Lecture II:

Electromagnetic Response of Carbon Nanostructures and Materials In Terahertz Range

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OUTLINE

1. ***Introduction:***
2. ***Electrodynamics of carbon nanotubes***
   2.1 Effective boundary conditions
   2.2 Slowing-down of surface wave in CNTs
   2.3 Experimental verification
   2.4 CNT as a traveling wave tube
3. ***Graphene***
4. ***Conclusion: Going to nanoscale***

2DSense
next about sensing

Current trend in applied electromagnetics: going to nanoscale

- **Miniaturization of electric circuits & components …**

  miniaturization is on the nanoscale: IBM Introduces the World's First 2-nm Node Chip

- **Energy consumption dropping …**

  VLSI and heat sink on a chip again leads us to necessity of the operational current dropping and nanoscale miniaturization

- **Opening up the THz frequency range for communication**

  Nanosized circuits' components, nanoscale integration, nanomaterials

- **Advanced EM materials**

  nanostructured composite materials, nanosized fillers

One of the basic trend in applied electromagnetics is exploiting ***NANO***:

- ***nanosized*** **circuits components design**
- ***nanoscale*** **level of integration on a chip**
- ***nanostructured*** **materials**

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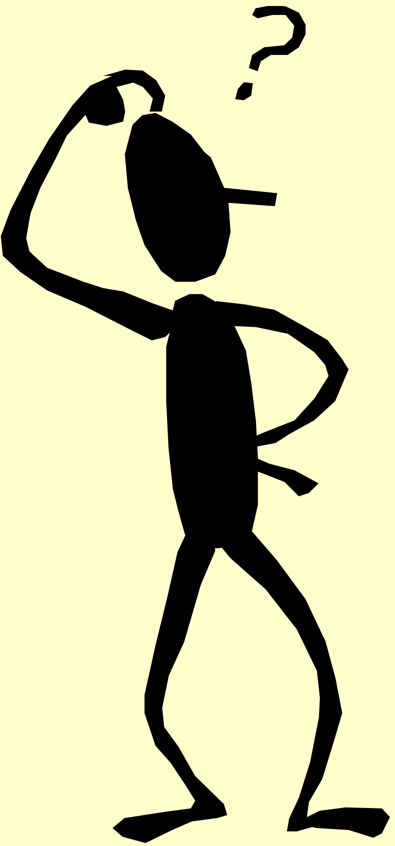
Factors of importance

Progress in nanoscience is dictated by the progress in

- **Synthesis of nanostructures**
- **Control and measurements technique**
- **Physical basis of novel devices and systems**
- **Reproducibility and recurrence of technological solutions**

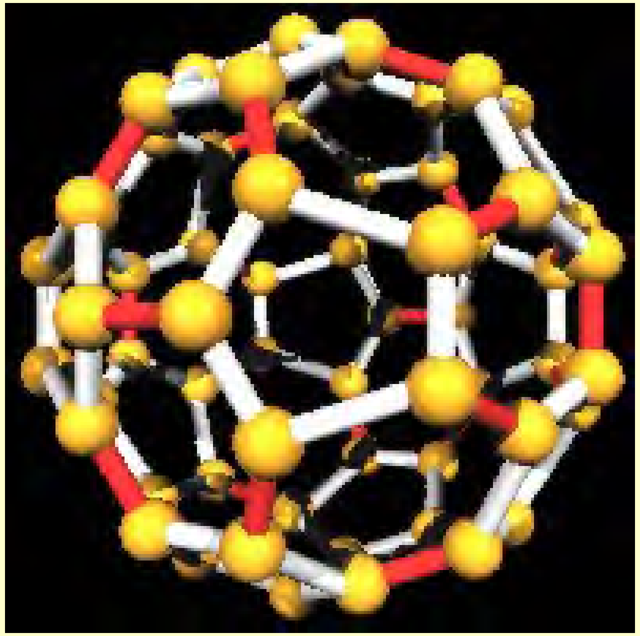
As different from the past, R&D in nanosci & nanotechn from the very beginning is oriented on the achieving of commercial result

General questions

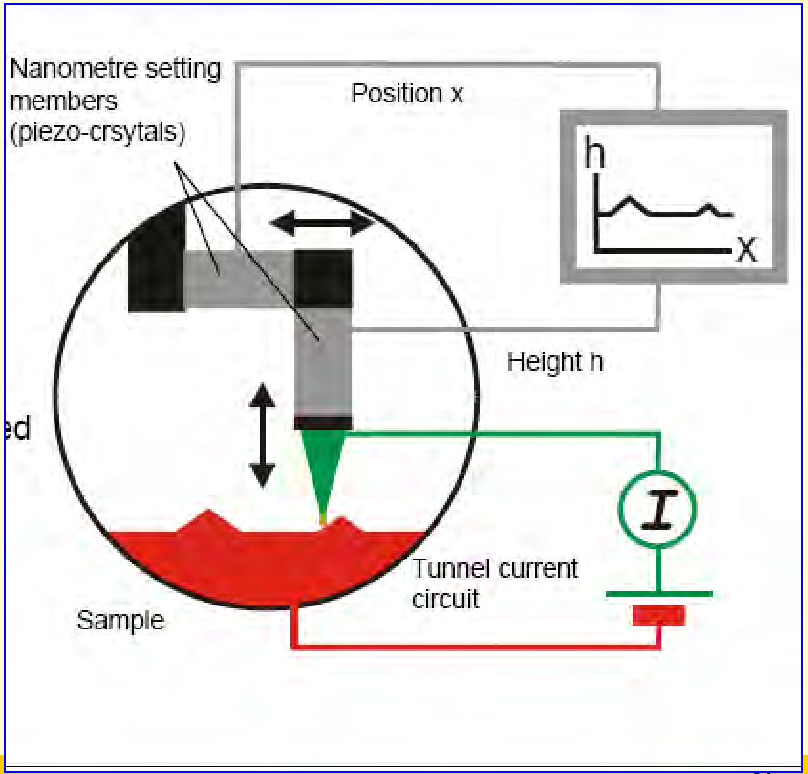


- How to synthesize and how to control synthesis?
- How to visualize and measure results?
- How to describe and predict properties?

Two breakthrough inventions



The first **fullerene molecule** C_{60}, was manufactured in 1985 by Richard Smalley, Robert Curl, James Heath, Sean O'Brien, and Harold Kroto at Rice University **The Nobel Prize in Chemistry 1996**



A **scanning tunnelling microscope** (**STM**) is an instrument for imaging surfaces at the atomic level. It was invented in 1981 by Gerd Binnig and Heinrich Rohrer (IBM Zürich). **The Nobel Prize in Physics in 1986**

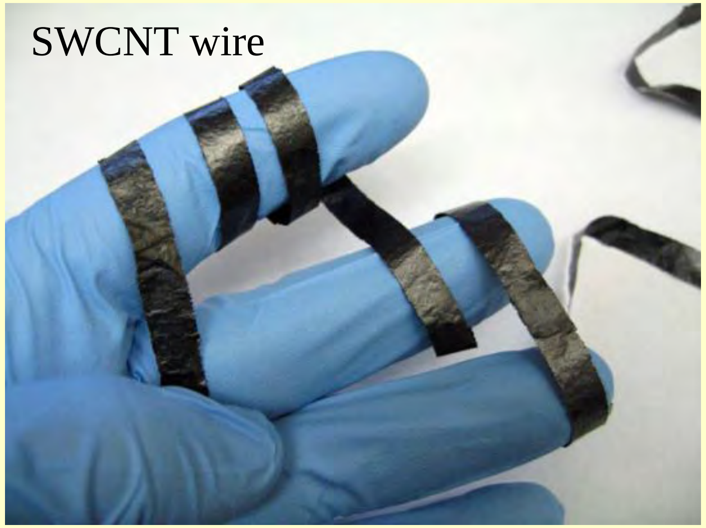
Nanocarbon in EM materials and macrodevices

The total harness mass is approximately 10% of that of the total spacecraft. The harness mass includes

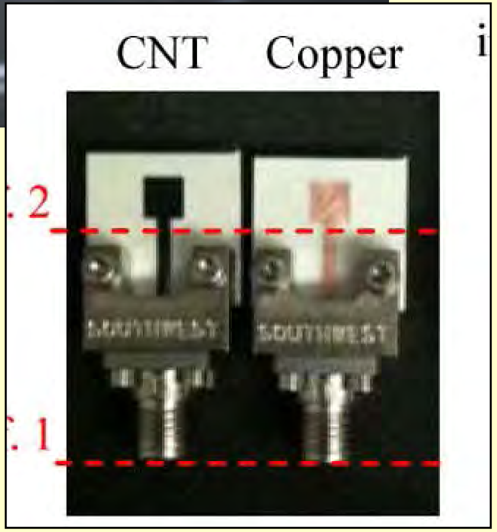
- the power distribution cables (~25%),
- data transfer cables (~55%),
- the mechanical fasteners and shielding (20%).

If the wire associated with the solar panel interconnects were included, the harness mass is even a larger percentage of the total spacecraft mass.

RIT - NanoPower Labs www.rit.edu

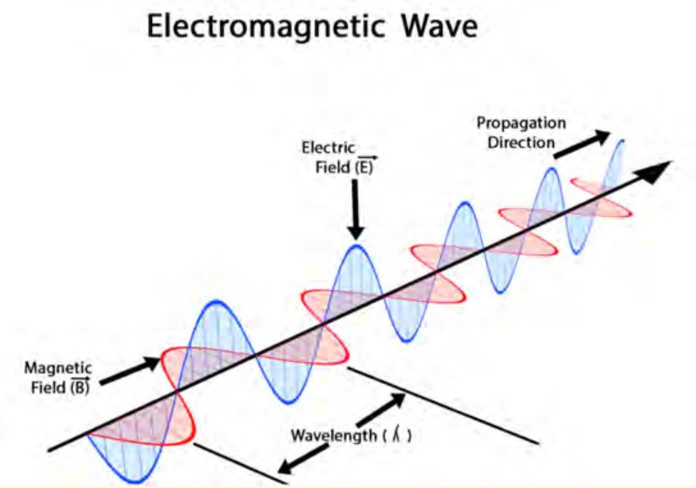


https://www.rit.edu/gis/research-centers/nanopower/rcn_5.html



Fabricated copper and CNT monopole antenna

Time to go to electrodynamics of nanocarbons



Self-consistent boundary – value problems: Schrödinger +Maxwell

Quantum Mechanics

$$i\hbar\frac{\partial}{\partial t}\left|\psi^i\right\rangle = \left[\mathcal{H}_0 - e\mathbf{r}\cdot\mathbf{E}'(\mathbf{r}_0,t)\right]\left|\psi^i\right\rangle$$

Statistical summation

$$\mathbf{P}(\mathbf{r}_0,t) = e\sum_i \left\langle\psi^i\left|\mathbf{r}\right|\psi^i\right\rangle\delta(\mathbf{r}_{0i}-\mathbf{r}_0)$$

Electrodynamics

$$\nabla\times[\nabla\times\mathbf{E}(\mathbf{r}_0,t)] + \frac{1}{c^2}\frac{\partial^2}{\partial t^2}\mathbf{E}(\mathbf{r}_0,t) = -\mu_0\frac{\partial^2}{\partial t^2}\mathbf{P}(\mathbf{r}_0,t)$$

Self-consistent field: $\mathbf{E}' = \mathbf{E}$

Approximate self-consistence

$$\mathbf{P}(\mathbf{r}_0,t) = \varepsilon_0\chi\mathbf{E}'(\mathbf{r}_0,t)$$

$$\mathbf{P} = \varepsilon_0\chi\mathbf{E}$$

In that case the only parameter coupling Maxwell and Schrödinger is the **surface current density**

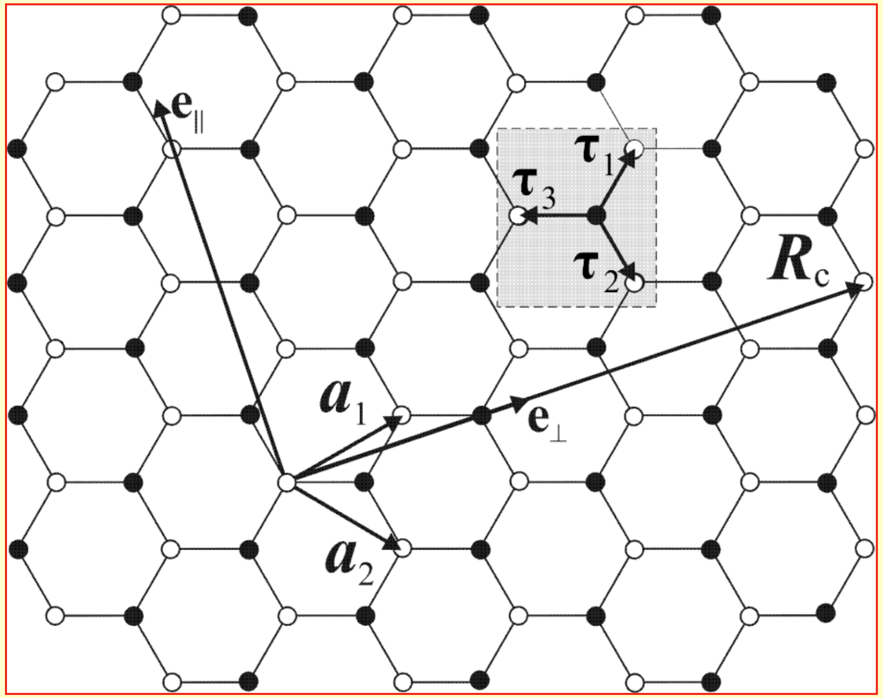
$$\boxed{H_{1t} - H_{2t} = J_s,}$$

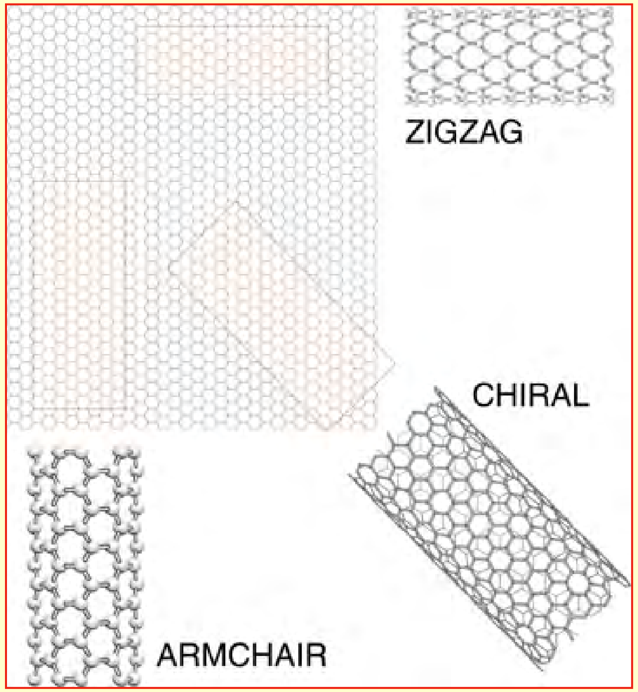
$$J \sim \sigma E$$

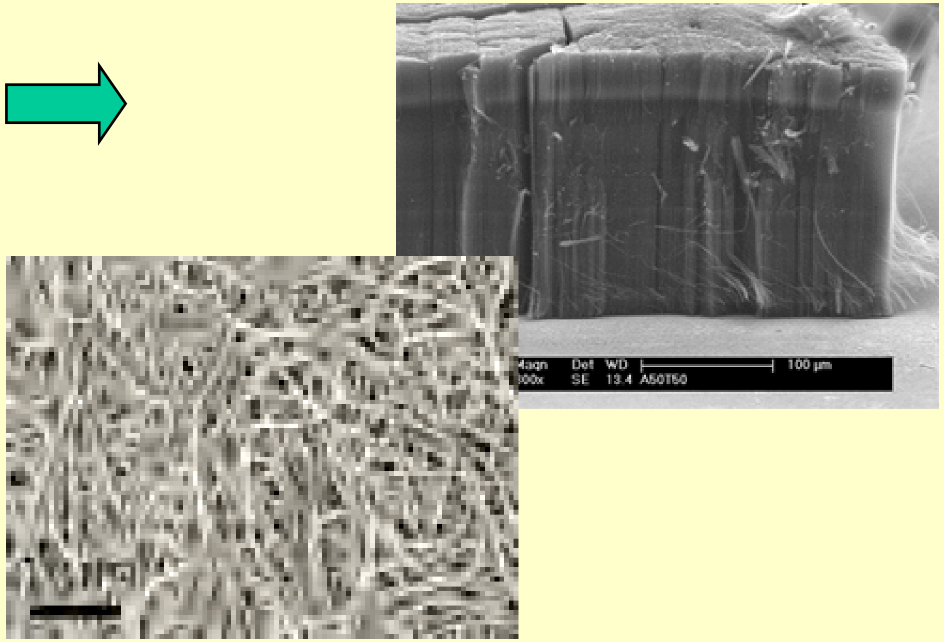
What is why the primary concern for us is

to reveal the conductivity law

Electrodynamics of carbon nanotubes



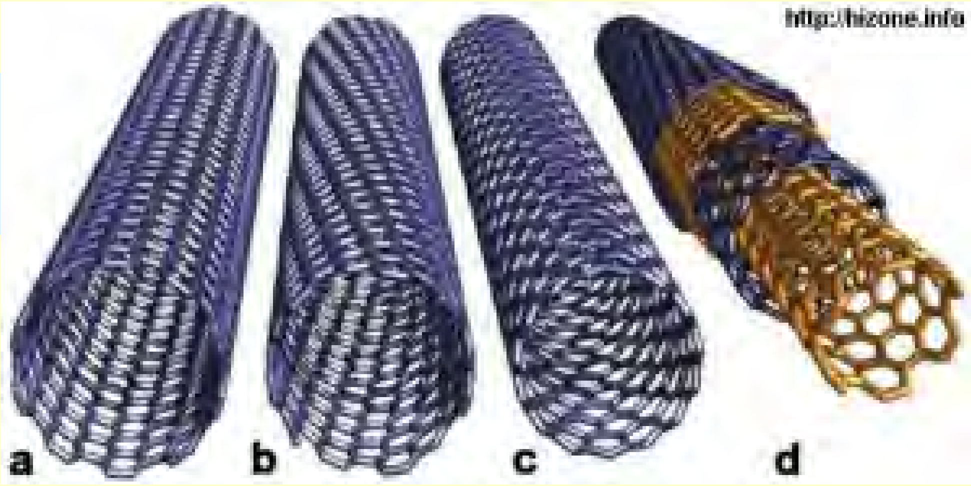




$R_c = m\boldsymbol{a}_1 + n\boldsymbol{a}_2$ SWCNT (m,n)

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

MWCNT forest



Length: 1-10 mkm
Diameter: 1-3 nm
Conductivity type: **metallic or semiconductor**

Graphene & CNTs:Physical properties

2DSense next about sensing

	Si	Cu	SWCNT	MWCNT	Graphene or GNR
Max current density (A/cm^2)	-	10^7	$>1\times10^9$ Radosavljevic, et al., *Phys. Rev. B*, 2001	$>1\times10^9$ Wei, et al., *Appl. Phys. Let.*, 2001	$>1\times10^8$ Novoselov, et al., *Science*, 2001
Melting point (K)	1687	1356	3800 (graphite)		
Tensile strength (GPa)	7	0.22	22.2 ± 2.2	11-63	
Mobility (cm^2/V-s)	1400		>10000		>10000
Thermal conductivity ($\times10^3$ W/m-K)	0.15	0.385	1.75-5.8 Hone, et al., *Phys. Rev. B*, 1999	3.0 Kim, et al., *Phys. Rev. Let.*, 2001	3.0-5.0 Balandin, et al., *Nano Let.*, 2008
Temp. Coefficient of Resistance (10^{-3} /K)	-	4	<1.1 Kane, et al., *Europhys. Lett.*, 1998	-1.37 Kwano et al., *Nano Lett.*, 2007	-1.47 Shao et al., *Appl. Phys. Lett.*, 2008
Mean free path (nm) @ room temp.	30	40	>1,000 McEuen, et al., *Trans. Nano.*, 2002	25,000 Li, et al., *Phys. Rev. Let.*, 2005	~1,000 Bolotin, et al., *Phys. Rev. Let.*, 2008

UC SANTA BARBARA engineering

Kaustav Banerjee, UCSB

Objects with such fascinate properties are certainly in the focus of interest for physicists, chemists and engineers

Table 1
Carbon nanotube properties.

doi: 10.1016/j.carbon.2018.02.005

Parameter	Room temperature value
Thermal conductivity	$\simeq$ 3500 W/m/K[a]
Density	$\simeq$ 1.3 g/cm^3[a]
Young's moduli	$\simeq$ 1.28 TPa[b]
Current density	$> 10^9$ A/cm^2[a]
Breaking strain	63 GPa[b]
Mobility	10000-50000 cm^{2}V^{-1}s^{-1}
Mean free path (ballistic transport)	300-700 nm (Semiconductor CNTs) 1000-3000 nm (Metallic CNTs)

[a] The data refers to the SWCNTs.
[b] The data refers to the MWCNTs.

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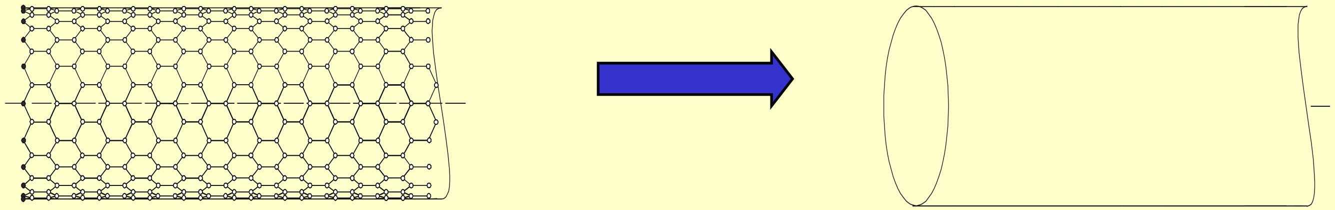
Effective boundary conditions

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

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



$$\lambda >> b, \quad \lambda >> R_{\text{cn}}, \quad b = 0.142\,\text{нм}$$

The basic idea of the EBC method is that a smooth homogeneous surface is considered instead of a periodic structure, and appropriate EBCs for the electromagnetic field are stated for this surface. These conditions are chosen in such a way that the spatial structures of the electromagnetic field due to an effective current induced on the homogeneous surface, and the electromagnetic field of the real current in the lattice turn out to be identical some distance away from the CNT surface.

Effective boundary conditions

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The EBCs are obtained as a result of the spatial averaging of macroscopic fields over a physically infinitesimal element of the cylindrical surface. The condition that the tangential electric field component and the axial component of the magnetic field be continuous on the CN surface yields

$$E_{\varphi,z}\big|_{\rho=R_{\rm CN}+0} - E_{\varphi,z}\big|_{\rho=R_{\rm CN}-0} = 0\,, \qquad H_{z}\big|_{\rho=R_{\rm CN}+0} - H_{z}\big|_{\rho=R_{\rm CN}-0} = 0\,.$$

The next condition follows from the equation for the CN axial conductivity [41, 42]. Its derivation utilizes the relation between the surface current density $j_z(\omega)$ and the discontinuity of the magnetic field component H_φ at the CN surface; i.e.,

$$H_{\varphi}\big|_{\rho=R_{\rm CN}+0} - H_{\varphi}\big|_{\rho=R_{\rm CN}-0} = \frac{4\pi}{c}\sigma_{zz}(\omega)E_z\big|_{\rho=R_{\rm CN}}\,,$$

where c is the speed of light in the vacuum.

We neglect here the spatial dispersion which is quite small for for metallic CNTs

$$D_{1n} - D_{2n} = \rho_v,$$

$$E_{1t} = E_{2t},$$

$$B_{1n} = B_{2n},$$

$$H_{1t} - H_{2t} = J_s,$$

Obtained as a solution of the rigorous quantum-mechanical (or semi-classical) model, axial conductivity in these boundary conditions couples Maxwell and Schrödinger

Dynamical conductivity of CNT

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Semi classical approximation:

The motion of p-electrons over the CNT surface is described in semiclassical approximation: dispersion law is taken from the quantum-mechanical model, while the motion of the ensemble is described by **the classical kinetic Boltzman equation** for the distribution function $f(\mathbf{p}, z, t)$:

nonlocality

$$\frac{\partial f}{\partial t} + eE_z \frac{\partial f}{\partial p_z} + \upsilon_z \frac{\partial f}{\partial z} = J(F(\mathbf{p}); f(\mathbf{p}, z, t))$$

$\upsilon_z = \partial\mathcal{E}(\mathbf{p})/\partial p_z$	is the π-electron velocity
$J(F, f)$	is the collision integral
$F(\mathbf{p}) = \left[1 + \exp\{\mathcal{E}(\mathbf{p})/k_B T\}\right]^{-1}$	is the Fermi equilibrium distribution function
Relaxation time approximation:	$J(F(\mathbf{p}), f(\mathbf{p}, z, t)) \cong \nu[F(\mathbf{p}) - f(\mathbf{p}, z, t)]$

$\nu = 1/\tau$ is the relaxation frequency. There are different estimates of the relaxation time. In our calculations we take $\tau = 3\times 10^{-13}$ sec.

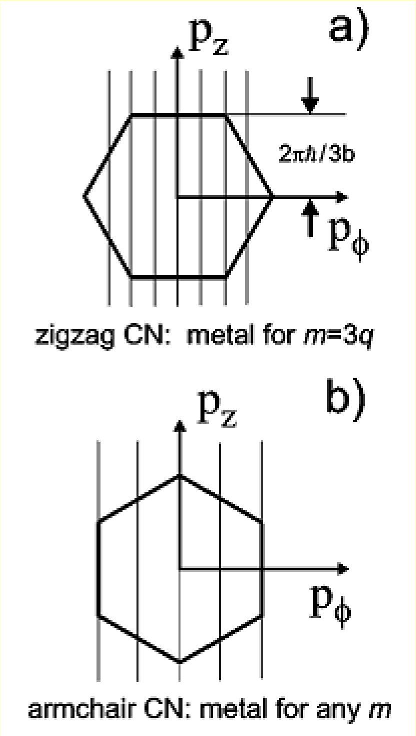
Semiclassical model accounts only for intraband motion and does not account for interband transitions. This restricts applicability of the model from above in frequency:

Dynamical conductivity of CNT

Radial dependence of the conductivity below the optical transitions band

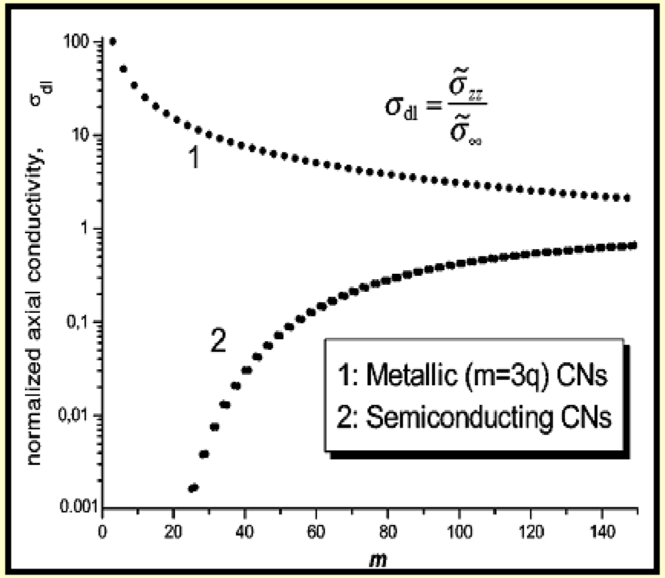
$$R_h = \frac{\sqrt{3}}{2\pi} d \sqrt{m^2 + mn + n^2}$$

d =1.42A is the interatomic distance in graphene

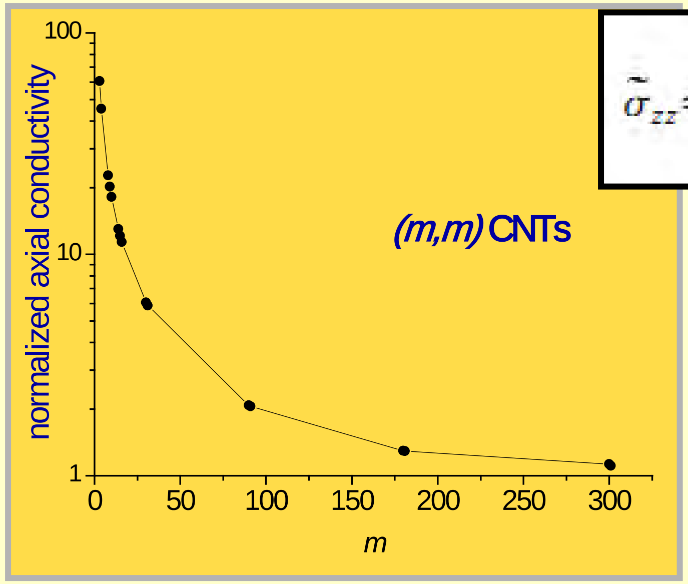


Configuration of the first Brillouin zone for zigzag and armchair CNT's.

zigzag



amchair



$$\tilde{\sigma}_{zz} \simeq i \frac{2\sqrt{3} e^2 \gamma_0}{m \pi \hbar^2 (\omega + i\nu)}, \qquad m = 3q,$$

metallic zigzag

$$\tilde{\sigma}_{zz} \simeq i \frac{2 e^2 \gamma_0}{m \pi \hbar^2 (\omega + i\nu)}$$

amchair

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The axial conductivity, based on quantum transport theory

$$\sigma_{zz}(\omega) = -\frac{ie^2\omega}{\pi^2\hbar R}\left\{\frac{1}{\omega(\omega+i\nu)}\sum_{s=1}^{m}\int_{1stBZ}\frac{\partial \mathrm{E}_c}{\partial p_z}\frac{\partial F_c}{\partial p_z}d\,p_z - 2\sum_{s=1}^{m}\int_{1stBZ}|R_{c\upsilon}|^2\,\mathrm{E}_c\frac{F_c - F_v}{\hbar^2\omega(\omega+i\nu)-4\mathrm{E}_c^2}dp_z\right\},$$

the equilibrium distribution function

$$F(\mathbf{p}) = \frac{1}{1+\exp\{\varepsilon(\mathbf{p})/K_B T\}}$$

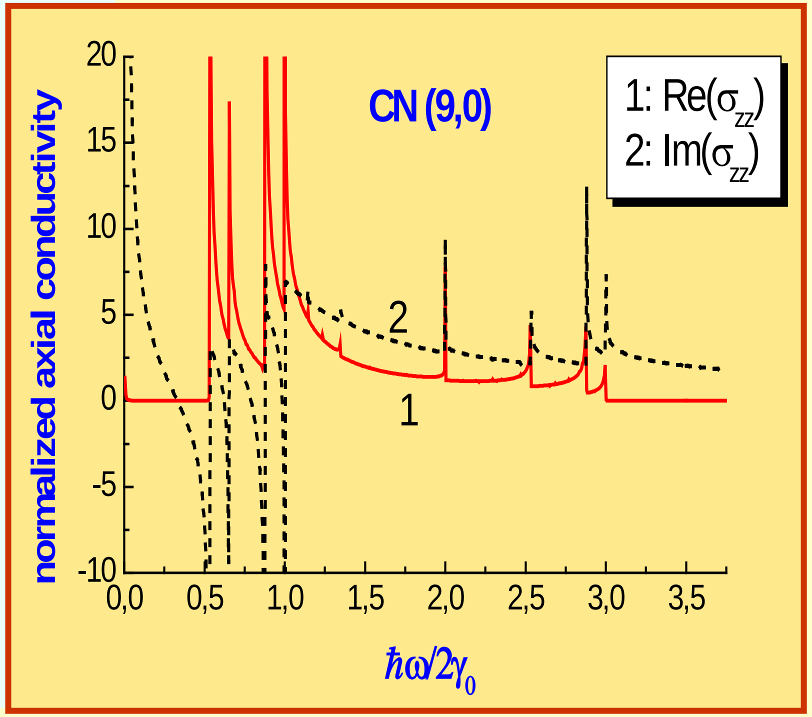
Normalized matrix elements of the dipole transition between conduction and valence bands

$$R_{c,\nu}(p_z,s) = -\frac{b\gamma_0^2}{2\mathrm{E}_{c,\nu}^2(p_z,s)}\left[1+\cos(ap_z)\cos\left(\frac{\pi s}{m}\right)-2\cos^2\left(\frac{\pi s}{m}\right)\right]$$

Electron energy for zigzag CNT **(**tight-binding approximation):

$$\mathrm{E}_{c,\nu}(p_z,s) = \pm\gamma_0\sqrt{1+4\cos(ap_z)\cos\left(\frac{\pi s}{m}\right)+4\cos^2\left(\frac{\pi s}{m}\right)}$$

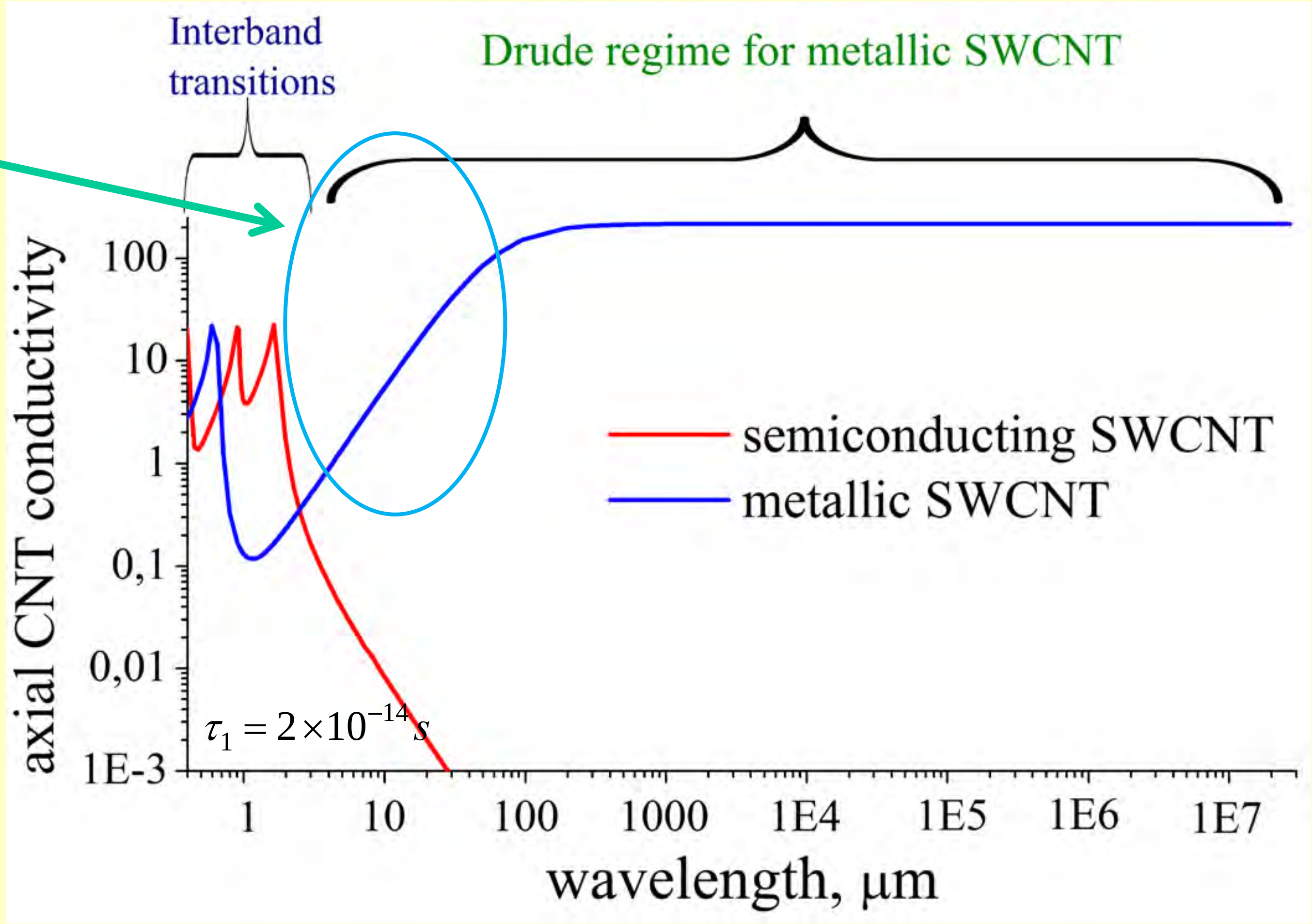
overlapping integral γ_0 =2.7 eV,   C-C bond length *b* =1.42 Å



Axial surface conductivity of isolated single-wall carbon nanotube

$$\sigma_{zz}(\omega) = -\frac{ie^2\omega}{\pi^2\hbar R}\left\{\frac{1}{\omega(\omega+i/\tau_1)}\sum_{s=1}^{m}\int_{1stBZ}\frac{\partial \mathrm{E}_c}{\partial p_z}\frac{\partial F_c}{\partial p_z}d\,p_z - 2\sum_{s=1}^{m}\int_{1stBZ}|R_{c\upsilon}|^2\,\mathrm{E}_c\frac{F_c-F_v}{\hbar^2\omega(\omega+i/\tau_1)-4\mathrm{E}_c^2}dp_z\right\},$$

THz range



Finite-length effects in CNTs

Length:	1-10 mkm
Diameter:	1-3 nm
Conductivity type:	metallic or semiconductor

At optical frequencies, the CNT's cross-sectional radius and the length satisfy the following conditions:

$$kR_{cn} << 1, \quad kl_{cn} \sim 1, \quad k = \omega / c = 2\pi / \lambda$$

Clearly, although the cross-sectional radius is electrically small, the length is electrically large - conditions that are characteristic of wire antennas. Thus, we can **suppose** that

an isolated metallic CNT is a wire nano-antenna at optical frequencies.

Is this statement true?

To make a correct conclusion is this statement true or not we should solve the scattering problem for an isolated CNT of a finite length. The key problem for the CNT electromagnetic response modeling is the evaluation of its conductivity low, what we did in Lecture I.

Hertz potential

Electric field strength can be defined in terms of the scalar and vector potentials

$$\mathbf{E} = -\nabla\phi - \frac{\partial \mathbf{A}}{\partial t}$$

let

$$\phi = -\nabla \cdot \mathbf{\Pi}_e$$

$$\mathbf{A} = \mu\epsilon \frac{\partial \mathbf{\Pi}_e}{\partial t}$$

$$\mathbf{E} = \nabla(\nabla \cdot \mathbf{\Pi}_e) - \mu\epsilon \frac{\partial^2 \mathbf{\Pi}_e}{\partial t^2}$$

$$\mathbf{B} = \mu\epsilon \frac{\partial}{\partial t}(\nabla \times \mathbf{\Pi}_e)$$

In k –space and letting μ=1

$$\int dt d\mathbf{r} e^{i\mathbf{kr} - i\omega t}$$

$$\mathbf{E} = \nabla(\nabla \cdot \mathbf{\Pi}_\varepsilon) + k^2 \mathbf{\Pi}_\varepsilon ;$$

$$\mathbf{H} = -ik\nabla \times \mathbf{\Pi}_\varepsilon .$$

<u>The problem statement:</u>

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].

Maxwell equations for the Hertz potential

$$\mathbf{E} = \nabla \frac{\partial \Pi_e}{\partial z} + k^2 \Pi_e \mathbf{u}_z, \quad \mathbf{H} = -ik(\nabla \Pi_e) \times \mathbf{u}_z$$

Electric Hertz vector has only the axial component and its z dependence is in the form of a traveling wave. Hence, it is represented by

$$\mathbf{\Pi}_\varepsilon = A\mathbf{e}_z \begin{Bmatrix} I_q(\kappa\rho)K_q(\kappa R) \\ I_q(\kappa R)K_q(\kappa\rho) \end{Bmatrix} e^{ihz} e^{iq\phi} \qquad \kappa = \sqrt{h^2 - k^2}$$

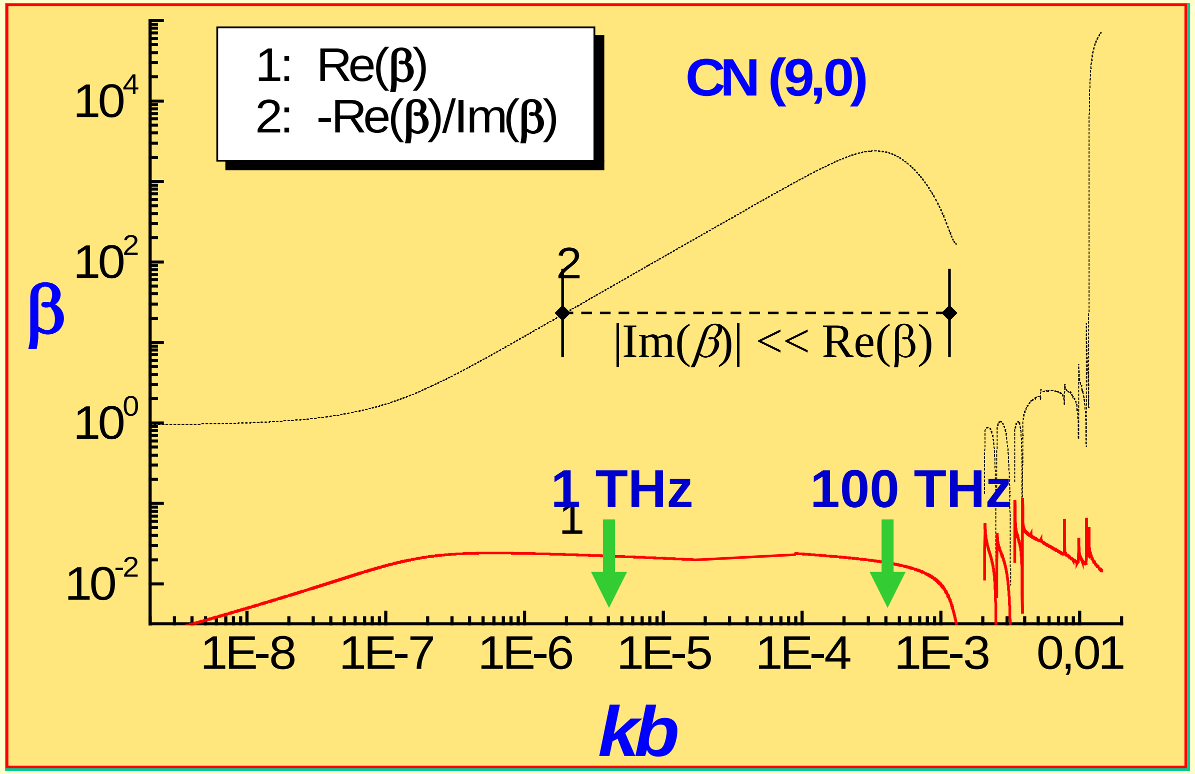
Dispersion equation of surface waves

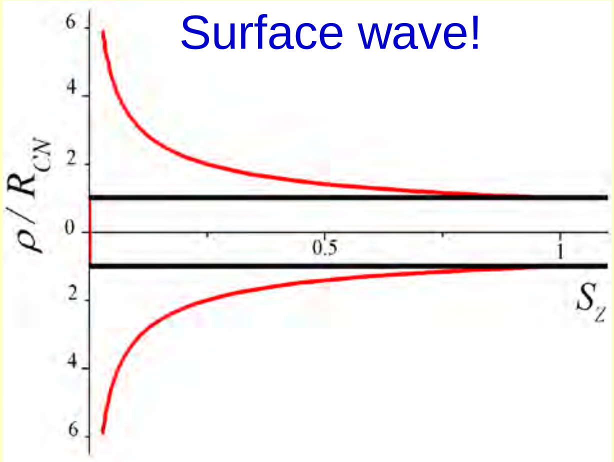
$$\boxed{\frac{\kappa^2}{k^2} K_q(\kappa R) I_q(\kappa R) = \frac{ic}{4\pi R \sigma_{zz}}}$$

Dispersion equation of surface waves

Complex-valued slow-wave coefficient β
for a polar-symmetric surface wave

$$\beta = \frac{k}{h} = \frac{k}{h' + ih''}; \quad \mathrm{Re}\,\beta = \frac{v_{ph}}{c}$$





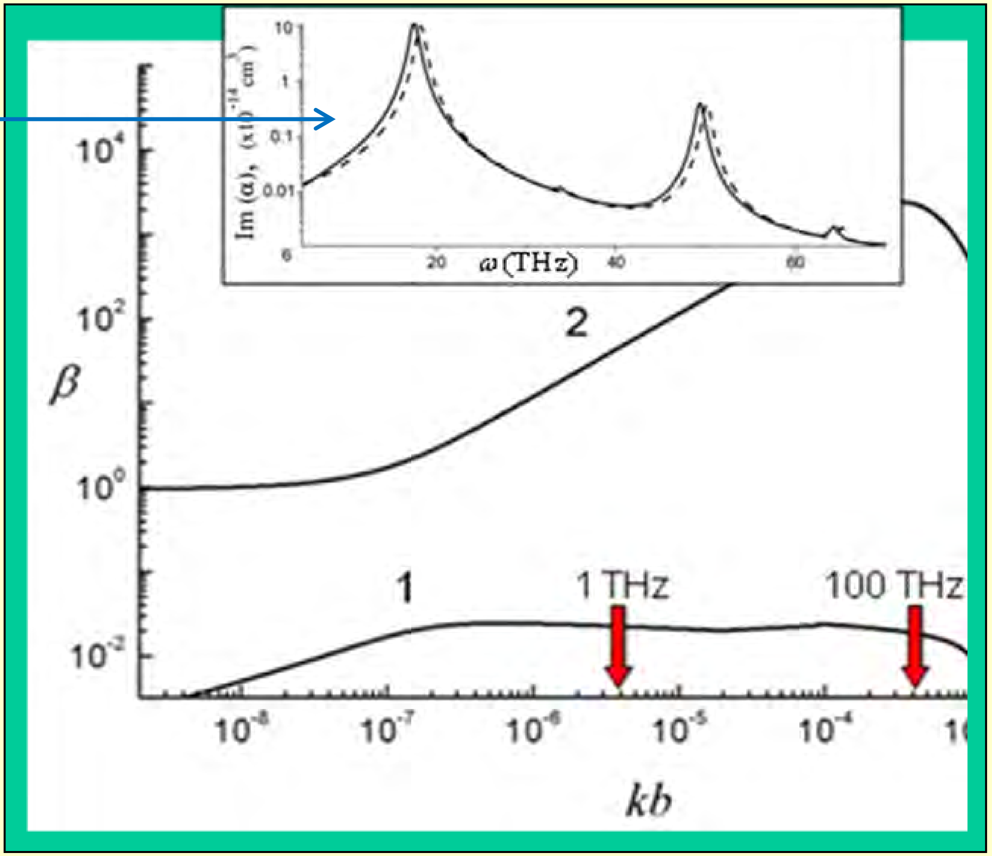
Axial component of the time-averaged Poynting vector

What Can We Learn from the Picture?

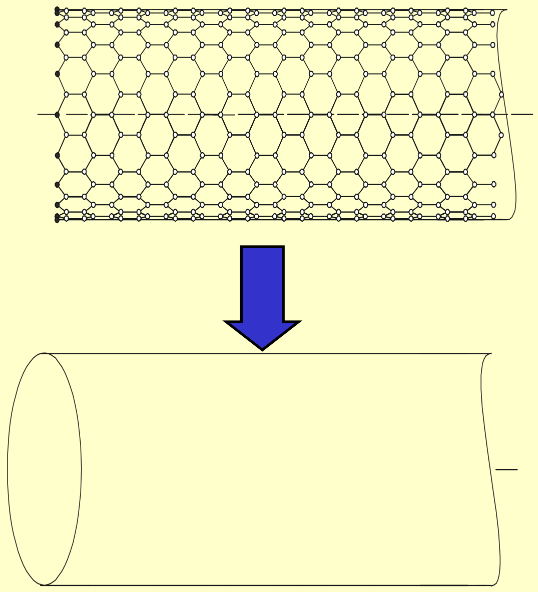
Carbon Nanotube as EM device (primarily in THz range):

- ✓ Electromagnetic slow-wave line: v_{ph}/c~0.02
- ✓ Dispersionless surface wave nanowaveguide and high-quality interconnects (PRB 1999)
- ✓ Terahertz-range antenna (PRB 1999,PRB 2006, PRB 2010, PRB2012)
- ✓ Thermal antenna (PRL 2008)
- ✓ Monomolecular traveling wave tube (PRB 2009)
- ✓ Strong influencing the spontaneous decay rate (PRL 2002)

Antenna resonances for 1 mkm CNT are in the THz range because the plasmon slowing



CNT Antenna Theory



PHYSICAL REVIEW B 73, 195416 (2006)

Theory of optical scattering by achiral carbon nanotubes and their potential as optical nanoantennas

G. Ya. Slepyan, M. V. Shuba, and S. A. Maksimenko A. Lakhtakia

Double-side effective boundary conditions for the Hertz potential

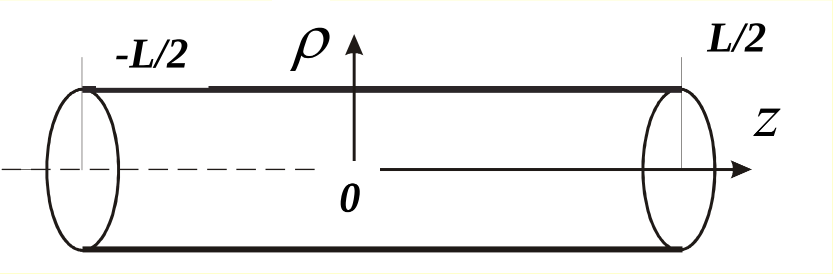
$$\left.\frac{\partial \Pi}{\partial \rho}\right|_{\rho=R+0} - \left.\frac{\partial \Pi}{\partial \rho}\right|_{\rho=R-0} = \frac{4\pi\sigma_{zz}}{ikc}\left(\frac{\partial^2 \Pi}{\partial z^2} + k^2\Pi + E_{0z}(z)\right) \quad \text{if} \quad |z| < L/2,$$

$$\left.\frac{\partial \Pi}{\partial \rho}\right|_{\rho=R+0} = \left.\frac{\partial \Pi}{\partial \rho}\right|_{\rho=R-0} \quad \text{if} \quad |z| > L/2,$$

$$\Pi\big|_{\rho=R+0} = \Pi_{\rho=R-0} \quad \text{if} \quad \infty < z < \infty,$$

radiation condition

$$\lim_{r\to\infty} r\left(\frac{\partial \Pi}{\partial r} + ik\Pi\right) = 0$$



Leontovich-Type Equation for the Current

$$\boxed{\left\{\frac{\partial^2}{\partial z^2}+\left(k^2-\cancel{\frac{i\omega}{2\pi\sigma_{zz}RX}}\right)\right\}j(z)=-\frac{i\omega}{2\pi RX}E_{0z}(z)+\frac{1}{X}\cancel{\left\{\frac{d^2}{dz^2}+k^2\right\}}V(z,j(z))}$$

$$p=R^{-1}\exp(X/2) \qquad X=-2K_0(\kappa R)I_0(\kappa R)$$

$\kappa=\sqrt{h^2-k^2}$ is complex-valued wavenumber emerging from the dispersion equation for azimuthally symmetrical surface waves

$$\frac{\kappa^2}{k^2}K_0(\kappa R)I_0(\kappa R)=\frac{ic}{4\pi R\sigma_{zz}}$$

I As $1/\sigma_{zz}\to 0$, equation is reduced to the Leontovich-Levin equation for perfectly conducting dipole antenna

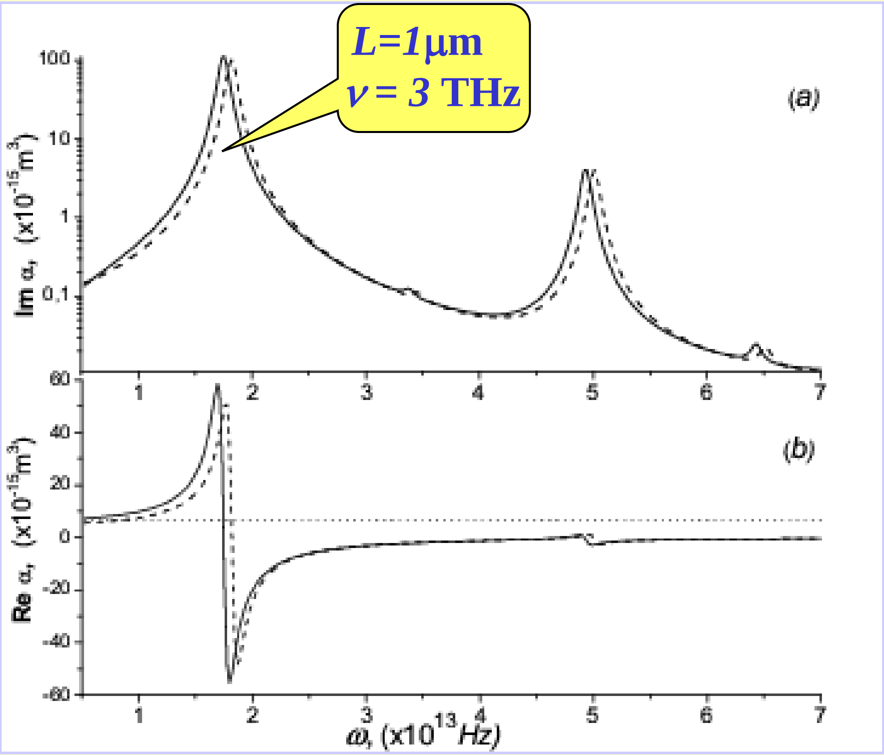
II Neglecting the role of incident field in the current distribution over the CNT, that is, assuming $1/X \ll 1$, we come to the non-self-consistent model of P. Burke, et al.

Phys.Rev. B 73, 195416, 2006

CNT as an antenna for the THz range

A vibrator antenna radiates effectively if its length equals to an integer number of halfwaves; for perfectly conducting wire it is $kL=\pi m$, $m=1,2,3\ldots$. Because of the large slow-wave effect, $h/k=c/v_{ph}=1/\beta\sim 50$, at optical lengths ~ 1 mkm the geometrical resonances $hL=\pi m$ are shifted to THz:

$$\mathrm{Re}\left(1/\beta\right)=\frac{c}{v_{ph}}\sim 50\div 100$$



An isolated metallic CNT is a wire nano-antenna at optical frequencies: is it true or not?

Now we see that the huge slowing down shifts antenna resonances into THz range

We need experiment!

Experimental observations of THz peak in CNT composites. Two hypothesises

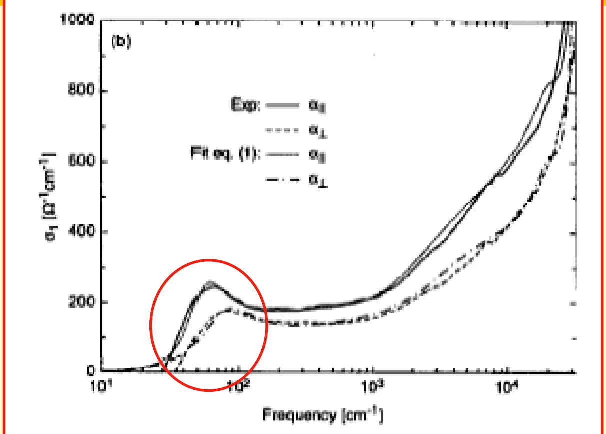


Fig. 1. (a) [redacted] (b) optical conductivity of oriented nanotubes films along the $\alpha_{\parallel}$ and $\alpha_{\perp}$ directions. The MG fits [Equation (1)] are also presented.

Bommeli F., et al. Synt. Met. **86,** 2307 (1997).

BORONDICS *et al.* Phys. Rev. B 74, 045431 (2006)

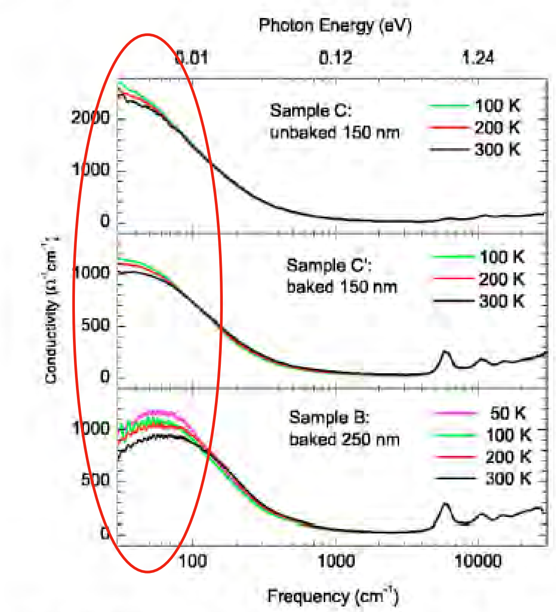
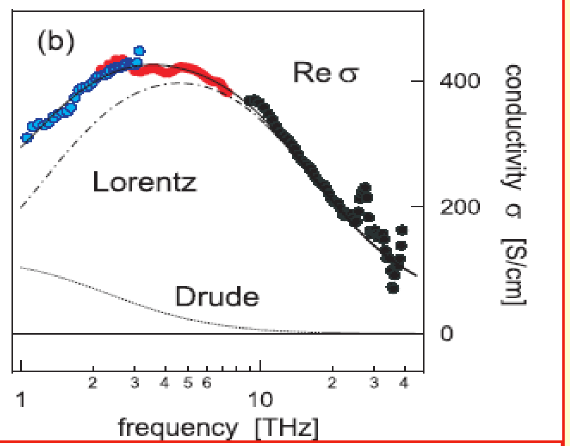


FIG. 3. (Color online) Temperature dependence of the optical conductivity of the two samples.

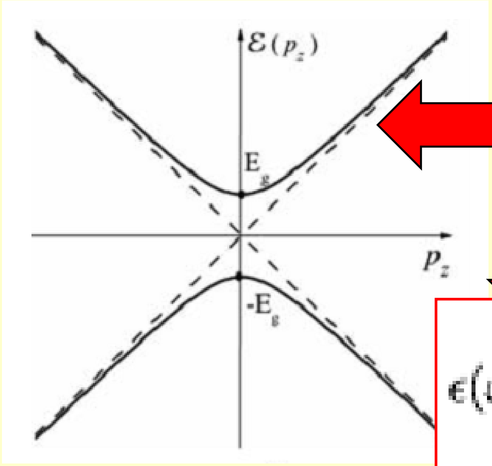
Finite-length hypothesis:
antenna resonances



(b) Real part of the conductivity together with the Drude and Lorentz contributions to the overall fit (solid line).

T. Kampfrath, phys. stat. sol. (b) 244, No. 11, 3950–3954 (2007)

26



Finite-radius hypothesis
A small gap in metallic CNTs due to curvature

$$\epsilon(\omega) = \frac{-\omega_p^2}{\omega^2 + i\Gamma\omega} + \sum_l \frac{\omega_{p,l}^2}{(\omega_l^2 - \omega^2) - i\Gamma_l\omega} + \epsilon_\infty,$$

THz peak: experiment

PHYSICAL REVIEW B **85**, 165435 (2012)

Experimental evidence of localized plasmon resonance in composite materials containing single-wall carbon nanotubes

M. V. Shuba, A. G. Paddubskaya, A. O. Plyushch, P. P. Kuzhir, G. Ya. Slepyan, and S. A. Maksimenko
Institute for Nuclear Problems, Belarus State University, Bobruiskaya 11, 220050 Minsk, Belarus

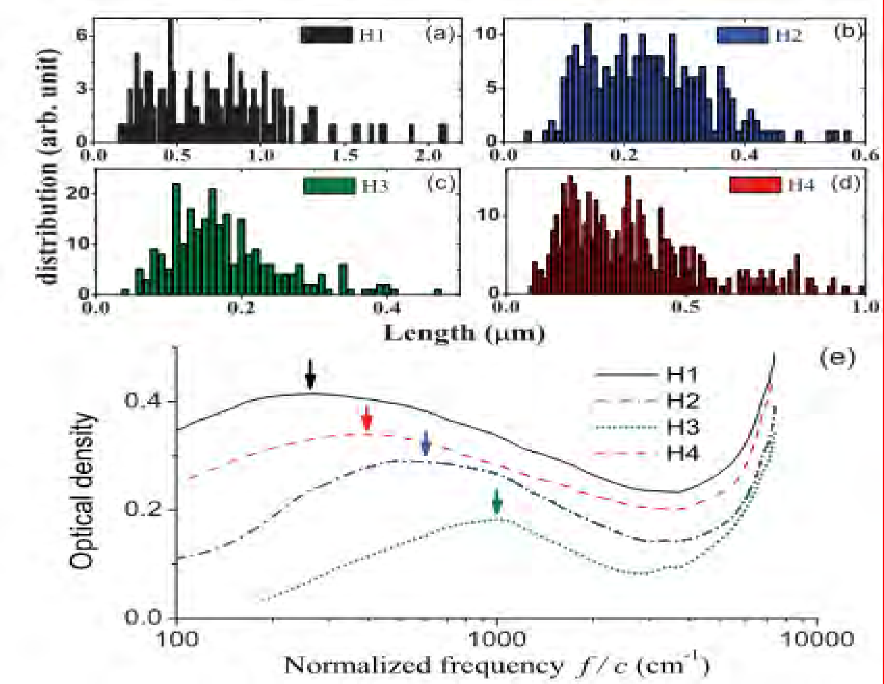
V. K. Ksenevich and P. Buka
Department of Physics, Belarus State University, Nezalezhnastsi Avenue 4, 220030 Minsk, Belarus

D. Seliuta, I. Kasalynas, J. Macutkevic, and G. Valusis
Center for Physical Sciences and Technology, A. Gostauto 11, LT-01108 Vilnius, Lithuania

C. Thomsen
Institut für Festkörperphusik, Technische Universität Berlin, Hardenbergstraße 36, D-10623 Berlin, Germany

A. Lakhtakia
Nanoengineered Metamaterials Group, Department of Engineering Science and Mechanics, Pennsylvania State University, University Park, Pennsylvania 16802-6812, USA

Thin SWNT films of thickness 100 – 500 nm were prepared by spraying the suspensions on heated silicon. To avoid agglomeration of SWNTs (formation of thick bundles) during film preparation we (i) prepared SWNT suspensions of low concentration (<10^−3 g/l), (ii) employed continuous powerful ultrasonic stirring of the suspensions during spraying, and (iii) heated silicon substrates to quickly evaporate the solvent.

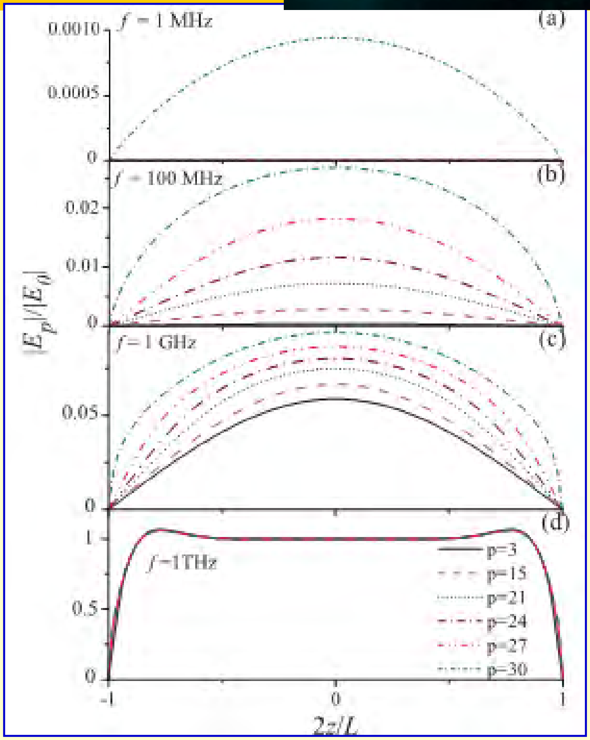


Direct experimental demonstration of the correlation between the THz peak frequency and the SWCNT length. That, is direct experimental evidence of the slowing down in CNTs and FIR-THz antenna

The first experimental observation of the CNT antenna effect!

Express method of the mean CNT length measurement!

New terahertz material with tunable electric properties!



Screening effect in MWCNTs

Novel functional materials for THz range.
Tunable at the origin by controlling:

- **Nanotube length**
- **Number of walls**
- **Doping**

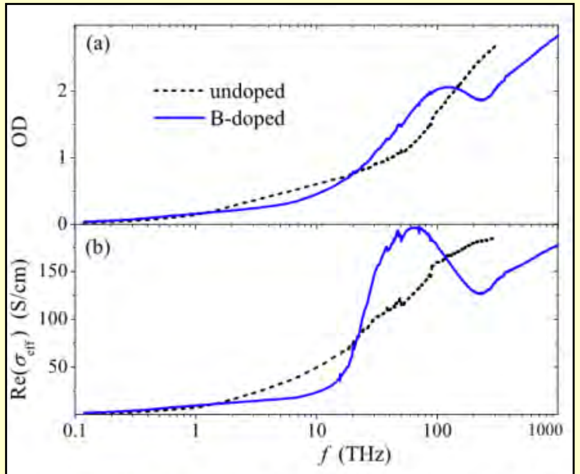
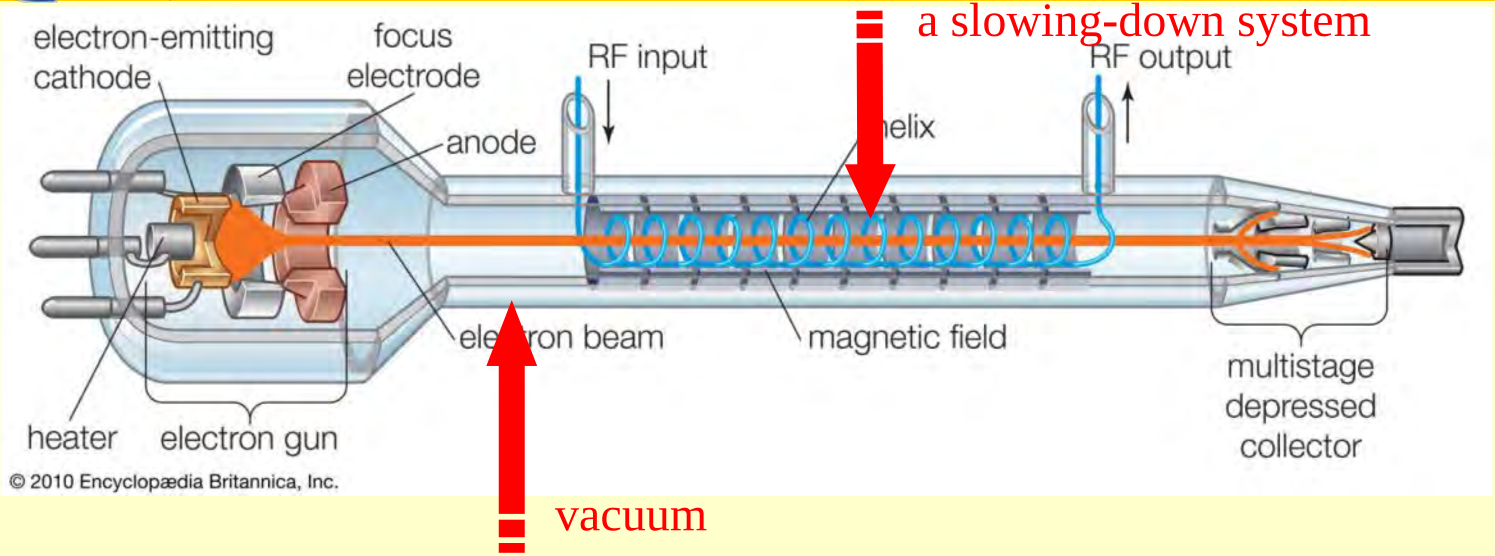


FIG. 2. (a) Optical density and (b) conductivity spectra of the films comprising undoped and B-doped CNTs.

Boron-doped MWCNTs have the average length of ≈300 nm and diameter of 10–30 nm.

Travelling-wave tubes



Can one provide the generation conditions on nanoscale?

- Ballisticity of electron motion on the proper distance
- Slowing down of EM wave to satisfy the synchronism condition with electron beam
- Large enough current density in a nanoobject

The Cherenkov radiation is governed by the synchronization condition $\omega-\mathbf{ku}=0$, where $\mathbf{k}$ is the wave vector and $\mathbf{u}$ is the electron velocity

Travelling-wave tubes:
R Kompfner
1952 *Rep. Prog. Phys.* **15** 275

- an electron gun,
- a focusing structure,
- a slowing-down system,
- an electron collector

The basis of generation in CNTs and graphene

2DSense
next about sensing

$$\mathrm{Re}\left(1/\beta\right) = \frac{c}{v_{ph}} \sim 50 \div 100$$

The possibility of strong slowing down of EM wave

- G.Ya. Slepyan, et al., Phys. Rev. B 60, 17136 (1999).
- M.V. Shuba et al., Phys. Rev. B 85 165435, 2012

Very large current density (up to 10^{10} A/cm^2)

- M. Radosavljevi´c, et al., Phys. Rev. B 64, 241307, 2001;
- S.-B. Lee, et al., J. Vac. Sci. Technol. B 20, 2773 (2002);

Ballistic electron transport (up to tens of μm)

- C. Berger, et al. J. Nanosci. Nanotechn., 3, 171 (2003);
- J. Baringhaus, et al., Nature 506, 349–354, 2014

	Si	Cu	SWCNT	
Max current density (A/cm^2)	-	10^7	$>1\times10^9$ Radosavljevic, et al., Phys. Rev. B, 2001	
Melting point (K)	1687	1356		38
Tensile strength (GPa)	7	0.22	22.2 ± 2.2	
Mobility (cm^2/V-s)	1400		>10000	
Thermal conductivity ($\times10^3$ W/m-K)	0.15	0.385	1.75-5.8 Hone, et al., Phys. Rev. B, 1999	
Temp. Coefficient of Resistance (10^{-3} /K)	-	4	<1.1 Kane, et al., Europhys. Lett., 1998	
Mean free path (nm) @ room temp.	30	40	>1,000 McEuen, et al., Trans. Nano., 2002	

UC SANTA BARBARA engineering   Kaustav Banerjee, UCSB

Threshold Current and Instability Increment

Radiation generation is already possible at the current stage of the nanotechnology development

PHYSICAL REVIEW B **79**, 125408 (2009)

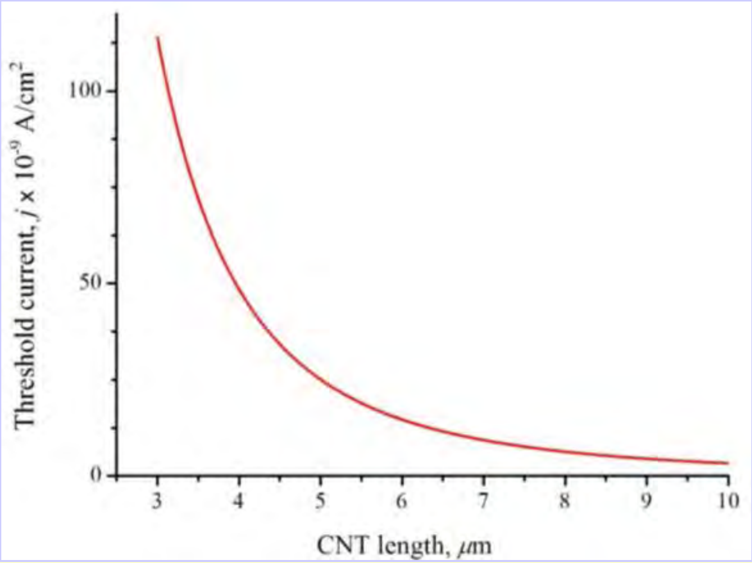
Carbon nanotube as a Cherenkov-type light emitter and free electron laser

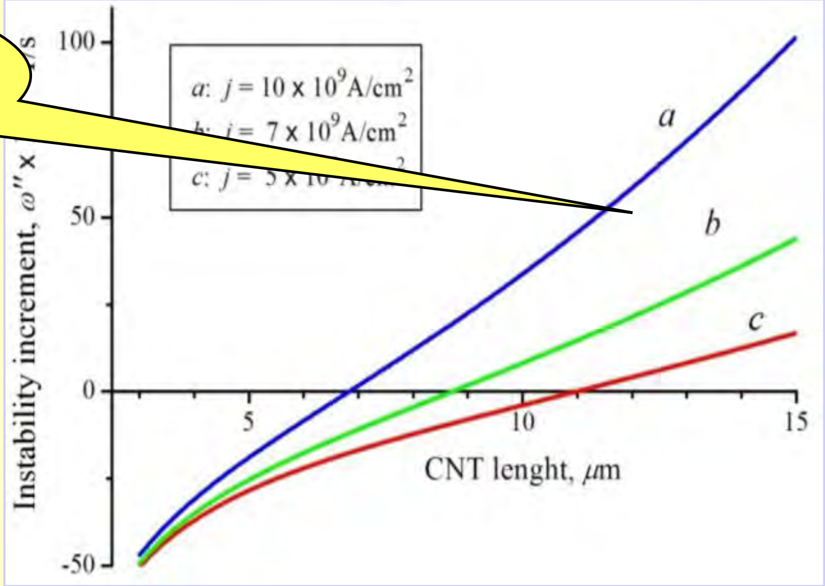
K. G. Batrakov, S. A. Maksimenko, and P. P. Kuzhir
Institute for Nuclear Problems, Belarus State University, Bobruiskaya 11, 220050 Minsk, Belarus

C. Thomsen

Gain per unit length increment is extremely large comparing with macrodevices

j=10^{10} A/cm^2
L=10 – 30 µm





It allows proposing CNTs as candidates for the development of nano-sized Chernekov-type emitters for THz range

Advantage of using MWCNTs or multi-layered graphene

Estimated wave retardation in a SWCNT reaches 50-100 times

- G. Slepyan et al, PRB 1999

In double-walled CNT:

For long wavelength, when λ>>*d* (*d* is the distance between CNTs), frequencies can be approximately written as:

$\omega_+ \sim \omega_1(R_1)+\omega_2(R_2)$ and $\omega_- \sim |\omega_1(R_1)-\omega_2(R_2)|$

Phase velocity corresponding to frequency ω_-, $v_{ph-} = \omega_- / k$, can be significantly less than the phase velocities in a single walled nanotube K.G. Batrakov, et al., Physica B, 405, 3050(2010),

However $\omega_1(R_1) \neq \omega_2(R_2)$, *therefore*
decreasing of phase velocity in two-walled CNT is limited.

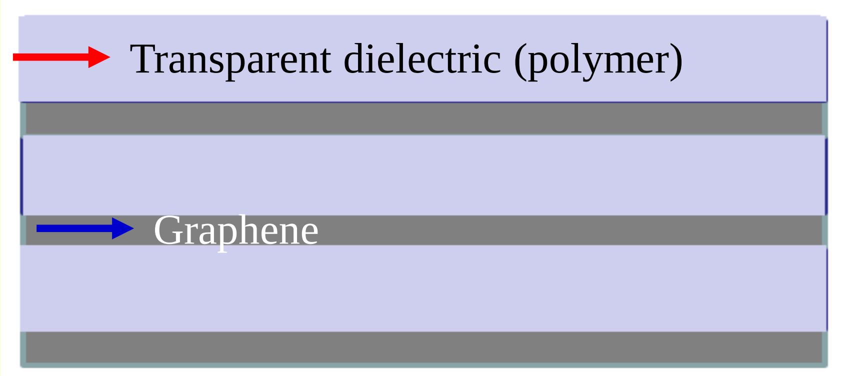
Does bilayer graphene show no such drawback?.....

Does bilayer graphene show no such drawback?.....

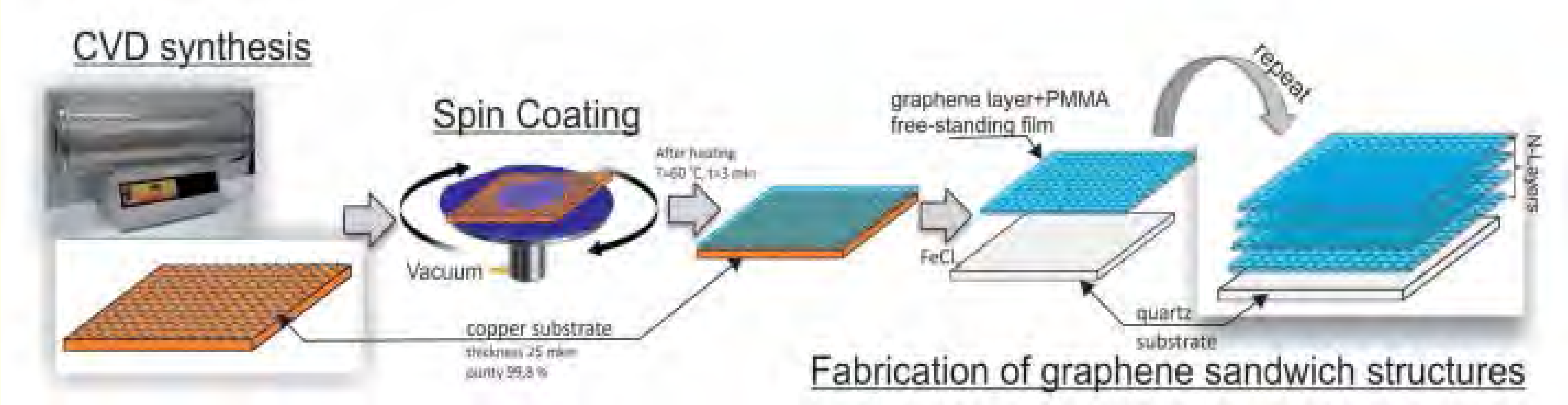
It turns out that the phase velocity in bilayer graphene exceeds phase velocity in graphene monolayer. Electron tunneling between graphene layers is guilty.

Tunneling should be suppressed.

It can be realized in spatially separated double-layer or multilayer graphene



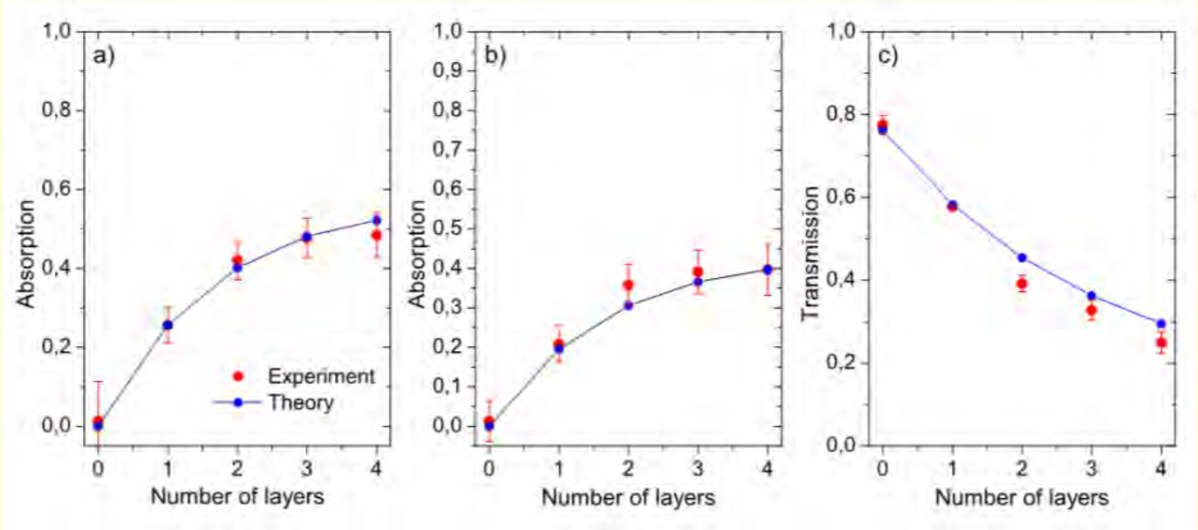
Fabrication of multi-layerd PMMA/Graphene structures



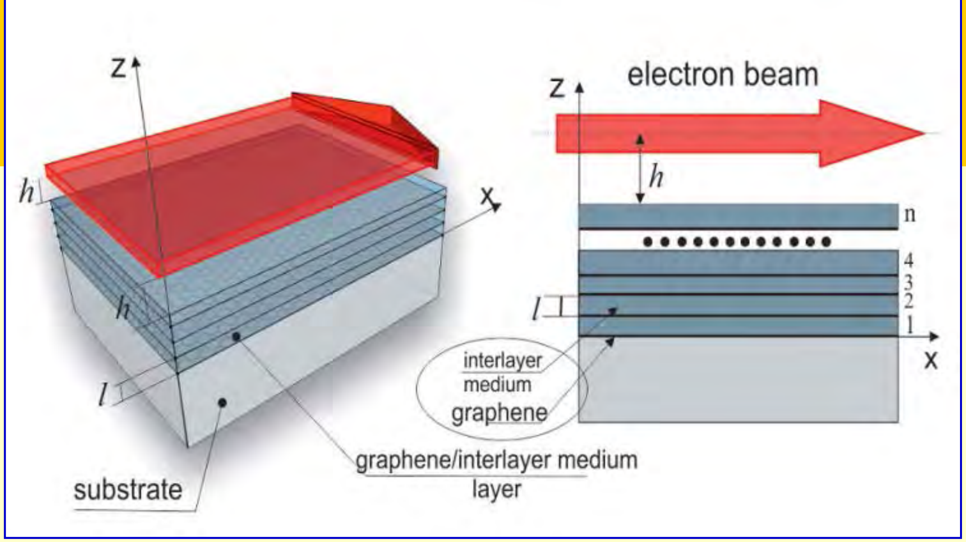
Schematic representation of graphene sandwich fabrication, consisting of a number of repeating steps, and final graphene/PMMA multilayer structure containing here four graphene sheets. The lateral dimensions of the samples are 7.2 mm * 3.4 mm for MW measurements and cycle sample with diameter 1 cm for THz measurements.

Minsk, INP

Science Report 2014



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



EM wave generation in a graphene/polymer sandwich

The problem statement

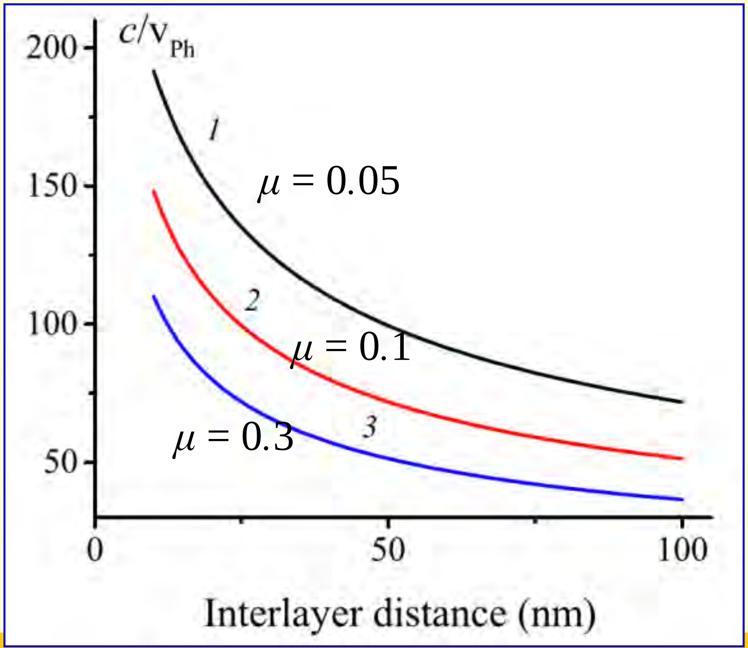
Consider an electron beam propagating along the *x* axis parallel to a multilayer graphene sandwich with graphene sheets separated by layers of a medium with a dielectric functions ε.

Let us examine the propagation of surface waves along the sandwich in free space, assuming the distances between the graphene layers to be large enough to neglect electron interlayer tunneling.

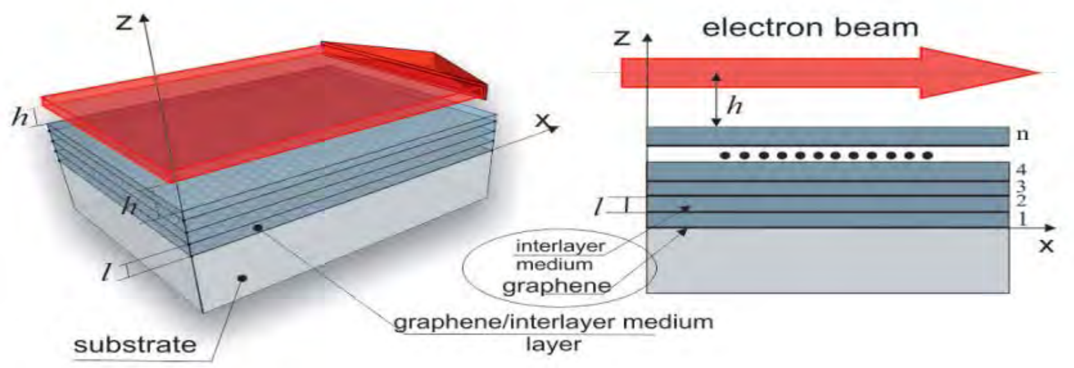
The eigenwaves under study satisfy the Maxwell equations, the boundary conditions at the graphene surfaces in each layer, and the condition that there are no exterior current sources at infinity.

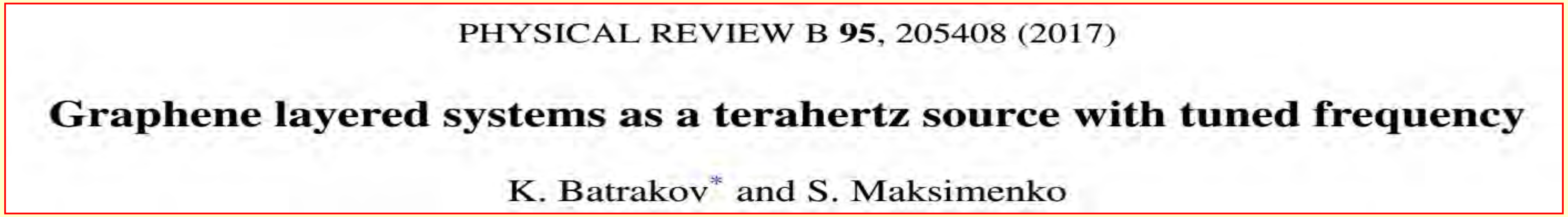
The advantage achieved by graphene doubling is the appearance of an acoustic mode among the plasmon oscillations inherent in the system. This mode's frequency is proportional to the difference in frequencies of the plasmonic oscillations in the layers.

As a result, the phase velocity of this wave appears to be much less than that achievable in monolayers. Owing to such a large slowing down, one can meet Cherenkov synchronism even for graphene π electrons whose velocity is ≈300 less than the speed of light.



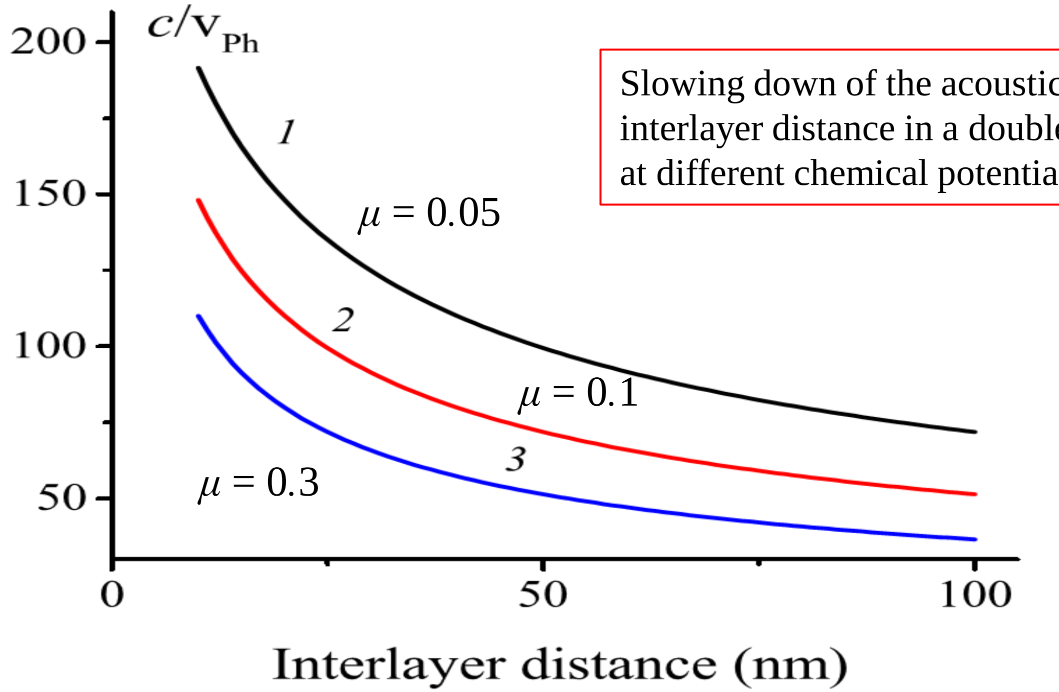
Quasi-Cherenkov radiation of an electron beam passing over the graphene/polymer sandwich structure



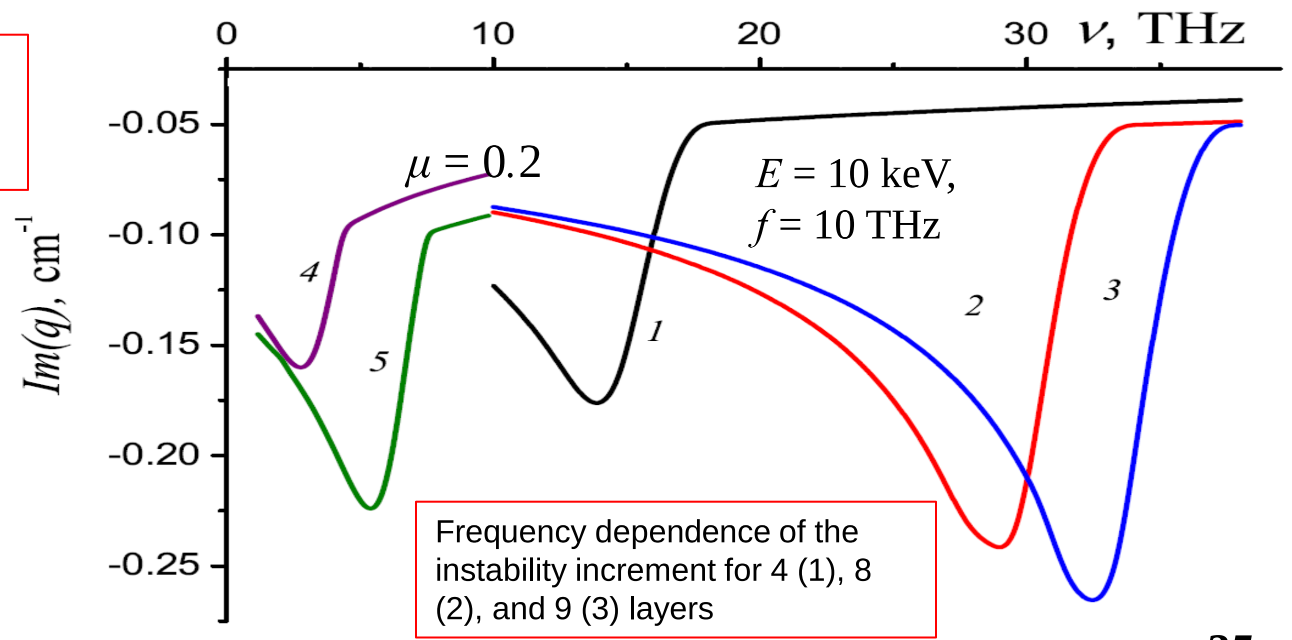

PHYSICAL REVIEW B **95**, 205408 (2017)

Graphene layered systems as a terahertz source with tuned frequency

K. Batrakov* and S. Maksimenko



Slowing down of the acoustic mode vs interlayer distance in a double graphene at different chemical potentials



Frequency dependence of the instability increment for 4 (1), 8 (2), and 9 (3) layers

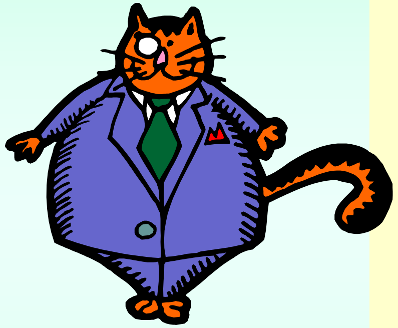
- We theoretically predicted and proved experimentally strong slowing down of surface EM waves in CNTs and graphene
- We theoretically demonstrate feasibility of extra small THz range sources based on CNTs
- We theoretically predicted and experimentally proved strong absrption of GHz- & THz waves in grapahene
- We propose more realistic THz-range source on the base of multilayered graphene/polymer structures

Conclusion: Where we go?

V. Vasnetsov, Knight at the parting of the ways, 1882, State Russian Museum

Problems on the NEM list

- ***Circuit components and devices design and modeling***
  interconnects, capacitors, inductors, antennae, transmission lines, active components, CNT-QD pairs
- ***Electromagnetic compatibility on nanoscale***
  non planewave excitations, thermal noise, electromagnetic coupling
- ***Nanocomposites And Metamaterials***
  EM shielding and absorption, heat transfer
- ***Instabilities***
  monomolecular travelling wave tube, active circuit elements



- ***Phototermal effect, medicine***
  Electromagnetic heating of CNTs and CNT thermo-dynamics, heat transfer on nanoscale
- ***Near-field optics & quantum information processing***
  Parcell effect, Few-photon (quantum) circuits, quantum-EMC

Международные проекты

Institutional Development of Applied Nanoelectromagnetics: Belarus in ERA Widening
FP7-266529 BY-NanoERA

Graphene/polymer based flexible transparent EM shielding for GHz and THz applications
GRAPHENE FLAGSHIP
FP7- 604391, H2020-649953

Multifunctional Graphene-based Nanocomposites with Robust EM and Thermal Properties for 3D-printing Application
H2020-734164 Graphene 3D

Radiation tolerant THz sensor
ATTRACT
H2020-207210 ROTOR

Globular carbon based structures and metamaterials for enhanced electromagnetic protection
NATO SPS G5697 CERTAIN

2D Material-Based Low Cost Sensor of Aggressive Substances
NATO SPS G5777 2DSENSE

Collective Excitations In Advanced Nanostructures
H2020 - 644076 COEXAN

Dirac Semimetals based Terahertz Components
H2020-823728 DISETCOM

Chiral Metamaterials for THz Polarization Control
H2020-101007896 CHARTIST

Terahertz Antennas with Self-Amplified Spontaneous Emission
H2020-823878 TERASSE

Novel Light Sources: Theory and Experiment
H2020-872196 N-LIGHT

Nanocarbon based components and materials for high frequency electronics
FP7-247007 CACOMEL

Terahertz applications of carbon-based nanostructures
FP7-230778 TERACAN

Nanocarbon based composite materials for electromagnetic Applications
ISTC B-1708

Carbon-nanotube-based terahertz-to-optics rectenna
FP7-612285 CANTOR

Fundamental and Applied Electromagnetics of Nano-Carbons
FP7- 318617 FAEMCAR

Nano-Thin and Micro-Sized Carbons: Toward EMC Application
FP7-610875 NAMICEMC

Nanosized Cherenkov-type THz light emitter based on double-walled carbon,
CRDF # AF20-15-61804-1

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Thank you for your attention!