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Low –Terahertz Transmissivity and Broadband Planar Filters Using Graphene-Dielectric Stack

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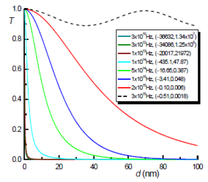
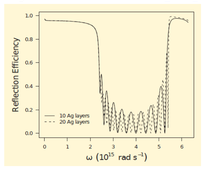
Background and Motivation

➢**Extremely thin** conducting layers are **almost opaque**

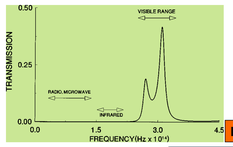




I. **R. Hooper et al.**, *Opt. Express*, 16, 17249 (2008)
II. **M. R. Gadsdon et al.**, *J. Opt. Soc. Am. B*, 26, 734 (2009)

➢**However**, multilayer metal-dielectric PBG-like structures **become transparent** within certain frequency bands in the optical regime

Microwave transmissivity of a metamaterial-dielectric stack



Can a similar effect be observed at microwaves??

Feng et al., *Phys. Rev. B.* , 82, 085117(2005)

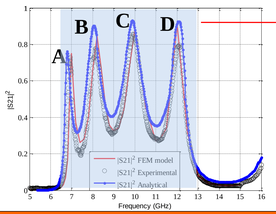
Scalora et al., *Jour. App. Physics* , 83, 2377–2383 (1998)

The metal films are substituted by perforated metal layers

Yakovlev et al., *3rd Int. Congress on Advan. Electromag. Materi. in Microwa. and Optic.*, (2009)

Butler et al., *Appl. Phys. Lett.*, 95, 174101 (2009)

Unit cell is much smaller than λ



Characteristic Band

What is the nature of these resonances ??
- can we tune them
- can we predict the band

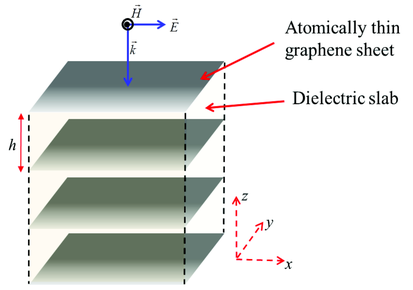
Kaipa et al., *Opt. Express.*, 18, 13309-13320 (2010)

Stacked metallic mesh **grids** have been accurately analyzed using **circuit models**

The number of transmission peaks is equal to the number of layers (resonators)

Statement of the Problem

We are interested in the analysis of the transmission features of the stack of monolayer graphene sheets separated by dielectric slabs at low-terahertz frequencies



Theory

Surface conductivity of graphene [Kubo formula]

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

Intraband contributions

$$\sigma_{\text{intra}} = -j\frac{e^2 k_B T}{\pi\hbar^2(\omega - j\Gamma)}\left(\frac{\mu_c}{k_B T} + 2\ln\left(e^{-\mu_c/k_B T}+1\right)\right)$$

Interband contributions

$$k_B T << |\mu_c|, \hbar\omega$$

$$\sigma_{\text{inter}} = \frac{-je^2}{4\pi\hbar}\ln\left(\frac{2|\mu_c| - (\omega - j\Gamma)\hbar}{2|\mu_c| + (\omega - j\Gamma)\hbar}\right)$$

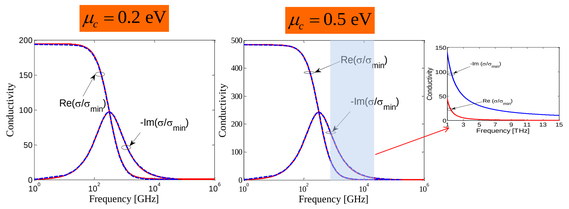
G. W. Hanson, *J. Appl. Phys.*, 103, 064302 (2008)

$-e$: **charge of electron**, T : **temperature**, ε: **energy**
ω: **angular frequency**, $\hbar = h/2\pi$: **reduced Planck's constant**
μ_c: **chemical potential**, Γ : **phenomenological scattering rate**

In the far-infrared regime, the contribution due to the interband electron transition is negligible

$Z_s = 1/\sigma$, which at low-terahertz frequencies behaves as a low-loss inductive surface

Surface Conductivity of Graphene



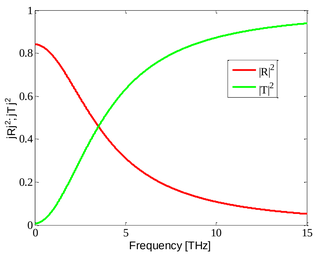
$\Gamma = 1/\tau = 1.32$ meV, $\tau = 0.5$ ps, $T = 300$ K

$\sigma_{\min} = \pi e^2/2h = 6.085\times10^{-5}$ S

Solid lines: approximate closed-form expressions (intraband + interband)
Dashed lines: numerical integration [Kubo formula]

Free-Standing Graphene

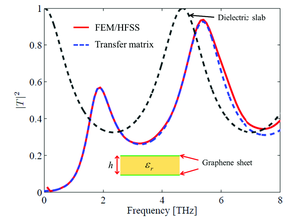
Reflectivity and Transmissivity for normal incidence



$\Gamma = 1/\tau = 1.32$ meV
$\tau = 0.5$ ps
$T = 300$ K
$\mu_c = 1$ eV

Single sheet of graphene is highly reflective at low-THz frequencies Behaves similar to an Inductive grid (metallic meshes) at microwaves

Two-sided Graphene Structure



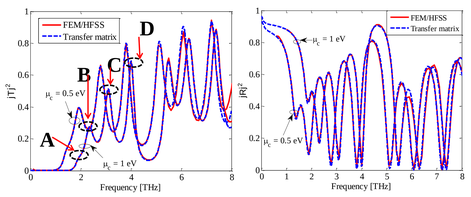
Thickness (*h*): 10 μm
Permittivity: 10.2

μ_c = 0.5 eV

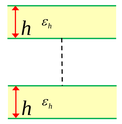
$\Gamma = 1/\tau = 1.32$ meV
$\tau = 0.5$ ps, T = 300 K

✓ **Transmission** resonance appears at low frequencies
✓ FP-type resonance of dielectric slab loaded with graphene sheets
✓ Graphene sheets effectively increase the electrical length

Power Transmission Spectra



4 layer graphene structure
- 4 dielectric slabs
- 5 graphene sheets

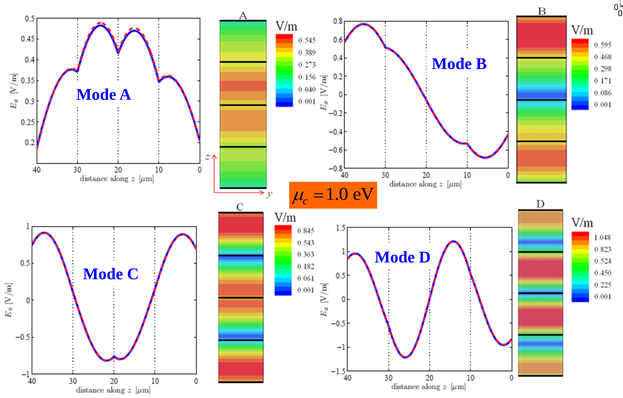


Thickness (*h*): 10 μm
Permittivity: 10.2

$\Gamma = 1/\tau = 1.32$ meV
$\tau = 0.5$ ps, T = 300 K

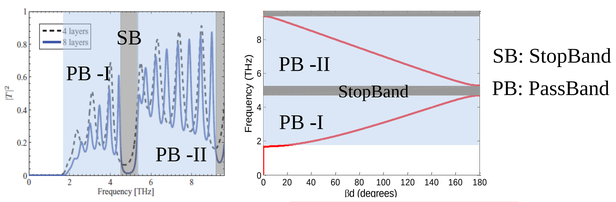
✓Enhanced transmission at low-THz
✓Fabry-Perot resonances of the individual open/coupled cavities

Electric Field Distributions



μ_c = 1.0 eV

Brillouin Diagrams – Passbands And Stopbands

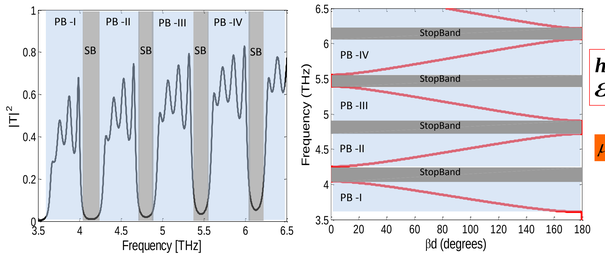


SB: StopBand
PB: PassBand

μ_c = 1.0 eV

Thickness (*h*): 10 μm
Permittivity: 10.2

Four-layer graphene-dielectric stack

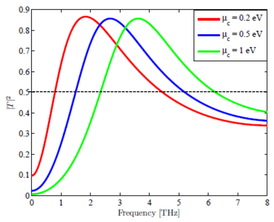


h: 150 μm
$\mathcal{E}_r$: 2.2

μ_c = 1.0 eV

✓ A thick dielectric slab is sometimes needed for mechanical handling
✓ Exhibits a series of bandpass regions separated by bandgaps

Broadband Planar Filters



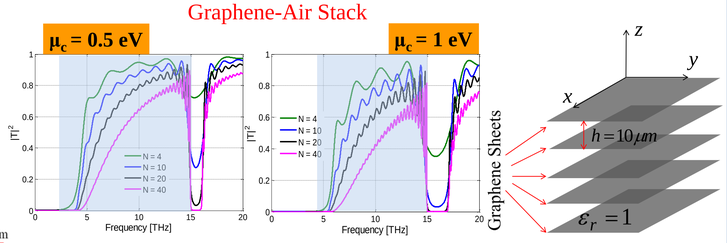
Thickness (*h*): 10 μm
Permittivity: 10.2

Dielectric slabs

μ_c (eV)	f_{LB} (THz)	f_{UB} (THz)	BW (THz)
1	2.33	6.24	3.91
0.5	1.49	5.20	3.71
0.2	0.78	4.44	3.66

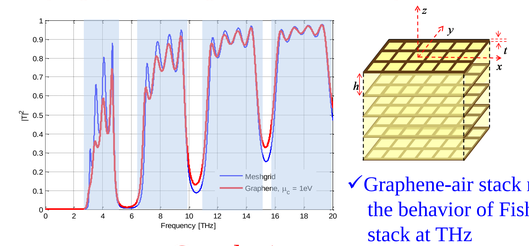
✓ Broadband transmission
✓ Can be tuned by varying the chemical potential

Graphene-Air Stack



- Number of peaks correspond to number of layers (N)
- With increase in 'N', all peaks lie in a characteristic frequency band
- Acts as a Wideband Bandpass filter

Five-layer graphene/meshgrid stacks separated by free-space



✓Graphene-air stack mimics the behavior of Fishnet-air stack at THz

Conclusion

- ❑ **We mimic the enhanced transmission at optical frequencies with a metal-dielectric stack and in the microwave regime with stacked-metascreens, at low-THz using stacked-graphene**
- ❑ **The range of frequencies where the peaks are expected for a finite graphene-dielectric stacked structure can be analytically and accurately estimated from the Bloch analysis**
- ❑ **Tunable structures can be designed using stacked graphene sheets**
- ❑ **Excess length concept has been successfully demonstrated**
- ❑ **Broadband planar filters have been realized using a stack of graphene sheets in free-space**