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METAMATERIALS AND TRANSFORMATION OPTICS

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Abstract: The paper discusses one of the most popular fields in the optical research of materials that has undergone a remarkable transformation. The study of metamaterials gives birth to a whole new scientific field called „transformation optics" which promises to greatly increase the potential of manufacturing of synthetic nano-optical materials whose structure is located within the sub-wavelengths. Interactions of electric and magnetic field waves with modules of sub-wavelength produce effects that are impossible to get in natural materials, such as negative refractive index, unlimited degree of inertia and so on. Their development has offered an exciting potential to design a completely new type of optical materials.

Keywords: metamaterials, transformation optics, diffraction limits, quantum phenomena, negative refractive index, negative dielectric permittivity, magnetic field, doppler effect.

1. INTRODUCTION

Metamaterials are a new paradigm in modern science. Over the past few years, numerous international scientific journals paid significant attention to the results of experiments that included work with metamaterials. The prefix „meta", as a rule, is given to materials which own their specific characteristics primarily to their structure and not the composition, which is usually considered in explaining the behavior of different compounds. Thanks to its structure, metamaterials possess electromagnetic properties that cannot be found in nature. Due to its periodicity, these structures have the ability to control electromagnetic waves and to act as frequency and spatial filters. Since the possibilities of their application in different sectors of the industry (especially the military) and health are large, interest in them is not fading, which places them in the focus of research.

The first generation of metamaterials is made of identical and uniformly distributed structures within the sub-wavelengths. Now metamaterials are produced with the negative dielectric constant and permeability at the same frequency, a negative phase velocity, negative refraction and inverse Doppler effect. An especially interesting feature of the metamaterial is the possibility of obtaining a negative refractive index in a wide frequency band, therefore, metamaterials are most commonly related to negative refraction. This feature is a cause of different refraction of light than normal and it is now given special that would enable the effects of an invisible cloak or be used as microscopic super-resolution devices. In recent years, the field of metamaterials has experienced enormous expansion on a global scale, as evidenced by the exponential increase in the number of scientific papers published in this field. Wide use of metamaterials is found in electromagnetics assisting in the development of sophisticated optical and microwave devices, RF systems for wireless communication of a new generation, split-ring resonators (SRR), lasers, lenses, the development of cheap, lightweight, multi-functional, or „smart" hardware that would be used for various services, all of which is not attainable without the use of these new technologies, primarily metamaterials.

The development of super compact, inexpensive and multifunctional circuits that operate at different frequency bands, is a condition for their competitiveness and their further development.

This means that metamaterials are artificial periodic structures whose electromagnetic characteristics vary according to the shape and arrangement of the elements of the periodic inserted into the base material, and not to the chemical composition of the material itself. Dimensions of the unit cells constituting the metamaterials are substantially smaller than a wavelength, of 1/10 of wavelengths, therefore, quasi-static analysis and the concept of effective medium can be applied to metamaterials. Metamaterials can be viewed as a homogeneous medium with effective parameters − effective permittivity and effective permeability. By careful selection of the

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shape and geometrical distribution of the unit cells, the effective parameters can be made arbitrarily large or small, or even negative.

The European Commission has begun to fund research in this area back in the Framework Program 5 (FP5) for projects in the ICT program (Information Communication Society). In FP6, research in this area is funded through the Network of Excellence „Metamorphose“ (Network of Excellence, NoE) under NPM Program (Nanotechnology and Nanosciences, knowledge-based multifunctional materials and new production processes and devices).

Metamaterials have unusual characteristics such as, for example, a negative index of refraction or an unlimited degree of inertia, the characteristics which are not possessed by the materials that can be found in nature. Their three-dimensional periodic structure of the cell is therefore the product of a man, made in order to achieve specific and astounding results.

Metamaterial structure that has the ability to affect the electromagnetic waves must be made up of fragments whose size does not exceed the length of the wave with which it comes into contact. When it comes to light, the wavelength is less than a micrometer (about 560 nanometers), so the size of fragments of the metamaterials that would affect the behavior of these waves would also have to be measured in nanometers. Since metamaterials are produced by a man, today's technology is busily preparing itself for the new nanometer challenges. In the case of microwaves, fragments of the periodic metamaterial structures are of the decimeter magnitude, so they are already at the stage of research and development.

The specific structure of metamaterials has many similarities with the crystals of the photon and the selectively permeable surfaces, while the differences are derived from the wavelength-size relationship of the fragment structure, which carries the specificities of their interaction. In short, the metamaterial has the property to conduct a specific wave so that after passing through it, the impression is made that the wave has not come across any kind of obstacle, like in a situation when water bypasses a stone in its way.

2. METAMATERIALS

The first theoretical analysis of the fundamental properties of metamaterials was given by the Russian physicist Victor Veselago in 1967, [1]. He published a paper in which he speculated about electrodynamics of the so-called double-negative materials − materials that would also have a negative permittivity and negative permeability. As the refractive index is by definition equal to the square root of the product of the relative dielectric permittivity and relative magnetic permeability of the material, it follows that its value may be either positive or negative. Also, it can be assumed that the dielectric permittivity and magnetic permeability can simultaneously be negative.

The dielectric constant ε and magnetic permeability μ are the basic values that describe the propagation of electromagnetic waves in a material, [10,18,20]. These are actually the only substance parameters which exist in the dispersion equation:

$$\left| \frac{\omega^2}{c^2} - \varepsilon_{il}\mu_{lj} - k^2\delta_{ij} + k_i k_j \right| = 0 \qquad (1)$$

and that in effect provide a link between the frequency **ω** of the monochromatic wave and its wave vector κ. In the case of an isotropic substance, it receives a simpler form:

$$k^2 = \frac{\omega^2}{c^2} n^2 \qquad (2)$$

where $\mathbf{n}^2$ is the square of the refractive index of the substance given as $\mathbf{n}^2 = \varepsilon\mu$. If we neglect losses in the equation and look at the parameters **n, ε** and **μ** as real numbers, the equation shows that the simultaneous changes of the sign ε and μ are not effective in this instance. However, this situation can be seen in three different ways. First, we can conclude that the simultaneous change of the sign **ε** and **μ** does not affect the characteristics of the substance itself. Secondly, the possibility that the **ε** and **μ** are simultaneously negative is in contradiction with the fundamental laws of nature, and therefore, the substance with negative **ε** and **μ** cannot exist. In the end, we can assume that substances with negative **ε** and **μ** have some characteristics different from the substances with positive **ε** and **μ**. It is clear that the law of electromagnetics is essentially connected with the sign of **ε** and **μ**, but if we look at Maxwell relation where **ε** and **μ** exist individually and not in the form of previous equations, we obtain the expressions:

$$rot\,E = -\frac{1}{c}\frac{\partial B}{\partial t},\ rot\,H = \frac{1}{c}\frac{\partial D}{\partial t},\quad \text{where is}\quad B = \mu H \ \ a\ D = \varepsilon E \qquad (3)$$

For planar monochromatic wave, in which all sizes are proportional to $e^{i(kz-\omega t)}$, the previous expressions become:

$$[kE] = \frac{\omega}{c}\mu H \quad , \quad [kH] = -\frac{\omega}{c}\varepsilon E \qquad (4)$$

As it can be seen from these equations, if the ε and μ are greater than zero, then the **E, H**, and **k** form a right-triplet of vectors (RH - Right Handed Triplet), [6,11,22] and if the ε and μ are less than zero, then the expression is in the form of the left triplet of vectors (LH − Left Handed Triplet). If we now introduce the cosine of the direction of the vectors **E, H** and **k**, and respectively label them with $\boldsymbol{\alpha_i}$, $\boldsymbol{\beta_i}$ and $\boldsymbol{\gamma i}$, then the propagation of the waves through the given medium can be described with the matrix:

$$G = \begin{pmatrix} \alpha_1 & \alpha_2 & \alpha_3 \\ \beta_1 & \beta_2 & \beta_3 \\ \gamma_1 & \gamma_2 & \gamma_3 \end{pmatrix} \quad (5)$$

The determinant of this matrix is equal to +1 if the vectors **E, H** and **k** Right Handed Triplet, while in the opposite case is equal to -1 if the vectors **E, H** and **k** Left Handed Triplet, Figure 1.

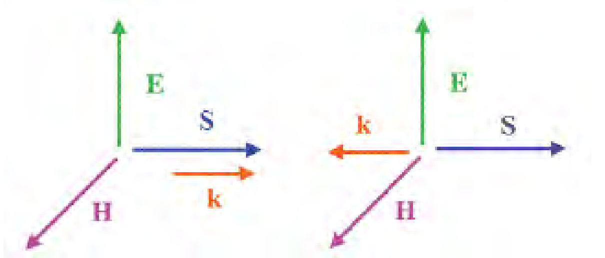


*Figure 1. The orientation of the electric **E**, magnetic field **H** and wave propagation vector **k** forming the triple by a rule (a) for the right hand RH, (b) for the left hand LH of the materials. Energy (Poynting vector) and wavefronts propagating in the (a) the same direction, while in (b) the case of LH material travel in the opposite direction.*

Veselago showed that in this case the propagation constant would be real, or that double-negative metamaterials would support the wave propagation. Moreover, constant propagation would be negative, which was not the case for any material known to date. As a consequence of Maxwell's equations, in this case the wave vector k would change the direction and for the set of vectors **k, E, H**, the so-called right hand rule would not be true, but rather the rule of the left hand.

According to Veselago, one of the difficulties that existed in the search for a natural, double-negative substance is in the fact that the ranges of resonance frequencies at which a negative permittivity and negative permeability occur are very narrow, whereby the resonant frequencies at which the permittivity becomes negative are usually much greater than those for which the permeability is less than zero. Veselago predicted unique electromagnetic properties LH medium and showed that the propagation of electromagnetic waves is possible in such a medium, but with a negative constant of propagation. Energy would be extended from the source, but the wave fronts would be traveling in the opposite direction. As a result, vectors of electric and magnetic fields would form the triplet of the left hand rule with the vector of wave propagation. This is how these materials got their name as left-handed. In LH, MTM-phase and group velocity are of the same course but opposite directions, causing the refractive index to be negative.

Classical physics phenomena such as the Doppler effect, Vavilov-Cherenkov radiation, Snellius effect, focusing lenses and Mr. Henkel-effect do „rotate“. The figure shows the effect of altered Snellius law in the case of LH-lens application, in Figure 2.

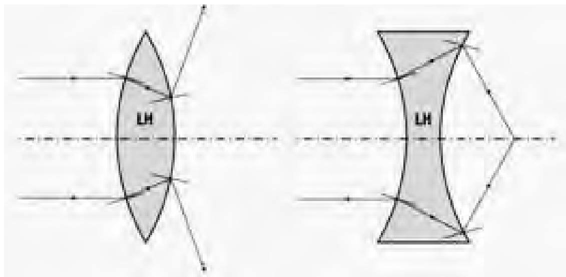


Figure 2. Wrap at LH -lens - a direct consequence of the changed Snellius law.

The first experimental confirmation of Veselago’s theoretical research took place only 30 years later, when Pendry [2] designed the first geometric pattern that shows a negative permittivity at microwave frequencies. Three years later, the same author also proposed a sample which is called interrupted annular resonator (split-ring resonator) SRR [23], which gives a negative permeability in the narrow range of frequency, Figure 3.

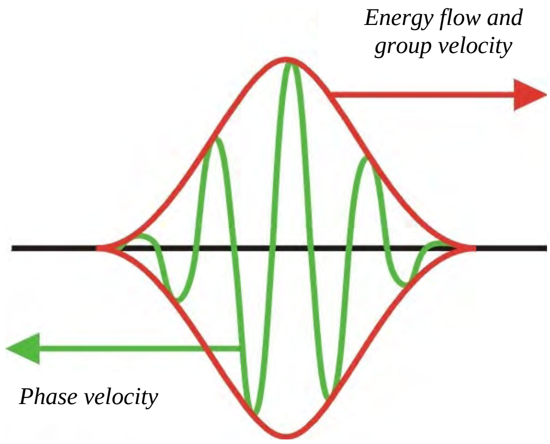


Figure 3. The result arising from the negative refraction makes the air speed (ie. group velocity) and phase velocity must be pointed in opposite directions

3. METAMATERIALS WITH NEGATIVE MAGNETIC PERMEABILITY

Pendry [3] and his team have proposed a structure that provides a negative permeability. It is a periodic structure with a period less than a wavelength, with the basic forms of the metallization in the form of a broken ring (Eng. Split ring), [12,18], shown in Figure 4. When this material is exposed to the normal magnetic field, currents are induced in the rings due to whose flow a gap in the ring behaves like a virtual capacitor. Since the ring is of an inductive nature, such a structure has a resonant nature. Effective permeability of the surface made by repeating this unit cell is also of a resonance character. It may be noted that there is a narrow range of frequencies just above the resonance in which the permeability is negative. Due to their small size, these elements can be treated as elements with quasi-concentrated parameters. Although showing negative effective parameters in a very narrow range, these resonators have attracted much attention, of both engineers and physicists, and they are used in a number of applications of microwave circuits, Figure 5.

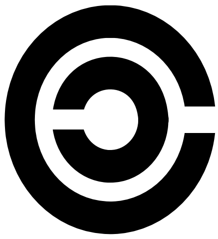


Figure 4. Double stop ring, the unit cell structure proposed by Pendry for obtaining negative permeability

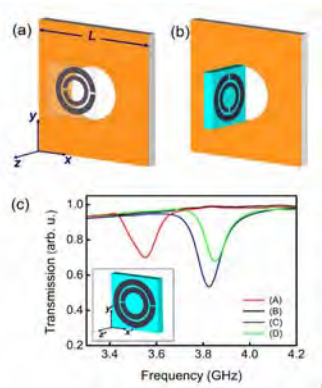


Figure 5. Scheme of the gap in the metal plate and in the SRR (a) parallel and (b) a normal orientation with respect to that plane. (c) The transmission spectrum of the unit SRR shown in its four different orientations relative to the basic plane.

When exposed to a magnetic field, perpendicular to the plane of the rings, the resonant current would be induced in the loop, so the equivalent magnetic dipole moments will be generated as well. Each element of the structure acts as a magnetic dipole, and the structure can be regarded as a material with the dependence of the relative magnetic permeability of the frequency plasmatic type [13]:

$$\mu(\omega)=1-\frac{A\omega_{om}^2}{\omega^2-\omega_{om}^2+j\gamma\omega}, \qquad (6)$$

where A is a constant which depends on the internal radius of the smaller ring, ω_{0m} is adjustable magnetic resonance frequency, and γ represents the damping ratio which includes all the losses (and mechanisms for scattering) in the metal.

Wired field of metamaterials

Metamaterials are metal dielectric composites that possess exotic optical properties throughout its sub-wavelength structure. The type of their structure certainly varies in accordance with the selected electromagnetic response. More particularly, the hyperbolic metamaterials are one of the most important classes of metamaterials which possess extreme anisotropy and a hyperbolic or an undefined dispersion, where the main components of the dielectric constant and permeability tensor have opposite signs with respect to the other components.

Field of metal wires in the dielectric environment behaves as a hyperbolic metamaterial at frequencies below the effective plasma frequency determined by the geometry of fields, enabling very unusual propagation of waves with hyperbolic dispersion and extremely strong spatial transversion frequencies. Bearing in mind the macroscopic electro neutrality, plasma is considered to be the only available dielectric that exhibits a negative permittivity (a magnetic permeability positive). In view of approximation of the electrical properties of the plasma in the microwave regime, in the early fifties a structure made of dielectric material was proposed with a series of periodically spaced metal rods. Later on, Pendry has introduced a theory that allows the connection of quantum plasma parameters with the geometrical dimensions of a set of rods.

Hyperbolic metamaterials are spatial hyperbolic dispersing medium for the frequencies lower than the effective plasma frequency in the structure. Three types of this structure can be defined: TE, TM and quasi-TEM, in Figure 6.

At low frequencies (~ GHz), the dissipation is very important and makes it virtually impossible to observe this phenomenon. The solution that is proposed by Pendry [3] comprises a periodical structure consisting of a number of metal wires, which permits the reduction of the average concentration of charge in the material.

In addition, an electric field is applied to the structure parallel to the axis of the wires, so the currents will be induced along the wires. It comes to the increase of the effective mass of the electrons due to inductance of each of the rods, leading to a shift in the plasmon frequency in the microwave range.

$$\varepsilon(\omega)=1-\frac{\omega_p^2}{\omega\ -(\omega\ +j\gamma)} \qquad (7)$$

where γ is a parameter of dissipation, and ω is an angular frequency of the incident wave.

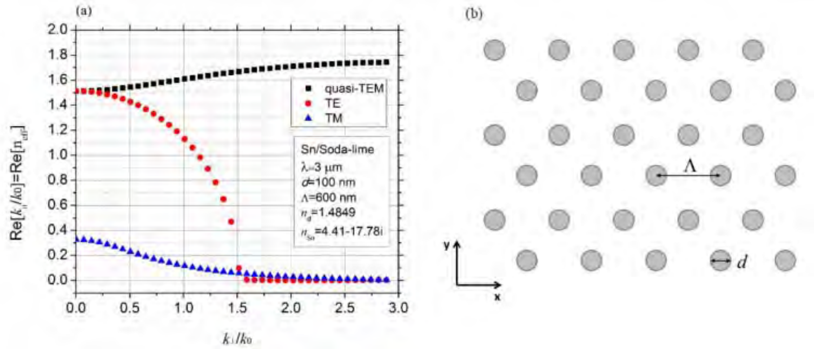


Figure 6. (a) isofrequent curves, three modes of wired fields, Sn / soda-lime system, d = 100 nm, L = 600 nm and λ = 3 micrometers. (B) Scheme of a hexagonal wire field.

Shelby, Smith and Schultz [4] made the first LH-material and measured the negative refractive indexes in 2000, based on the work done by Pendry. Figure 7 shows the layout of the first LH-materials. Experimental confirmation of the LH effect was made by combining two geometries proposed by Pendry. A periodic structure that was used consisted of a square split ring resonator and the thin metal strips of copper but at the same time a negative permittivity and permeability in the range of 10.2 − 10.8 GHz was showed.

Experiments have shown the existence of a negative refractive index, measuring the angle at which the wave travelled after passing through the prism of metamaterials.

Metamaterials proposed as an alternative to LH MTM structures for overcoming some of the difficulties imposed by reducing the geometric dimensions and inertial properties of electrons are called Fishnet. This type of metamaterial because of its appearance resembles a fishing net, figure 8. The structure is composed of two metal plates that are placed next to each other and separated by a dielectric, and evenly drilled (through both layers). Fishnet Metamaterials have a simpler design than the previously discussed structure because they are in the form of square resonators. They are easy to fabricate, so it is easier to implement them at smaller dimensions, Figure 8.

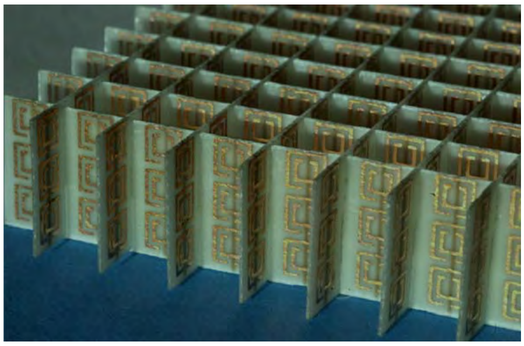


Figure 7. First LH MTM with negative index of refraction (ε <0, μ <0), which consists of parallel metal strips (65 nm thick gold) on one side of the substrate and the split-ring resonator on the other side (65 nm thick gold).

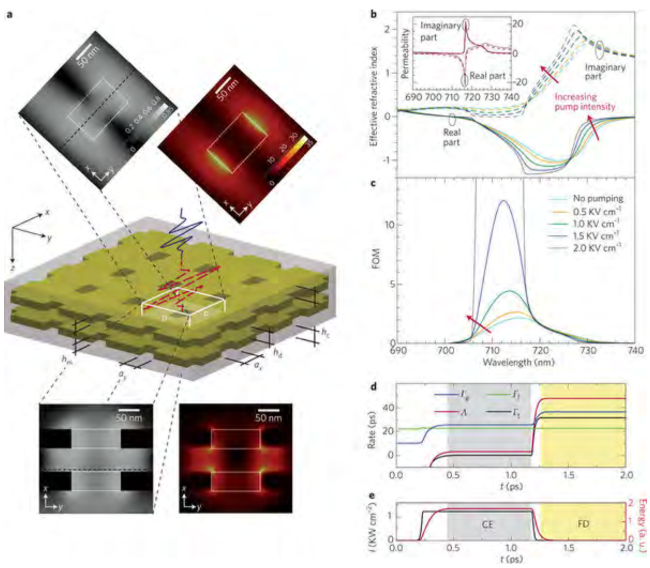


Figure 8. (a) Schematic representation of Fishnet metamaterials with profiles for the inversion (left) and amplitudes of the electric field (right) of wavelength 710 nm, observed in the xy-plane (above) and the zx-plane (below). Left, reduced and dark objects represent the high and low power of inversion. hm, hc and hd indicate the height of metal-coated with a dielectric layer, Ax and Ay are the widths of rectangular holes, p is the periodicity. (B) The real and imaginary parts of the effective extraction of the refractive index n for diffrerent amplitudes. The amplitude of the electric field ranges from 0.5 kV increments cm^{-1}, to a maximum of 2.0 kV $^{cm-1}$

Metamaterials based on a graphene

Based on recent research and analysis, it can be seen that graphene (Graphene) can replace metal in terms of conducting electricity in metamaterials [21]. Graphene is a one-dimensional nano thin layer (in one plane) of individual carbon atoms attached to a hexagonal grid, Figure 9. On the other hand, it has been experimentally proven that graphene can modify an optical response in the electromagnetic interaction with the metal-based metamaterials. It turned out that the weak optical response of graphene can be dramatically modified in conjunction with a strong resonant field of metal structures. The key element that determines the strength of this interaction is the orientation of the resonant field. If the resonant electric field is parallel to the sheet of graphene (as in complementary split-ring metamaterial), Figure 10, its resonance can be very dimmed. If the resonant field is perpendicular to the sheet of graphene (as in wire-pair metamaterials), there will be no interaction.

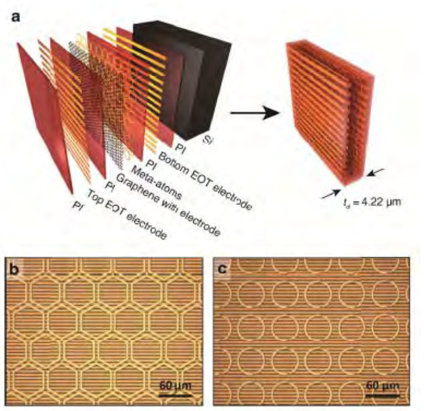


Figure 9. Schematic representation of gate-controlled active graphene metamaterials. (a) The fabrication of the active graphene metamaterials, (b) optical micrograph of a fabricated hexagonal graphene meta-atoms, (c) Asymmetric double split ring meta-atoms.

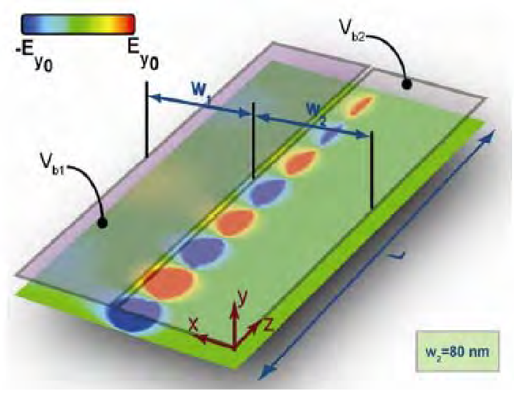


Figure 10. Distribution of Ey IR wave at f = 30 THz, supported along the border line between the two sections of the same sheet of graphene, which has two regions of the conductivity (L = 250 nm, W = 80 nm).

As it can be seen, for the complementary SRR metamaterials, in spite of small surface conductivity, graphene can significantly attenuate the resonance of quasi static and plasmon elements when they are exposed to a strong resonance electric field, generated by the current in the metal element of the metamaterials.

For wire-pair structure, this effect is not possible if the resonant electric field is perpendicular to the plane of the graphite sheet. This conclusion may be useful in „adjustable“ metamaterials design. Graphene can also be awaken by an electrical potential (bias), allowing potentially large amount of modulation of the electro-optical control of the metamaterial state. This approach is possible only with metamaterials of the SRR-type with a resonant electric field parallel to the graphene sheet. Full control of electromagnetic waves, such as managing and air shaping, constitute one of the most important challenges of applied electromagnetics. By the discovery of properties of graphene and metamaterials based on it, new ways to design quickly adjustable electromagnetic devices are created. By electrical or optical changes of the Fermi level of graphene, conductivity of the material can be changed. Applications have been developed in the field of transformation optics, integrated photonics or optical signal processing systems.

4. TRANSFORMATIONAL OPTICS

If there is no presence of strong gravitational fields in sight, visible light, microwave radiation and all other electromagnetic waves always spread in a straight line, but when they encounter an obstacle, they can be reflected, partially permeable or absorbed. Light will never naturally bypass a body, like water does when it encounters an obstacle. When moving between the points in space, light takes the shortest path or a straight line. When it comes to metamaterials, the shortest path may be the one that directs the light around the objects coated with this coating. It is the curved light that represents the most interesting application of metamaterials. When it comes to light, the wavelength is less than a micrometer (about 560 nanometers), so the size of the fragment of metamaterials that would affect the behavior of these waves should be measured in nanometers as well. Simply, the basic idea of the use of metamaterials is to force the light to bypass the object, like water does when it encounters a stone. It is possible by using metamaterials since they have a precise refractive index that allows bending of electromagnetic waves around them in the randomly selected direction.

Conventional fields: electric field, magnetic induction field and Poynting's vector in this case can be spread within a new coordinate system, all depending on the selected anisotropic and spatially dispersive metamaterial, Figure 11.

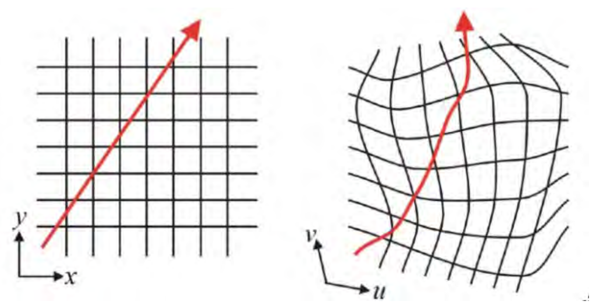


Figure 11. Left, a field in free space shown in the Cartesian coordinate system, right, deformed field lines in a deformed coordinate system

Coated with the layer of nanometer precision metal structure, any object can become invisible to the observer, regardless of the direction the light is coming from. The effect of concealing depends on the composition of metamaterials, namely the index of reflection, or its ability to influence the direction of light that comes across to it, based on a negative index of refraction, Figure 12.

Dekartes coordinate system can be described over u **(x, y, z), v (x, y, z), w (x, y, z)**. In the new coordinate system, renormalization values for the dielectric constant and permeability must be used:

$$\tilde{\varepsilon}_u = \varepsilon_u \frac{Q_u Q_v Q_w}{Q^2{}_u},\ \tilde{\mu}_u = \mu_u \frac{Q_u Q_v Q_w}{Q^2{}_u},\ldots \qquad (8)$$

Where:

$$Q_u{}^2 = \left(\frac{\partial x}{\partial u}\right)^2 + \left(\frac{\partial y}{\partial u}\right)^2 + \left(\frac{\partial z}{\partial u}\right)^2,\ldots \qquad (9)$$

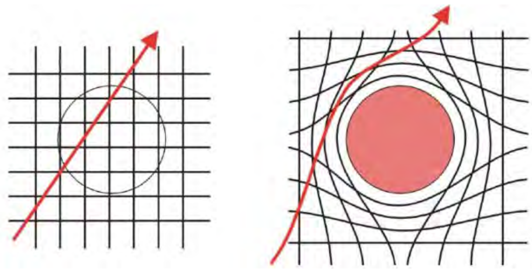
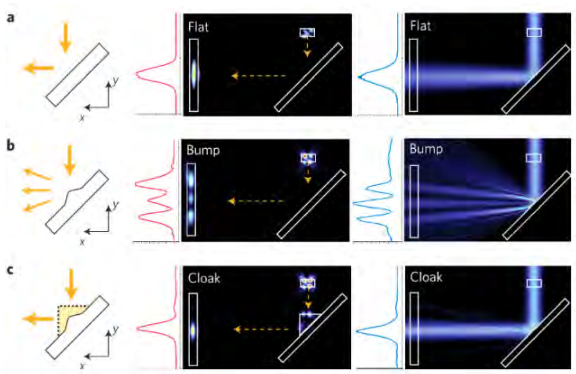


Figure 12. Left the air in free space is displayed in the Cartesian coordinate system, right, strong distortion of the coordinate system that creates a 'hole' which hides the needed zone

Namely, after bending around the object, the light must be directed to the same path which it followed before encountering the object. In this way, the air will continue with its original path and sooner or later come across the object that will reject it and send it back to the viewer. In case that the metamaterial has adequate structure, reflected light which comes back, will bypass the hidden object in the same way as during the first passage and will not leave a shadow. If this condition was not met, the viewer would see a hidden object that was illuminated with the background light or by a reflected beam that travels back. The result of one such experiment is shown in Figure 13.



c) *Wave reflection from a flat surface*

b) *Wave reflection from a curved surface*

a) *Wave reflection from a curved surface coated with metamaterial*

Figure 13. Experiment of optical hiding.

The ideal hiding cloak

„Hyperstealth Biotechnology", a Canadian company that manufactures this metamaterial cloak claims that it can deceive even the glasses for night vision. Its product, which is already offered to Canadian and the US Army, is kept confidential to such an extent that the company offers just a simulation of its specific functionality on the website. Therefore, some of the observers are skeptical, but Guy Cramer, executive director of „Hyperstealth Biotechnology" claims that everyone who has seen the fabric can confirm that it is not a manipulation of video and photo footage, Figure14. The people concerned are working, apparently, in the US Army and two private Canadian military groups, and the anti-terrorist units. An interesting fact is that an aircraft covered with metamaterials not only remains completely invisible to electromagnetic waves of certain frequencies emitted by radar but also is unable to register them itself. In this case, navigating the hidden aircraft would be completely dependent on the pilots because the shield would prevent any radar guidance. Solutions to this problem are being urgently searched for.

Figure 14. Metamaterial hiding cloak.

Such a cloak was first experimentally carried out by Schurig, forming a plane of cylindrical rings [14,23]. The structural parameters of this metamaterial by observing a single cylinder were calculated by using the equations:

$$\varepsilon_r = \mu_r = \frac{r-a}{r},\quad \varepsilon_\varphi = \mu_\varphi = \frac{r}{r-a},\quad \varepsilon_z = \mu_z = \left(\frac{b}{b-a}\right)^2 \frac{r-a}{r} \quad (10)$$

Axis of the cylinder is set to be in the z-direction, and the inner and outer radius of the shield is a = 2.71 cm and b = 5.89 cm, respectively. All the components of the tensor (r, φ and z) of the dielectric constant and the magnetic permeability have a gradient in the function of radius. Incident wave is in the TMZ polarization when an electric field is parallel to the z axis, at the operating frequency of 8.5 GHz, Figure 15. Distribution of the electric field is given in Figure 16.

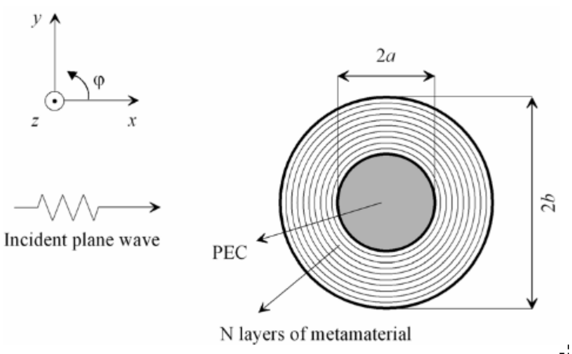


Figure 15. The cross section of the cylinder of metamaterials.

Based on these findings of the Department of Physics of the Korean University, Kyoung-Ho Kim [25] and his associates lay the foundation for the „invisible“ hyperbolic metamaterial consisting of a plurality of carbon nanotubes composed of metal and dielectric layers of the material. Selected thin layers of metals and dielectrics allow propagation of light through a nanotube without distortion of the input light, Figure 17.

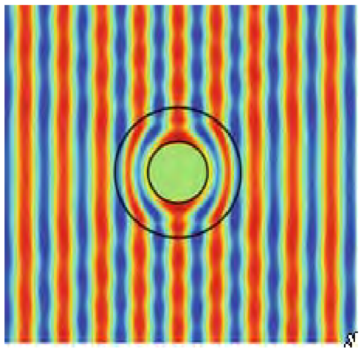


Figure 16. The distribution of an electric field in the field of the 10-layer realization of an ideal cylinder for hiding (TMZ polarization).

Theoretical study on dispersion of light approaching almost zero was observed in multilayer nanotubes at specific wavelengths, and in the transverse − electric (TE) and in the transverse − magnetic polarization of the incoming light. Also, in order to better understand this matter of low light scattering, multi layered nanotubes were modeled as radially anisotropic hyperbolic metamaterials and the scattering of light of the incident beam was observed. It was concluded that the low light scattering under specific incidence angle occurs when the effective dielectric constant of the hyperbolic nanotube is close to zero [21]. Thus, analyzing the corresponding nanotube, it was observed that the characteristics of 'invisibility' can be effectively designed and adjusted, and later on used for their practical implementation in unique nanophotonic devices.

The study focused on the optical properties of multilayer nanotube structures with core diametar of 100 nm and a layer of 60 nm, where the thickness of both layers composed of Ag and TiO_2 was set to be

10 nm, Figure 17a.

As it can be seen from Figure 17b, the scattering efficiency occurs as a function of the wavelength (using a Lorentz-Mie light scattering method), in both TE and TM polarization of light that is perpendicular to the side of the nanotube.

It is observed that the efficiency of the scattering spectrum dramatically reduces at a wavelength of ~ 450 nm for both polarizations, and that the visibility of the nanotubes is significantly lower in the reduced region. In order to explain such 'invisibility' of nanotubes, a normalized magnetic field, distributed around the nanotube of wavelength of 450 nm, was designed for the TE polarized input light and a simulation procedure known as a full-wave finite element was used, Figure 17 c. For comparison, the magnetic field was distributed and normalized and the calculations for the wavelength of 525 nm were made, showing the maximum scattering efficiency for the same multi-layer nanotube with the same direction of polarization of incoming light Figure17d. At a wavelength of the input ray of 450 nm, the interferential pattern induced by dispersible light from the nanotube is insignificant. It causes the destruction of the scattering of light waves that interact with the metal and dielectric layers of the nanotube. And for the TM polarized input light there is also the destruction of the scattering of light waves from different layers of the multilayer nanotube. Therefore, the entire field distribution is not deformed.

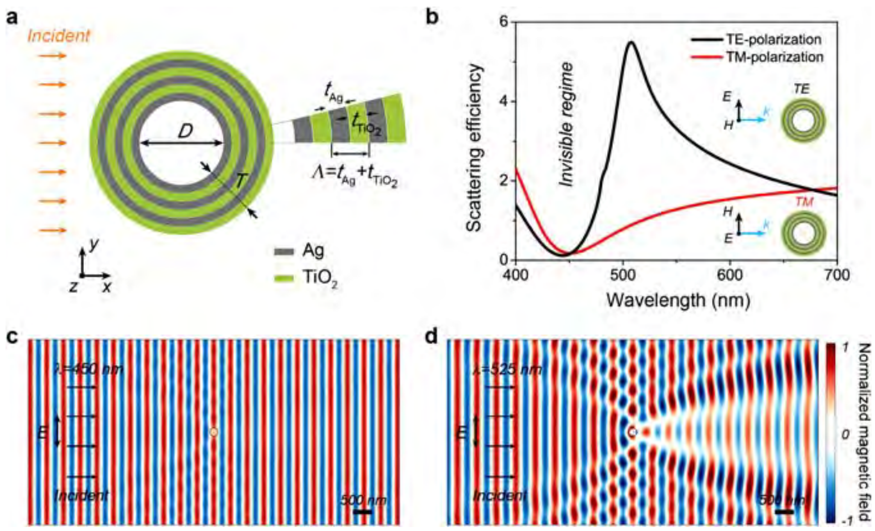


Figure 17. Light scattering in the metal-dielectric layer of the nanotube.

5. CONCLUSION

Metamaterials are named in the Journal of Science as one of the ten most important scientific achievements in 2003. This paper presents the properties of metamaterials, amazing features and characteristics of transformational optics.

A large number of challenges stand in front of researchers in this new field. Firstly, the research is closely linked with the progress of materials of the nanometer scale. Therefore, in view of even greater miniaturization of the unit cells, it is necessary to develop a technology of fabrication (LTCC, MMIC, nanotechnology). Applications in the optical range depend greatly on the development of new non-LH metal structures. Finally, the analysis of the periodic structures with a large number of complex unit cells represents a non-trivial and often impossible task to solve for the existing numerical and simulation tools for circuit analysis.

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МЕТАМАТЕРИЈАЛИ И ТРАНСФОРМАЦИОНА ОПТИКА

Сажетак: У раду се разматра једно од најактуелнијих поља у оптичком истраживању материјала које пролази кроз неочекивану трансформацију. Истраживање метаматеријала рађа потпуно нову научну област под називом „трансформациона оптика“ која обећава да ће у великој мери повећати потенцијал израде синтетичких нано-оптичких материјала чија се структура налази у оквиру супталасних дужина. Интеракције таласа електричног и магнетног поља са модулима супталасних дужина производе ефекте које је немогуће произвести у природним материјалима, као што су негативни индекси преламања, неограничен степен инерције итд. Њихов развој понудио је велики потенцијал за дизајнирање потпуно нове врсте оптичких материјала.

Кључне речи: метаматеријали, трансформациона оптика, лимити дифракције, квантни феномен, негативни индекс преламања, негативна диелектрична константа, магнетно поље, доплеров ефекат.

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