Study of Electromagnetic Wave Absorption in Graphene

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We consider the possibility of theoretically achieving 100% absorbance in single layer and bi-layer transparent graphene systems. Transparent graphene is useful for optical devices, such as liquid-crystal displays (LCDs) and light-emitting diodes (LEDs). However, in order to develop other optical devices, such as photodetectors, optical antennas, and solar cells, high optical absorption in graphene is required to generate a sufficiently large photocurrent. Current methods are much more complicated and expensive, thus making them less viable and accessible. Our objective is to use incident electromagnetic waves in the terahertz region to enhance the optical absorption of the graphene systems. We will place the single layer graphene in between two separate dielectric media to construct a total internal reflection geometry, and we will add a second graphene layer and a third dielectric medium to construct the bi-layer graphene's total internal reflection geometry. The total internal reflection geometry is desired because it produces the highest absorbance values. This work is very similar to M. S. Ukhtary, E. H. Hasdeo, A. R. T. Nugraha and R. Saito's paper "Fermi energy-dependence of electromagnetic wave absorption in graphene" where they theorize 100% optical absorption of graphene with microwaves. With terahertz waves, we have theorized nearly 100% absorption with both single-layer and bi-layer graphene systems and these results can allow for the development of the other optical devices listed earlier. This talk will demonstrate how changing parameters that affect graphene's conductivity and optical absorbance can create a graphene system with an optical absorbance of 100%.

Study of Absorption of Terahertz Waves in Graphene

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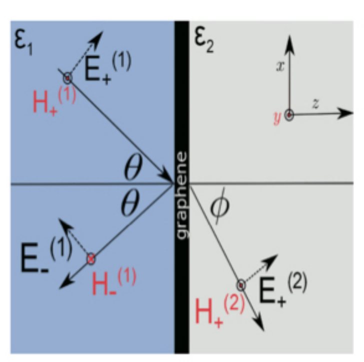
Objective/Purpose

Transparent graphene is useful for optical devices. However, in order to develop other optical devices, such as photodetectors, high optical absorption in graphene is required to generate a sufficiently large photocurrent. Our objective is to use incident electromagnetic waves in the terahertz region to enhance the optical absorption of the graphene systems.

Single Layer Method

Introduce an Angle of Incidence



$$R = \left|\frac{Z_2 cos\psi - Z_1\cos\theta - Z_1 Z_2 \sigma cos\theta cos\psi}{Z_2 cos\psi + Z_1\cos\theta + Z_1 Z_2 \sigma cos\theta cos\psi}\right|^2$$

$$T = \frac{4 Z_1 Z_2 cos\theta cos\phi}{|Z_2 cos\psi + Z_1\cos\theta + Z_1 Z_2 \sigma cos\theta cos\psi|^2}$$

$$A = 1 - T - R$$

Graphene's conductivity?

Determine the Conductivity of graphene

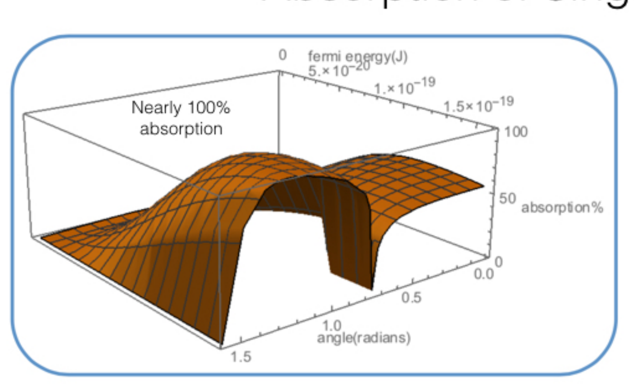
$$\sigma(\omega) = \sigma_D + Re\sigma_E + Im\sigma_E$$

Drude interband

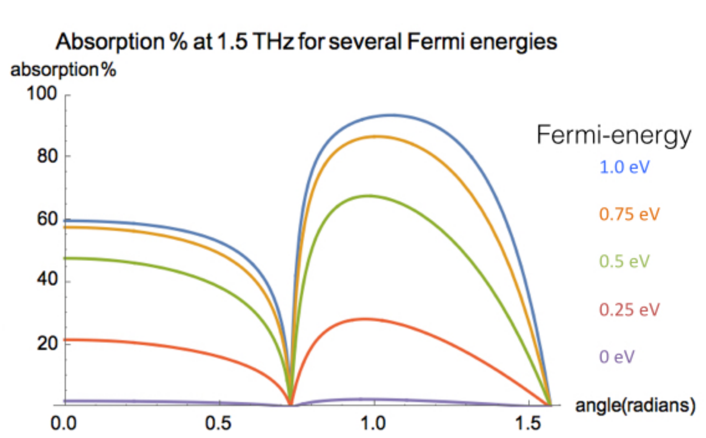
$$\sigma_D(\omega) = \frac{E_F e^2}{\pi\hbar}\frac{i}{\hbar\omega + i\hbar/\tau}$$

$$\sigma_E(\omega) = \frac{e^2}{4\hbar}\Theta(\hbar\omega - 2E_F) + \frac{ie^2}{4\pi\hbar}\ln\left|\frac{2E_F - \hbar\omega}{2E_F + \hbar\omega}\right|$$

Absorption of Single Layer Graphene



- Using Kono Sensei's graphene, the absorption = 80-100% when
  - EF> 0.75 eV
- As we increase the fermi-energy, the max absorption % will increase as well



What about more than one layer of graphene?

Acknowledgement

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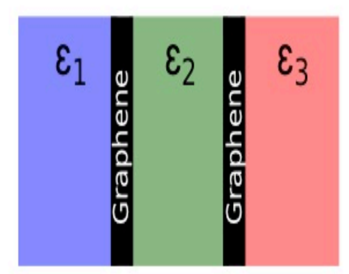
Transfer Matrix Method with Graphene



Boundary Conditions $H_y^{(k)} = i\omega\varepsilon_0\varepsilon_k\int E_x^{(k)}dz$

$$E_x^{(1)} = E_x^{(2)}$$

$$H_y^{(2)} - H_y^{(1)} = -\sigma E_y^{(2)} \qquad \alpha_i = \frac{k_{zi}\sigma}{\omega\varepsilon_0\varepsilon_i} \qquad \beta_i = \frac{k_{zi}}{k_{z,i+1}}\frac{\varepsilon_{i+1}}{\varepsilon_i}$$

Medium 1

$$E_x^{(1)}(z) = A_{x+}^{(1)}e^{ik_{z1}z} + A_{x-}^{(1)}e^{-ik_{z1}z} \qquad H_y^{(1)}(z) = \frac{\omega\varepsilon_0\varepsilon_1}{k_{z1}}(A_{x+}^{(1)}e^{ik_{z1}z} - A_{x-}^{(1)}e^{-ik_{z1}z})$$

Medium 2

$$E_x^{(2)}(z) = A_{x+}^{(2)}e^{ik_{z2}z} + A_{x-}^{(2)}e^{-ik_{z2}z} \qquad H_y^{(2)}(z) = \frac{\omega\varepsilon_0\varepsilon_1}{k_{z2}}(A_{x+}^{(2)}e^{ik_{z2}z} - A_{x-}^{(2)}e^{-ik_{z2}z})$$

G

$$\begin{pmatrix}A_{x+}^{(1)}\\A_{x-}^{(1)}\end{pmatrix} = \frac{1}{2}\begin{pmatrix}1+\beta_1+\alpha_1 & 1-\beta_1+\alpha_1\\ 1-\beta_1-\alpha_1 & 1+\beta_1-\alpha_1\end{pmatrix}\begin{pmatrix}A_{x+}^{(2)}\\A_{x-}^{(2)}\end{pmatrix}$$

Propagation Matrix

P

$$\begin{pmatrix}A_{x+}^{(2)}\\A_{x-}^{(2)}\end{pmatrix} = \begin{pmatrix}e^{-ik_{z2}d} & 0\\ 0 & e^{ik_{z2}d}\end{pmatrix}\begin{pmatrix}A_{x+}^{(2b)}\\A_{x-}^{(2b)}\end{pmatrix}$$

(substitute into first matrix)

G P

$$\begin{pmatrix}A_{x+}^{(1)}\\A_{x-}^{(1)}\end{pmatrix} = \frac{1}{2}\begin{pmatrix}1+\beta_1+\alpha_1 & 1-\beta_1+\alpha_1\\ 1-\beta_1-\alpha_1 & 1+\beta_1-\alpha_1\end{pmatrix}\begin{pmatrix}e^{-ik_{z2}d} & 0\\ 0 & e^{ik_{z2}d}\end{pmatrix}\begin{pmatrix}A_{x+}^{(2b)}\\A_{x-}^{(2b)}\end{pmatrix}$$

Add second graphene…

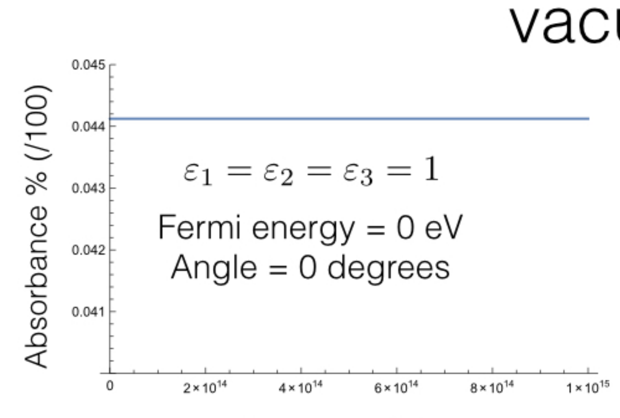
G P G

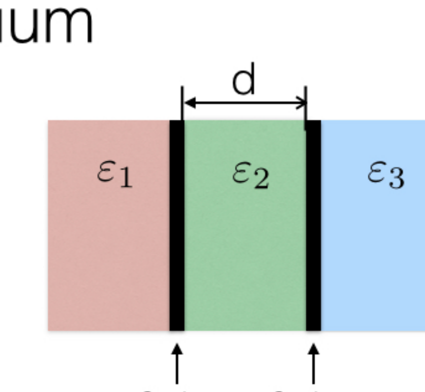
$$\begin{pmatrix}A_{x+}^{(1)}\\A_{x-}^{(1)}\end{pmatrix} = \frac{1}{2}\begin{pmatrix}1+\beta_1+\alpha_1 & 1-\beta_1+\alpha_1\\ 1-\beta_1-\alpha_1 & 1+\beta_1-\alpha_1\end{pmatrix}\begin{pmatrix}e^{-ik_{z2}d} & 0\\ 0 & e^{ik_{z2}d}\end{pmatrix}\frac{1}{2}\begin{pmatrix}1+\beta_2+\alpha_2 & 1-\beta_2+\alpha_2\\ 1-\beta_2-\alpha_2 & 1+\beta_2-\alpha_2\end{pmatrix}\begin{pmatrix}A_{x+}^{(2)}\\A_{x-}^{(2)}\end{pmatrix}$$

$$\begin{pmatrix}A_{x+}^{(1)}\\A_{x-}^{(1)}\end{pmatrix} = \begin{pmatrix}a & b\\ c & d\end{pmatrix}\begin{pmatrix}A_{x+}^{(2)}\\0\end{pmatrix} \qquad \frac{A_{x-}^{(1)}}{A_{x+}^{(1)}} = \rho = \frac{c}{a} \qquad \frac{A_{x+}^{(2)}}{A^{(1)}} = \tau = \frac{1}{a}$$

$$R = |\rho|^2 \qquad T = \frac{Z_1\cos\theta_3}{Z_3\cos\theta_1}\left|\frac{\cos\theta_1}{\cos\theta_3}\tau_{total}\right|$$

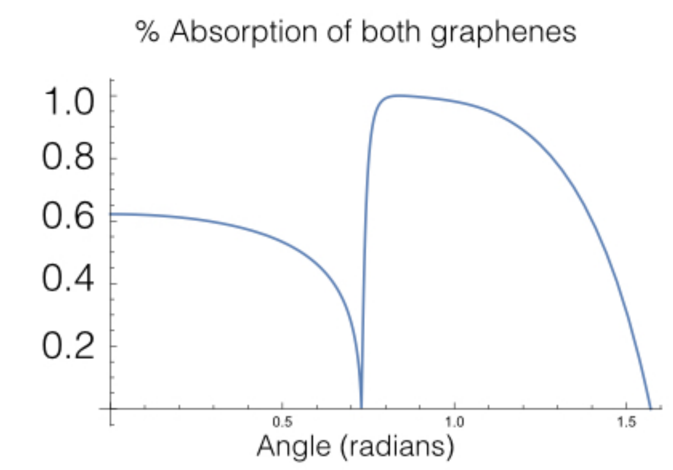
Bi-layer Graphene absorption in vacuum



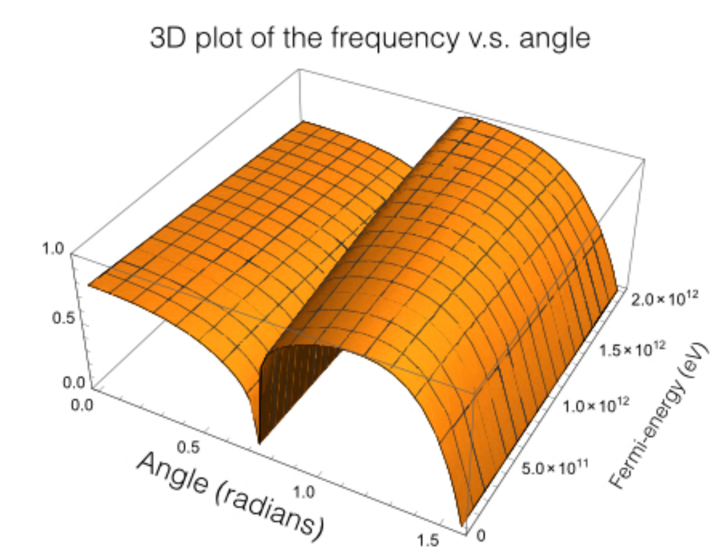


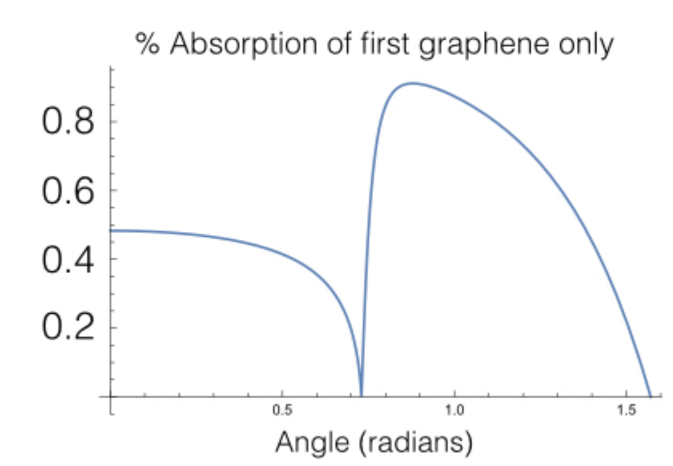
In a vacuum, the undoped bi-layer graphene system absorbs 4.4% of the EM wave, which is what we calculated with the transfer matrix method

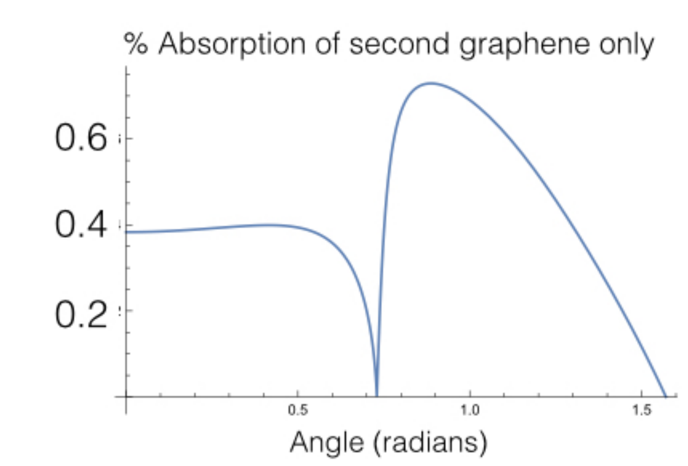
Results

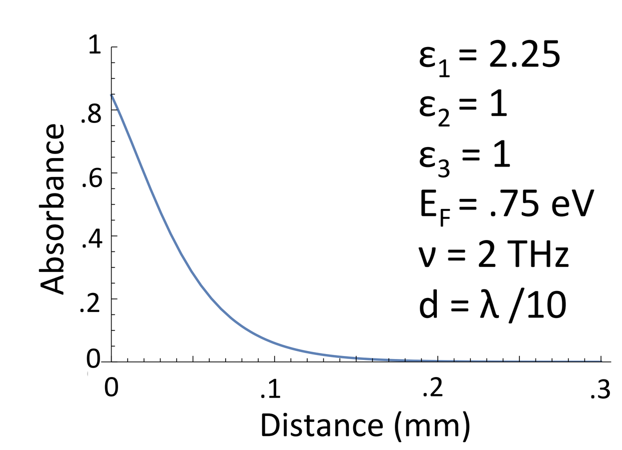


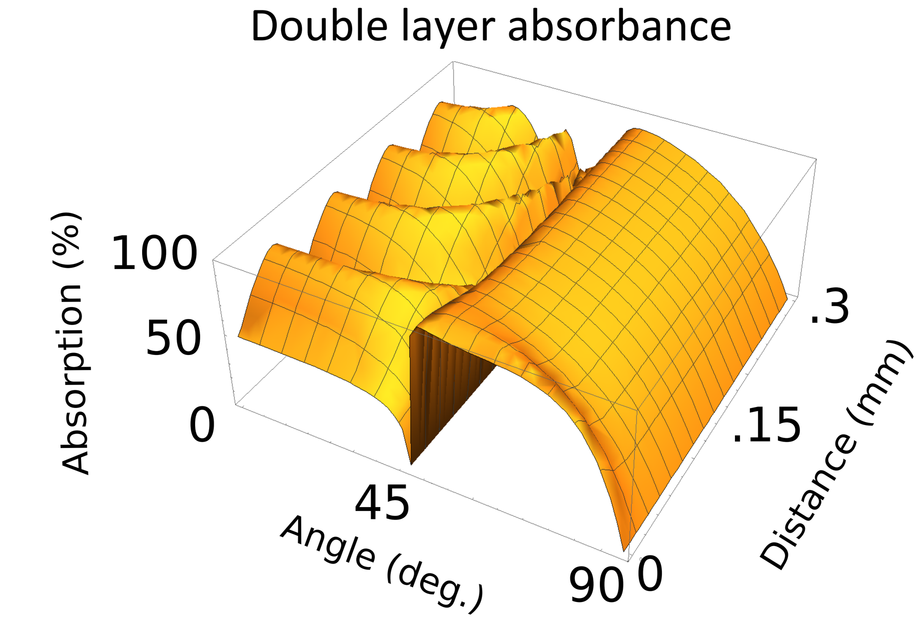
- Frequency = 2 THz
- d = .1 wavelength
- $\varepsilon_1 = 2.25$, $\varepsilon_2 = 1$, $\varepsilon_3 = 1$











Conclusion

- Single layer graphene system is very difficult to achieve 100% absorbance with because its properties are difficult to obtain experimentally
- Double layer graphene system is much easier to achieve 100% absorption with, and can be achieved with experimentally obtainable parameters.

Future Work