Surface plasmons in active systems and 2D materials

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September 17, 2015
Colloquium at Wesleyan University

WESLEYAN UNIVERSITY

Outline

I. Introduction to Surface Plasmon Polaritons

II. Active (gain) Dielectrics in Plasmonics

III. Surface Plasmons in 2-Dimensional Materials

IV. Open Issues & Conclusion

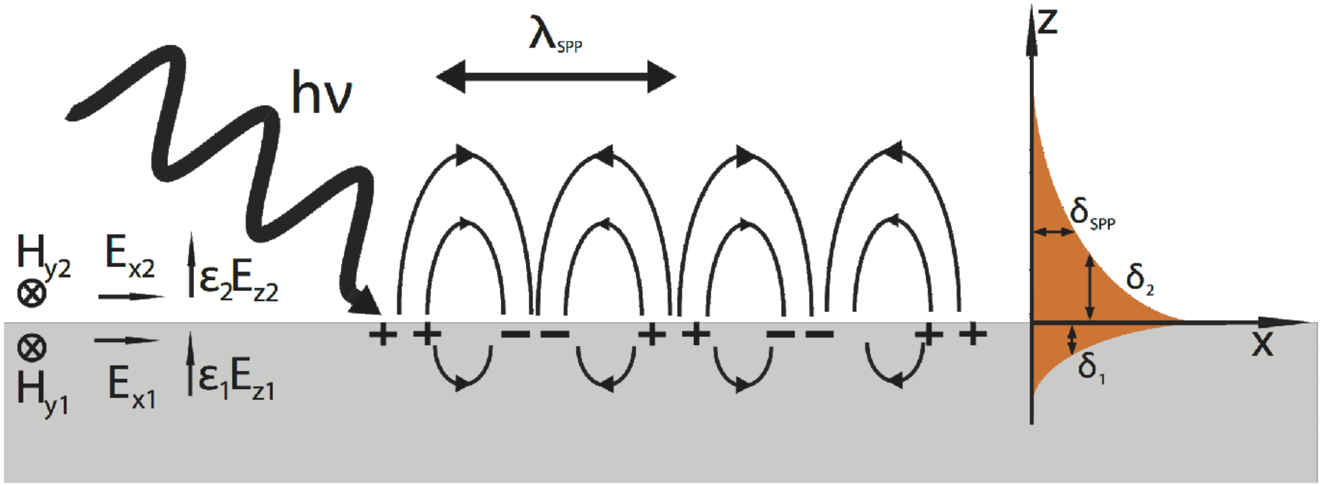
What are plasmons

The electrons in metals are free to move sustaining collective oscillations with normal modes.

Plasmon is the quantum of free electrons oscillation in a conducting media (plasma oscillation).

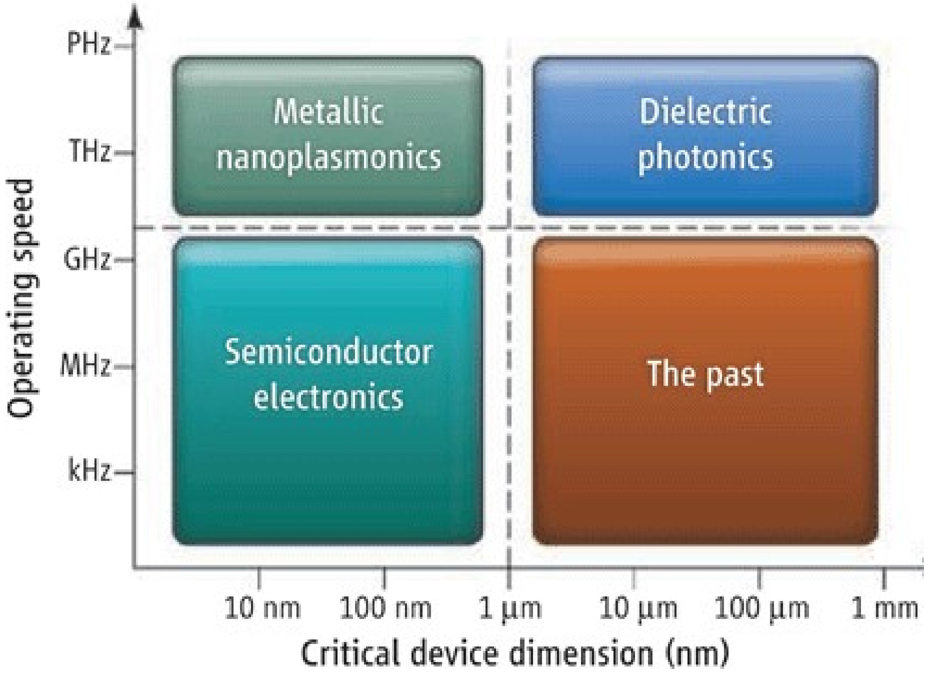
Plasmon Polariton is a quasi particle formed by the plasmon-photon coupling.

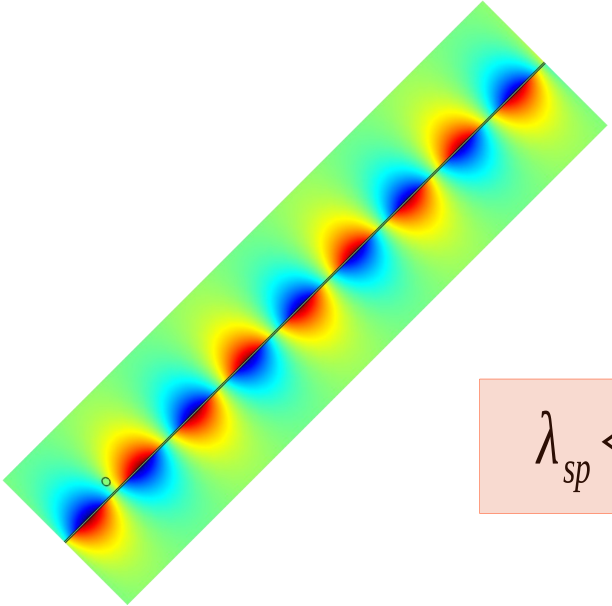
Surface Plasmon Polaritons are EM surface waves coupled to charge excitations at the surface of metal.



Plasmonics can:

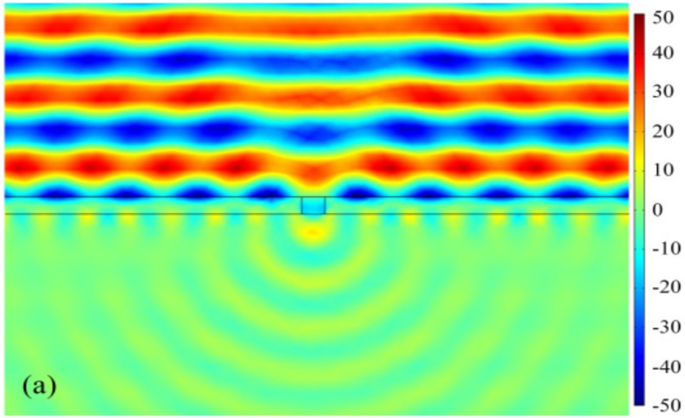
- Beat the diffraction limit (sub-wavelength optics).
- Strong localization of EM field (enhanced EM field, nonlinear optics).
- Built extremely small and ultrafast opto-electronic devices (integrated circuits, plasmonic laser).
- Control electromagnetic energy in subwavelength scales (nano-waveguides, nano-antennas).
- Be high sensitive in dielectric properties (detectors, lenses).



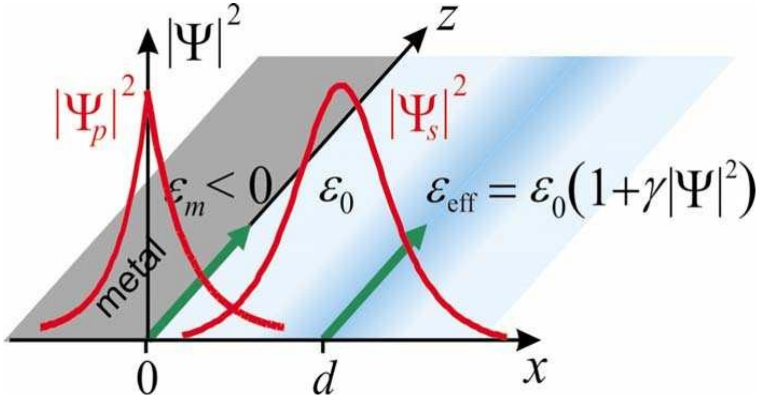


$$\lambda_{sp} \ll \lambda_{photon}$$

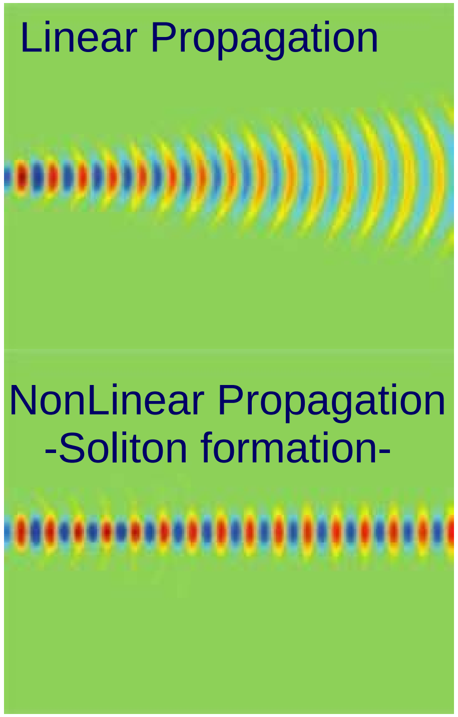
Applications I

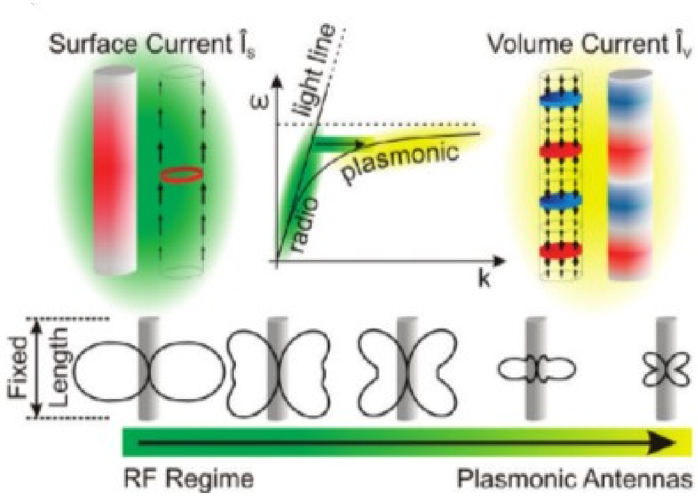


[1]**Subwavelength Optics:** 150nm slit fabricated in Ag film when illuminated by 488nm laser beam.

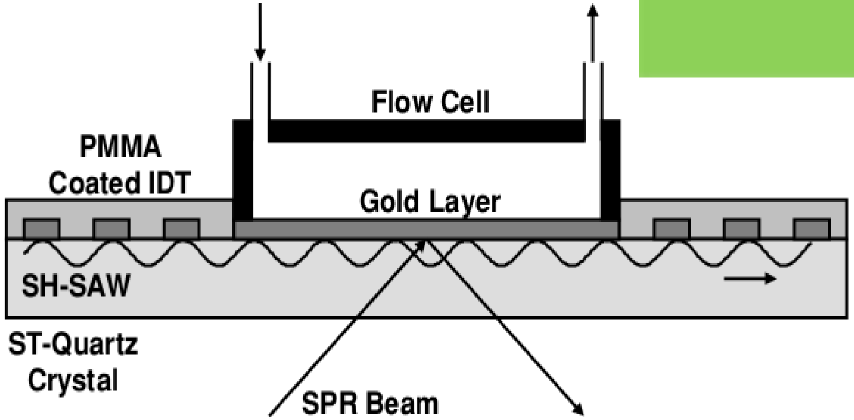


[2,3]**Nonlinear Optics:**
[2]Plasmon-soliton interaction **(Left).**
[3]SPP soliton formation **(Right).**





[4]**Plasmonics Nanoantennas:** Antennas with very short wavelength resonance.



[5,6]**Biomolecules detectors:** SPPs with surface acoustic waves characterize biomolecules.

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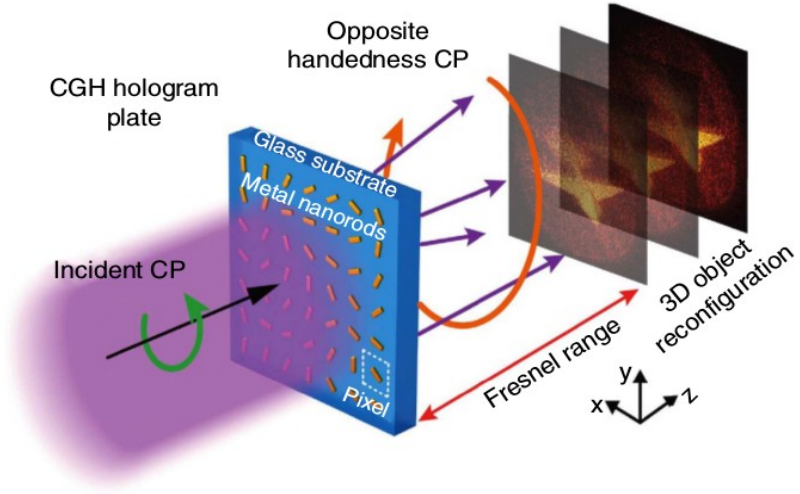
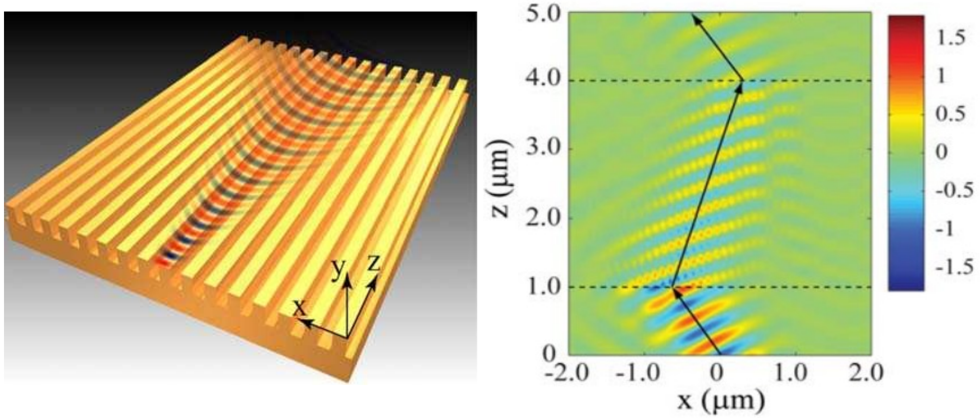
[1] V.A.G. Rivera *et al.,* inTech (2012)
[2] K. Y. Bliokh *et. al.*, Phys. Rev. A **79** (2009)
[3] A.R Davoyan *et. al.*, Opt. Express **17** (2009)
[4] J. Dorfmuller *et al.*, Nano Lett. **10** (2010)
[5] F. Bender *et al.*, Science and Technology **20** (2009)
[6] J.M. Friedt *et al.,* J. Appl. Phys. **95** (2004)

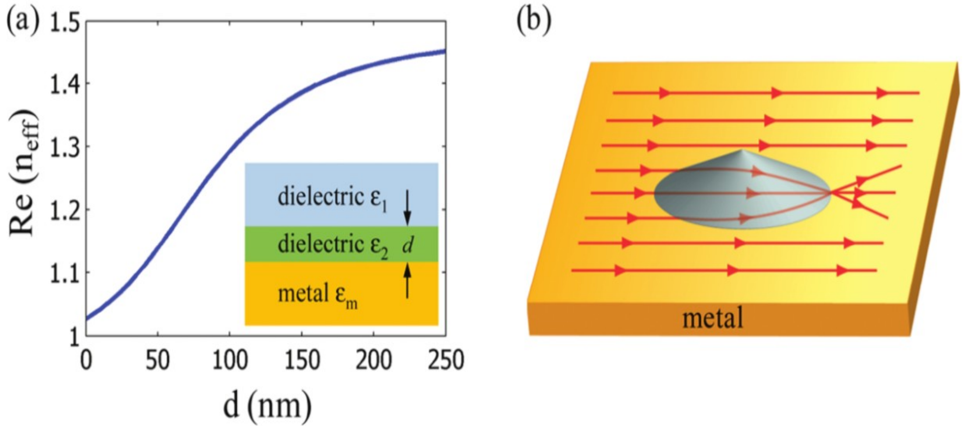
Applications II



[1]**Optical Holography:** Plasmonics meta-surfaces offers 3D optical holography.



[2]**Plasmonic Metamaterials:** Flat silver-air layers form a plasmonic metasurface providing (left) SPPs with hyperbolic phase fronts and (right) negative refraction.



[3,4]**GRadient INdex lenses (GRIN):** Regular dielectrics form plasmonics metaterials lenses.

- ✓ Plasmonic solar cells.
- ✓ Plasmonic nanolithography.
- ✓ Plasmonic waveguides.
- ✓ Integrated plasmonic circuits.
- ✓ Plasmonic laser.

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...a very promising and
various scientific field...

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[1] L. Huang *et al.,* Nature Communications **4** (2013)

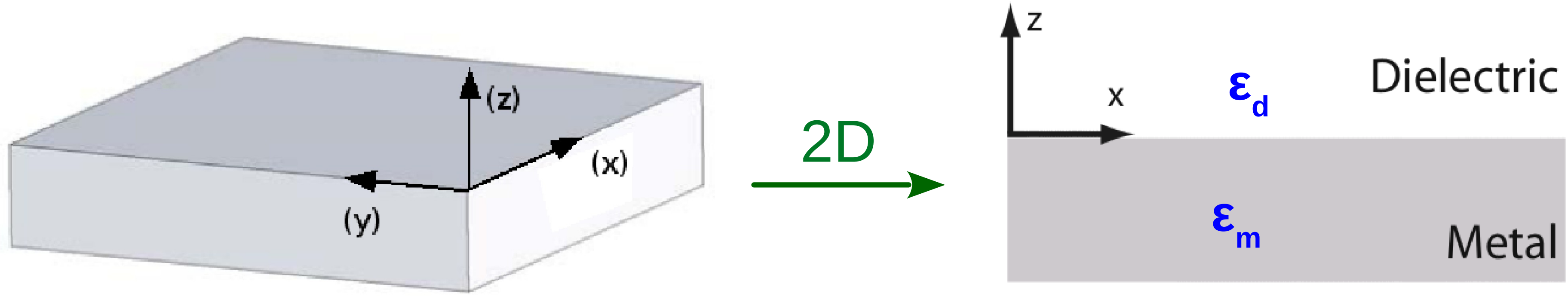
[2] Y. Liu *et. al.*, Appl. Phys. Lett. **14** (2013)

[3] Y. Liu *et. al.*, Nano Letters **10** (2010)

[4] T. Zentgra *et al.,***10** Nat. Nanotechnology (2011)

Maxwell Equations

A metal-dielectric interface is located at z = 0



Surface Waves

propagating

decaying

$$\begin{pmatrix}\vec{E}\\ \vec{B}\end{pmatrix}_{spp} \sim e^{iqx - k_{zj}|z|}$$

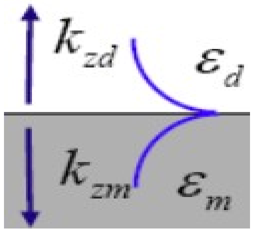
$j=(d,m)$

- q is the SPP wave number
- $k_{zj}^2 = q^2 - k_0^2\varepsilon_j$
- Propagation along x direction
- Evanescent along z direction

Conditions

A) $\Re[\varepsilon_m] < 0$ → Metals, semimetals semiconductor

B) $k_{zj}^2 > 0 \Rightarrow q^2 > k_0^2\varepsilon_j$ →



C) $\vec{E} = (E_x, 0, E_z)$, $\vec{H} = (0, H_y, 0)$ → TM polarization EM waves

Drude Metals

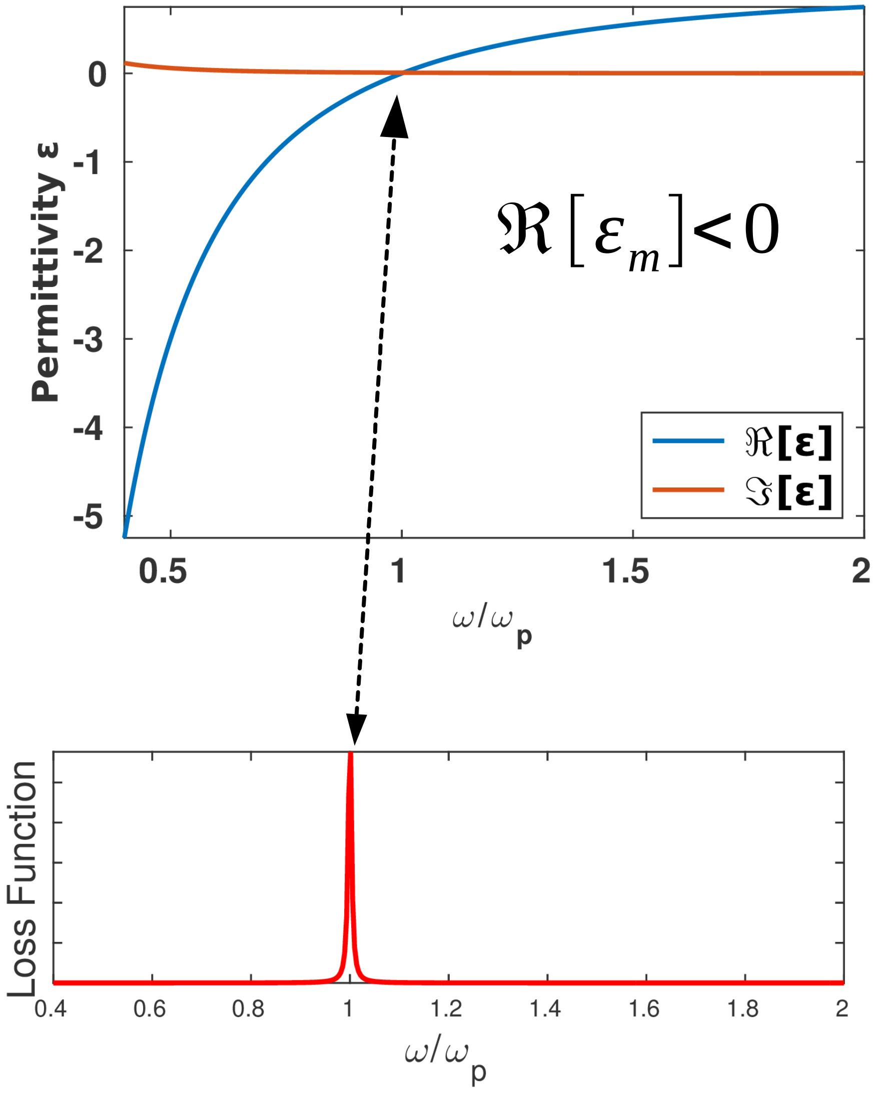
Drude model for metals:

$$\varepsilon_m(\omega)=\varepsilon_h-\frac{\omega_p^2}{\omega^2+i\Gamma\omega}$$

- ε_h : high frequency permittivity
- ω_p: plasma frequency
- Γ : metal losses (in freq. units)

SILVER

- $\varepsilon_h = 1$
- $\omega_p = 1.367\ 10^{16}$ Hz
- $\Gamma = 1.018\ 10^{14}$ Hz



Loss Function *L*(ω):

$$L=-\Im\left[\frac{1}{\varepsilon}\right]=\frac{\Im[\varepsilon]}{|\varepsilon|^2}$$

A useful quantity to determine SPP regime:

Maxima of *L* show plasmon resonance.
SPPs are found before but near to a peak.

Dispersion Relation

Dispersion Relation q(ω):

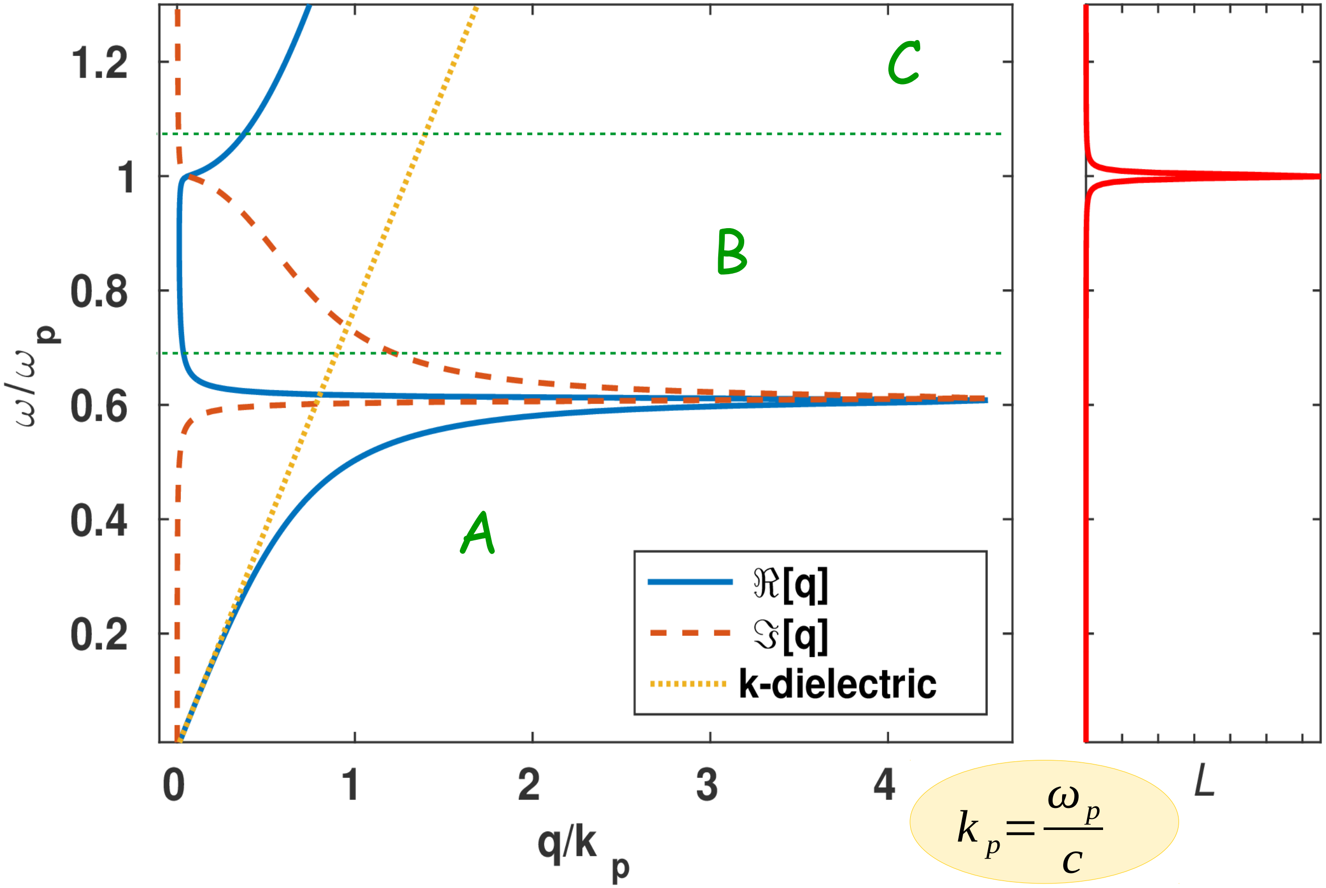
$$q(\omega)=k_0\sqrt{\frac{\varepsilon_d\varepsilon_m}{\varepsilon_d+\varepsilon_m}}$$

$$k_0=\frac{\omega}{c}=\frac{2\pi c}{\lambda_0}$$

SPP wavelength λ_{sp}:

$$\lambda_{sp}=\lambda_0\sqrt{\frac{\varepsilon_d+\varepsilon_m}{\varepsilon_d\varepsilon_m}}$$

SubWavelength
$\lambda_{sp}<\lambda_0$



$$k_p=\frac{\omega_p}{c}$$

A. Bound Modes

$$\varepsilon_m<-\varepsilon_d<0$$

q : Real
$k_{z:}$: Real

B. Quasi-Bound Modes

$$-\varepsilon_d<\varepsilon_m<0$$

q : Imaginary
$k_{z:}$: Imaginary

C. Radiative Modes

$$\varepsilon_m>0$$

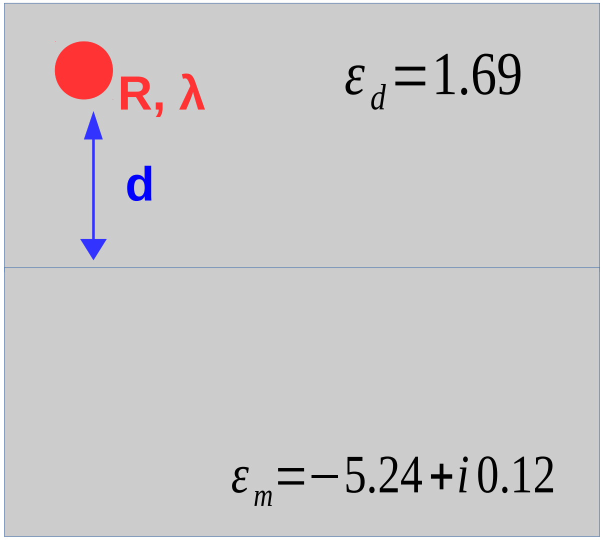
q : Real
$k_{z:}$: Imaginary

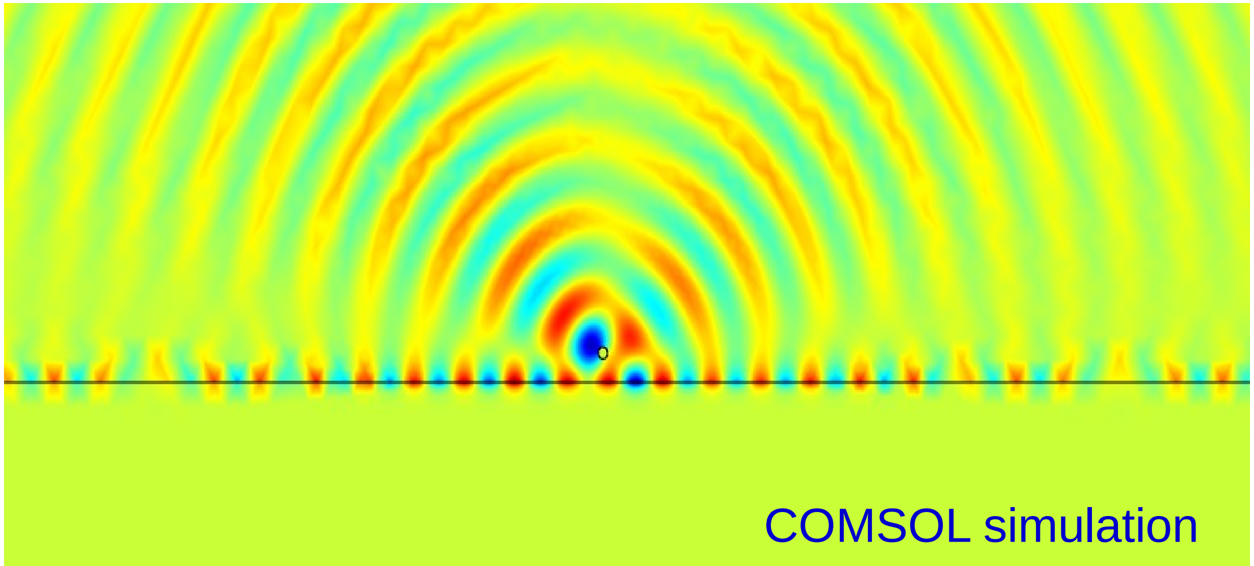
SPPs excitation

Near Field[1] method used for excitation of SPPs:

A point source with R=20nm located d=100nm above the metal surface acts as a point source since λ<<R.

Monochromatic TM EM source with λ=345nm.
Silica glass is used as dielectric with ε_d=1.69.
Silver is used as metal at f=870THz.




COMSOL simulation

SubWavelength Optics

$$\frac{\lambda_0}{\lambda_{sp}} = 1.6$$

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[1] SA Maier. Plasmonics: Fundamentals and applications. Plasmonics: Fundamentals and Applications (2007).

Lossy propagation

Metal's permittivity is a complex function

$$\varepsilon_m(\omega)=\varepsilon_{1m}+i\varepsilon_{2m} \rightarrow \text{METAL LOSSES}$$

Drude Model

$$\varepsilon_m(\omega)=\varepsilon_h-\frac{\omega_p^2}{\omega^2+\Gamma^2}+i\frac{\omega_p^2\Gamma}{\omega^3+\omega\Gamma^2}$$

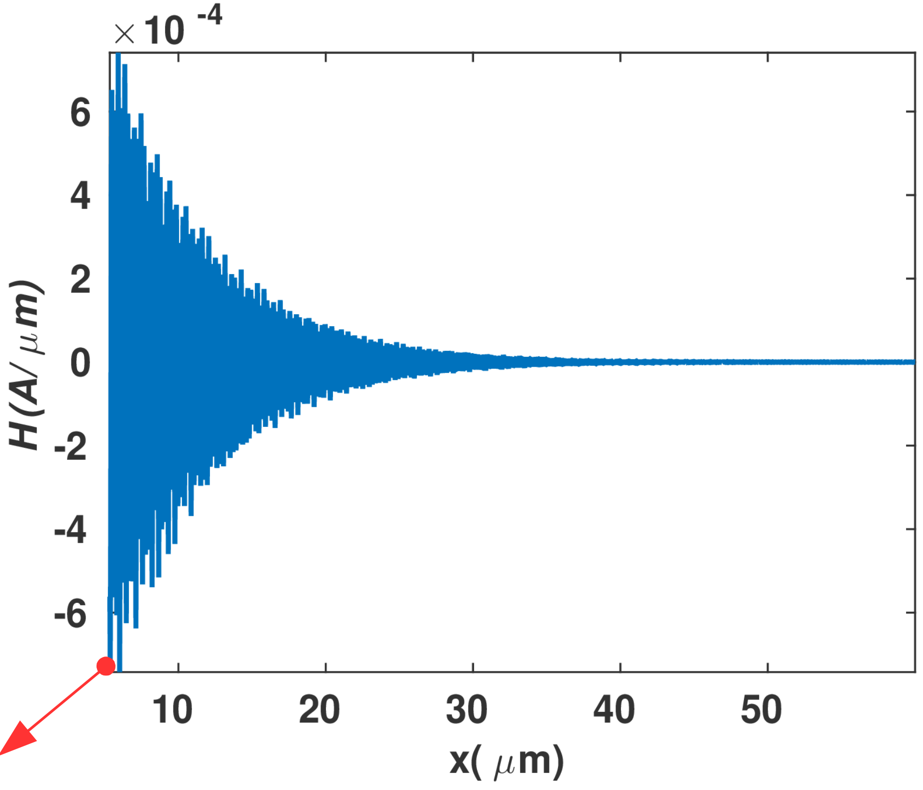
Resulting to complex q and lossy SPPs propagation

$$q(\omega)=q_1+iq_2$$

Propagation length

The rate of change of the SPP EM energy attenuation

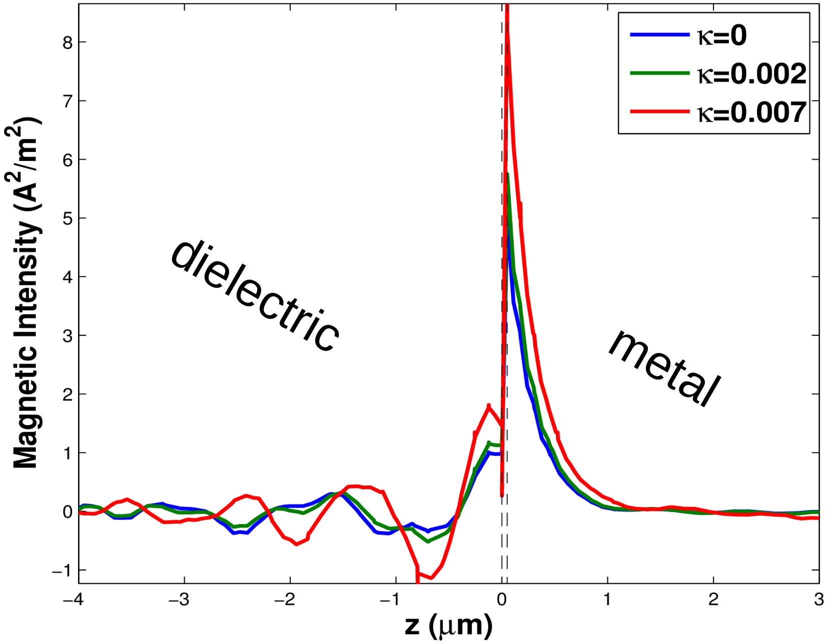
$$L_I=\frac{1}{\Im[q]}$$

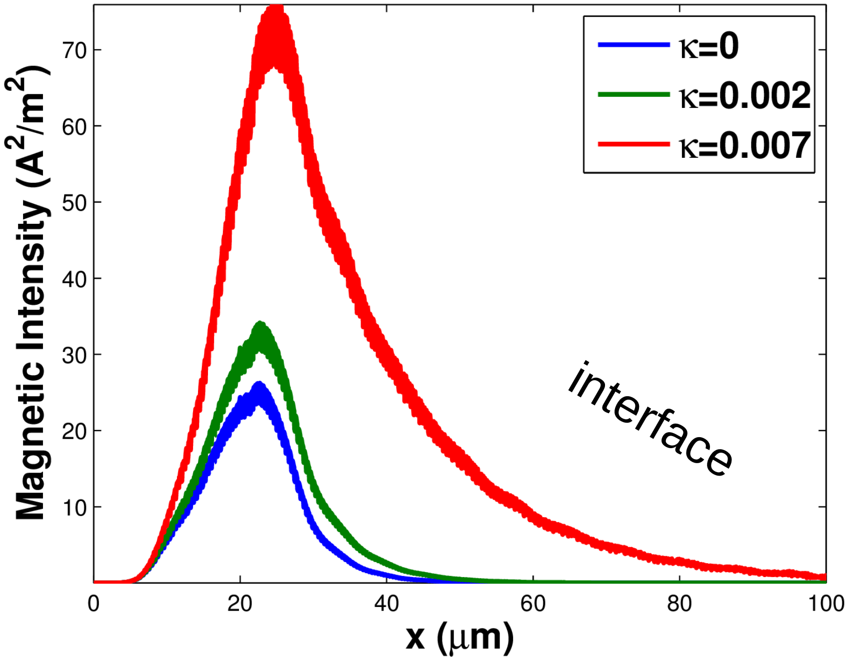


Point Source x-location

Active (gain) dielectrics

- Dielectrics with complex permittivity $\varepsilon_d = \varepsilon_{1d} + i\varepsilon_{2d}$ ($\varepsilon_{1d} > 0$) and complex refractive index $n = n_r + i\kappa$ ($\varepsilon_d = n^2$).
- The imaginary part accounts for gain (in opposite to metal losses).
- Gain materials counterbalance metal losses resulting to:
  - Enhanced SPP EM intensity I.
  - Larger penetration length.
  - Longer SPPs propagation length L_l.





M. Mattheakis *et al*. Expert from the Proceedings of the 2014 COMSOL conference in Cambridge (2014).

Lossless SPPs propagation

Q.

Is there any gain ε_{2d} for which SPPs propagate without losses?

A.

Yes . It is given by the solution of equation: $\boxed{\Im\left[q\left(\varepsilon_{2d}\right)\right]=0}$

$$\Im[q]=0 \quad \Rightarrow \quad L_I \rightarrow \infty$$

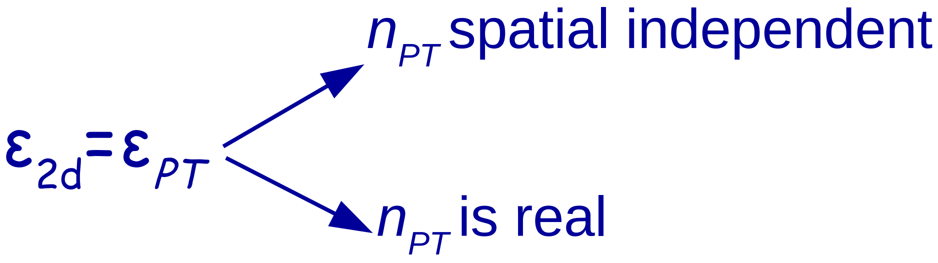
Effective SPP refractive index

$$n_{SP}=\frac{q}{k_0}=\sqrt{\frac{\varepsilon_d\,\varepsilon_m}{\varepsilon_d+\varepsilon_m}}$$

This gain satisfies the *PT* symmetry

***PT* Symmetry**

$$n(-x)=\bar{n}(x)$$



$\varepsilon_{2d}=\varepsilon_{PT}$

n_{PT} spatial independent

n_{PT} is real

$$\boxed{n_{SP}=\bar{n}_{SP}}$$

Trivial case of *PT* symmetry

Gain Overcomes Losses

Complex SPP wave number q: $q = q_1 + i q_2$

Demand $q_2=0$:

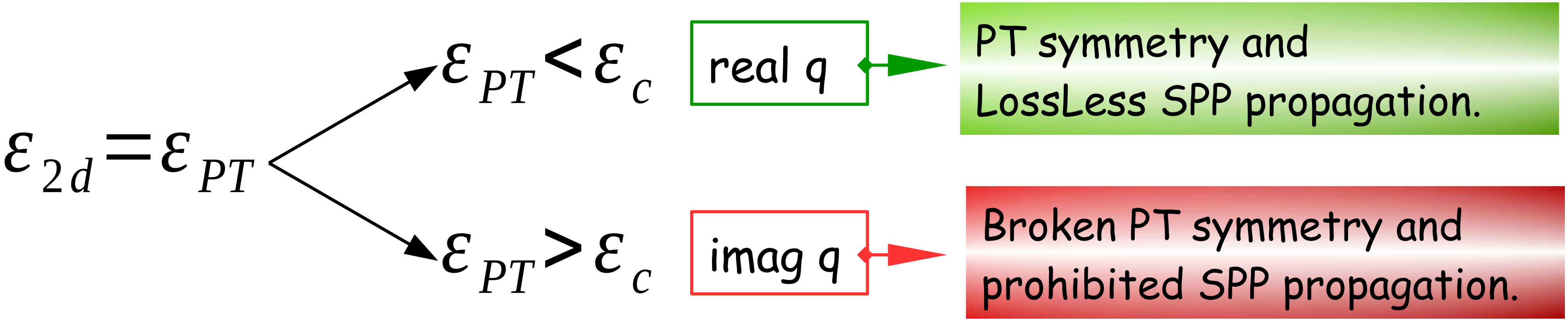
$$\varepsilon_{PT} = \frac{|\varepsilon_m|^2}{2\varepsilon_{2m}} \left(1 - \sqrt{1 - \left(\frac{2\varepsilon_{1d}\varepsilon_{2m}}{|\varepsilon_m|^2} \right)^2} \right)$$

Demand q_1=real:

$$\varepsilon_{PT} < \varepsilon_{1d} \sqrt{\frac{|\varepsilon_m|^2}{\varepsilon_{1d}\varepsilon_{1m}} - 1} \equiv \varepsilon_c$$

ε_{PT} and ε_c are given in terms of the optical properties of the interface.

Limits of *PT* symmetry and of lossless SPPs propagation



$\varepsilon_{2d} = \varepsilon_{PT}$

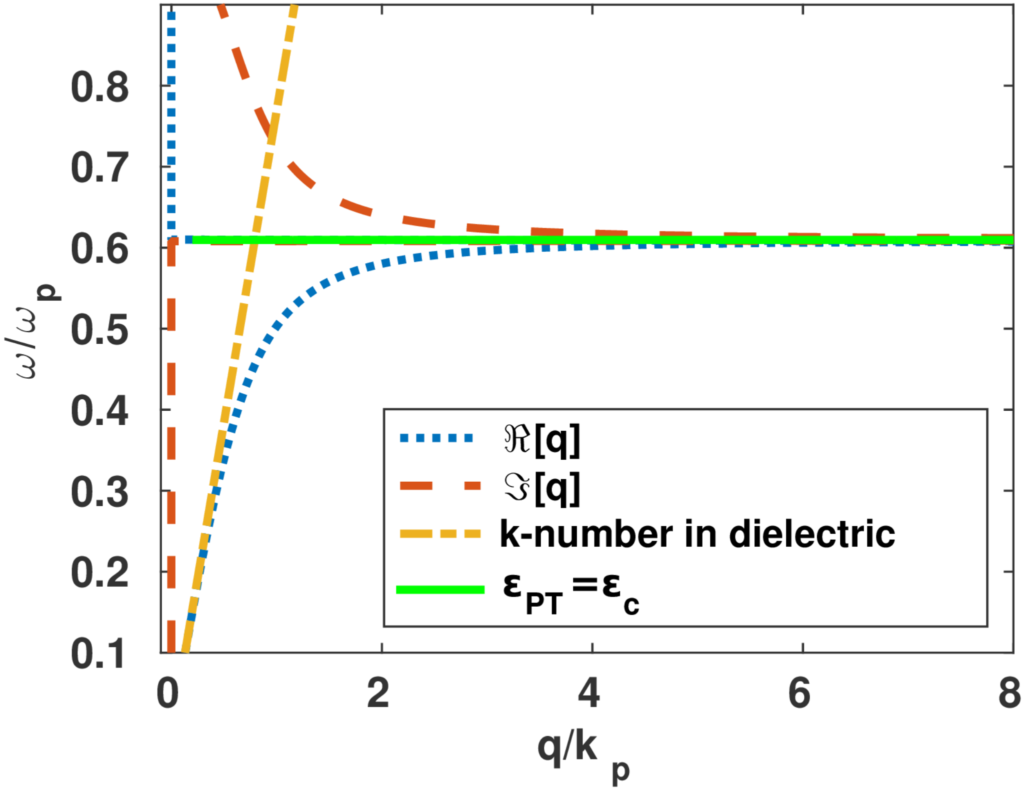
- $\varepsilon_{PT} < \varepsilon_c$ → real q → PT symmetry and LossLess SPP propagation.
- $\varepsilon_{PT} > \varepsilon_c$ → imag q → Broken PT symmetry and prohibited SPP propagation.

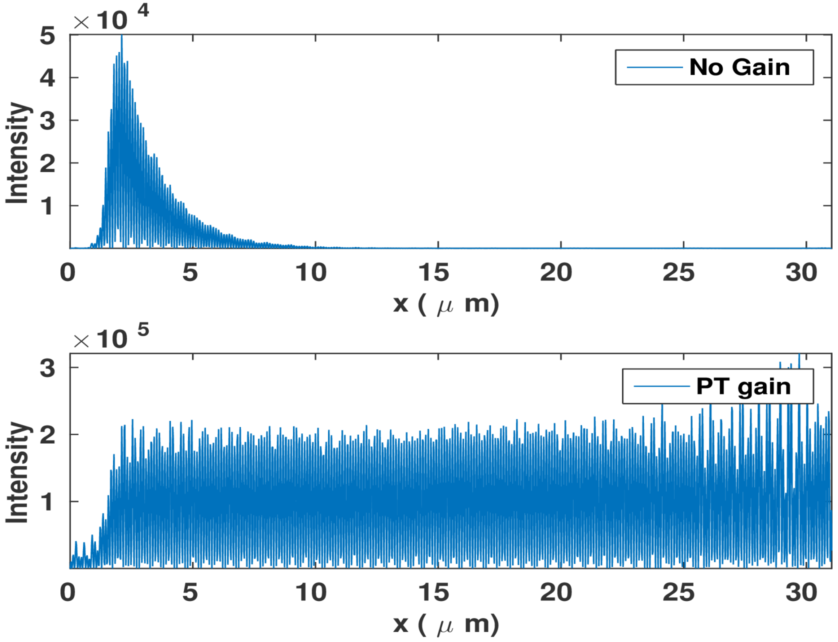
M. Mattheakis *et al.*, arXiv:1507.08167

Lossless SPPs propagation

SPPs dispersion relation under *PT* symmetry.

- ➔ Interchange between real and imaginary part of q at $\varepsilon_{PT}=\varepsilon_c$





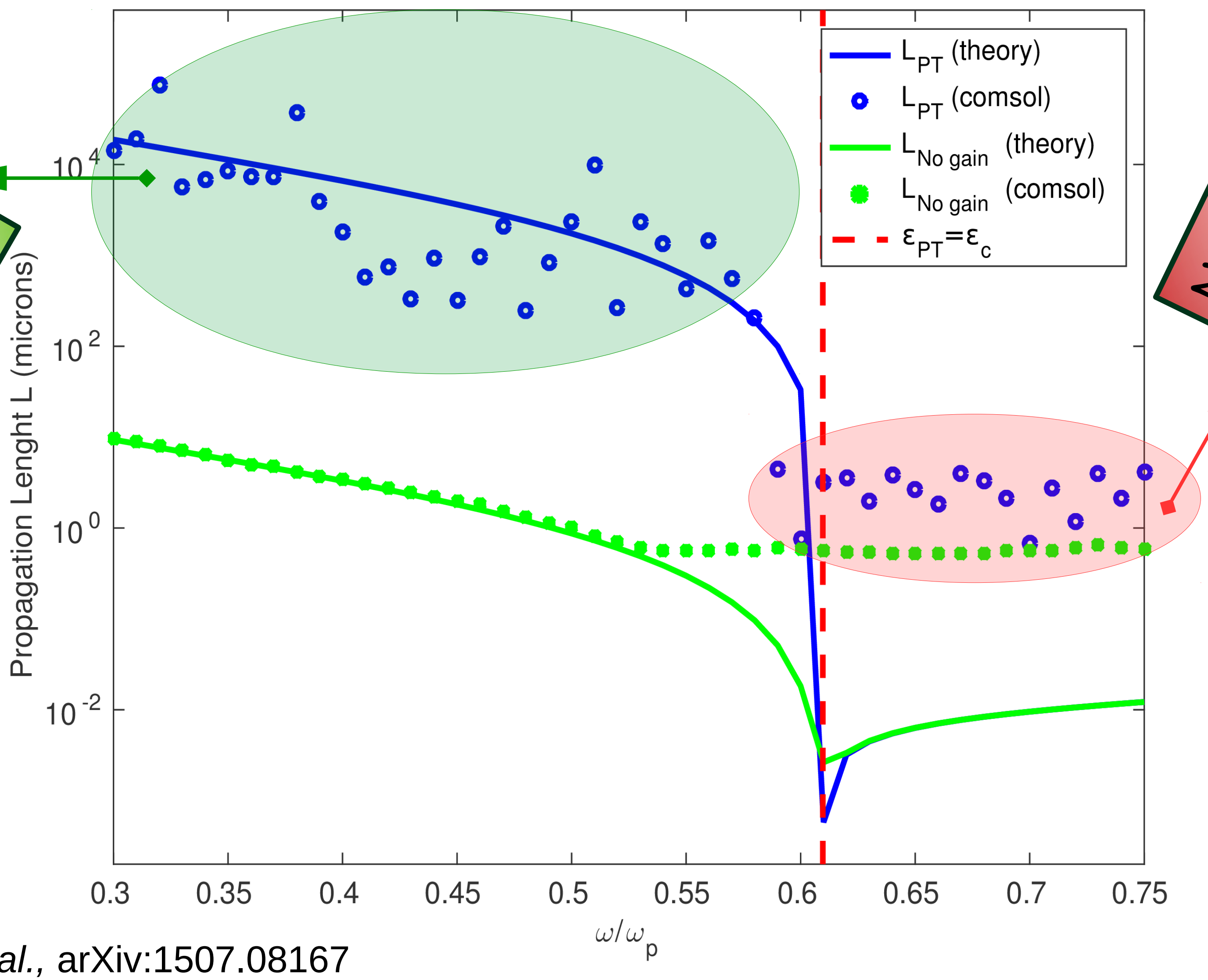
SPPs COMSOL simulations.

- ➔ Lossy SPPs propagation $\varepsilon_{2d}=0$ (up)
- ➔ Lossless SPPs propagation $\varepsilon_{2d}=\varepsilon_{PT}$ (down)

M. Mattheakis *et al.*, arXiv:1507.08167

Gain Saturation

A steep phase transition is expected to propagation length SPPs L_l
Because of the sudden interchange in imaginary part of q.



Lossless SPPs propagation

NO SPPs modes. Quasi-bound modes

M. Mattheakis *et al.*, arXiv:1507.08167

Main Result

So,

An active (gain) metamaterial, with the desirable frequency-dependent dielectric function (ε_{PT}), may be designed for the fabrication of *PT* symmetric plasmonic systems, providing infinite SPPs propagation for any surface plasmon eigen-frequencies.

M. Mattheakis *et al.*, arXiv:1507.08167

SPPs in ultra-thin layers

Assume an ultra thin metallic film of thickness d → 0, sandwiched by two dielectrics with ε_1 and ε_2.

[1,2]Dispersion Relation q(ω):

$$q(\omega)=k_0\frac{\varepsilon_1+\varepsilon_2}{1-\varepsilon_m}$$

$$k_0=\frac{\omega}{c}$$

[1,2]A very good approximation near to plasmon resonance, where **$q \gg k_0$**

Case with same dielectrics ($\varepsilon_1=\varepsilon_2=\varepsilon_d$)

$$q(\omega)=k_0\frac{2\varepsilon_d}{1-\varepsilon_m}$$

These dispersion relations should be useful for studying plasmons in 2D materials.

---

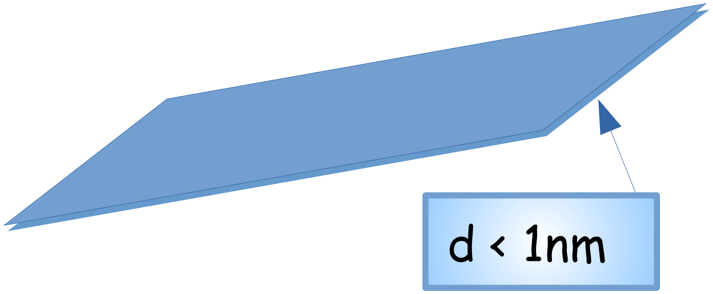
[1]M. Jablan *et al*. Proceeding of the IEEE, **101** 7 (2013)

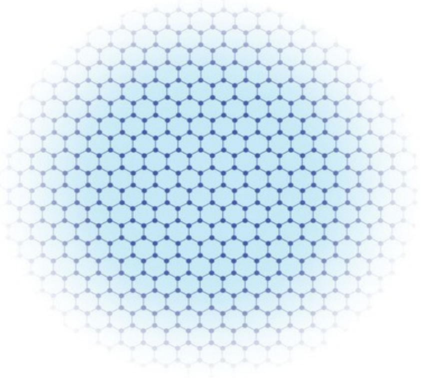
[2]T. Low *et al*. Phys. Rev. Lettof, **113** (2014)

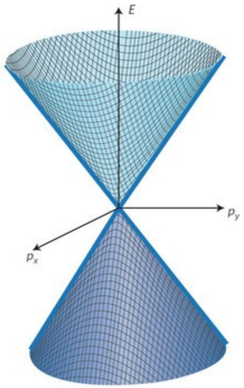
Two Dimensional Materials

The Flatland is real !!!

- **2D Materials** are crystalline materials consisting of few layers of atoms.
- In 2D materials the width *d* is much smaller than the other dimensions, the width is **less than 1nm!!!**
- The properties are dramatically changing when we are going from 3D to 2D.

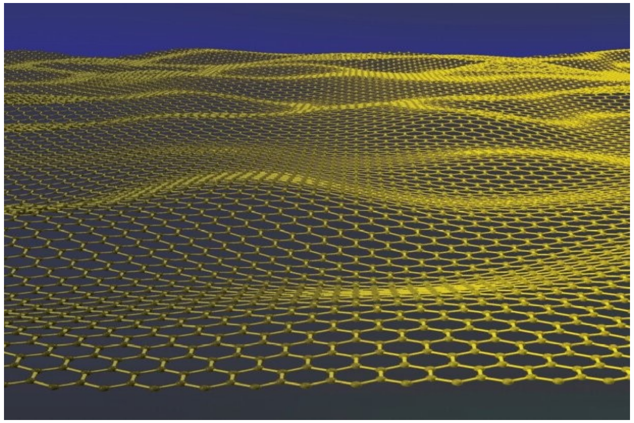






Graphene is an atomically thick **(d=0.32nm)** sheet honeycomb lattice of carbon atoms.

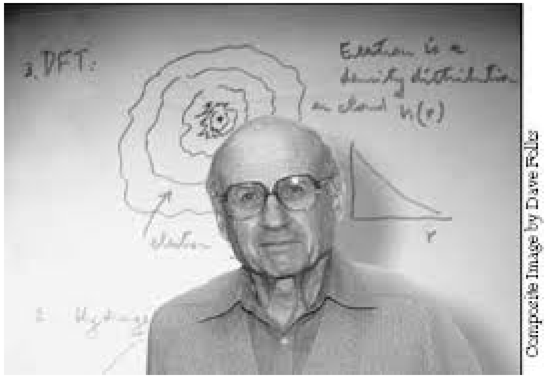
- ➔ It is hundreds of times stronger than steel.
- ➔ It has the largest thermal and electrical conductivity that is known.
- ➔ It supports plasmon modes with very short wavelength.



Ab initio Calculations

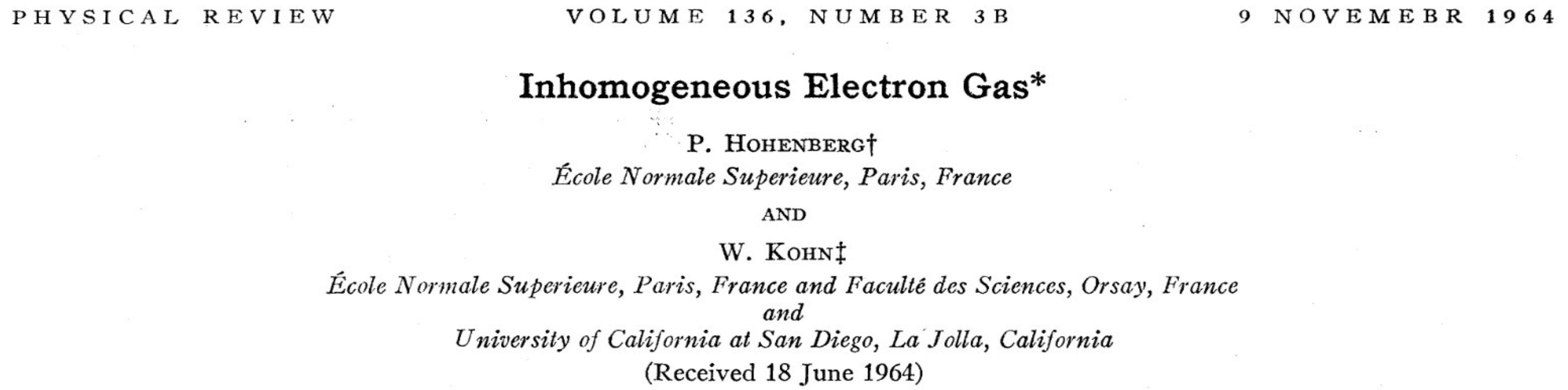
Permittivity ε is calculated by first principles, i.e. by solving quantum mechanics equations.

Density **F**unctional **T**heory (DFT) is a computational quantum mechanical modeling method for investigating the electronic structure.



Composite Image by Dave Folks

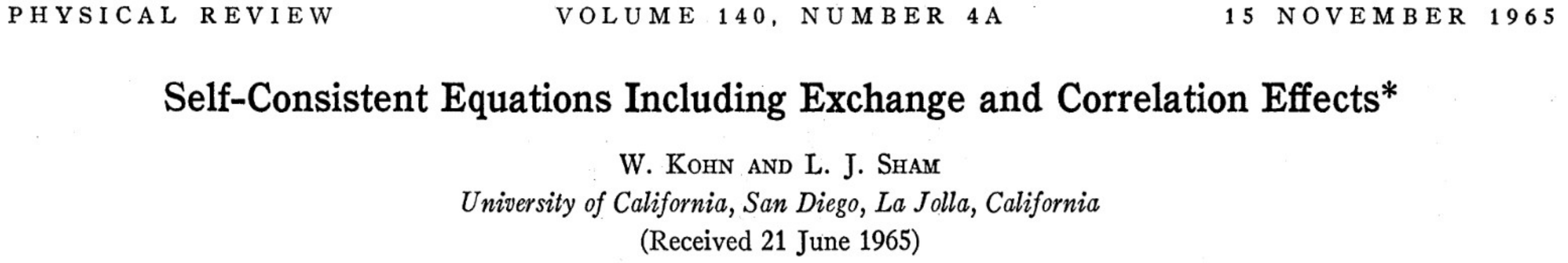
Walter Kohn chemistry Nobel prize 1998



PHYSICAL REVIEW VOLUME 136, NUMBER 3B 9 NOVEMEBR 1964

Inhomogeneous Electron Gas*

P. HOHENBERG†
École Normale Superieure, Paris, France
AND
W. KOHN‡
École Normale Superieure, Paris, France and Faculté des Sciences, Orsay, France
and
University of California at San Diego, La Jolla, California
(Received 18 June 1964)



PHYSICAL REVIEW VOLUME 140, NUMBER 4A 15 NOVEMBER 1965

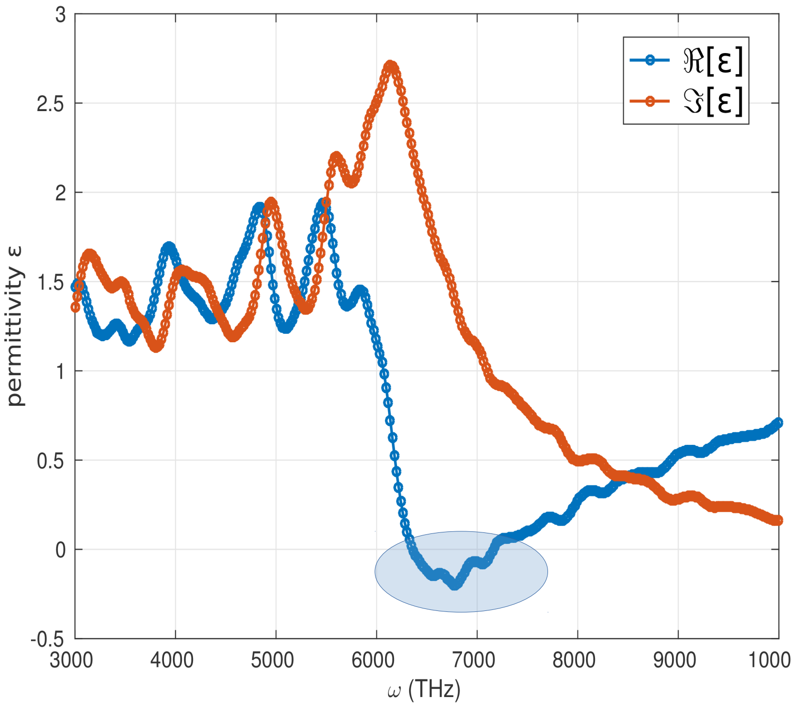
Self-Consistent Equations Including Exchange and Correlation Effects*

W. KOHN AND L. J. SHAM
University of California, San Diego, La Jolla, California
(Received 21 June 1965)

Graphene

Graphene has negative permittivity for a small regime, so we expect to support surface plasmons.

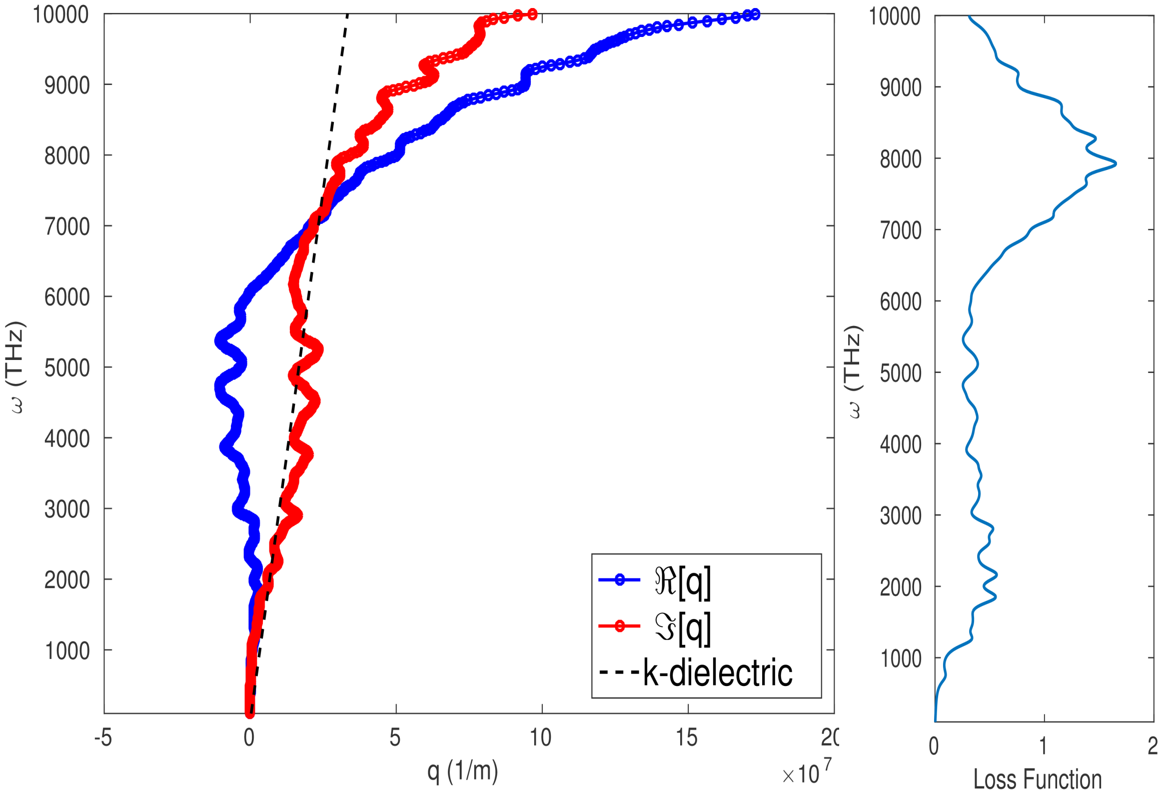
Graphene permittivity obtained by DFT



A small negative ε regime, with high losses (Im[ε]).

Air is used as enviroment $\varepsilon_1=\varepsilon_2=1$

Dispersion Relation q(ω) and Loss function:

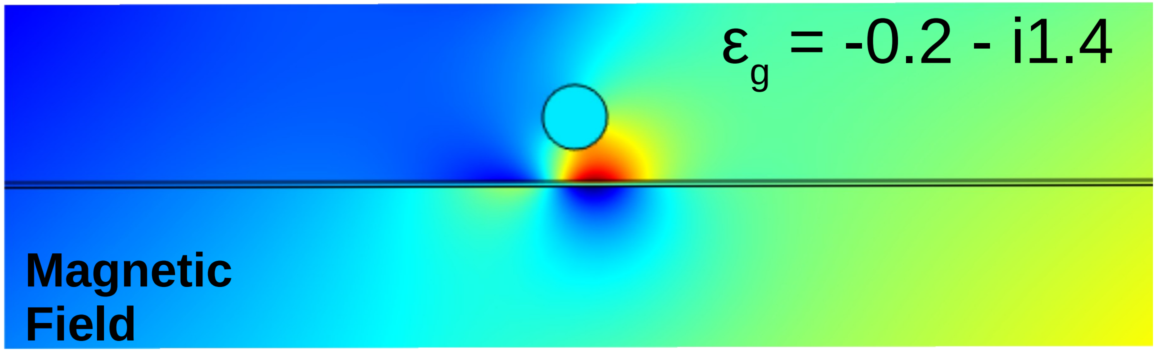


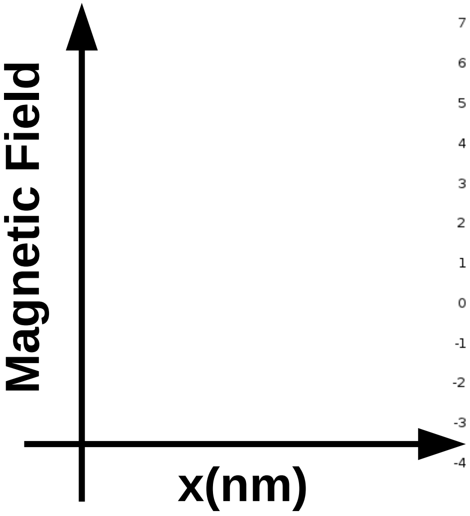
SPPs in Graphene

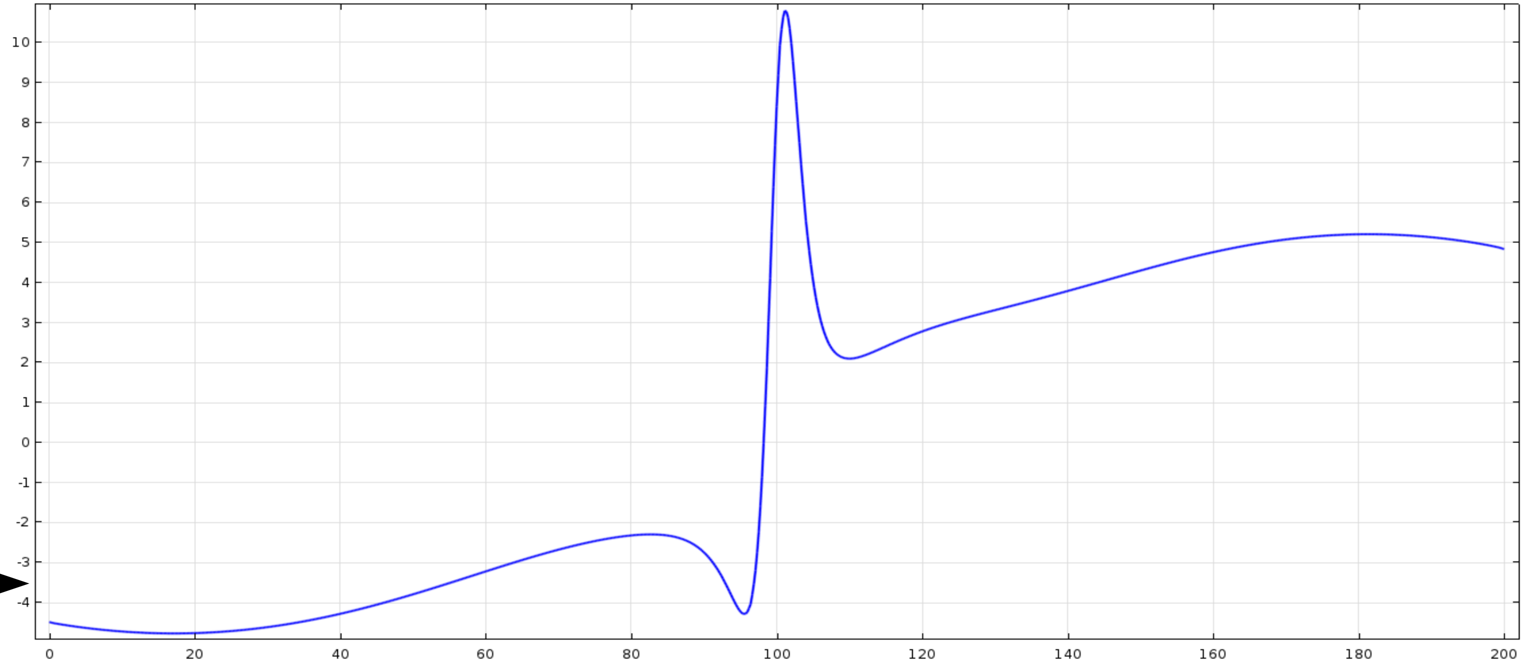
- COMSOL simulation for SPP propagation.
- Point source of ω=6770THz and λ=278nm.
- SSP is generated but cannot propagate for long due to high losses.
- It could be applied as a photo-sensor for high frequencies.

Subwavelength

$$\frac{\lambda_0}{\lambda_{sp}} \sim 20$$

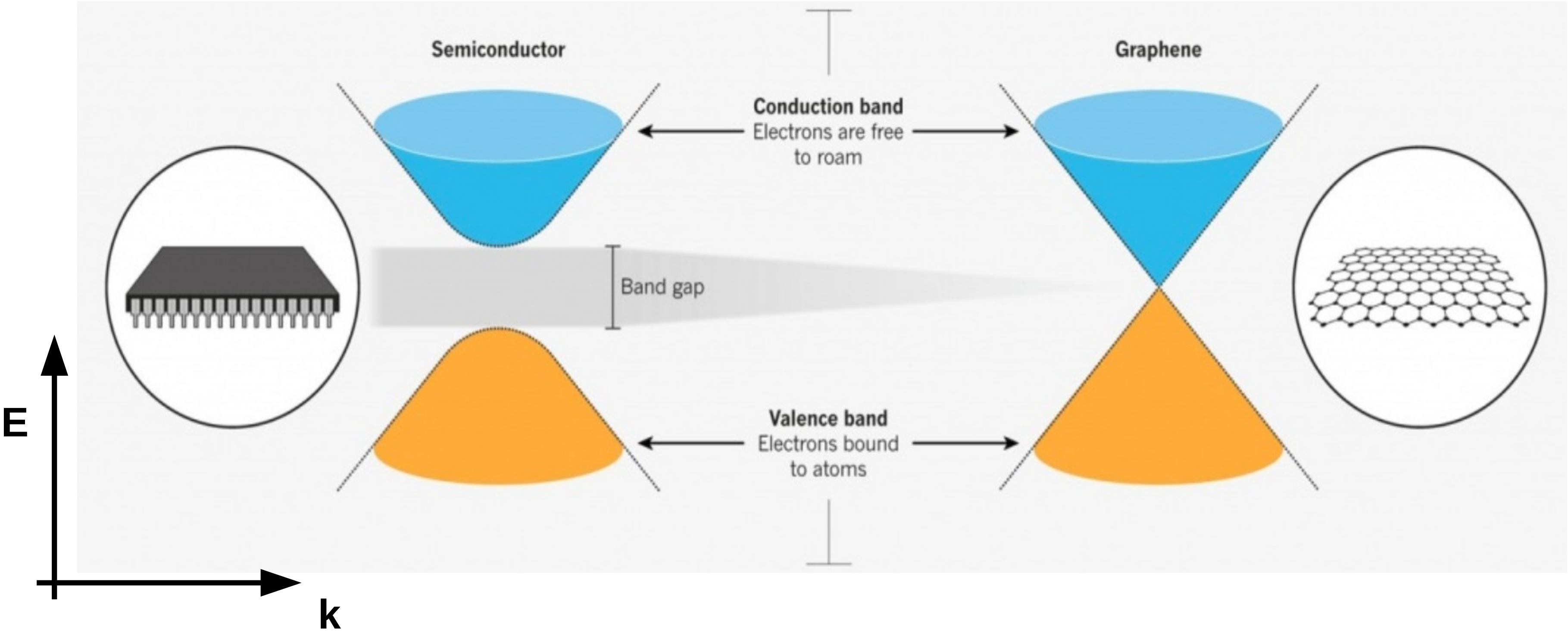






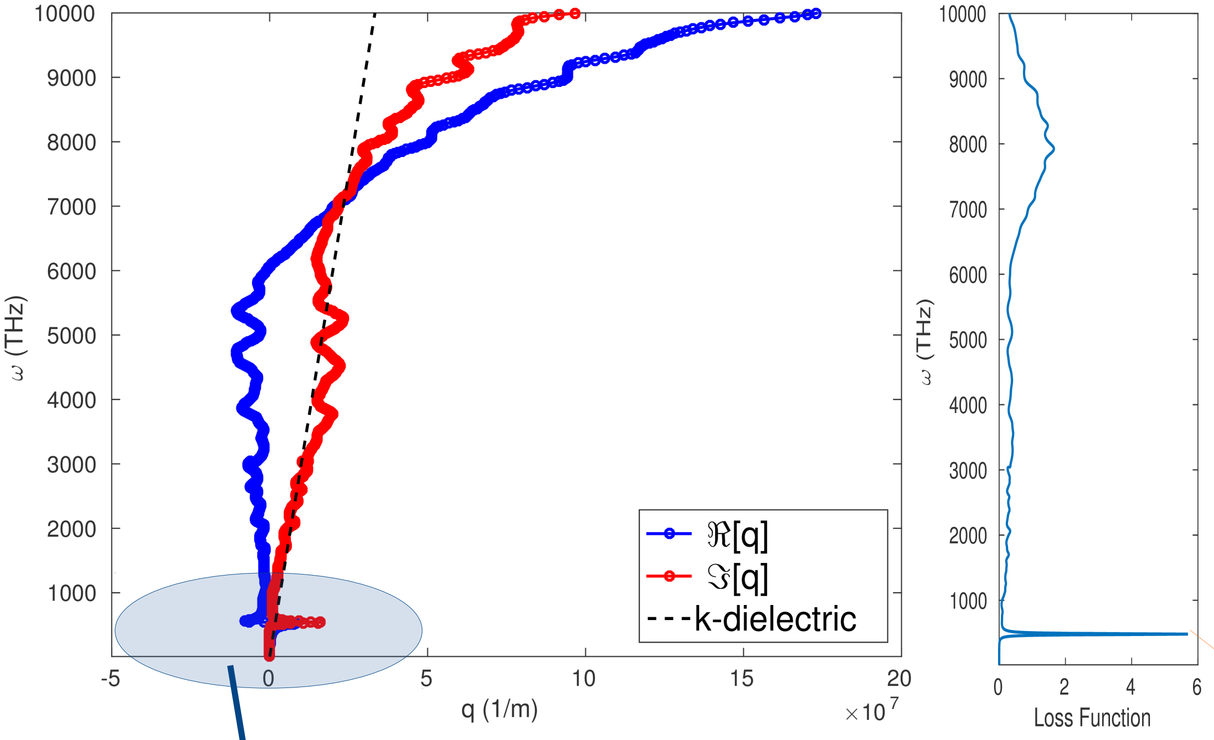
Doping materials

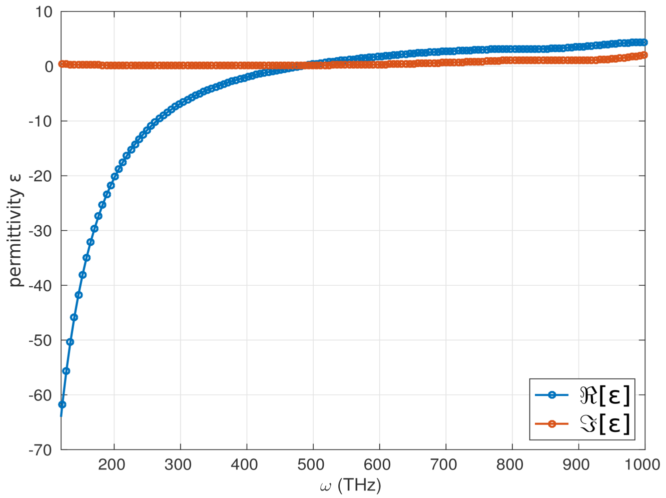
- With **doping** we **add** electrons to the conduction band or **remove** from the valence band. As a result, **the conductivity** of the material is increased, because more electrons can move free.
- The doping can be performed by **chemical** reactions or by applying external **voltage.**
- The amount of doping **controls the plasmon resonace frequency.** More doping leads to higher plasmon frequency and vice versa.
- It is a way to use semi-conductors for plasmonics.

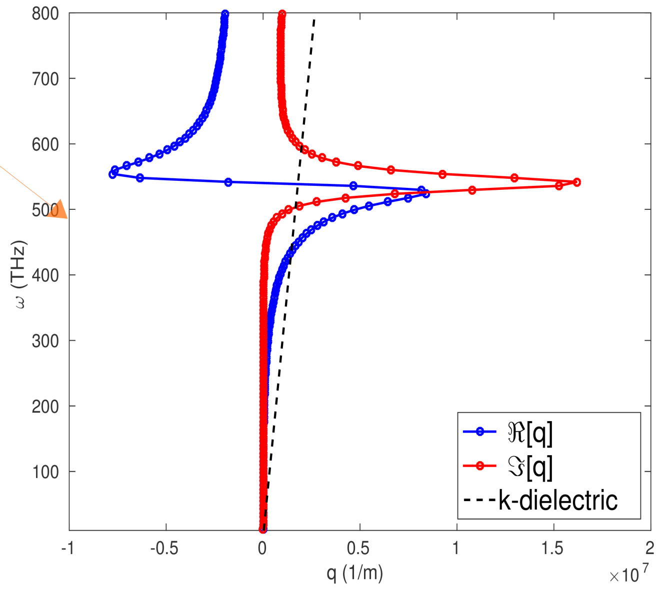


Doped Graphene

Doped graphene shows a new plasmon resonance, at lower frequency.





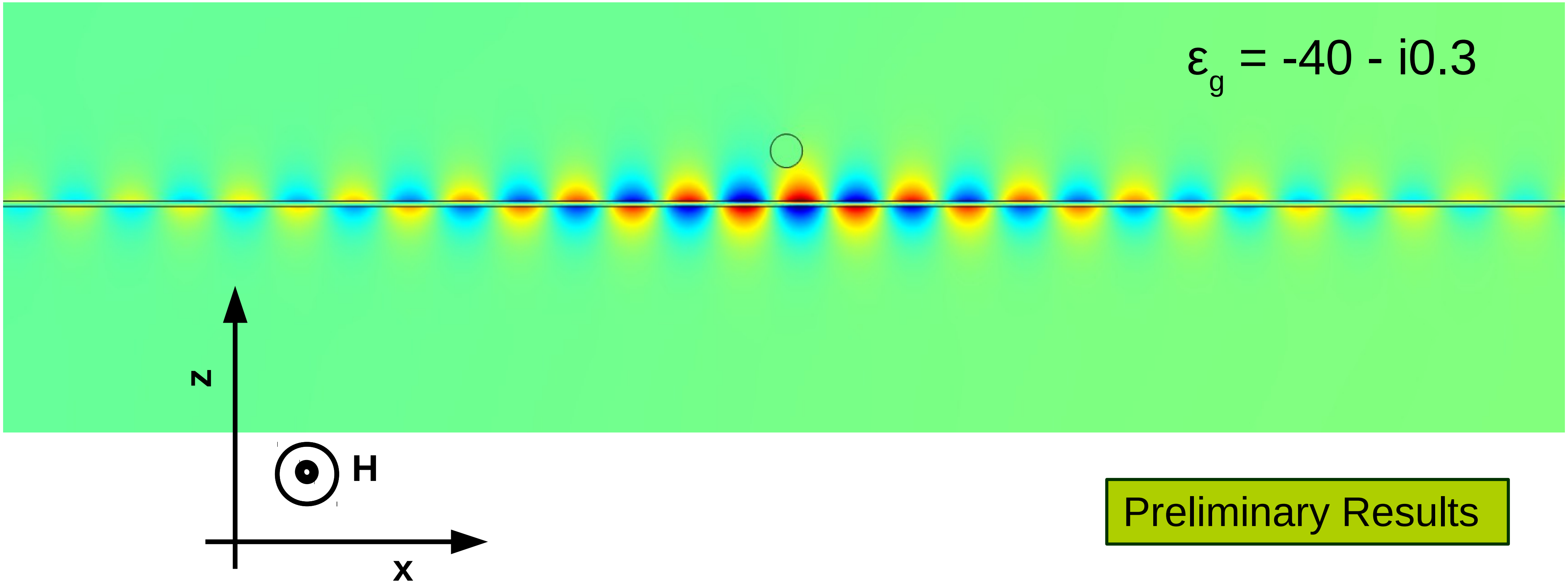


- New plasmon resonance at lower frequency.
- The new plasmon resonance frequency can be tuned by the amount of doping.

Preliminary Results

SPPs in Doped Graphene

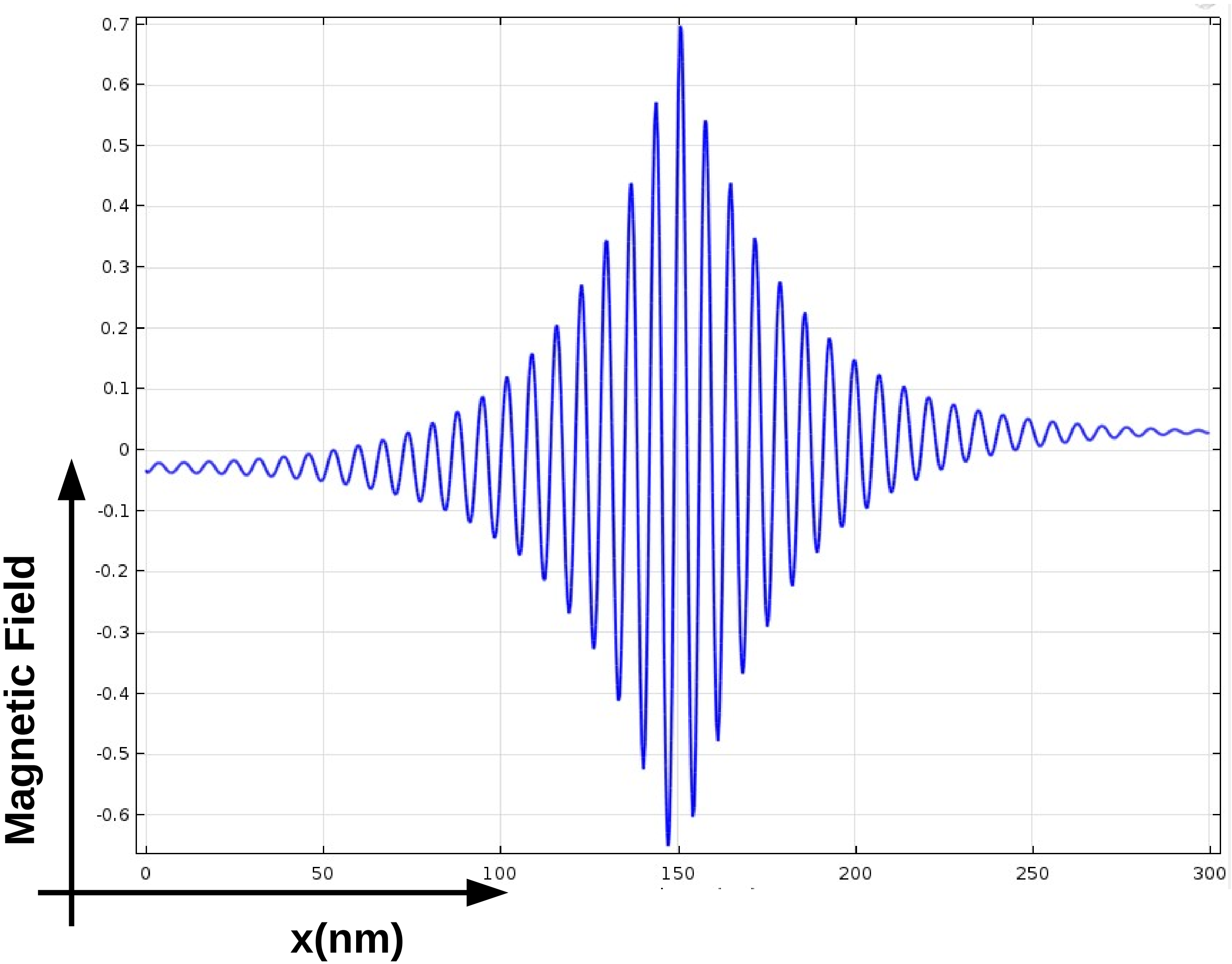
- COMSOL simulation for SPP propagation.
- The doped graphene layer of thickness d=0.33nm surrounded by air.
- A point EM source is located 3nm above the graphene layer. The source is monochromatic with ω=300THz and λ=6.3μm.
- The magnetic field is illustrated showing the SPP propagation



Preliminary Results

Graphene and subwavelength optics

- COMSOL simulation for SPP propagation.
- Magnetic field on the graphene surface.



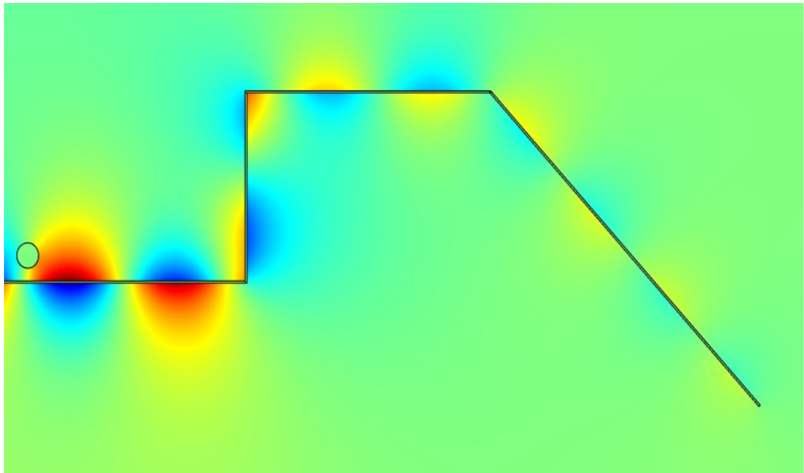
Extreme small wavelength!

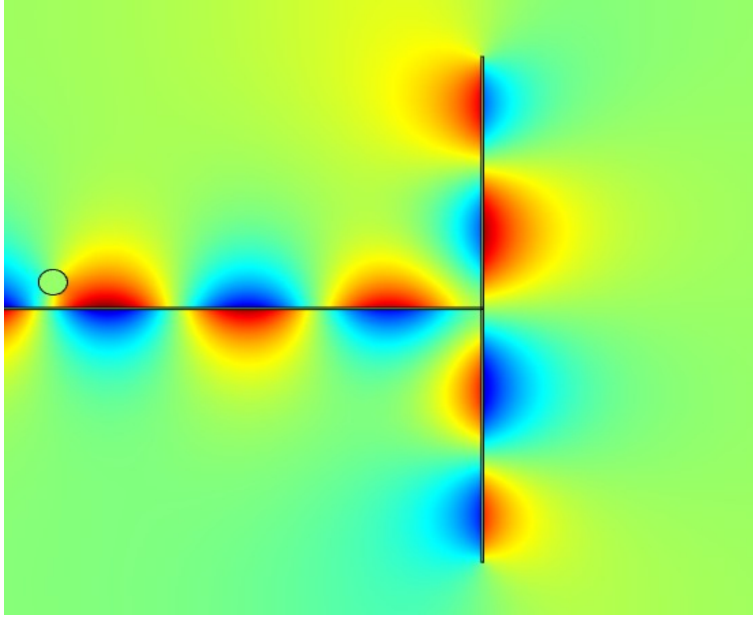
$$\frac{\lambda_0}{\lambda_{sp}} = 900$$

Preliminary Results

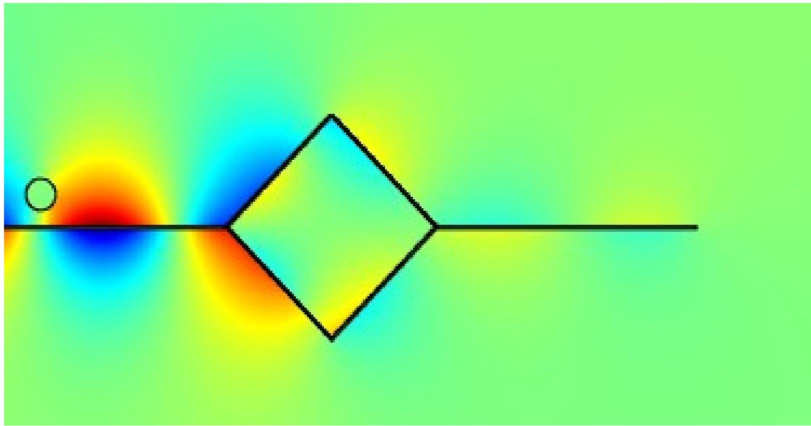
More Configurations

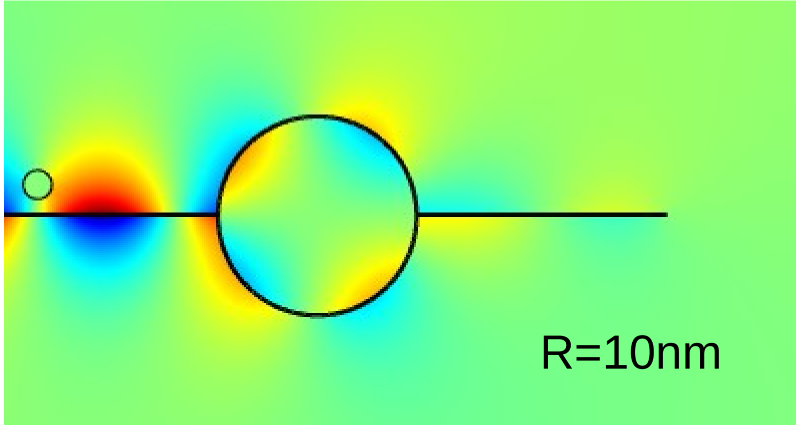
Graphene sheet as SPPs waveguide and splitter





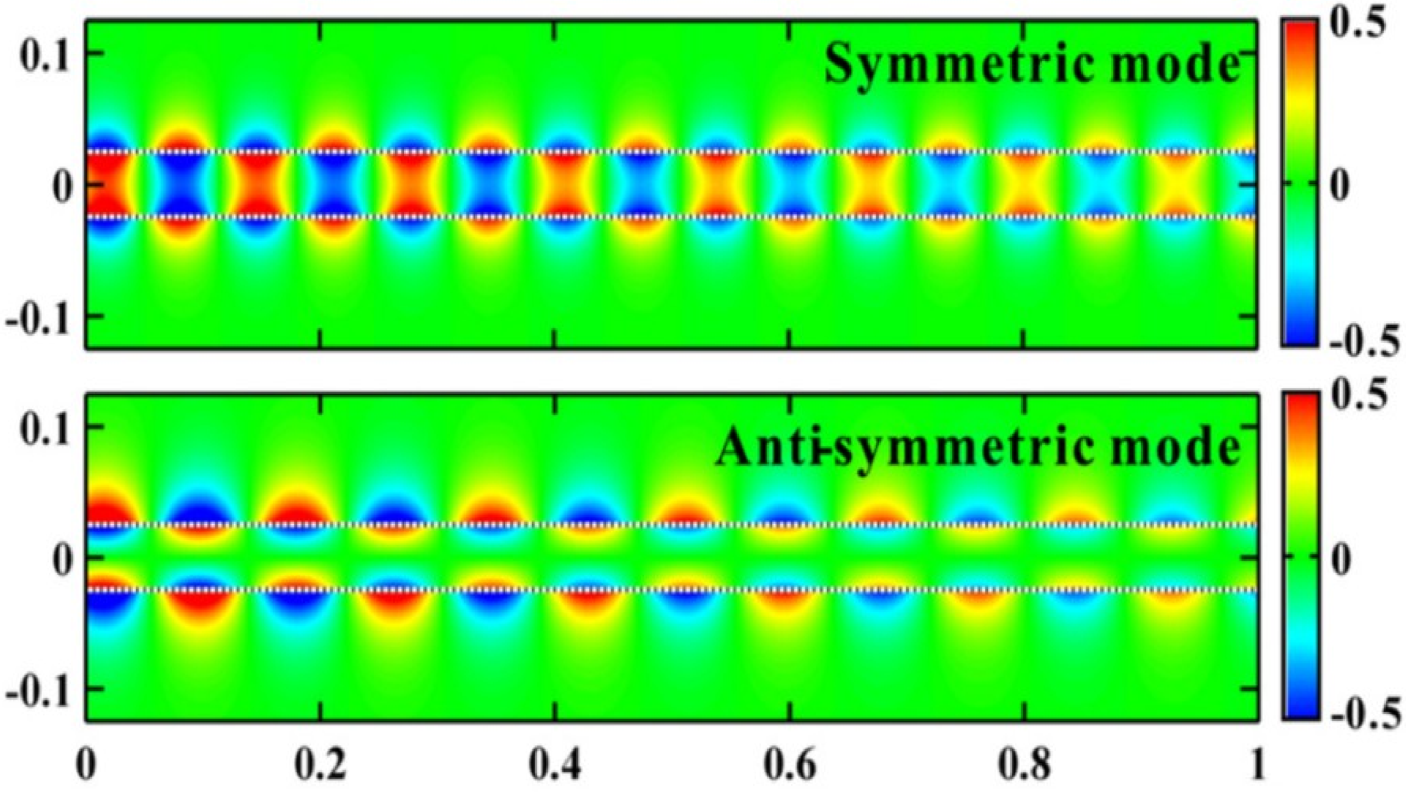
Graphene is splitting and rejoining SPPs





Two Graphene layers

New plasmonics modes arise in a system of two layers of graphene.



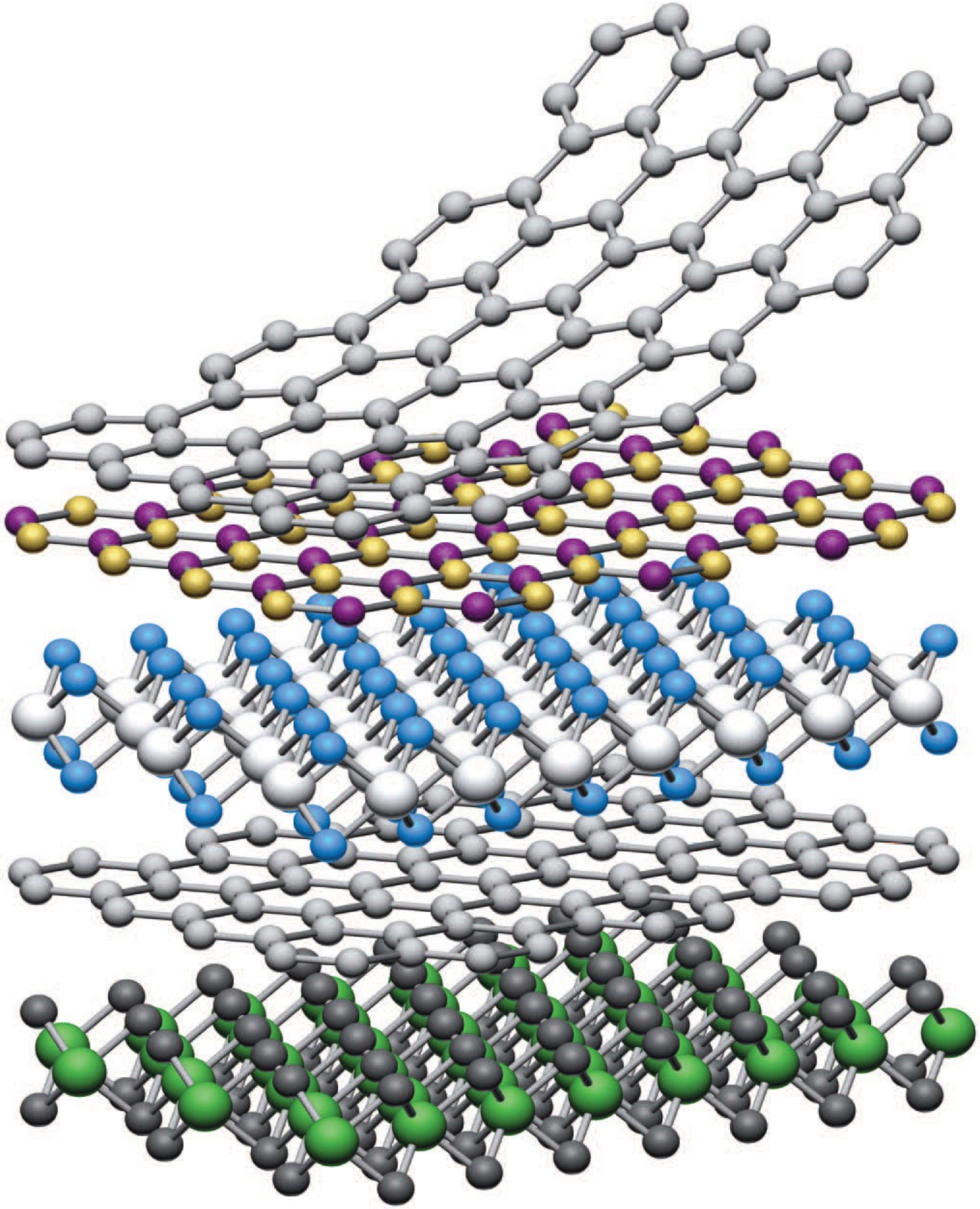
Wang *et al*., Appl. Phys. Lett. **100** (2012)

Results

- Graphene is a great material for doing subwavelength optics.
- Graphene supports plasmons in several frequencies.
- Graphene offers SPP near to optical frequencies.
- SPP spectrum can be tuned by doping amount.
- Graphene can be used as SPP nano-waveguides.
- It is a great material for designing of integrated nano circuits.
- More SPP modes arise in multilayer of graphene.

Open Issues

Heterostructures of 2D materials



Geim *et. al.*, Nature **499**, 419–425 (2013)

A very promising field is the **heterostructures** of 2D materials

...Future Goals...

Find a heterostructure which...

- supports SPPs and has low losses
- supports SPPs on optical frequencies
- SPP with even shorter wavelength

Quantum Plasmonics

Quantum plasmonics[1] has been studied the last years revealing a lot of quantum properties.

- Interaction or/and coupled with other quasi particles
  - ➔ Plasmon-Phonon[2] interaction
  - ➔ Plasmon-Exciton Interaction[3] (Plexciton)
  - ➔ Plasmon-Plasmon[4] Interaction
  - ➔ Plasmon decays to phonons[5]
  - ➔ Phonons decay to plasmons[5]

- Quantum Information Theory
  - ➔ Plasmonic Entaglement[6]

- Quantum Plasmonic Metamaterials[7,8]

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[1] M.S. Tame *et al.,* Nature Physics **9** (2013)
[2] V. B. Brar *et. al.*, Nano. Lett. **10** (2014)
[3] A. Manjavacas *et. al.*, Nano. Lett. **11** (2011)
[4] Y.A. Akimov *et. al.*, Nanotech. **23** (2012)
[5] V.H. Nguyen *et al.,* Nanosci. Nanotech. **6** (2015)
[6] J.S. Fakonas *et. al.*, Nat. Phot. **8** (2014)
[7] N. Papasimakis *et. al.*, Opt. Express **18** (2010)
[8] J. Cheng *et. al.*, Nano. Lett. **14** (2014)

Conclusion

- Surface Plasmon Polaritons (SPPs) are EM surface waves coupled to charge excitations at the surface of a conductors.
  - ➔ Dispersion Relation and SPP wavelength.
  - ➔ SPPs provide nano scale exploration (subwavelength optics).
- Active or Gain materials.
  - ➔ Enhance SPPs propagation.
  - ➔ *PT* symmetry in plasmonic systems.
  - ➔ Lossless and prohibited SPP propagation.
- Two Dimensional materials, graphene.
  - ➔ Graphene supports plasmons at high frequencies.
  - ➔ Doped graphene and new plasmonic resonance.
  - ➔ Even smaller SPP wavelength.
  - ➔ Graphene as SPP waveguide, cloak and splitter.
- Heterostructures of 2D materials and Quantum plasmonics.

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Thank you for your attention!

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