CHALLENGES and PERSPECTIVES in NANOSCALE ELECTROMAGNETICs

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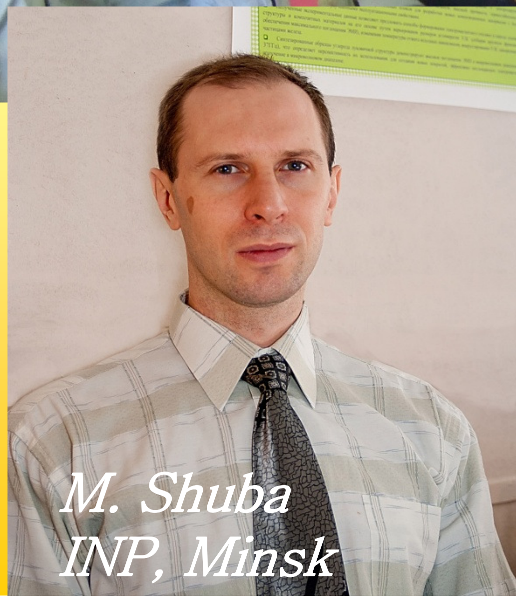
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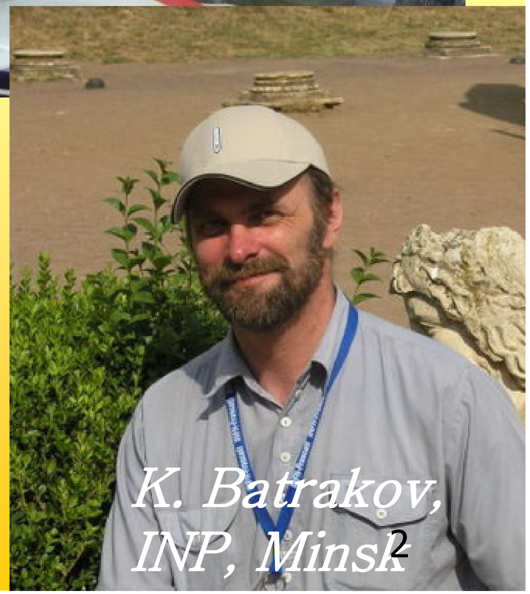
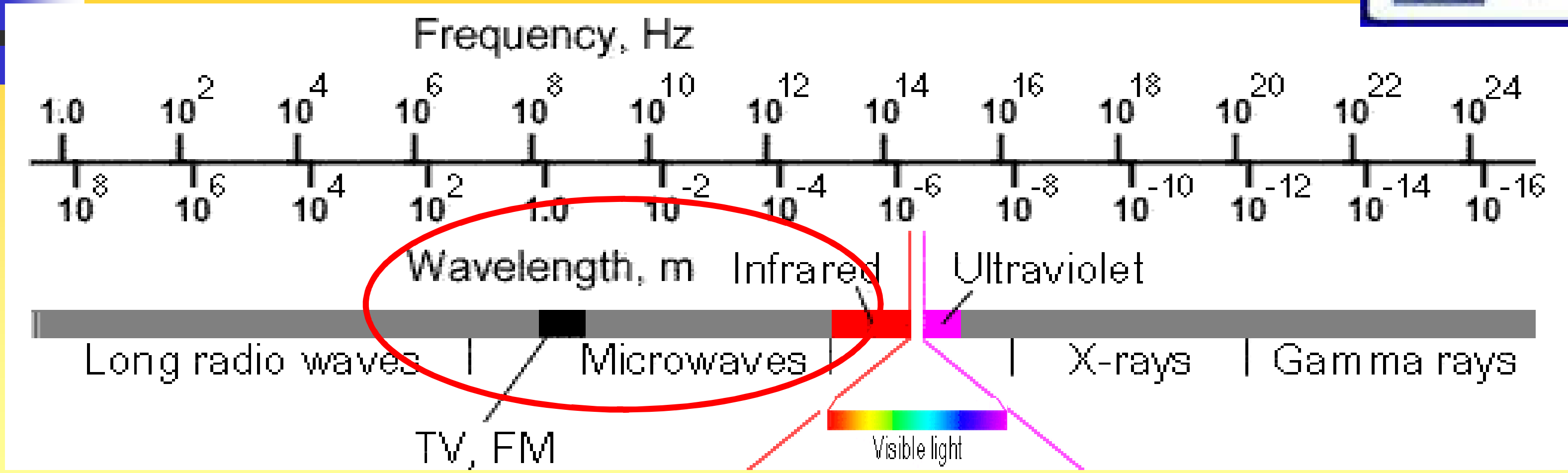

K. Batrakov,
INP, Minsk

Outline

1. Introduction
2. Nanoelectromagnetics
3. Carbon nanotubes: physical properties, conductivity modeling, etc.
4. Surface plasmon in CNT
5. CNT antenna resonance and THz absorption peak in CNT composites
6. Screening effect in Finite-Length MWCNTs
7. CNT as THz TWT
8. Conclusion & Acknowledgments

1.Introduction



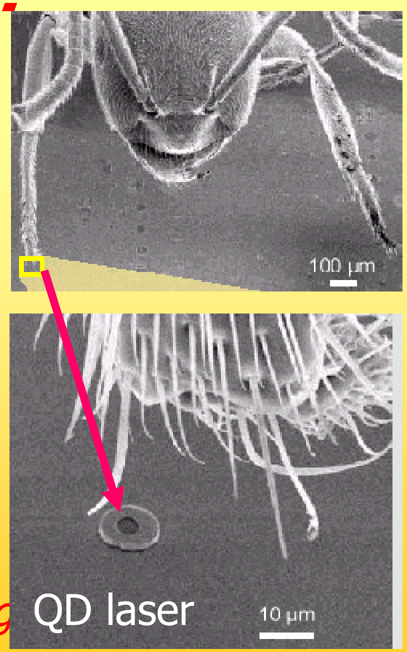
What are current trends in electromagnetics?

- 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 …

mechanical eigenfrequencies are in GHz and THz range, intracellular heating



On the way to integrated systems …

NANO LETTERS
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Vol. 7, No. 11
3296–3299

Carbon Nanotube Radio

Chris Rutherglen and Peter Burke*

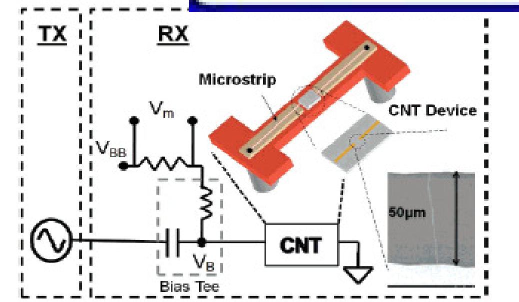

Figure 1. Schematic of the test-setup for the CNT-based AM demodulator. SEM image of a CNT (right).

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2007
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Nanotube Radio

K. Jensen, J. Weldon, H. Garcia, and A. Zettl*

Department of Physics, Center of Integrated Nanomechanical Systems, University of California at Berkeley, Berkeley, California 94720, and Materials Sciences Division, Lawrence Berkeley National Laboratory, Berkeley, California 94720

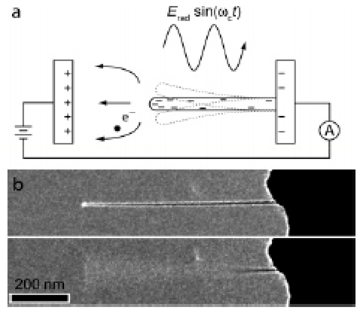


Figure 2. (a) Schematic of the nanotube radio. Radio transmissions tuned to the nanotube's resonance frequency force the charged nanotube to vibrate. Field emission of electrons from the tip of the

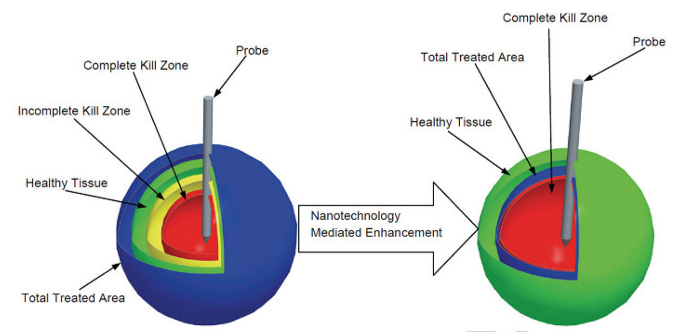
Am J Cancer Res 2011;1(4):507-519
www.ajcr.us /ISSN:2156-6976/ajcr0000046

Review Article

Nanotechnology for energy-based cancer therapies

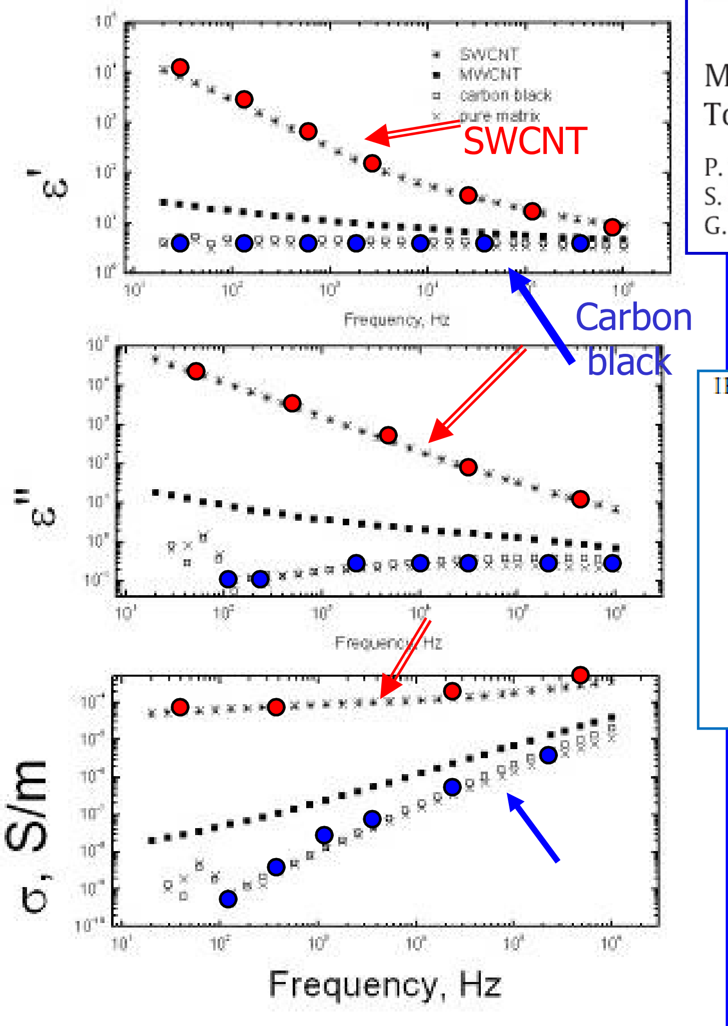
Kyle Gilstrap[1,2], Xiaoxiao Hu[3], Xiongbin Lu[3], Xiaoming He[1,2]

[1]*Department of Mechanical Engineering, and* [2]*Biomedical Engineering Program, University of South Caroli*
bia, SC 29208; [3]*Department of Cancer Biology, University of Texas M.D. Anderson Cancer Center, Houston, TX 77030, USA.*



Advanced EM materials

Quasi-static regime, *f*<1 MHz



Thin Solid Films 519 (2011) 4114–4118

Contents lists available at ScienceDirect

Thin Solid Films

journal homepage: www.elsevier.com/locate/tsf

Microwave probing of nanocarbon based epoxy resin composite films: Toward electromagnetic shielding

P. Kuzhir [a,*], A. Paddubskaya [a], D. Bychanok [a], A. Nemilentsau [a], M. Shuba [a], A. Plusch [a], S. Maksimenko [a], S. Bellucci [b], L. Coderoni [b], F. Micciulla [b], I. Sacco [b], G. Rinaldi [c], J. Macutkevic [d], D. Seliuta [d], G. Valusis [d], J. Banys [e]

Comparative study of electromagnetic response properties of commercially available forms of nanocarbon

IEEE TRANSACTIONS ON ANTENNAS AND PROPAGATION 2010

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,

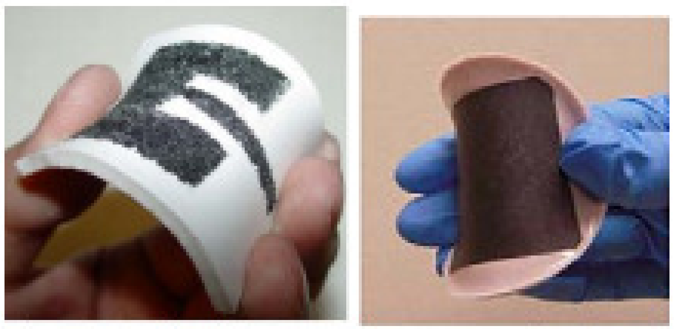


Fig. 1 Very flexible E-textile antenna printed on polymer composite

2. Nanoelectromagnetics

Prefix "nano-" is the necessary element in all present-day approaches to solve the problems mentioned:

- ✓ *Nanoelectronics,*
- ✓ *Nanophotonics,*
- ✓ *Nanosensorics,*
- ✓ *Nano….*
- ✓ *Nano…*
- ✓ *Nanoelectromagnetics*

Nanophotonics

subject is the study of the behavior of light on the nanometre scale.

motivation The ability to fabricate devices in nanoscale that has been developed recently provided the catalyst for this area of study.

Wikipedia

Nanoelectromagnetics

a research discipline studying the behavior of high-frequency electromagnetic radiation on nanometer scale

Nanoelectromagnetics

is currently emerging as a synthesis of macroscopic electrodynamics and microscopic theory of electronic properties of different nanostructures.

Electromagnetic field diffraction

Diffraction Theory

Boundary-value problems for complex-shaped regions:
Complex geometry, ordinary electronics

Confinement of the charge carrier motion

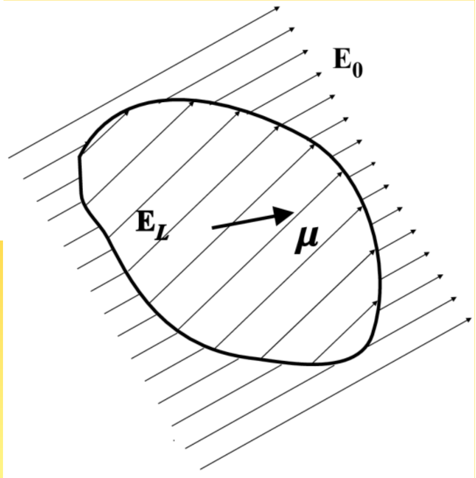
Condensed Matter Physics

Quasi-particle concept:
Electrons, phonons, magnons…
Complex electronics, ordinary geometry

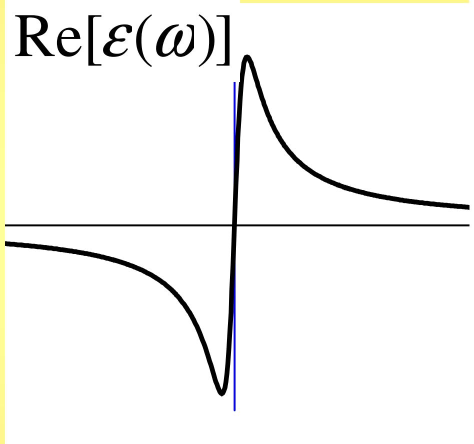
NANOELECTROMAGNETICS

Permittivity of a QD-exciton

After: S.A. Maksimenko, et al., Semicond. Sci. Technol. 15, 491 (2000)



$$\varepsilon_{QD}(\omega) = \varepsilon_{Bulk} + \frac{w g_{QD}}{(\omega - \omega_0 + i/\tau_{dephasing})}$$



$w = \pm 1 \quad \textit{is the QD population} \ (w = 1 \Rightarrow \textit{inversion})$

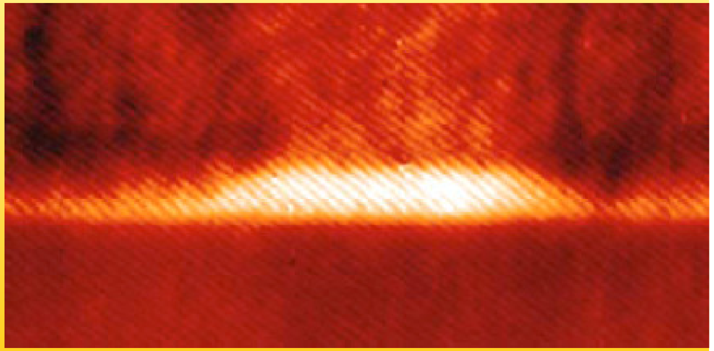
$g_{QD} \cong 7.10^{14}\, s^{-1} \quad \textit{estimated from experiment}$

$(g_{QD} \cong 10^{14}\, s^{-1} \ \textit{estimated from laser transparancy})$

$\tau_{dephasing} \approx 600\, ps \quad (Borri) \Rightarrow$

$$\varepsilon_{QD}(\omega_0) = g_{QD}\tau \approx 4.2 \times 10^5$$

Strong interaction between QD-exciton and EM-field



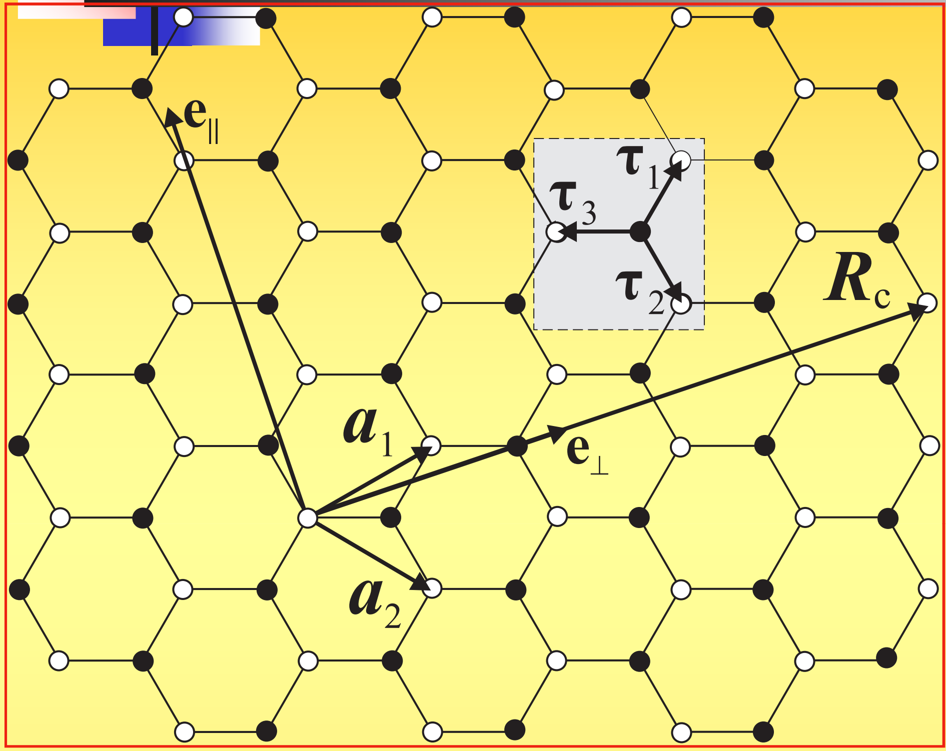
FUNDAMENTAL CHALENGE in NANOSCALE ELECTROMAGNETICS is

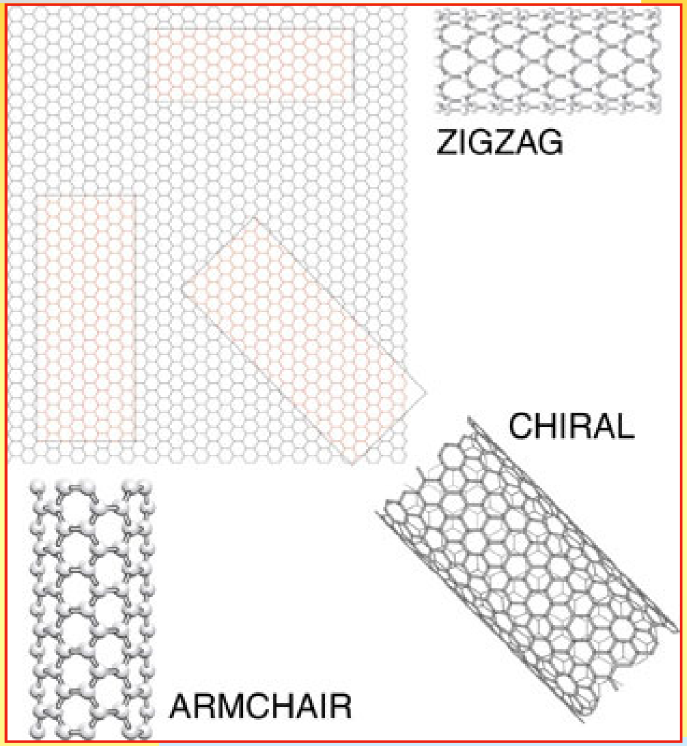
unusual constitutive properties of structural materials due to spatial confinement of the charge carriers motion

or

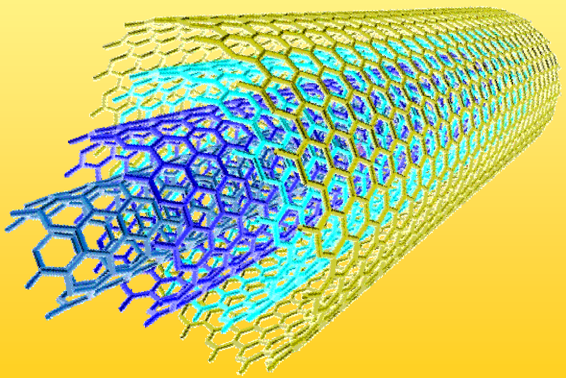
INTERPLAY of
SCHROEDINGER and MAXWELL EQUATIONS

3. Carbon Nanotube





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



$R_c = m\boldsymbol{a}_1 + n\boldsymbol{a}_2$

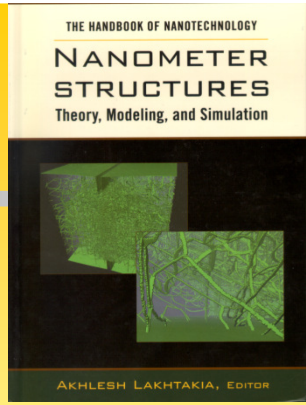
SWCNT *(m,n)*

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

Basic Properties of Si, Cu, CNT and GNR

	Si	Cu	SWCNT	MWCNT	Graphene or GNR
Max current density (A/cm^2)	-	10^7	$>1x10^9$ Radosavljevic, et al., *Phys. Rev. B*, 2001	$>1x10^9$ Wei, et al., *Appl. Phys. Let.*, 2001	$>1x10^8$ 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 ($\times 10^3$ 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

The Handbook of Nanotechnology. Nanometer Structure: Theory, Modeling, and Simulation," Ed. by A. Lakhtakia, SPIE Press, Bellingham, 2004



CNT electromagnetics: from *Phys Rev* to *IEEE Trans*

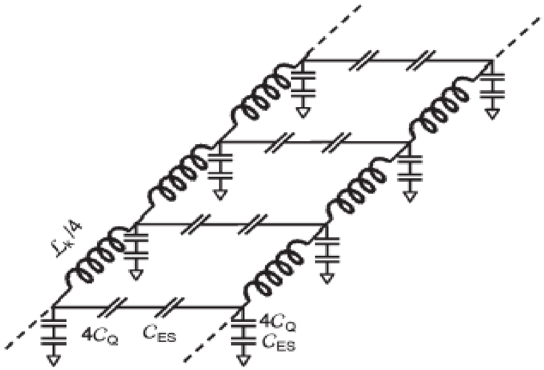
Chapter 5

Nanoelectromagnetics of Low-dimensional Structures

Sergey A. Maksimenko and Gregory Ya. Slepyan

Nanoelectromagnetics: Circuit and Electromagnetic Properties of Carbon Nanotubes

*Chris Rutherglen and Peter Burke**



From the Contents

This Review presents a discussion of the electromagnetic properties of nanoscale electrical conductors, which are

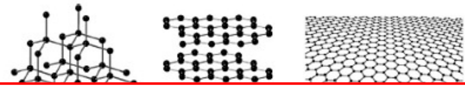
IEEE TRANSACTIONS ON ELECTRON DEVICES, VOL. 56, NO. 9, SEPTEMBER 2009 1799

Carbon Nanomaterials for Next-Generation Interconnects and Passives: Physics, Status, and Prospects

Hong Li, *Student Member, IEEE*, Chuan Xu, *Student Member, IEEE*, Navin Srivastava, *Student Member, IEEE*, and Kaustav Banerjee, *Senior Member, IEEE*

(Invited Paper)

***Abstract*—This paper reviews the current state of research in carbon-based nanomaterials, particularly the one-dimensional (1-D) forms, carbon nanotubes (CNTs) and graphene nanoribbons (GNRs), whose promising electrical, thermal, and mechanical properti integrat physics related f trical a various compare guidelin single-w better p GNR in both int achieved**



The current issue and full text archive of this journal is available at www.emeraldinsight.com/0332-1649.htm

Electromagnetic models for metallic carbon nanotube interconnects

Andrea Gaetano Chiariello and Giovanni Miano
DIEL, Università degli Studi di Napoli "Federico II" Italy, and
Antonio Maffucci, Fabio Villone and Walter Zamboni
DAEIMI, Università degli Studi di Cassino, Italy

Nota Bene!

When we think about CNT as an high-frequency circuit element, we should clearly realize:

- ***CNT is not a metal even if shows metallic properties;***
- ***Contact barrier determines the total resistivity and has quantum-mechanical nature;***
- ***Finite-length effects are generally of importance in electromagnetic response of single- and multi-walled CNTs***

Just an advice: *Do not use standard EM solvers for CNT component modeling without accounting for the peculiar conductivity law (see below)*

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55, 273-280 (2001)

AEÜ Interna… of Elec… and Co…

Scattering of Electromagnetic Waves by a Semi-Infinite Carbon Nanotube

Gregory Ya. Slepyan, Nikolai A. Krapivin, Sergey A. Maksimenko, Akhlesh Lakhtakia and Oleg M. Yevtushenko

Abstract **Scattering of electromagnetic cylindrical waves by an isolated, semi-infinite, open-ended, single-shell, zigzag carbon nanotube (CN) is considered in the optical regime. The CN is modeled as a smooth homogeneous cylindrical surface with impedance boundary conditions known from quantum-mechanical transport theory. An exact solution of the diffraction problem is obtained by the Wiener-Hopf technique. The differences between the scattering responses of metallic and semiconducting CNs are discussed.**

Keywords **Carbon nanotube, Diffraction, Impedance boundary conditions, Wiener-Hopf technique**

At optical frequencies, the cross-sectional radius R and the length L of actual CNs satisfy the following conditions with respect to the free-space wavenumber k:

$$kR \ll 1\,, \quad kL \sim 1\,. \tag{1}$$

Clearly, although the cross-sectional radius is electrically small, the length is electrically large – conditions that are characteristic of wire antennas at microwave frequencies

"Clearly, although the cross-sectional radius is electrically small, the length is electrically large - conditions that are characteristic of wire antennas…" Thus,

an isolated CNT is a wire nano-antenna

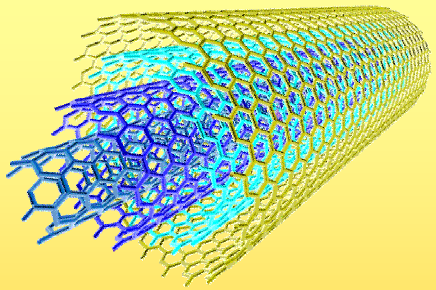
The key problem for the CNT electromagnetic response modeling is the conductivity low evaluation

CNT Modeling

- *Dynamical conductivity of an isolated SWCNT*
- *Polarizability of a finite-length CNT*
- *Homogenization procedure for CNT composites*

Evaluation of the dynamical conductivity

Quantum-mechanical problem



nanoelectromagnetics

Solution of the scattering problem
Homogenization

Classical electrodynamic problem

Dynamical conductivity of CNT

Semi classical approximation:

The motion of π-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
$F(\mathbf{p})=\left[1+\exp\{\mathcal{E}(\mathbf{p})/k_BT\}\right]^{-1}$	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 $\tau=3\times10^{-13}$ sec.

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

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

Dynamical conductivity of CNT

Further we apply standard perturbation procedure of the Boltzman equation solution:

Let us set $E_z = \Re[E_z^0 e^{i(hz-\omega t)}]$ in the Boltzmann kinetic equation (1), where h is the axial wavenumber (not to be confused with the Planck constant $\hbar$) and ω is the angular frequency of the exciting electromagnetic field. Setting $f = F + \Re[\delta f e^{i(hz-\omega t)}]$ with δf as a small quantity to be found, and keeping only linear terms in E_z^0, we then obtain

$$\delta f = -i \frac{\partial F}{\partial p_z} \frac{e E_z^0}{\omega - h v_z + i \nu}. \tag{4}$$

The axial surface current density $J_z = \Re[J_z^0 e^{i(hz-\omega t)}]$ is to be determined by the relation

$$J_z = \frac{2e}{(2\pi\hbar)^2} \int\int v_z f d^2\mathbf{p}, \tag{5}$$

with e as the electron charge. Using both foregoing equations, we get

The dynamical conductivity law

$$\mathbf{J} = \sigma(\omega)\mathbf{E}$$

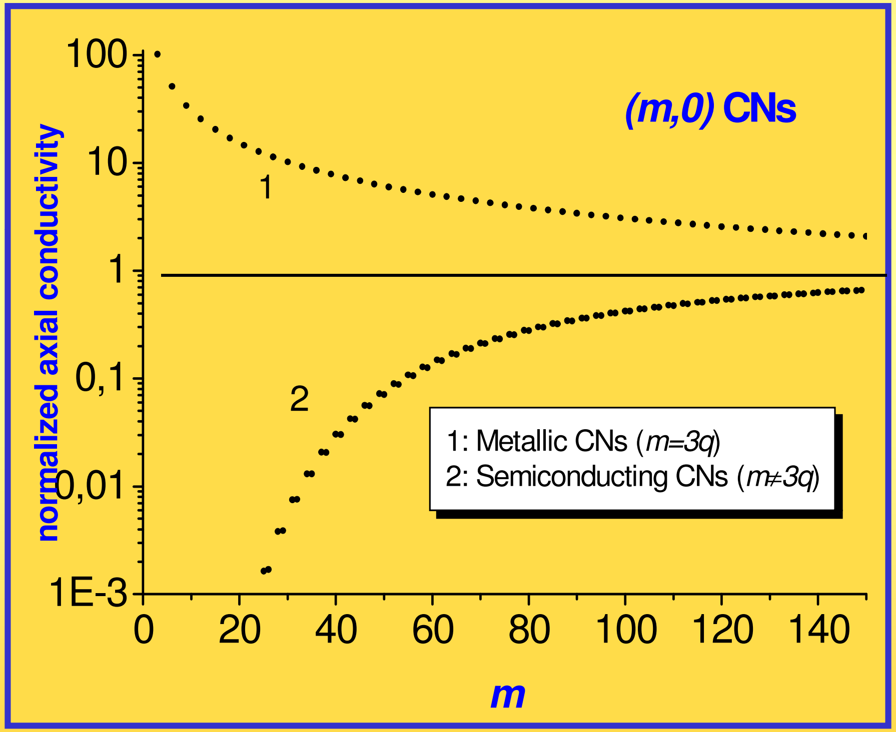
$$\sigma_{zz}(h,\omega) = \frac{2e^2}{(2\pi\hbar)^2} \iint \frac{\partial F}{\partial p_z} \frac{\upsilon_z d^2\mathbf{p}}{\omega - h\upsilon_z + i\nu}$$

These equations are analogous to constitutive equations of balk conducting media in classical electrodynamics. However, there is significant distinction: In our case we deals with surface current but not with bulk current.

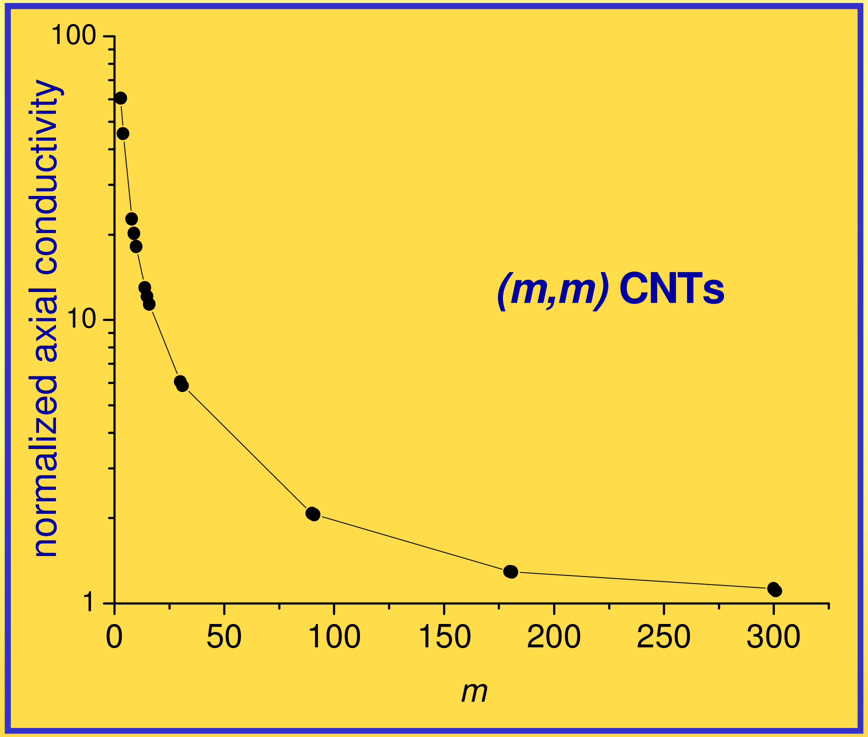
Dynamical conductivity of CNT

Radial dependence of the conductivity below the optical transitions band

zigzag



amchair



$$R_{\mathrm{cn}} = \frac{\sqrt{3}}{2\pi} b \sqrt{m^2 + mn + n^2},$$

Dynamical conductivity of CNT

The axial conductivity, based on quantum transport theory

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

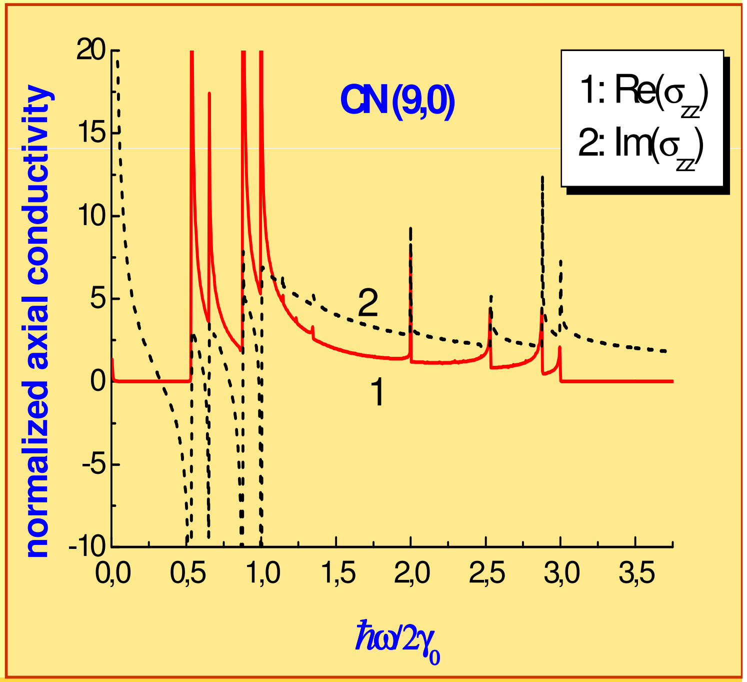
Normalized matrix elements of the dipole transition between conduction and valence bands

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

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



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

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

4. EM modeling of CNT

Integral equation technique as applied to a finite-length CNT - dipole antenna has been developed in

Conductivity law in the tight-binding approximation, EBCs

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
Institute of Nuclear Problems, Belarus State University, Bobruisk A. V. Gusakov *50, Belarus*
A. Lakhtakia O. Yevtushenko

a Hallén's-type integral equation

3426 IEEE TRANSACTIONS ON ANTENNAS AND PROPAGATION, VOL. 53, NO. 11, NOVEMBER 2005

Fundamental Transmitting Properties of Carbon Nanotube Antennas

G. W. Hanson, *Senior Member, IEEE*

a Leontovich-Levin integral equation

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
Institute for Nuclear Problems, Belarus State University, Bobruiskaya 11, 220050 Minsk, Belarus

A. Lakhtakia

A frequency-domain integral formulation for metallic CNT+conductors

IEEE TRANSACTIONS ON ANTENNAS AND PROPAGATION, VOL. 54, NO. 10, OCTOBER 2006 2713

An Integral Formulation for the Electrodynamics of Metallic Carbon Nanotubes Based on a Fluid Model

Giovanni Miano and Fabio Villone

EBCs for carbon nanotubes

PHYSICAL REVIEW B VOLUME 60, NUMBER 24 15 DECE

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

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In optical range $\lambda >> b, \quad \lambda >> R_{\mathrm{cn}}, \quad b = 0.142\,\text{нм}$

$$\left(1+\frac{l_0}{k^2(1+i/\omega\tau)^2}\frac{\partial^2}{\partial z^2}\right)\left(H_\phi\Big|_{\rho=R+0}-H_\phi\Big|_{\rho=R-0}\right)=\frac{4\pi}{c}\sigma_{zz}E_z\Big|_{\rho=R},$$

$$H_z\,|_{\rho=R-0} - H_z\,|_{\rho=R+0}=0,\ E_{z,\varphi}\,|_{\rho=R-0} - E_{z,\varphi}\,|_{\rho=R+0}=0$$

Spatial dispersion parameter $l_0 \sim 10^{-5}$ for metallic CNTs

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

Surface Waves 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].

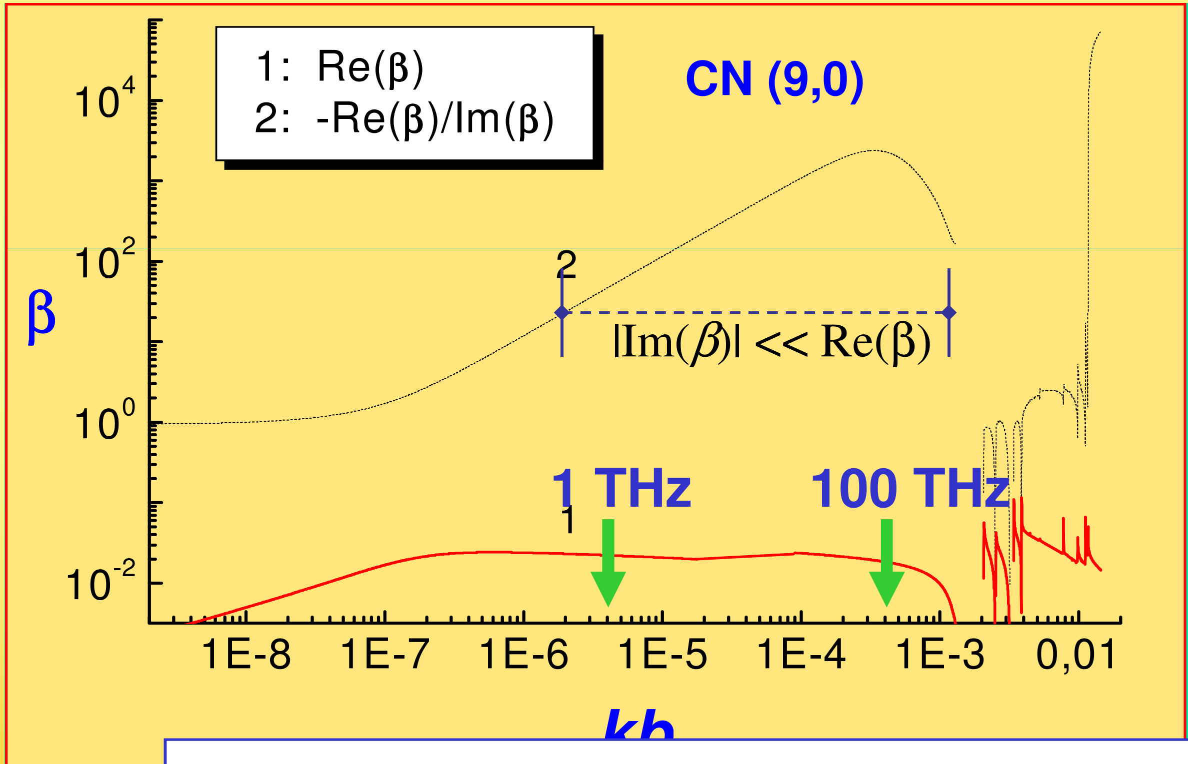
Dispersion equation of surface waves

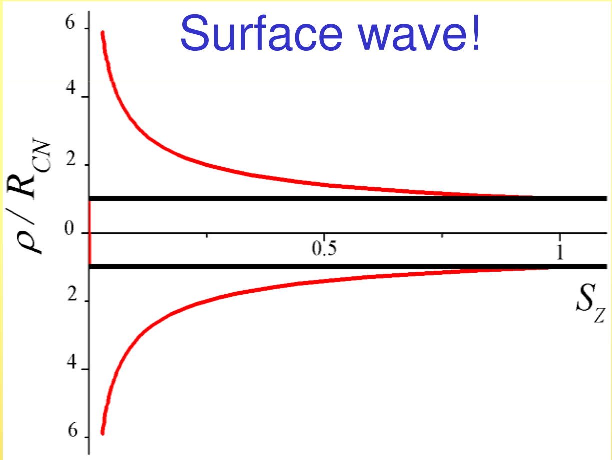
$$\frac{\kappa^2}{k^2} K_q(\kappa R) I_q(\kappa R) = \frac{ic}{4\pi R \sigma_{zz}} \left(1 - \frac{\kappa^2 + k^2}{(\omega + i/\tau)^2} c^2 l_0 \right).$$

Surface Wave Propagation

Complex-valued slow-wave coefficient ***b*** for a polar-symmetric surface wave

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





Axial component of the time-averaged Poynting vector

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

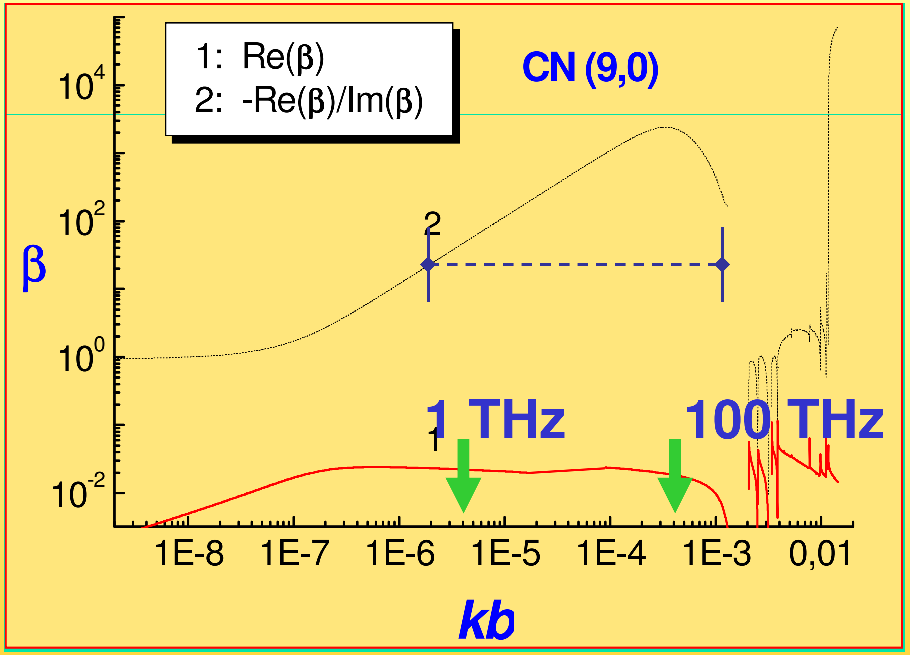
Electrodynamics of carbon nanotubes: Dynamic conductivity, impedance boundary conditions, and surface wave propagation

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

What Can We Learn from the Picture?

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

- **Electromagnetic slow-wave line: v_{ph}/c~0.02**
- **Dispersionless surface wave nanowaveguide and high-quality interconnects**
- **Terahertz-range antenna**
- **Thermal antenna**
- **Monomolecular traveling wave tube**



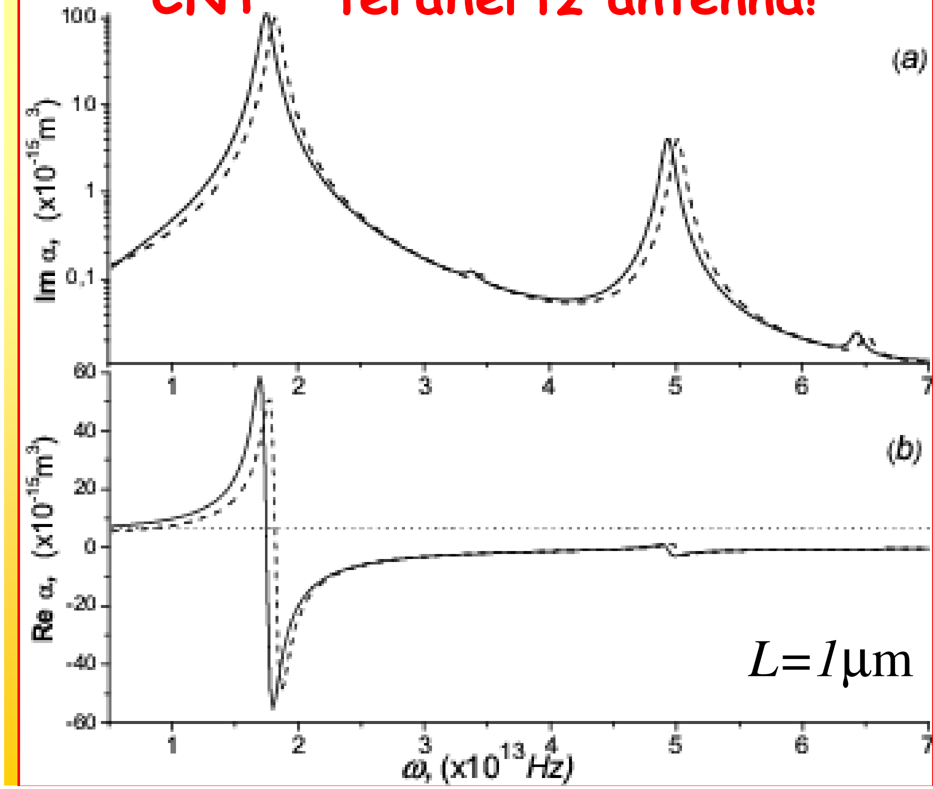
5. geometrical (antenna) resonances

A vibrator antenna radiates effectively if its length equals to an integer number of halfwaves; for perfectly conducting wire it is $kL=\pi m$, $m=1,2,3$…..

Geometrical resonances: $hL=\pi m$

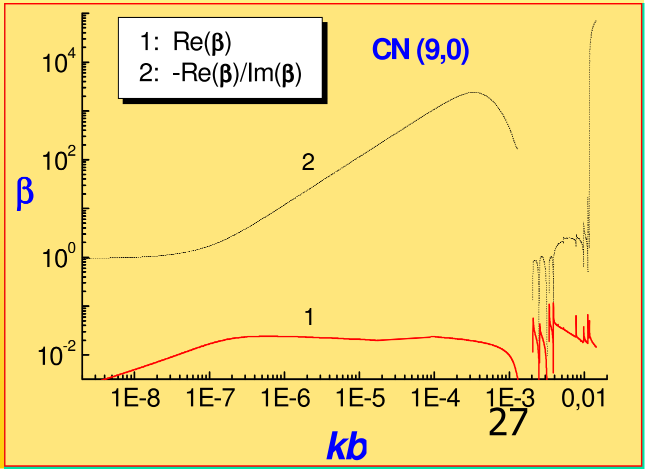
Because of the large slow-wave effect, $h/k=c/v_{ph}=1/\beta\sim50$, at optical lengths ~ 1 mkm the geometrical resonances are shifted to THz

CNT – terahertz antenna!



We need experiment!

Slepyan et al., PRB 2006



Experimental observations of THz peak in CNT-based composites

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

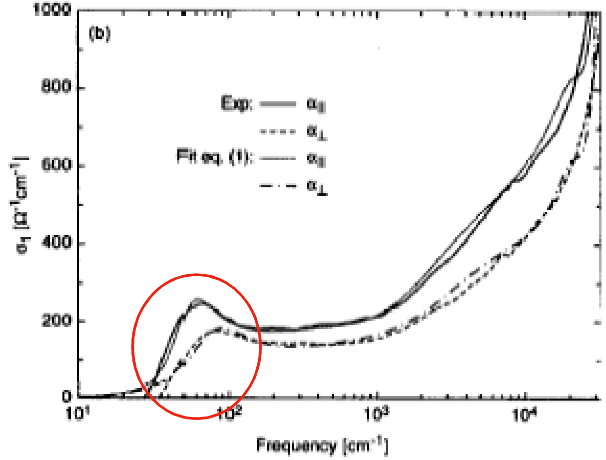


Fig. 1. (a) [redacted] (b) optical conductivity of oriented nanotubes films along the $\alpha_\parallel$ and $\alpha_\perp$ directions. The MG fits [Equation (1)] are also presented.

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

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

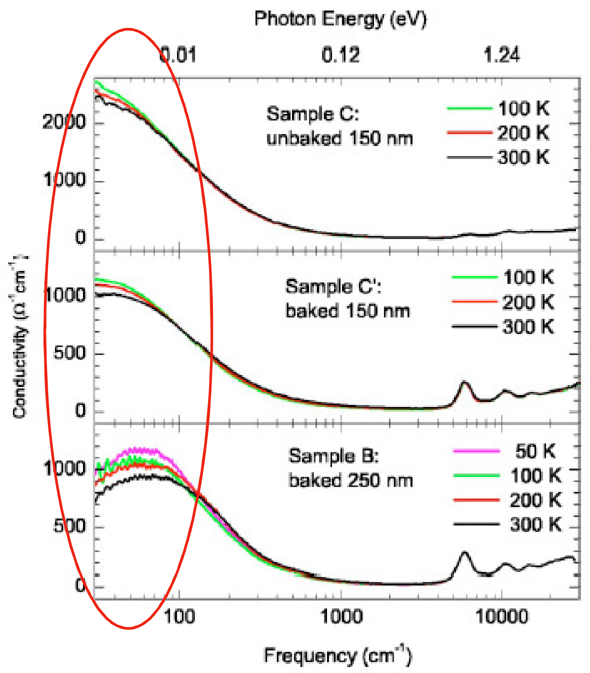
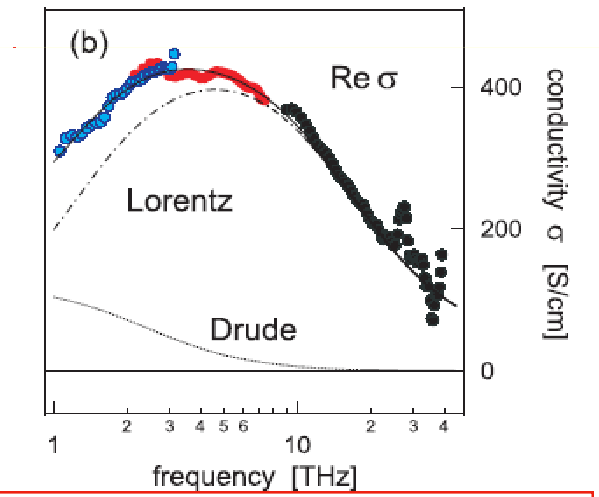


FIG. 3. (Color online) Temperature dependence of the optical conductivity of the two samples.



(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)

$$\epsilon(\omega) = \frac{-\omega_p^2}{\omega^2 + i\Gamma\omega} + \sum_i \frac{\omega_{p,i}^2}{(\omega_i^2 - \omega^2) - i\Gamma_i\omega} + \epsilon_\infty,$$

Homogenization procedure

Consider a dilute composite material comprising CNTs

- ***randomly dispersed;***
- ***randomly oriented;***
- ***achiral;***

Low-frequency approach: Waterman-Truell formula ($kL<\pi/5$)

$$n_{eff}(\omega) = \sqrt{1+\frac{4\pi f}{3k^2}\sum_j F_j(0,\omega,L)N_j(L)dL}$$

$$k = 2\pi/\lambda = \omega/c$$

$$\sigma_{eff}(\omega) = \omega[n_{eff}^2(\omega)-1]/4i\pi$$

P. C. Waterman and R. Truell, J. Math. Phys. 2, 512 (1961).
A. Lakhtakia, Int. J. Electron. 75, 1243 (1993).

$$F_j(0,\omega,L) = k^2\alpha_j(\omega,L)$$

polarizability

is the plane-wave scattering amplitude of an isolated SWCNT at angle θ with respect to the direction of propagation of a plane wave by an SWCNT of type *j* and length *L*.

Comparison with experiment

PHYSICAL REVIEW B **81**, 205423 (2010)

Terahertz conductivity peak in composite materials containing carbon nanotubes: Theory and interpretation of experiment

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

The predicted amplitudes of resonance lines due to first two optical transitions of the semiconducting SWCNTs coincide reasonably well with the experimental values.

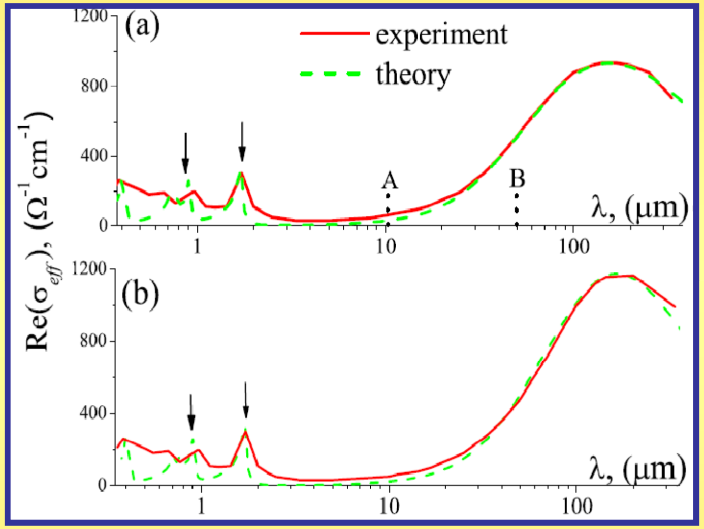
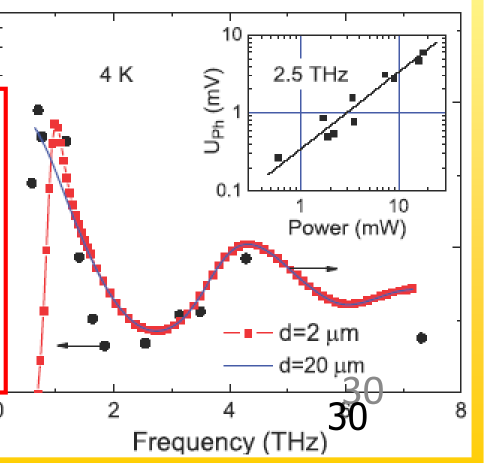


FIG. 3. (Color online) Variations in Re(σ_{eff}) with λ at (a) $T=300$ K and (b) $T=50$ K. Solid lines: experimental data from Fig. 3 of Ref. 18. Dashed lines: theoretical results. When the long-wavelength Approach A was used, we set (a) $\nu=3\times10^{13}$ rad s^{-1} and (b) $\nu=2.3\times10^{13}$ rad s^{-1}.

APPLIED PHYSICS LETTERS **97**, 073116 (2010)

Terahertz sensing with carbon nanotube layers coated on silica fibers: Carrier transport versus nanoantenna effects

Dalius Seliuta,[1,2,a)] Irmantas Kašalynas,[1] Jan Macutkevic,[1] Gintaras Valušis,[1] Mikhail V. Shuba,[3] Polina P. Kuzhir,[3] Gregory Ya. Slepyan,[3] Sergey A. Maksimenko,[3] Vitaly K. Ksenevich,[4] Vladimir Samuilov,[5] and Qi Lu[5]



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
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D. Seliuta, I. Kasalynas, J. Macutkevic, and G. Valusis
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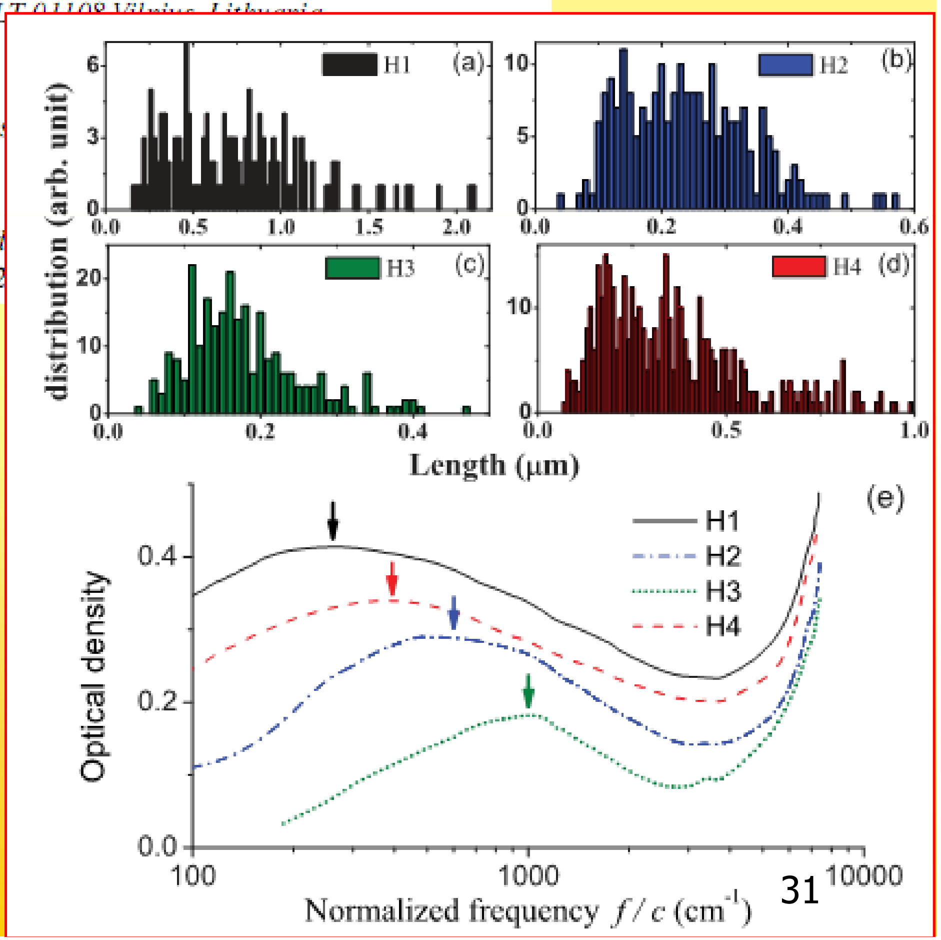
C. Thomsen
Institut für Festkörperphusik, Technische Universität Berlin, Hardenberg

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

THz peak: experiment

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



6. Multiwalled carbon nanotube

PHYSICAL REVIEW B 79, 155403 (2009)

Theory of multiwall carbon nanotubes as waveguides and antennas in the infrared and the visible regimes

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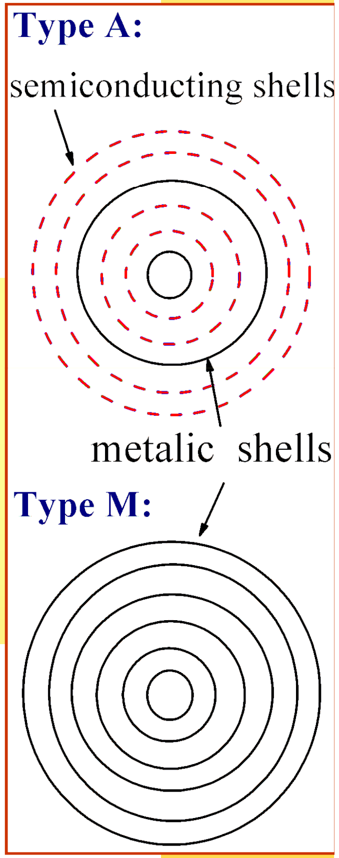


we take into consideration

1. the electromagnetic coupling of shells in the MWCNTs;
2. the finite length and diameter of MWCNTs.

IEEE Trans. Nanotechnology, 11(3) pp. 554 - 564 (2012)

Transmission Line Model for Multiwall Carbon Nanotubes with Intershell Tunneling

C. Forestiere, A. Maffucci, *Senior Member, IEEE,* S. A. Maksimenko, G. Miano, G. Ya. Slepyan

Multi-walled carbon nanotube

JOURNAL OF APPLIED PHYSICS **108**, 114302 (2010)

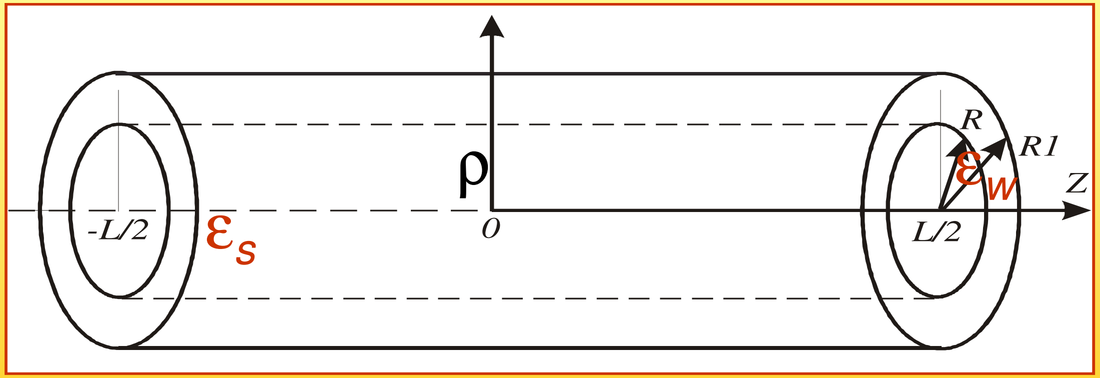
Radiofrequency field absorption by carbon nanotubes embedded in a conductive host

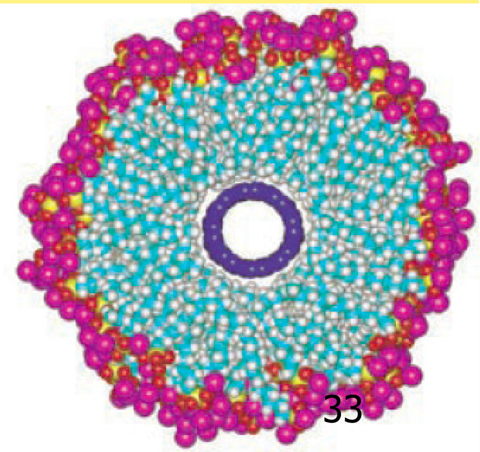
Mikhail V. Shuba,[1,a] Gregory Ya. Slepyan,[2] Sergey A. Maksimenko,[2] and George W. Hanson[2,b]
[1]*Institute for Nuclear Problems, Belarus State University, Bobruiskaya 11, 220030 Minsk, Belarus*
[2]*Department of Electrical Engineering, University of Wisconsin-Milwaukee, 3200 N. Cramer St., Milwaukee, Wisconsin 53211, USA*

(Received 11 August 2010; accepted 15 October 2010; published online 1 December 2010)

Understanding the electromagnetic response of carbon nanotubes (CNTs) in the radio frequency range is very important for experimental development of therapeutic and diagnostic CNT applications, including selective thermolysis of cancer cells and thermoacoustic imaging. In this study, we present the theory of electromagnetic wave scattering by several finite length CNT

O'Connell, *et al.* Cross-section model of an individual fullerene nanotube in a cylindrical SDS micelle, ***Science*** **297**, 593 (2002)





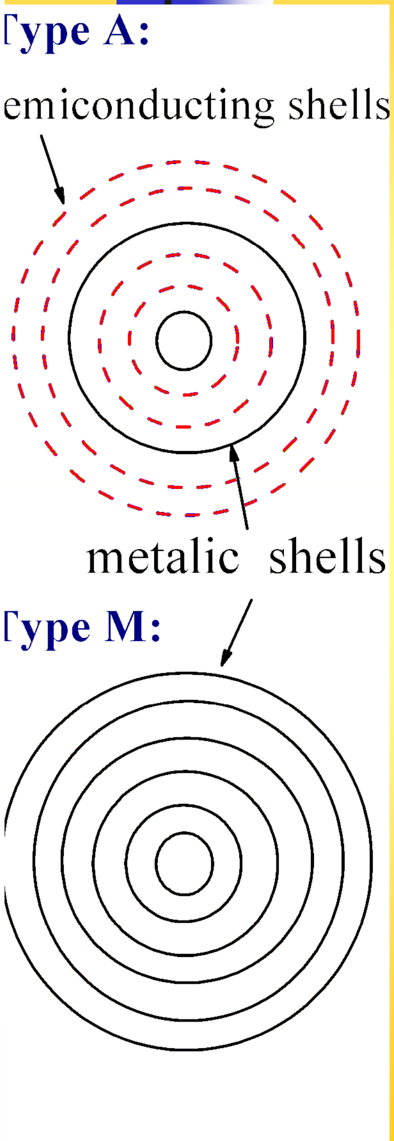
MWCNT

MWCNT: what new we can expect in electromagnetic response?

1. Decrease slowing-down effect

2. Screening effect

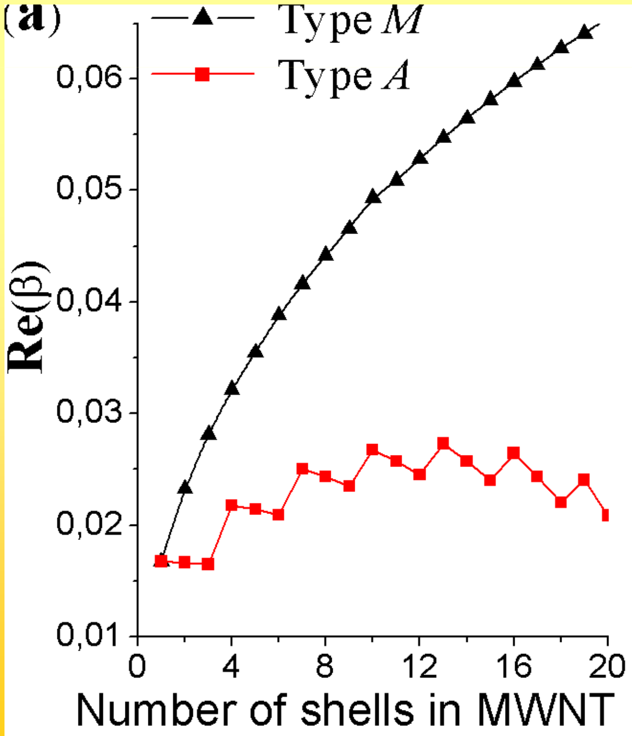
Slow-wave coefficient vs the number of shells in MWNT

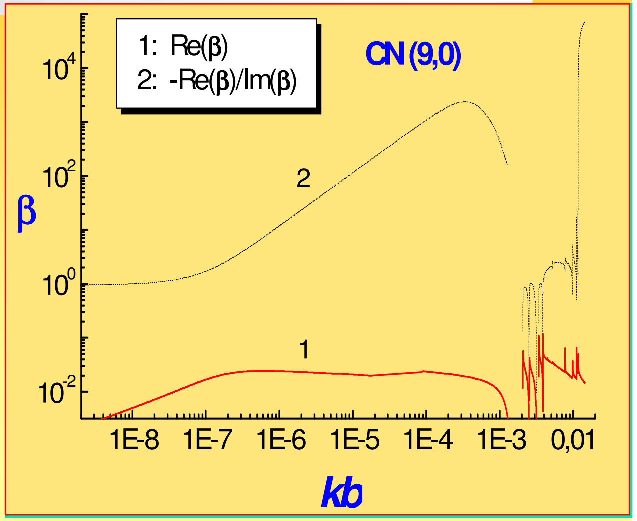


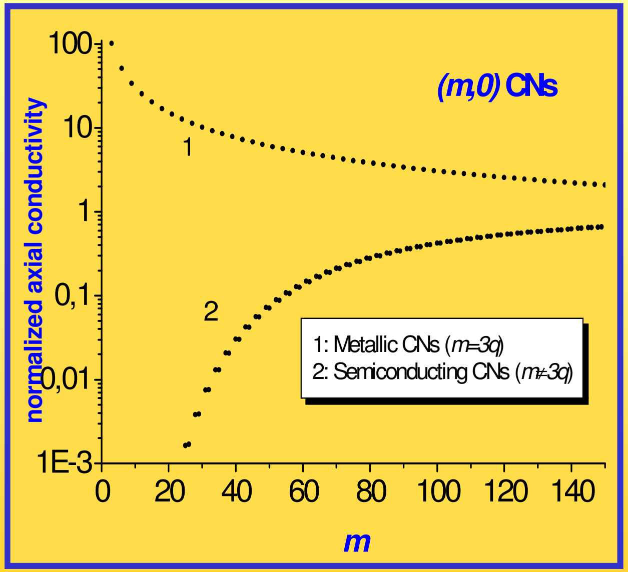
$$\beta = \frac{v_{ph}}{c} = \frac{k}{h} = \frac{k}{h' + ih''}$$

Re (β) --> 1:

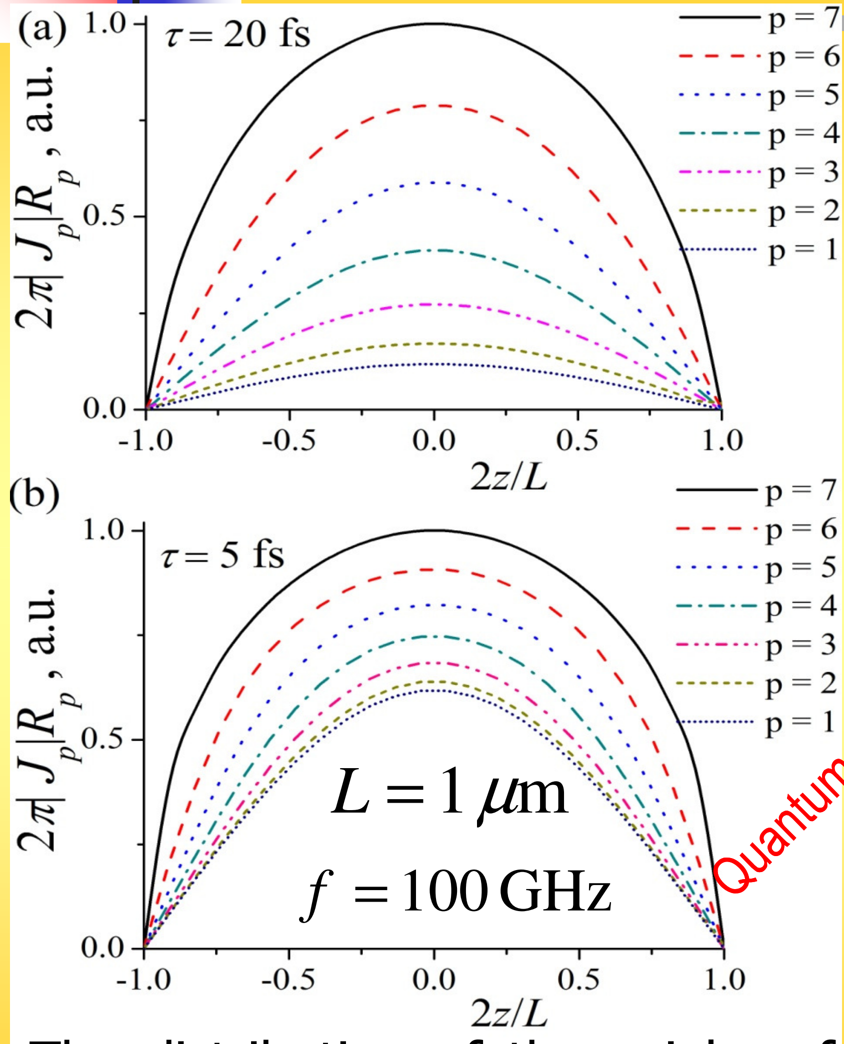
Effect of "graphitization"







Screening effect in finite-length MWCNT due to strong depolarizing field



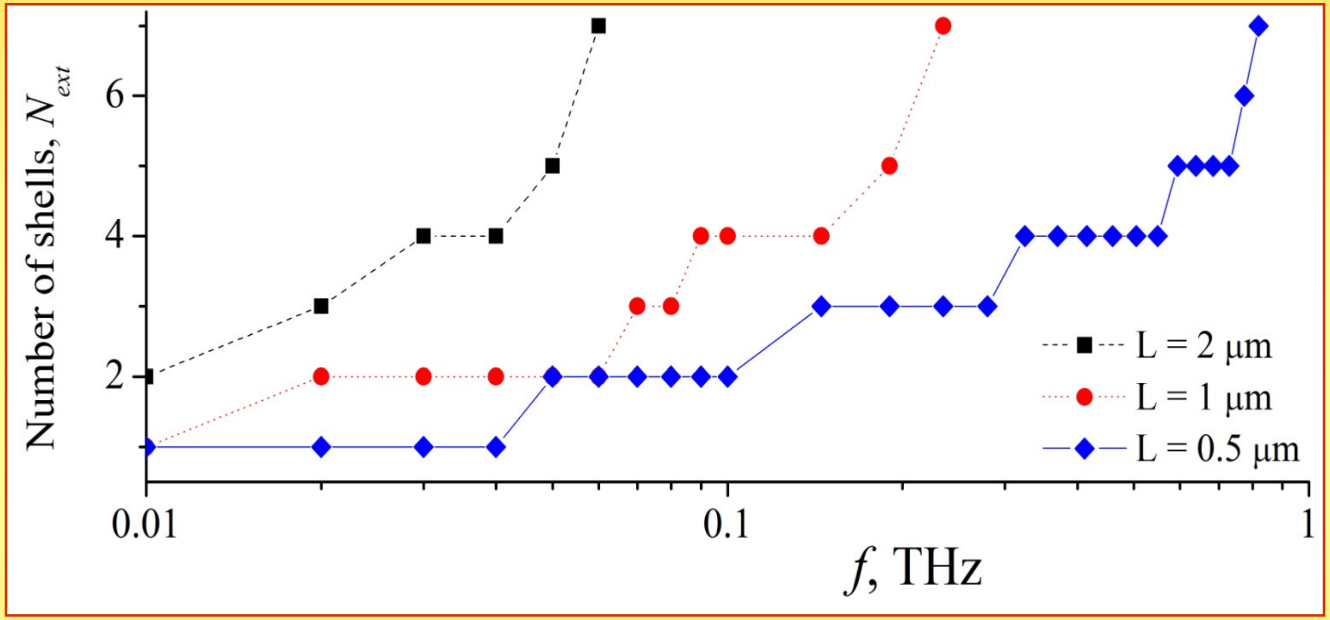
Quantum mechanics->

- 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 distribution of the axial surface current along the length of metallic shells of an MWNT exposed to a plane wave with electric field parallel to the CNT axis.

The electric field penetration depth in finite-length MWCNTs

Number N_{ext} is equivalent to the depth of penetration: the larger the value of N_{ext} the more the penetration.



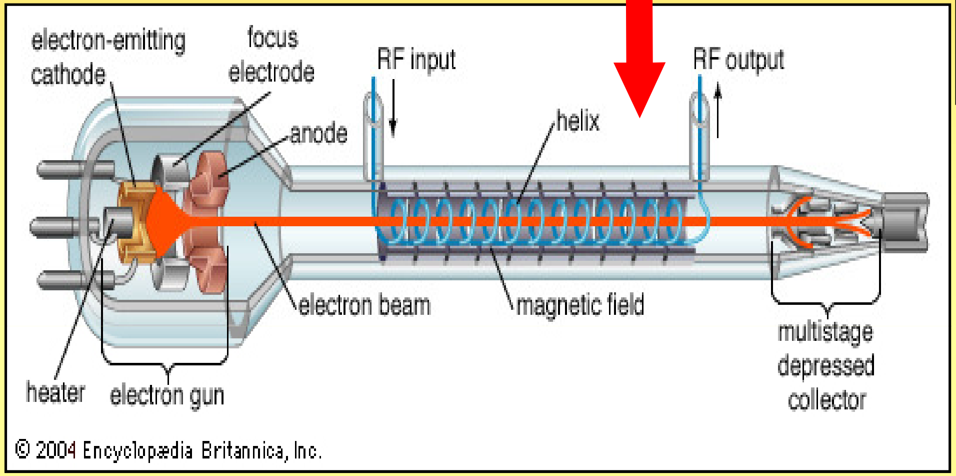
The frequency dependence of the number of external metallic shells providing screening the internal shells

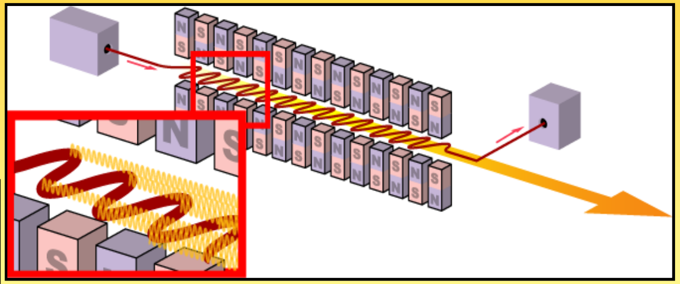
Our calculations demonstrate that in a finite-length MWNT interconnect, the outer metallic shells can be exploited for shielding the remaining inner shells from external spurious radiation, while the inner metallic shells can be used to trnasmit signals.

7. CNT as Nano – TWT

a slowing-down system

Macroscopic TWT

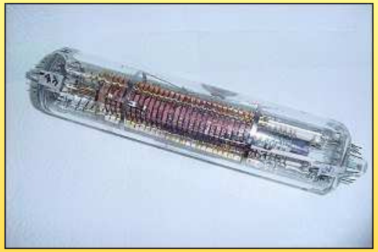


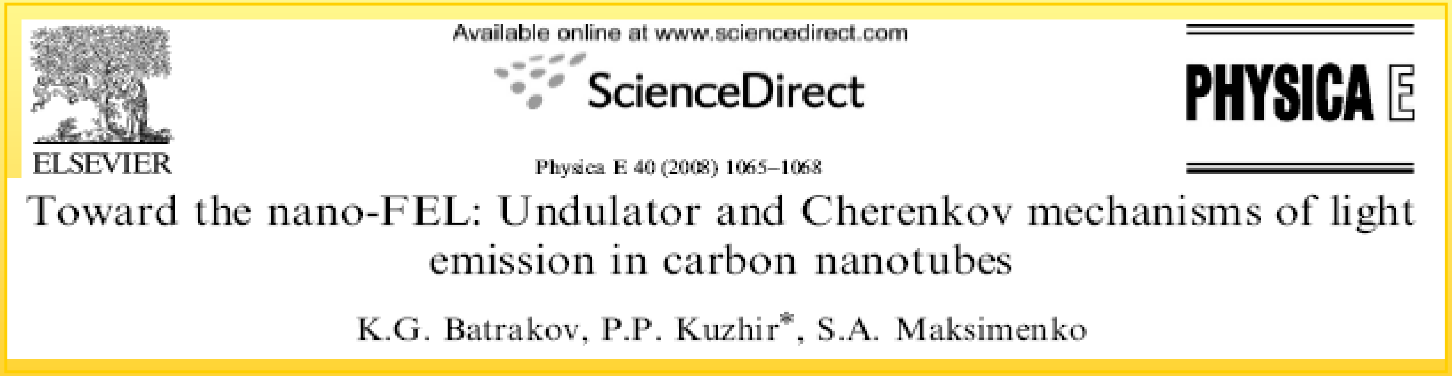


FEL

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

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





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Physica E 40 (2008) 1065–1068

Toward the nano-FEL: Undulator and Cherenkov mechanisms of light emission in carbon nanotubes

K.G. Batrakov, P.P. Kuzhir*, S.A. Maksimenko

Nano – TWT and NanoFEL: the Basic Idea

It is well-known, that electron beam in systems which slow down electromagnetic waves can emit radiation (Cherenkov, Smith-Purcell, quasi-Cherenkov mechanisms)

Combination in CNTs of three key properties,

- a strong slowing down of surface electromagnetic waves,
- ballisticity of the electron flow over typical CNT length, and
- extremely high electron current density,

allows proposing them as candidates for the development of nano-sized Chernekov-type emitters

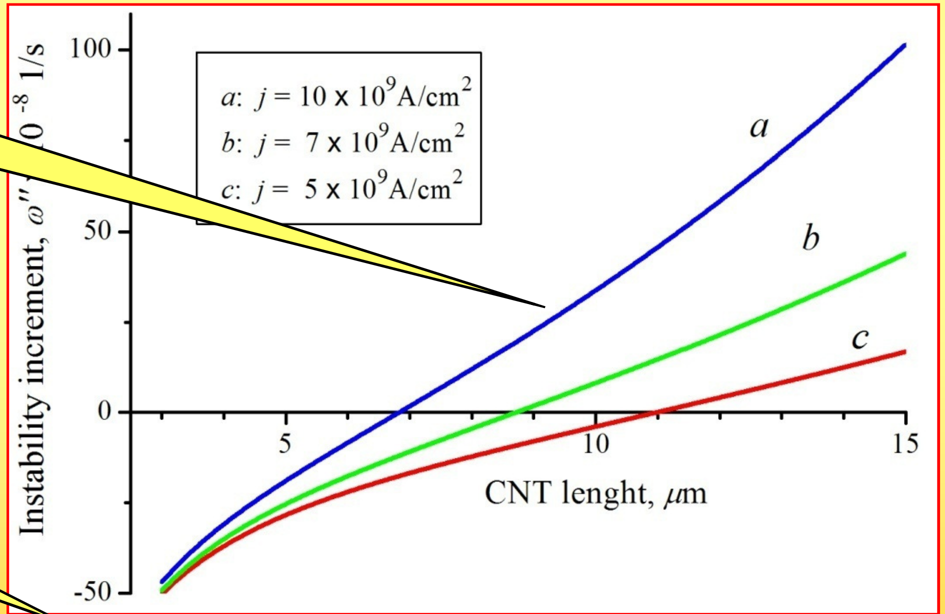
Threshold Current and Instability Increment

PHYSICAL REVIEW B 79, 125408 (2009)

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

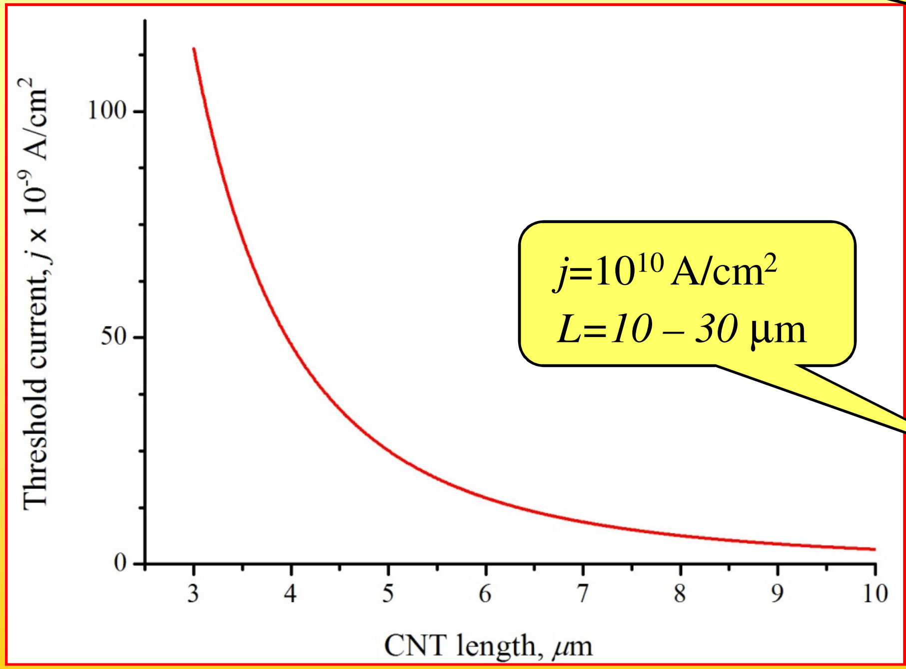
K. G. Batrakov, S. A. Maksimenko, and P. P. Kuzhir C. Thomsen

Gain per unit length is extremely large comparing with macrodevices



$j=10^{10}$ A/cm^2

L=10 – 30 μm



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

8. Conclusion: Where to 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***

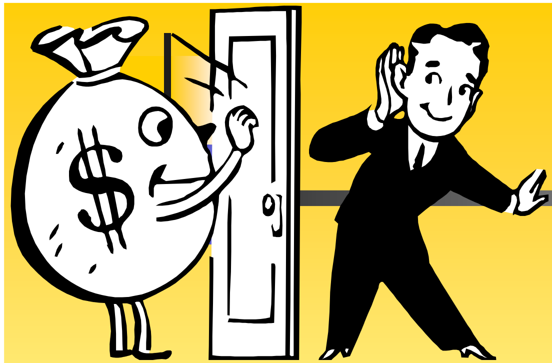
  monomolecular travelling wave tube, active circuit elements

- ***photothermal effect, medicine***

  Electromagnetic heating of CNTs and CNT thermo-dynamics, heat transfer on nanoscale

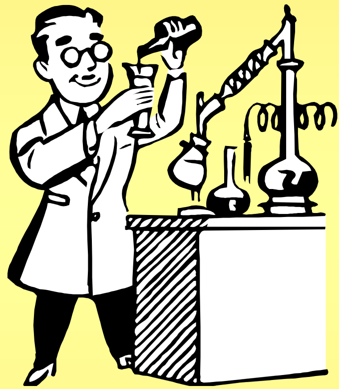
- ***Near-field optics & quantum information processing***

  Parcell effect, lifetime, Few-photon (quantum) circuits, quantum-EM



Acknowledgments

Support of the Research:



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B-1708

Thank you for your attention!