TERAHERTZ-RANGE APPLICATIONS OF NANOCARBON-BASED MATERIALS

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OUTLINE

1. Introduction
2. Surface plasmon in CNT and graphene
3. THz absorption peak
4. Metallization of doped CNTs
5. Screening effect in MWCNTs
6. Conclusion & Acknowledgments
What are current trends in electromagnetics?

- Miniaturization of electric circuits components ... 
- Energy consumption dropping ... 
  
  *electronic devices currently account for 15 percent of household*

- Opening up the THz & FIR frequency ranges
- Advanced EM materials...
- Cross-border and unconventional fields ... 

*Security and medical imaging*
On the way to HF integrated systems...

Carbon Nanotube Radio

Chris Rutherglen and Peter Burke

NANO LETTERS
2007
Vol. 7, No. 11
3296–3299

Proposal for all-graphene monolithic logic circuits

Jiahao Kang, Deblina Sarkar, Yasin Khatami, and Kaustav Banerjee

CNT interconnects
Nanocarbon in EM materials and macrodevices

data cable

http://constructivematerials.wordpress.com/

E-textile Conductors and Polymer Composites for Conformal Light-Weight Antennas

Yakup Bayram, Senior Member IEEE, Yijun Zhou, Student Member IEEE, Bong Sup Shim, Shimei Xu, Jian Zhu, Nick A. Kotov, and John L. Volakis, Fellow IEEE
Length: 0.1-10 mkm
Diameter: 1-2 nm
Conductivity type: metallic or semiconductor

\[ R_c = m a_1 + n a_2 \]

\((m, 0)\) - zigzag,
\((m, m)\) - armchair

<table>
<thead>
<tr>
<th>Property</th>
<th>Si</th>
<th>Cu</th>
<th>SWCNT</th>
<th>MWCNT</th>
</tr>
</thead>
<tbody>
<tr>
<td>Max current density (A/cm²)</td>
<td>-</td>
<td>10⁷</td>
<td>&gt;1x10⁹</td>
<td>&gt;1x10⁹</td>
</tr>
<tr>
<td>Melting point (K)</td>
<td>1687</td>
<td>1356</td>
<td>3800 (graphite)</td>
<td></td>
</tr>
<tr>
<td>Tensile strength (GPa)</td>
<td>7</td>
<td>0.22</td>
<td>22.2 ± 2.2</td>
<td>11-63</td>
</tr>
<tr>
<td>Mobility (cm²/V·s)</td>
<td>1400</td>
<td></td>
<td>&gt;10000</td>
<td></td>
</tr>
<tr>
<td>Thermal conductivity (x10⁳ W/m·K)</td>
<td>0.15</td>
<td>0.385</td>
<td>1.75-5.8</td>
<td>3.0</td>
</tr>
<tr>
<td>Temp. Coefficient of Resistance (10⁻³ /K)</td>
<td>-</td>
<td>4</td>
<td>&lt;1.1</td>
<td>-1.37</td>
</tr>
<tr>
<td>Mean free path (nm) @ room temp.</td>
<td>30</td>
<td>40</td>
<td>&gt;1,000</td>
<td>25,000</td>
</tr>
</tbody>
</table>

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UC SANTA BARBARA engineering

Kaustav Banerjee, UCSB
Finite-radius effect for a SWNT!

Radial dependence of the conductivity below and above the optical transitions band

\[ R_h = \frac{\sqrt{3}}{2\pi} d \sqrt{m^2 + mn + n^2} \]  
\[ d = 1.42\text{Å} \] is the interatomic distance in graphene

**Electrodynamics of carbon nanotubes: Dynamic conductivity, impedance boundary conditions, and surface wave propagation**

G. Ya. Słepian and S. A. Maksimenko  A. Lakhtakia  O. Yevtushenko  A. V. Gusakov

PHYSICAL REVIEW B  VOLUME 60, NUMBER 24  15 DECEMBER 1999-II
In optical range

\[ \lambda \gg b, \quad \lambda \gg R_{cn}, \quad b = 0.142 \text{ nm} \]

Solution of the conductivity problem accounting for the spatial confinement effects couples classical electrodynamics and physics of nanostructures.

Spatial dispersion parameter \( l_0 \sim 10^{-5} \) for metallic CNTs
Surface Wave in CNTs

The problem statement:
consider the propagation of surface waves along an isolated, infinitely long CNT in vacuum. The CNT conductivity is assumed to be axial. The investigated eigenwaves satisfy the Maxwell equations, EBCs and the radiation condition (absence of external field sources at the infinity)

The statement is analogous to the problem of macroscopic spiral slow-down systems for microwave range [L. Weinstein, Electromagnetic waves, 1988].

Dispersion equation of surface waves

\[ \frac{k^2}{\kappa^2} K_q(\kappa R) I_q(\kappa R) = \frac{ic}{4 \pi R \sigma_{zz}} \left( 1 - \frac{k^2 + k^2}{(\omega + i \tau)^2 c^2 l_0} \right). \]
Complex-valued slow-wave coefficient $b$ for a polar-symmetric surface wave.

\[
\beta = \frac{v_{ph}}{c} = \frac{k}{h} = \frac{k}{h' + ih''}
\]

1: $\text{Re}(\beta)$
2: $-\frac{\text{Re}(\beta)}{\text{Im}(\beta)}$

CN (9,0)

$|\text{Im}(\beta)| \ll \text{Re}(\beta)$

1 THz 100 THz

Axial component of the time-averaged Poynting vector

Surface wave!

Electrodynamics of carbon nanotubes: Dynamic conductivity, impedance boundary conditions, and surface wave propagation

G. Ya. Slepyan and S. A. Maksimenko  A. Lakhtakia  O. Yevtushenko  A. V. Gusakov

PHYSICAL REVIEW B  VOLUME 60, NUMBER 24 15 DECEMBER 1999-II
What Can We Learn from the Picture?

Carbon Nanotube as EM device (primarily in THz range):

- Electromagnetic slow-wave line: $\nu_{ph}/c \sim 0.02$
- Dispersionless surface wave nanowaveguide and high-quality interconnects (PRB 1999)
- Terahertz-range antenna (PRB 1999, PRB 2010, PRB 2012)
- Thermal antenna (PRL 2008)
- Monomolecular traveling wave tube (PRB 2009)
- Strong influencing the spontaneous decay rate (PRL 2002)
It is seen that the slowing down in a single-layer graphene is 3 to 5 times at the typical electron doping $\sim 10^{12} \, \text{cm}^{-2}$.

For the Čerenkov radiation by electrons with nonrelativistic electron energies, corresponding to the electron bands in graphene, a stronger deceleration is required (up to 300 times). Such slowing can be reached in bilayer and multilayer graphene structures. The tunneling between graphene layers can suppress the strong slowing effect in multilayer structures, therefore reducing the tunneling is extremely desirable.

The SPP wave phase velocity $v_{ph}/c$ vs the wave number in a single-layer graphene for the densities of the doping electrons

- (1) $1 \times 10^{12} \, \text{1/cm}^2$ and
- (2) $5 \times 10^{12} \, \text{1/cm}^2$
Axial surface conductivity of isolated single-wall carbon nanotube

\[
\sigma_{zz}(\omega) = -\frac{ie^2 \omega}{\pi^2 \hbar R} \left\{ \frac{1}{\omega(\omega + i/\tau_1)} \sum_{s=1}^{m} \int_{1stBZ} \frac{\partial E_c}{\partial p_z} \frac{\partial F_c}{\partial p_z} d\rho_z - 2 \sum_{s=1}^{m} \int_{1stBZ} |R_{cv}|^2 E_c \frac{F_c - F_v}{\hbar \omega(\omega + i/\tau_1) - 4E_c^2} d\rho_z \right\},
\]

Interband transitions

Drude regime for metallic SWCNT

axial CNT conductivity

semiconducting SWCNT

metallic SWCNT

\[\tau_1 = 2 \times 10^{-11} \text{s}\]
Experimental observations of THz peak in CNT-based composites

One can suppose that THz finite-length (antenna) resonances explain THz conductivity peak in CNT composites.


FIG. 3. (Color online) Temperature dependence of the optical conductivity of the two samples.

T. Kampfrath, phys. stat. sol. (b) 244, No. 11, 3950–3954 (2007)
Soft cutting of single-wall carbon nanotubes by low temperature ultrasonication in a mixture of sulfuric and nitric acids

Length and diameter distribution of bundles of H-SWCNTs for samples H0 and H3 before (a) and after (b) cutting

Raman spectra (633 nm excitation) for D and G modes for H-SWCNTs at different cutting times: 0 h (H0), 10 h (H1), 20 h (H2), 30 h (H3).
Experimental evidence of localized plasmon resonance in composite materials containing single-wall carbon nanotubes

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**THz peak: experiment**

Direct experimental demonstration of the correlation between the THz peak frequency and the SWCNT length. That is, the direct experimental evidence of the slowing down in CNTs and the FIR-THz antenna.
Experimental evidence of localized plasmon resonance in composite materials containing single-wall carbon nanotubes

Experimental proof of localized plasmon resonance was found in thin films containing either single-walled carbon nanotubes (SWNT) or SWNT bundles of different length. All samples were prepared by a simple technique.

Our result has been confirmed in *Nano Letters* 13, 5991 (2013):

Plasmonic Nature of the Terahertz Conductivity Peak in Single-Wall Carbon Nanotubes

Qi Zhang, † Erik H. Hároz, † Zehua Jin, † Lei Ren, † Xuan Wang, † Rolf S. Arvidson, ‡ Andreas Lütteg, ‡,§ and Junichiro Kono*, †,‖

samples. Our experimental results show that the broad THz peak originates from a plasmon resonance in both the metallic and the doped semiconducting carbon nanotubes rather than the interband excitation of the curvature-induced gap in nonarmchair metallic nanotubes. The intraband free electron
Substitutional doping of carbon nanotubes to control their electromagnetic characteristics

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Lomonosov Moscow State University, Leninskie Prospekt 47, 119991 Moscow, Russia

A. Lakhtakia

Metallization of semiconducting SWNTs caused by doping exclusively by either boron or nitrogen increases the axial polarizability, the antenna efficiency, and the intensity enhancement factor of SWNT bundles; likewise, the conductivity of SWNT-based...
Length Dependent Plasmon Resonance in Single-Walled Carbon Nanotubes

Takahiro Morimoto, Soon-Kil Joung, Takeshi Saito, Don N. Futaba, Kenji Hata, and Toshiya Okazaki

ACS Nano, 2014, 8 (10), pp 9897–9904

DOI: 10.1021/nn505430s • Publication Date (Web): 06 Oct 2014
• Due to the screening effect, the axial surface current reduces in magnitude for successive internal shells.

• The screening effect is stronger for shorter MWNTs.

• Screening effect is more pronounced when the electron relaxation time is larger. Indeed, the larger the relaxation time, the larger is the axial surface conductivity and the stronger is the screening effect.

The axial total field distribution on the surface of the p-th shell at different frequencies for a MWCNT of diameter 20 nm and length 10 μm. The incident electric field \( E_0 \) is aligned parallel to the z axis.
THZ frequency range

Anisotropic electromagnetic properties of polymer composites containing oriented multiwall carbon nanotubes in respect to terahertz polarizer applications

D. S. Bychanok,¹,a) M. V. Shuba,¹ P. P. Kuzhir,¹ S. A. Maksimenko,¹ V. V. Kubarev,² M. A. Kanygin,³ O. V. Sedelnikova,³ L. G. Bulusheva,³ and A. V. Okotrub³

FIG. 1. (a) SEM and (b) TEM images of MWCNTs used for composite preparation. (c) TEM image of MWCNTs extracted from composite by polystyrene dissolving.
Microwave absorption properties of pyrolytic carbon nanofilm

Polina P Kuzhir, Alesya G Paddubskaya, Sergey A Maksimenko, Tommi Kaplas, and Yuri Svirko

Pyrolytic carbon is amorphous material consisting of disordered and intertwined graphite flakes.

Optical microscope image of PyC thin film of 25-nm thickness deposited on silica substrate.

EM properties of the 25-nm-thick PyC in Ka band.
Microwave probing of PyC films

The thickest PyC films demonstrate significant EMI SE. Only 22, 18 and 16 % of microwave signal could penetrate through the PyC film with thickness of 75 nm, 110 nm and 241 nm, respectively, deposited on silica substrate.

TEM image of 75 nm thick PyC film.

Enhanced microwave shielding effectiveness of ultrathin pyrolytic carbon films

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1Research Institute for Nuclear Problems, Belarusian State University, Minsk 220030, Belarus
2Department of Physics and Mathematics, University of Eastern Finland, Joensuu FI-80101, Finland
Graphene-like thin films in microwaves

Graphene-like films being 100-1000 times thinner than skin depth provide reasonably high EM attenuation properties in microwave frequency range, caused by absorption mechanism.

EM absorption is as high as 50% for PyC film of 75 nm thickness and a few layers graphene, 1.5-2 nm thick.
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