September 20, 2017

Propagation and Generation of Electromagnetic Waves in Carbon Nanotubes and Graphene

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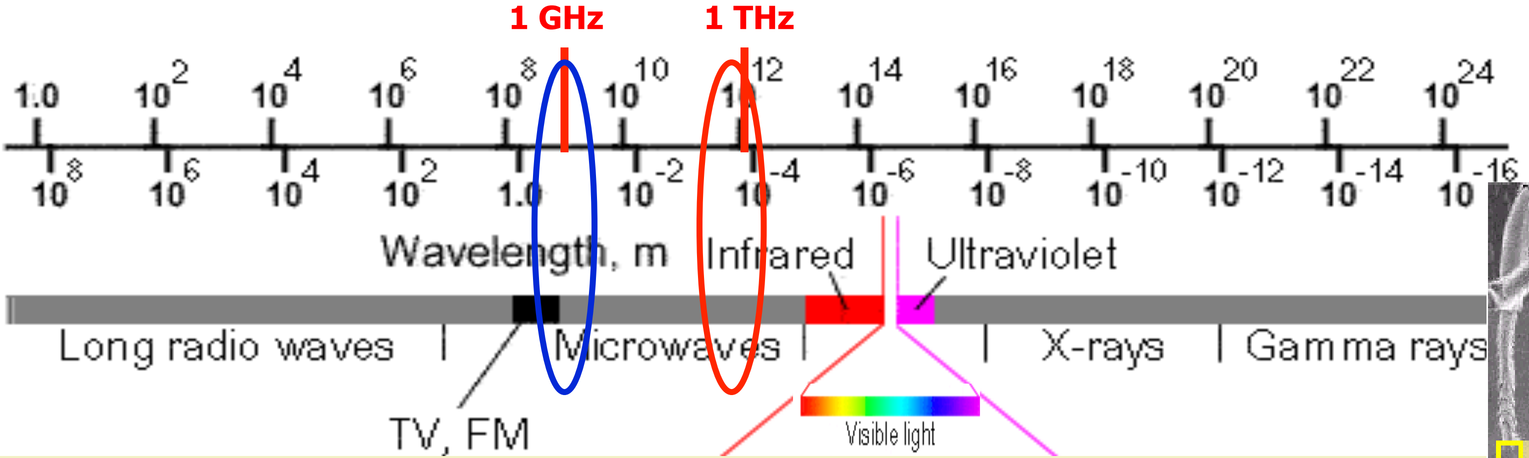
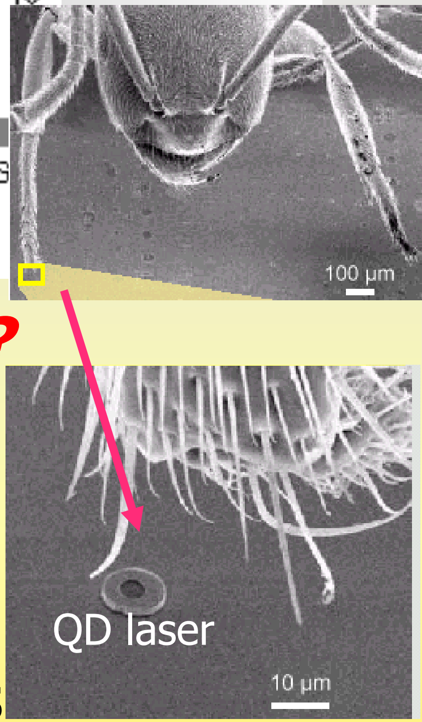
OUTLINE

1. *Introduction*
2. *Graphene and CNTs: physical properties*
3. *Surface plasmon slowing down in CNT and graphene*
4. *THz absorption peak*
5. *Nano –Traveling Wave Tube*
6. *Enhanced absorption in multi-layer graphene*
7. *Conclusion & Acknowledgments*





Which are current trends in electromagnetics?

- Miniaturization of electric circuits components …
- Energy consumption dropping …

electronic devices currently account for 15 percent of household

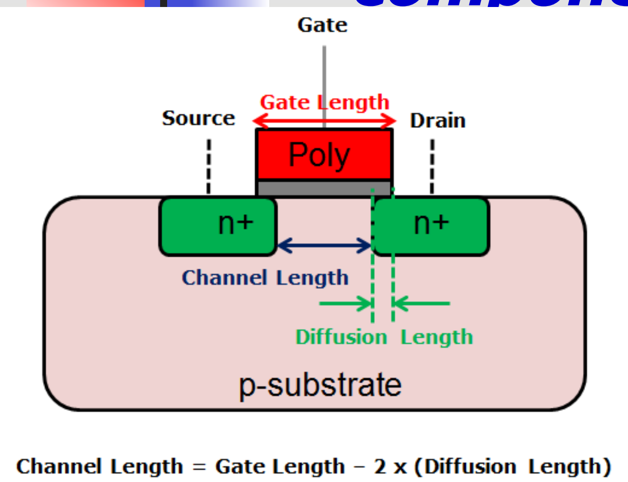
- Opening up the mm-Wave & THz frequency ranges

The wireless community has announced the 5G – a new generation of mobile wireless technology that will deliver multi-gigabit-per-second data speeds, with orders of magnitude more capacity and lower latency than today's wireless systems. Millimeter-wave (mmWave) and THz frequencies …

- Advanced EM materials…
- Cross-border and unconventional fields …

Security and medical imaging

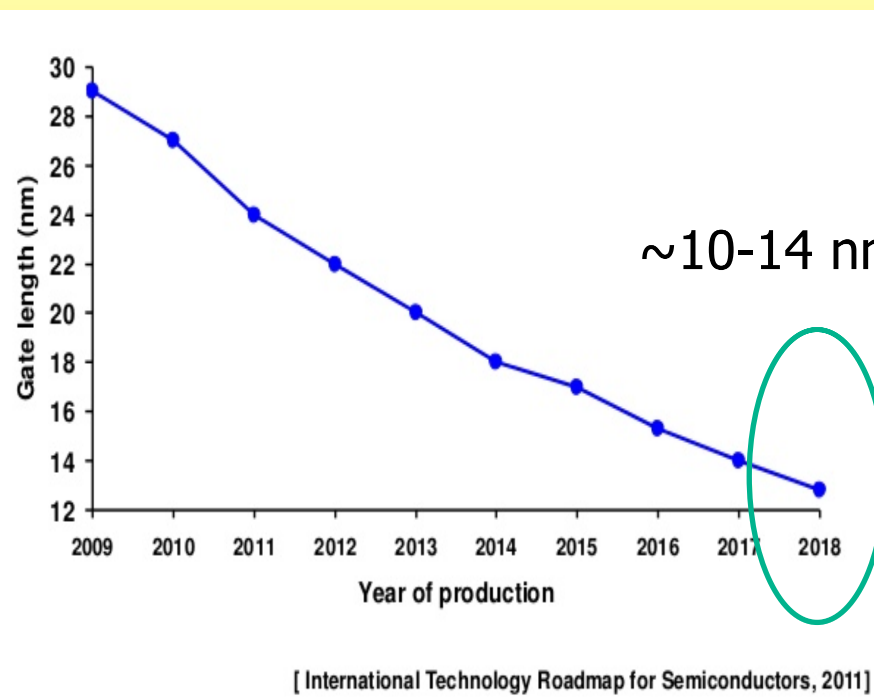
Miniaturization of electric circuits components …



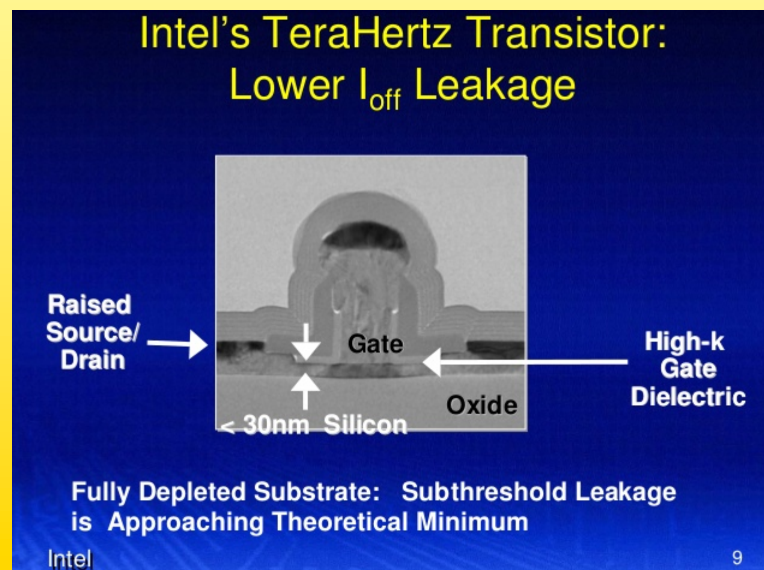
n-type field effect transistor

De Broglie wavelength of electron in typical semiconductor is of the order of ~ 70 – 7 nm (>> lattice constant) at 300 K and, thus, is comparable to the gate length (i.e. semiconductor nanostructures and devices)

Operating frequency of present-day microprocessors approaching 10 GHz and expected to enter the THz range



~10-14 nm

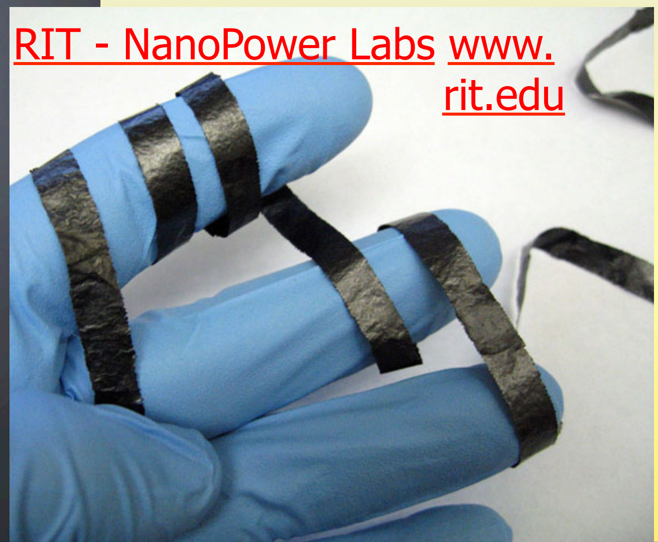


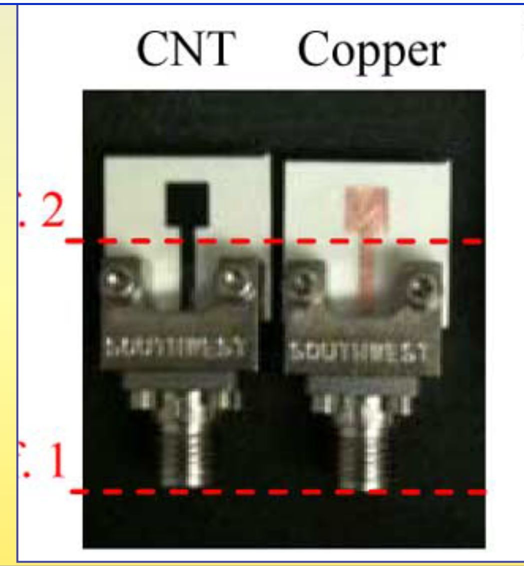
Nanocarbon in EM materials and macrodevices

3572 IEEE TRANSACTIONS ON ANTENNAS AND PROPAGATION, VOL. 59, NO. 10, OCTOBER 2011

Carbon Nanotube Composites for Wideband Millimeter-Wave Antenna Applications

Aidin Mehdipour, *Member, IEEE*, Iosif D. Rosca, Abdel-Razik Sebak, *Fellow, IEEE*, Christopher W. Trueman, and Suong V. Hoa





IEEE TRANSACTIONS ON ANTENNAS AND PROPAGATION

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*

Fig. 1 Very flexible E-textile antenna printed on polyn

Nanoelectromagnetics

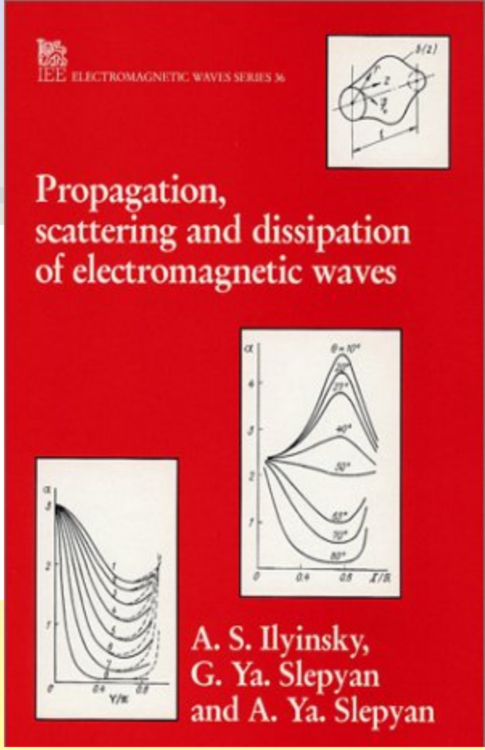
A research discipline studying the behaviour of high-frequency electromagnetic radiation on nanometer scale is currently emerging as a synthesis of macroscopic electrodynamics and microscopic theory of electronic properties of different nanostructures

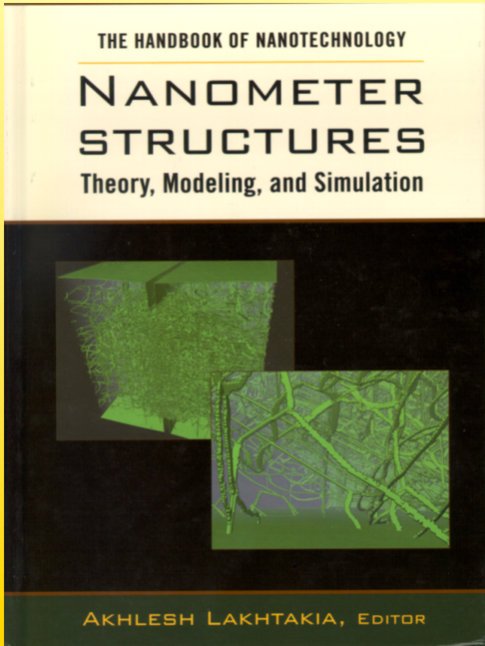
FUNDAMENTAL CHALENGE in NANOSCALE ELECTROMAGNETICS is

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

or

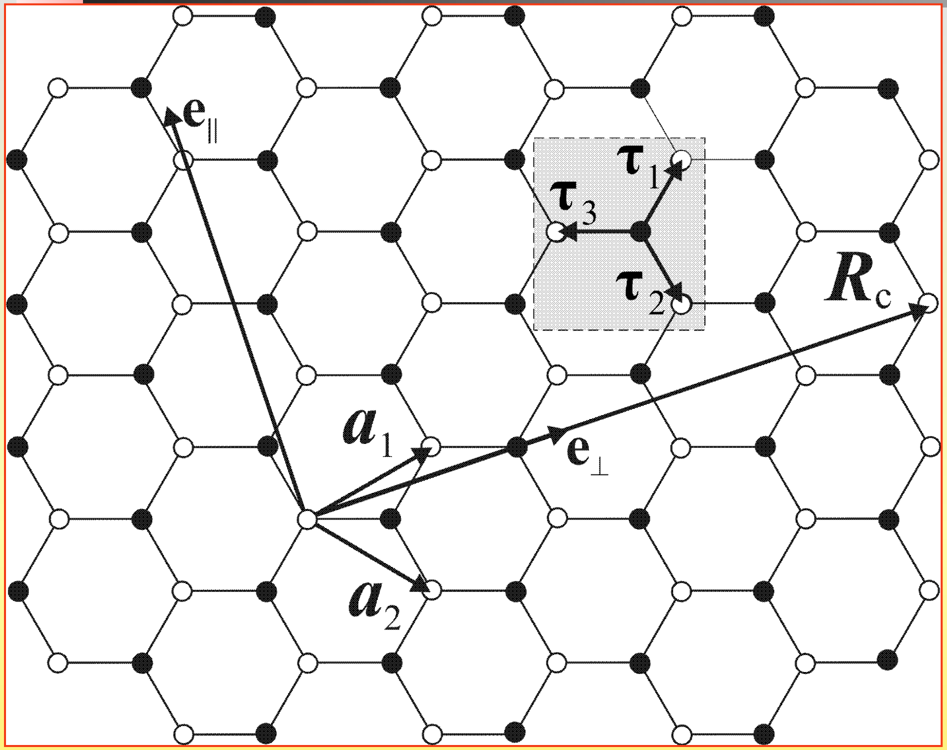
INTERPLAY of SCHROEDINGER and MAXWELL EQUATIONS

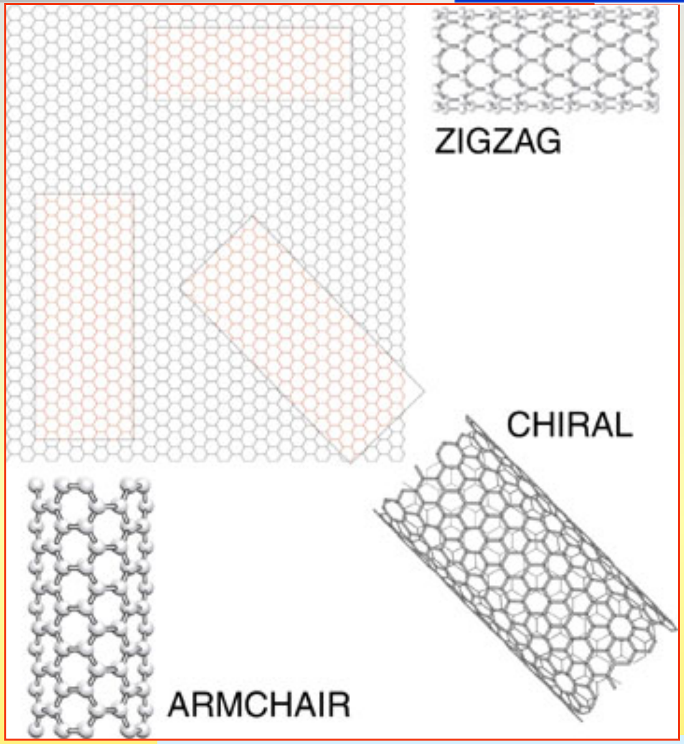




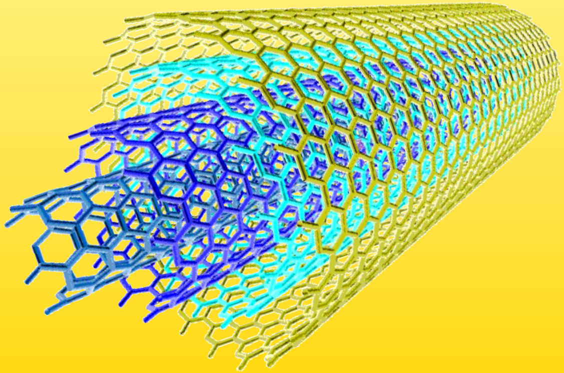
Maksimenko & Slepyan, Nanoelectromagnetics of low-dimensional structures

Graphene & Carbon Nanotube





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



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

SWCNT *(m,n)*

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

Graphene & CNTs:Physical properties

BSU INP

	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

CNT as nanoantenna

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http://www.urbanfischer.de/journals/aeue

55, 273-280 (2001)

AEÜ International Journal of Electronics and Communications

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

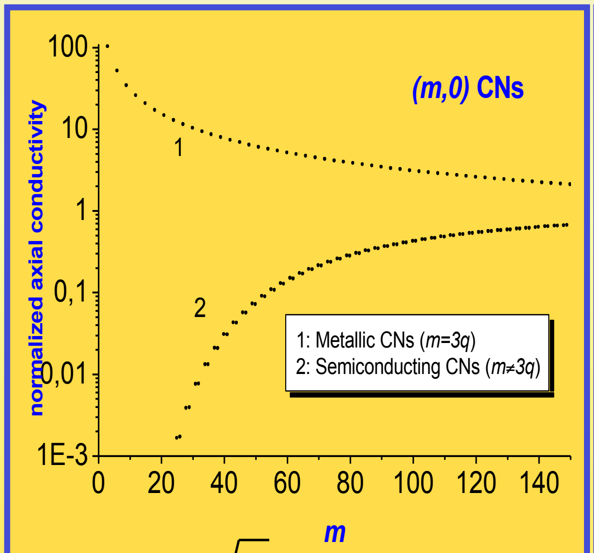
The key problem for the CNT electromagnetic response modeling is the conductivity low evaluation

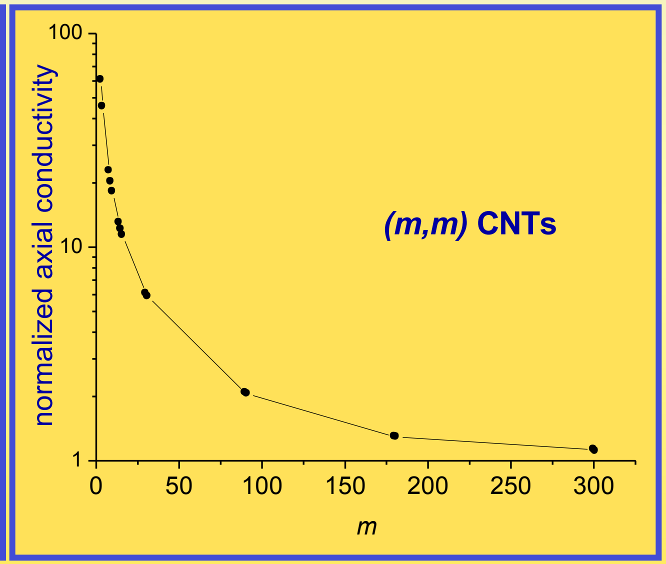
Dynamical conductivity of CNT

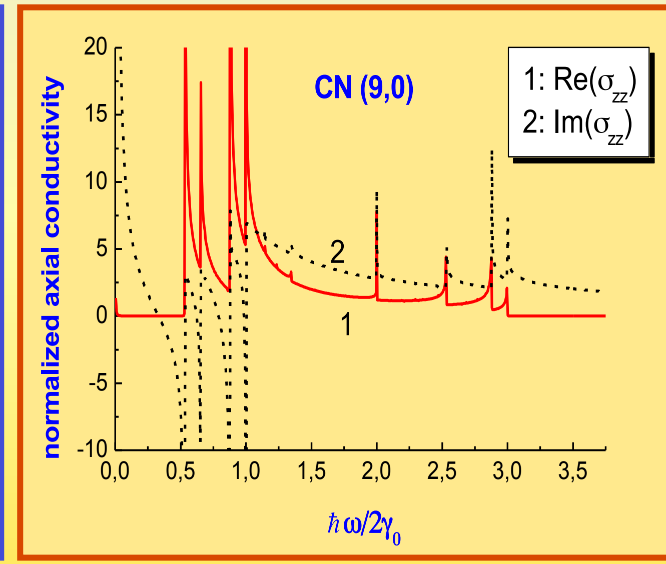
Radial dependence of the conductivity below and in the optical transitions band

zigzag

amchair







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

d =1.42A is the interatomic distance in graphene

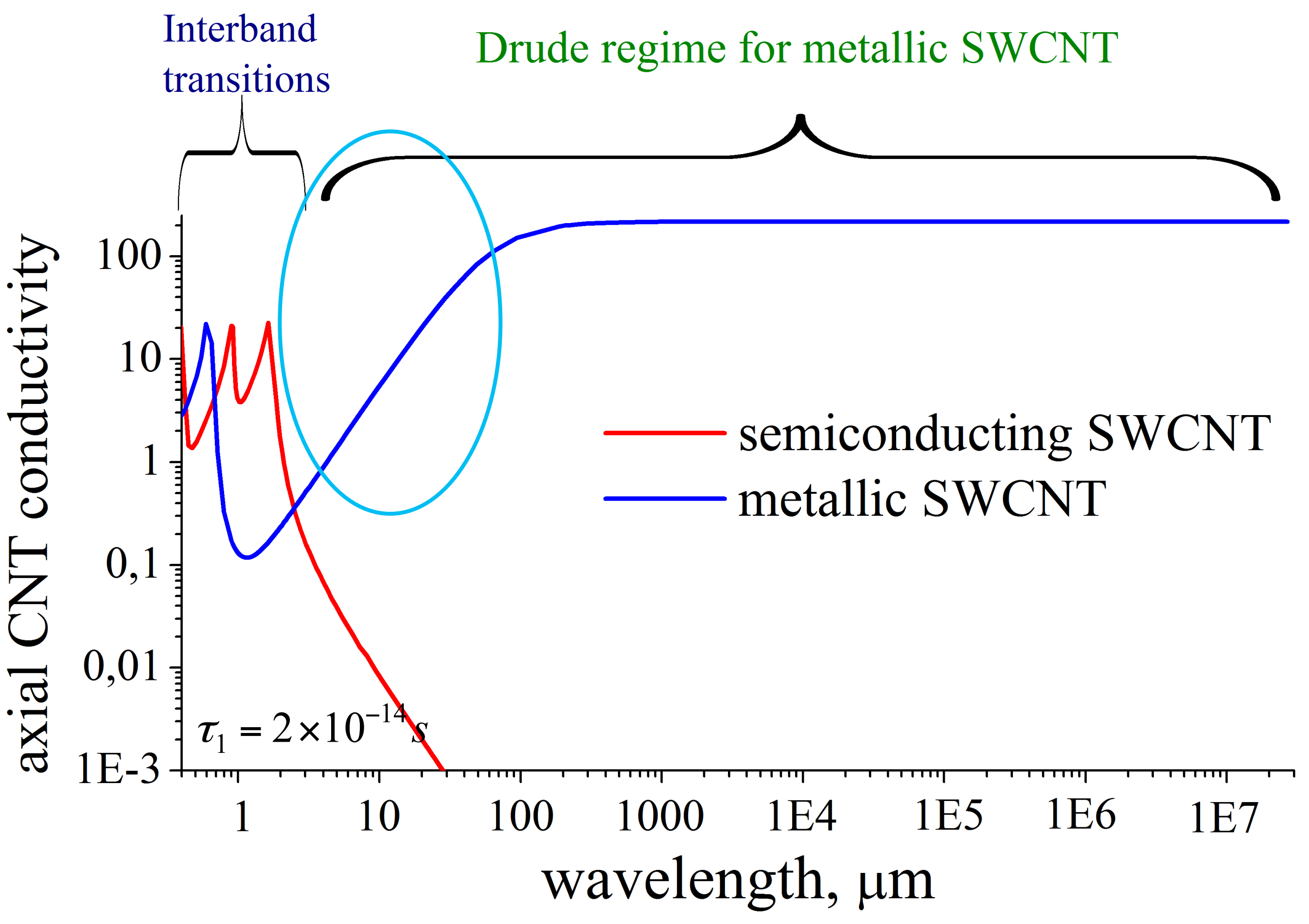
PHYSICAL REVIEW B VOLUME 60, NUMBER 24 15 DECEMBER 1999-II

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

Axial surface conductivity of isolated single-wall carbon nanotube

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



Electrodynamics of CNTs

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

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

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In optical and below ranges

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

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

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

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 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].

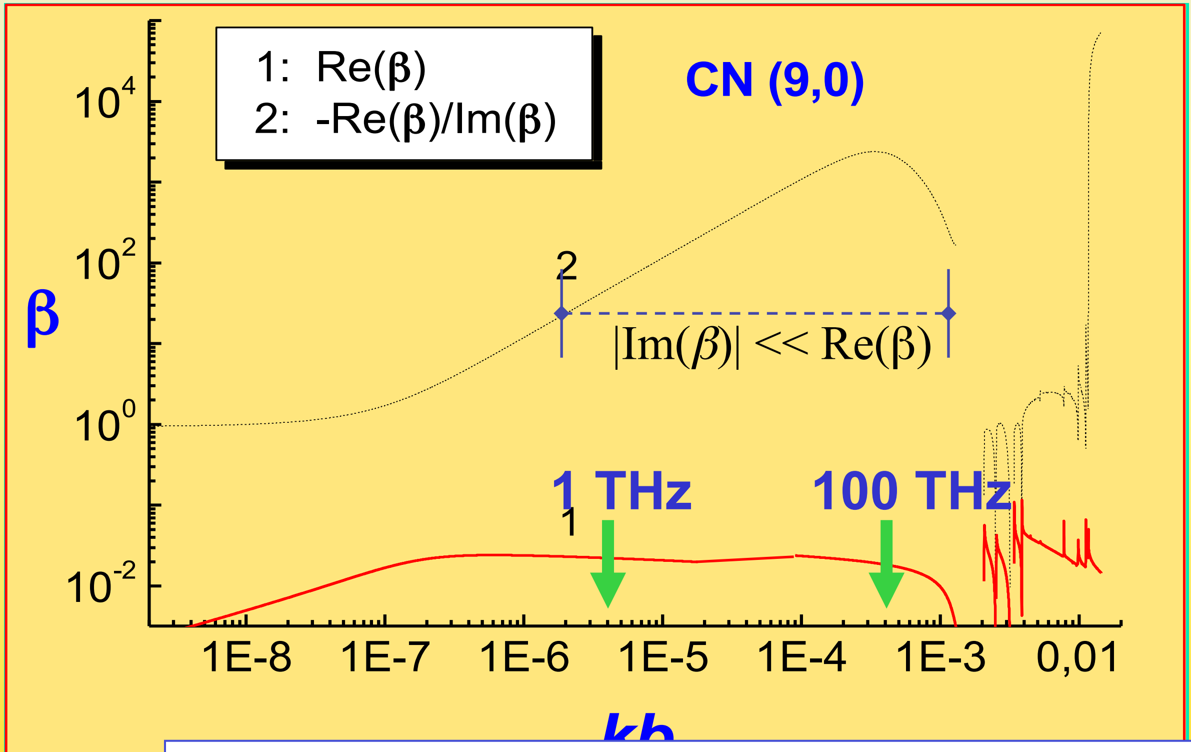
Dispersion equation of surface waves

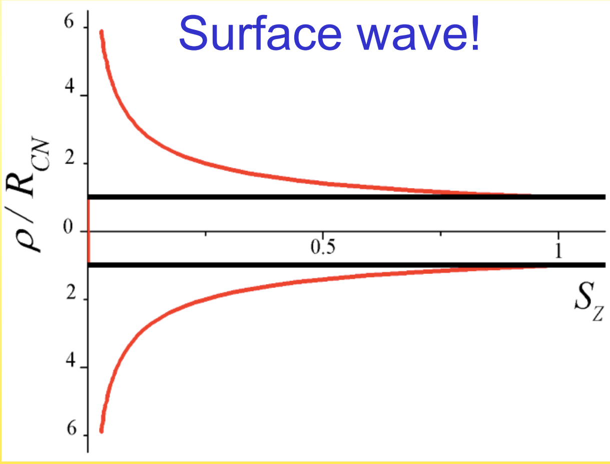
$$\frac{\kappa^2}{k^2} K_q(\kappa R) I_q(\kappa R) = \frac{ic}{4\pi R \sigma_{zz}} \left(1 - \frac{\kappa^2 + k^2}{(\omega + i/\tau)^2} c^2 l_0 \right).$$

Surface Wave Propagation

Complex-valued slow-wave coefficient β 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

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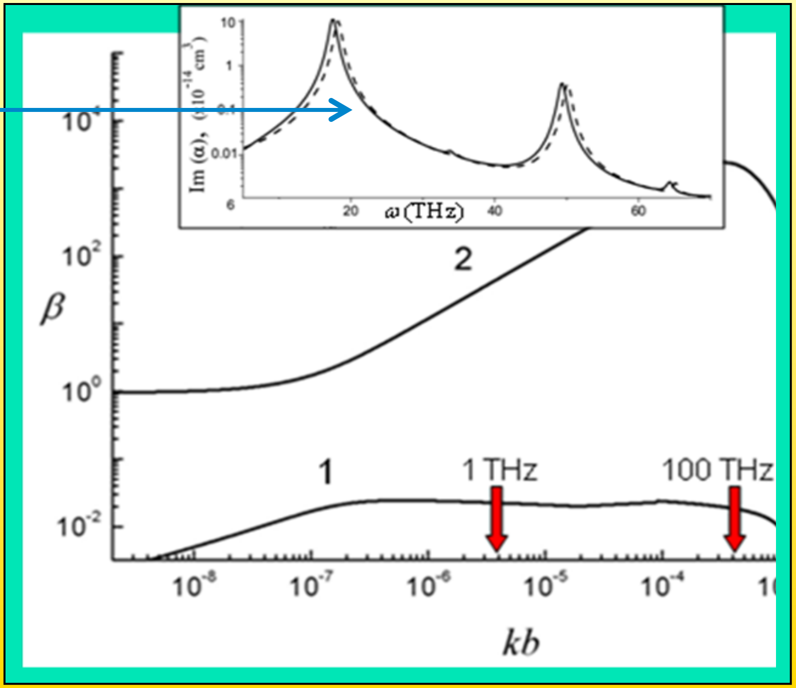
What Can We Learn from the Picture?

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

- ✓ Electromagnetic slow-wave line: $v_{ph}/c \sim 0.02$
- ✓ 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

Experimental observations of THz peak in CNT-based composites

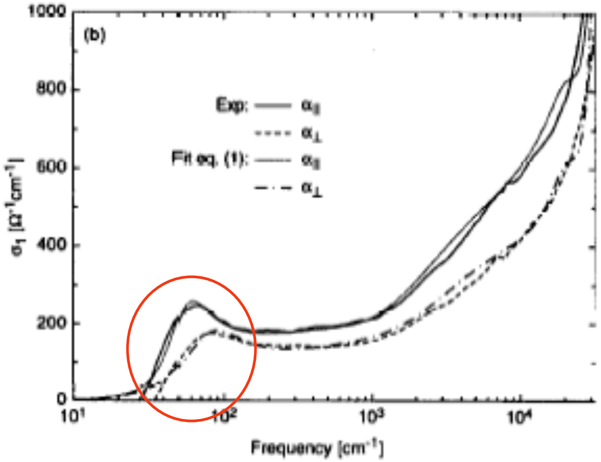


Fig. 1. (a) [redacted] (b) optical conductivity of oriented nanotubes films along the $\alpha_\parallel$ and $\alpha_\perp$ directions. The MG fits [Equation (1)] are also presented.

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

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

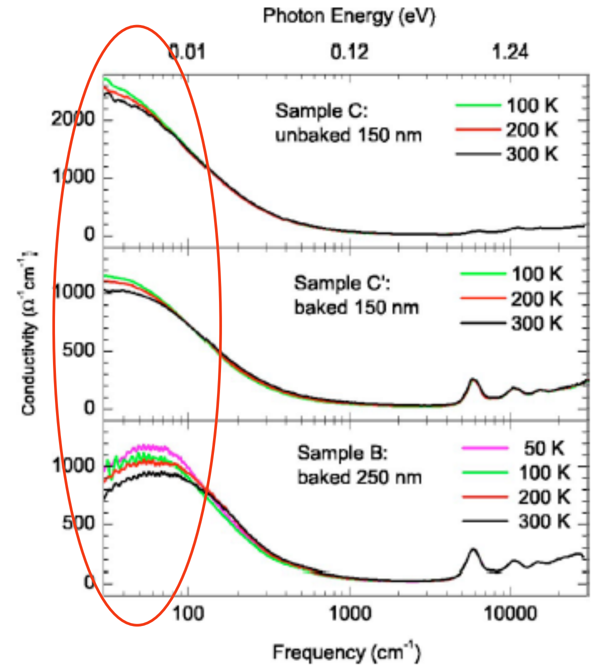
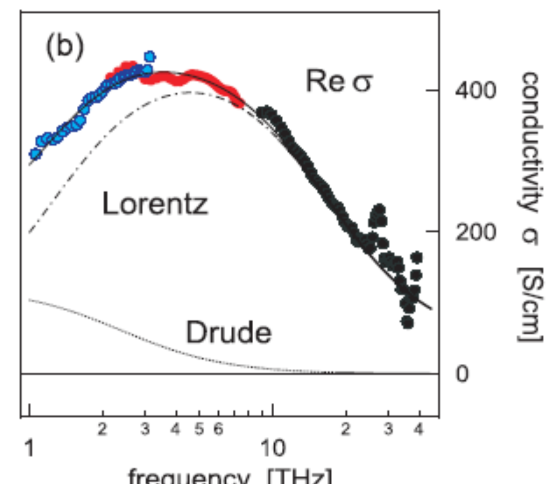


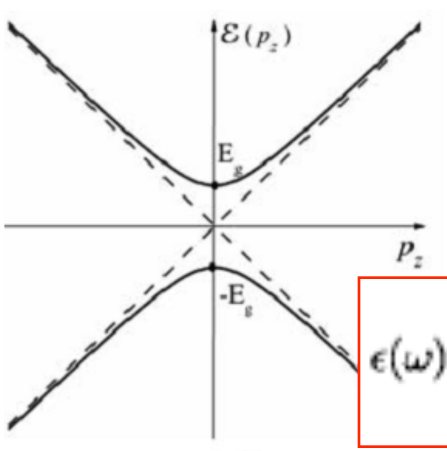
FIG. 3. (Color online) Temperature dependence of the optical conductivity of the two samples.

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



(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)



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

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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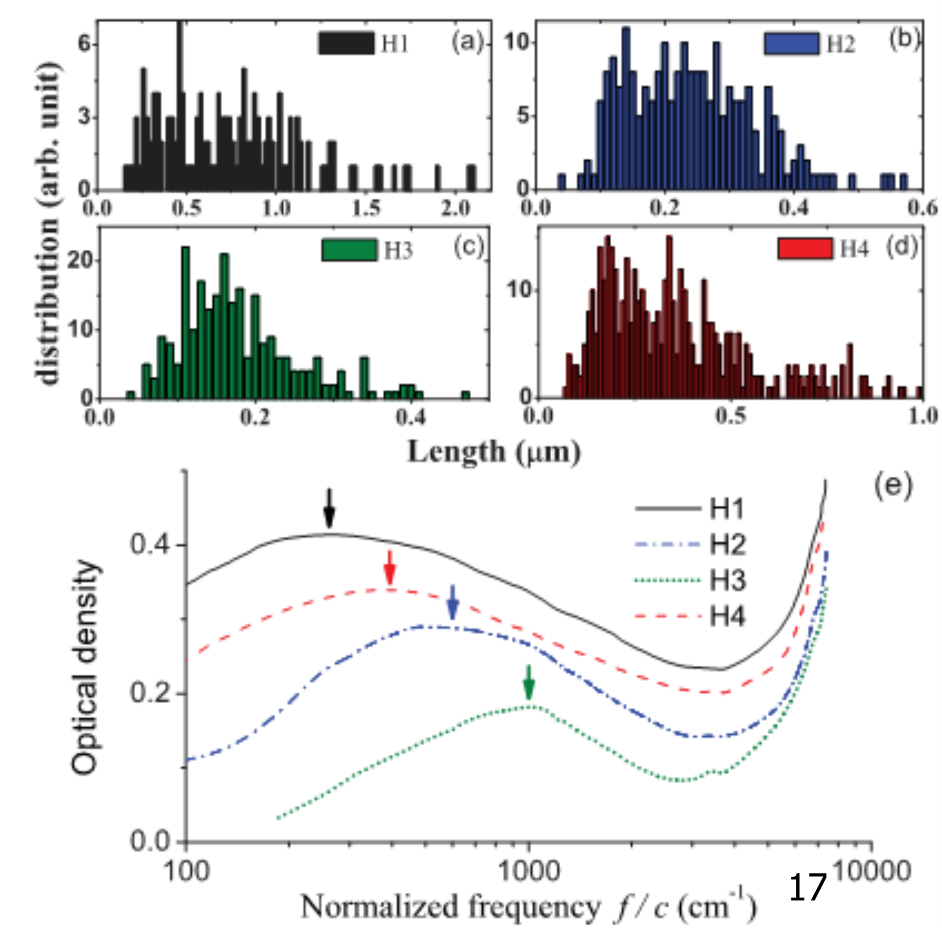
THz peak: experiment

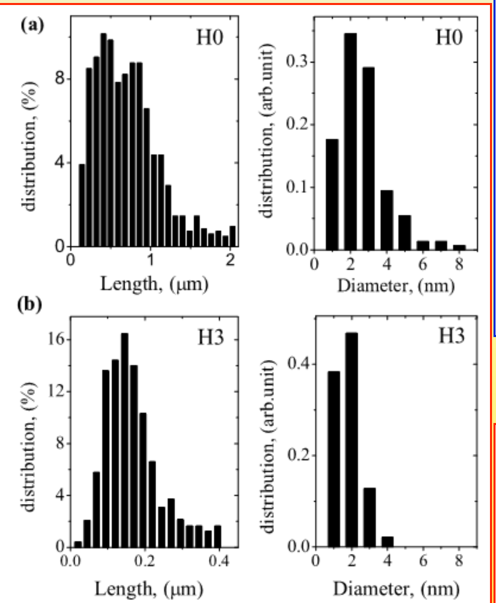
Direct experimental demonstration of the correlation between the THz peak frequency and the SWCNT length. That is, the direct experimental evidence of the slowing down in CNTs and the FIR-THz antenna

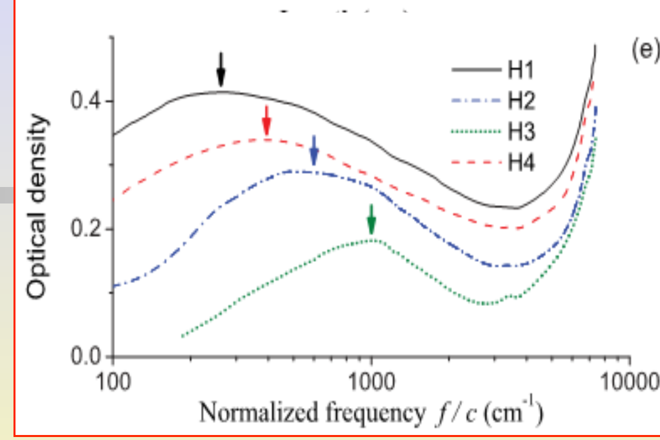


Functional materials for THz range

Method of the calibrated CNTs fabrication

Distribution of the CNT bundles before (a) and after (b) treatment

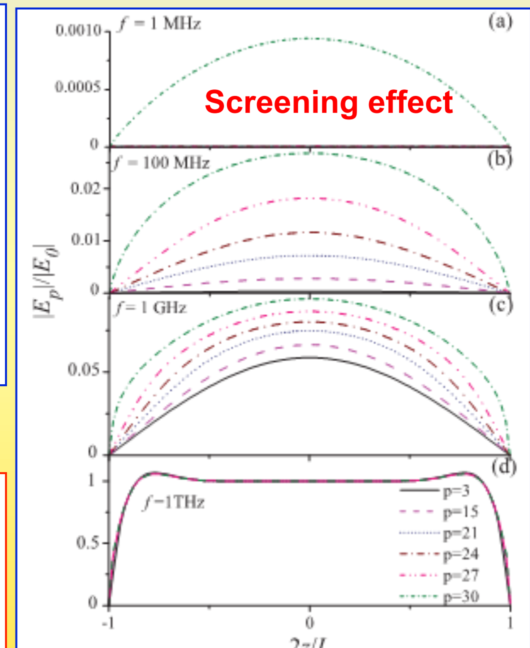




IOP Publishing NANOTECHNOLOGY
Nanotechnology **23** (2012) 495714 (9pp) doi:10.1088/0957-4484/23/49/495714

Soft cutting of single-wall carbon nanotubes by low temperature ultrasonication in a mixture of sulfuric and nitric acids

M V Shuba[1], A G Paddubskaya[1], P P Kuzhir[1], S A Maksimenko[1], V K Ksenevich[2], G Niaura[3], D Seliuta[3], I Kasalynas[3] and G Valusis[3]



Letters
IOP Publishing Journal of Physics D: Applied Physics
J. Phys. D: Appl. Phys. **50** (2017) 08LT01 (6pp) doi:10.1088/1361-6463/aa5628

Letter

Short-length carbon nanotubes as building blocks for high dielectric constant materials in the terahertz range

M V Shuba[1,7], A G Paddubskaya[2], P P Kuzhir[1,3], S A Maksimenko[1,3], E Flahaut[4], V Fierro[5], A Celzard[5] and G Valusis[2,6]

Shuba et al., PRB 2013

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

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

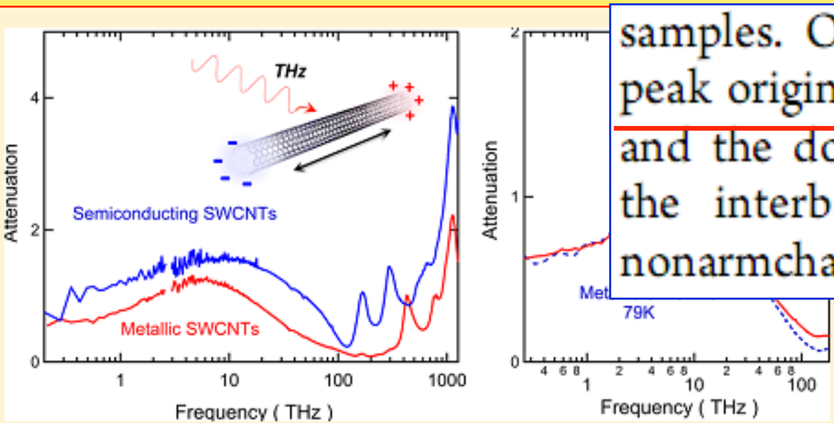
Experimental proof of localized plasmon resonance was found in thin films containing either single-walled carbon nanotubes (SWNT) or SWNT bundles of different length. All samples were prepared by a simple technique

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

NANO LETTERS
Letter
pubs.acs.org/NanoLett

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 Lüttge,[‡,§] and Junichiro Kono*,[†,∥]

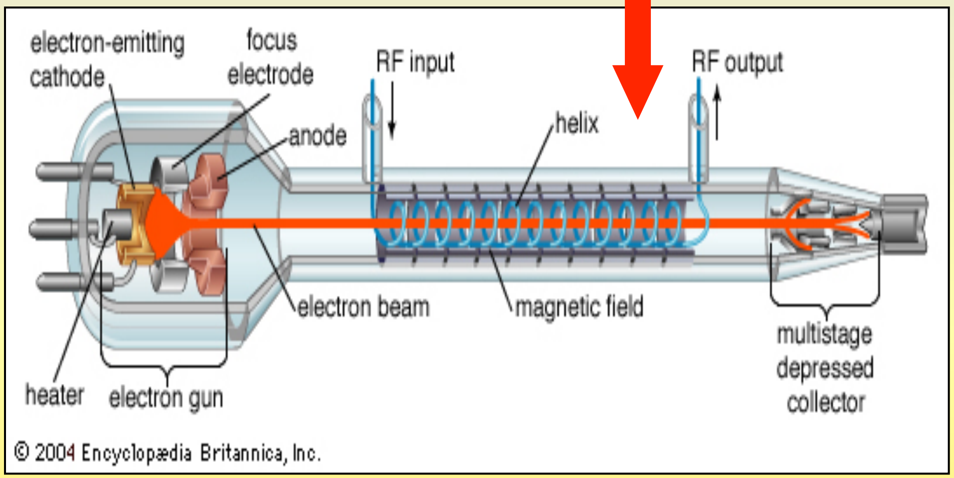


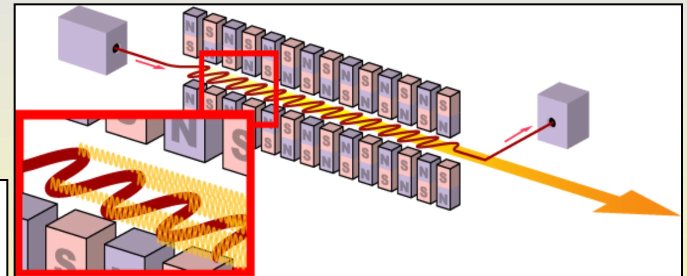
samples. Our experimental results show that the broad THz peak originates from a plasmon resonance in both the metallic and the doped semiconducting carbon nanotubes rather than the interband excitation of the curvature-induced gap in nonarmchair metallic nanotubes. The intraband free electron

Nano – TWT and Nano-FEL

a slowing-down system

Macroscopic TWT

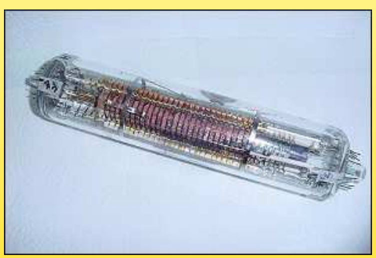




FEL

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

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



Available online at www.sciencedirect.com
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PHYSICA E
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, v/c~0.02
- ballisticity of the electron flow over typical CNT length, *l*~1-10 μm
- extremely high electron current density, I~10^10 A/cm^2

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

Threshold Current and Instability Increment

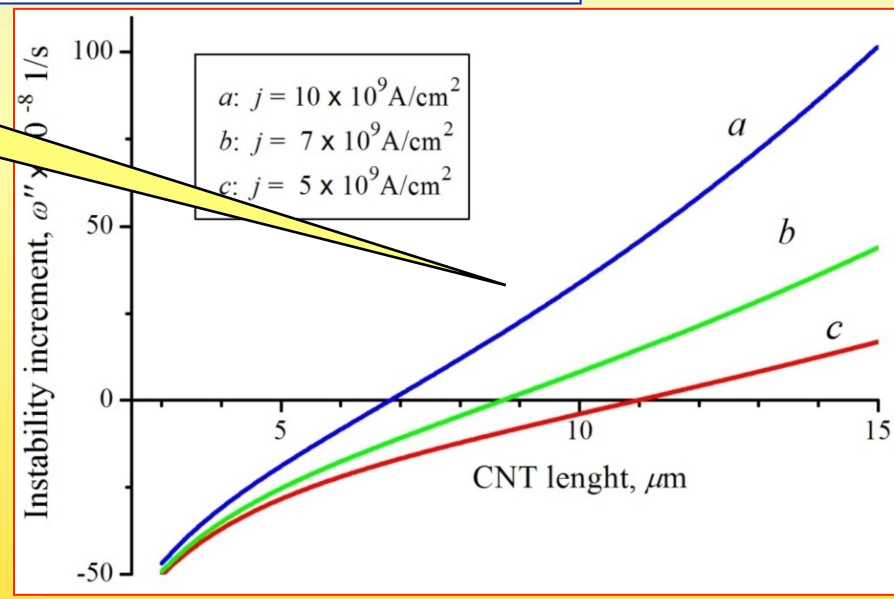
PHYSICAL REVIEW B **79**, 125408 (2009)

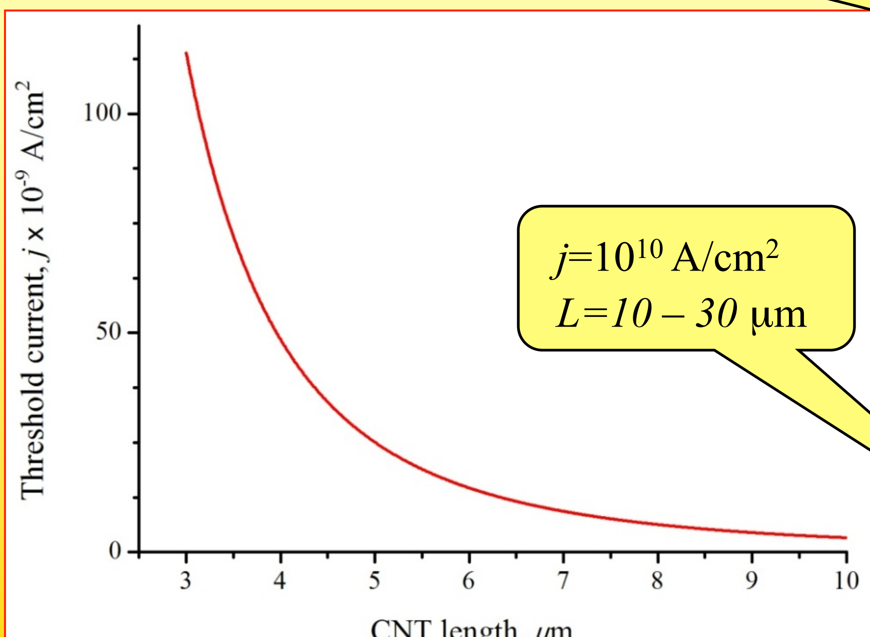
Carbon nanotube as a Cherenkov-type light emitter and free electron laser

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

C. Thomsen

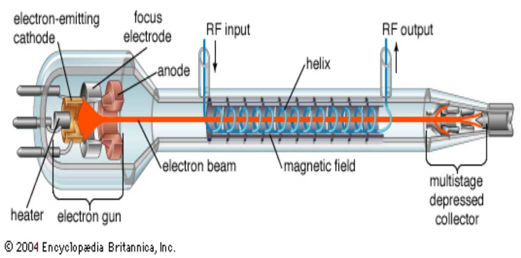
Gain per unit length is extremely large comparing with macrodevices



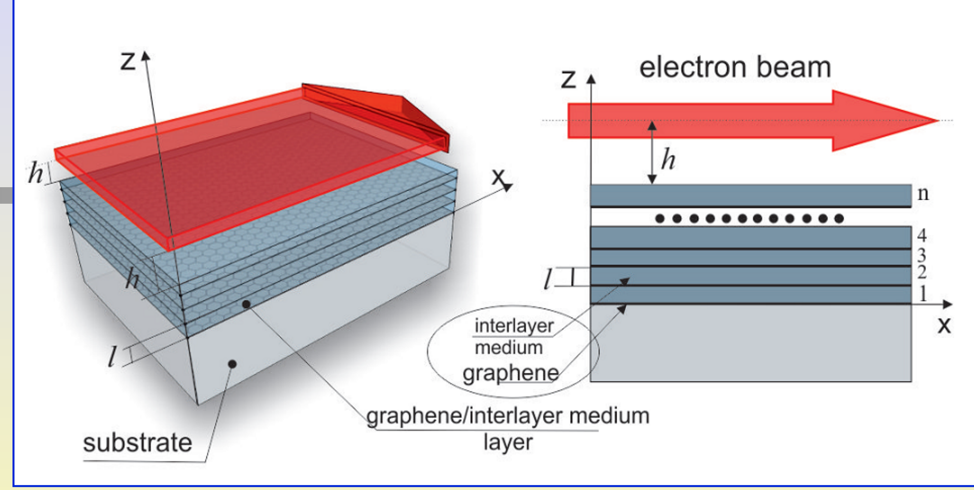


j=10^{10} A/cm^2
L=10 – 30 μm

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



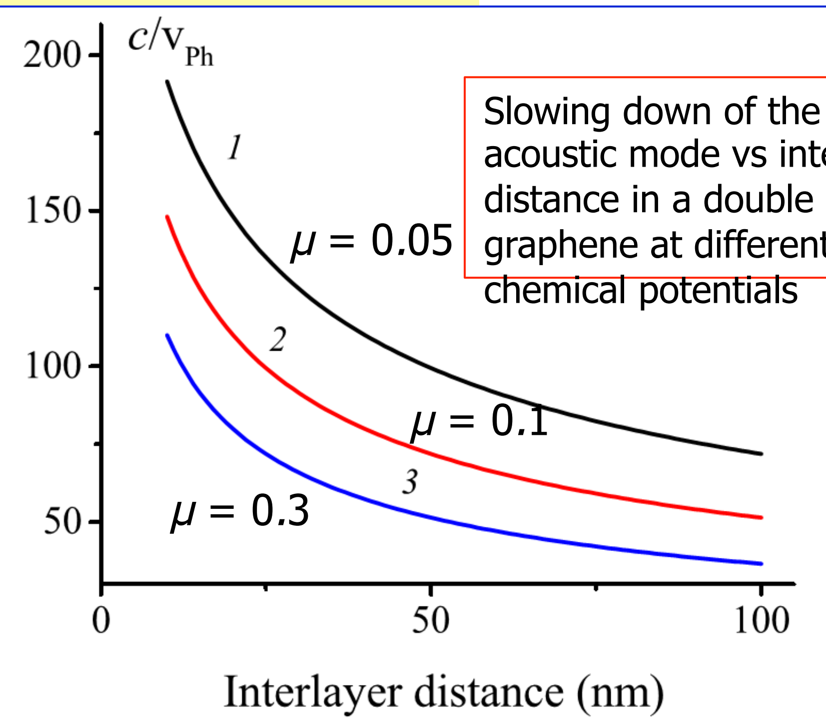
Quasi-cherenkov radiation of an electron beam passing over the graphene/polymer sandwich structure



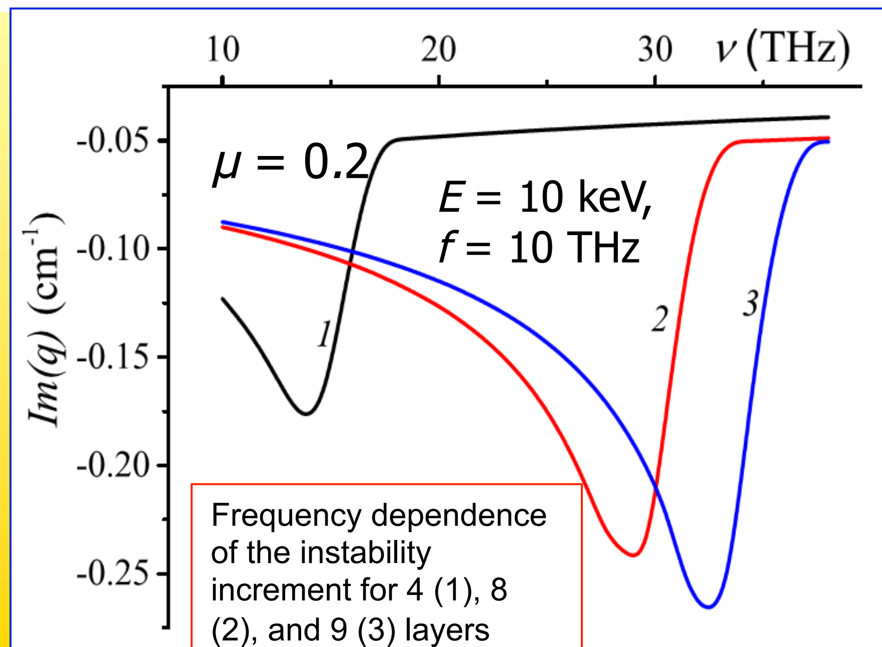
PHYSICAL REVIEW B **95**, 205408 (2017)

Graphene layered systems as a terahertz source with tuned frequency

K. Batrakov* and S. Maksimenko

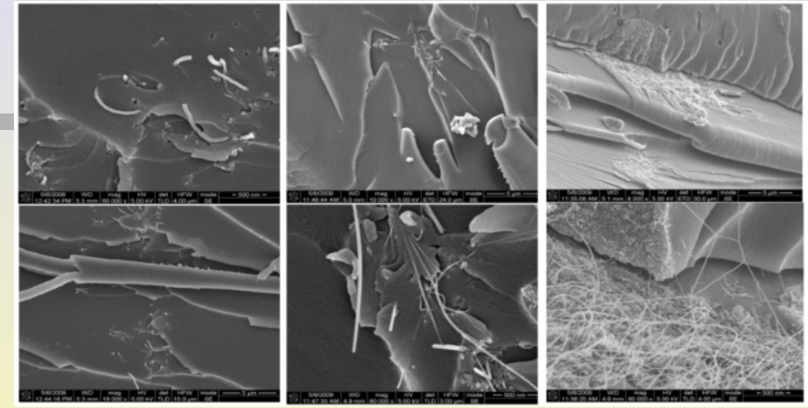


Slowing down of the acoustic mode vs interlayer distance in a double graphene at different chemical potentials

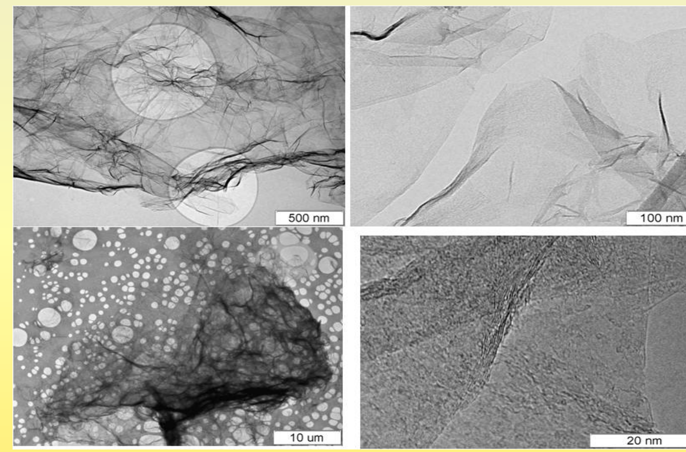


Frequency dependence of the instability increment for 4 (1), 8 (2), and 9 (3) layers

EM properties and application of nanocarbon materials in GHz and THz ranges

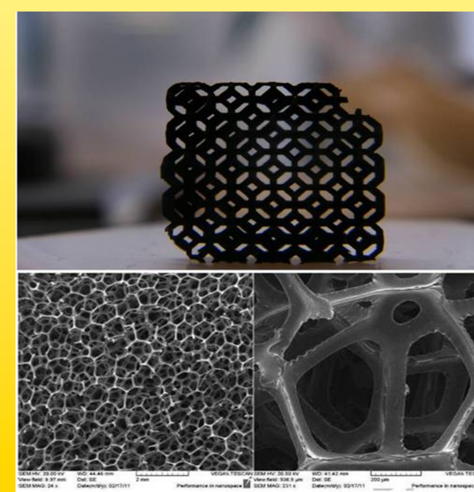


Three classes of ultralight and/or ultrathin EM materials are under study



(i) Polymer composites filled with various carbon micro/nanoparticles of high surface area:CNTs, GNP, OLC, EG, AC, CBH, magnetic nano-particles

(ii) CNT-, Graphene and carbon ultra-thin films (CNT films, few-layers graphene, graphene / PMMA sandwiches, graphene-like films)



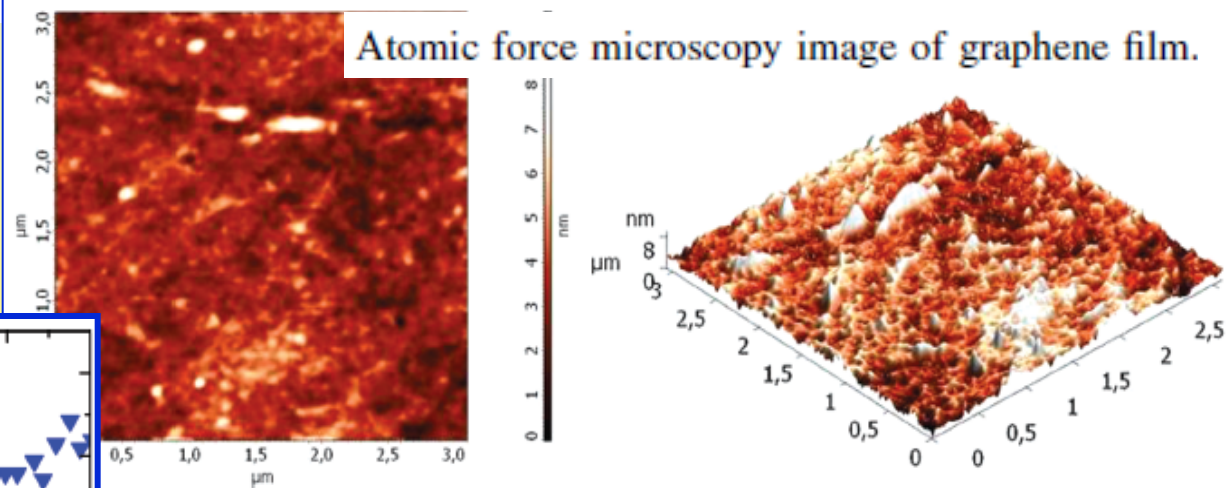
(iii) Cellular carbon structures (carbon foams, mesogels, aerogels, 3D architectures)

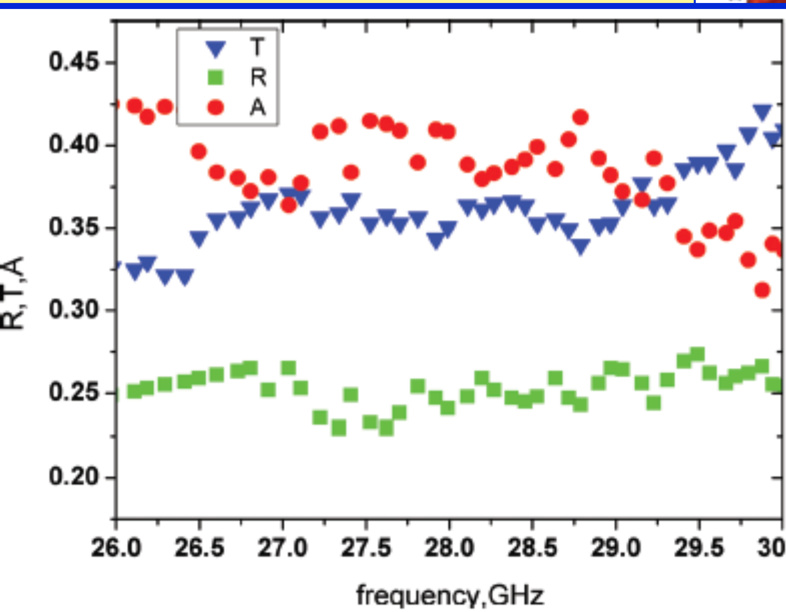
Journal of Nanoscience and Nanotechnology
Vol. 13, 5864–5867, 2013

Multilayered Graphene in K_a-Band: Nanoscale Coating for Aerospace Applications

P. Kuzhir[1,*], N. Volynets[1], S. Maksimenko[1], T. Kaplas[2], and Yu. Svirko[2]

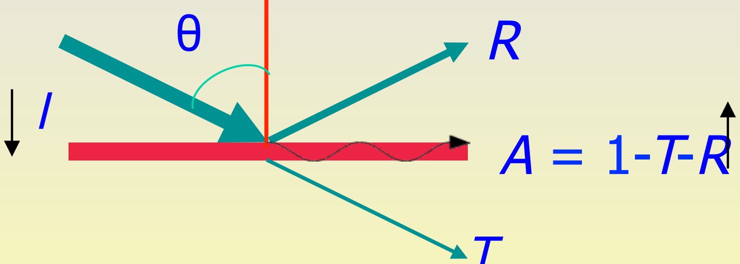
The layer thickness ~ 5 nm





In *Ka-band we observed that multilayered graphene being* thousands times thinner than skin depth provide reasonably high EM attenuation, caused by absorption of EM signal. EM absorption is as high as 43% at 26 GHz for graphene film of 5 nm thickness.

Thin conductive film



$l \ll$ skin depth

Im $\varepsilon \gg 1$

$l\sqrt{\varepsilon} \ll \lambda$

For a thin film in free air,
A **peaks at 50 % when** $l = l_\sigma$

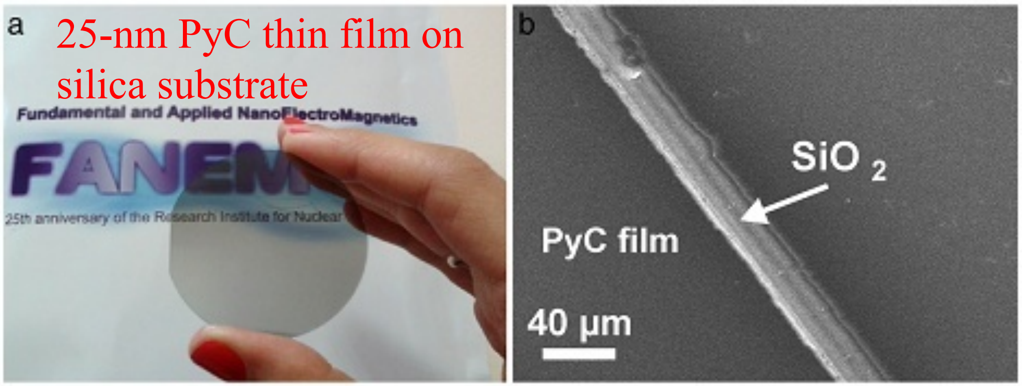
$l_\sigma \approx 1/\sigma$:
A=50%, R=25%, T=25%.

For every conductive material which satisfies

$l \ll l_{scin}$, $Im\, \varepsilon \gg 1$, $l\sqrt{\varepsilon} \ll \lambda$,

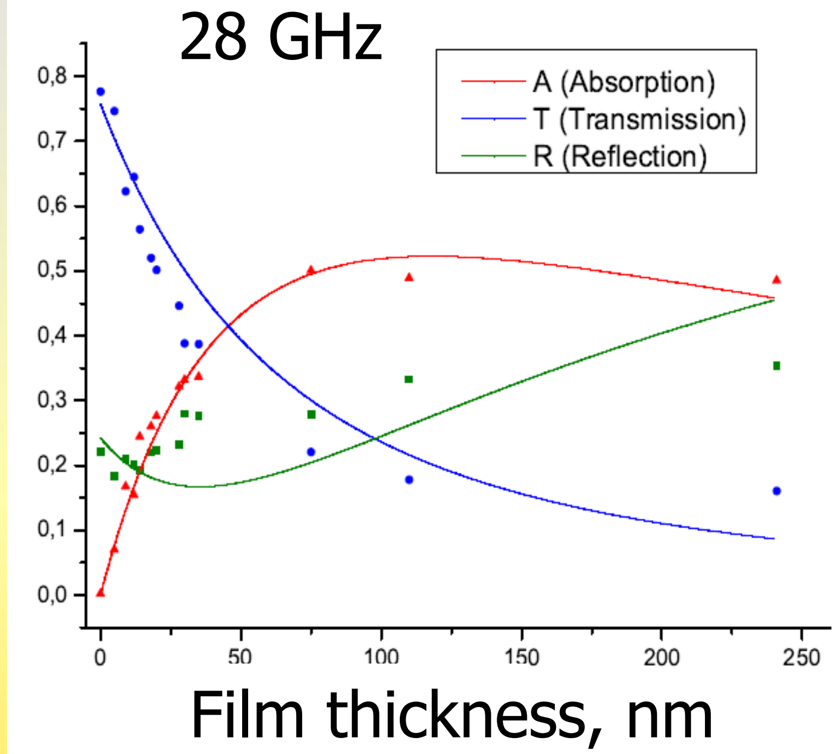
There is an optimal thickness l_σ, inversely proportional to film conductivity σ for which absorbance A, reflectance R and transmittance T are A=50%, R=25%, T=25% correspondently.

Microwave probing of PyC films



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

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.



APPLIED PHYSICS LETTERS **103**, 073117 (2013)

Enhanced microwave shielding effectiveness of ultrathin pyrolytic carbon films

K. Batrakov,[1,a),b)] P. Kuzhir,[1,b),c)] S. Maksimenko,[1] A. Paddubskaya,[1] S. Voronovich,[1] T. Kaplas,[2] and Yu. Svirko[2]
[1]*Research Institute for Nuclear Problems, Belarusian State University, Minsk 220030, Belarus*
[2]*Department 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 in microwave frequency range, caused by absorption mechanism

SCIENTIFIC REPORTS

4 : 7191 (2014)

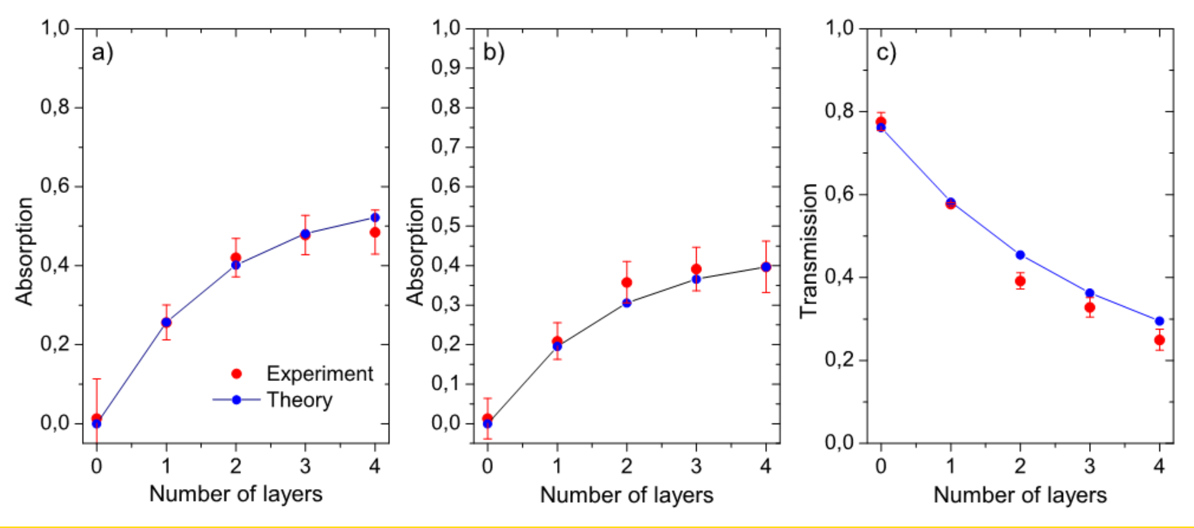
OPEN

SUBJECT AREAS:
GRAPHENE
ELECTRONIC PROPERTIES AND DEVICES
NANOSCALE MATERIALS

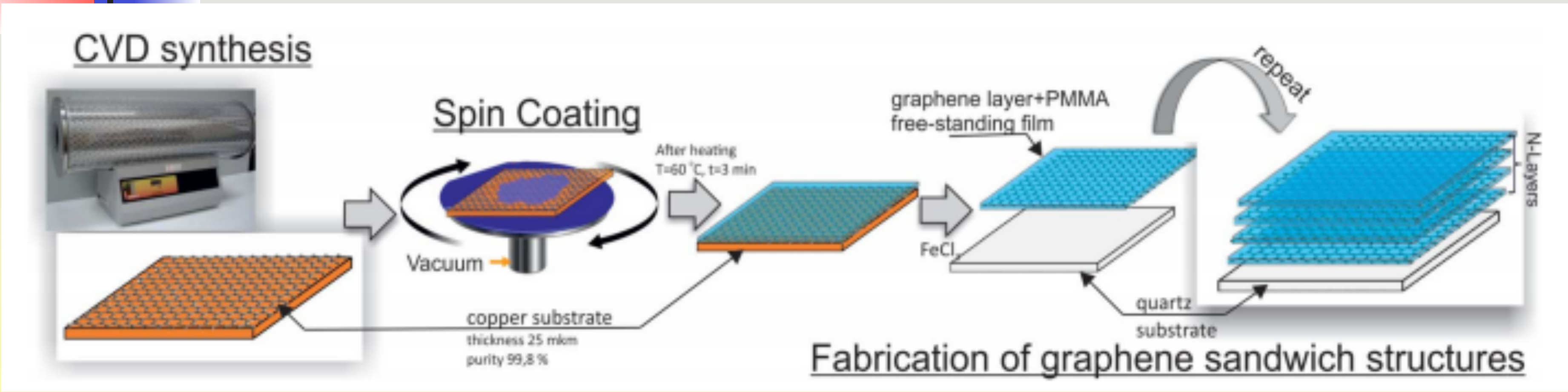
Flexible transparent graphene/polymer multilayers for efficient electromagnetic field absorption

K. Batrakov[1], P. Kuzhir[1], S. Maksimenko[1], A. Paddubskaya[1], S. Voronovich[1], Ph Lambin[2], T. Kaplas[3] & Yu Svirko[3]

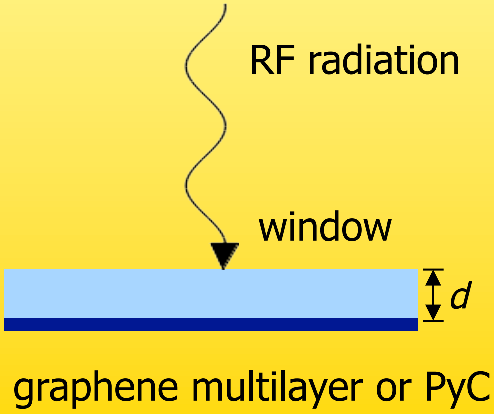
EM absorption is as high as 50% for PyC film of 75 nm thickness and a few layers graphene, 1.5-2 nm thick.

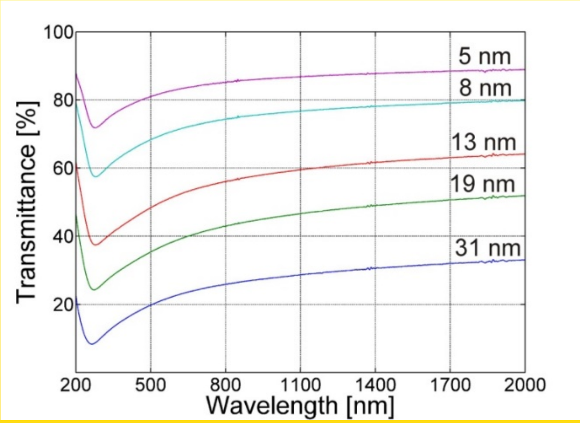


Fabrication of multi-layerd PMMA/Graphene structures



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 microwave measurements and cycle sample with diameter 1 cm for THz measurements.



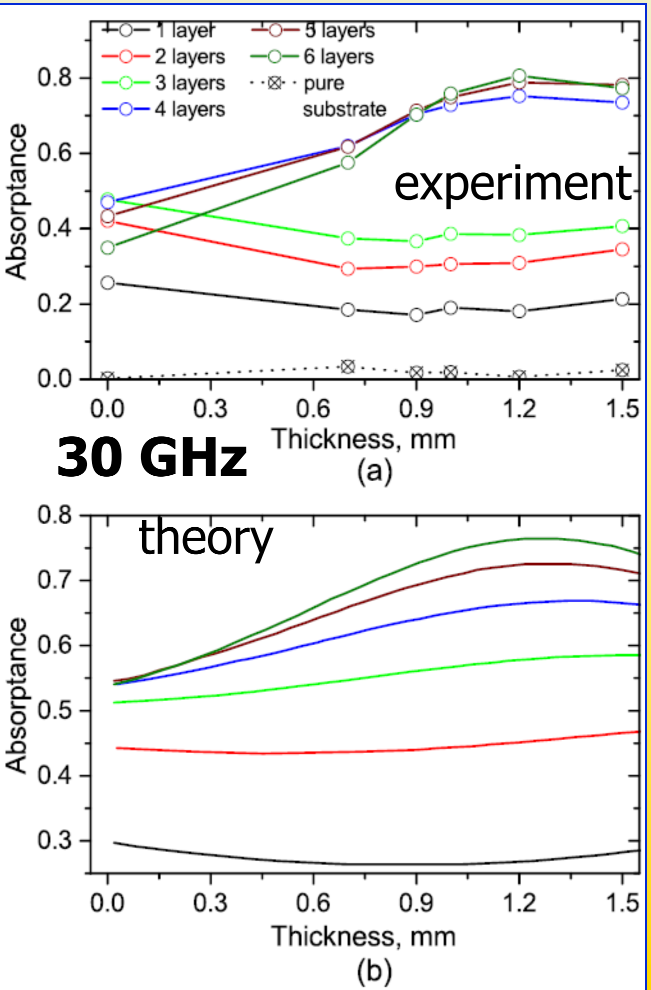


Optimization of the absorption in graphene/polymer structures by dielectric substrate

APPLIED PHYSICS LETTERS **108**, 123101 (2016)

Enhanced microwave-to-terahertz absorption in graphene

K. Batrakov,[1,a)] P. Kuzhir,[1] S. Maksimenko,[1] N. Volynets,[1] S. Voronovich,[1] A. Paddubskaya,[2]
G. Valusis,[2] T. Kaplas,[3] Yu. Svirko,[3] and Ph. Lambin[4]



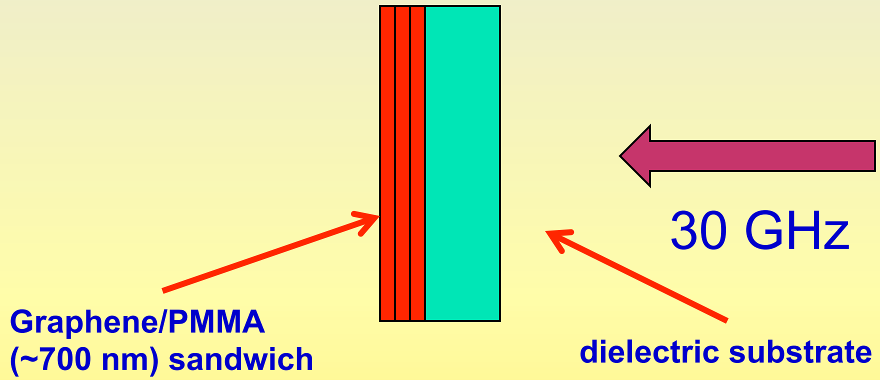
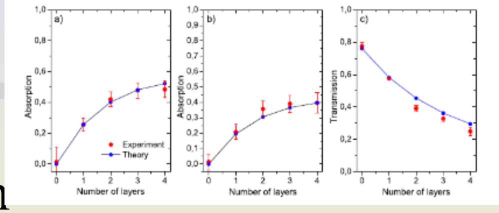
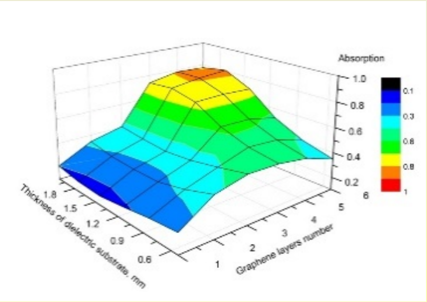


FIG. 2. Dependence of the absorbance of graphene/PMMA stacks and containing 1, 2. 6 graphene layers on thickness of the epoxy resin coating. (a) panel displays experimental data. Bottom curve presents absorption measured for the case of pure substrate with epoxide resin layers. (b) presents theoretical results. The following values of dielectric constants are used: $\varepsilon_{quartz} = 3.7$, $\varepsilon_{epoxy} = 3$. The absorptance depends on a non monotonous way on the overall substrate thickness, due to interference effects. When the thickness corresponds to a quarter of the effective wavelength in the substrate, the absorptance reaches a minimum or a maximum, depending on the total sheet conductance σ' of the graphene-PMMA multilayer. The turnover between these two behaviors in the wave-guide geometry corresponds to $N = 3$.

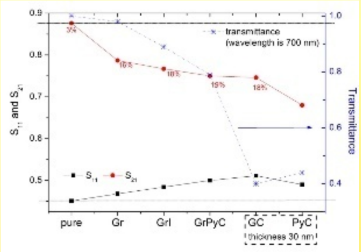
Conclusions, thin carbon films



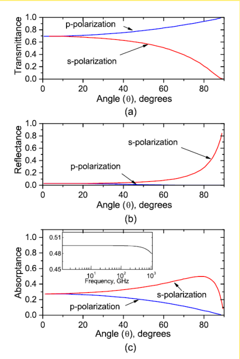
1. Manipulation with the CNT length allows fabrication of THz range EM materials with tailored absorption



2. A few free standing graphene layers in free space absorb 50% of microwave radiation

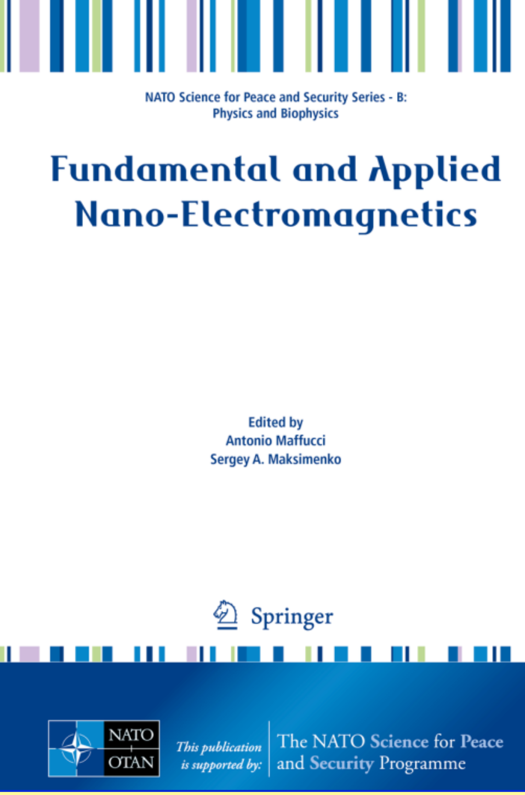


3. The absorption can be significantly enhanced by putting graphene heterostructure on the top of dielectric substate



4. Graphene is the best candidate for electromagnetic absorption in case if optical transparency is also needed.

5. Polarization selectivity of graphene/polymer sandwiches could be used for real device production (polarizer, filter and collimator for THz and microwave radiation).



FANEM2018
In the process

S. Maksimenko, INP BSU

Problems on the NEM list

- ***Circuit components and devices design and modeling***

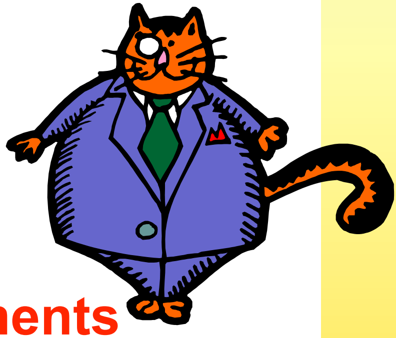
  interconnects, capacitors, inductors, antennae, transmission lines, hybrid structures, etc.

- ***Electromagnetic compatibility on nanoscale***

  non planewave excitations, thermal noise, quantum EMC

- ***Nanocomposites and metamaterials***

  EM shielding and absorption, coatings, etc.

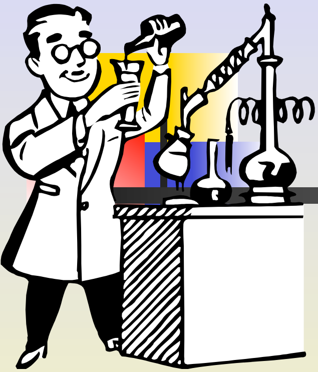


- ***Instabilities***

  THz radiation generation, TWT, active circuit elements

- ***Photothermal effect, medicine***

  EM heating of nanocarbons, heat transfer on nanoscale



Acknowledgments

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604391 GRAPHENE FLAGSHIP

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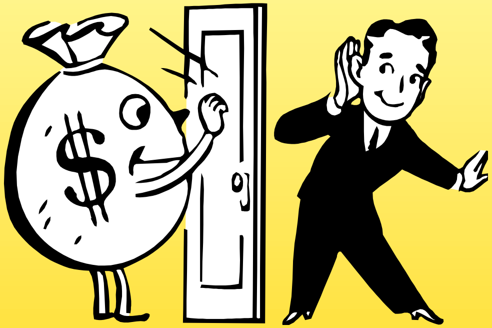
734164 GRAPHENE 3D

U.S. Air Force
AF20-15-61804-1 CRDF Global Agreement




Thank you for
your attention!