# Electromagnetics of perfect absorbers:

## *Part 1: 2D vs 3D geometry*

## *Part 2: Composite materials filled with carbon nano- and micro-inclusions*

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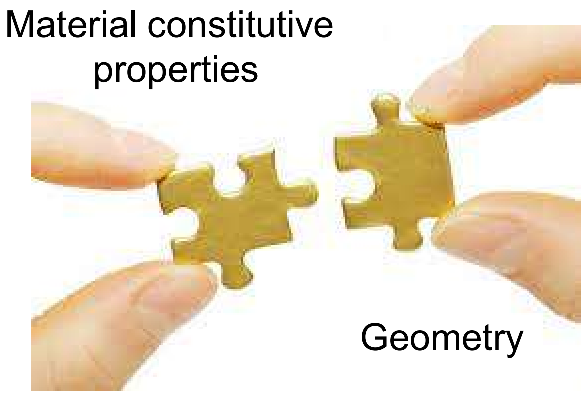


*Joensuu - Cassino – Minsk, May 24-25, 2021*

# Microwave and THz absorbing materials/devices

The general requirements can be summarized:

- ✓ It should minimize the reflection of EM waves at the air to absorber interface
- ✓ It should have strong absorption of electromagnetic waves
- ✓ It is expected to have broad bandwidth and angular response
- ✓ It should have low weight and as small as possible thickness

All techniques can be divided:

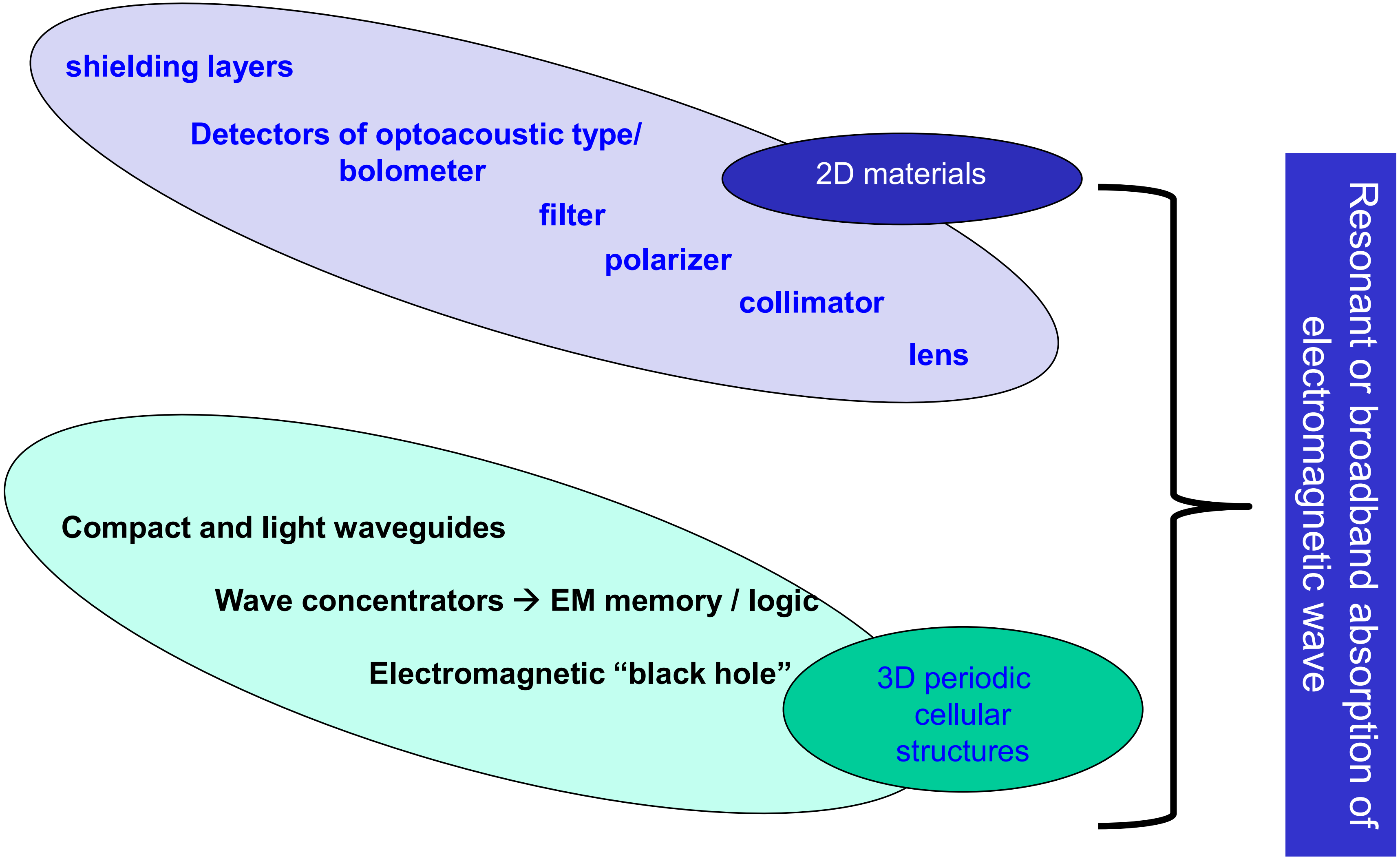
- ▪ Material based (dielectric and magnetic losses)
- ▪ Geometry based (e.g. Salisbury screen ideology, (2n+1) $\lambda/4$ thickness suppressing reflection, 0 index substrate …… )
- ▪ Combination of both

**Electromagnetics of perfect absorbers**:

Part 1: 2D vs 3D geometry (geometry-based)

Part 2: Composite materials filled with carbon nano- and micro-inclusions (material based and combination of both)

# MW and THz passive components



shielding layers

Detectors of optoacoustic type/ bolometer

filter

polarizer

collimator

lens

2D materials

Compact and light waveguides

Wave concentrators → EM memory / logic

Electromagnetic “black hole”

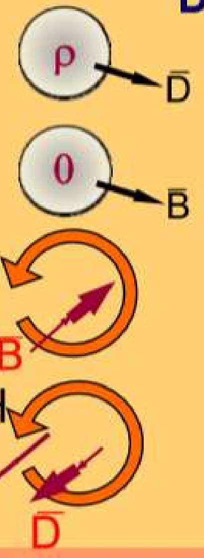
3D periodic cellular structures

Resonant or broadband absorption of electromagnetic wave

# OUTLINE

1. ELECTROMANGTICS FUNDAMENTALS: Maxwell’s equations, boundary conditions, constitutive relations
2. Thin conductive films
3. Graphene, its electromagnetics in microwave and THz range
4. Passive devices made of graphene
5. 3D carbon made architectures: perfect resonant absorbers
6. 2D material + 3D geometry: THz metasurfaces

# MAXWELL'S EQUATIONS



**Integral Form:** **Differential Form:**

$$\oiint_S \bar{D}\bullet\hat{n}da = \oiiint_V \rho\, dv \quad\Leftrightarrow\quad \nabla\bullet\bar{D}=\rho$$

$$\bar{D}=\varepsilon\bar{E},\ \bar{B}=\mu\bar{H} \qquad \oiint_S \bar{B}\bullet\hat{n}da = 0 \quad\Leftrightarrow\quad \nabla\bullet\bar{B}=0$$

Gauss's laws for electric and magnetic fields

$$\oint_c \bar{E}\bullet d\bar{s} = -\cancelto{0}{\frac{\partial}{\partial t}}\iint_A \bar{B}\bullet\hat{n}da \quad\Leftrightarrow\quad \nabla\times\bar{E}=-\frac{\partial\bar{B}}{\partial t}$$

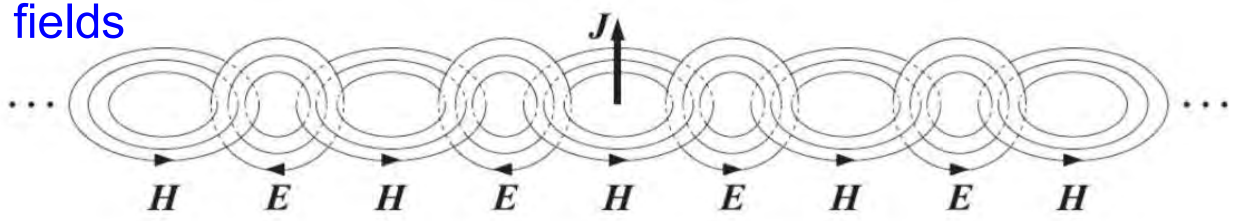
Faraday's law of induction

$$\oint_c \bar{H}\bullet d\bar{s} = \iint_A \bar{J}\bullet\hat{n}da + \cancelto{0}{\frac{\partial}{\partial t}}\iint_A \bar{D}\bullet\hat{n}da \quad\Leftrightarrow\quad \nabla\times\bar{H}=\bar{J}+\frac{\partial\bar{D}}{\partial t}$$

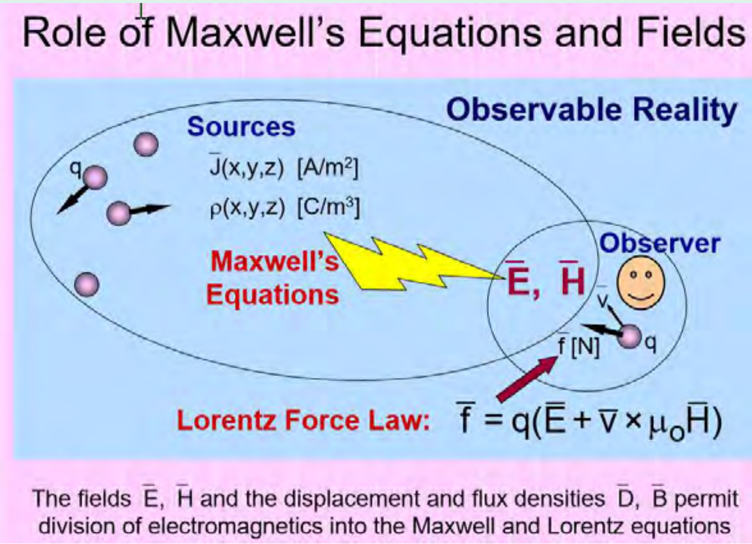
Ampere's law (establishing charge conservation).
The displacement current is essential in predicting the propagation of EM wave.

| | | |
|---|---|---|
| $\bar{E}$ | Electric field | [volts/meter, V m$^{-1}$] |
| $\bar{H}$ | Magnetic field | [amperes/meter, A m$^{-1}$] |
| $\bar{B}$ | Magnetic flux density | [Tesla, T] |
| $\bar{D}$ | Electric displacement | [ampere sec/m$^2$, A s m$^{-2}$] |
| $\bar{J}$ | Electric current density | [amperes/m$^2$, A m$^{-2}$] |
| $\rho$ | Electric charge density | [coulombs/m$^3$, C m$^{-3}$] |

Propagation of EM fields

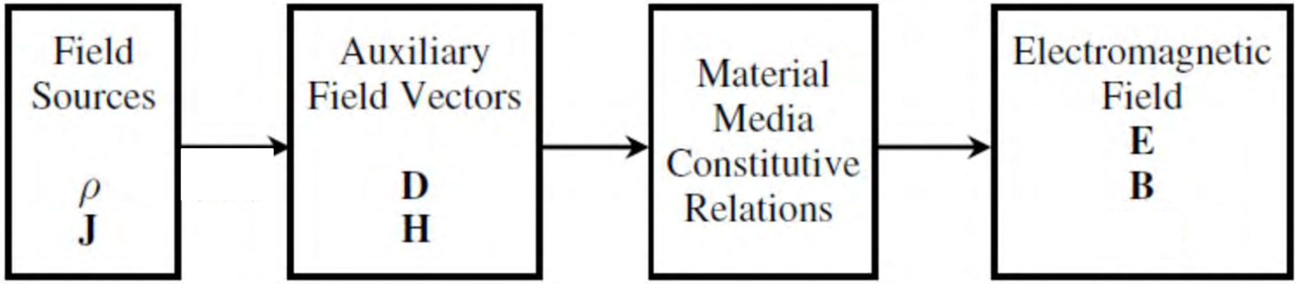


# Constitutive Relations



Role of Maxwell's Equations and Fields

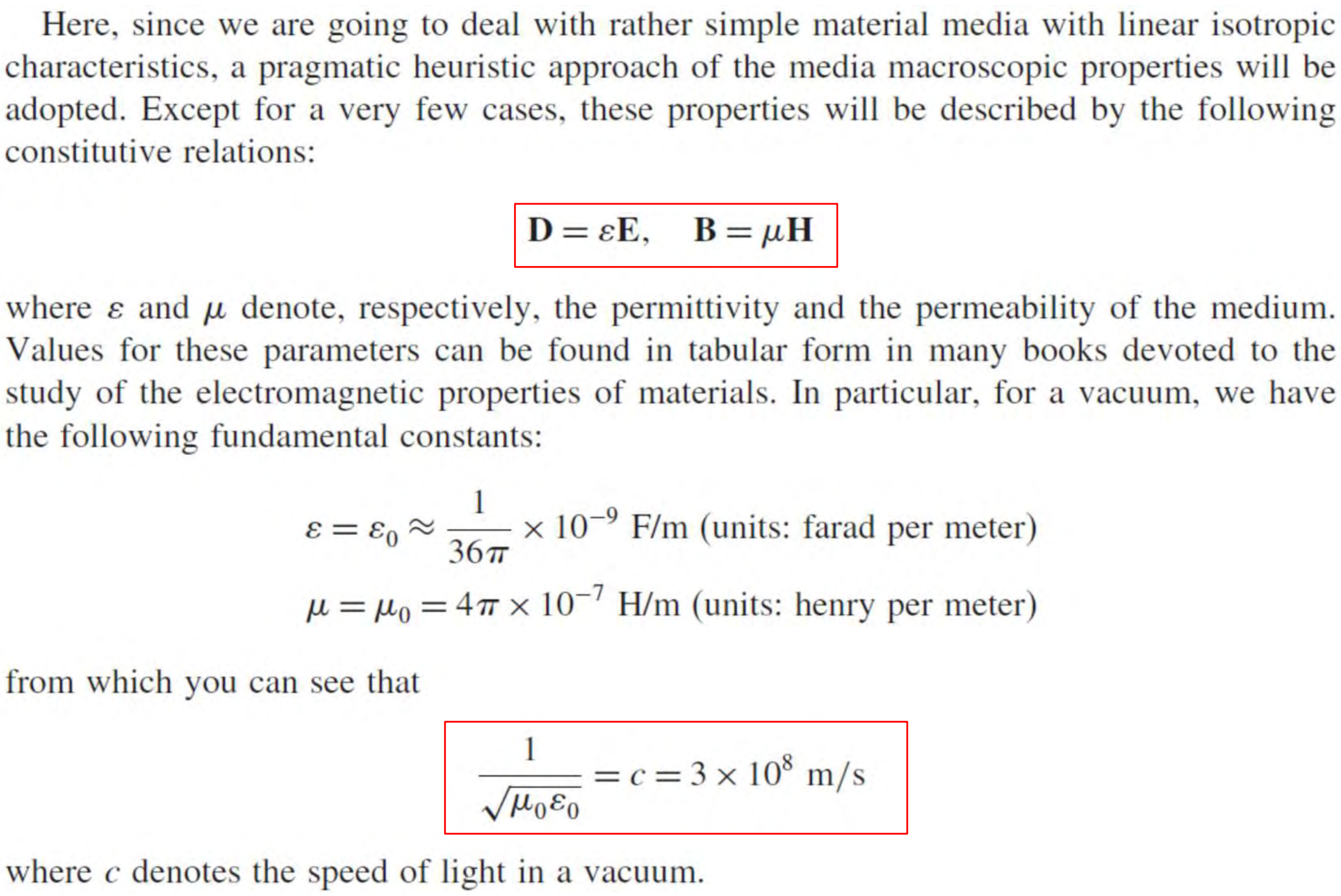
The fields $\bar{E}$, $\bar{H}$ and the displacement and flux densities $\bar{D}$, $\bar{B}$ permit division of electromagnetics into the Maxwell and Lorentz equations



The connections between (**D, H**) and (**E, B**) are related to the interaction of the electromagnetic field with the material media where fields are impressed.

# Constitutive Relations

Linear isotropic media …



Here, since we are going to deal with rather simple material media with linear isotropic characteristics, a pragmatic heuristic approach of the media macroscopic properties will be adopted. Except for a very few cases, these properties will be described by the following constitutive relations:

$$\boxed{\mathbf{D} = \varepsilon \mathbf{E}, \quad \mathbf{B} = \mu \mathbf{H}}$$

where $\varepsilon$ and $\mu$ denote, respectively, the permittivity and the permeability of the medium. Values for these parameters can be found in tabular form in many books devoted to the study of the electromagnetic properties of materials. In particular, for a vacuum, we have the following fundamental constants:

$$\varepsilon = \varepsilon_0 \approx \frac{1}{36\pi} \times 10^{-9} \text{ F/m (units: farad per meter)}$$

$$\mu = \mu_0 = 4\pi \times 10^{-7} \text{ H/m (units: henry per meter)}$$

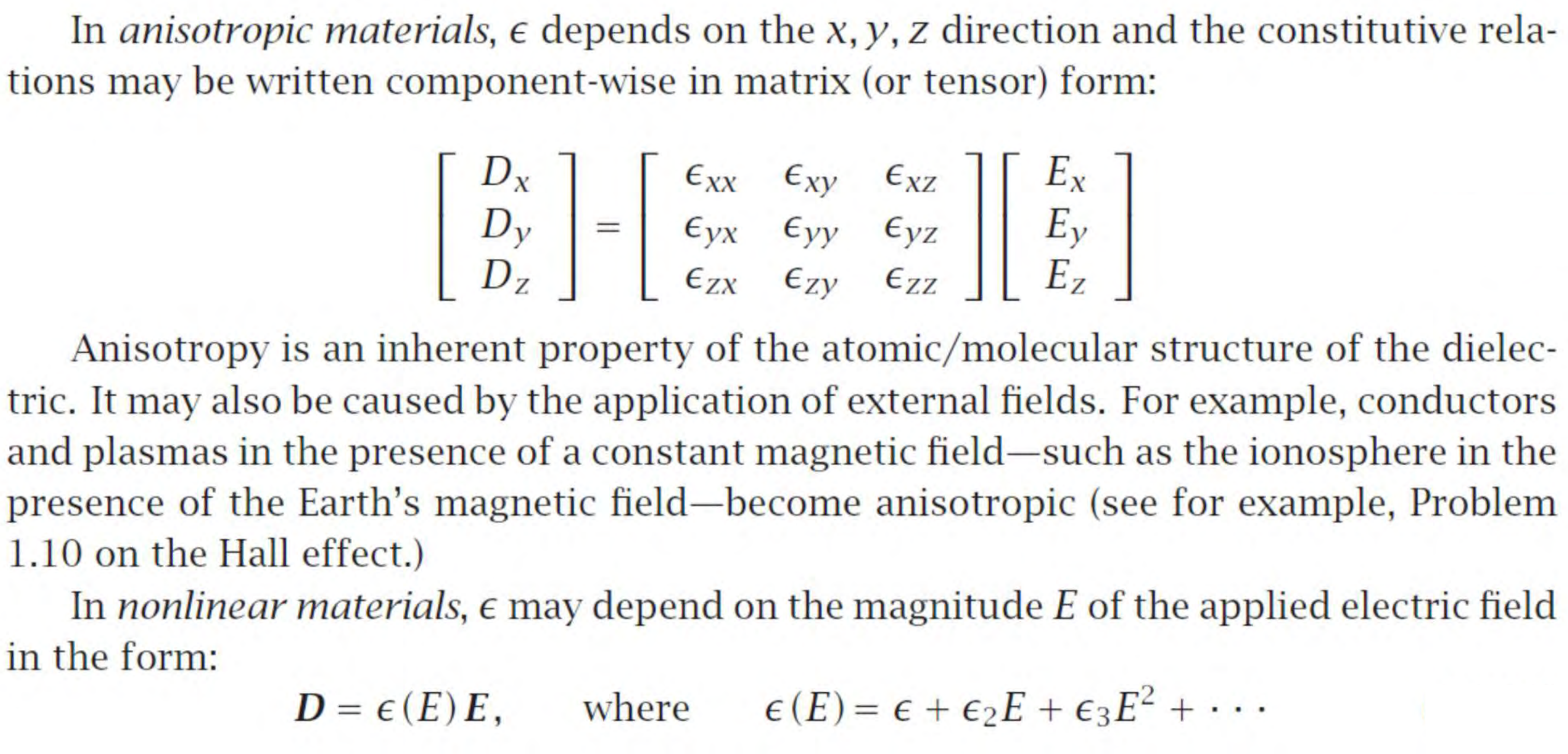
from which you can see that

$$\boxed{\frac{1}{\sqrt{\mu_0 \varepsilon_0}} = c = 3 \times 10^8 \text{ m/s}}$$

where $c$ denotes the speed of light in a vacuum.

# Constitutive relations

anisotropic media …



In *anisotropic materials*, $\epsilon$ depends on the $x, y, z$ direction and the constitutive relations may be written component-wise in matrix (or tensor) form:

$$\begin{bmatrix} D_x \\ D_y \\ D_z \end{bmatrix} = \begin{bmatrix} \epsilon_{xx} & \epsilon_{xy} & \epsilon_{xz} \\ \epsilon_{yx} & \epsilon_{yy} & \epsilon_{yz} \\ \epsilon_{zx} & \epsilon_{zy} & \epsilon_{zz} \end{bmatrix} \begin{bmatrix} E_x \\ E_y \\ E_z \end{bmatrix}$$

Anisotropy is an inherent property of the atomic/molecular structure of the dielectric. It may also be caused by the application of external fields. For example, conductors and plasmas in the presence of a constant magnetic field—such as the ionosphere in the presence of the Earth's magnetic field—become anisotropic (see for example, Problem 1.10 on the Hall effect.)

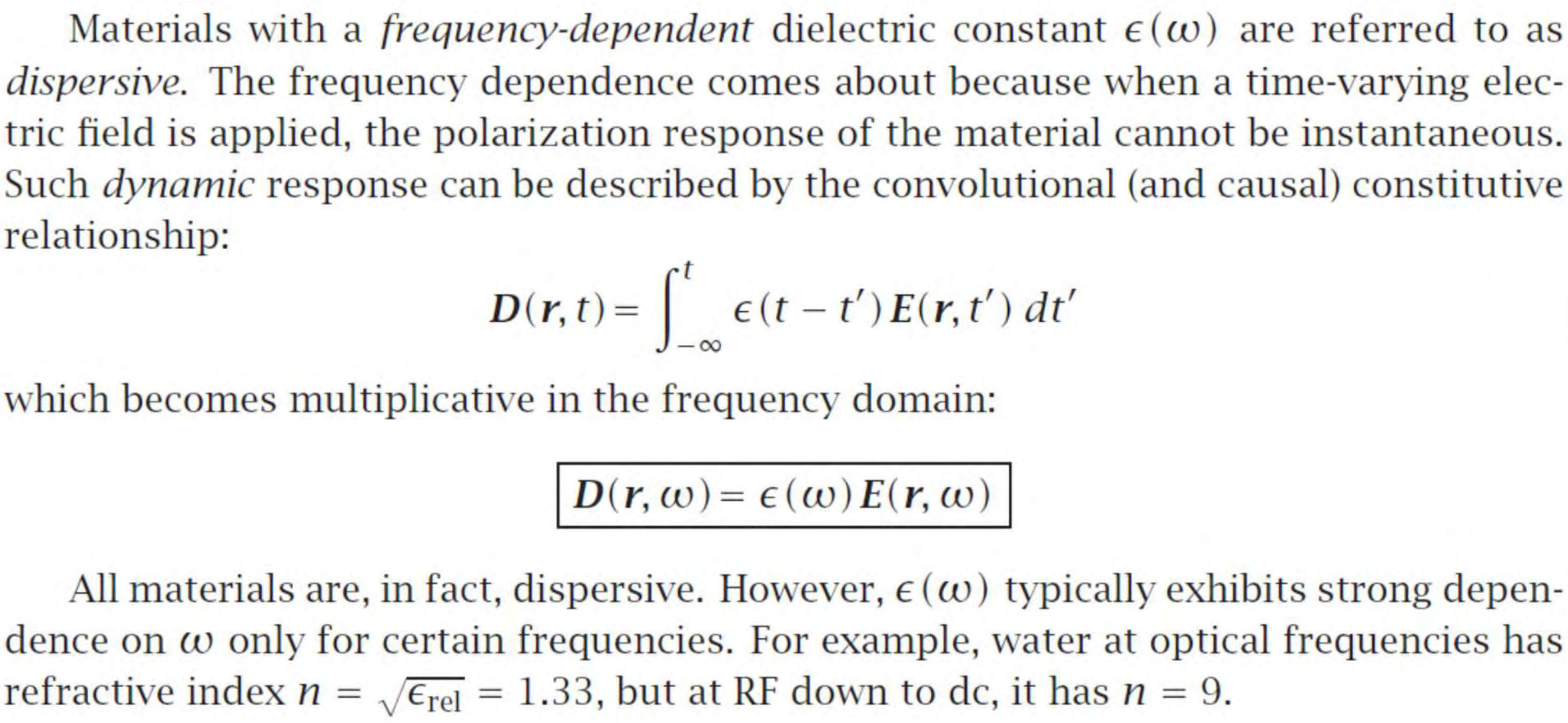
In *nonlinear materials*, $\epsilon$ may depend on the magnitude $E$ of the applied electric field in the form:

$$\mathbf{D} = \epsilon(E)\,\mathbf{E}, \qquad \text{where} \qquad \epsilon(E) = \epsilon + \epsilon_2 E + \epsilon_3 E^2 + \cdots$$

nonlinear media …

# Constitutive relations

dispersive media …



Materials with a *frequency-dependent* dielectric constant $\epsilon(\omega)$ are referred to as *dispersive.* The frequency dependence comes about because when a time-varying electric field is applied, the polarization response of the material cannot be instantaneous. Such *dynamic* response can be described by the convolutional (and causal) constitutive relationship:

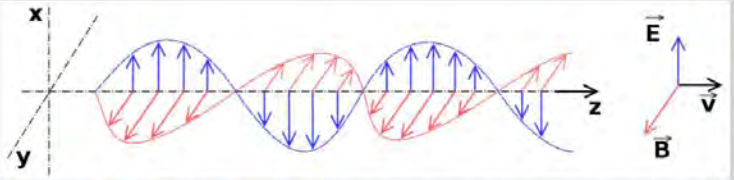
$$\boldsymbol{D}(\boldsymbol{r},t)=\int_{-\infty}^{t}\epsilon(t-t')\,\boldsymbol{E}(\boldsymbol{r},t')\,dt'$$

which becomes multiplicative in the frequency domain:

$$\boxed{\boldsymbol{D}(\boldsymbol{r},\omega)=\epsilon(\omega)\,\boldsymbol{E}(\boldsymbol{r},\omega)}$$

All materials are, in fact, dispersive. However, $\epsilon(\omega)$ typically exhibits strong dependence on $\omega$ only for certain frequencies. For example, water at optical frequencies has refractive index $n = \sqrt{\epsilon_{\text{rel}}} = 1.33$, but at RF down to dc, it has $n = 9$.

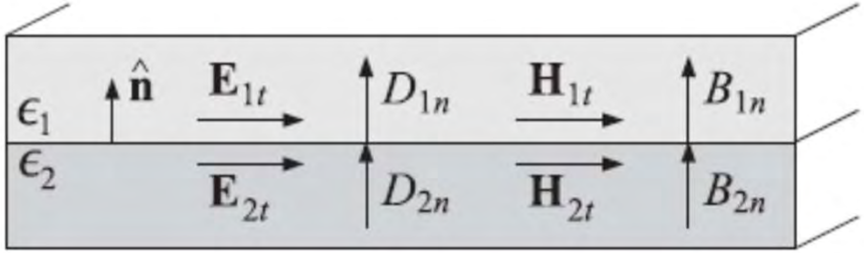
# Boundary conditions



A linearly polarized sinusoidal electromagnetic wave, propagating in the direction +**z** through a homogeneous, isotropic, dissipationless medium, such as vacuum. The electric field (blue arrows) oscillates in the ±**x**-direction, and the orthogonal magnetic field (red arrows) oscillates in phase with the electric field, but in the ±**y**-direction.

The boundary conditions for the electromagnetic fields across material boundaries are given below:

$$\boxed{\begin{aligned} E_{1t} - E_{2t} &= 0 \\ H_{1t} - H_{2t} &= J_s \times \hat{\mathbf{n}} \\ D_{1n} - D_{2n} &= \rho_s \\ B_{1n} - B_{2n} &= 0 \end{aligned}}$$



where $\hat{\mathbf{n}}$ is a unit vector normal to the boundary pointing from medium-2 into medium-1. The quantities $\rho_s, \mathbf{J}_s$ are any external *surface charge* and *surface current* densities on the boundary surface and are measured in units of [coulomb/m$^2$] and [ampere/m].

In words, the *tangential* components of the *E*-field are continuous across the interface; the difference of the *tangential* components of the *H*-field are equal to the surface current.

# Boundary conditions for perfect conductors

$\mathbf{J} = \sigma \mathbf{E}$ ← perfect conductors $(\sigma \to \infty)$

Scalar form

$$E_{1\tau} = 0$$

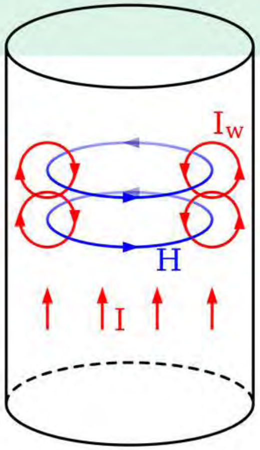
$$H_{1\tau} = J_s$$

$$D_{1n} = \rho_s$$

$$B_{1n} = 0$$

Electric field could not penetrate to the perfect conductor:
The tangential component of electric field is vanished on the conductor

# Skin Effect

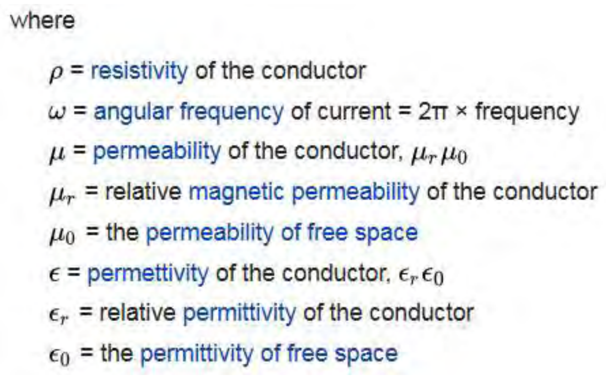


The AC current density $J$ in a conductor decreases exponentially from its value at the surface $J_S$ according to the depth $d$ from the surface, as follows:

$$J = J_S \, e^{-(1+j)d/\delta}$$

$$\delta = \sqrt{\frac{2\rho}{\omega\mu}}.$$

where $\delta$ is called the *skin depth*.



where

$\rho$ = resistivity of the conductor

$\omega$ = angular frequency of current = 2π × frequency

$\mu$ = permeability of the conductor, $\mu_r \mu_0$

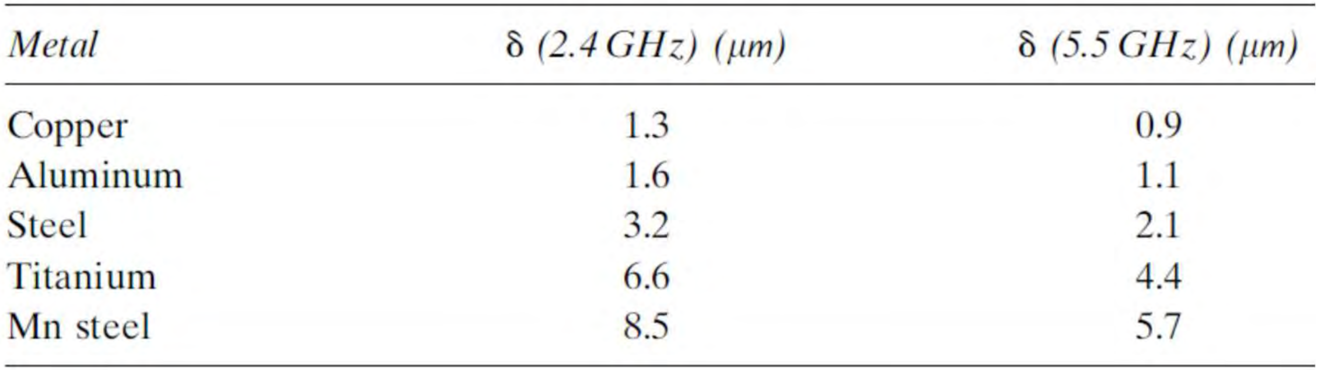
$\mu_r$ = relative magnetic permeability of the conductor

$\mu_0$ = the permeability of free space

$\epsilon$ = permettivity of the conductor, $\epsilon_r \epsilon_0$

$\epsilon_r$ = relative permittivity of the conductor

$\epsilon_0$ = the permittivity of free space



| *Metal* | δ *(2.4 GHz) (μm)* | δ *(5.5 GHz) (μm)* |
|---|---|---|
| Copper | 1.3 | 0.9 |
| Aluminum | 1.6 | 1.1 |
| Steel | 3.2 | 2.1 |
| Titanium | 6.6 | 4.4 |
| Mn steel | 8.5 | 5.7 |

**Skin effect** is the tendency of an AC to distribute itself within a conductor, so that the current density near the surface of the conductor is greater than that at its core.

# EM wave interaction with matter

When propagating in a material,

$$\begin{aligned} c &\rightarrow c/n \\ \lambda_0 &\rightarrow \lambda_0/n \\ k_0 &\rightarrow k_0 n \end{aligned}$$

$$E(t,z) = Re\{\tilde{E}_0 e^{-\alpha z/2} e^{j(\omega t - k_0 n z)}\}$$

Absorption coefficient

Refractive index

## Absorption

$$I(z) = I_0 e^{-\alpha z}$$

Absorption of electromagnetic radiation shows how matter takes up a photon's energy and transforms electromagnetic energy into internal energy of the absorber (for example, thermal energy).

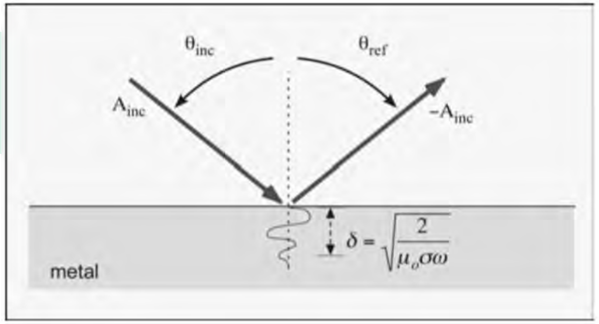
## Joule Heating

The production of heat by a current is called Joule heating or, sometimes, Ohmic heating.

$$\boxed{dW/dt = I^2R}$$

# Reflection by Metals

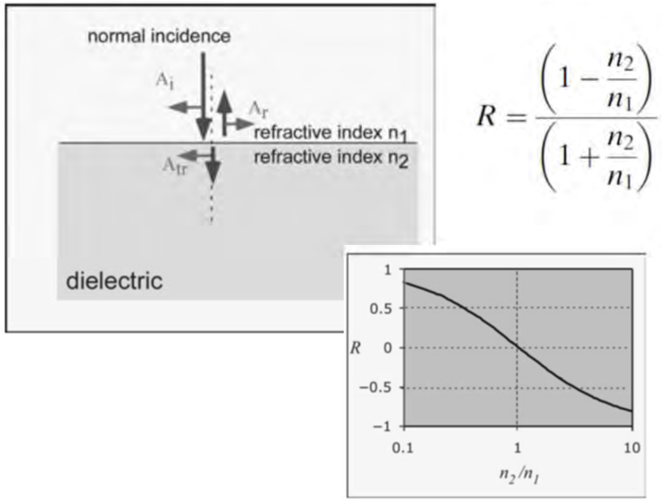
If the thickness of the metal is much larger than the skin depth, no signal will be transmitted into the bulk of the metal. A bulk metal surface reflects almost all the impinging energy. The angle of reflection, measured with respect to the normal to the surface, is equal to the angle of incidence.



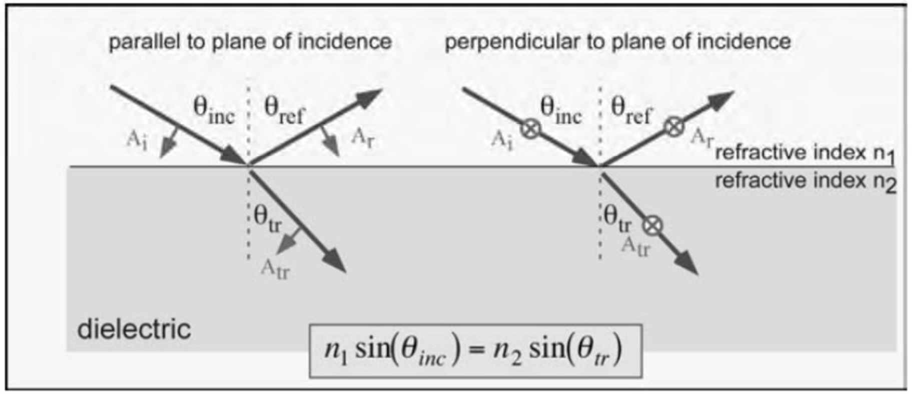
# Reflection and Refraction by Dielectrics

Typical dielectric materials create both reflected and refracted waves (the latter also being subject to significant absorption for many materials of practical interest).

The amount of incident radiation that is reflected and refracted is a function of the refractive indices of the media, the angle of incidence, and the polarization of the radiation.



$$R = \frac{\left(1 - \frac{n_2}{n_1}\right)}{\left(1 + \frac{n_2}{n_1}\right)} \qquad T = \frac{2}{\left(1 + \frac{n_2}{n_1}\right)}$$



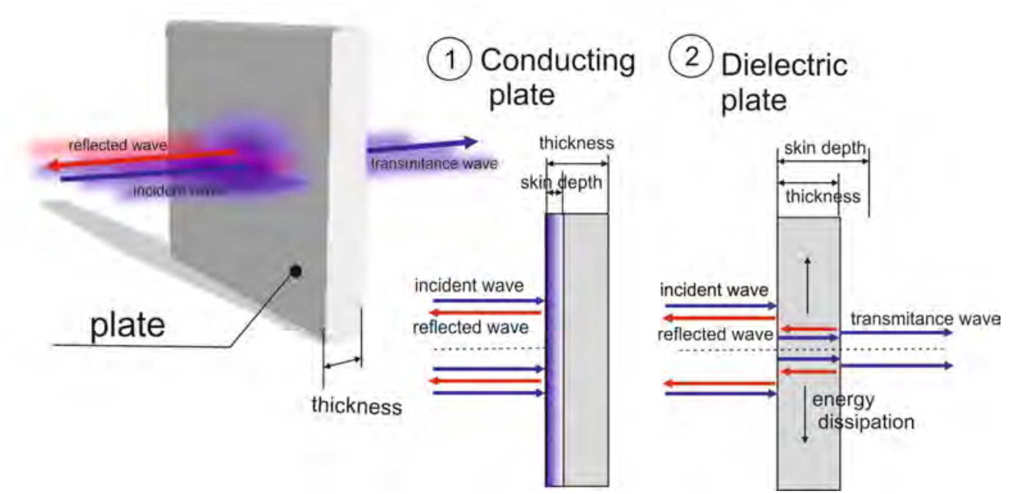
$$n_1 \sin(\theta_{inc}) = n_2 \sin(\theta_{tr})$$

**Classification of materials based on permittivity**

| $\frac{\varepsilon_r''}{\varepsilon_r'}$ | Current conduction | Field propagation |
|---|---|---|
| 0 | | perfect dielectric<br>lossless medium |
| $\ll 1$ | low-conductivity material<br>poor conductor | low-loss medium<br>good dielectric |
| $\approx 1$ | lossy conducting material | lossy propagation medium |
| $\gg 1$ | high-conductivity material<br>good conductor | high-loss medium<br>poor dielectric |
| $\infty$ | perfect conductor | |

# Losses……
# …… Absorption of the electromagnetic radiation

## BULK (plane parallel plate)

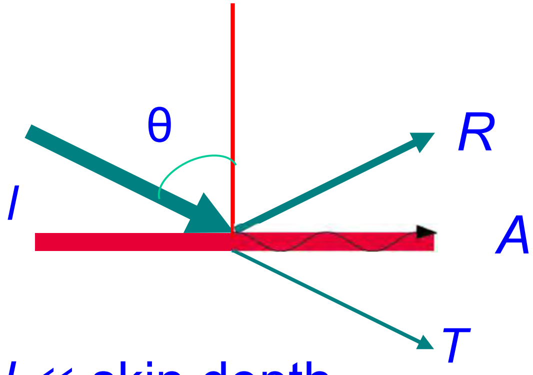


Constructive interference

- ✓ Perfect conductor being thicker than skin depth reflect EM radiation
- ✓ Non-perfect conductor: allows penetration of EM field inside up to the skin depth (small absorption)
- ✓ Poor dielectric being conductive supports losses through Joule heating

Conductor + dielectric + geometry (resonator, waveguides, etc) =
= wanted EM response

# Specific case: thin conductive film



$A = 1 - T - R$

$l \ll$ skin depth

$\mathrm{Im}\,\varepsilon \gg 1$

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

$$T = \frac{1}{(1 + l/l_\sigma)^2}$$

$$R = \frac{(l/l_\sigma)^2}{(1 + l/l_\sigma)^2}$$

$$A = \frac{2\,l/l_\sigma}{(1 + l/l_\sigma)^2}$$

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

$\boxed{l_\sigma \approx 1/\sigma}$ *A=50%, R=25%, T=25%.*

# 2D geometry (thin conductive films)

# GRAPHENE

2D crystalline materials were thermodynamically unstable and could not exist……

The Nobel Prize in Physics 2010

More

The Nobel Prize in Physics 2010

Andre Geim
Konstantin Novoselov

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## The Nobel Prize in Physics 2010

© The Nobel Foundation. Photo: U. Montan

Andre Geim

Prize share: 1/2

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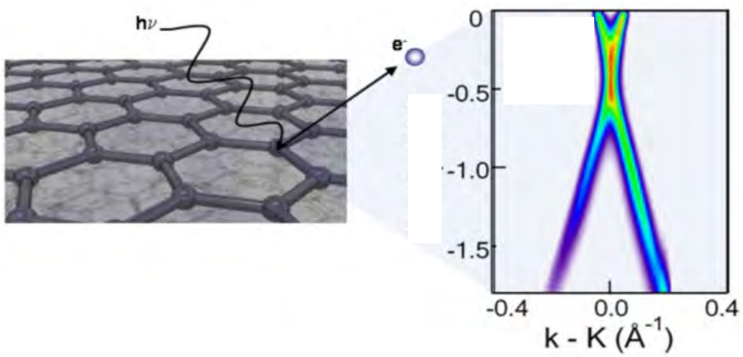
Konstantin Novoselov

Prize share: 1/2

The Nobel Prize in Physics 2010 was awarded jointly to Andre Geim and Konstantin Novoselov "for groundbreaking experiments regarding the two-dimensional material graphene."

**Novoselov et al. Science 2004**

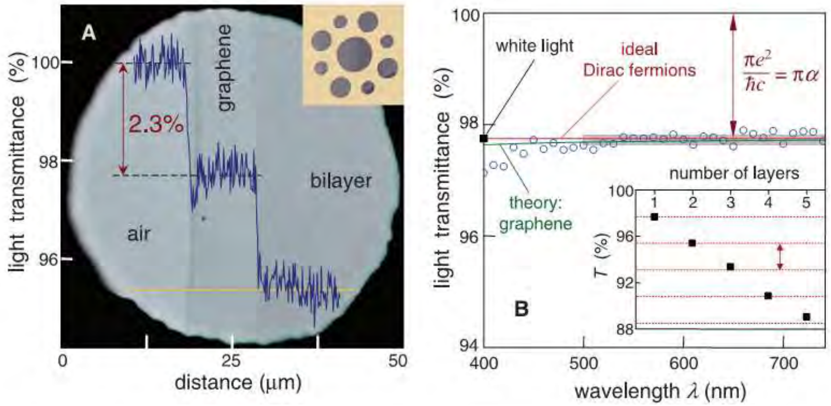


Graphene is Hexagonal lattice of carbon atoms, Atomically thin monolayer of graphite

# WHY GRAPHENE?

## TRANPARENT CONDUCTOR

In optical range single graphene layer absorbs $\pi\alpha$=2.3% due to interband transitions

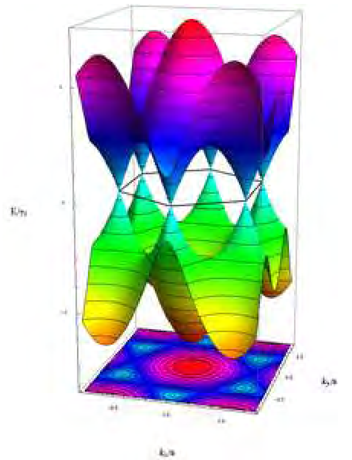


**Fine Structure Constant Defines Visual Transparency of Graphene**

R. R. Nair,[1] P. Blake,[1] A. N. Grigorenko,[1] K. S. Novoselov,[1] T. J. Booth,[1] T. Stauber,[2] N. M. R. Peres,[2] A. K. Geim[1]*

6 JUNE 2008 VOL 320 SCIENCE

Valence and conductive bands are touch each other in Dirac point

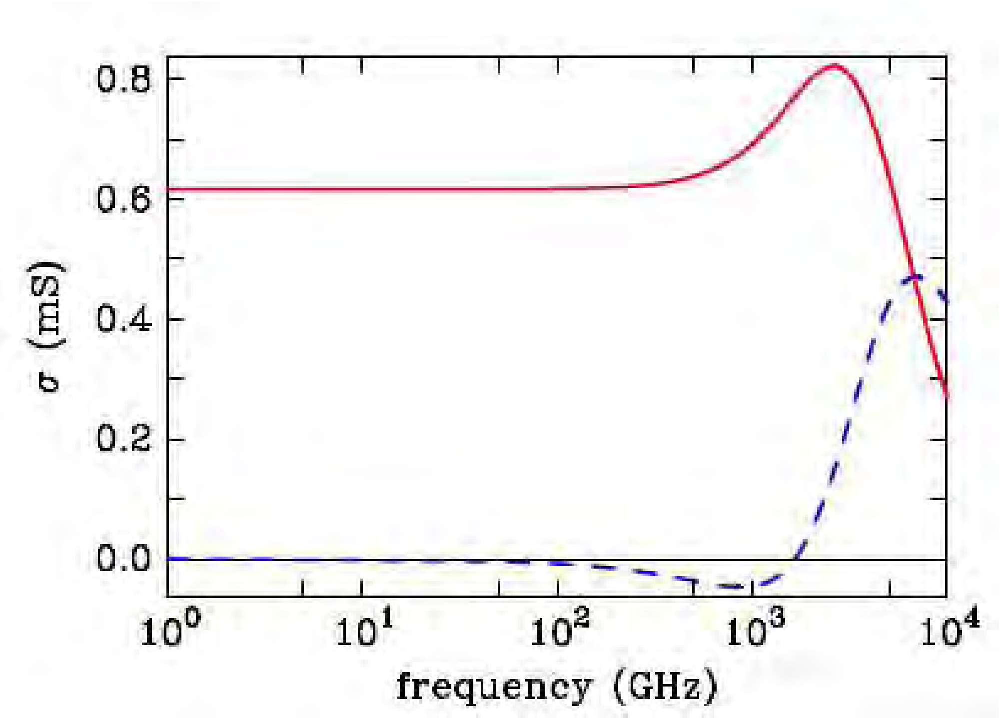


Easy to tune the Fermi level by external forces (mechanical, electrostatic doping, irradiation, using any substrate)

In THz and MW ranges single graphene layer expected to absorb >>2.3% due to intarband transitions

## TRANPARENT TUNABLE CONDUCTOR

# Graphene conductivity vs frequency



No-dispersive in MW-THz ranges

BROADBAND behavior

At μ>> *h*ν, the intraband transition contribute dominantly in graphene conductivity. It has a Drude-like form.

Drude-Smith model of the conductance of a typical graphene sample produced by CVD on a commercial copper foil[1] (continuous line: real part, imaginary part: dashed line).

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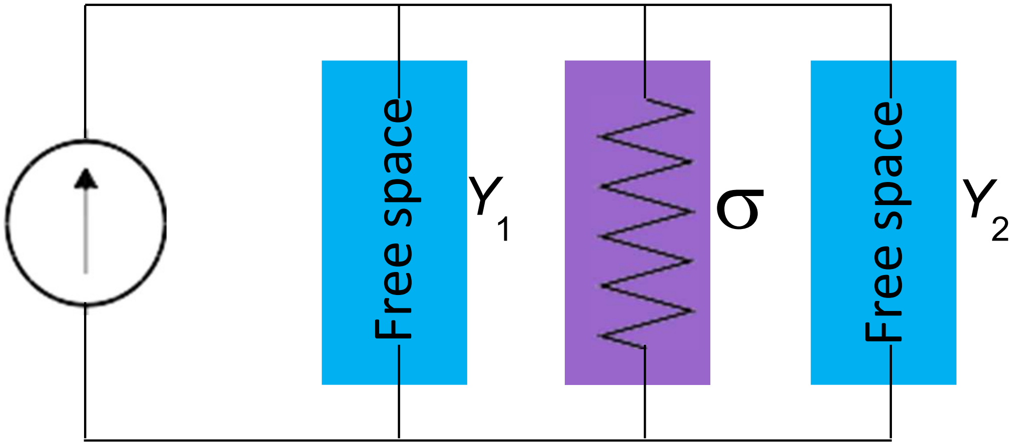
[1] J.D. Buron et al, Nano Lett. 14 (2014) 6348.

# Admittance-matching condition. Equivalent electric circuit



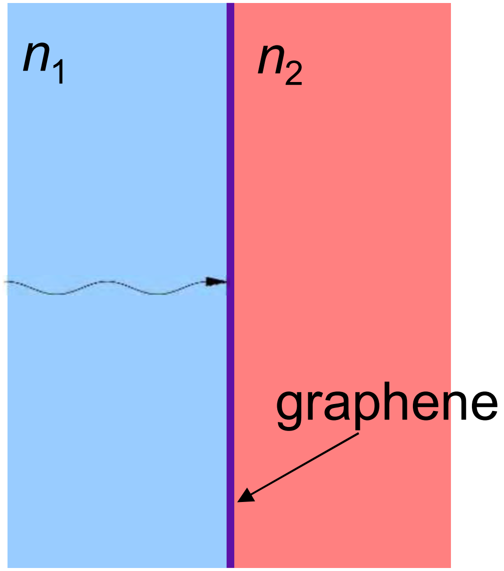
$$\sigma = 2\, Y_{\text{free space}} = 2\, \varepsilon_0 c$$

*A=50%, R=25%, T=25%.*

A very good graphene sample, such as required for high-frequency nanoelectronics studies, may have a sheet conductance of 2.5 mS/sq under appropriate gate voltage. This value is very close to the admittance of free space space $\varepsilon_0 c$ = 2.7 mS. Graphene samples of usual quality produced by CVD have an intrinsic conductance roughly a factor of 2-4 times smaller. According to the admittance matching condition, it requires a few graphene planes to achieve the optimum absorbance in the GHz range.

# Optical properties of graphene

Fresnel formulas applied to a thin conducting sheet at the interface between two dielectric media, normal incidence from medium 1

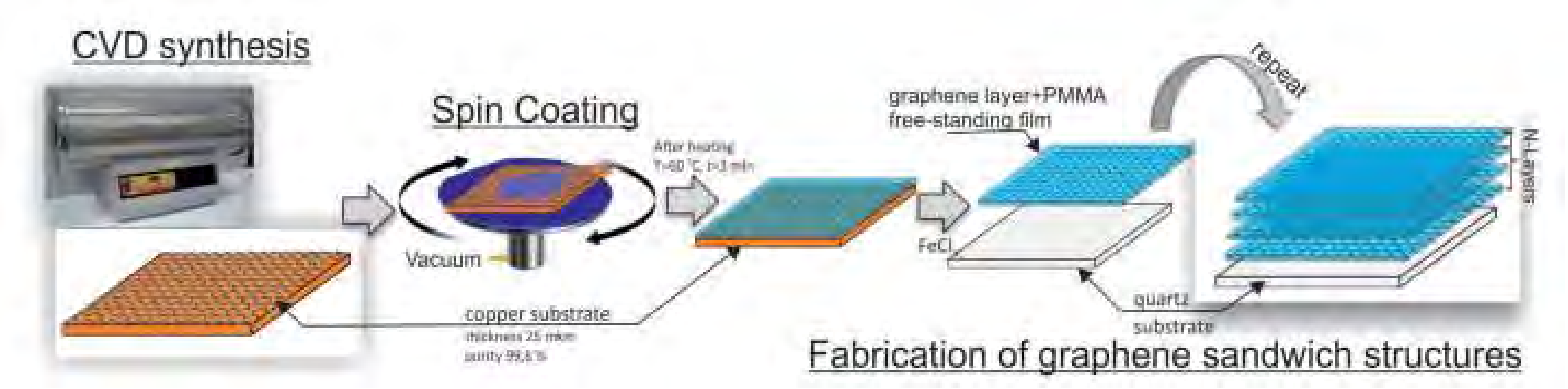


$$R = \left| \frac{n_2 - n_1 + \frac{\sigma}{\epsilon_0 c}}{n_2 + n_1 + \frac{\sigma}{\epsilon_0 c}} \right|^2 \qquad T = \frac{4 n_1 n_2}{|n_1 + n_2 + \frac{\sigma}{\epsilon_0 c}|^2}$$

$$A = \frac{4 n_1 \frac{\mathrm{Re}\,\sigma}{\epsilon_0 c}}{|n_1 + n_2 + \frac{\sigma}{\epsilon_0 c}|^2}$$

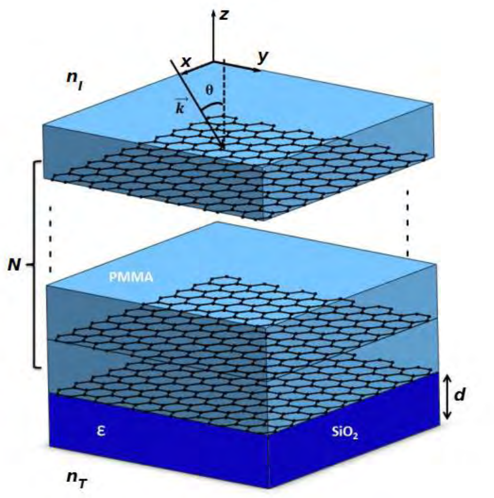
The maximum value of the absorbance $A = n_1/(n_1+n_2)$ that exceeds 50% if $n_1 > n_2$, which is remarkably high for a one-atom thick material. This maximum is realized for Im σ = 0 and Re σ = $(n_1+n_2)\varepsilon_0 c$.

# Making and transfer of graphene planes



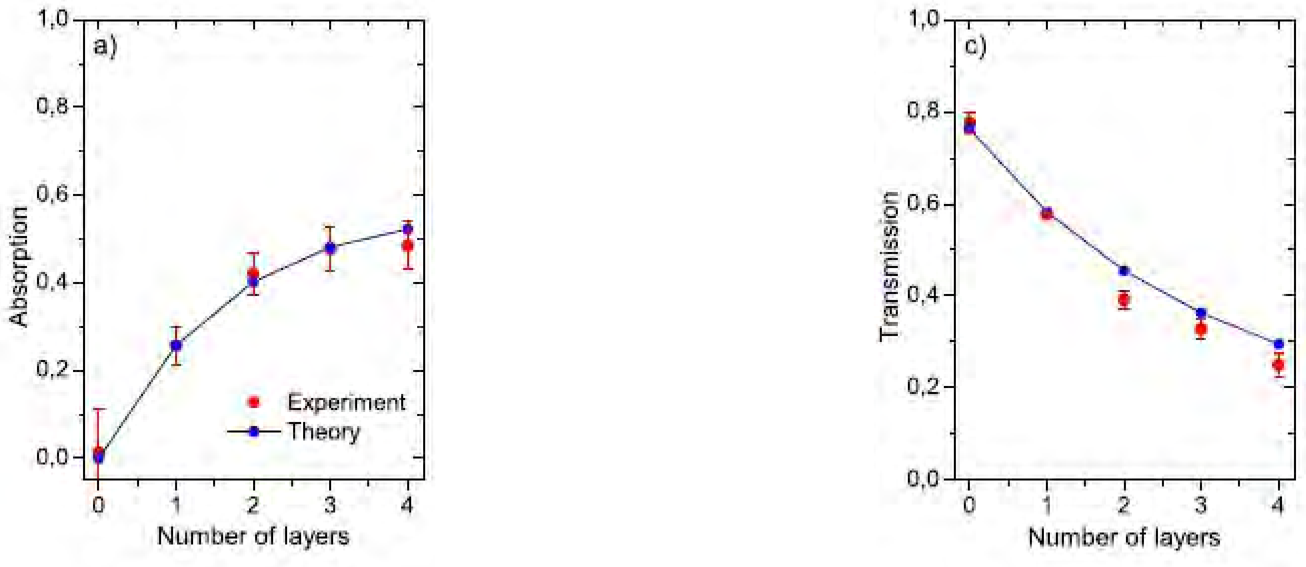
Schematic representation of graphene sandwich fabrication, consisting of a number of repeating steps, and final graphene/PMMA multilayer structure containing here four graphene sheets. The lateral dimensions of the samples are 7.2 mm * 3.4 mm for microwave measurements and cycle sample with diameter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

# Measured electromagnetic properties. Microwave range



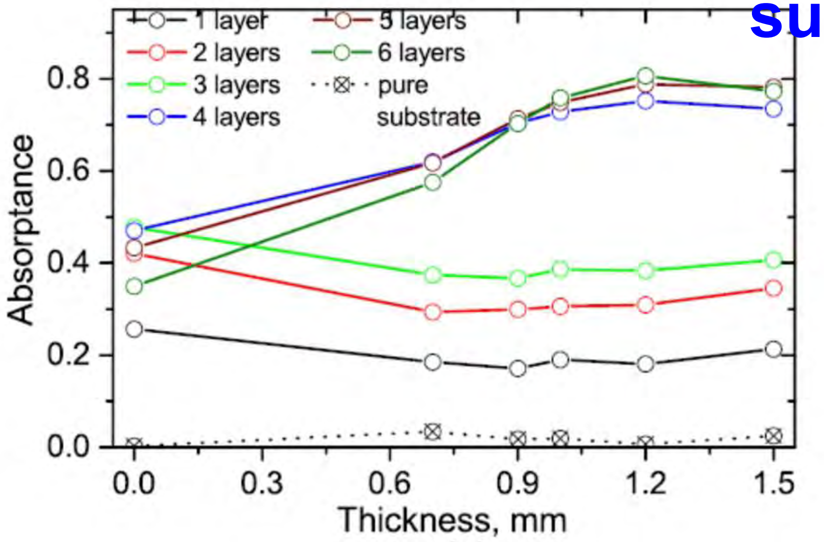
Separated graphene planes:

$\sigma_{sandwich}$ = number of layers $*\sigma_{layer}$

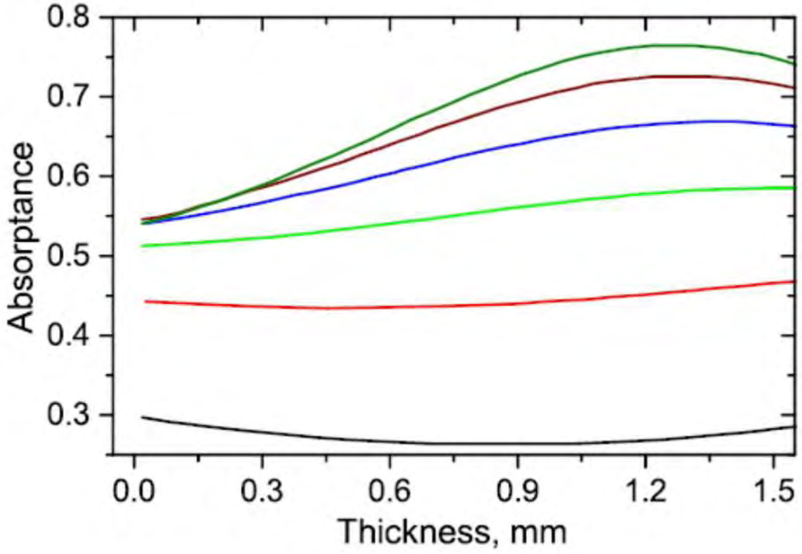


Konstantin Batrakov, SCIENTIFIC REPORTS | 4 : 7191 | DOI: 10.1038/srep07191

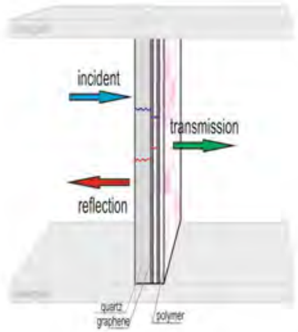
# Optimization of absorption in graphene/polymer heterostructures by depositing graphene on a dielectric substrate. Microwave measurements



(a)



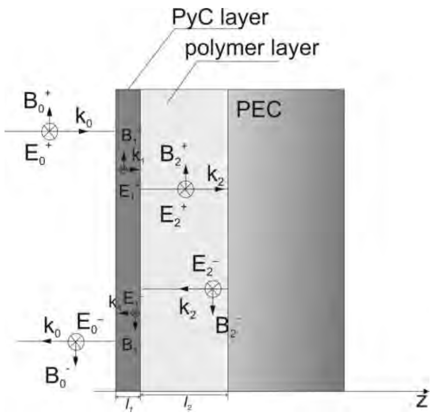
(b)

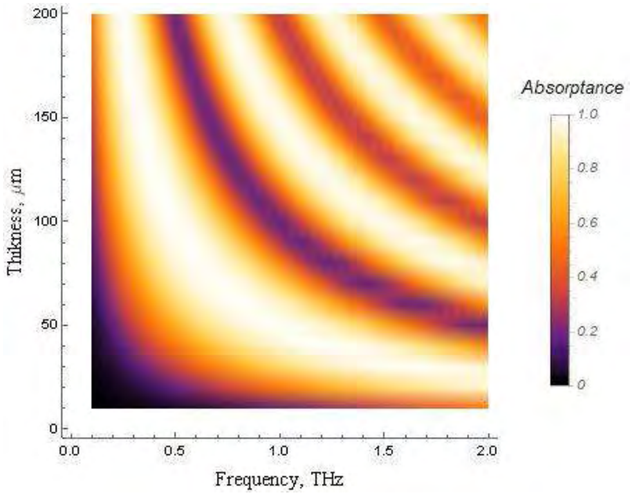


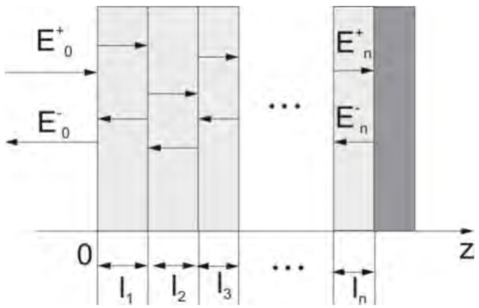
A thickness corresponding to a quarter wavelength reduces the reflectance to almost zero in case the radiations comes from the substrate side and increases the absorptance to a maximum value.

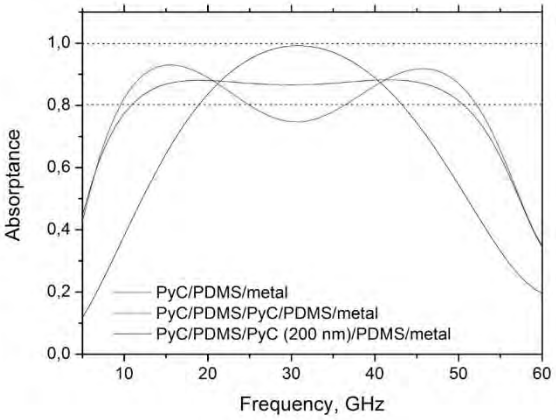
K. Batrakov et al, Appl. Phys. Lett. 108 (2016) 123101.

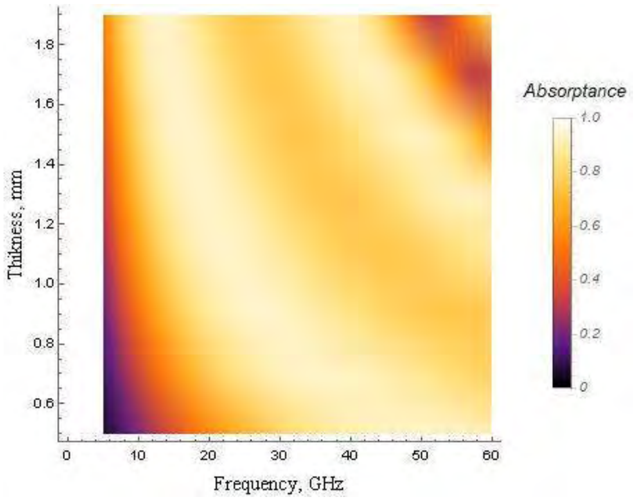
# Enhanced absorption:
# Salisbury screen, multilayered structures



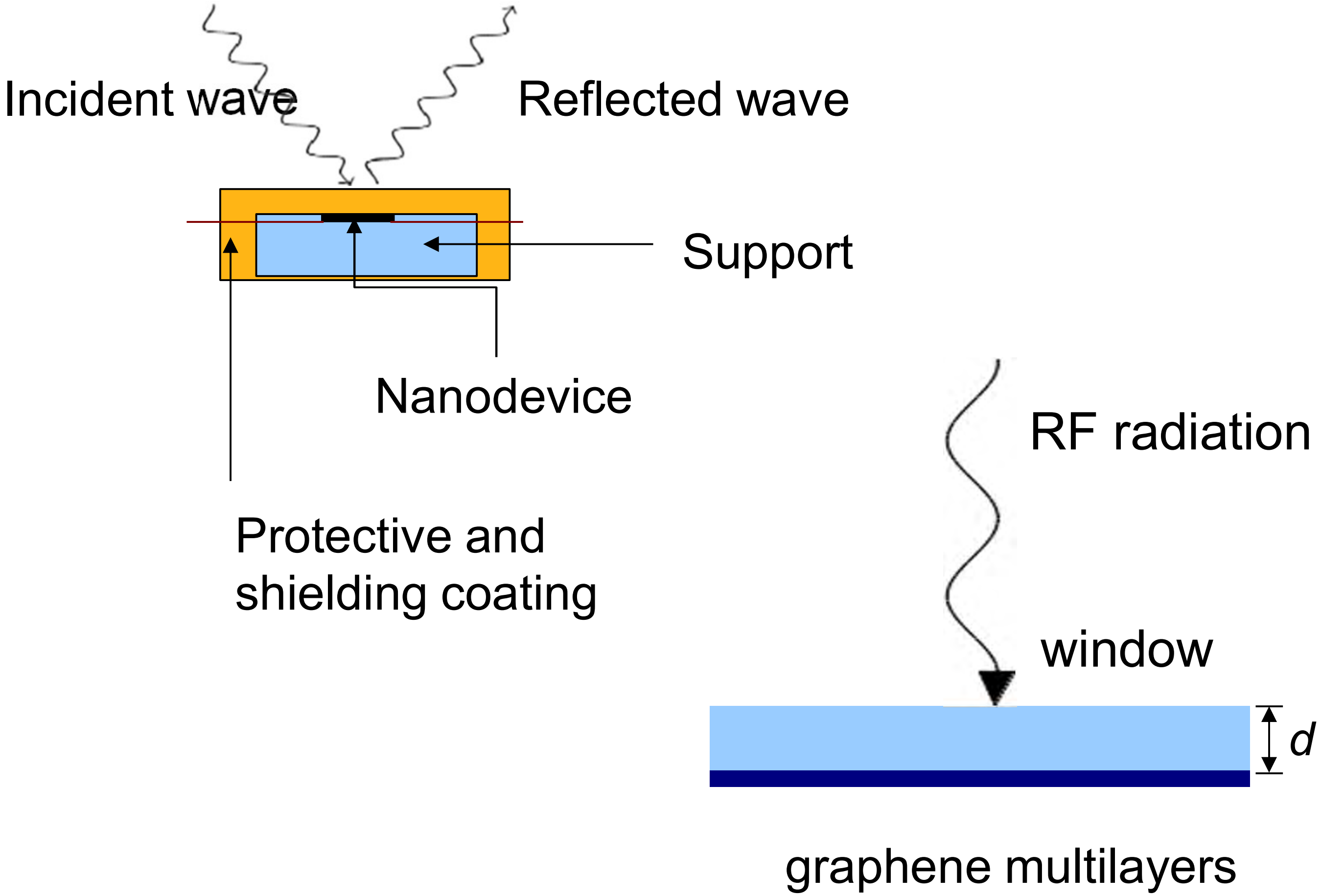








# Application: shielding of the optical window of an optoelectronic device



Incident wave

Reflected wave

Support

Nanodevice

Protective and
shielding coating

RF radiation

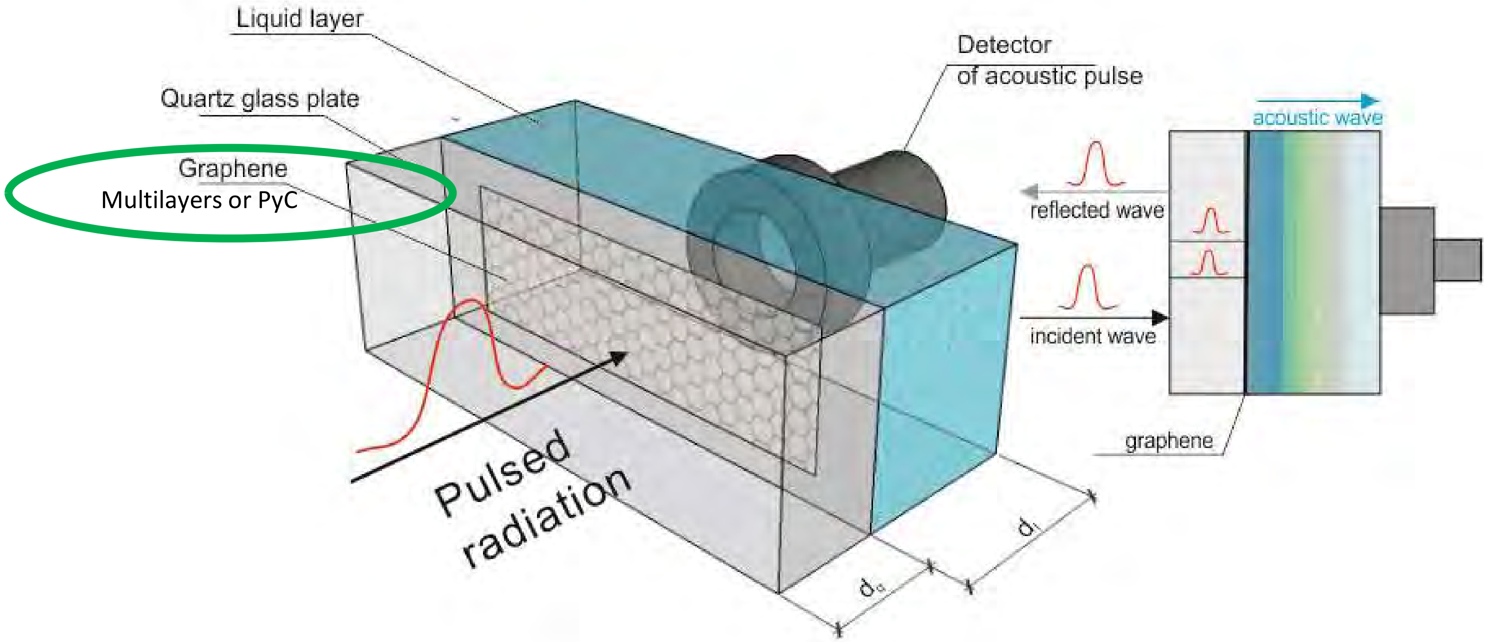
window

*d*

graphene multilayers

# Applications

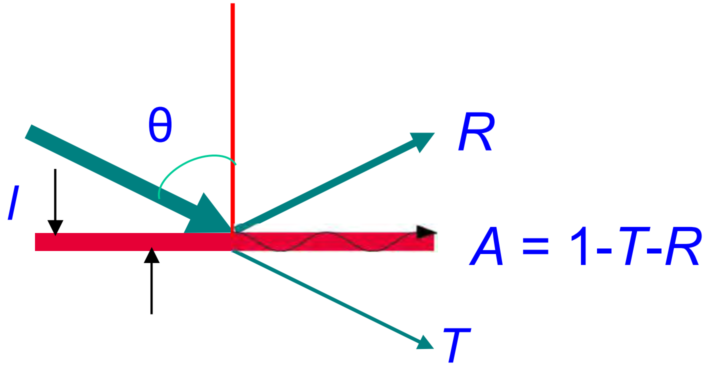
## Optoacoustic detector (sensor) of high-power microwave-THz pulses

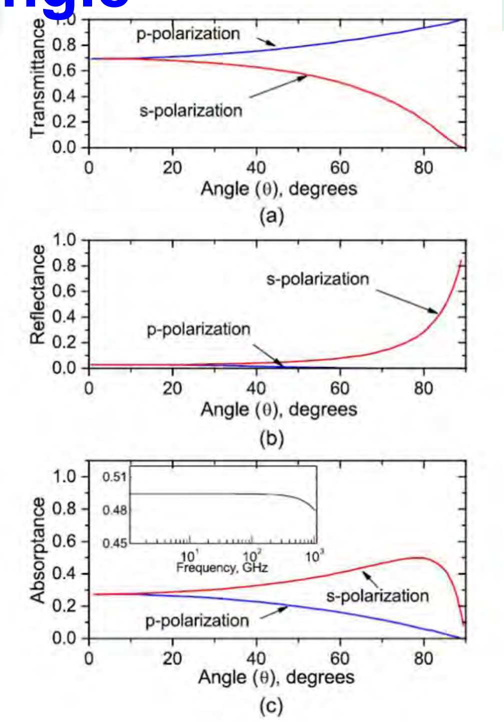


Liquid could be salted water, distillated water, ethyl alcohol

The idea was proposed in V. Andreev, et al, Basic principles of thermo-acoustic energy and temporal profile detection of microwave pulses, Atomic science and techniques, 2010, #5, p.24-26

# Graphene/PMMA sandwiches at 30 GHz. p- and s-polarized waves vs incident angle





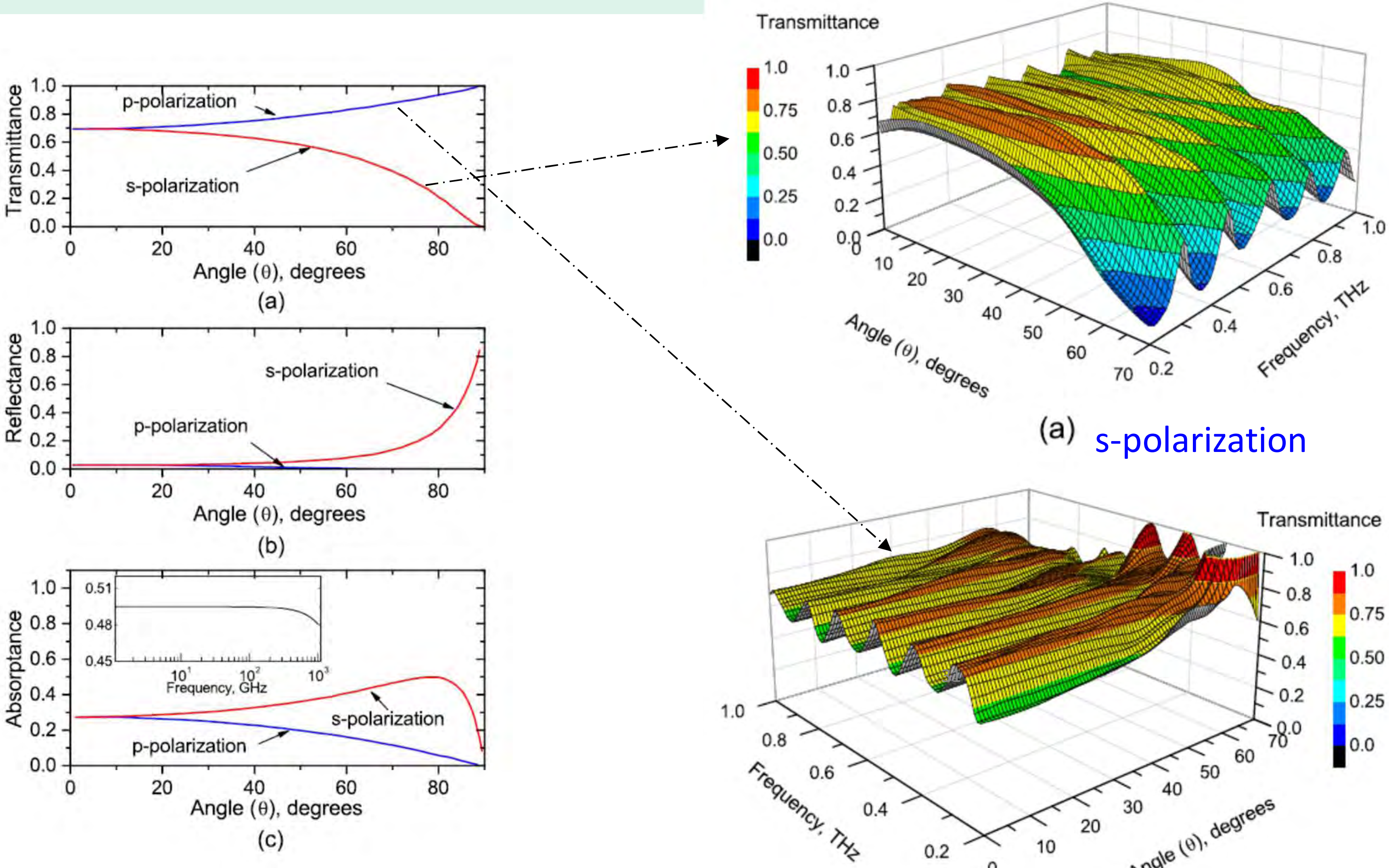
$$l_\sigma = 2\varepsilon_0 c\cos\theta/\sigma$$

$$l_\sigma = 2\varepsilon_0 c/(\sigma\cos\theta)$$

Effective film thickness increase with increasec of the incident angle – the case of **p-polarization**

Effective film thickness decrease with increasec of the incident angle – the case of **s-polarization**

# Possibility to tune electromagnetic response properties of graphene/polymer sandwiches. THz measurements

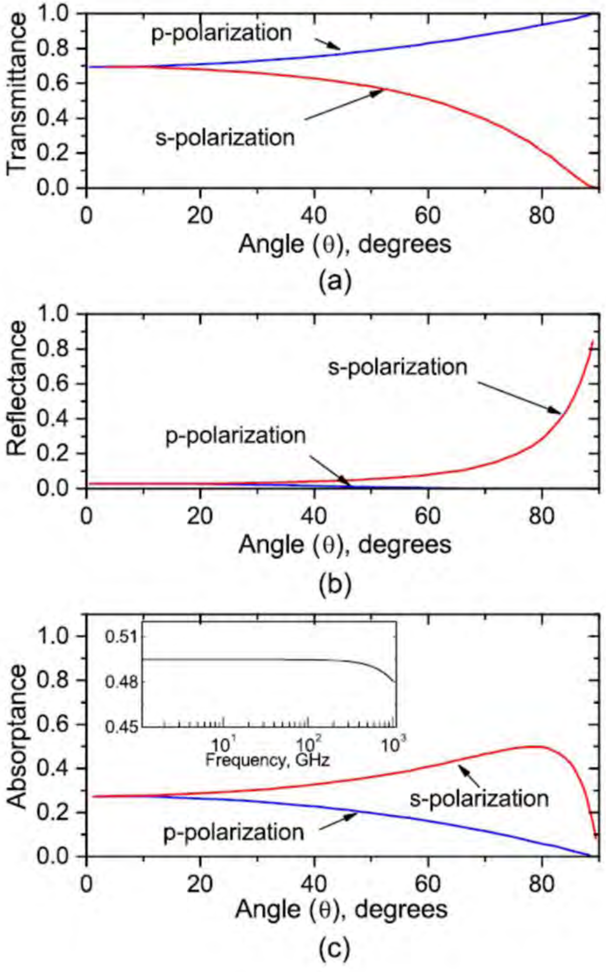


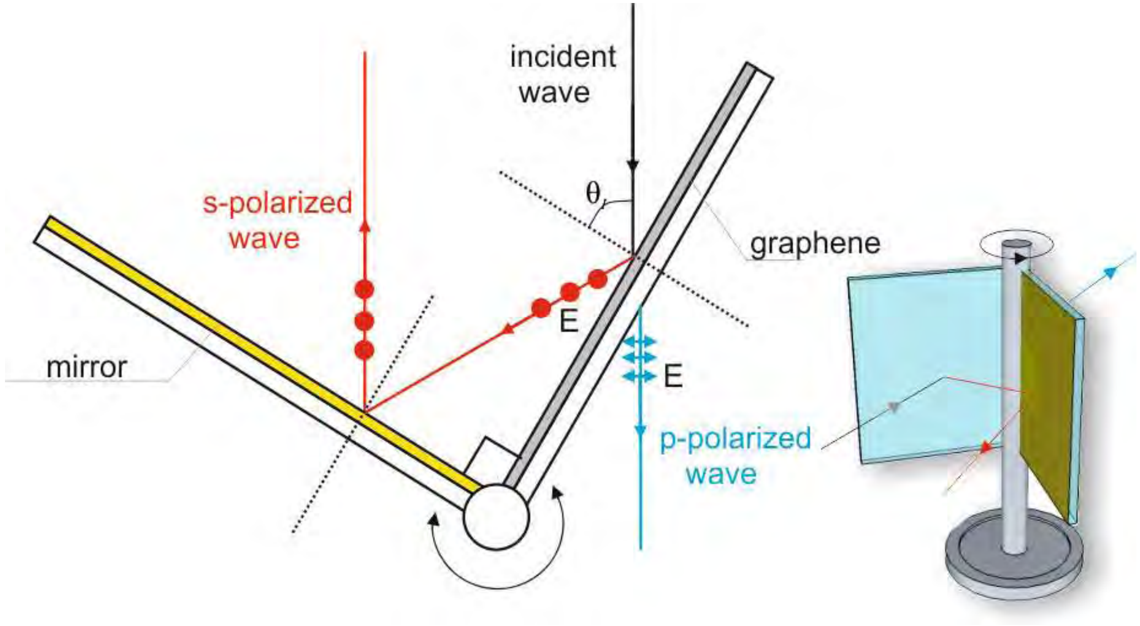
s-polarization

p-polarization

K. Batrakov et al, Appl. Phys. Lett. 108 (2016) 123101.

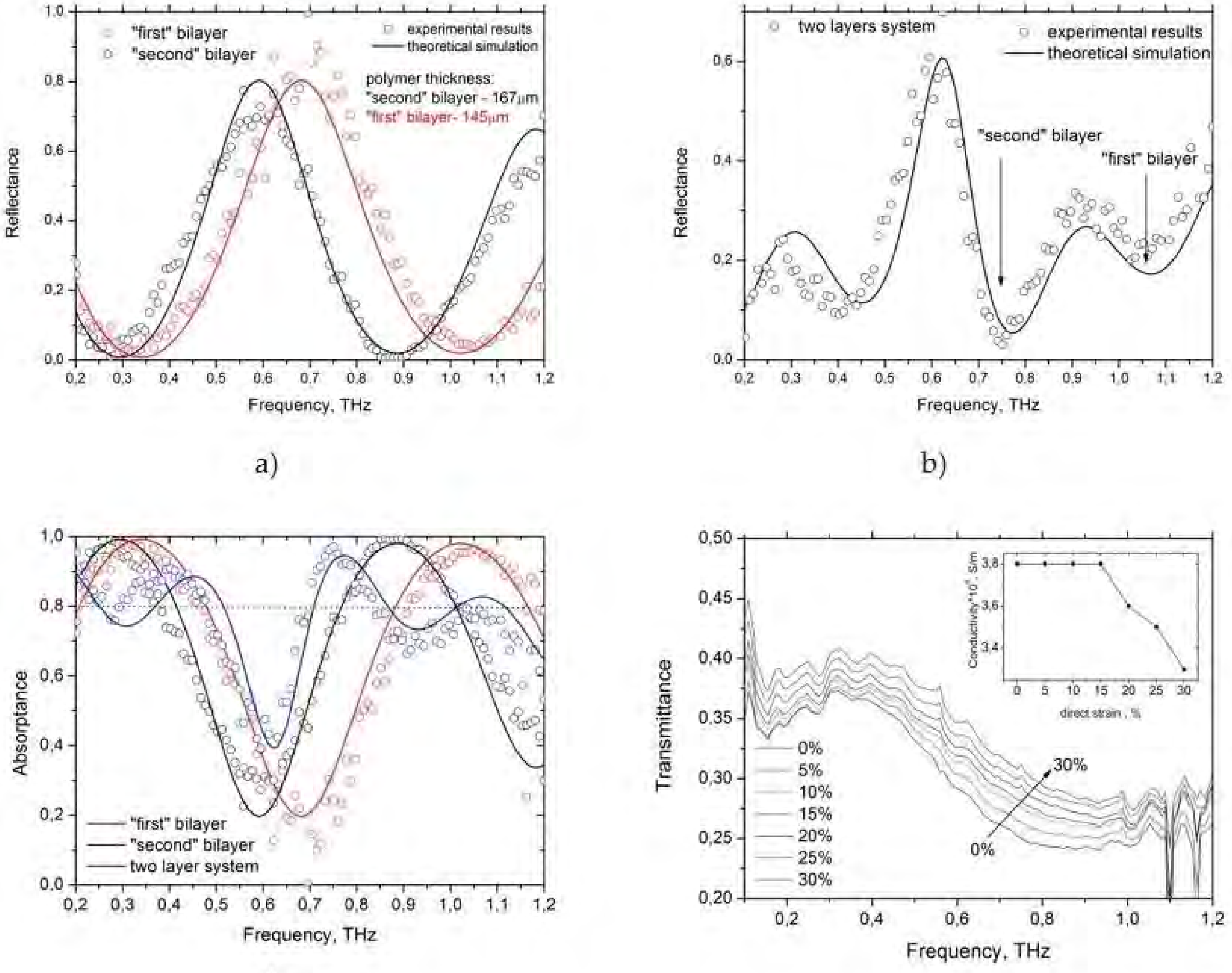
# Application: Graphene-based polarizer and \ or filter for microwave-to-THz radiation, experimental realization





Schematic representation of polarizer for THz radiation.

# Tunable Graphene Perfect Absorber of THz radiation (mechanical deformations)

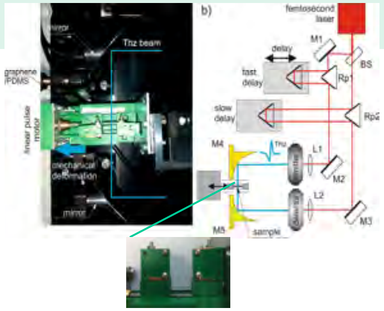


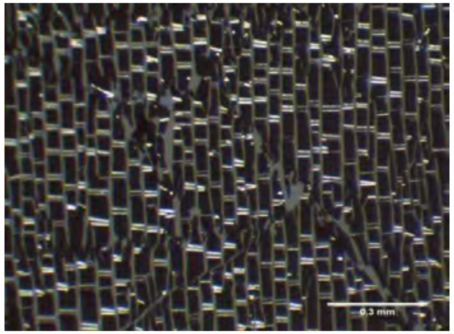
a)

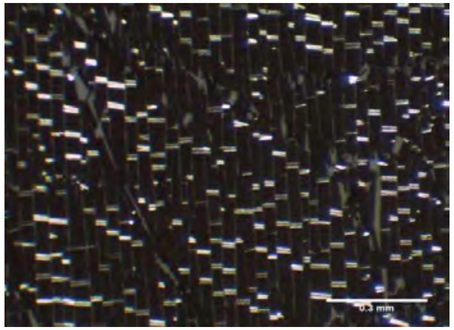
b)

c)

d)

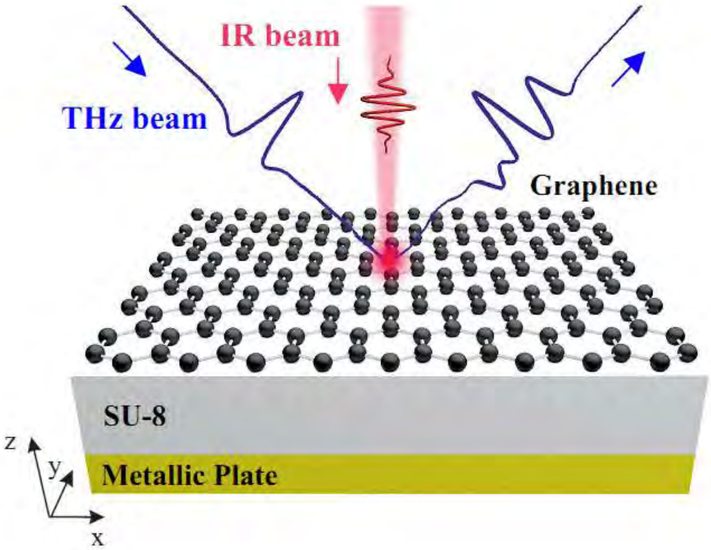


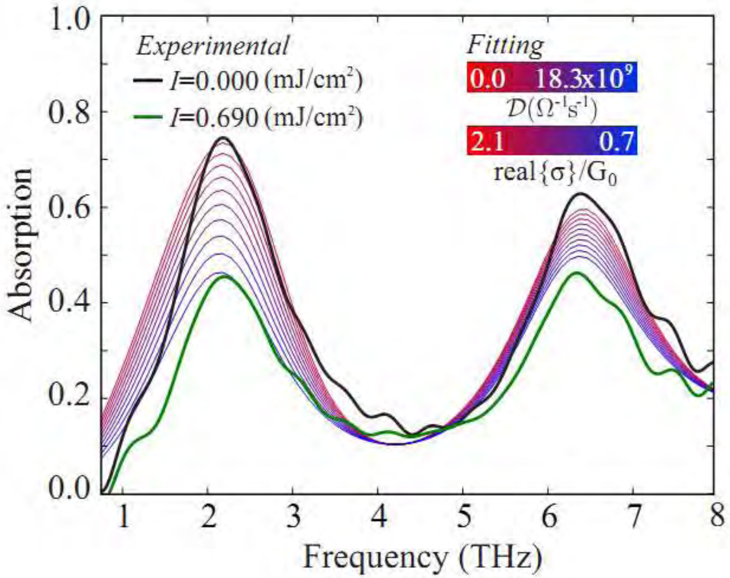




Reflectance (a)and(b), and absorptance spectra (c) of graphene/PDMS/gold and graphene/PDMS/graphene/PDMS/gold sandwich-like structures, respectively. (d) Frequency dependence of transmittance of graphene/PDMS bilayers vs the applied strain.

# Experimental demonstration of ultrafast THz modulation in a graphene-based absorber through negative photoinduced conductivity

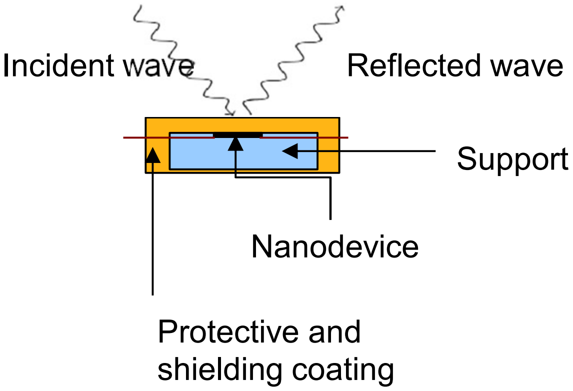




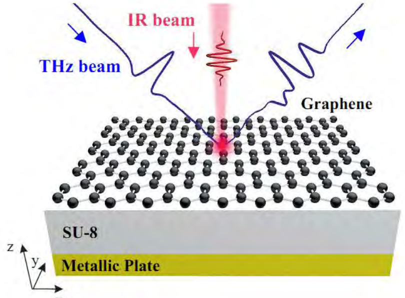
We report an ultrafast (2.79 ps) absorption modulation in the order of 40% upon photoexcitation. Our results provide evidence that the optical pump excitation results in the degradation of the graphene THz conductivity, which is connected with the generation of hot carriers, the increase of the electronic temperature and the dominant increase of the scattering rate over the carrier concentration as found in highly doped samples.

ACS Photonics (2019)

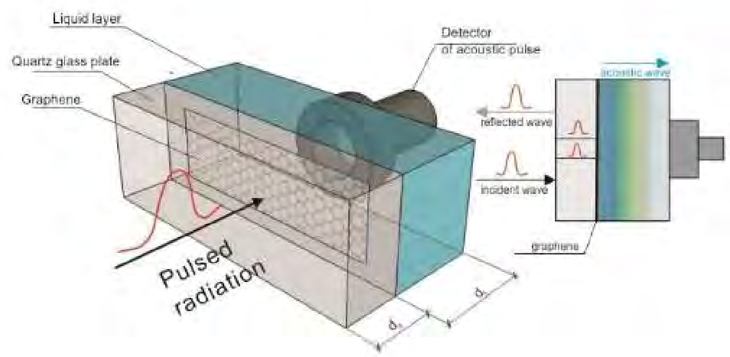
# THz passive devices



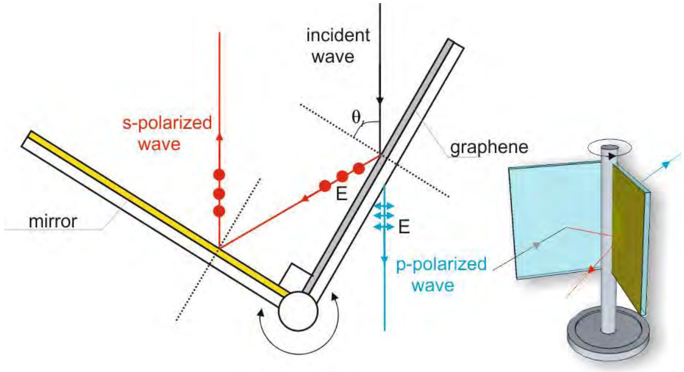
shielding layers



Ultrafast modulator



Detectors of optoacoustic type

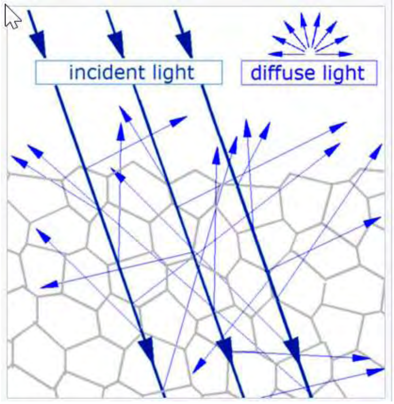


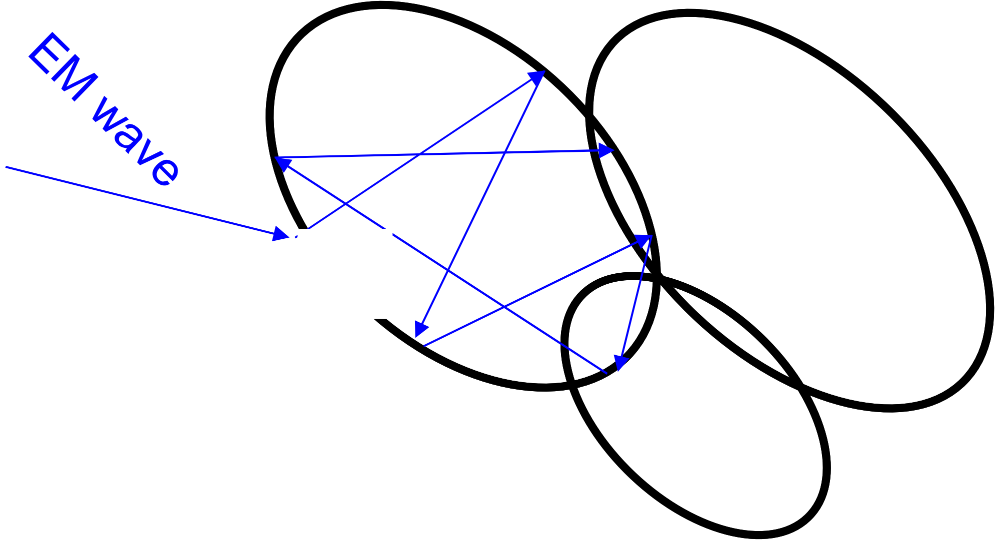
polarizer

# 3D architectures

# What to do? For substantial absorption?

The skeleton is made of good conductor:



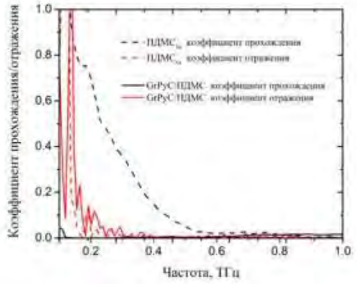


One should provides conditions for **multiple reflection within the cell, accompanied by Joule heating and then absorption.**

Skeleton thickness must be << skin depth (graphene foams)

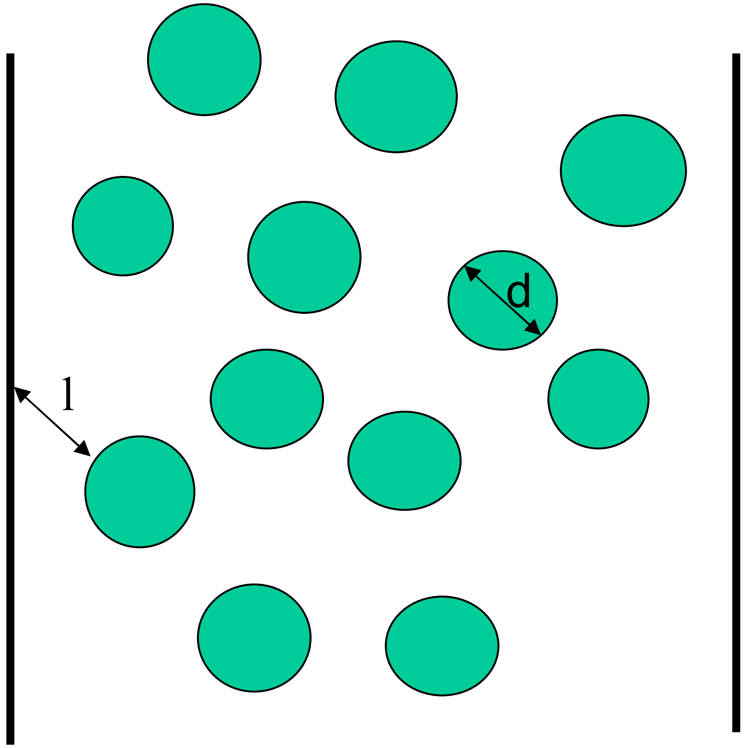
or

Open Cells should be large enough to allow EM wave to enter and then to reflect many times (and wavelength should be compatible with cell size for resonant effects).



Graphene foam

# Porous media (cellular structures)



If the pores are surrounded by electrically thick media (conductor being thicker than skin depth l > δ), the *porous media behaves as bulk conductor* (just the density is important). It reflects EM wave.

If the pores in highly conductive media are smaller than the wavelength $d << \lambda/\sqrt{\varepsilon}$ they are not visible for EM radiation.

# Periodic lattice:
# electromagnetic response vs

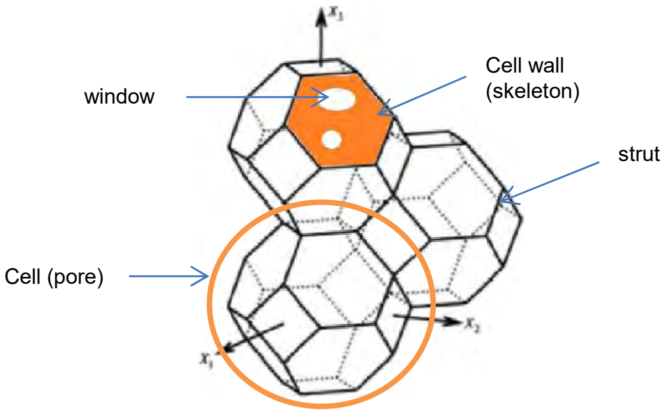
☐ CELL CIZE

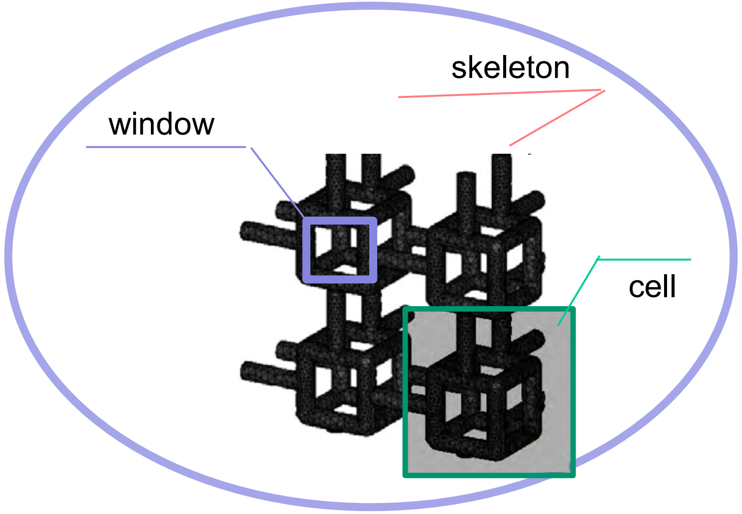
☐ WINDOW SIZE

☐ SKELETON THICKNESS

☐ SKELETON CONDUCTIVITY

☐ 3D crystal IMPREGNATION WITH THE DIELECTRIC MEDIA

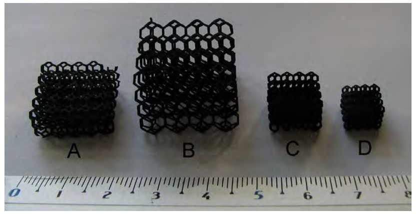




For any of permittivity/conductivity of skeleton we may find and optimize (possible) solution to achieve high absorption of EM waves.

# 3D periodic lattices with conductive skeleton

i. approach: Fully carbon periodic lattice



**3D printing of photocurable resin**

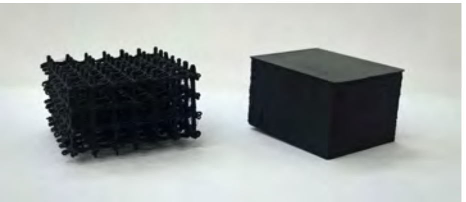
**Carbonization**

**Fully carbon periodic lattice**

**High conductive glassy carbon skeleton**

skeleton conductivity is 2 000 – 20 000 S/m

ii. approach: Composite based periodic lattice



**FDM 3D printing**

**Conductive filament = polymer / nano-carbon**

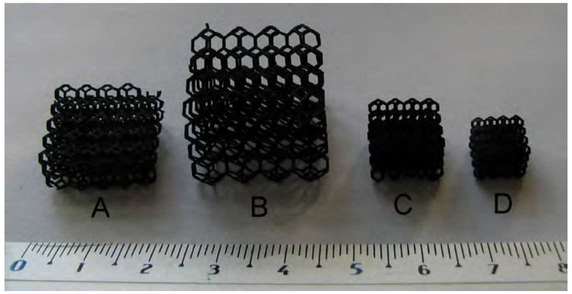
**Composite-based periodic lattice**

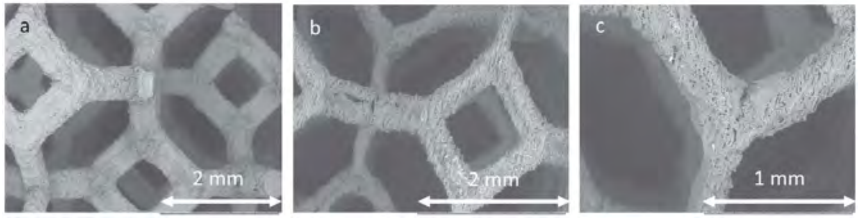
**Low conductive composite skeleton**

skeleton conductivity is 0.1– 200 S/m

# Carbon periodic LATTICE

i. Fully carbon periodic lattice
ii. Composite based periodic lattice

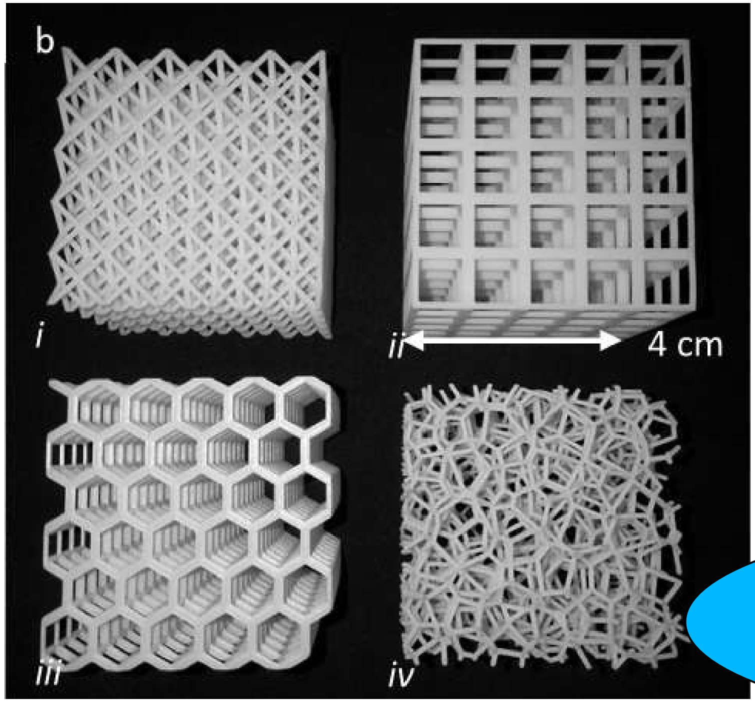




Large conductivity of carbon skeleton. Crystals made of glassy carbon 2000 - 20000 S/m

Andrzej Szczurek; et al., Carbon periodic cellular architectures, **Carbon**, 88 (2015) 70, 2015
M. Letellier, et al, Electromagnetic properties of model vitreous carbon foams, **Carbon**, 122 (2017) 217

# Periodic cellular architectures



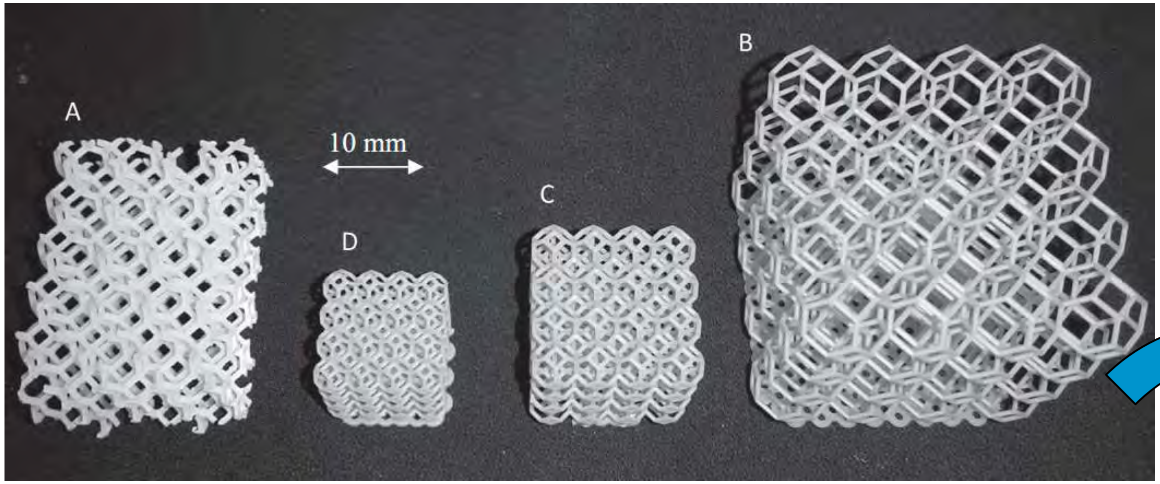
3D printing method:
Stereolithography (**SLA**)

First 3D-printed from photocurable resin …..

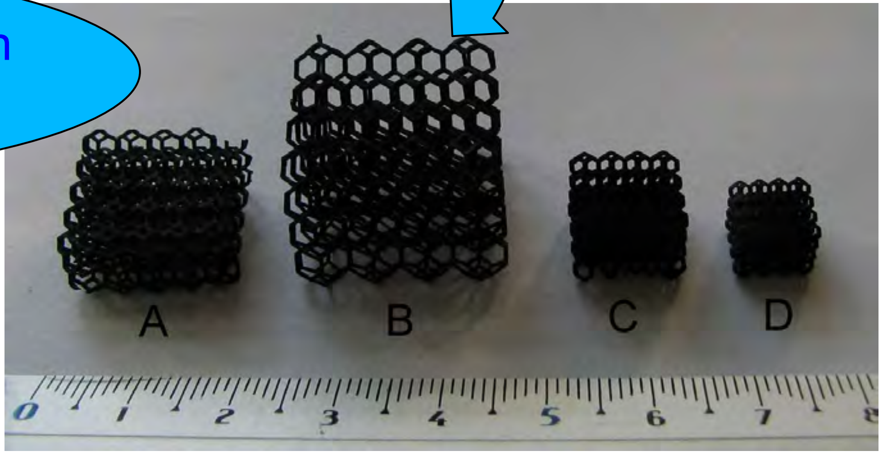
- ✓ Templates were 3D-printed (Eden 260 V 3D, Objet, Rehovot, Israel) with photosensitive resins (Fullcure 705 and 850 VeroGray, Object Ltd.), which were composed of acrylics, urethanes and epoxies. Resins were compounded with a photo-initiator that triggered the polymerisation under UV light.

- ✓ The print head jets microscopic layers of liquid photopolymer onto a build tray and instantly cures them with UV light.

# Fully carbon periodic lattice



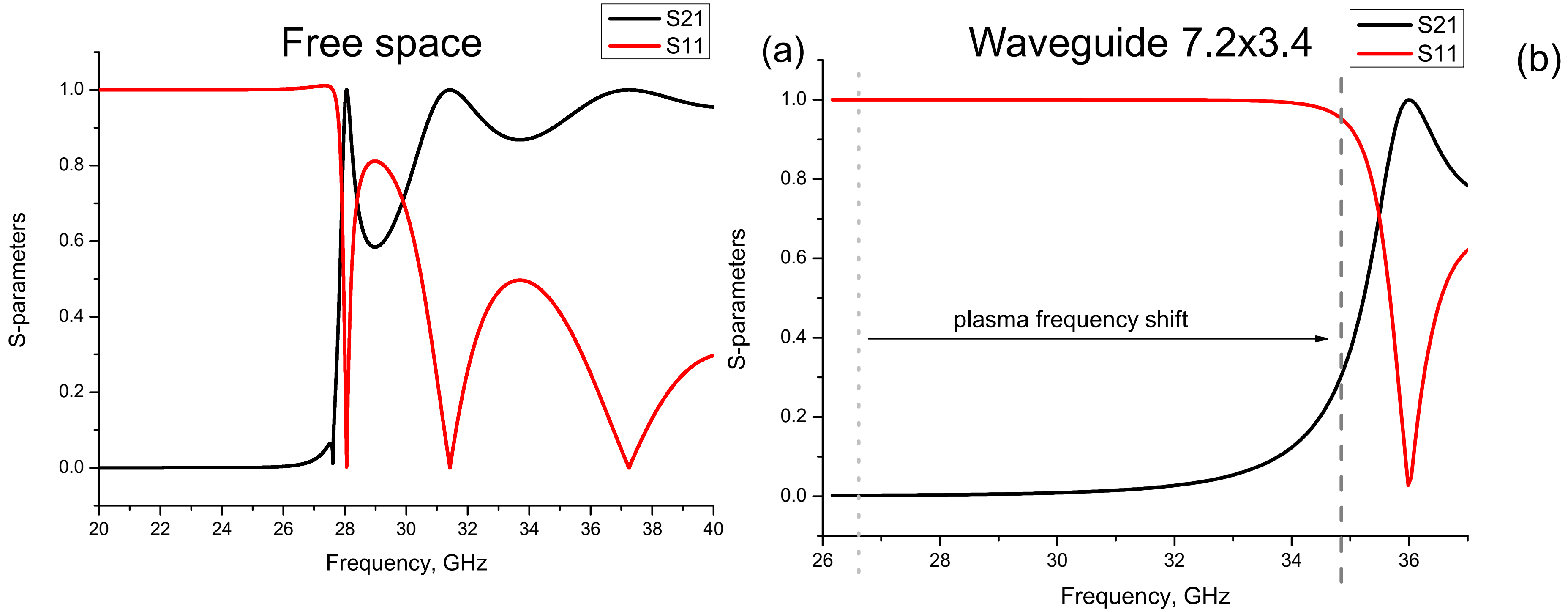
……….and then carbonized through catalytic graphitization.

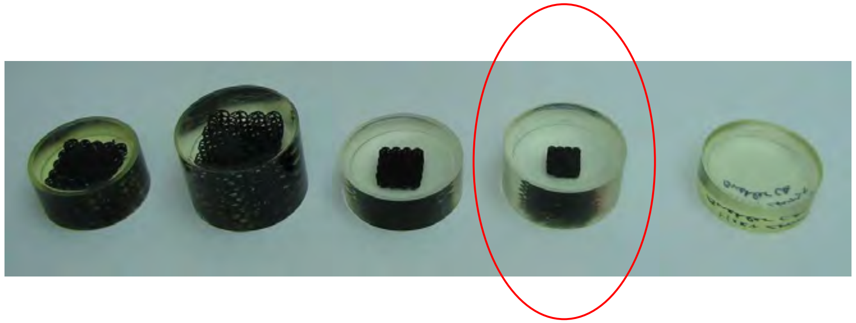


During the carbonization shrinkage appears.

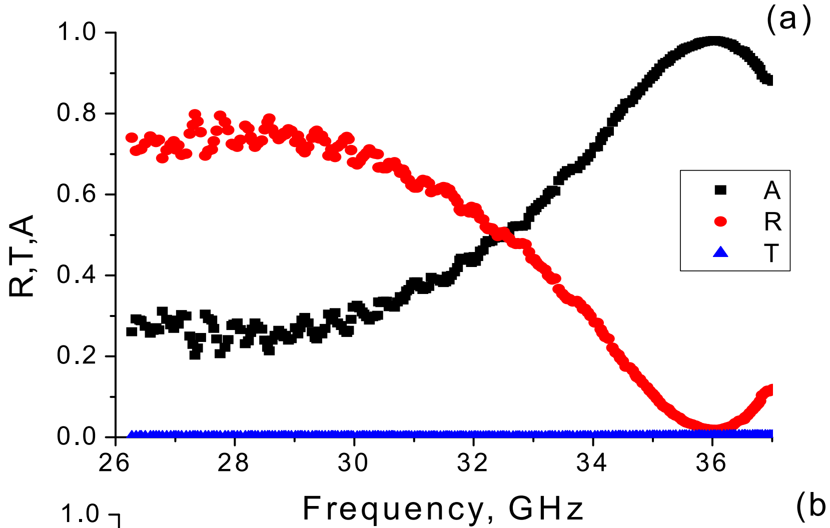
Kelvin cell

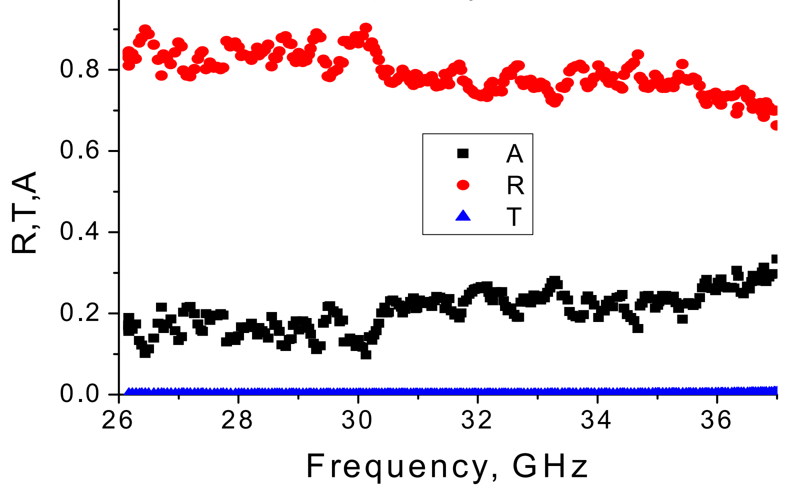
# Modeling of EM response near plasma frequency



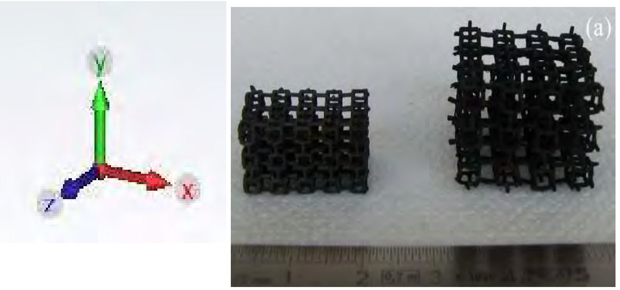


# Fully carbon photonic crystal

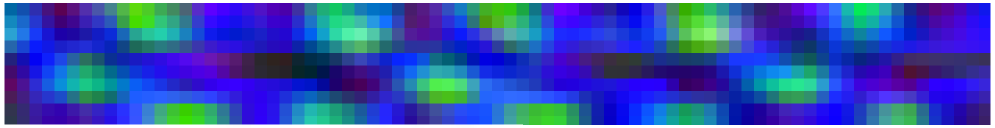


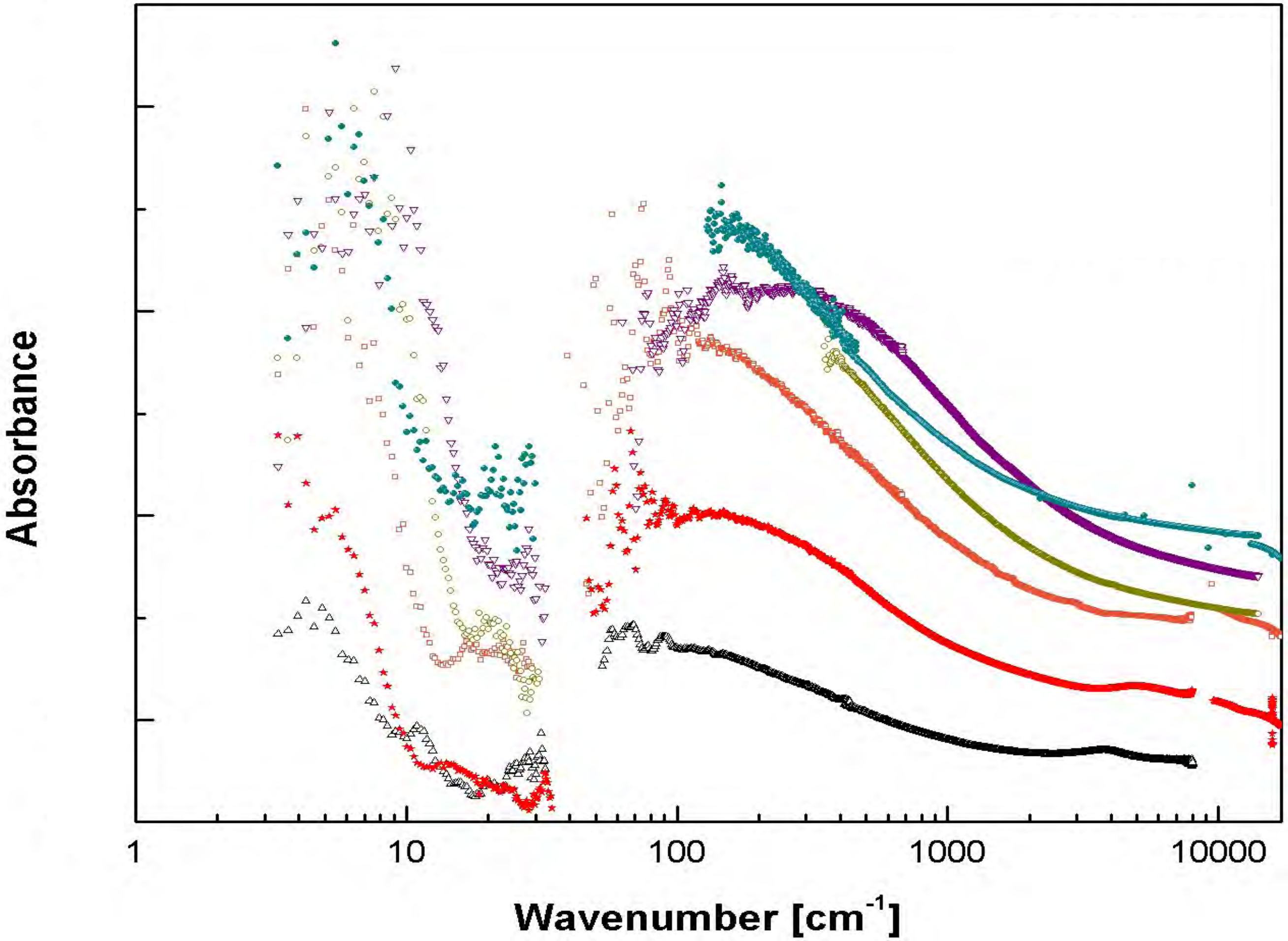


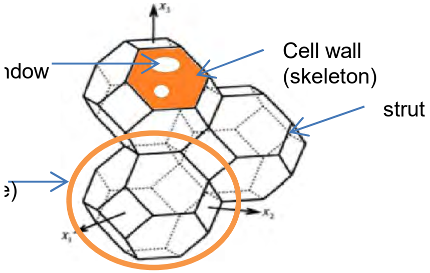
- ✓ A high absorption peak appears when the electric field vector E is parallel to Y direction.



# 3D periodic lattices with highly conductive skeleton

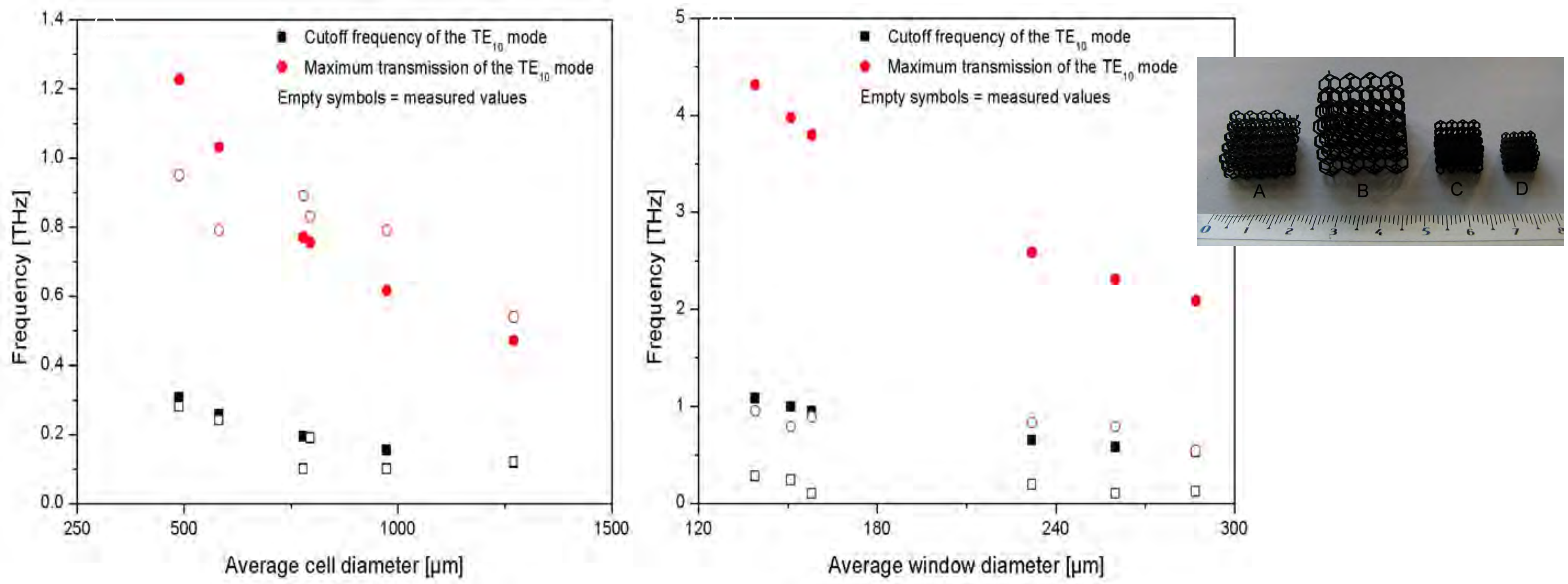






The smaller the cell / window the larger the absorption peak frequency.

# 3D periodic lattices with highly conductive skeleton



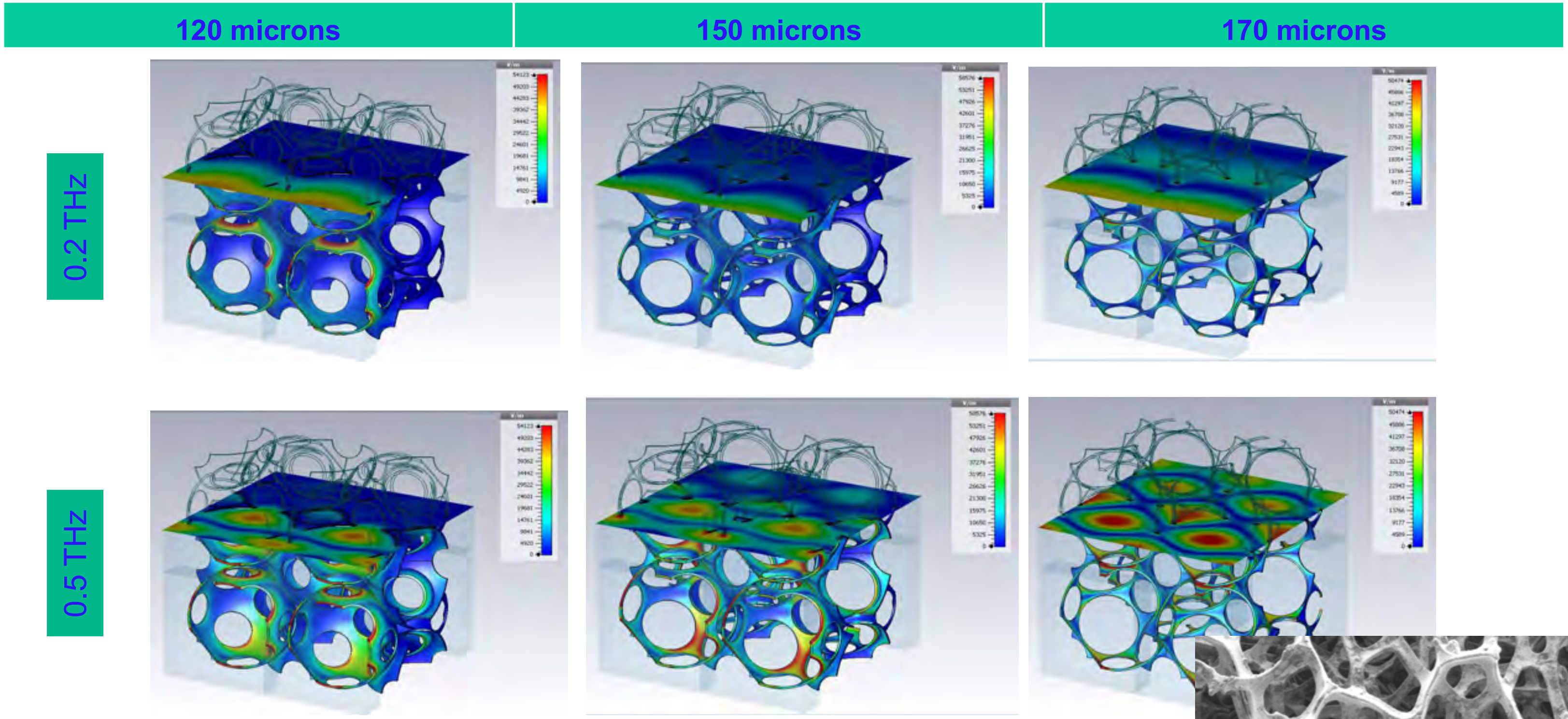
Comparison of calculated cut-off and maximum transmission frequencies of the $TE_{10}$ mode by considering: (a) cells, and (b) windows of RVC foams as rectangular waveguides, published in [11].

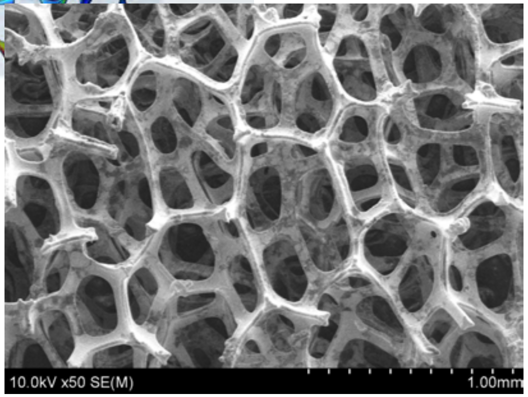
The cells or the windows might be seen as many waveguides throughout which only certain types of monochromatic waves, modes, could propagate depending on the dimensions of those waveguides.

These waveguides act as high-pass filters where different modes having different cut-off frequencies can propagates.

# EM field periodic concentration

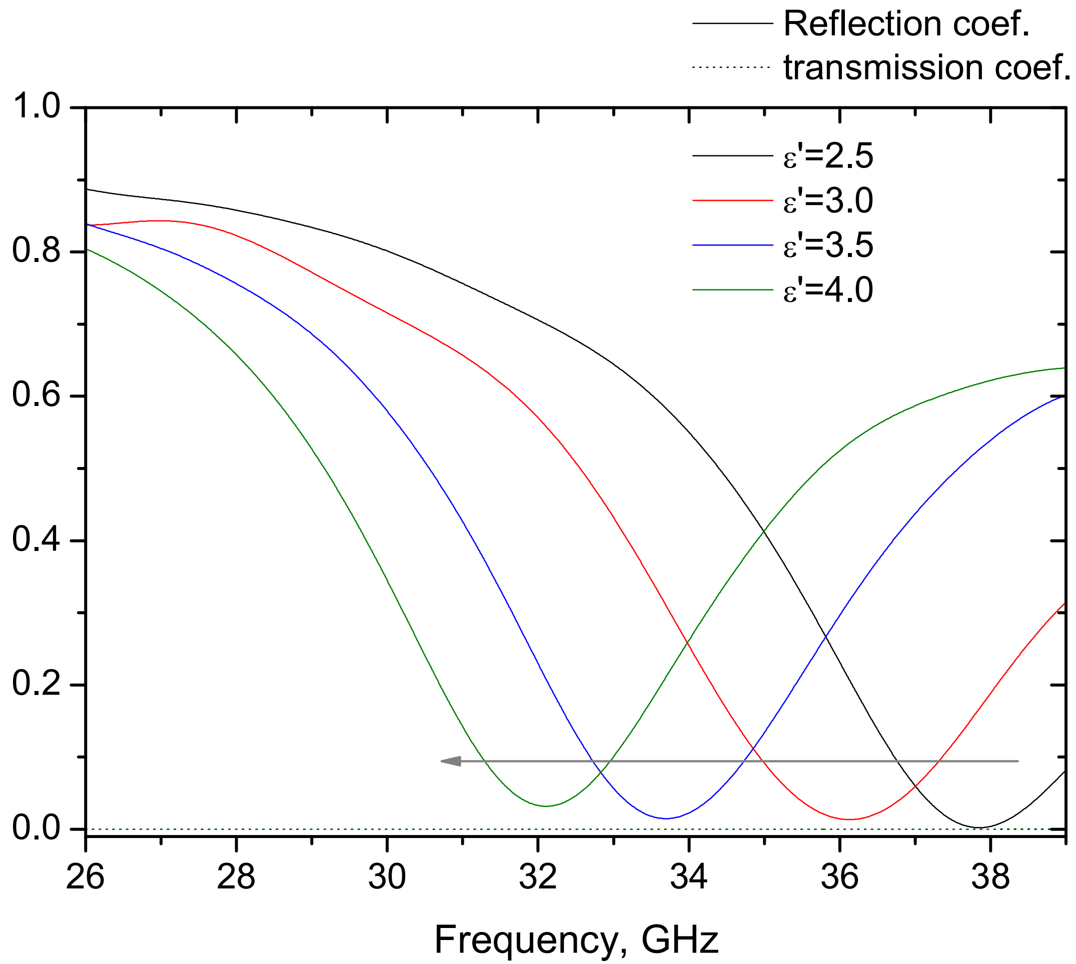
Cell simulation and field amplitude distribution at frequency of 0.2 THz and 0.5 THz for reticulated structures with widow sizes of 120, 150 and 170 microns, respectively. The pore size and thickness of skeleton structures relied constant (600 microns and 10 microns, respectively). The skeleton conductivity was 2000 S/m.





Changing the geometrical parameters one changes the resonant frequency:
Smooth TUNINING vs mechanical deformations

# Carbon lattice. Influence the dielectric properties of filling media: Smooth tunability



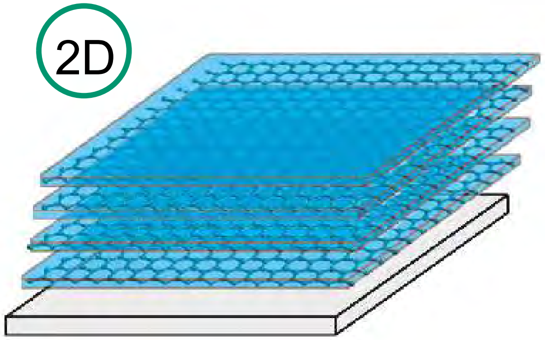
- ✓ The dielectric properties of the medium inside 3D carbon lattice influence significantly on the absorption peak position.
- ✓ This can be used to tune smoothly the electromagnetic response of 3D carbon photonic crystals by impregnation of the 3D lattice with gas / vapors.

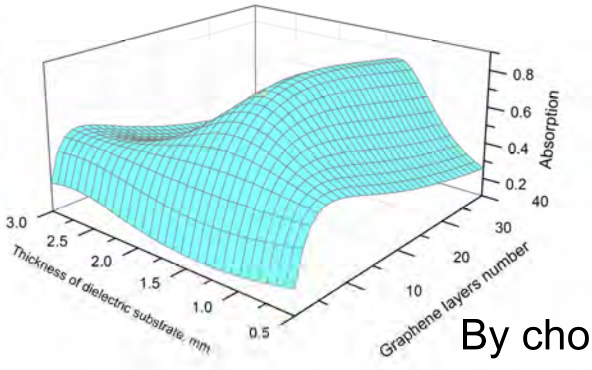
Dependence of the absorbance/transmittance through the 3D structure on the value of the real part of the dielectric permittivity of the filling matrix.

# 2D+3D

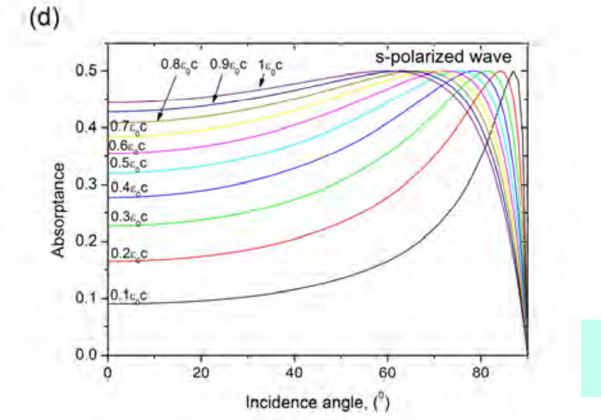
# Thin conductive film

Why 3D is important ?





By choosing properly the dielectric permittivity and the thickness of the sub-strate that holds the graphene layers



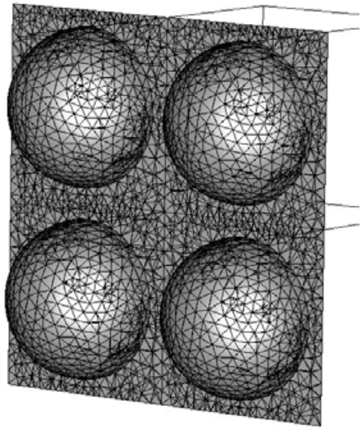
Absorption can be enhanced for some optimum incidence angle

Appl.Phys.Lett. 108, 123101, 2016
J. Nanophoton. 11 (3), 032504, 2017

Idea of combing optimal thickness and angle dependence

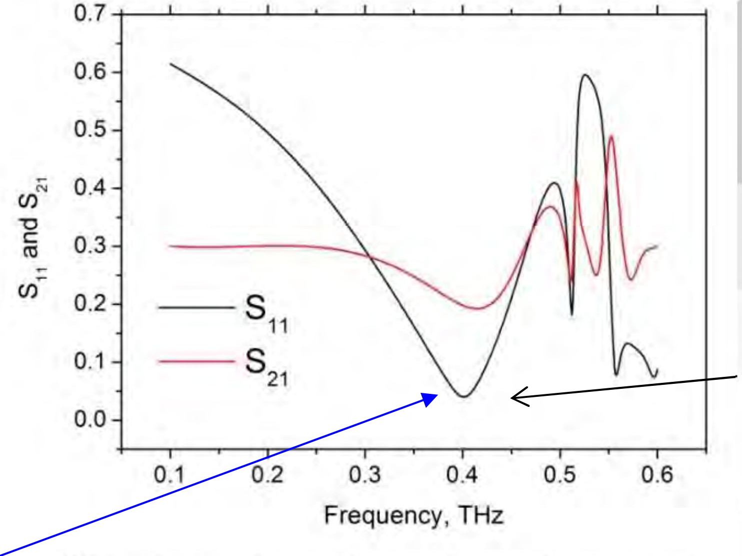
**3D metasurface**

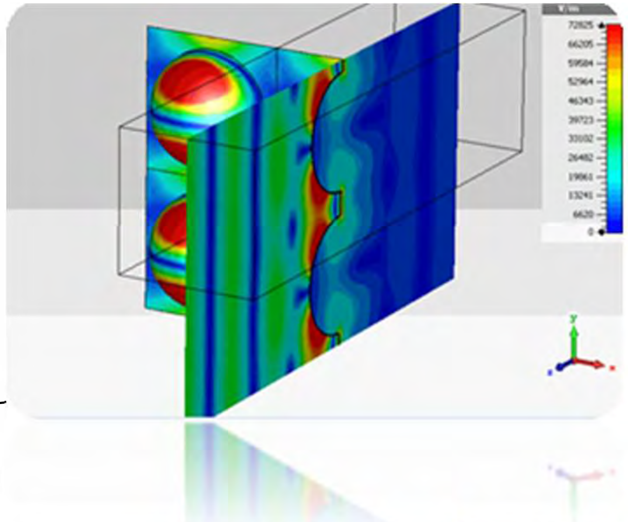
# 3D meta-surface: simulations



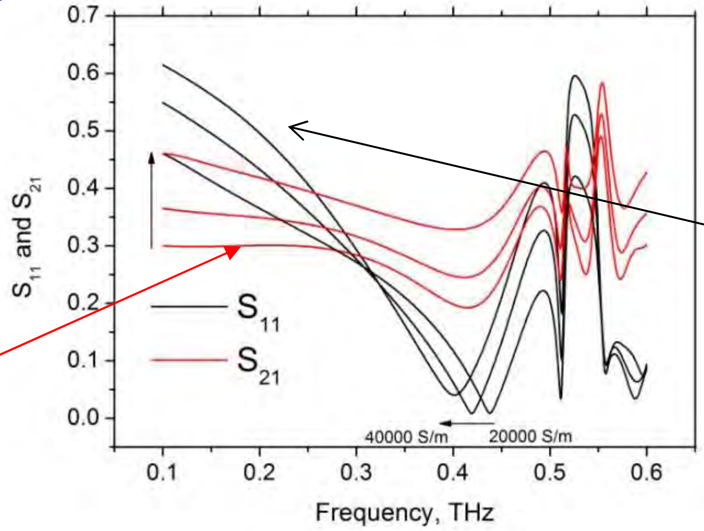
$$d = 500um$$

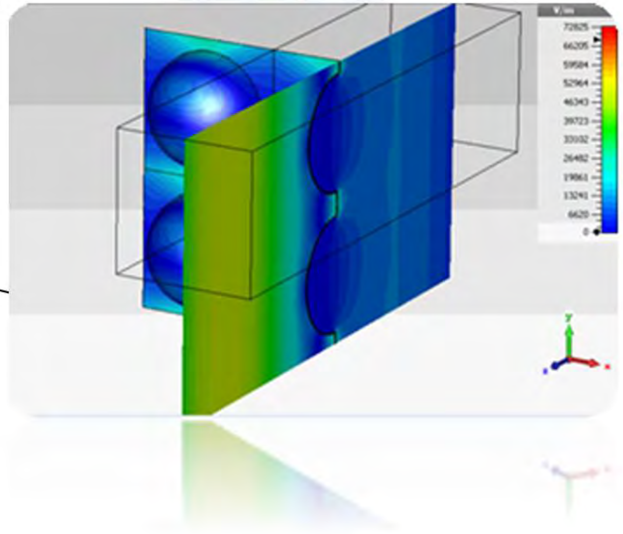
$$a = 600um$$





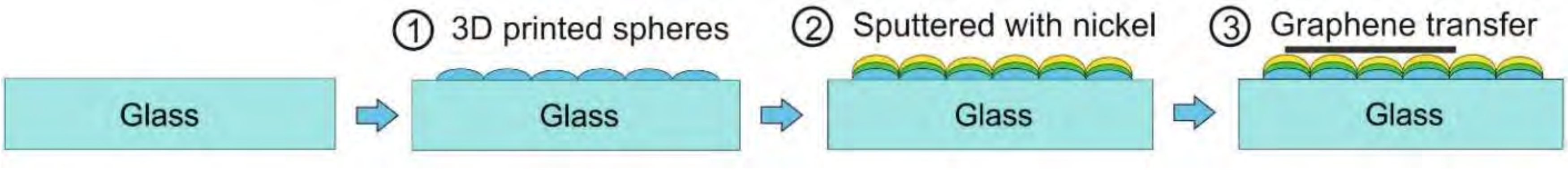
Almost perfect resonant absorption





High absorption (more than 50%) in broad THz range

# 3D metasurface based on graphene / carbon films



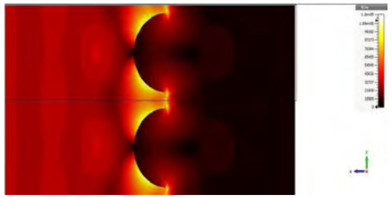
3D printing polymer template

**Plan A (supported metasurface)**

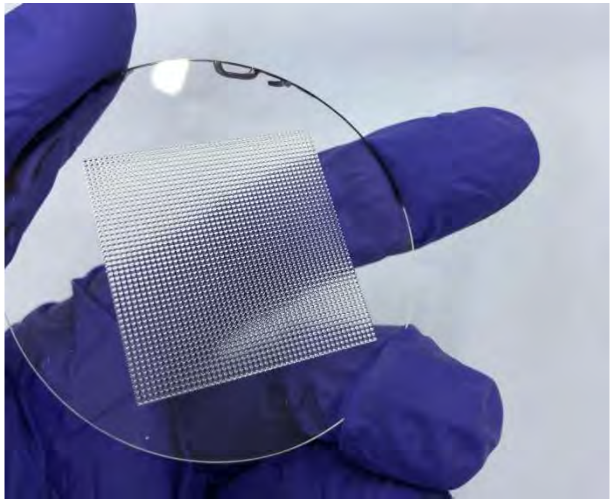
- ☐ Coating a 3D polymer template with a thin metal layer (gold, nickel) by thermal or magnetron sputtering.
- ☐ Transfer to the multilayer structure of CVD graphene.

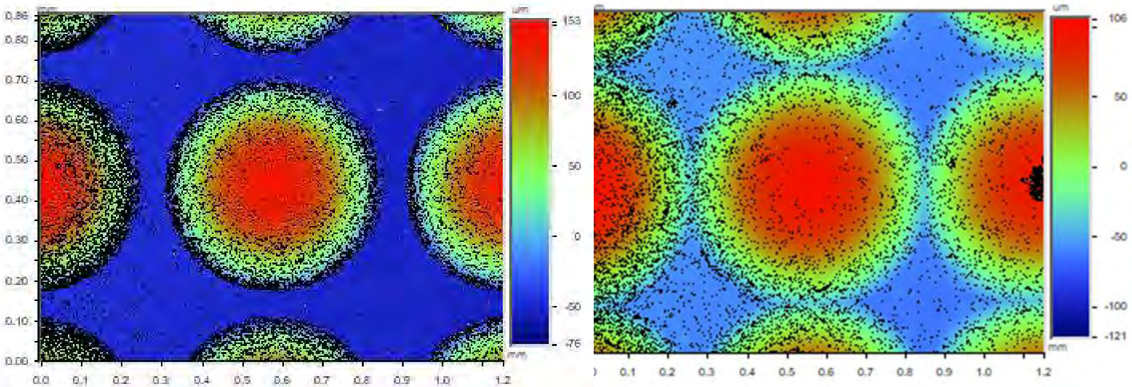
**Plan B (free stading metasurface)**

……………………



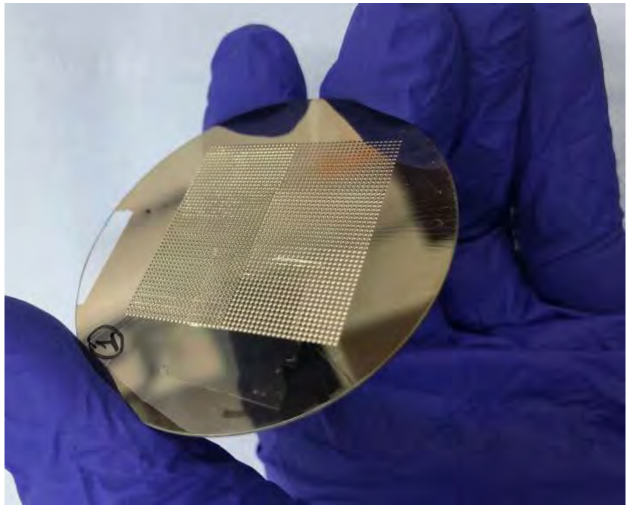
# 3D metasurface based on graphene / carbon films





3D metasurfaces of different periods with hemispheres of different diameters by optical profilometry

“Printed” on a quartz substrate polymer 3D templates.

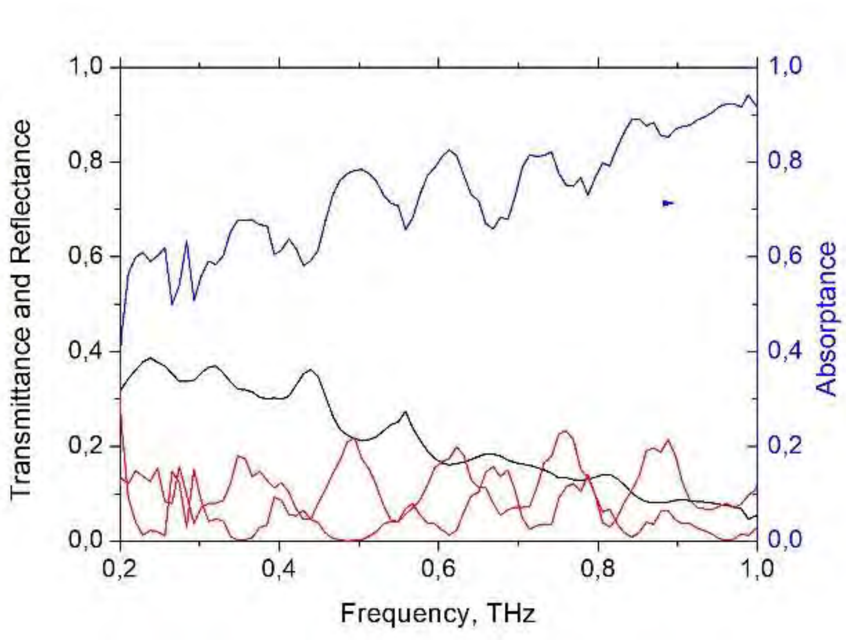


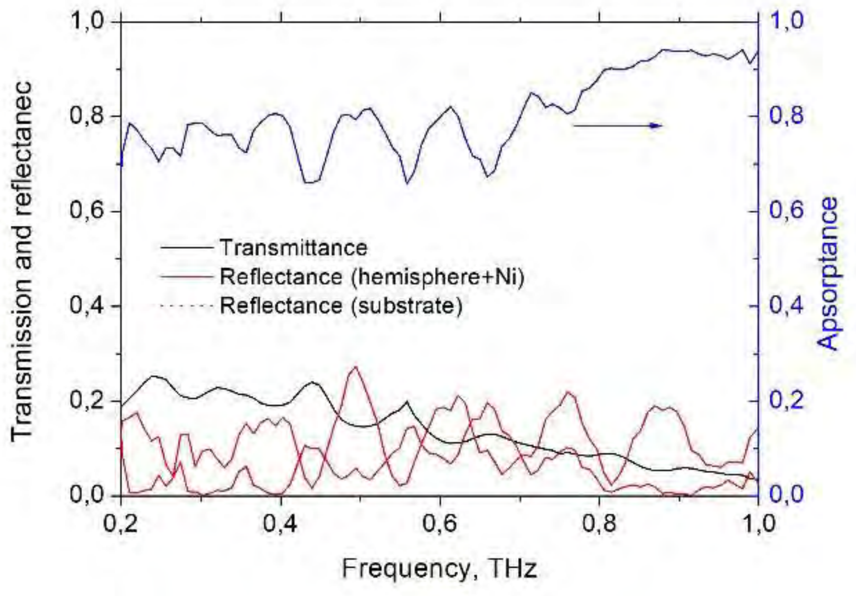
3D polymer template coated with a 30 nm thick nickel layer. The grayer part of the sample (lower left corner) is also covered with CVD graphene.

# 3D metasurface based on graphene films

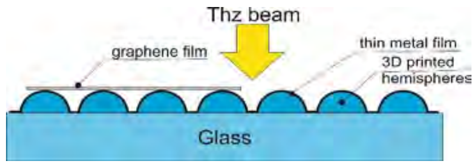
Quartz/hemispheres/Ni

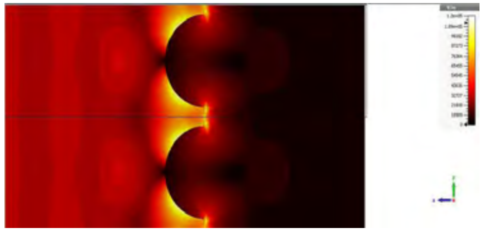
Quartz/hemispheres/Ni/graphene





hemispheres height 220 microns, period 600 microns





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תודה
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Paldies
Kiitos
Täname teid
谢谢
Thank You
Tak
感謝您
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Σας Ευχαριστούμ
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Tack