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Surface Plasmon Slowing Down and Cherenkov-Type THz Emission in Graphene Based Structure

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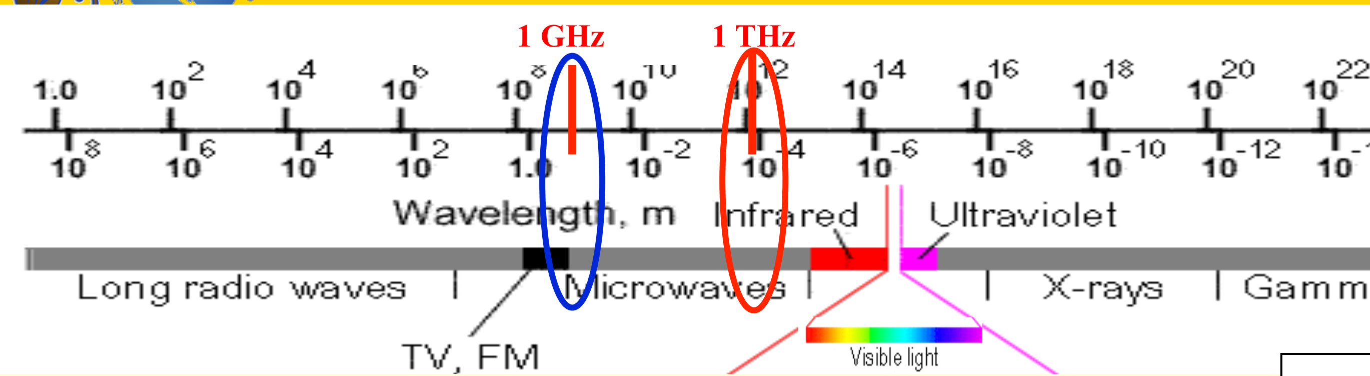
OUTLINE

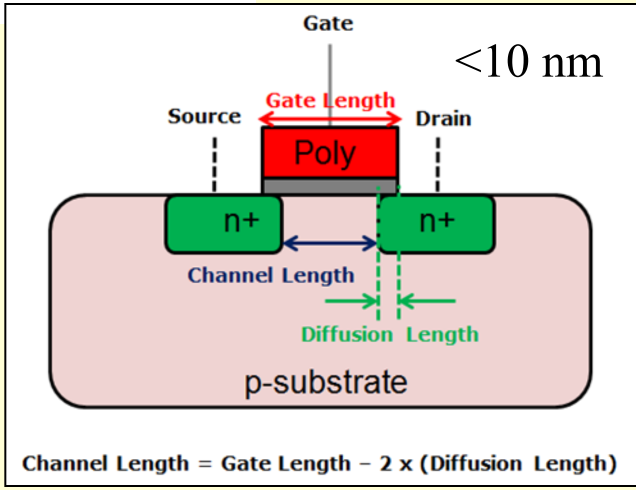
1. *Introduction*
2. Graphene and CNTs: physical properties
3. *Surface plasmon in CNT and graphene*
3. *THz absorption peak*
4. *Nano –Traveling Wave Tube*
5. *Generation of THz radiation in multi-layer graphene/ polymer sandwiches*
6. *Conclusion & Acknowledgments*

Motivation



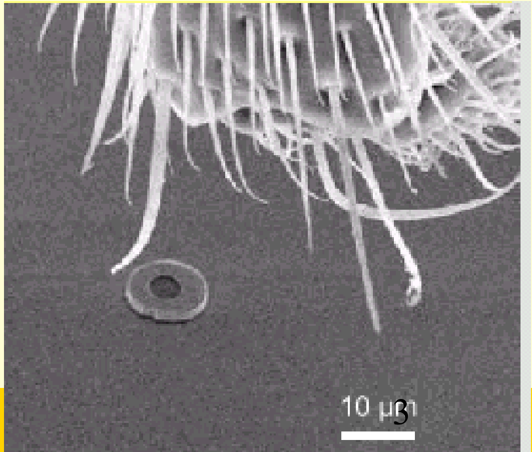
Which are current technological trends in applied electromagnetics?

- Miniaturization of electric circuits & components …
- Energy consumption dropping …
- Opening up the mm-Wave & THz frequency ranges

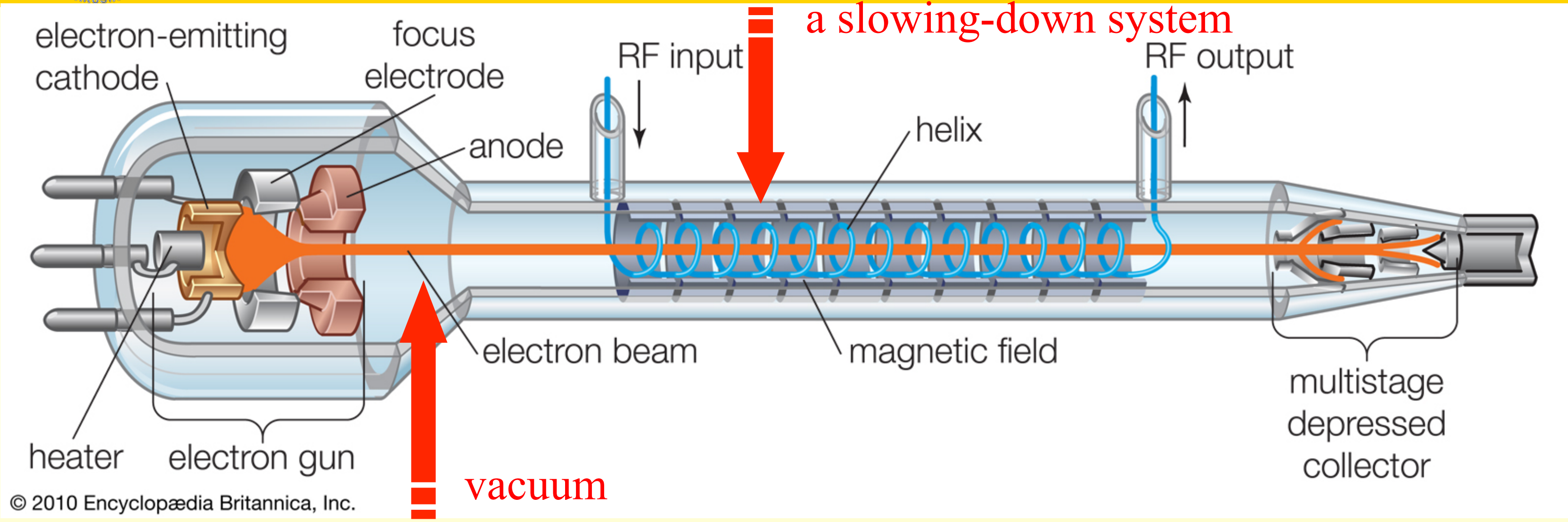


Owing to that, ***nanosized*** elementary circuits components, ***nanoscale*** integration, and ***nanostructured*** electromagnetic materials **are on demand**

Extra-small EM radiation sources are among them



Travelling-wave tubes



The Cherenkov radiation is governed by the synchronization condition w−**ku**=0, where **k** is the wave vector and **u** is the electron velocity

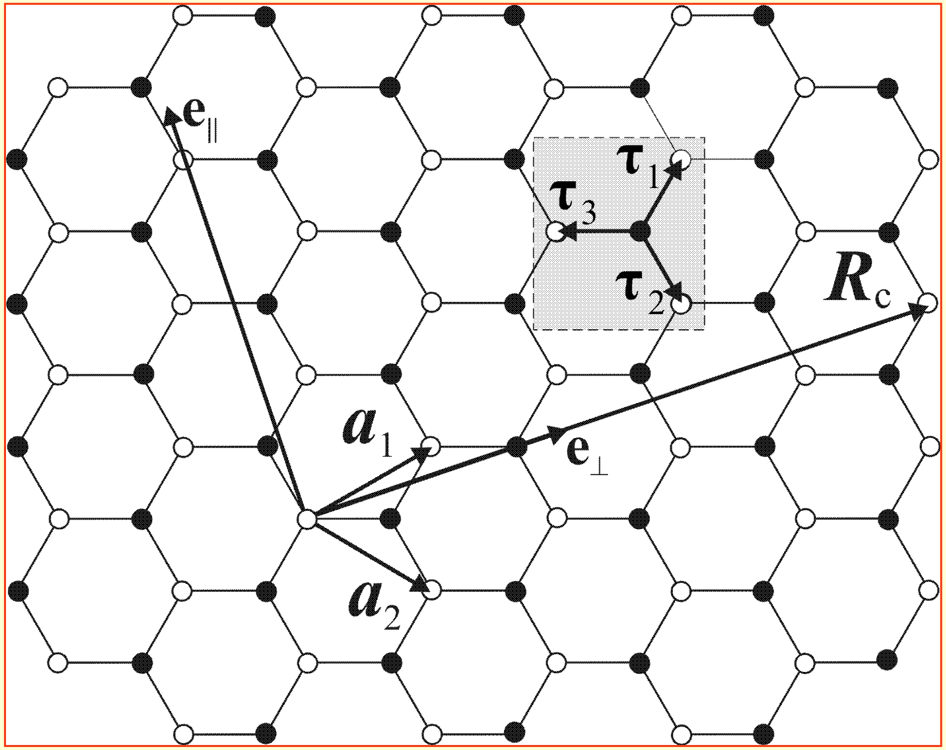
Travelling-wave tubes:
R Kompfner
1952 *Rep. Prog. Phys.* **15** 275

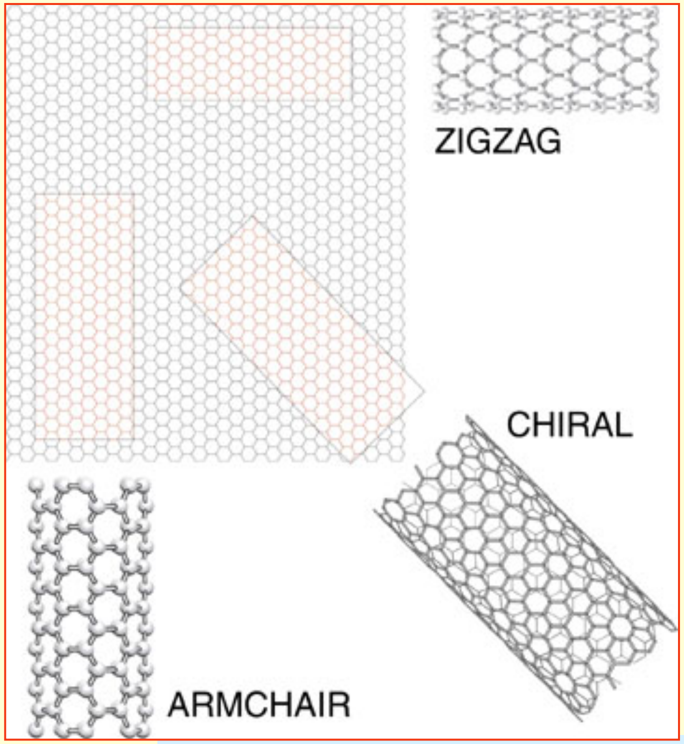
- an electron gun,
- a focusing structure,
- a slowing-down system,
- an electron collector

Can one provide the generation conditions on nanoscale?

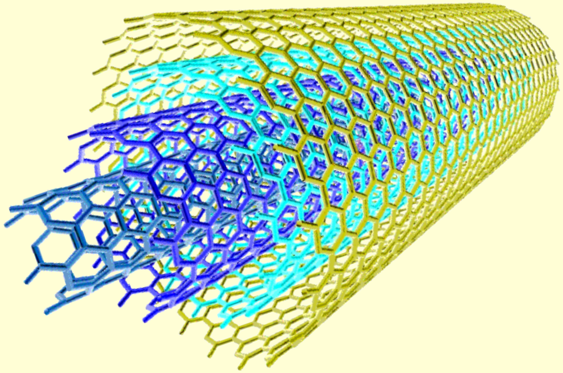
- Ballisticity of electron motion on the proper distance
- Slowing down of EM wave to satisfy the synchronism condition with electron beam
- Large enough current density in a nanoobject

Graphene & 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

Graphene & CNTs:Physical properties

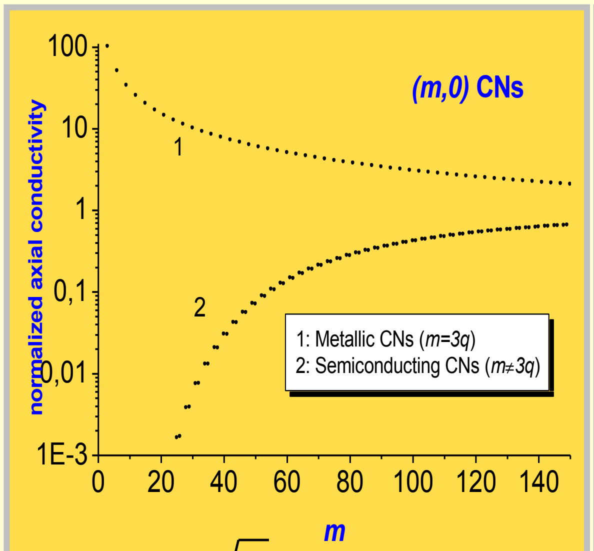
	Si	Cu	SWCNT	MWCNT	Graphene or GNR
Max current density (A/cm^2)	-	10^7	$>1x10^9$ Radosavljevic, et al., *Phys. Rev. B*, 2001	$>1x10^9$ Wei, et al., *Appl. Phys. Let.*, 2001	$>1x10^8$ Novoselov, et al., *Science*, 2001
Melting point (K)	1687	1356	3800 (graphite)		
Tensile strength (GPa)	7	0.22	22.2 ± 2.2	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

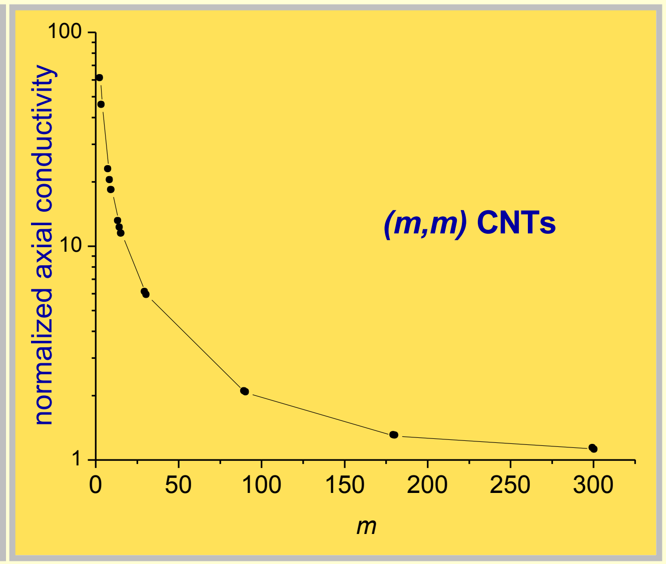
Dynamical conductivity of CNT

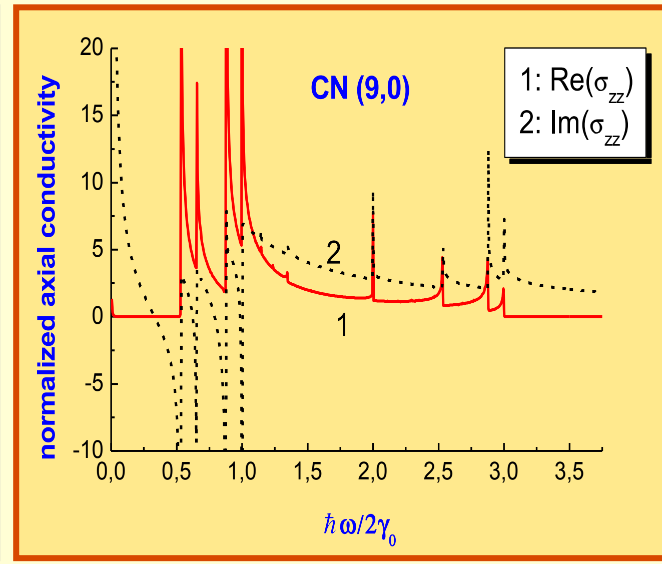
Radial dependence of the conductivity below and in the optical transitions band

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

Electrodynamics of CNTs

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

G. Ya. Slepyan and S. A. Maksimenk A. V. Gusakov
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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

<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].

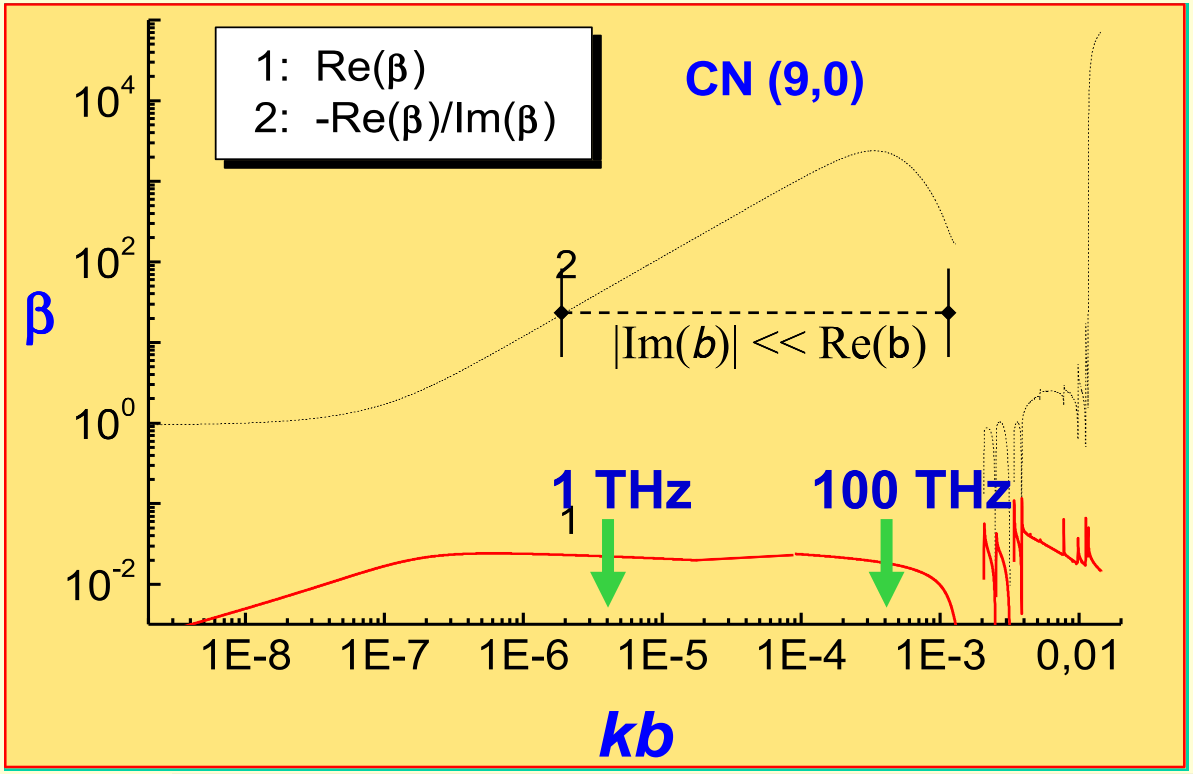
Dispersion equation of surface waves

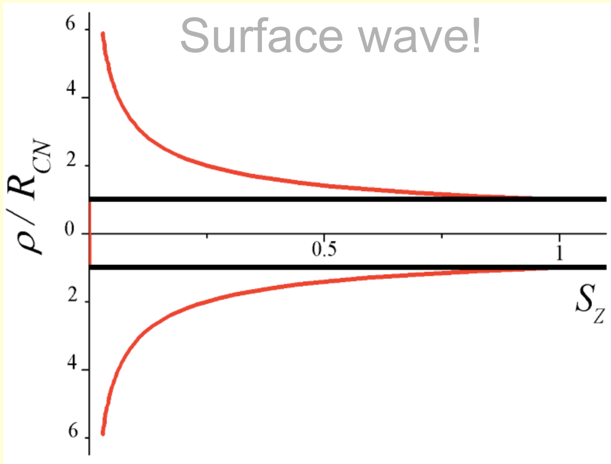
$$\frac{\kappa^2}{k^2} K_q(\kappa R) I_q(\kappa R) = \frac{ic}{4\pi R \sigma_{zz}} \left(1 - \frac{\kappa^2 + k^2}{(\omega + i/\tau)^2} c^2 l_0 \right).$$

Surface Wave Propagation

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

$$\mathrm{Re}\,\beta = \frac{v_{ph}}{c} = \mathrm{Re}\,\frac{k}{h}$$





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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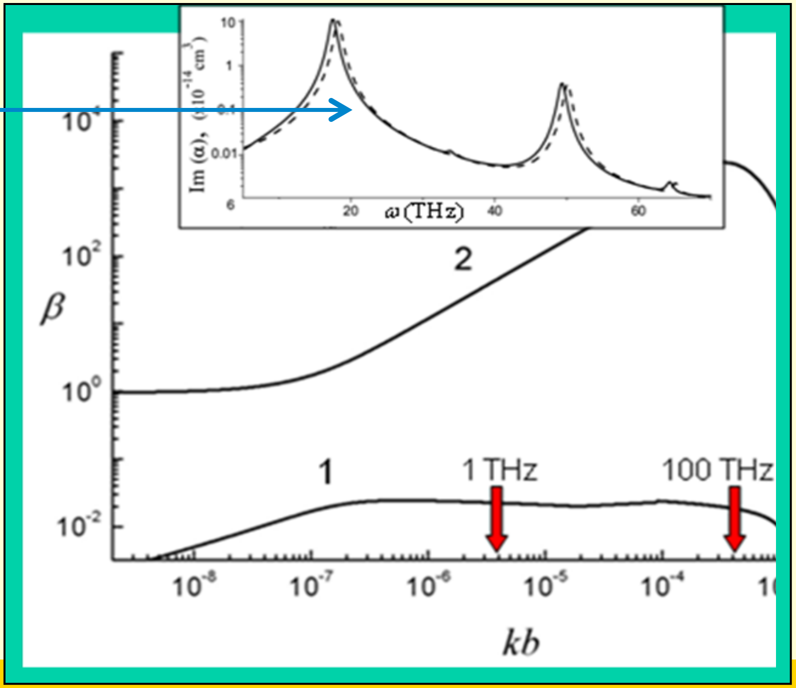
What Can We Learn from the Picture?

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)

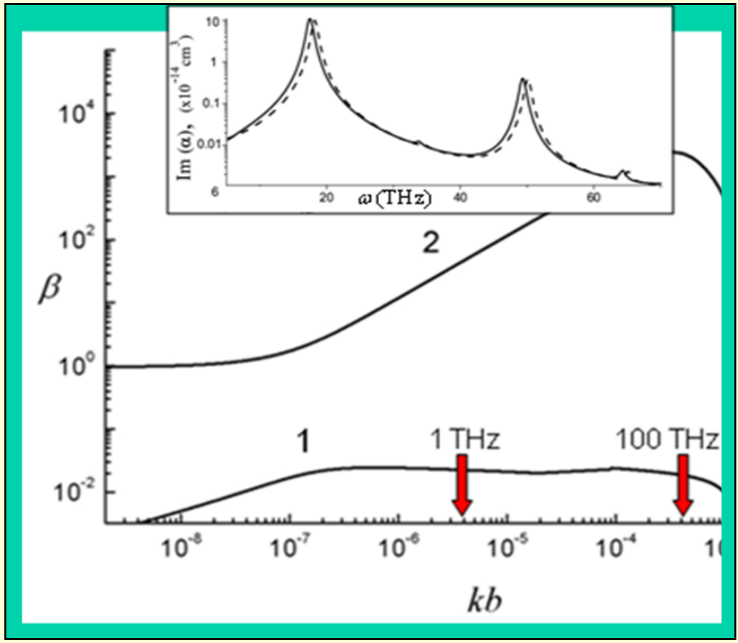


Antenna resonances for 1 mkm CNT are in the THz range because the plasmon slowing

Theory predicts the slowing-down of surface wave in a metallic SWCNT as much as 50-100 times;

Is it true?

The answer can be found from observing antenna resonances red shift



Experimental observations of THz peak in CNT-based composites

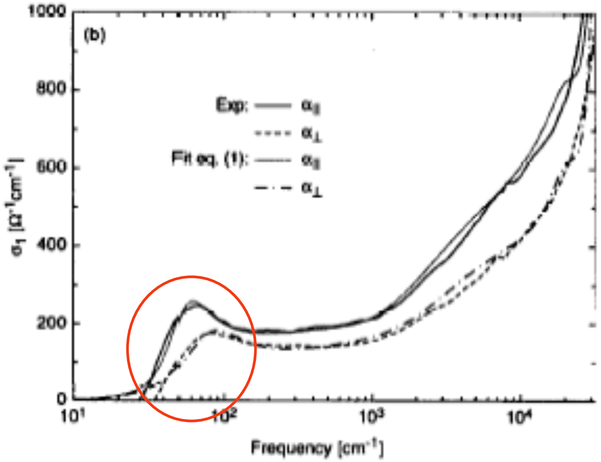


Fig. 1. (a) [redacted] (b) optical conductivity of oriented nanotubes films along the $\alpha_\parallel$ and $\alpha_\perp$ directions. The MG fits [Equation (1)] are also presented.

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

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

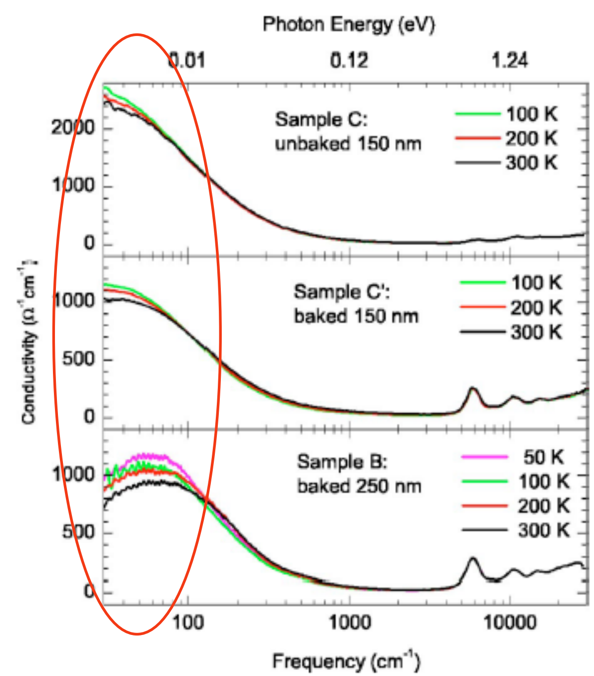
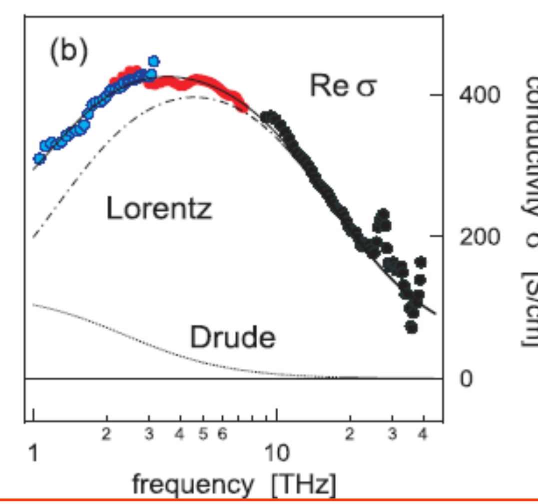


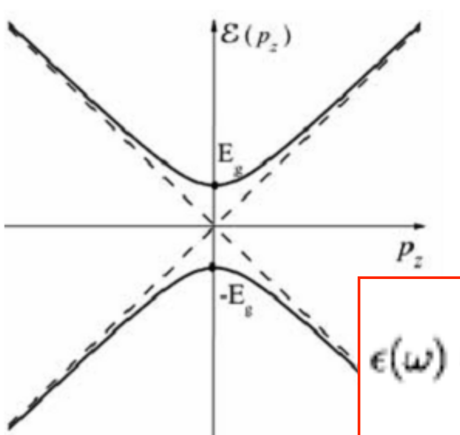
FIG. 3. (Color online) Temperature dependence of the optical conductivity of the two samples.

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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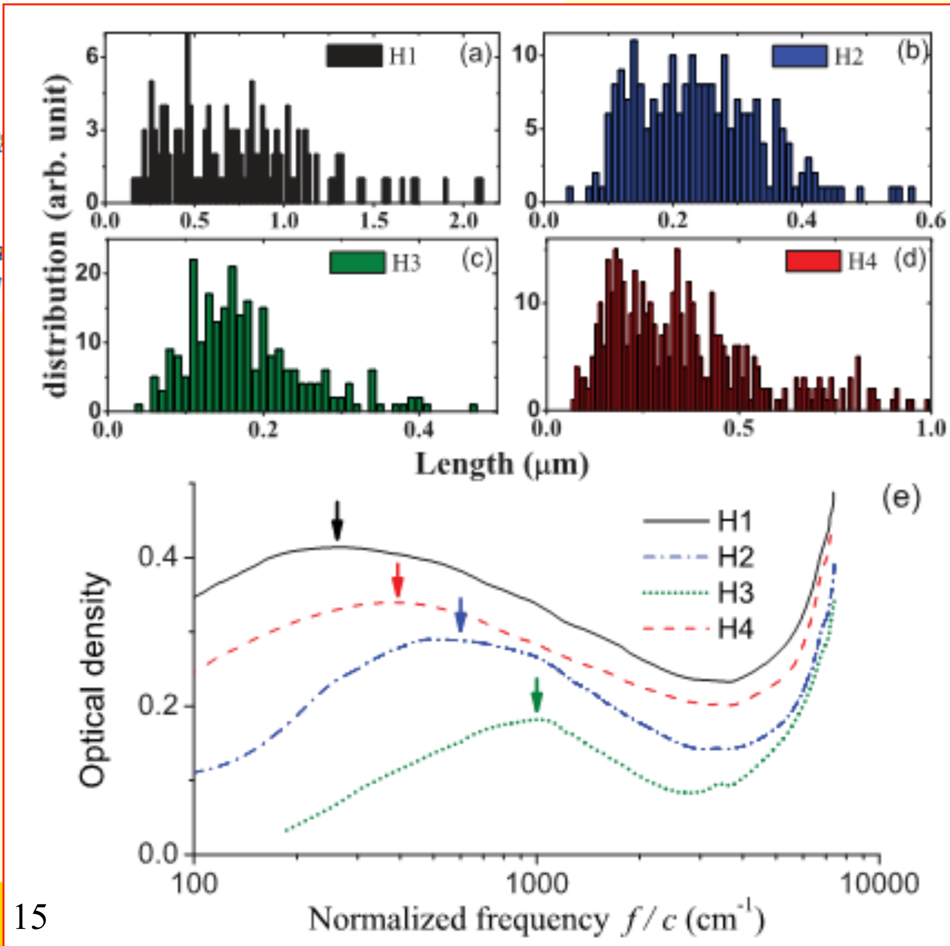
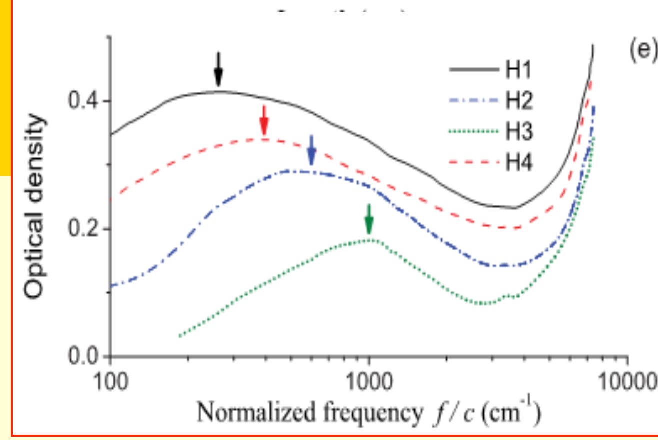
Nanoengineered Metamaterials Group, Department of Engineering Science an
University Park, Pennsylvania 16802-681



THz peak: experiment

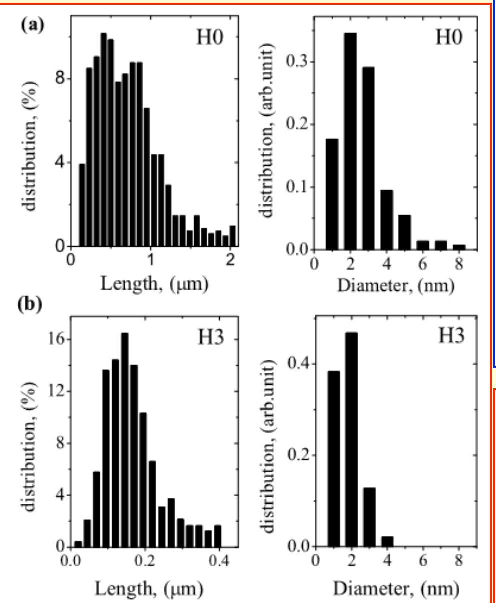
Direct experimental demonstration of the correlation between the THz peak frequency and the SWCNT length. That is, the direct experimental evidence of the slowing down in CNTs and the FIR-THz antenna

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

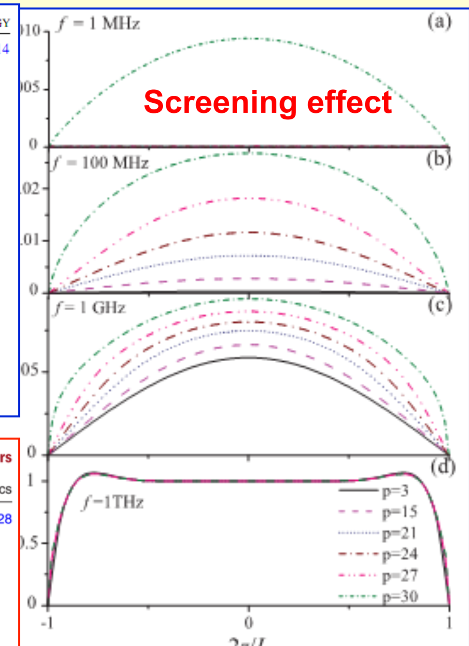
M V Shuba[1], A G Paddubskaya[1], P P Kuzhir[1], S A Maksimenko[1], V K Ksenevich[2], G Niaura[3], D Seliuta[3], I Kasalynas[3] and G Valusis[3]

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

The basis of generation in CNTs and graphene

The possibility of strong slowing down of EM wave

- G.Ya. Slepyan, S. A. Maksimenko, A. Lakhtakia, O. Yevtushenko, A.V. Gusakov, Phys. Rev. B 60, 17136 (1999).
- M.V. Shuba et al., Phys. Rev. B 85 165435, 2012

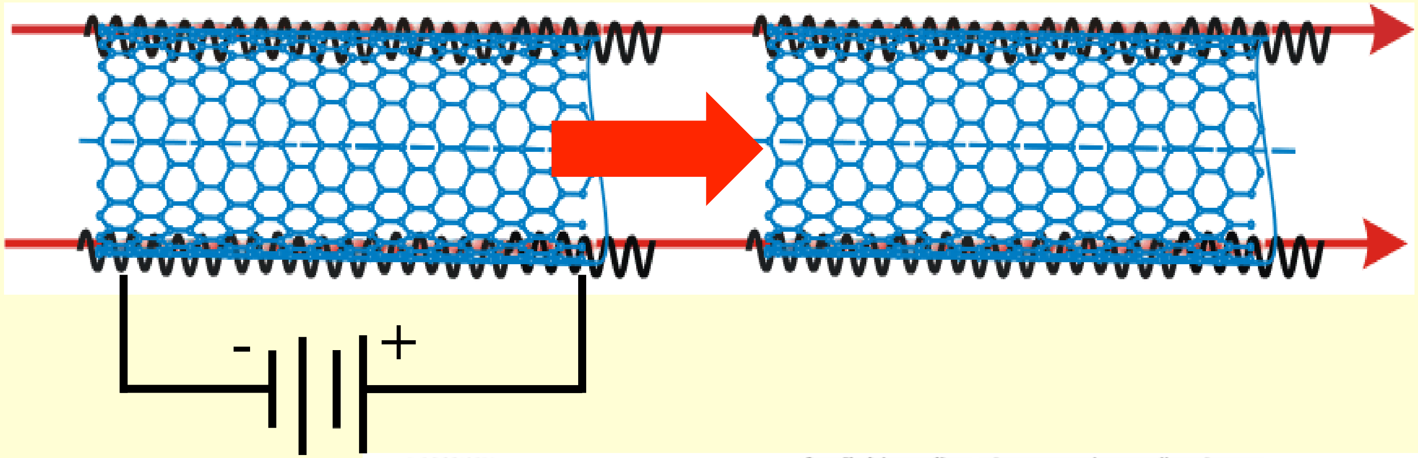
Ballistic electron transport (up to tens of μm)

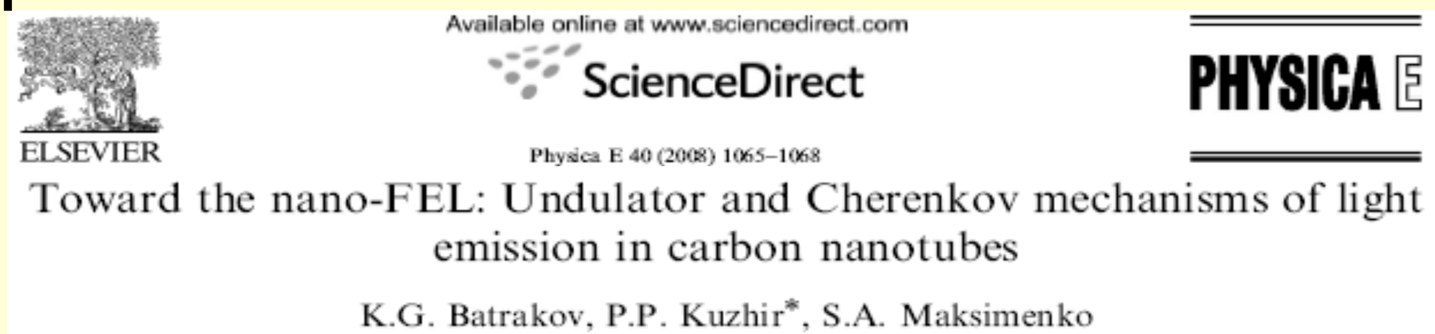
- C. Berger, P. Poncharal, Y. Yi, W.A. de Heer, J. Nanosci. Nanotechn., 3, 171 (2003);
- J. Baringhaus, M. Ruan, F. Edler, & W.A. de Heer, Nature 506, 349–354, 2014

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

- M. Radosavljevi´c, J. Lefebvre, and A. T. Johnson, Phys. Rev. B 64, 241307, 2001;
- S.-B. Lee, K.B.K. Teo, L.A.W. Robinson, et al., J. Vac. Sci. Technol. B 20, 2773 (2002);

Čerenkov lasing in a CNT





Available online at www.sciencedirect.com

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PHYSICA E

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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

K. G. Batrakov, P. P. Kuzhir, S. A. Maksimenko, *Proc.SPIE 6328, 63280Z (2006)*

K. G. Batrakov, S. A. Maksimenko, P. P. Kuzhir, and C. Tomsen, *Phys. Rev. B 79, 125408 (2009).*

K.G. Batrakov, O.V. Kibis, Polina P. Kuzhir, M. R. Costa, and M. E. Portnoi, Vol. **4**, 041665 (2010).

K. Batrakov, V. Saroka, S. Maksimenko, Chr. Thomsen, Journal of Nanophotonics, **6**, 061719 (2012).

Dispersion equation

$$k - k_m = -\frac{\omega_L^2}{8mk_mc^2}\sum_l B_{nl}\left\{\frac{1}{-\hbar\omega + \varepsilon_n(p_n) - \varepsilon_l(p_n - \hbar k)} + \frac{1}{\hbar\omega + \varepsilon_n(p_n) - \varepsilon_l(p_n + \hbar k)}\right\}$$

ω_L^2 is the Langmuir frequency squared, proportional to the current density.

$$\varepsilon_l(p_n \pm \hbar k) \approx \varepsilon_l(p_n) \pm \hbar k\frac{\partial \varepsilon_l}{\partial p_n} + \frac{\hbar^2 k^2}{2}\frac{\partial^2 \varepsilon_l}{\partial p_n^2}$$

$$v_l = \frac{\partial \varepsilon_l(p_n)}{\partial p_n}$$ → group velocity of nanotube electron

$$\pm\hbar\omega + \varepsilon_n(p_n) - \varepsilon_l(p_n \pm k) = \pm\hbar(\omega - kv_l \pm \Omega_{nl}) + \frac{\hbar^2}{2}\frac{\partial^2 \varepsilon_l}{\partial p_n^2}k^2$$

Typical dispersion equation for second order Cherenkov instability:

$$k - k_m \sim -\frac{\omega_L^2}{(\omega - kv_l)^2}$$

Threshold Current and Instability Increment

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

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

L=10 – 30 mm

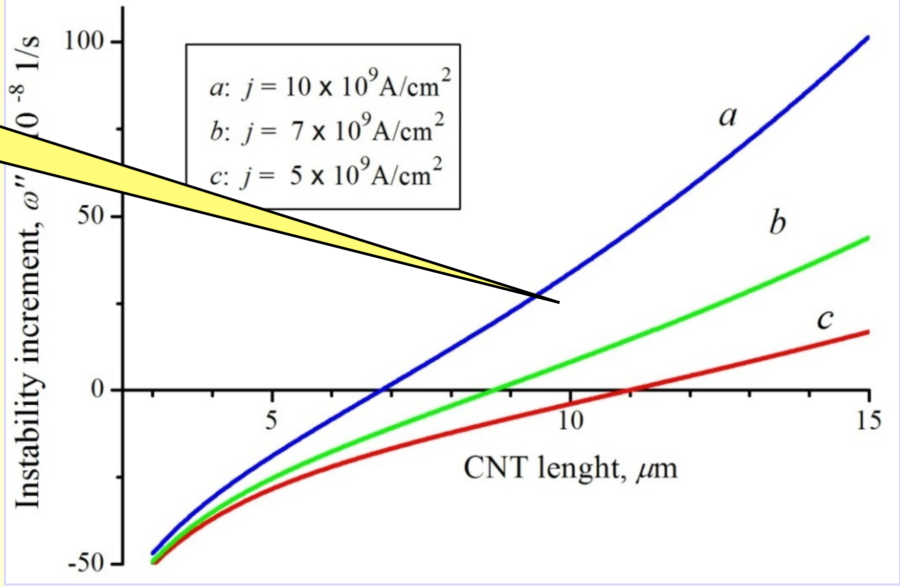
PHYSICAL REVIEW B **79**, 125408 (2009)

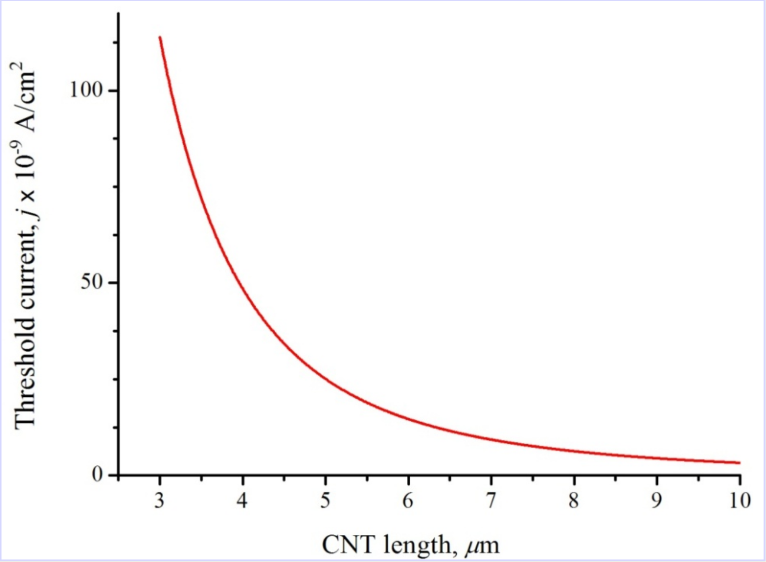
Carbon nanotube as a Cherenkov-type light emitter and free electron laser

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





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 l>>*d* (*d* is the distance between CNTs), frequencies can be approximately written as:

$$\omega_+ \sim \omega_1(R_1)+\omega_2(R_2) \quad \text{and} \quad \omega_- \sim |\,\omega_1(R_1)-\omega_2(R_2)\,|$$

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, P.P. Kuzhir, S.A. Maksimenko, 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?.....

Advantage of using MWCNTs or multi-layered graphene

Decreasing the phase velocity in two-walled CNT is limited.

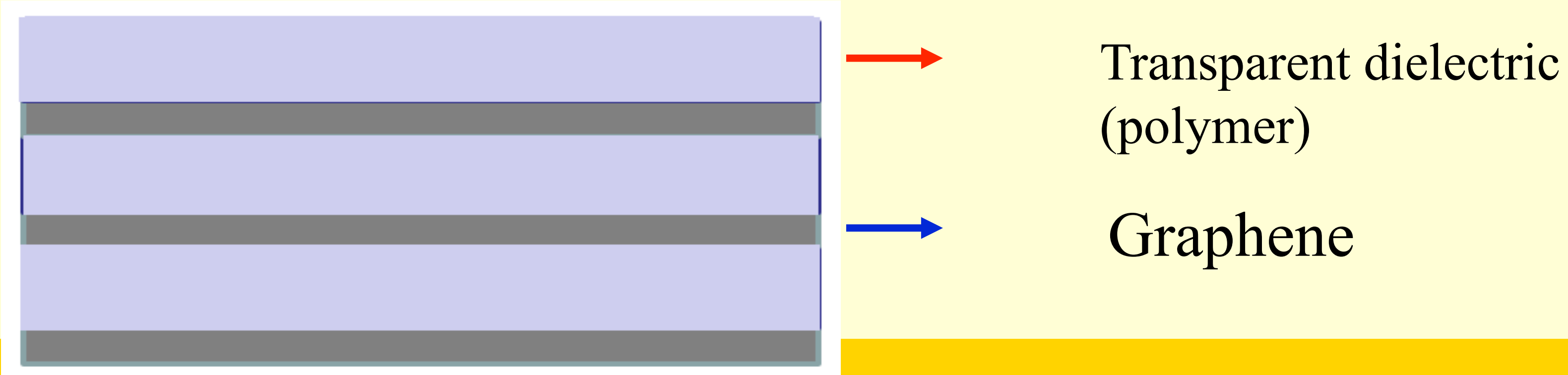
Does bilayer graphene show no such drawback?.....

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

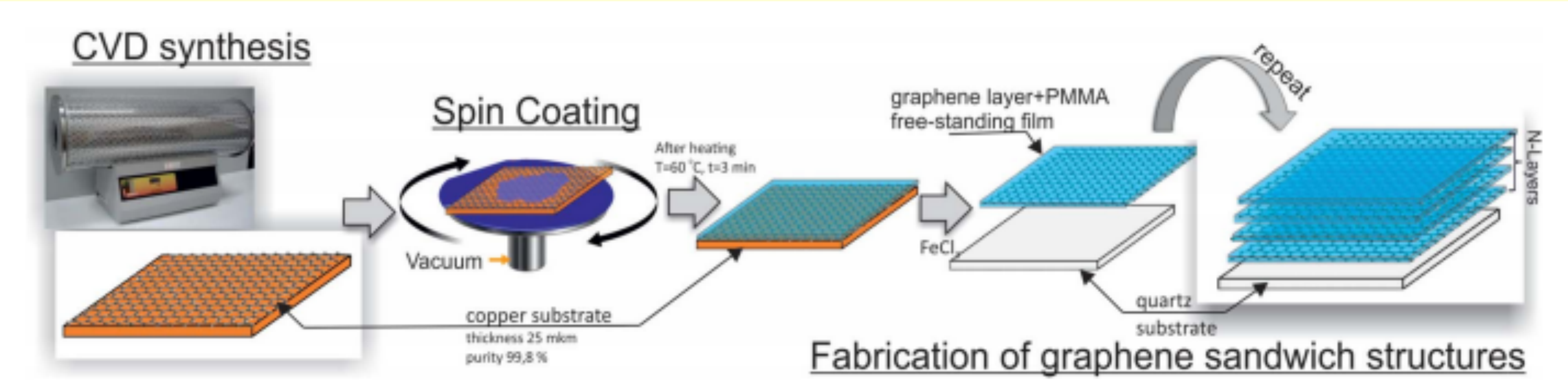
Tunneling should be suppressed.

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

- K. Batrakov, V. Saroka, S. Maksimenko, Chr. Thomsen, J. of Nanophotonics, **6**, 061719 (2012)



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.

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

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

SCIENTIFIC REPORTS

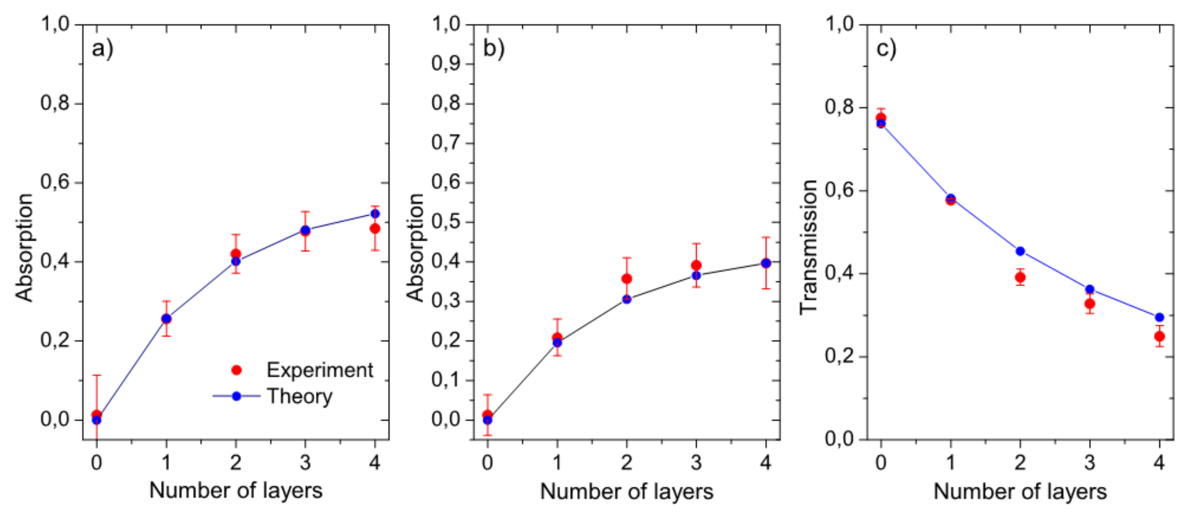
4 : 7191 (2014)

OPEN

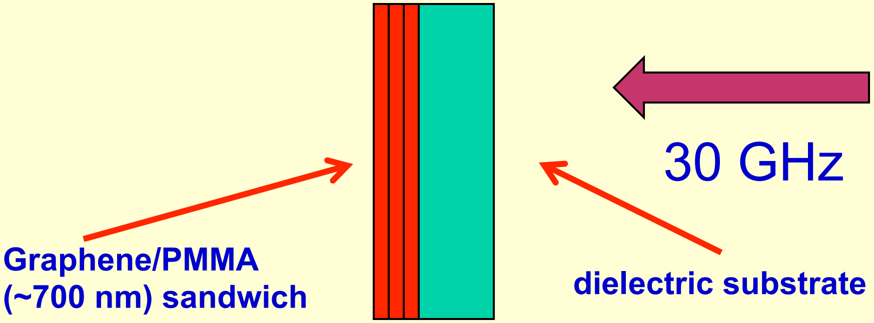
SUBJECT AREAS:
GRAPHENE
ELECTRONIC PROPERTIES AND DEVICES
NANOSCALE MATERIALS

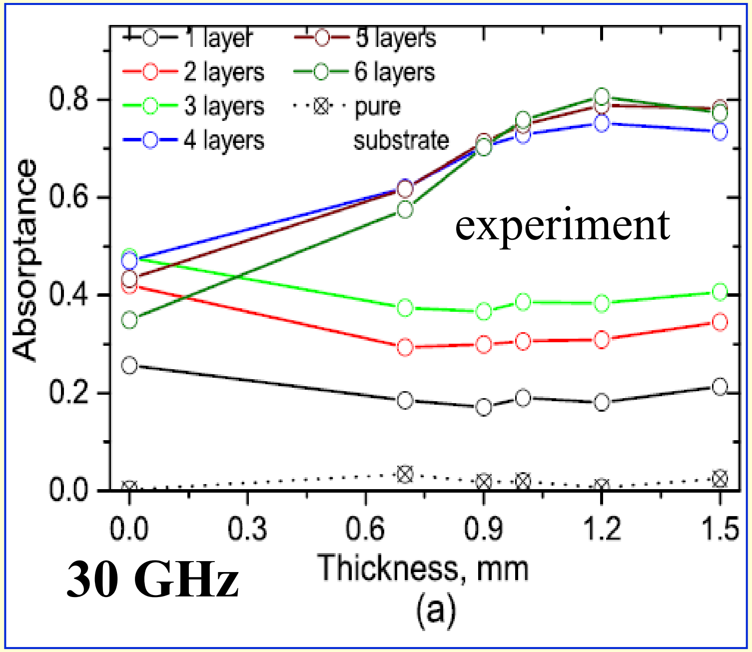
Flexible transparent graphene/polymer multilayers for efficient electromagnetic field absorption

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



Fabrication of multi-layerd PMMA/Graphene structures





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

Enhanced microwave-to-terahertz absorption in graphene

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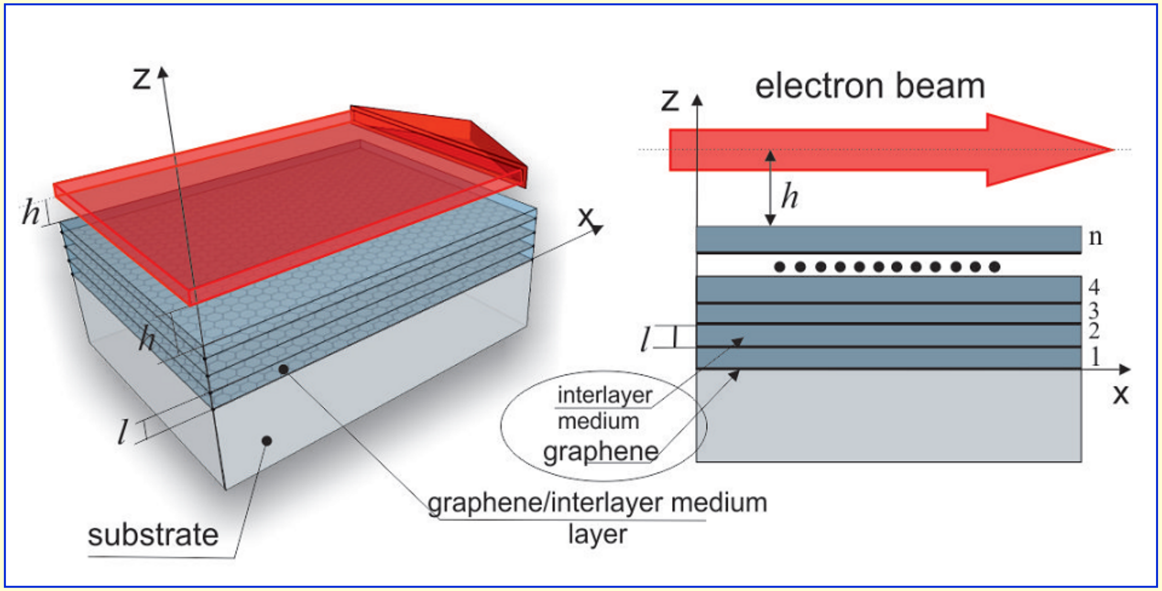
The problem statement



Consider an electron beam propagating along the x axis parallel to a graphene sheet or multilayer graphene sandwich comprising 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 on the atomic scale and, therefore, neglecting electron interlayer tunneling in the sandwich.

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.

Two spatially separated graphene monolayers

Solution of boundary problem with boundary conditions on graphene layers gives dispersion equation for eigenwaves

$$\mathbf{H}(z_i+0)-\mathbf{H}(z_i-0)=\frac{4\pi}{c}\left[\mathbf{j}_t(z_i)\times\mathbf{n}\right]$$

magnetic field discontinuity on opposite sides of graphene sheet

Dispersion equation for surface TM mode in two-layer graphene system

$$2+\frac{4\pi}{c}\sigma\frac{k_z c}{\omega}\pm\frac{4\pi}{c}\sigma\frac{k_z c}{\omega}\exp\{-\sqrt{q^2-\omega^2/c^2 l}\}=0$$

Here q is wave number, $k_z=\sqrt{\omega^2/c^2-q^2}$, l is distance between graphene layers

Graphene conductactivity:

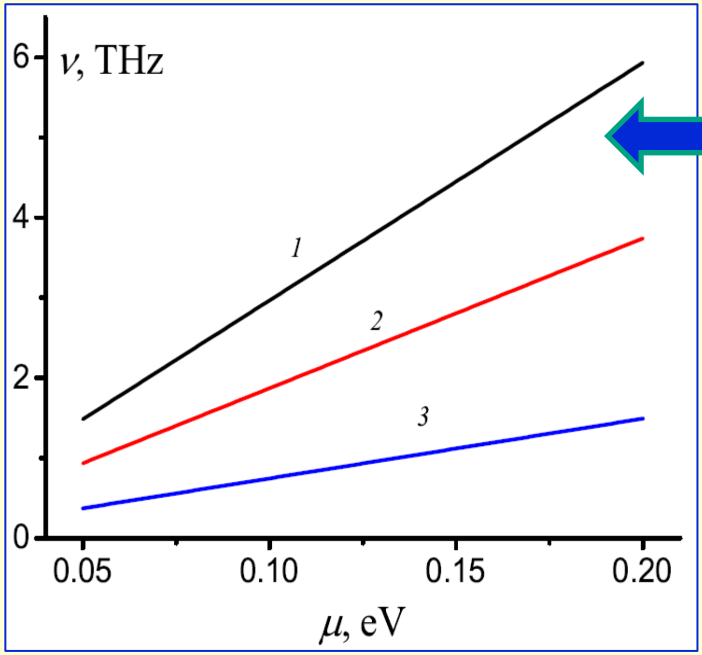
$$\sigma^{\mathrm{intra}}(\omega,\mu,T,\gamma_{\mathrm{trans}})=\frac{e^2 g_s g_v}{16\hbar}\frac{8T}{\pi\hbar}\ln\left[2\cosh\left(\frac{\mu}{2T}\right)\right]\frac{i}{\omega+i\gamma_{\mathrm{trans}}}$$

$$\tilde{\Omega}=\hbar(\omega+i\gamma_{\mathrm{opt}})/|\mu|$$

$$\sigma^{\mathrm{inter}}(\omega,\mu,T,\gamma_{\mathrm{opt}})=-\frac{ie^2 g_s g_v}{16\pi\hbar}\tilde{\Omega}\int_0^\infty\frac{\sinh(x|\mu|/T)}{\cosh(\mu/T)+\cosh(x\mu/T)}\frac{dx}{x^2-\tilde{\Omega}^2/4}$$

m is chemical potential, γ_{trans} γ_{opt} are broadening parameters

Frequency tuning

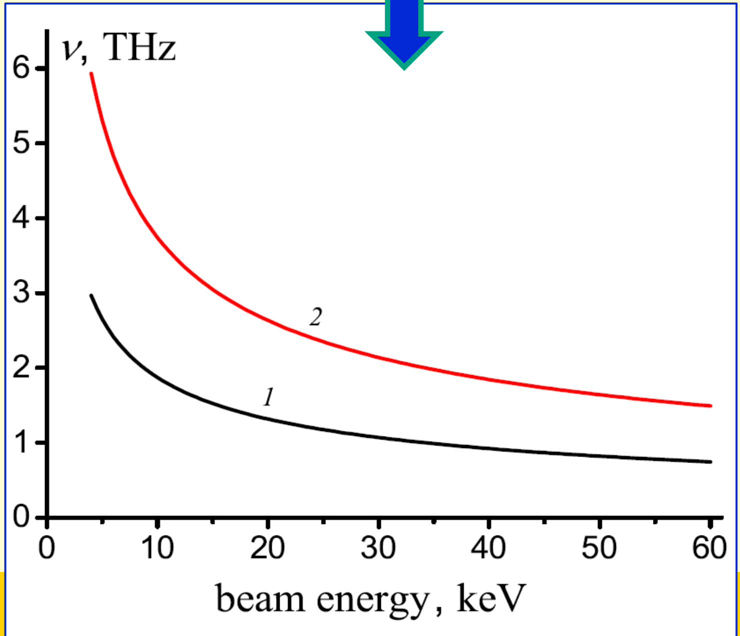


by varying the chemical potential

Cherenkov resonant frequency *vs* chemical potential at the electron beam energy 4 KeV (1), 10 KeV (2) and 60 KeV (3).

by varying the electron beam energy

The Cherenkov frequency dependence on the electron beam energy. Chemical potential 0.1 eV (1) and 0.2 eV (2).



Chemical potential can be tuned by:

1) electrostatic doping (smooth frequency tuning);
2) number of graphene layers, because in acoustic mode potential is proportional to this number (discrete tuning)

Generation equation

Continuity conditions on the beam boundaries and discontinuity conditions for magnetic field on graphene layers give dispersion equation for system “sandwich + electron beam” (generation equation)

$$I_b = -\frac{(2+\sigma_0)^2 - (\sigma_0)^2 \exp\{-2\sqrt{q^2-\omega^2/c^2}l\}}{\sigma_0\left[2+\sigma_0+\exp\{-2\sqrt{q^2-\omega^2/c^2}l\}(2-\sigma_0)\right]}$$

$$\sigma_0 = (4\pi/\omega)k_z\sigma$$

In this equation

$$I_b = \exp(2ik_z h)\frac{(k_{bz}^2-k_z^2)\{\exp(ik_{bz}\delta)-\exp(-ik_{bz}\delta)\}}{(k_{bz}-k_z)^2\exp(ik_{bz}\delta)-(k_{bz}+k_z)^2\exp(-ik_{bz}\delta)}$$

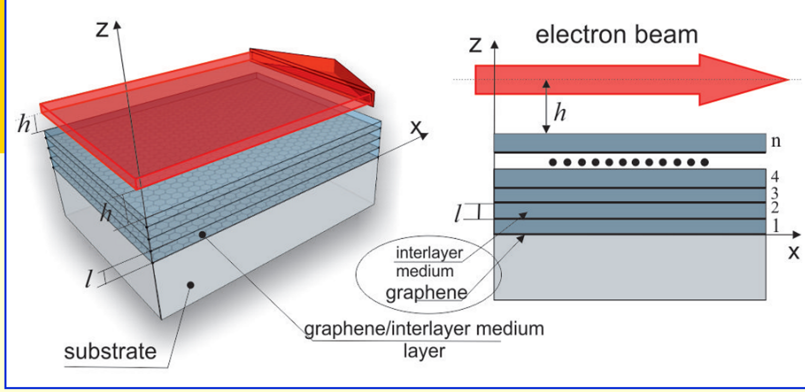
h is the distance between sandwich and electron beam,

d is the beam thickness,

w_l is the electron beam Langmuir frequen

$$k_{bz} = k_z\sqrt{1-\frac{\omega_l^2}{\gamma^3(\omega-qu)^2}}$$

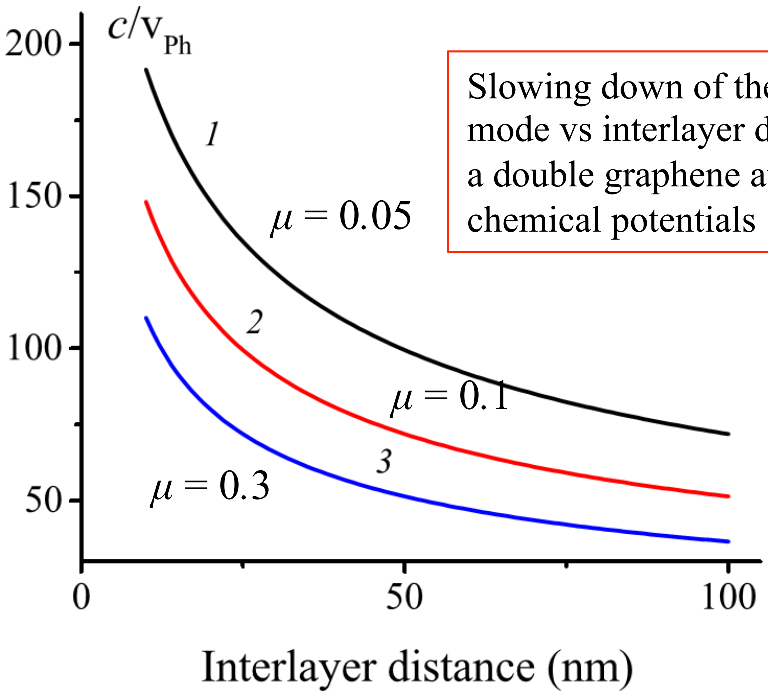
Quasi-Cherenkov radiation of an electron beam passing over the graphene/polymer sandwich structure



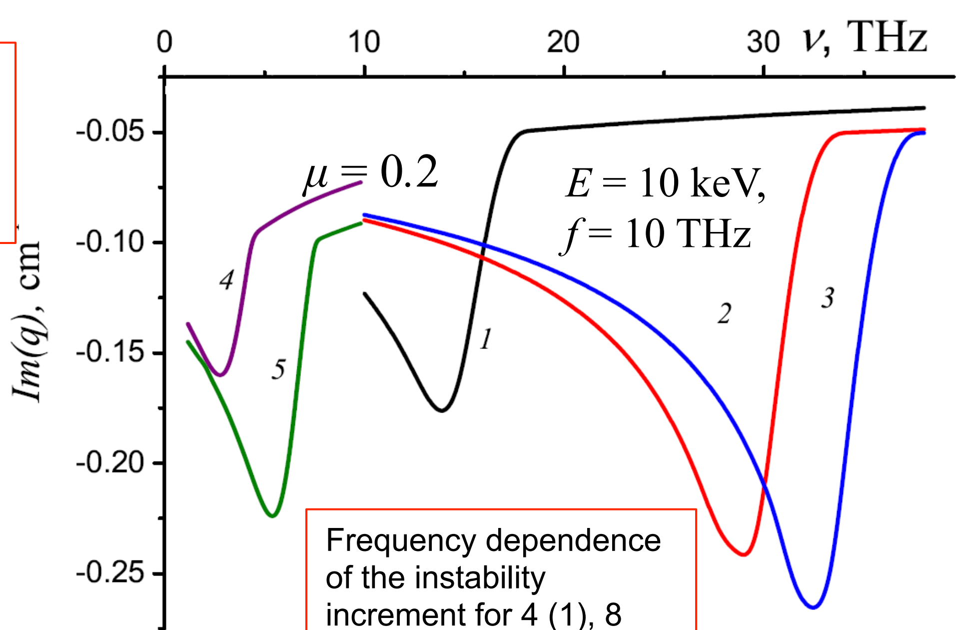
PHYSICAL REVIEW B **95**, 205408 (2017)

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

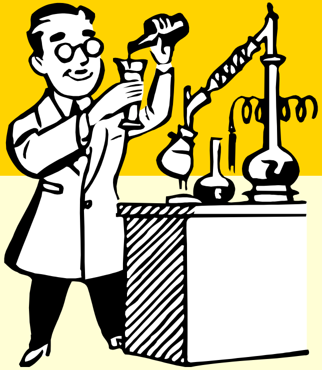
Conclusions

- 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



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U.S. Air Force

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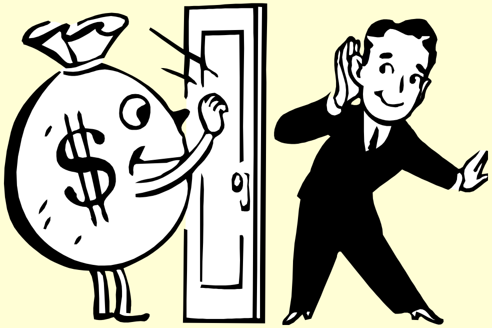



Thank you for
your attention!

Nanoelectromagnetics

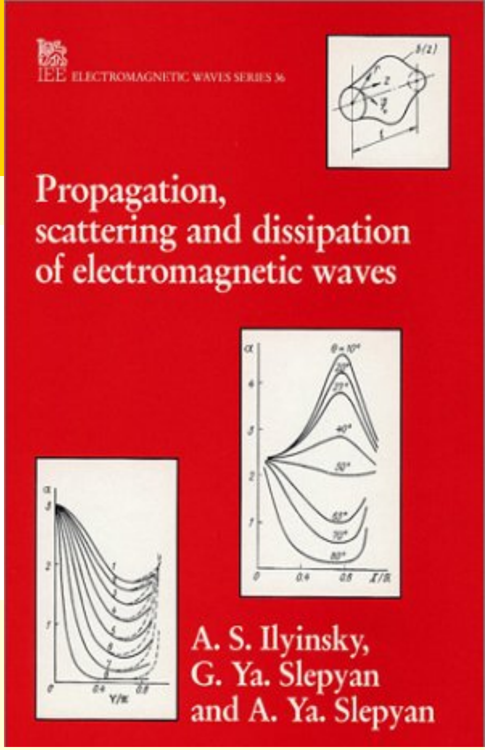
A research discipline studying the behaviour of high-frequency electromagnetic radiation on nanometer scale is currently emerging as a synthesis of macroscopic electrodynamics and microscopic theory of electronic properties of different nanostructures

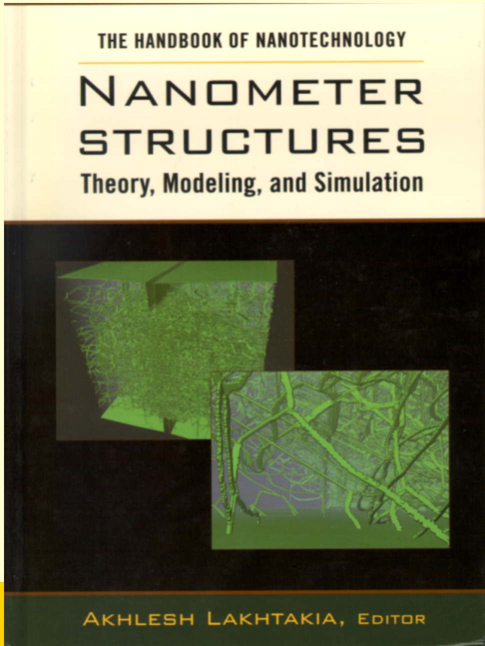
FUNDAMENTAL CHALENGE in NANOSCALE ELECTROMAGNETICS is

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

Institute for Nuclear Problems Belarusian State University

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Università degli Studi di Cassino e del Lazio Meridionale – 1979 –

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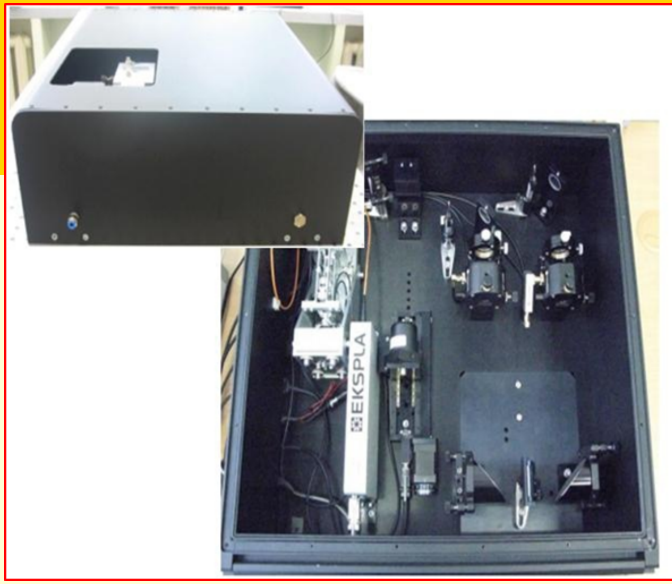
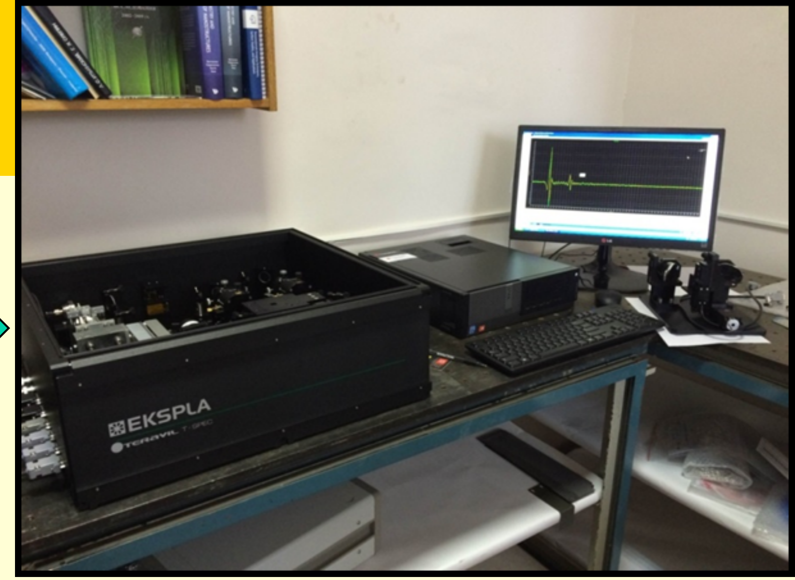




Commercial THz time-domain spectrometer T-Spec by EKSPLA.

A 1050+-40 nm wave length pumping laser having 50-150 fs pulse duration and more than 40 mW output power at approximately 80 MHz pulse repetition rate is used to excite a photoconductor antenna and produced THz radiation up to 2 THz.

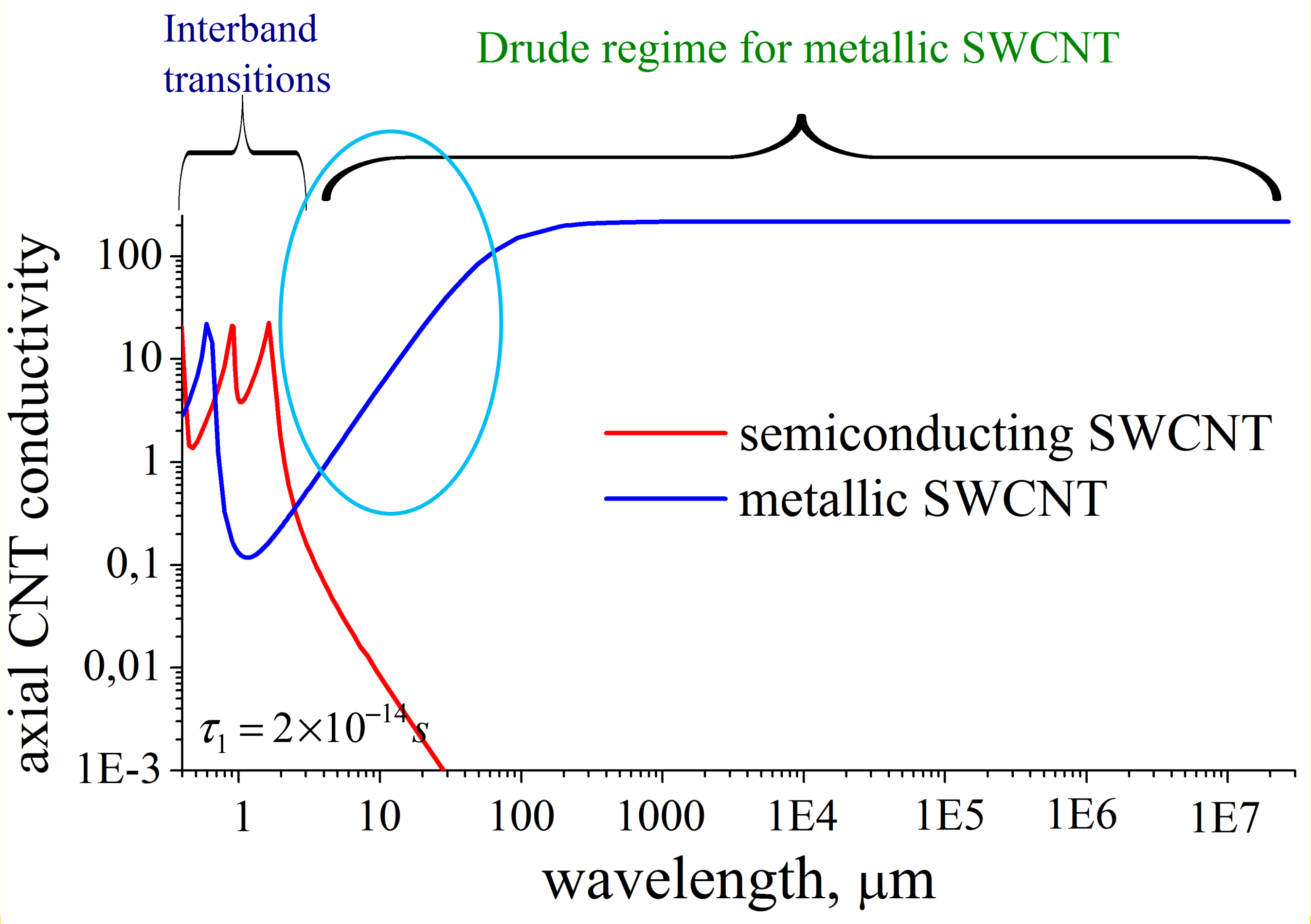
The spectrometer, THz emitter, and detector consist of a microstrip antenna integrated with a photoconductor and silicon lens.

The sample in the form of a plane parallel plate is placed between emitter and detector normally to the initial EM wave. The THz detector output is proportional to the instant electrical field strength of the THz pulse.

Scalar analyzer R2-408R(VSWR and Transmission Loss Meter R2-408R) 27-37 GHz

Axial surface conductivity of isolated single-wall carbon nanotube

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



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

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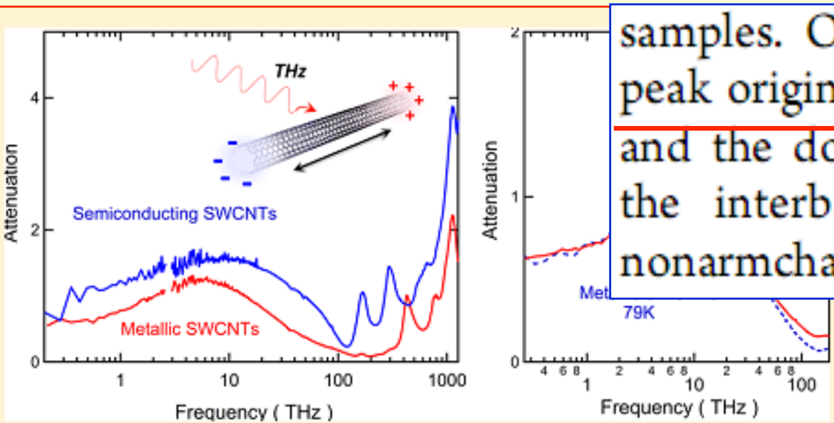
Plasmonic Nature of the Terahertz Conductivity Peak in Single-Wall Carbon Nanotubes

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