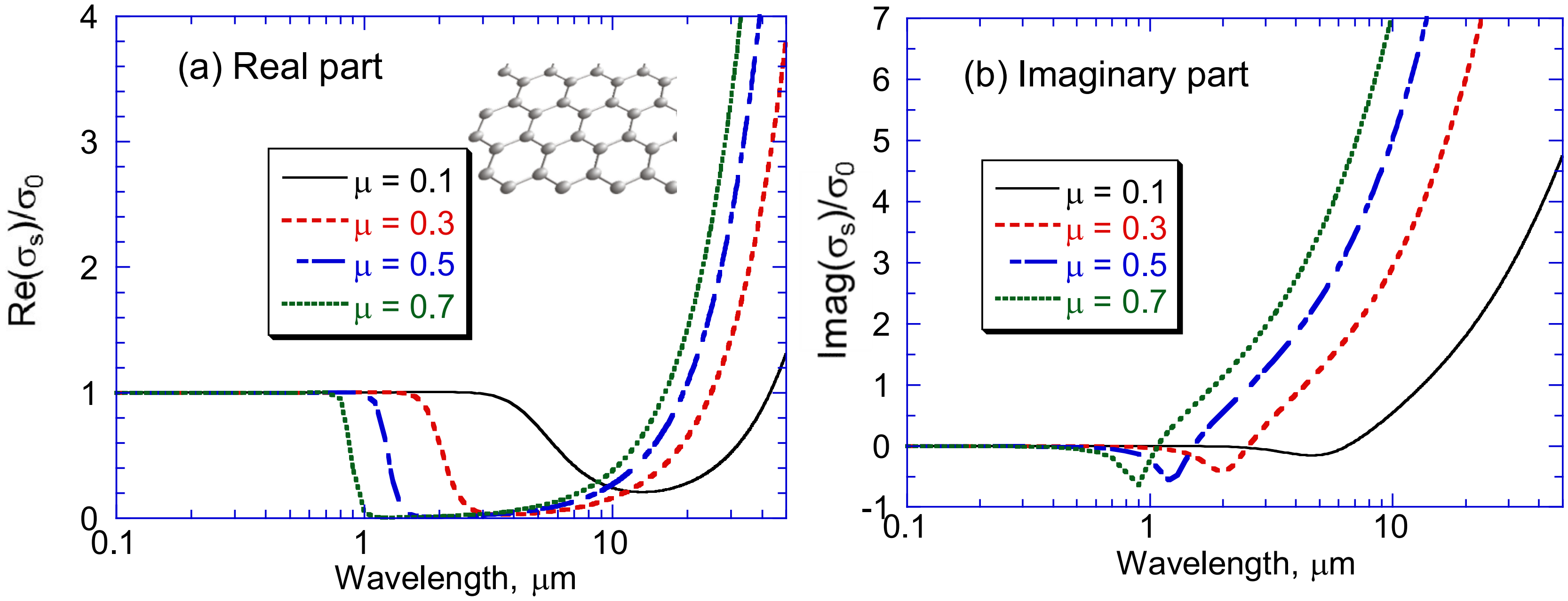
$$w = 0.85\ \mu\text{m}$$

Zhao et al. (2015) JTHT
Sakurai et al. (2015) JQSRT

Task 2

- Task 2: Radiative Properties of 2D Materials and the Coupling with Metamaterials
  - Graphene-covered Metal Gratings
  - Metal Gratings Covered by Hyperbolic Materials
  - Gratings Made of Hyperbolic Materials

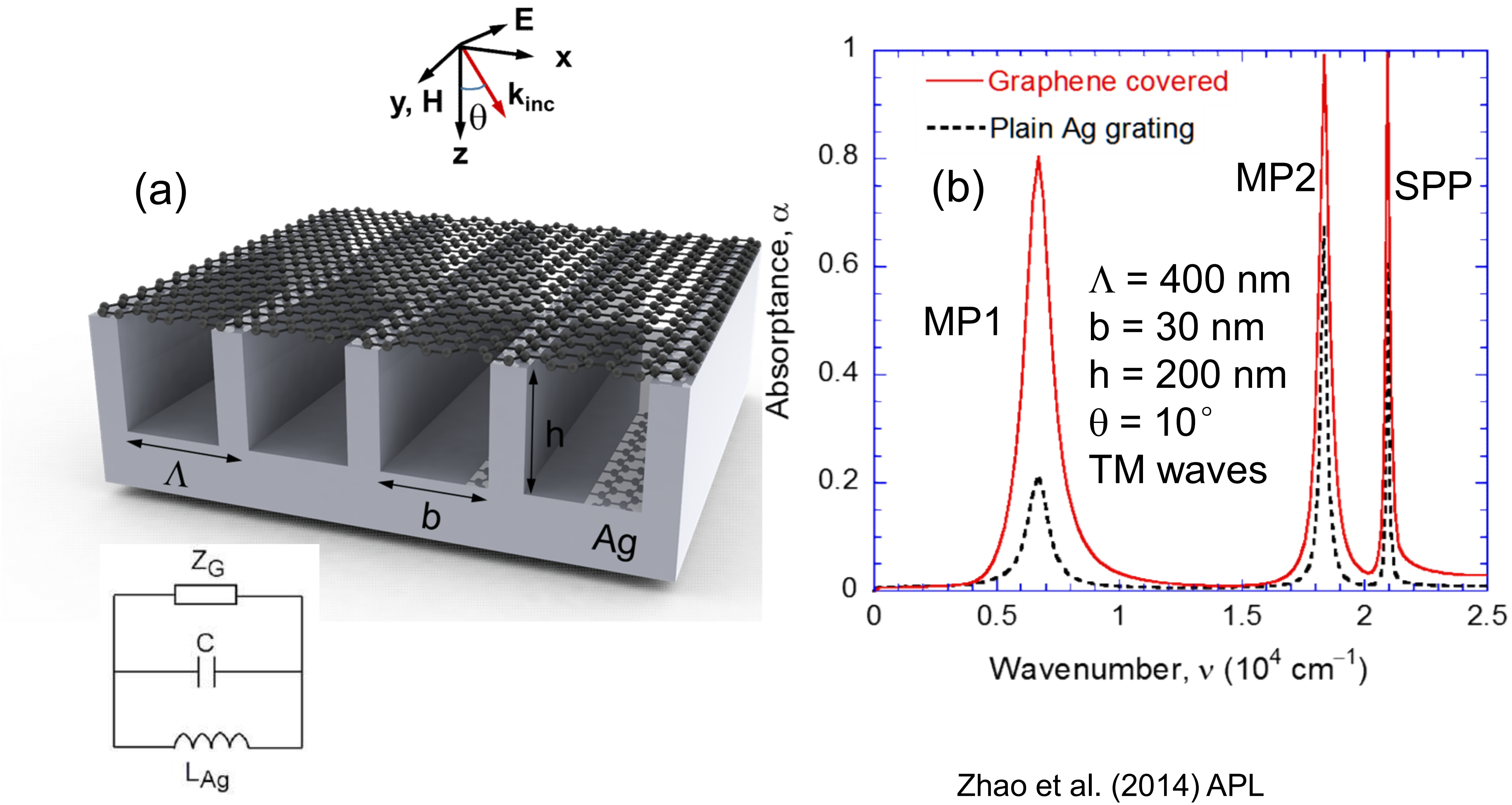
Sheet Conductivity of Graphene



In the visible and near-infrared: $$\sigma_s = \frac{e^2}{4\hbar}$$

In mid-infrared and longer wavelengths: $$\sigma_s = \frac{e^2 \mu}{\pi \hbar^2} \frac{\tau}{1 - i\omega\tau}$$

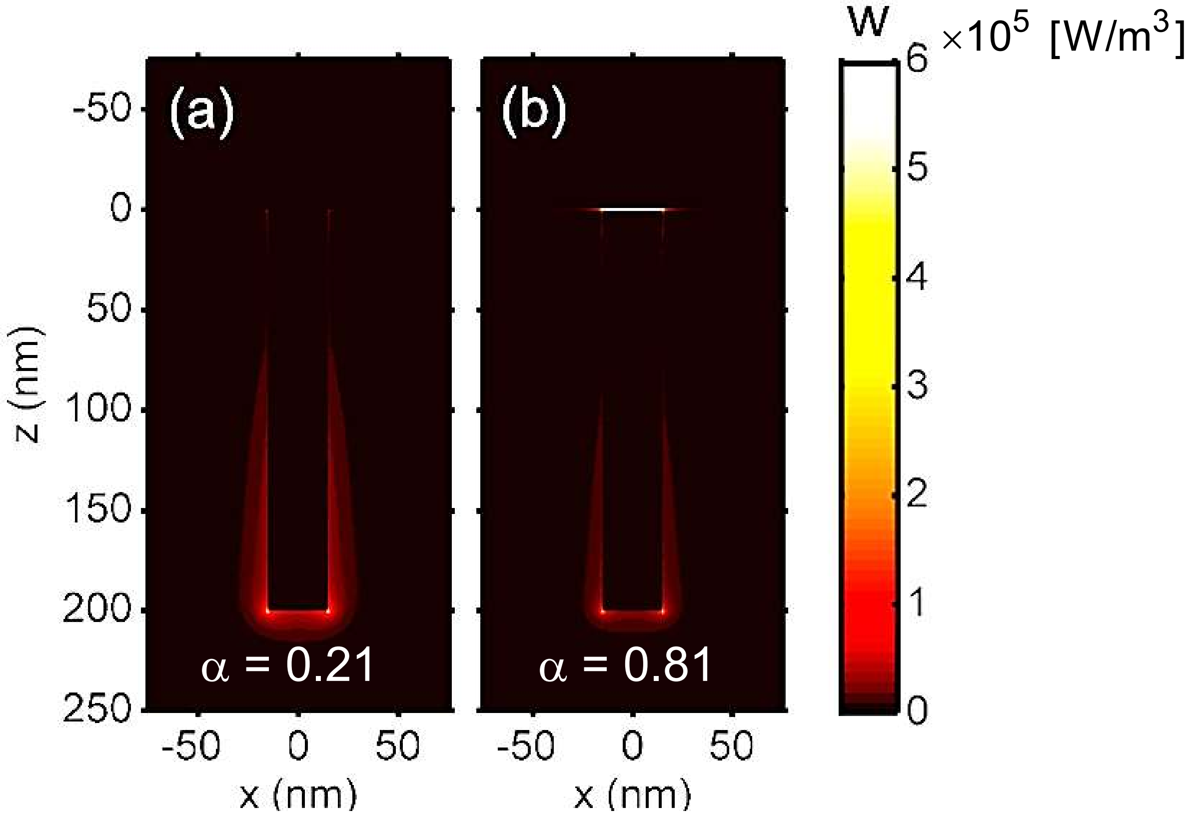
Enhanced Absorption in Graphene



Zhao et al. (2014) APL
Zhao et al. (2015) JOSAB

Power Dissipation Density

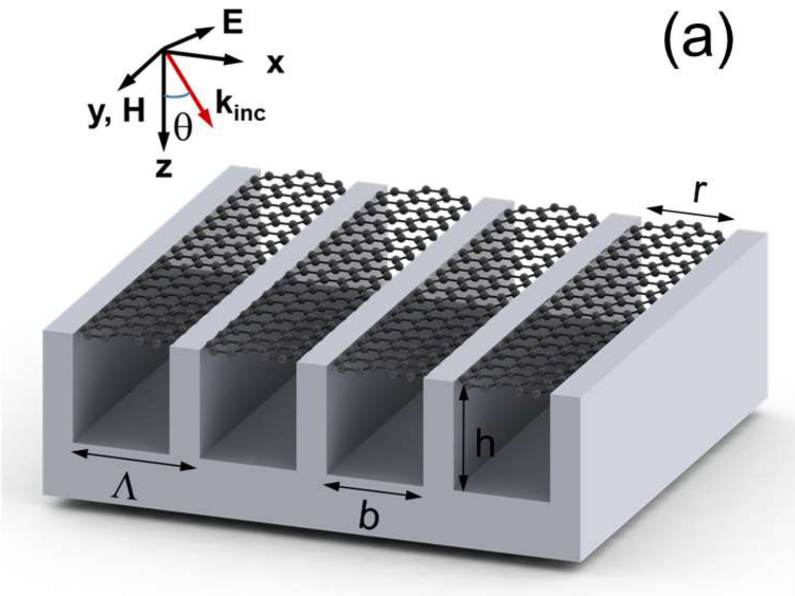
$$w(x,y,z)=\frac{1}{2}\varepsilon_0\omega\varepsilon''(x,y,z)\left|\mathbf{E}(x,y,z)\right|^2$$



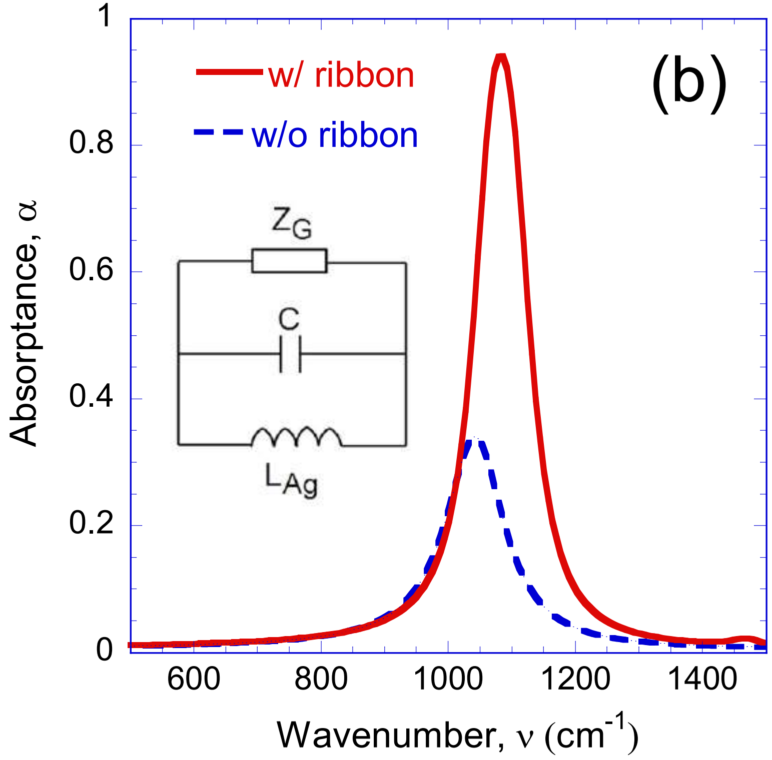
Graphene absorptance: 0.68 at MP1

Zhao et al. (2014) APL; Zhao et al. (2015) JOSAB

Plasmonic Coupling Between Graphene Ribbons and Metal Gratings

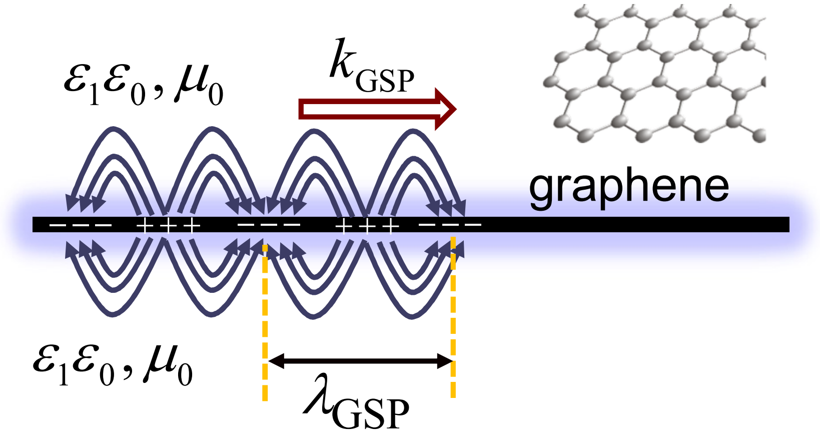


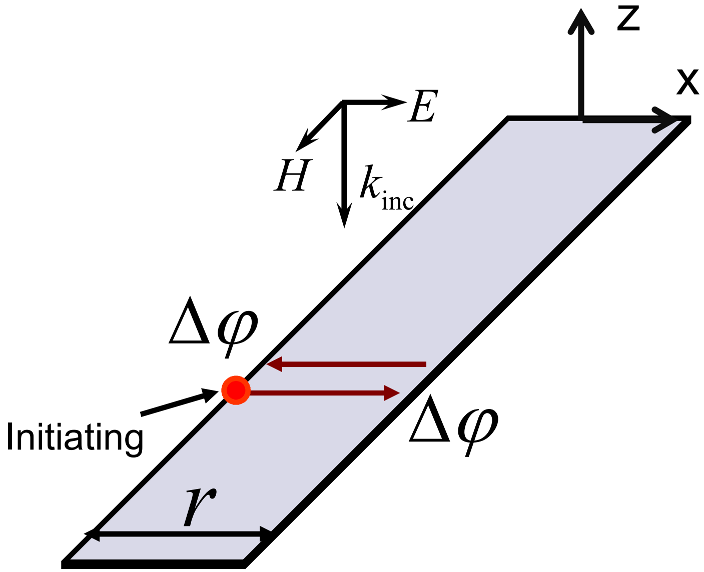
Λ = 4 μm b = 300 nm
h = 2 μm μ = 0.3 eV
TM waves
Normal incidence

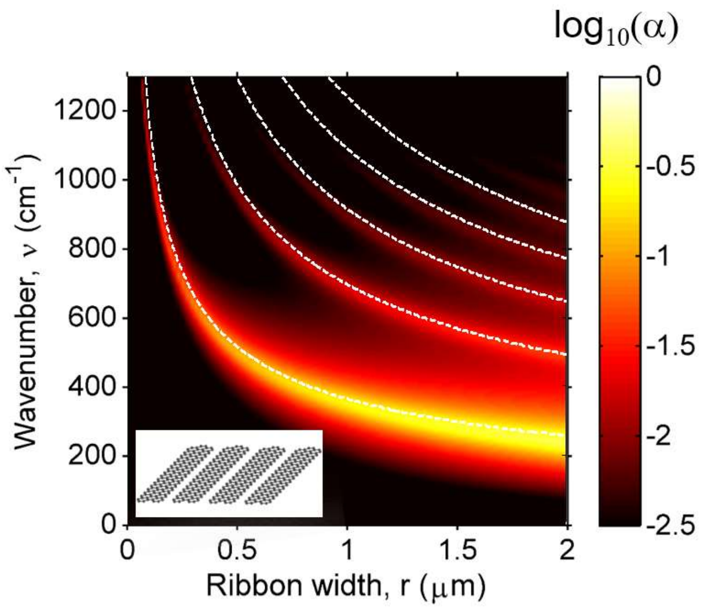


Zhao&Zhang (2015) ACS Photonics.

Surface Plasmons in Graphene Ribbons



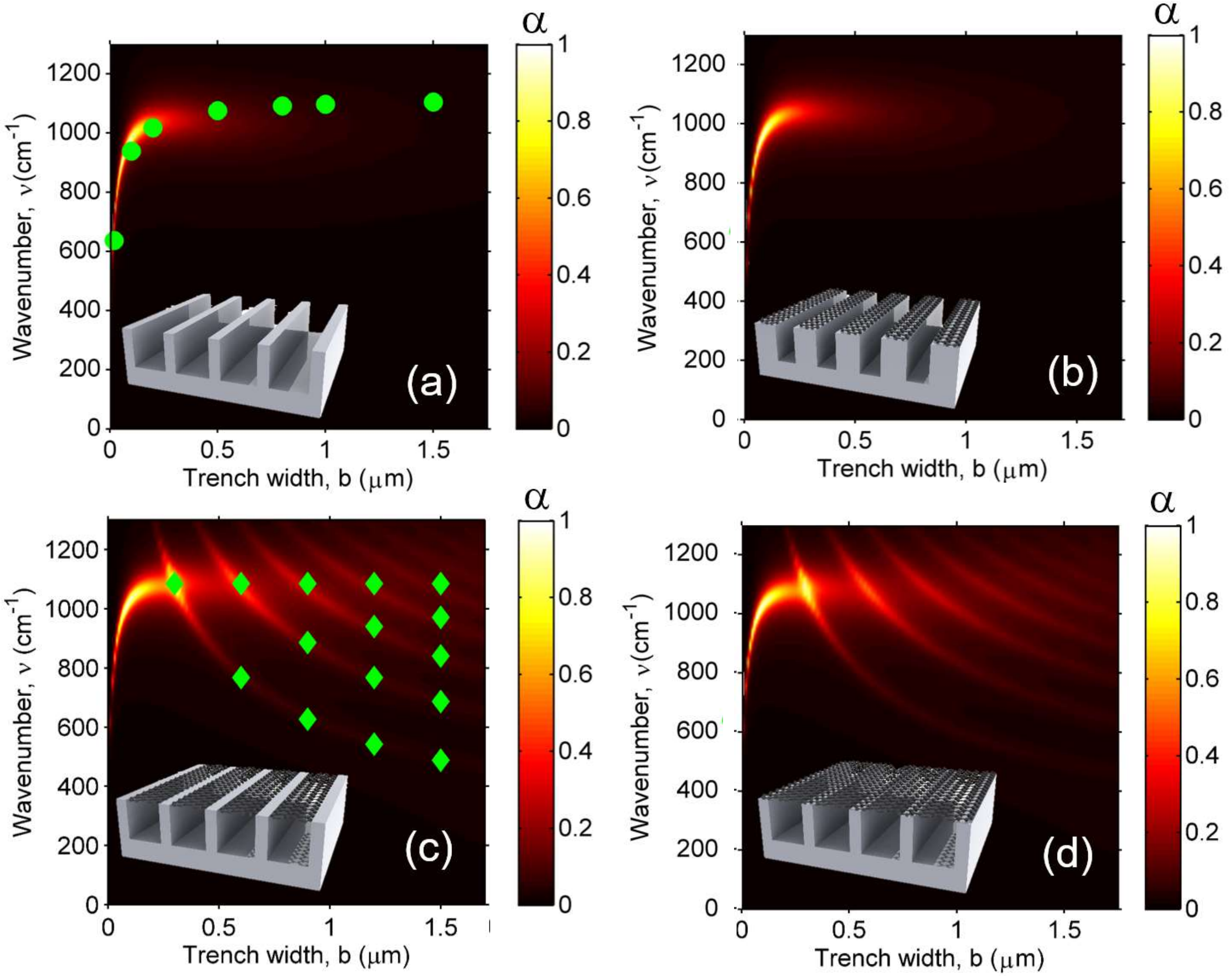




$$\nu = \sqrt{\frac{e^2\mu\left(m - \Delta\varphi/\pi\right)}{2\varepsilon_0\hbar^2 r}}, \quad \Delta\varphi = \frac{\pi}{4}$$

Du et al. (2014) Opt. Express.
Nikitin et al. (2014) PRB.

Coupling of MPs and Ribbon Resonances

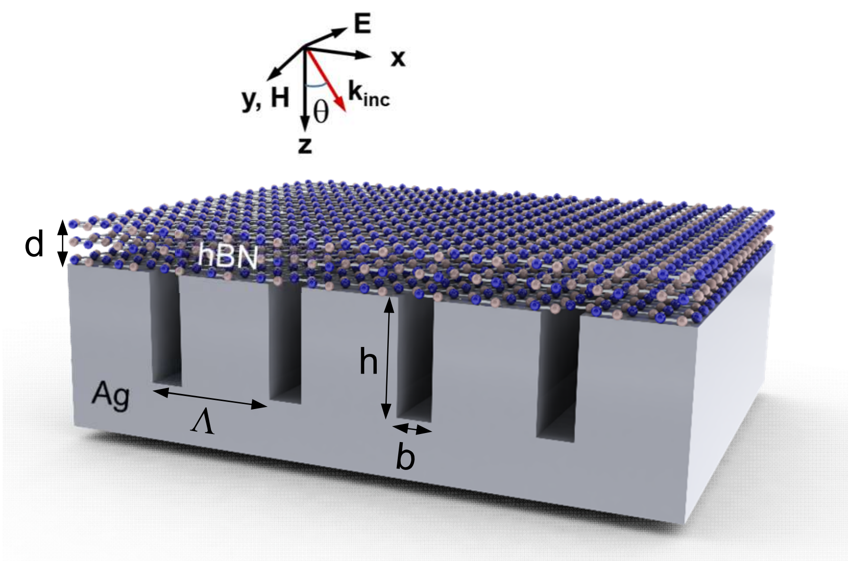


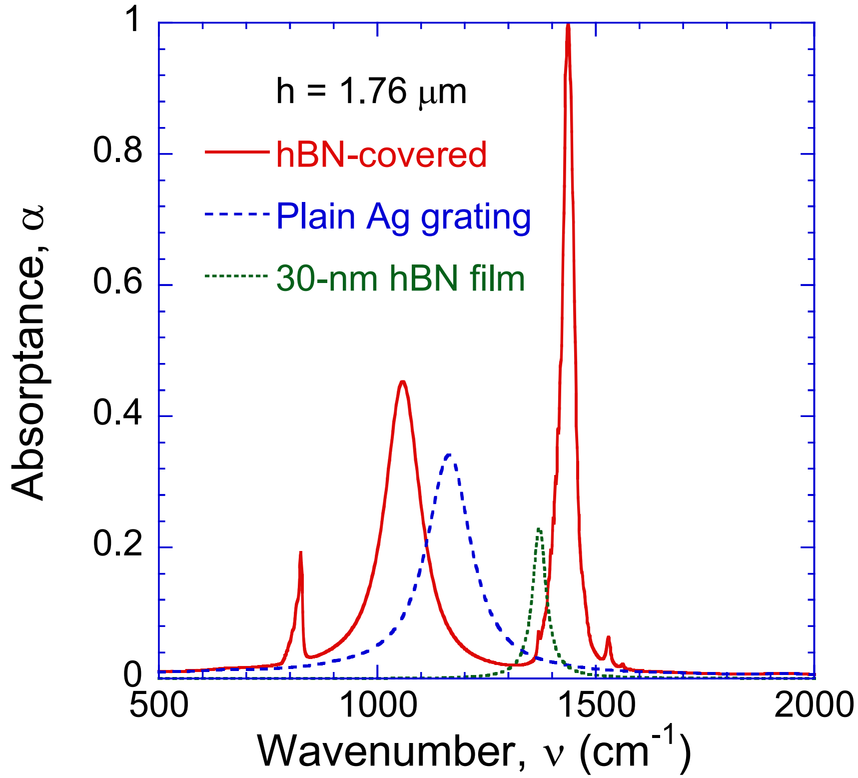
Zhao&Zhang (2015) ACS Photonics.

Task 2

- Task 2: Radiative Properties of 2D Materials and the Coupling with Metamaterials
  - Graphene-covered Metal Gratings
  - Metal Gratings Covered by Hyperbolic Materials
  - Gratings Made of Hyperbolic Materials

Perfect Absorption in hBN/Metal-Grating Anisotropic Structure





Λ = 4 μm

b = 300 nm

d = 30 nm

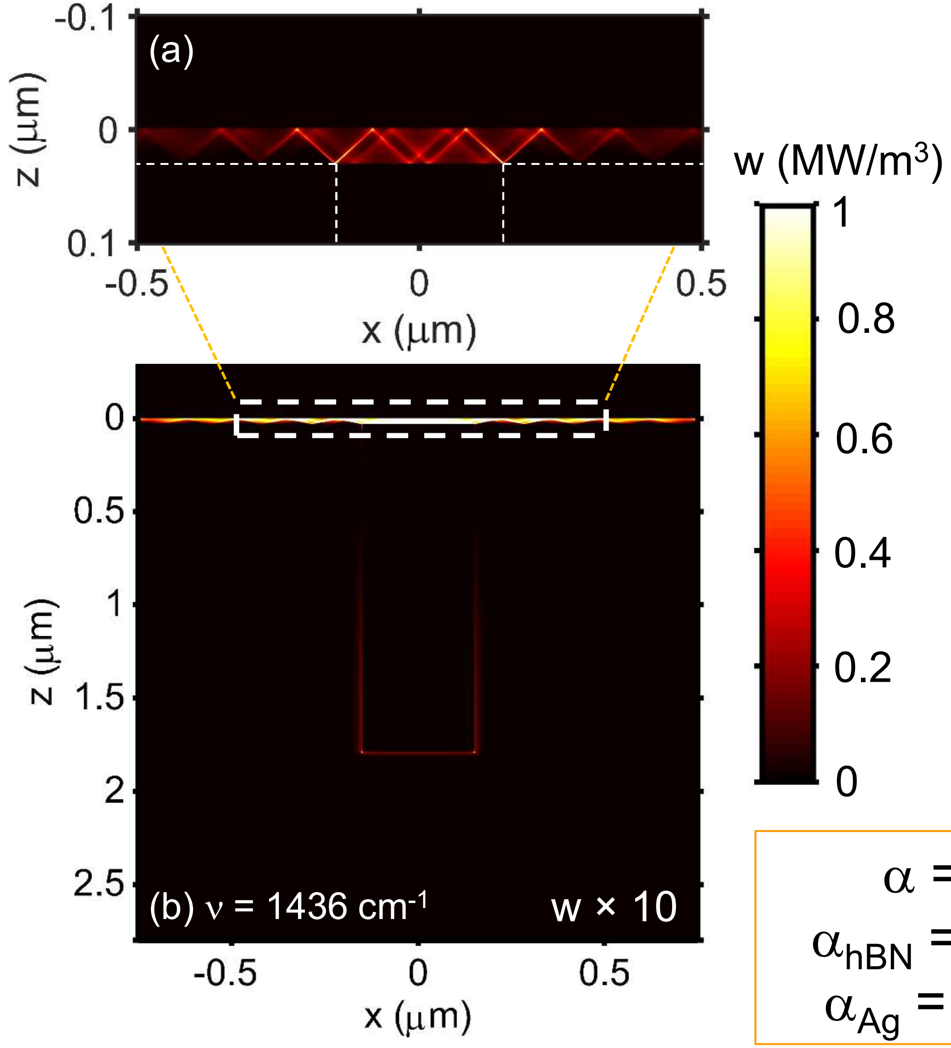
TM waves

Normal incidence

Perfect absorption @ ν = 1436 cm^{-1}

Zhao&Zhang (2016) Revision submitted.

Dissipation Profile at the Perfect Absorption

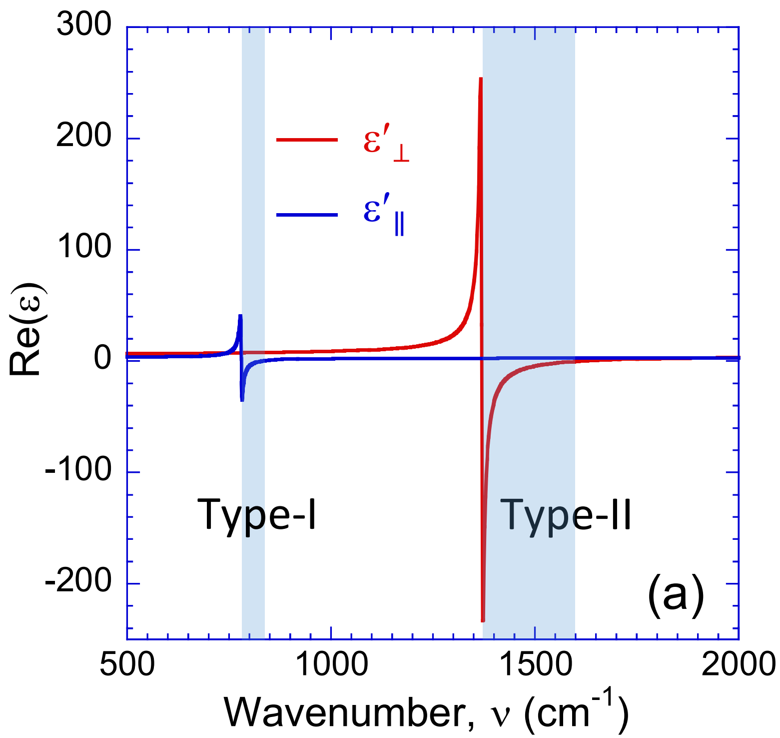


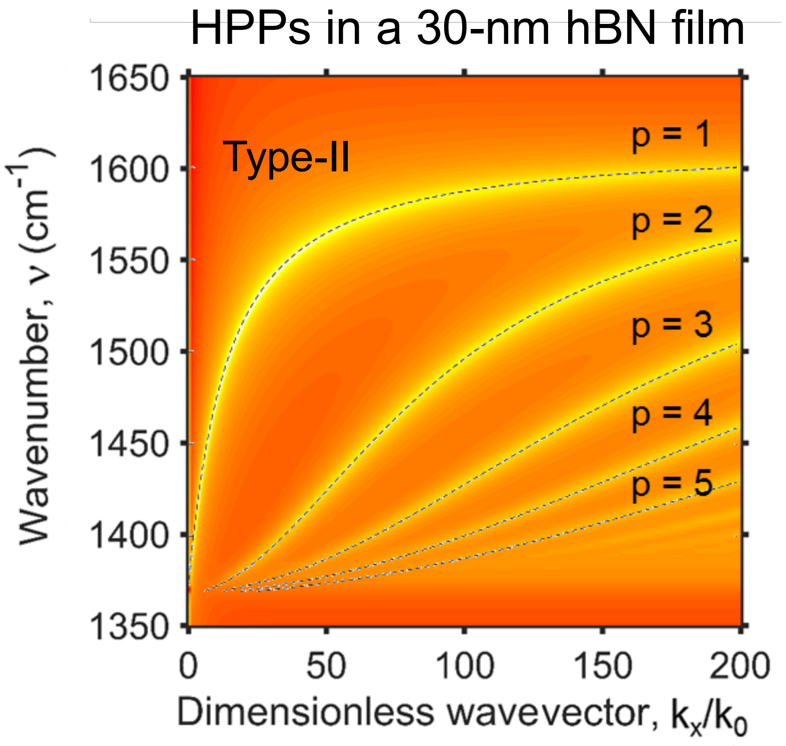
$\alpha = 1$

$\alpha_{hBN} = 0.91$

$\alpha_{Ag} = 0.09$

Hyperbolic Phonon-Polaritons (HPPs)





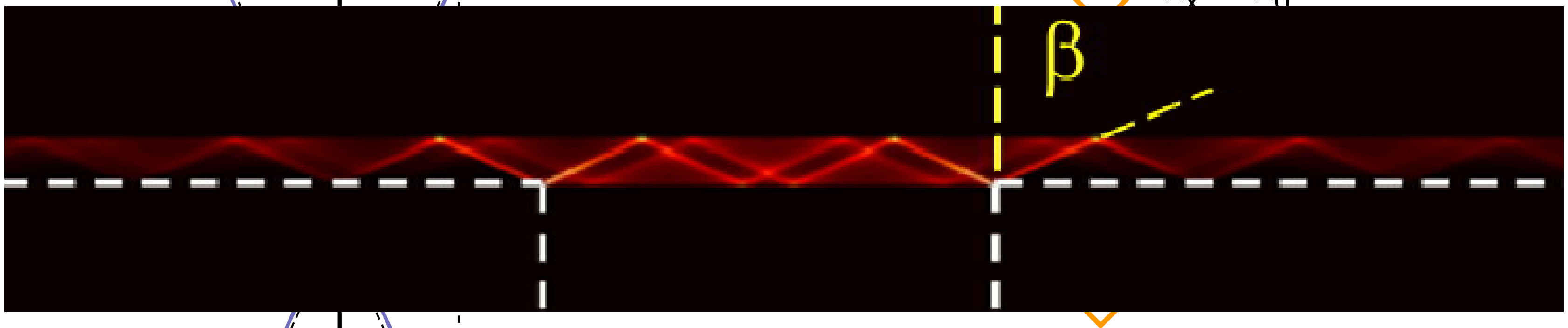
$$\begin{pmatrix} \varepsilon_\perp & 0 & 0 \\ 0 & \varepsilon_\perp & 0 \\ 0 & 0 & \varepsilon_\parallel \end{pmatrix}$$

$$k_x(\omega) = \frac{1}{d}\sqrt{-\frac{\varepsilon_\parallel}{\varepsilon_\perp}}\left[p\pi + 2\arctan\left(\frac{1}{\sqrt{-\varepsilon_\parallel \varepsilon_\perp}}\right)\right]$$

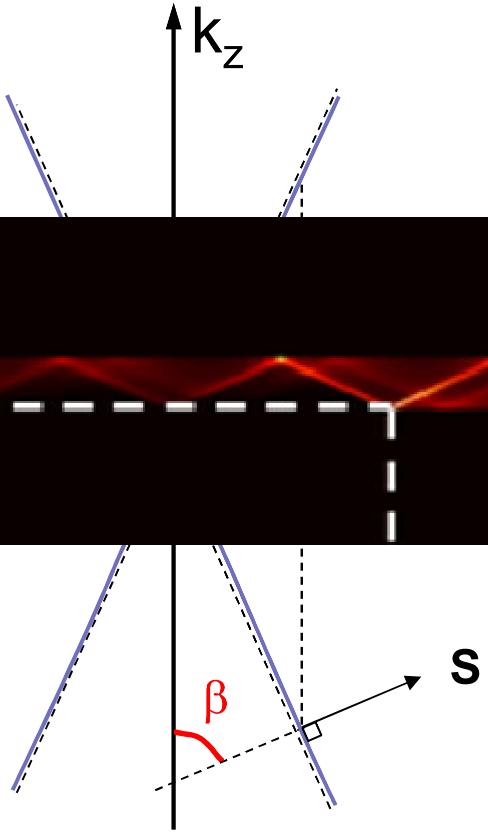
Propagation Direction of HPPs

$$\frac{k_z^2}{\varepsilon_\perp} + \frac{k_x^2}{\varepsilon_{||}} = k_0^2$$

$k_x >> k_0$



$\beta = 65.7°$ @ $\nu = 1436\ \text{cm}^{-1}$



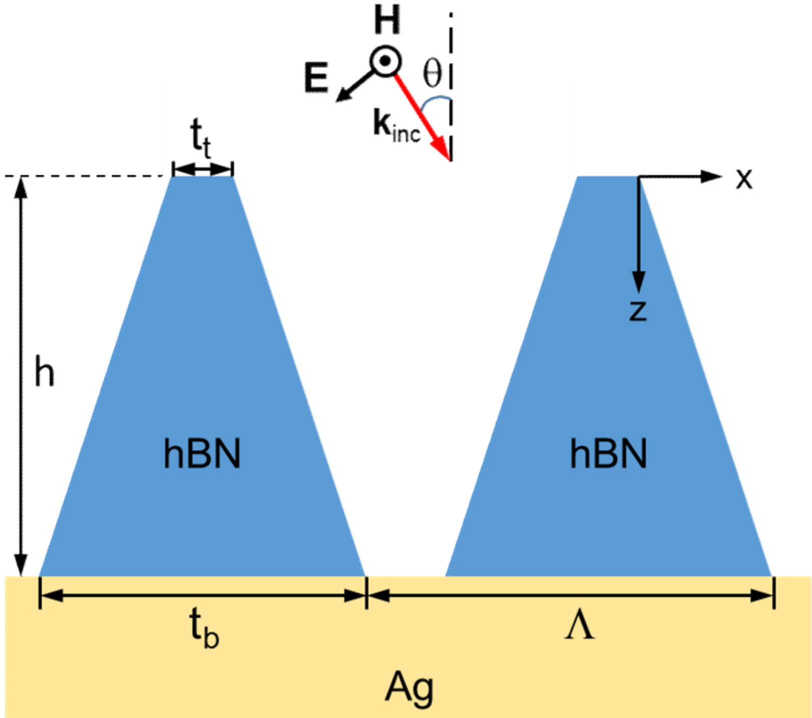
Type-II hyperbolicity

Zhao&Zhang (2016) Revision submitted.

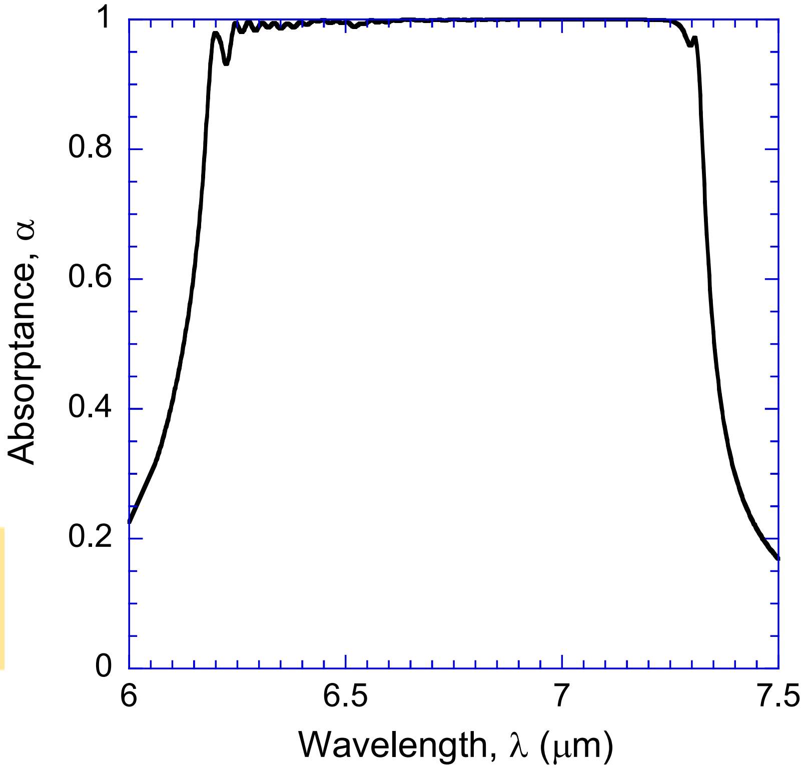
Task 2

- Task 2: Radiative Properties of 2D Materials and the Coupling with Metamaterials
  - Graphene-covered Metal Gratings
  - Metal Gratings Covered by Hyperbolic Materials
  - Gratings Made of Hyperbolic Materials

Broadband Perfect Absorption by Trapezoidal Gratings Made of hBN

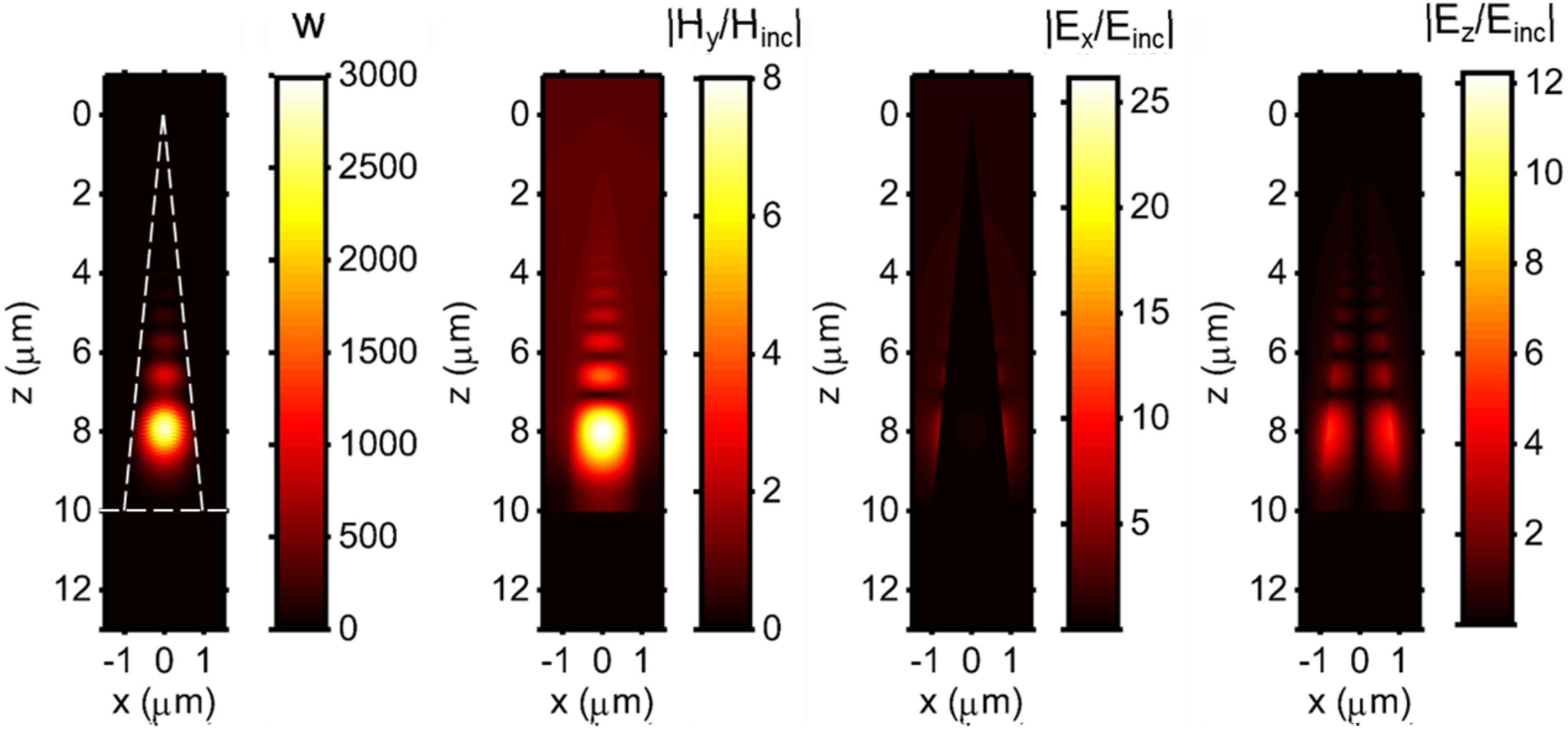


$\Lambda = 3\ \mu m$ $h = 10\ \mu m$
$t_b = 2\ \mu m$ $t_t = 40\ nm$



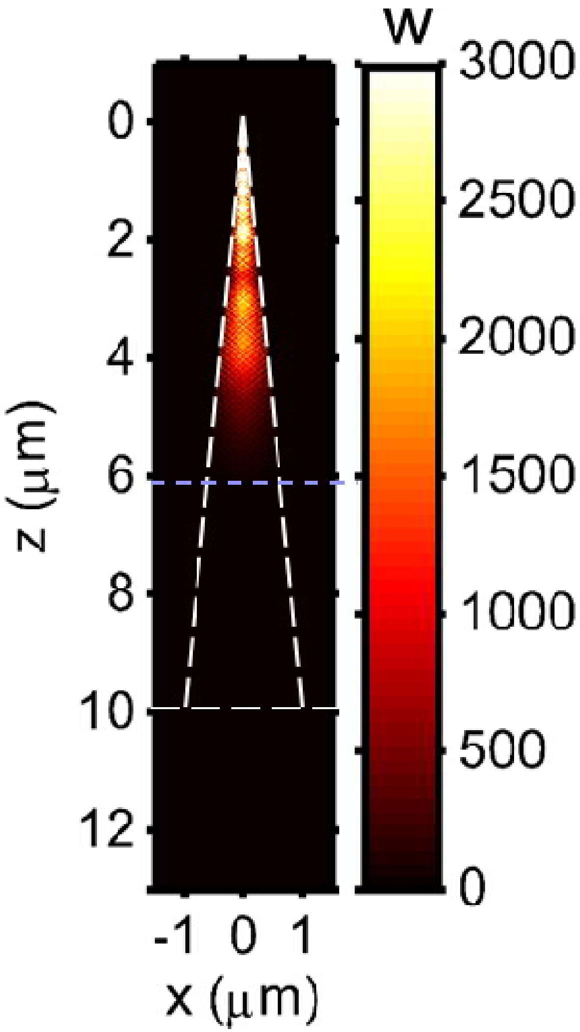
Zhao&Zhang (2016) To be submitted.

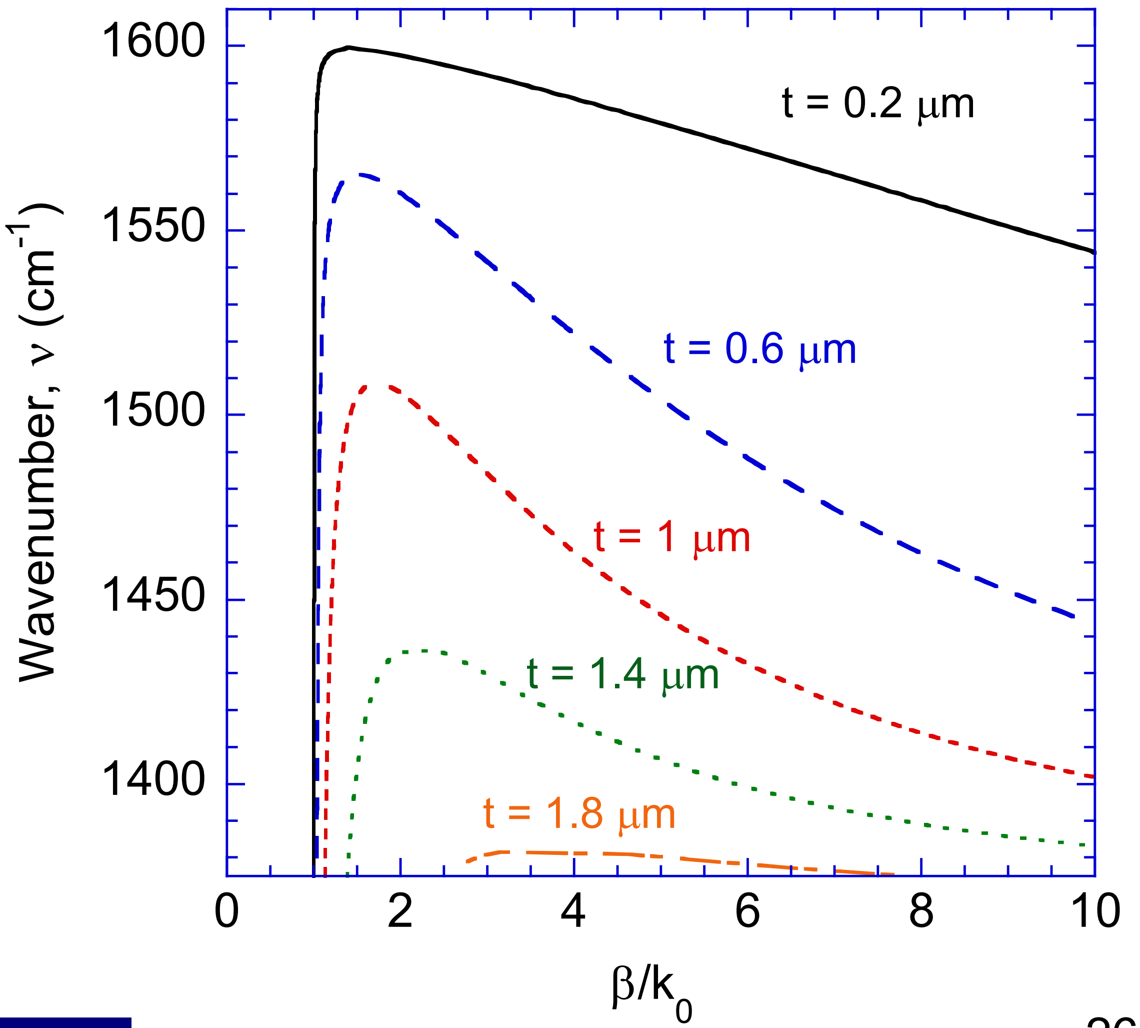
Electromagnetic Field and Dissipation



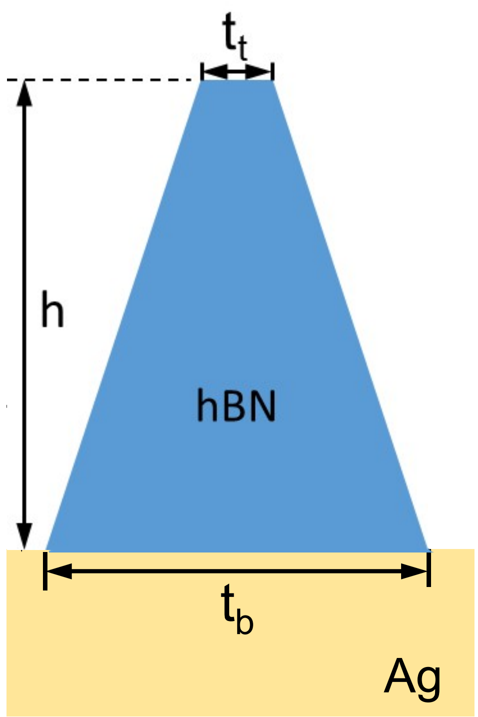
$\lambda = 7.2\ \mu m$

Dispersion of Hyperbolic Waveguides

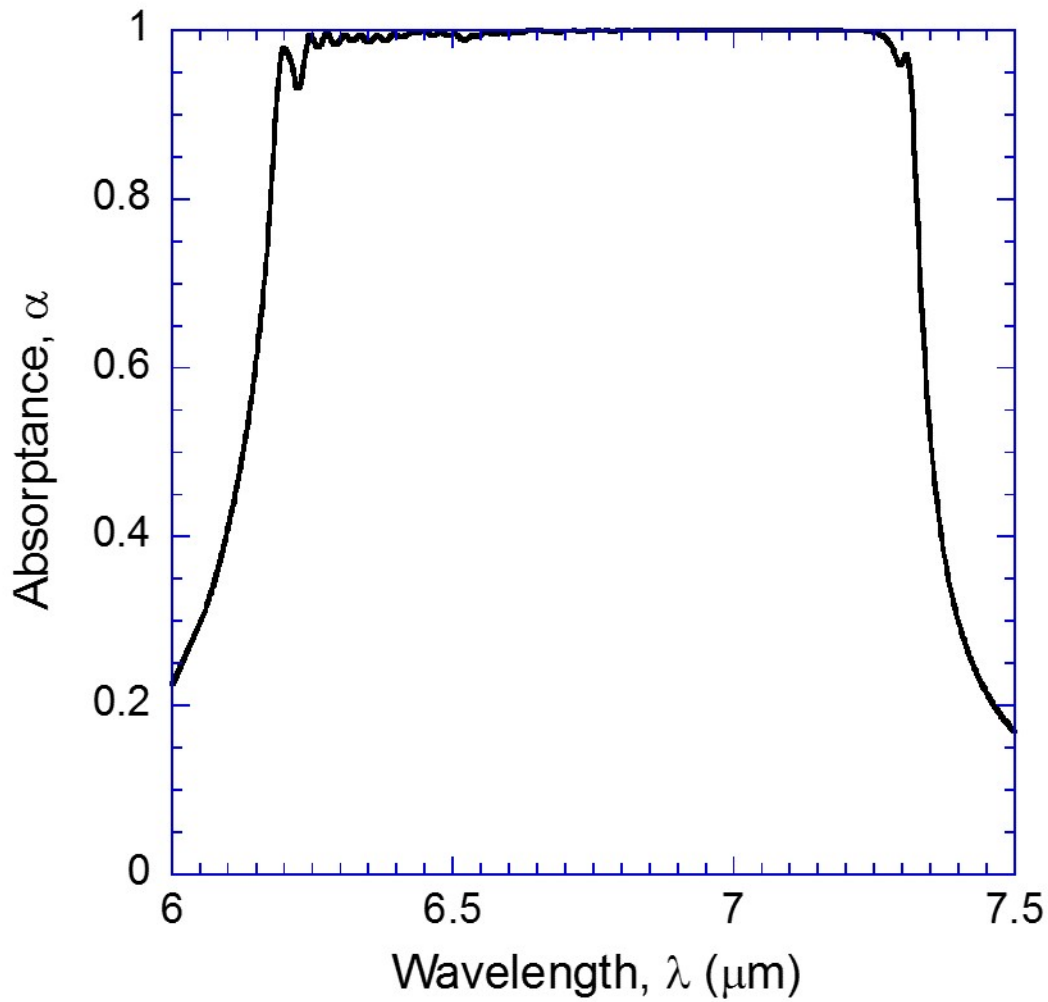




Short Trapezoidal Gratings Made of hBN

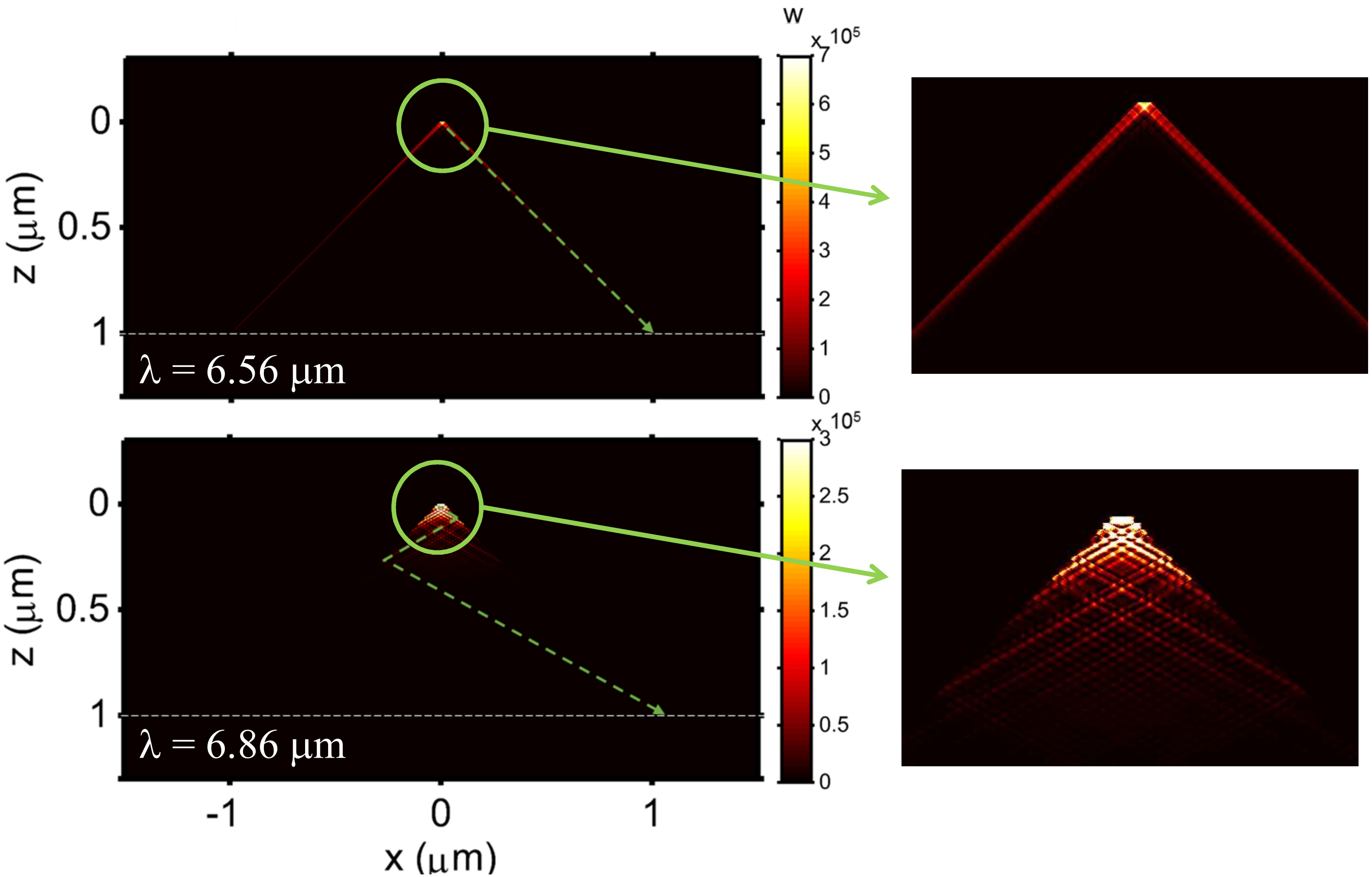


Λ = 3 μm h = 1 μm
t_b = 2 μm t_t = 40 nm

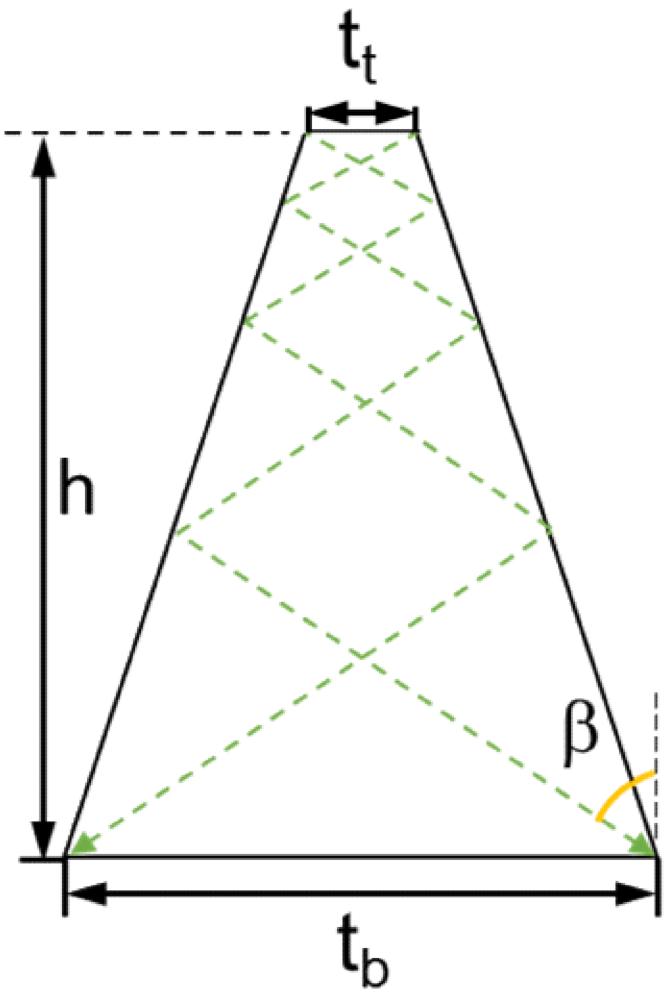


Zhao&Zhang (2016) To be submitted.

Local Dissipation at HPP Resonances



Resonance Absorption by HPPs



$$n = \frac{\ln\left(1 - \frac{t_b - t_t}{t_b}\right)}{\ln\left(\frac{2h\tan\beta(\lambda) - t_b + t_t}{2h\tan\beta(\lambda) + t_b - t_t}\right)}$$

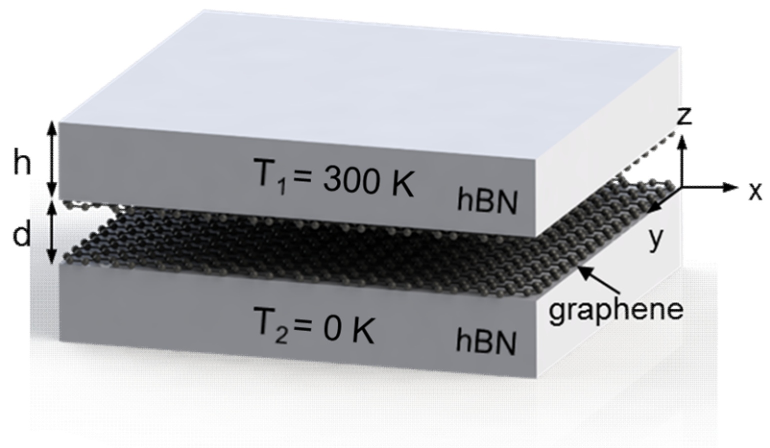
$$\boxed{\beta(\lambda) = \arctan\left(\sqrt{-\frac{\varepsilon_\perp}{\varepsilon_\parallel}}\right)}$$

unit: μm	n = 1	n = 2	n = 3	n = 4	n = 5
Calculation	6.56	6.72	6.86	6.97	7.05
Prediction	6.56	6.68	6.83	6.95	7.03

Task 3

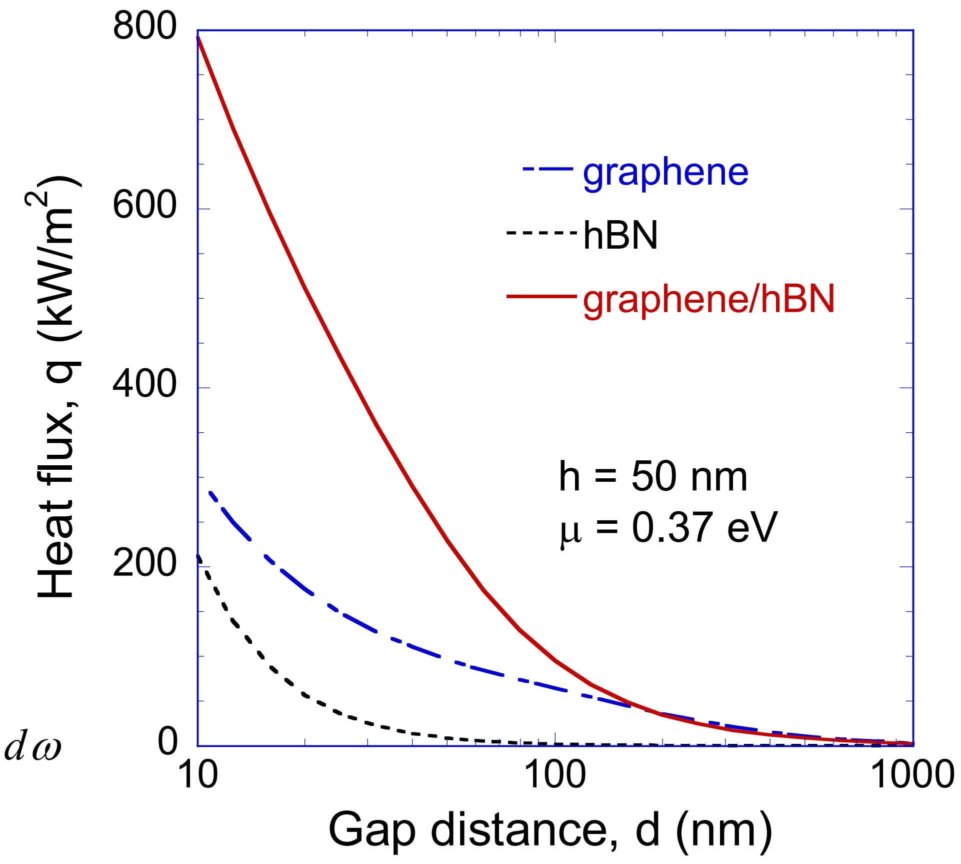
- Task 3: Near-Field Heat Transfer Between 2D Materials
  - Near-Field Heat Transfer Between Graphene/hBN Heterostructures

Near-field Radiative Heat Transfer Between Graphene/hBN Heterostructures

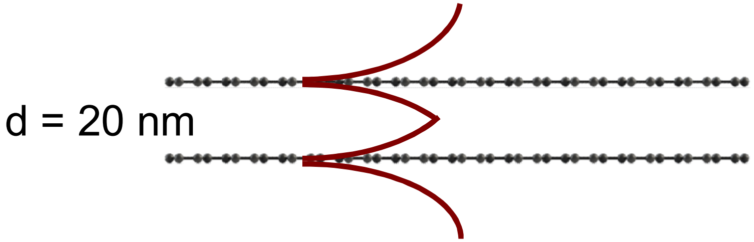


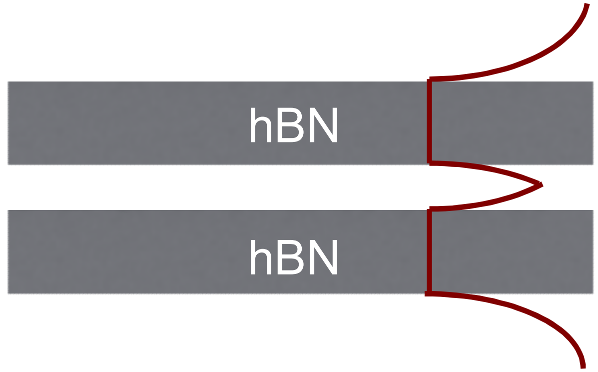
$$q = \int_0^\infty \frac{\Theta(\omega, T_1) - \Theta(\omega, T_2)}{4\pi^2}\left[\int_0^\infty \xi(\omega, \beta)\beta d\beta\right] d\omega$$

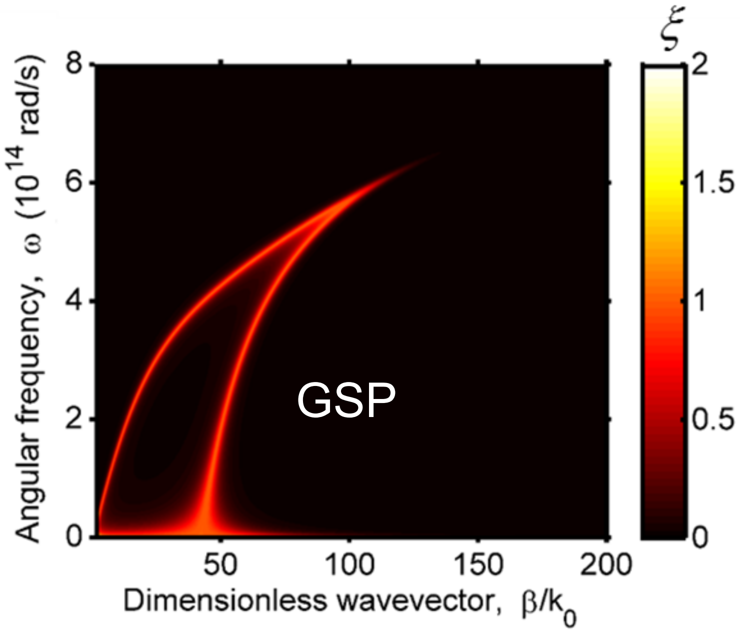
$$\Theta(\omega, T) = \frac{\hbar\omega}{e^{\hbar\omega/k_B T} - 1}$$

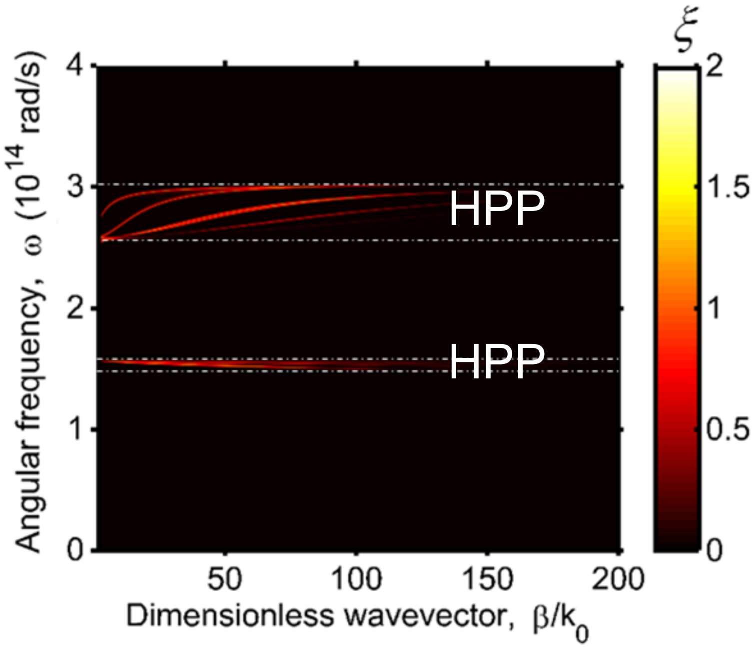


Photon Tunneling Between 2D Materials



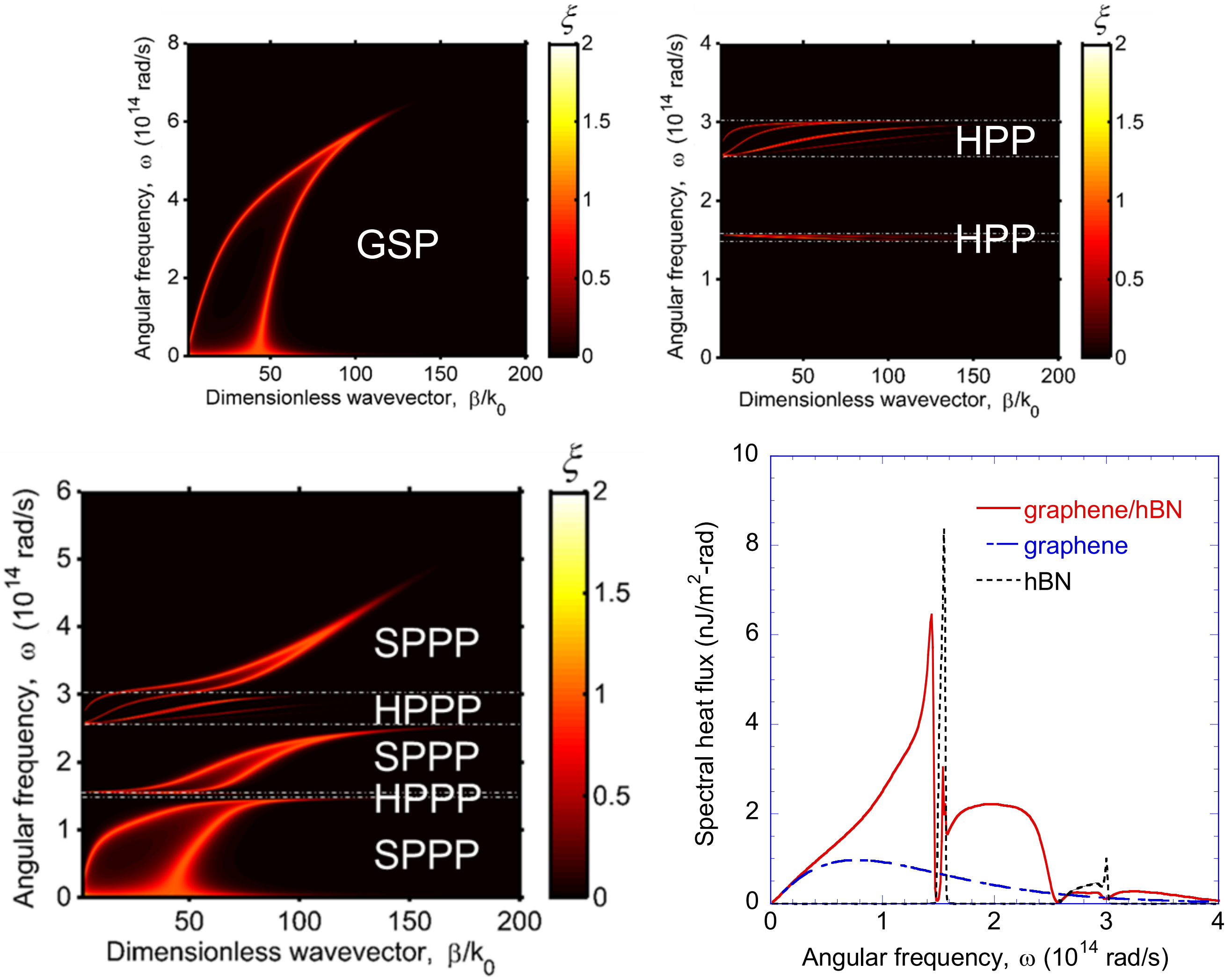




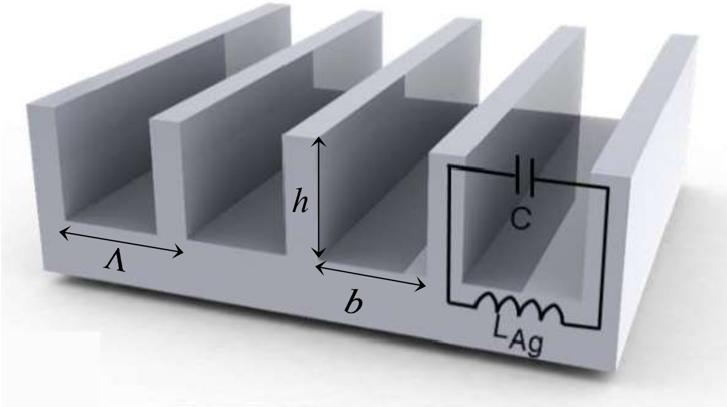


Zhao&Zhang (2016) JHT.

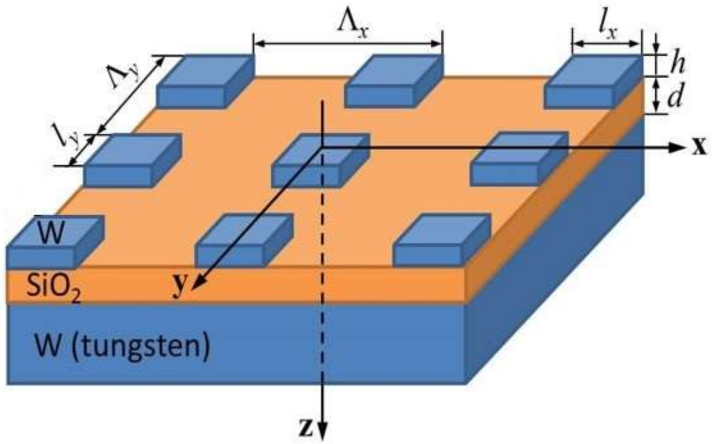
Enhanced Photon Tunneling by Surface Plasmon-Phonon Polaritons (SPPPs)



Contributions-I

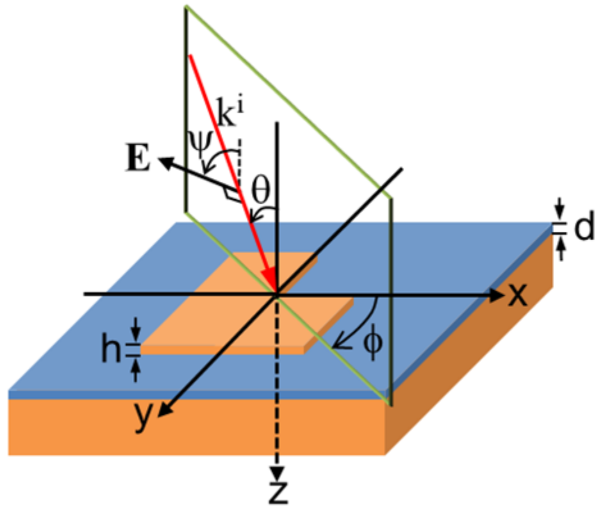


Deep metal gratings can support coherent thermal emission due to MPs. This work provides a method to **confine light in nanoscale** to achieve **coherent thermal emission**.

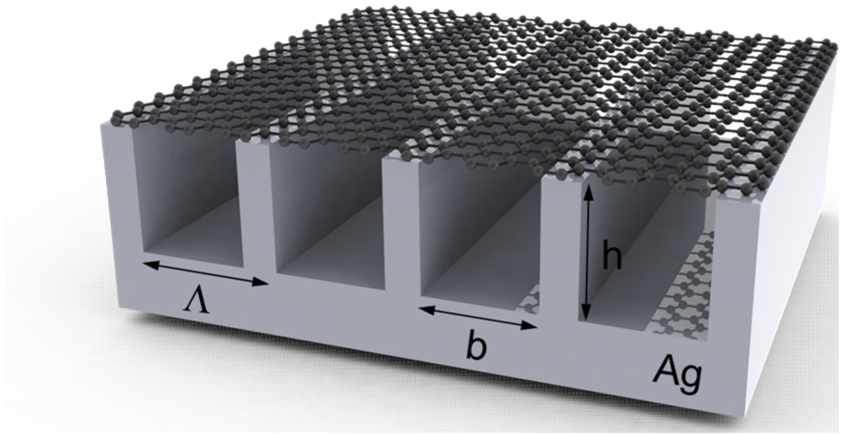


2D **metal/dielectric/metal** metamaterials can achieve **polarization-independent wavelength-selective** emission due to MPs, WAs, and SPPs. This work provides insights to use metamaterials for **energy-harvesting applications**.

Contributions-II

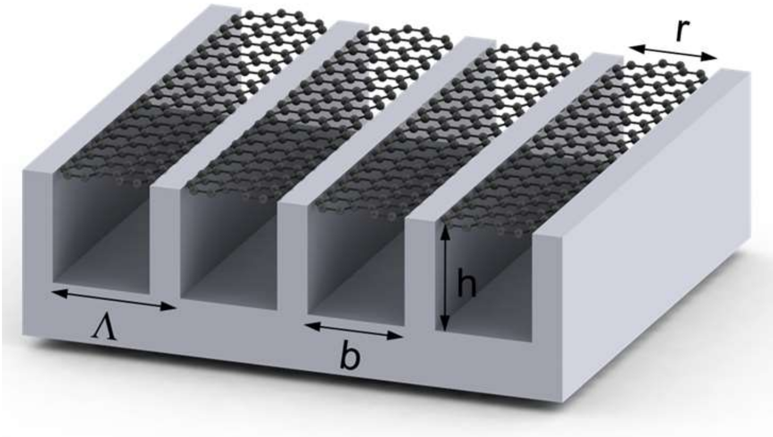


Anisotropic structures can support **polarization-dependent** excitation of MPs. This work demonstrates a way to design **highly polarization-dependent** radiative properties.

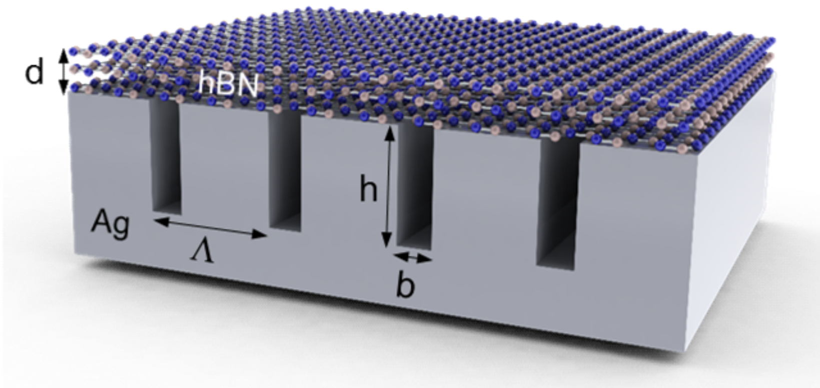


Metal gratings can **enhance** the **absorption of graphene** for photodetection purpose. This work provides a method to **use graphene and plasmonic metamaterials** to design unique radiative properties.

Contributions-III

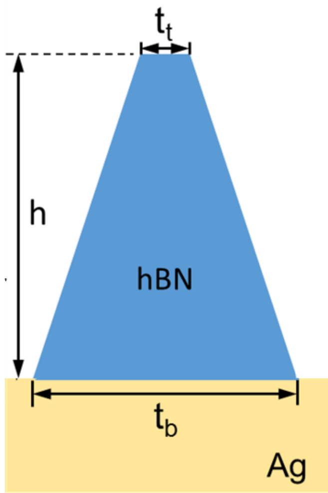


Strong plasmonic coupling can be achieved between **graphene SPP** and **MPs** in metal gratings. This work provides insights to use **plasmonic coupling** to achieve unique radiative properties.

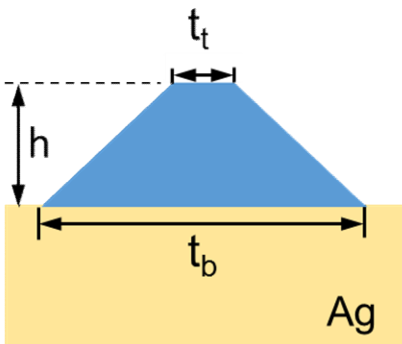


Metal gratings can excite **HPPs in hBN** and achieve **perfect absorption**. This work opens the door to use **natural hyperbolic material** to create **wavelength-selective perfect** absorption.

Contributions-IV

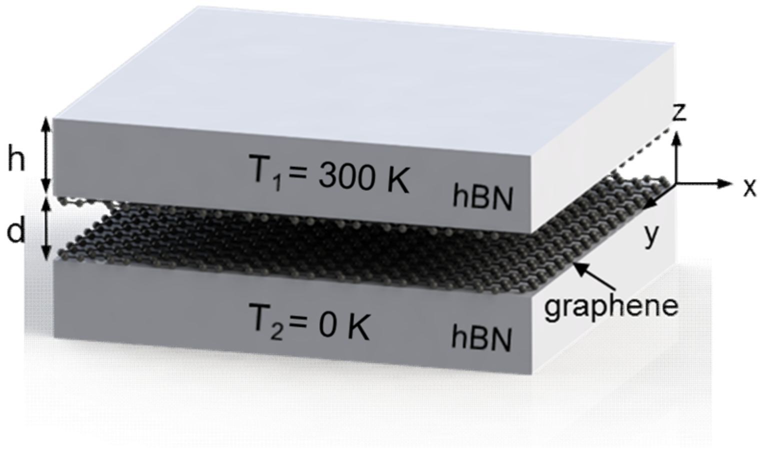


Trapezoidal hBN gratings can support **broadband perfect** absorption. This work provides insights to use **hyperbolic materials** to create broadband absorbers or emitters for **energy-harvesting applications**.



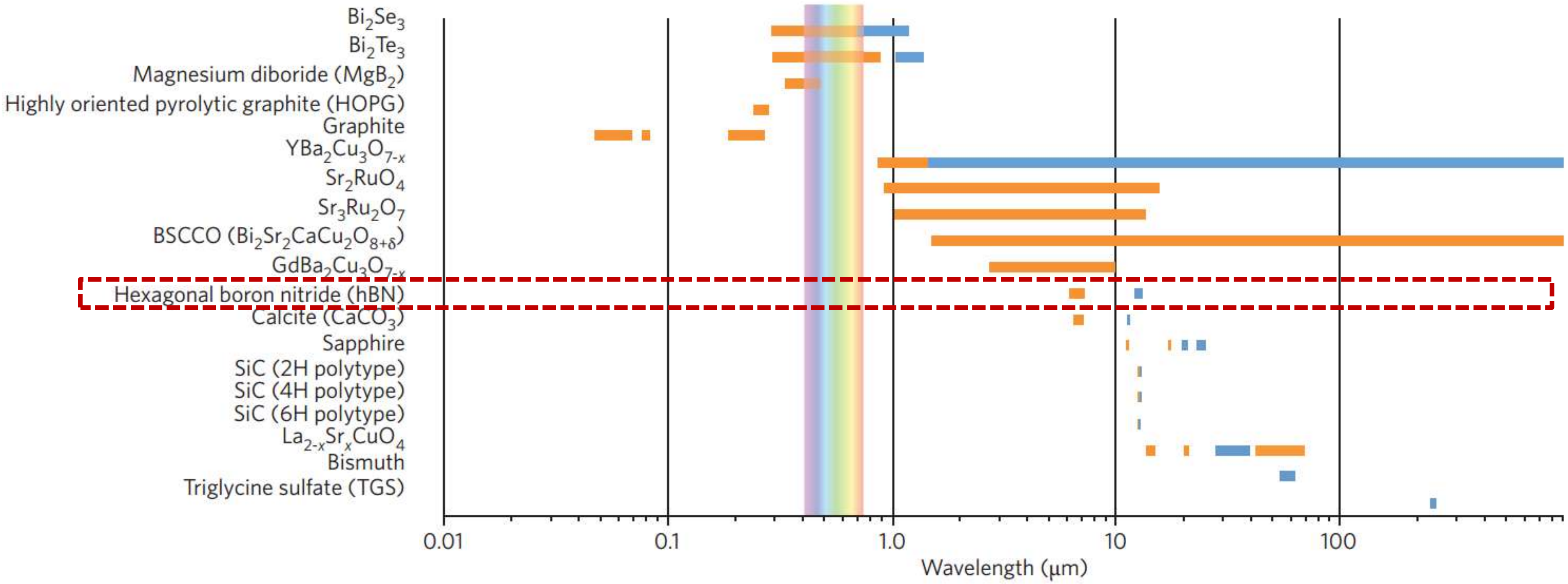
Trapezoidal hBN gratings can also support **resonance absorption** due to **HPPs**. This work opens the door to create **wavelength-selective** radiative properties using **hyperbolic materials** with different shapes of **resonators**.

Contributions-V



2D materials can **enhance photon tunneling** and near-field heat transfer. This work demonstrates the potentials of using **heterostructures** of 2D material to improve the performance of **near-field** imaging and energy-harvesting systems.

Outlook



Hyperbolic regions in natural materials.

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