Low-Terahertz Transmissivity with a Graphene-Dielectric Micro-Structure

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OUTLINE

- Introduction and Motivation
- Graphene-Dielectric Stack
  - Enhanced Transmission at low-THz
  - Broadband Filters
  - Frequency of Enhanced Transmission (Excess Length Concept)
- Results and Discussions
- Conclusions
Induced transparency in the optical regime

- Extremely thin conducting layers are almost opaque.


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

Can a similar effect be observed at microwaves??

The metal films are substituted by perforated metal layers


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

**BACKGROUND AND MOTIVATION (3)**

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

Graphene-Dielectric Stack

- Atomically thin graphene sheet
- Dielectric slab

$h$
Surface conductivity of graphene [Kubo formula]

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

Intraband contributions

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

Interband contributions

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

- \(e\) : charge of electron, \(T\) : temperature, \(\varepsilon\) : energy
- \(\omega\) : angular frequency, \(\hbar = h/2\pi\) : reduced Planck’s constant
- \(\mu_c\) : chemical potential, \(\Gamma\) : 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.

G. W. Hanson, J. Appl. Phys., 103, 064302 (2008)
Surface Conductivity Graphene

$\mu_c = 0.2 \text{ eV}$

$\mu_c = 0.5 \text{ eV}$

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

$\sigma_{\text{min}} = \pi e^2 / 2h = 6.085 \times 10^{-5} \text{ S}$

Solid lines: approximate closed-form expressions (intraband + interband)
Dashed lines: numerical integration [Kubo formula]
Single sheet of graphene is highly reflective at low-THz frequencies. Behaves similar to an Inductive grid (metallic meshes) at microwaves.

\[ \Gamma = \frac{1}{\tau} = 1.32 \text{ meV} \]
\[ \tau = 0.5 \text{ ps} \]
\[ T = 300 \text{ K} \]
\[ \mu_c = 1 \text{ eV} \]
**TWO-SIDED GRAPHENE STRUCTURE**

- Transmission resonance appears at low frequencies
- FP-type resonance of dielectric slab loaded with graphene sheets

Graphene sheets effectively increase the electrical length

Thickness \((h)\): 10 \(\mu\text{m}\)
Permittivity: 10.2

\[
\Gamma = \frac{1}{\tau} = 1.32 \text{ meV}
\]
\[
\tau = 0.5 \text{ ps}, T = 300 \text{ K}
\]

\[
\mu_c = 0.5 \text{ eV}
\]
The number of transmission peaks is equal to the number of dielectric slabs within the characteristic frequency band.
Power Transmission Spectra

Enhanced transmission at low-THz

Fabry-Perot resonances of the individual open/coupled cavities

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

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

\(\Gamma = 1/\tau = 1.32 \meV\)
\(\tau = 0.5 \text{ ps}, T = 300 \text{ K}\)
1.0 eV

Electric Field Distributions

\( \mu_c = 1.0 \text{ eV} \)
ELECTRIC FIELD DISTRIBUTIONS-ANIMATION PLOTS

Mode B

Mode D
**BRILLOUIN DIAGRAMS – PASSBANDS AND STOPBANDS**

**Multi-layer graphene-dielectric stack**

- **StopBand (SB)**
- **PassBand (PB)**

\[ \mu_c = 1.0 \text{ eV} \]

**Thickness (h): 10 \text{ \textmu m}**

**Permittivity: 10.2**

SB: StopBand

PB: PassBand
Graphene Thick Slabs Brillouin Diagrams

Four-layer graphene-dielectric stack

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

\[ \mu_c = 1.0 \text{ eV} \]

SB: StopBand
PB: PassBand

Thickness \((h)\): 150 \(\mu\)m

Permittivity: 2.2
**Excess Length**

FP resonance of dielectric slab

- Substrate thickness: 20 μm
- Dielectric permittivity: 2.2
- \( \mu_c = 0.5 \text{ eV} \)

FP resonance due to the presence of Graphene sheets

<table>
<thead>
<tr>
<th>( h ) (in μm)</th>
<th>( f_T ) (Approx.)</th>
<th>( f_T ) (Calculated)</th>
</tr>
</thead>
<tbody>
<tr>
<td>20</td>
<td>≈ 2.15 THz</td>
<td>2.89 THz</td>
</tr>
<tr>
<td>40</td>
<td>≈ 1.50 THz</td>
<td>1.75 THz</td>
</tr>
<tr>
<td>60</td>
<td>≈ 1.16 THz</td>
<td>1.28 THz</td>
</tr>
<tr>
<td>80</td>
<td>≈ 0.95 THz</td>
<td>1.01 THz</td>
</tr>
<tr>
<td>100</td>
<td>≈ 0.8 THz</td>
<td>0.84 THz</td>
</tr>
</tbody>
</table>

Accurate when \( h > \Delta h \)

- For larger separation between the Graphene sheets, \( f_T \) calculated using the excess lengths gives pretty close results to the analytical results.

- \( L_G = 0.01699 \text{ nH} \)

\[ \Delta h = \frac{2cL_G}{\eta_0} \approx 27.04 \text{ μm} \]

\[ f_T = \frac{c}{2(\epsilon + \Delta h) \sqrt{\epsilon}} \approx 2.15 \text{ THz} \]
Broadband Planar Filters

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

<table>
<thead>
<tr>
<th>$\mu_c$ (eV)</th>
<th>$f_{LB}$ (THz)</th>
<th>$f_{UB}$ (THz)</th>
<th>BW (THz)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>2.33</td>
<td>6.24</td>
<td>3.91</td>
</tr>
<tr>
<td>0.5</td>
<td>1.49</td>
<td>5.20</td>
<td>3.71</td>
</tr>
<tr>
<td>0.2</td>
<td>0.78</td>
<td>4.44</td>
<td>3.66</td>
</tr>
</tbody>
</table>

Thickness ($h$): 10 μm
Permittivity: 10.2
**BROADBAND PLANAR FILTERS**

- 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

$\mu_c = 0.5 \text{ eV}$

$\mu_c = 1 \text{ eV}$
**BROADBAND PLANAR FILTERS**

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

- $\text{Height (} h \text{)} = 30 \, \mu\text{m}$,
- Period ($D$) = $20 \, \mu\text{m}$,
- Strip width ($w$) = $2 \, \mu\text{m}$,
- $t = 0.4 \, \mu\text{m}$,
- Dielectric permittivity: 1

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

- 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.