INSTITUTE for NUCLEAR PROBLEMS
BELARUSIAN STATE UNIVERSITY

Sergey Maksimenko
sergey.maksimenko@gmail.com

Nanoelectromagnetics in THz range

INP BSU: Physics and technologies of the radiation-matter interaction

• Radiation-matter interaction and nuclear physics:

- Nuclear optics
- Volume free-electron laser,
- Novel scintillator materials and detectors for high energy physics and new methods of ionizing radiation control
- Magnetic explosion generator

• Particle and High Energy Physics:

- Collaboration with CERN and JINR,
- Participation in collaborations CMS, ATLAS, FCC, …
- Novel detectors, readout electronics

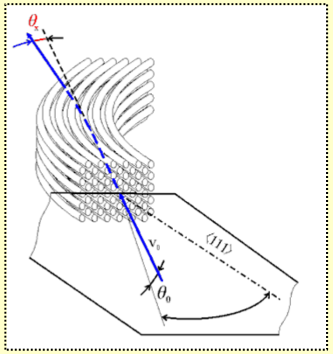
• Electromagnetics of complex media:

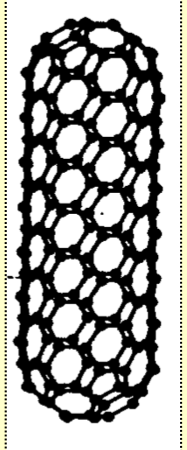
- Nanoelectromagnetics
- Novel composite, nano- and micro- structured materials
- Microwave technologies in agriculture and medicine

• Control of small doze radiation and radioactive pollution:

- Belarusian-American study of thyroid cancer and other thyroid diseases in Belarus caused by the Chernobyl disaster,
- Radioactive pollution control instrumentation

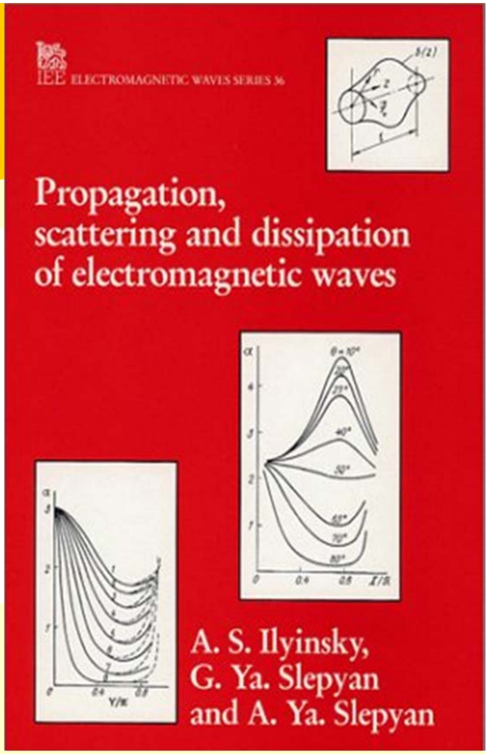
Staff total – *138*
Researchers – *80*
Dr.Sci. – *9*
Ph.D. – *26*





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



IEE ELECTROMAGNETIC WAVES SERIES 36

Propagation,
scattering and dissipation
of electromagnetic waves

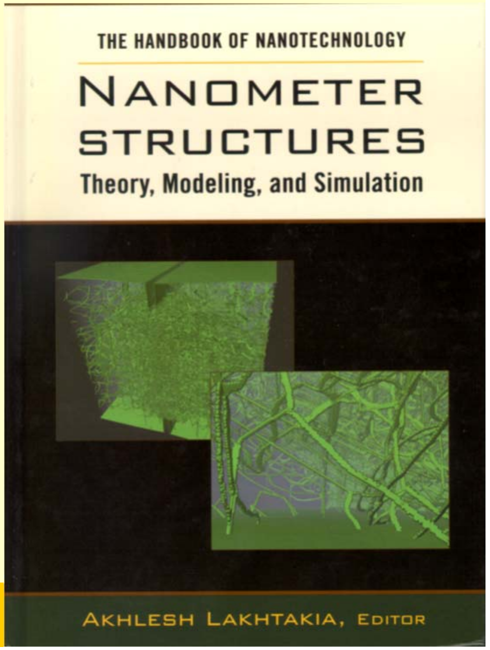
A. S. Ilyinsky,
G. Ya. Slepyan
and A. Ya. Slepyan

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



THE HANDBOOK OF NANOTECHNOLOGY

NANOMETER
STRUCTURES
Theory, Modeling, and Simulation

AKHLESH LAKHTAKIA, EDITOR

Maksimenko & Slepyan, Nanoelectromagnetics
of low-dimensional structures

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

G. Ya. Slepyan and S. A. Maksimenk A. V. Gusakov
Institute of Nuclear Problems, Belarus State University, Bobruiskaya str. 11, Minsk 220050, Belarus

A. Lakhtakia
CATMAS—Computational and Theoretical Materials Sciences Group, Department of Engineering Science and Mechanics,
Pennsylvania State University, University Park, Pennsylvania 16802-1401

O. Yevtushenko
Institute of Radiophysics and Electronics, National Academy Sciences of Ukraine, Ak. Proskura str. 12, Kharkov 310085, Ukraine

In optical and below ranges

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

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

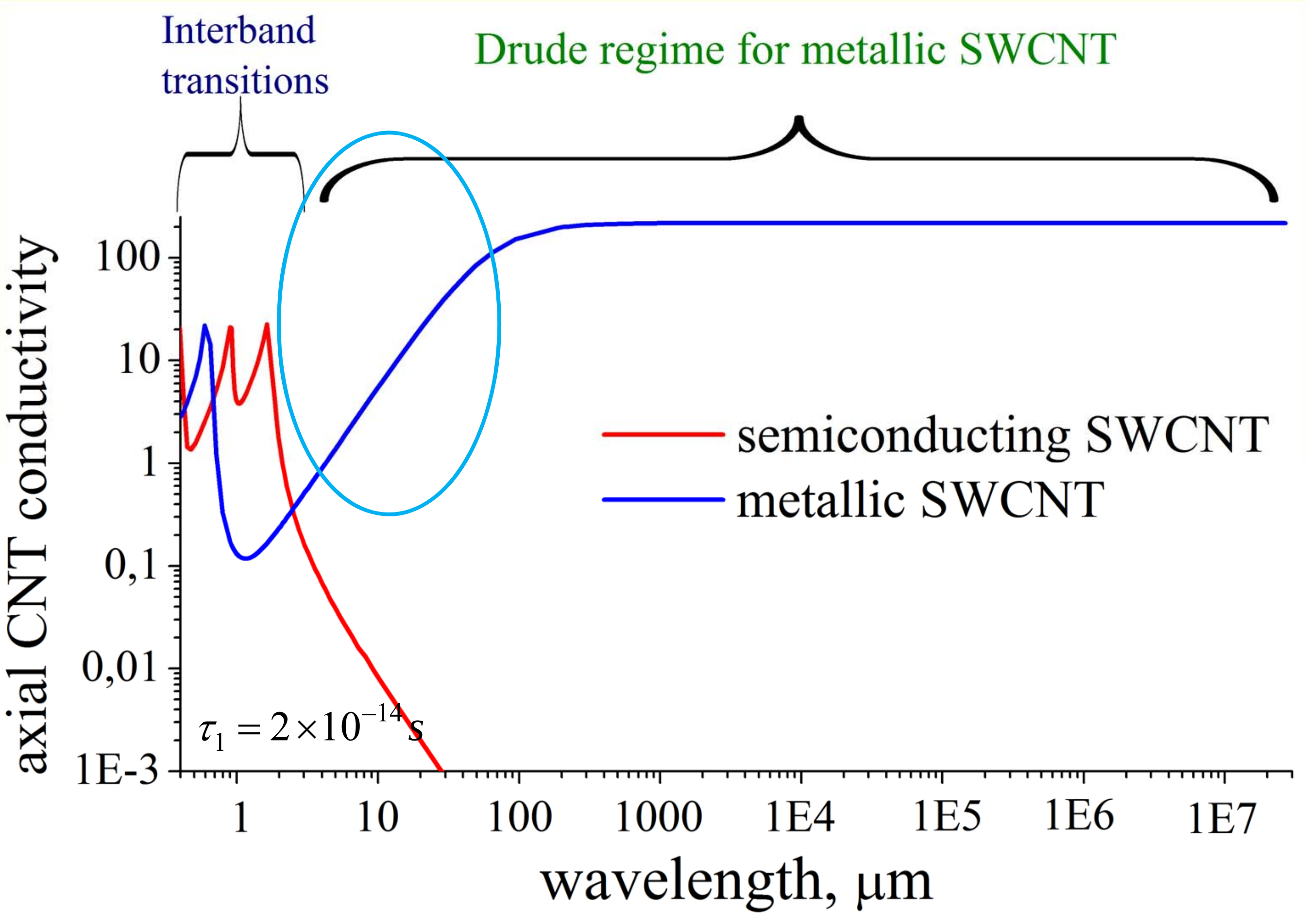
$$H_z\,|_{\rho=R-0} \;-\; H_z\,|_{\rho=R+0}=0,\;\; E_{z,\varphi}\,|_{\rho=R-0}-E_{z,\varphi}\,|_{\rho=R+0}=0$$

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

Axial surface conductivity of isolated single-wall carbon nanotube

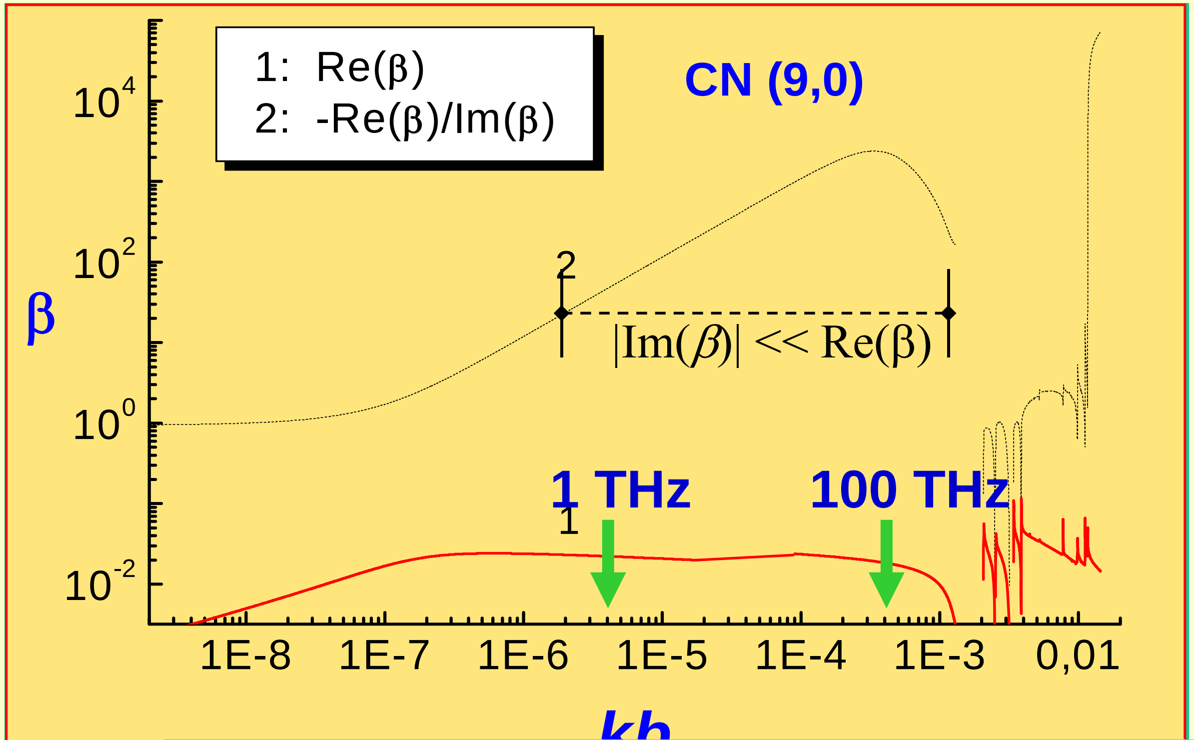
$$\sigma_{zz}(\omega)=-\frac{ie^2\omega}{\pi^2\hbar R}\left\{\frac{1}{\omega(\omega+i/\tau_1)}\sum_{s=1}^{m}\int_{1stBZ}\frac{\partial \mathrm{E}_c}{\partial p_z}\frac{\partial F_c}{\partial p_z}d\,p_z-2\sum_{s=1}^{m}\int_{1stBZ}|R_{c\upsilon}|^2\,\mathrm{E}_c\,\frac{F_c-F_v}{\hbar^2\omega(\omega+i/\tau_1)-4\mathrm{E}_c^2}dp_z\right\},$$

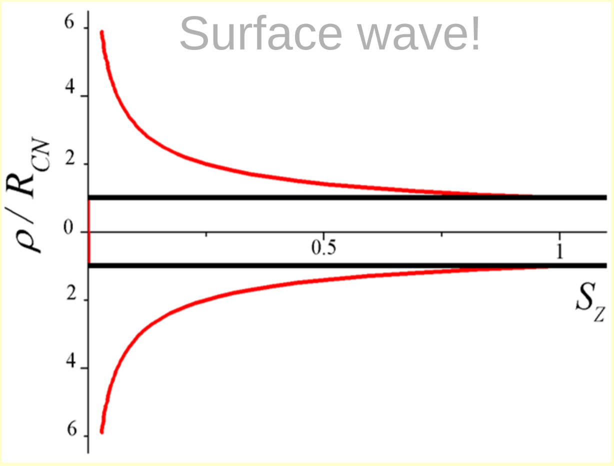


Surface Wave Propagation

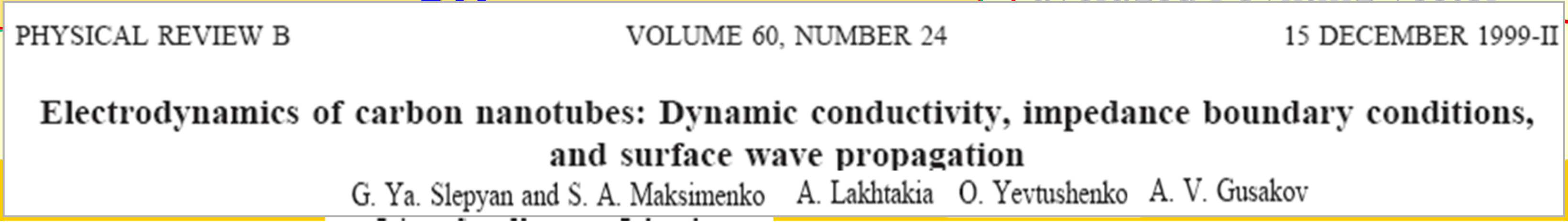
Complex-valued slow-wave coefficient β for a polar-symmetric surface wave

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





Axial component of the time-averaged Poynting vector


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

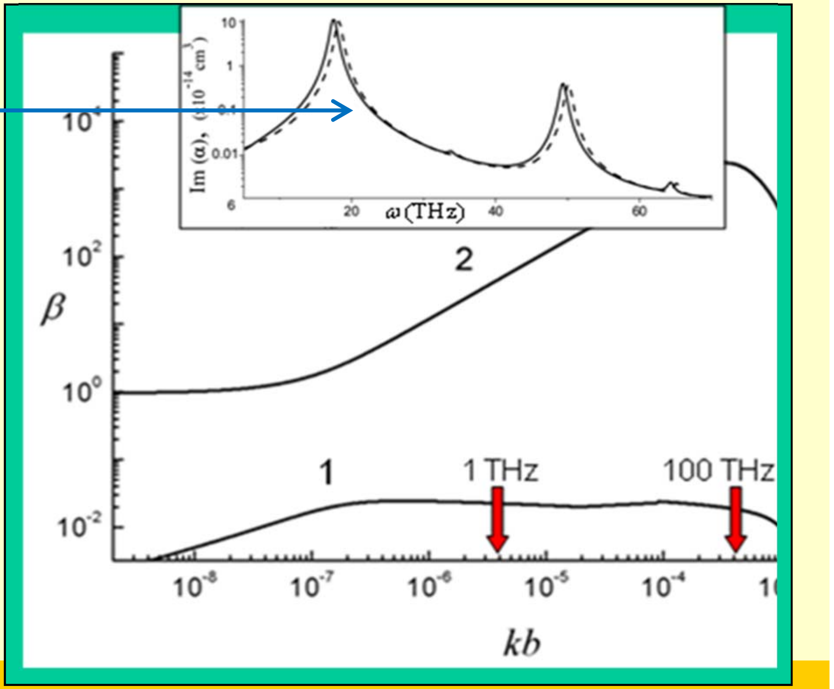
Electrodynamics of carbon nanotubes: Dynamic conductivity, impedance boundary conditions, and surface wave propagation

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

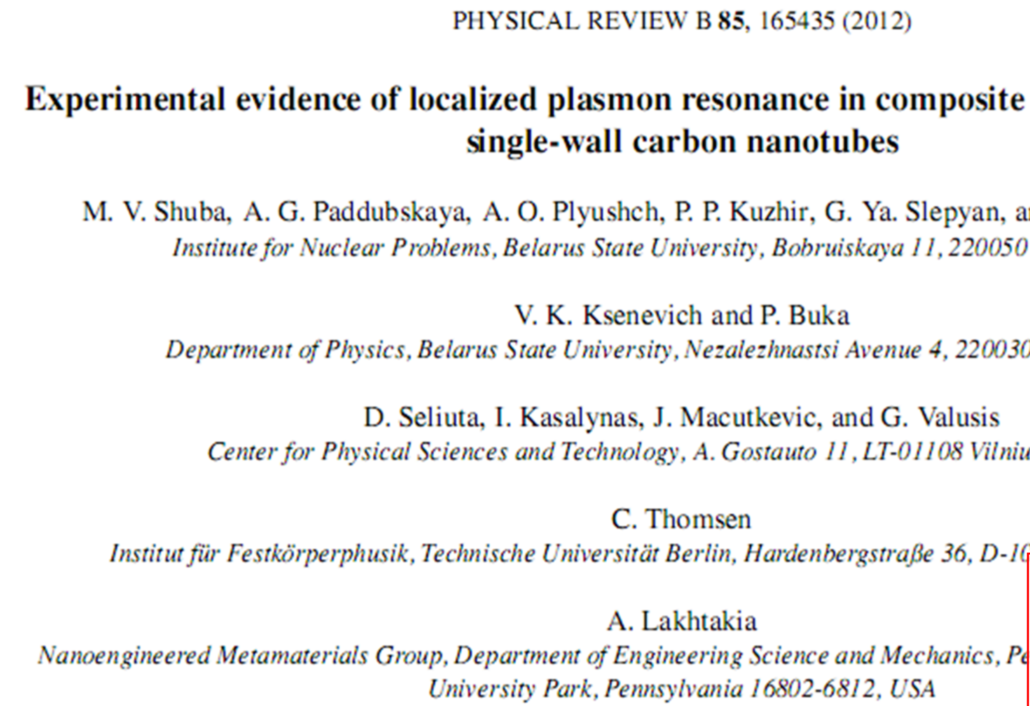
What Can We Learn from the Picture?

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

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



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



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

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

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

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

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

C. Thomsen
Institut für Festkörperphusik, Technische Universität Berlin, Hardenbergstraße 36, D-1

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

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

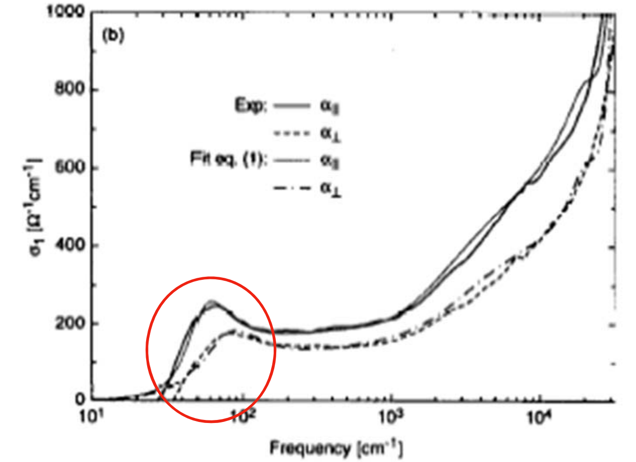
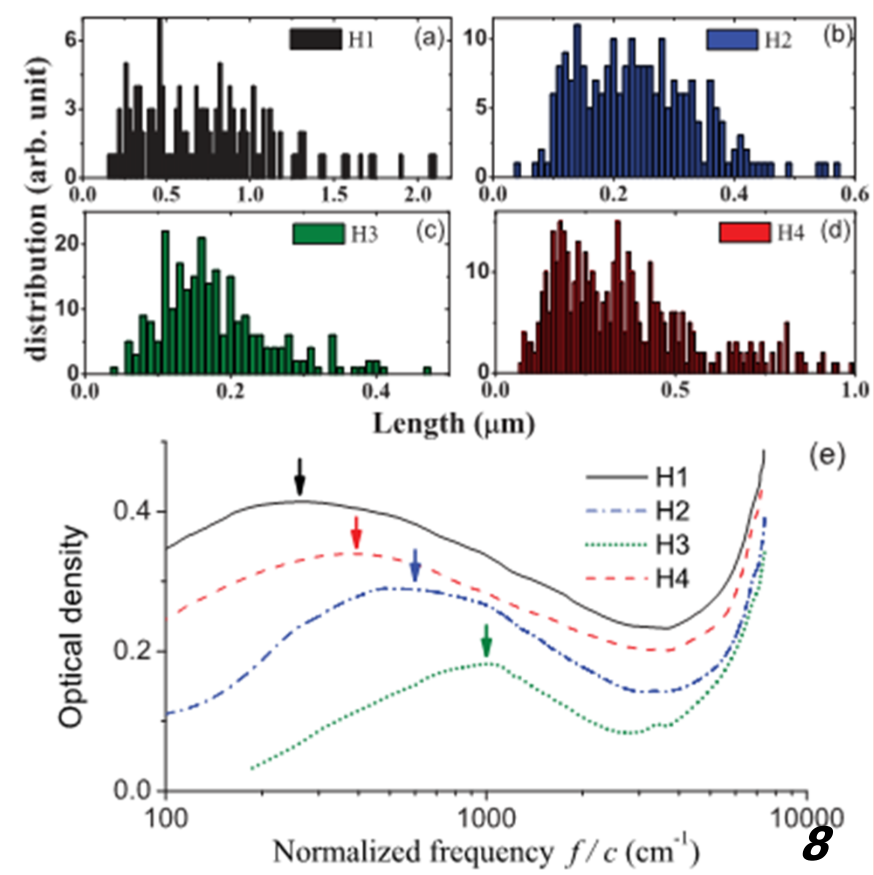


Fig. 1. (a) [redacted] (b) optical conductivity of oriented nanotubes films along the $\alpha_{\parallel}$ and $\alpha_{\perp}$ directions. The MG fits [Equation (1)] are also presented.

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

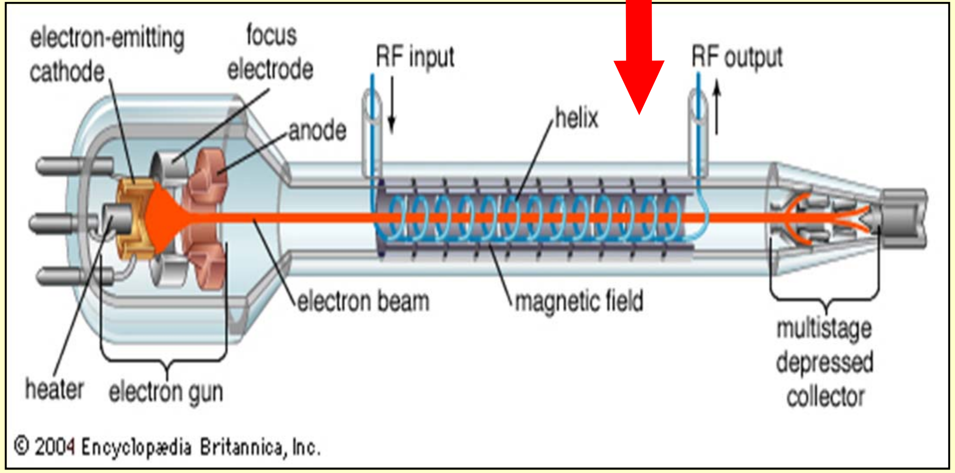
THz peak: experiment



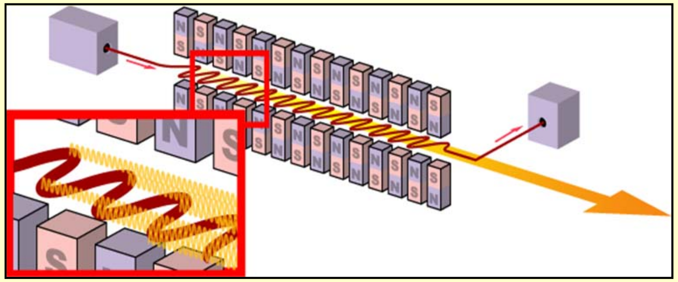
Nano – TWT and Nano-FEL

a slowing-down system

Macroscopic TWT



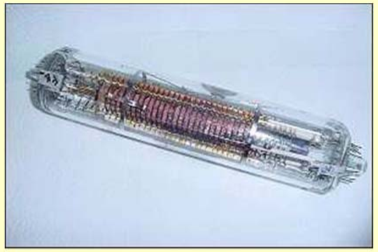
© 2004 Encyclopædia Britannica, Inc.

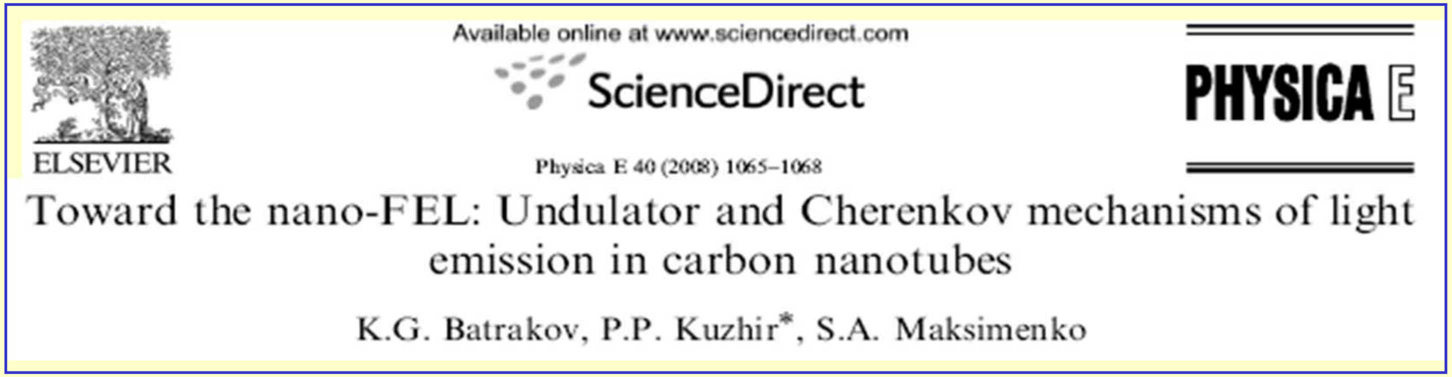


FEL

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

ScienceDirect

PHYSICA E

ELSEVIER

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 EM waves can emit radiation (Cherenkov, Smith-Purcell, quasi-Cherenkov mechanisms)

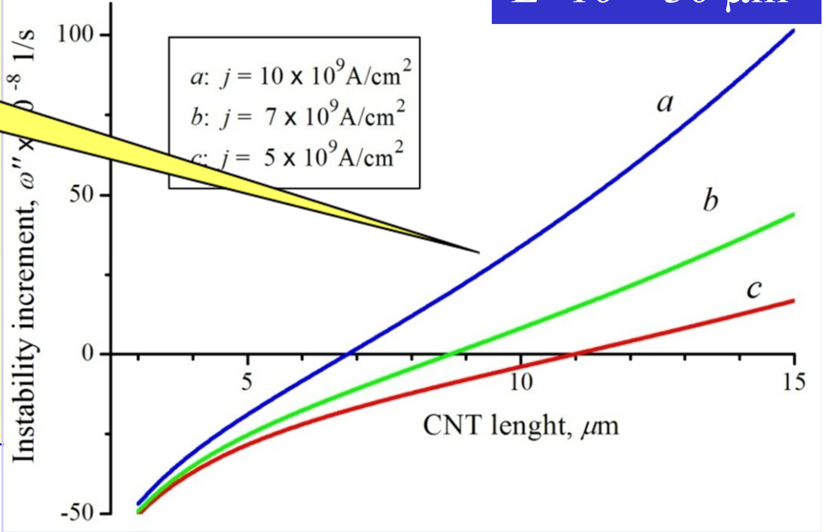
Combination in CNTs of three key properties,

- 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

$j=10^{10}$ A/cm^2
L=10 – 30 μm

Gain per unit length is extremely large comparing with macrodevices

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



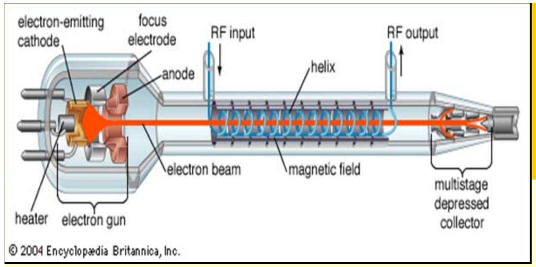
PHYSICAL REVIEW B **79**, 125408 (2009)

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

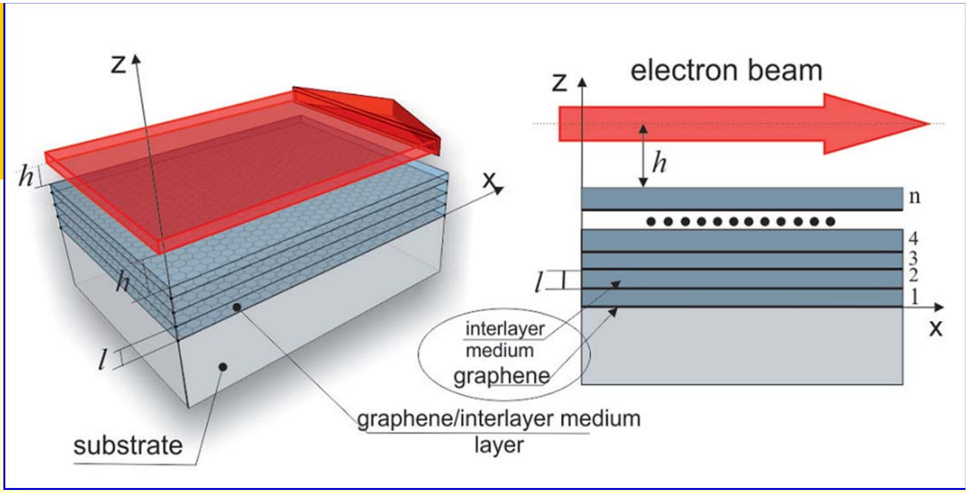
K. G. Batrakov, S. A. Maksimenko, and P. P. Kuzhir
Institute for Nuclear Problems, Belarus State University, Bobruiskaya 11, 220050 Minsk, Belarus

C. Thomsen

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



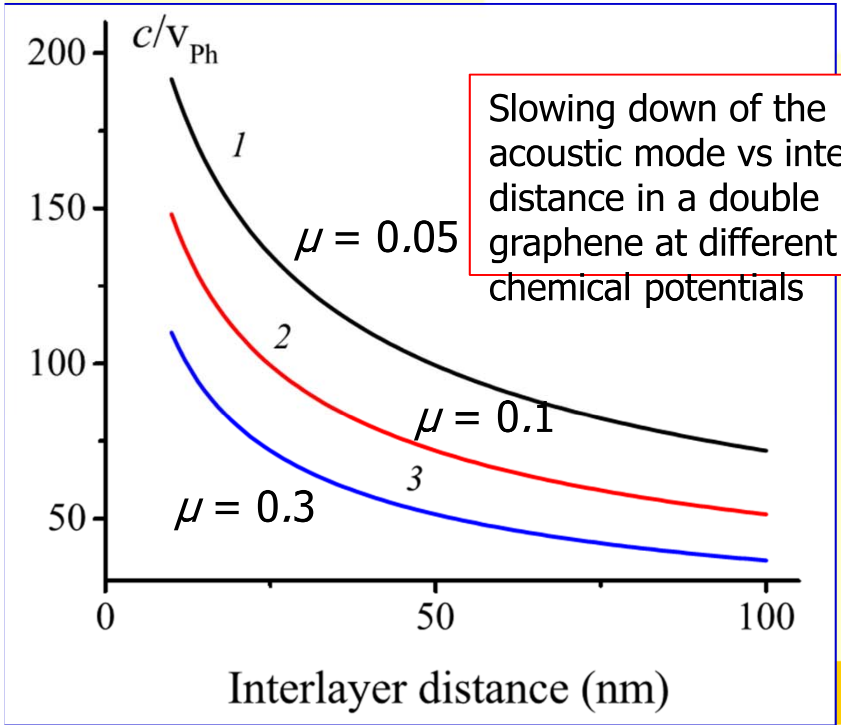
Quasi-cherenkov radiation of an electron beam passing over the graphene/polymer sandwich structure



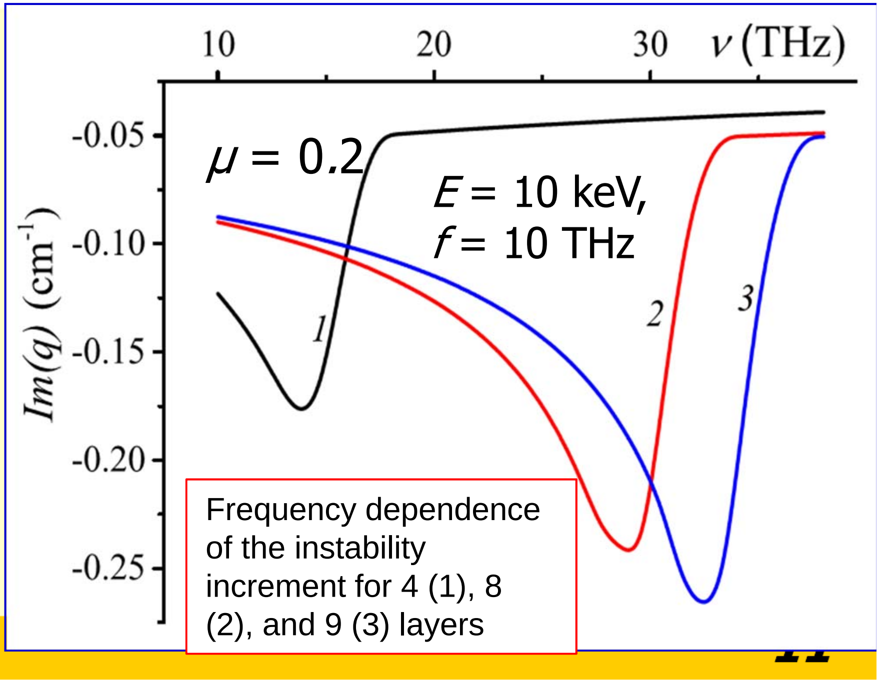
PHYSICAL REVIEW B **95**, 205408 (2017)

Graphene layered systems as a terahertz source with tuned frequency

K. Batrakov* and S. Maksimenko



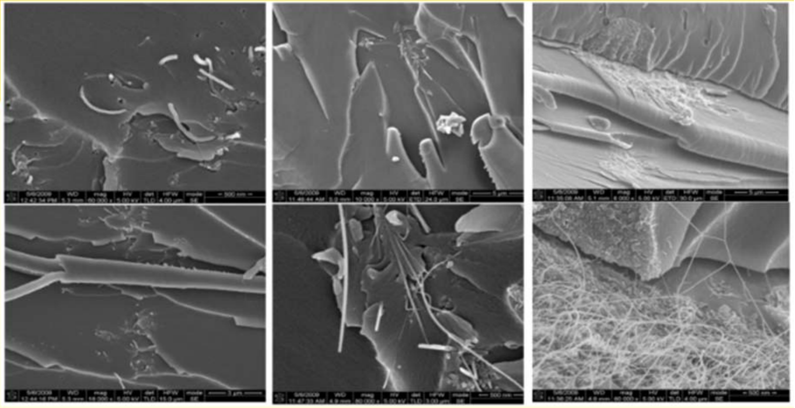
Slowing down of the acoustic mode vs interlayer distance in a double graphene at different chemical potentials



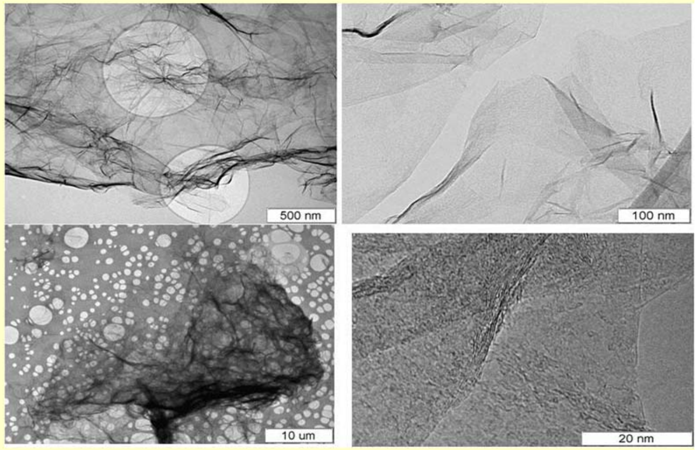
Frequency dependence of the instability increment for 4 (1), 8 (2), and 9 (3) layers

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

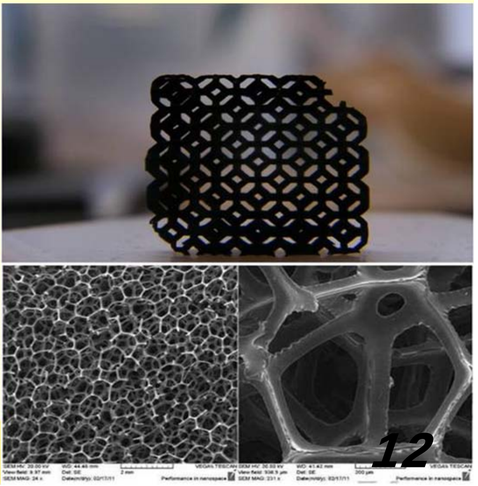
Three classes of ultralight and/or ultrathin EM materials are under study



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



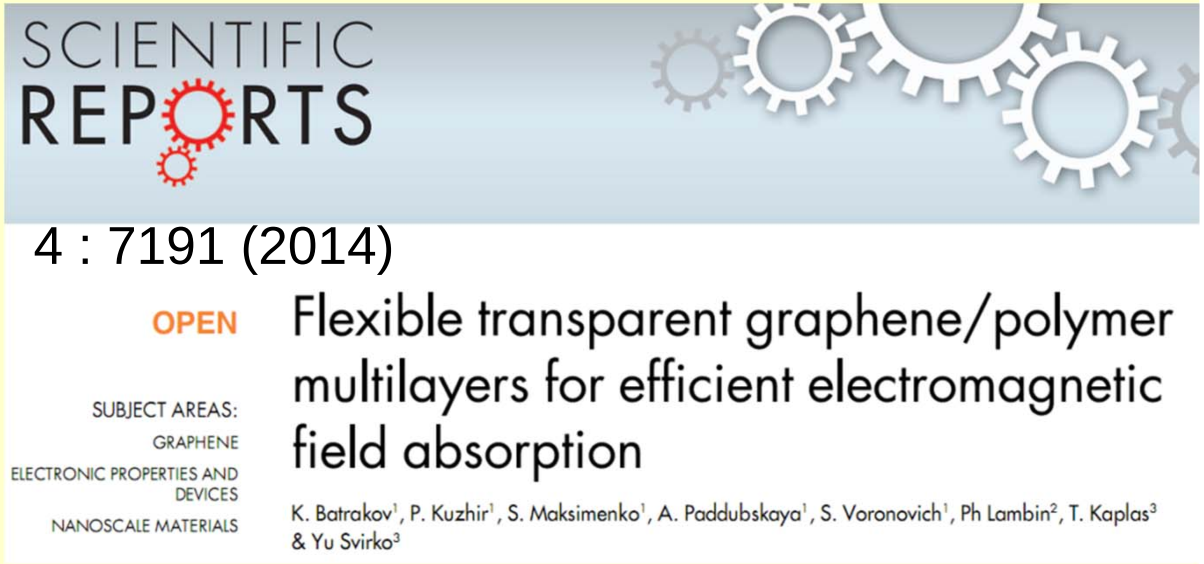
(ii) **CNT-, Graphene and carbon ultra-thin films** (CNT films, few-layers graphene, graphene / PMMA sandwiches, graphene-like films)



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

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)

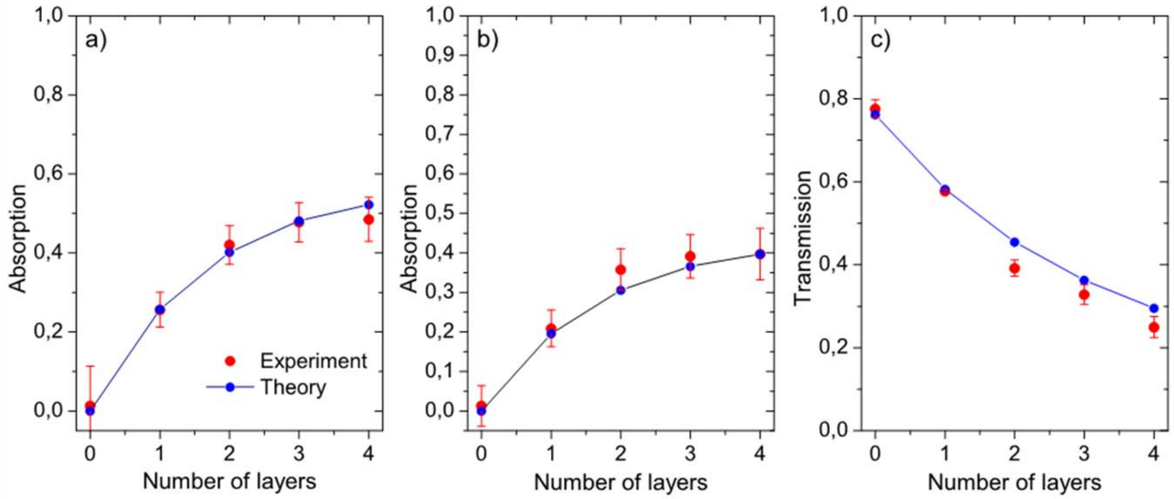
OPEN

SUBJECT AREAS:
GRAPHENE
ELECTRONIC PROPERTIES AND DEVICES
NANOSCALE MATERIALS

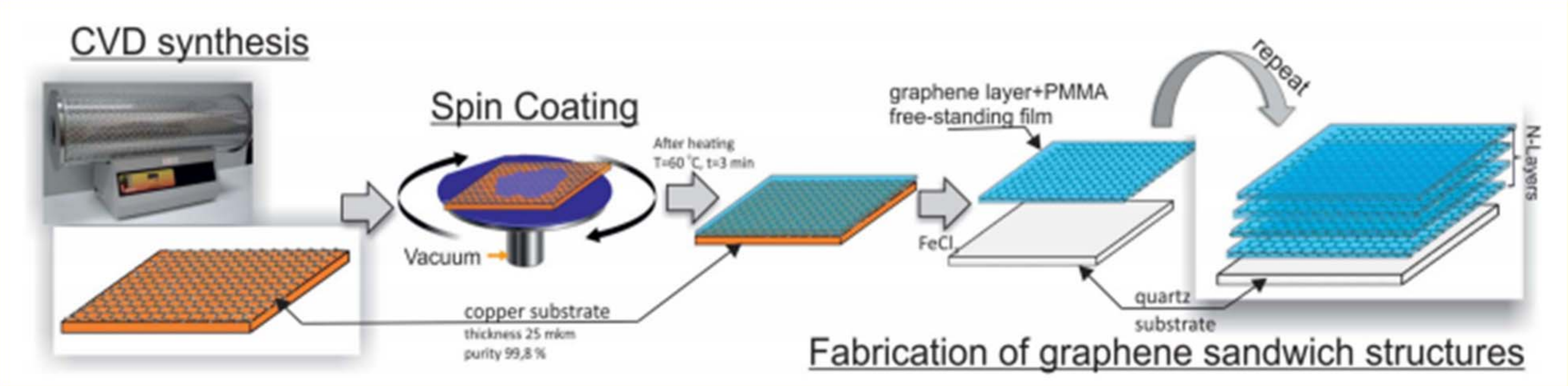
Flexible transparent graphene/polymer multilayers for efficient electromagnetic field absorption

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

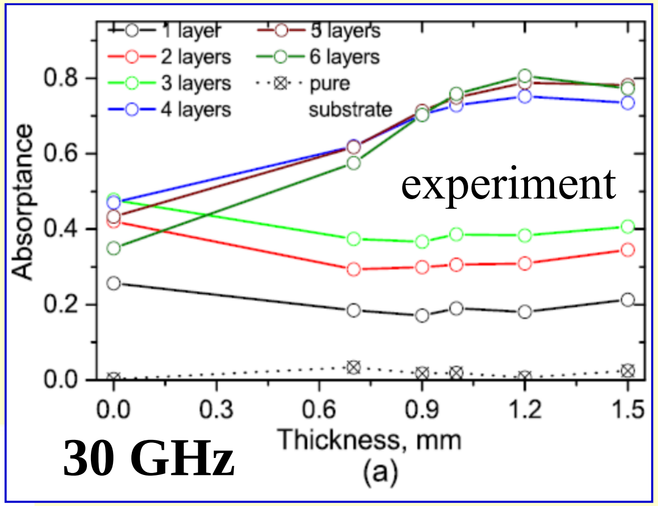
EM absorption is as high as 50% for PyC film of 75 nm thickness and a few layers graphene, 1.5-2 nm thick.

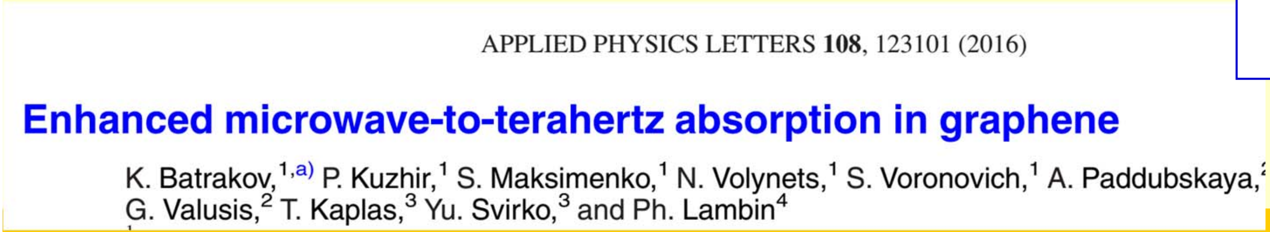


Fabrication of multi-layerd PMMA/Graphene structures



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.




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]

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***

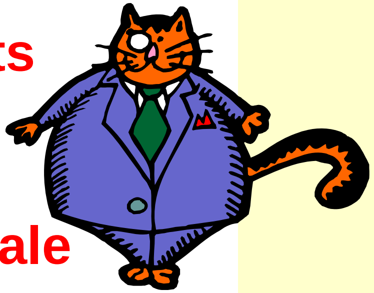
  EM shielding and absorption, coatings, 3D-arhitectures, sponges, aerogels, thin films, etc.

- ***Instabilities***

  THz radiation generation, TWT, active circuit elements

- ***Photothermal effect, medicine***

  EM heating of nanocarbons, heat transfer on nanoscale

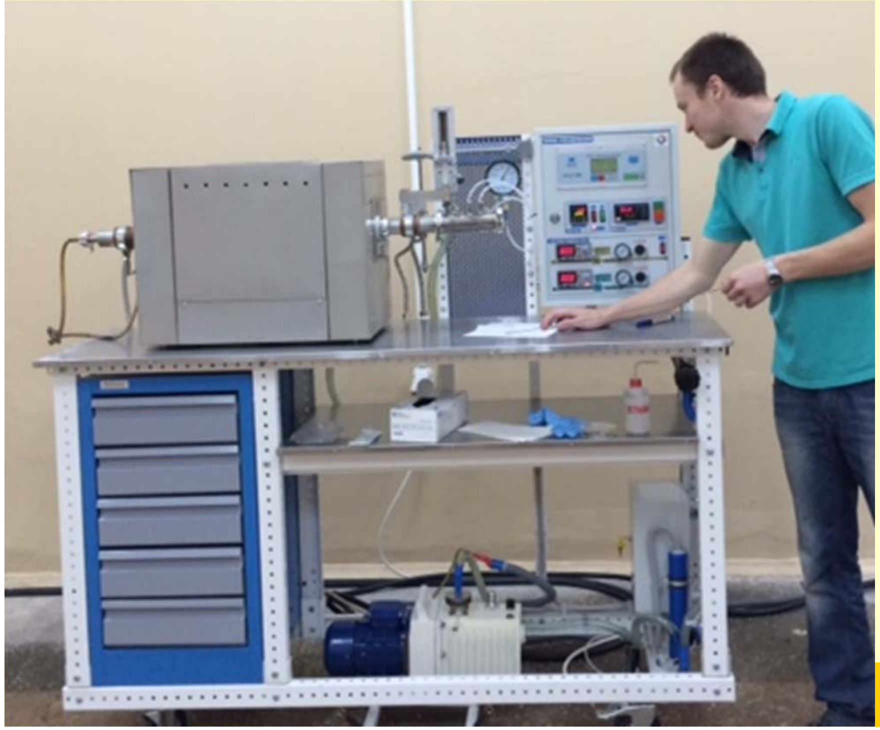


We are open for collaboration!

NANOCARBON Fabrication

CVD fabrication of MWCNTs & GNP

Vertical arrays of
Multi-walled carbon nanotubes



Graphene nanoplatelets, PyC, TEG, etc.

3D-printer

Probe station SPS-1000 MicroXact

Vector network analyzer MICRAN P4M

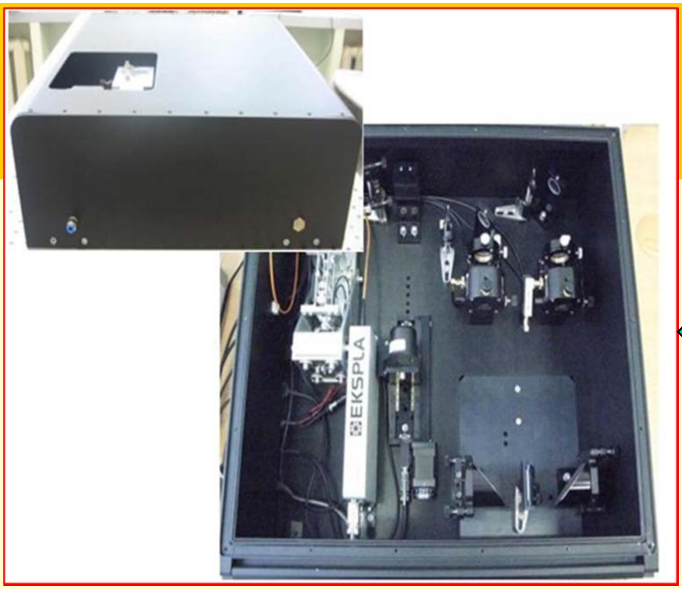
- Measurement of S-parameters from 10 MHz to 20 GHz
- Dynamic range more than 100 dB

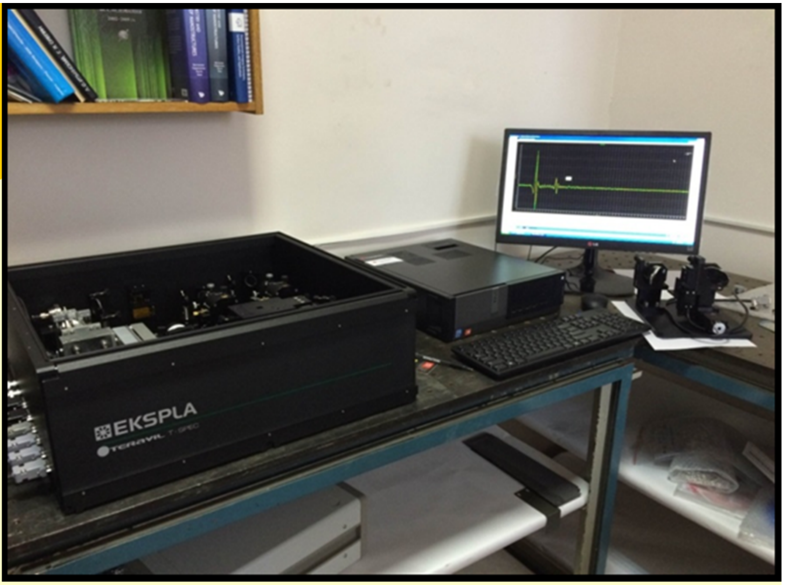
Fully manual stage assembly with precision cross roller bearings with 100 mm x 100 mm range.

Stereo zoom microscope with up to 200mm working distance and high-intensity LED lighting provide outstanding vision from 3.5X to 180X magnifications.

Isolated feed-through terminals located on both sides of station for convenient connection to micropositioners can be customized for BNC, Triax or DC pin connections or standard RF connections.

Vacuum chucks offered in either polished or gold-plated brass as well as anodized aluminum. Vacuum ports adjustable for samples as small as 2.5mm.





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

Fundamental & Applied NanoElectroMagnetics II

THz circuits, materials, devices

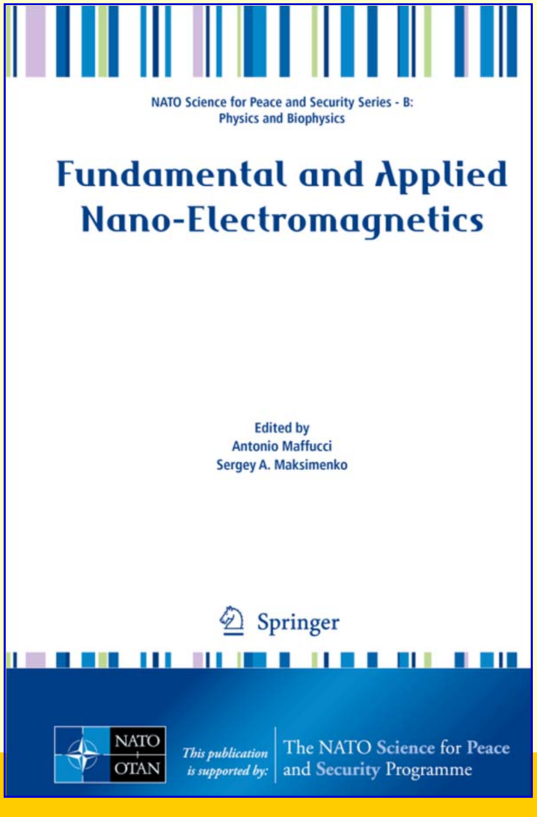
Minsk, June 5-7 2018

http://www.fanem.org/

Co-directors:

Prof. Antonio Maffucci

Prof. Sergey Maksimenko



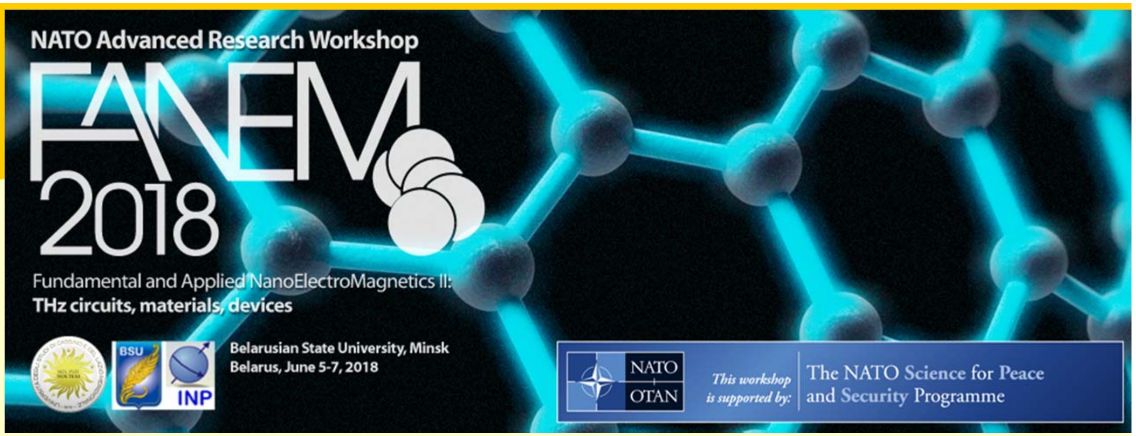
NATO Science for Peace and Security Series - B:
Physics and Biophysics

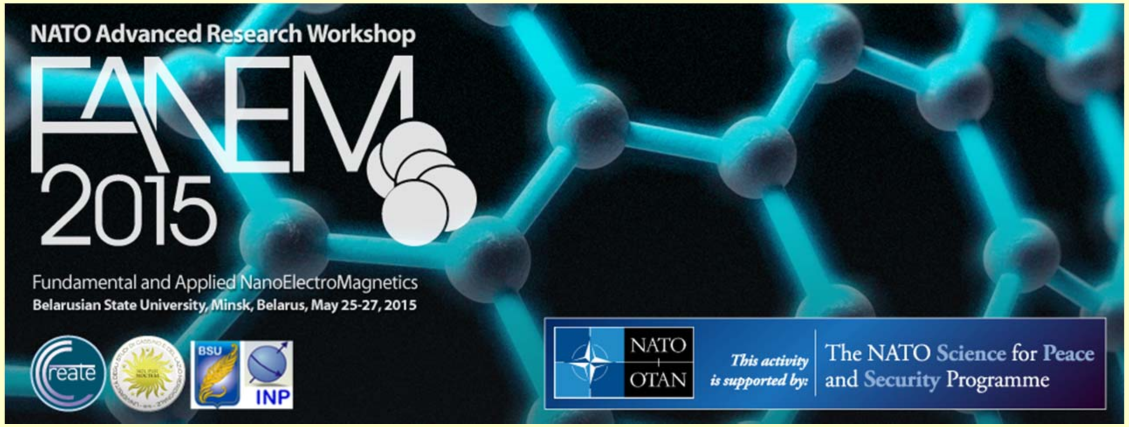
Fundamental and Applied Nano-Electromagnetics

Edited by
Antonio Maffucci
Sergey A. Maksimenko

Springer

NATO OTAN This publication is supported by: The NATO Science for Peace and Security Programme





Nanoelectro magnetics international projects

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

Collective Excitations In Advanced Nanostructures
Horizon 2020 - 644076
CoExAN

Graphene/polymer based flexible transparent EM shielding for GHz and THz applications

GRAPHENE FLAGSHIP

FP7- 604391, H2020-649953

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

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

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

Terahertz applications of carbon-based nanostructures
FP7-230778 TERACAN

Nanocarbon based composite materials for electromagnetic Applications
ISTC B-1708

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

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

Multifunctional Graphene-based Nanocomposites with Robust Electromagnetic and Thermal Properties for 3D-printing Application
Horizon 2020 734164 Graphene 3D

INSTITUTE FOR NUCLEAR PROBLEMS
BELARUSIAN STATE UNIVERSITY

Nikolaev Institute of
Inorganic Chemistry
Novosibirsk

National Research
Tomsk
State
University
TOMSK-1878

THE PENNSYLVANIA STATE UNIVERSITY
1855

UNIVERSITÀ DEGLI STUDI DI CASSINO E DEL LAZIO MERIDIONALE
SOL PER NOCTEM
1979

TEL AVIV
UNIVERSITY

UNIVERSITY OF
EXETER

INFN

TU berlin

CENTER
FOR PHYSICAL SCIENCES
AND TECHNOLOGY
Lithuania

ITÄ-SUOMEN
YLIOPISTO

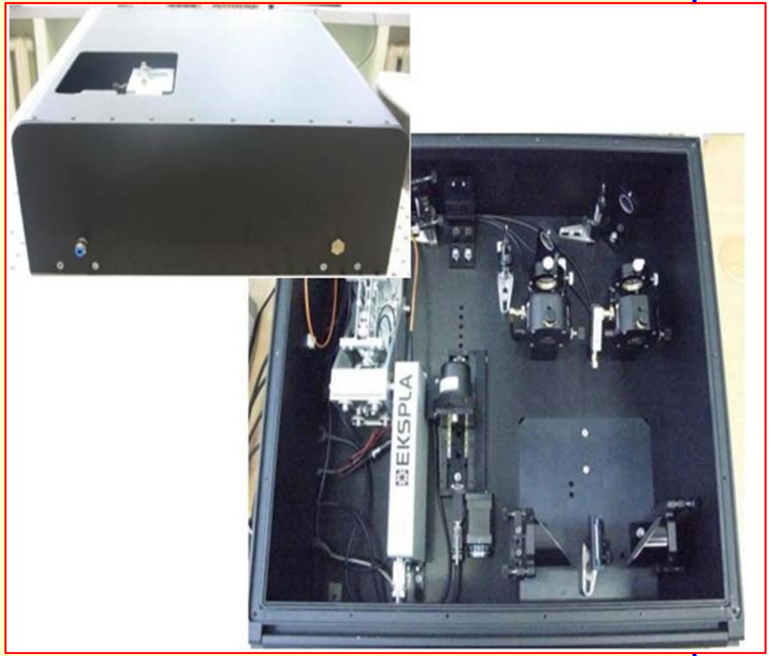
UNIVERSITÉ
DE NAMUR

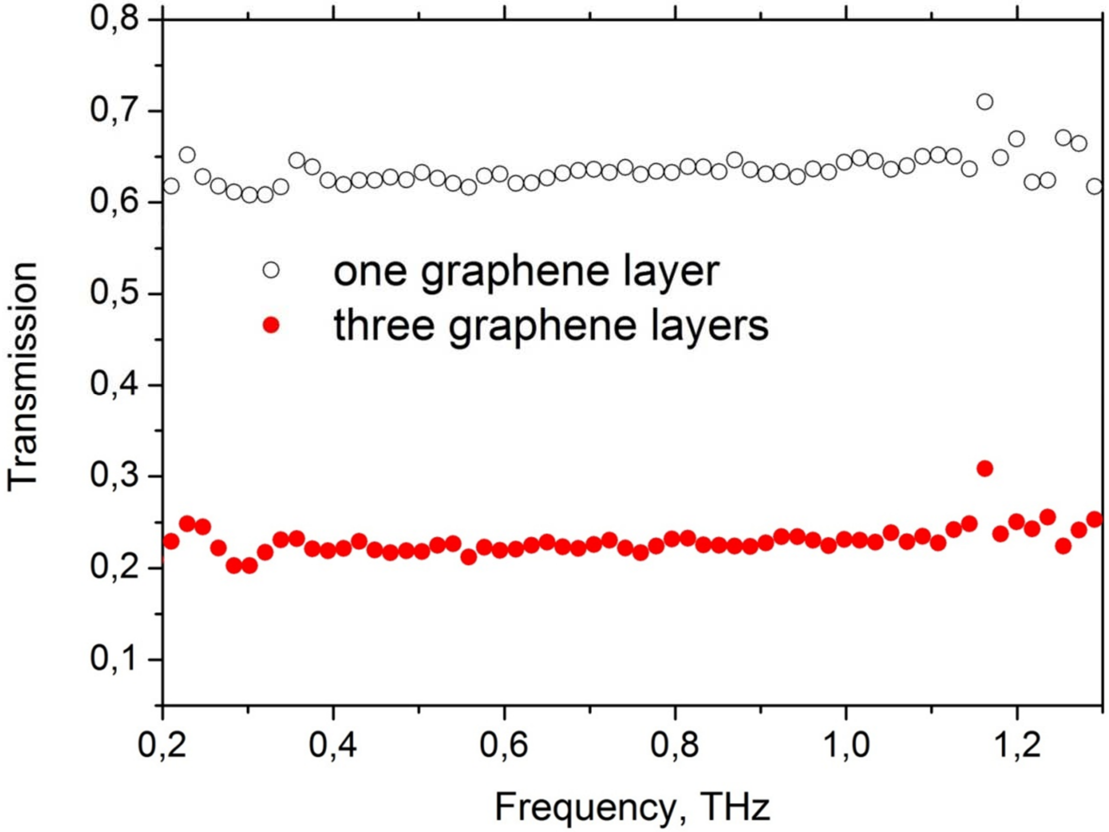
VILNIAUS UNIVERSITETAS
1579
UNIVERSITAS VILNENSIS

UNIVERSITÉ
DE LORRAINE
IUF
CNRS
IJL
Institut Jean Lamour

Thank you for your attention!

Terahertz properties of free standing graphene/PMMA sandwiches





In the frequency range from 100 GHz to 3 THz, measurements were performed by Time domain terahertz spectrometer (EKSPLA, Vilnius Lithunia) based on femtosecond laser (wavelength 1 µm, pulse duration less than 150 fs) and GaBiAs photoconductive switch as THz emitter and detector.