Metamaterials – Current and Future Trends

Elena Helerea*, Lia-Elena Aciu†
* Transilvania University of Braşov, Braşov, Romania, helerea@unitbv.ro
† Transilvania University of Braşov, Braşov, Romania, lia_aciu@unitbv.ro

***Abstract* - Recently, metamaterials have attracted considerable attention due to their feasibility and multiple applications. As man-made artificial structures, metamaterials possess properties that are not yet highlighted in the natural world, such as perfect lensing, negative refraction, and backward propagation. These properties are obtained by the proper design of the structure of metamaterials, with the periodic arrangement of unit cells, "meta-atoms", which have dimensions below the order of magnitude of the incident wavelength, at which resonance processes can be established. Thus, the electric and magnetic response of the metamaterial can be flexibly tailored to meet the desired macroscopic properties, in terms of effective electric permittivity and magnetic permeability. In this paper, a review of the state of research and development of metamaterials is made, highlighting the new challenges and ways to improve and to apply these new synthetic structures in electromagnetics and optics. There are analyzed the processes and structures of metamaterials used in various applications. Based on the actual researches, new classification of metamaterials with the criterion of the capabilities and flexibilities in controlling electromagnetic waves is described and analyzed.**

Cuvinte cheie: *metamateriale, structuri, proprietăți electromagnetice, clasificări, tendințe.*

Keywords: *metamaterials, structures, electromagnetic properties, classifications, trends.*

I. INTRODUCTION

In the last twenty years, as a result of technological development and the knowledge advancement, new category of synthetic materials has been developed, designed to obtain new, unconventional properties that are not normally found in nature.

Metamaterials provide unusual characteristics, such as negative refraction, perfect absorption or perfect transmission of electromagnetic waves, sub-wavelength resolution imaging, inverse Doppler effect, and backwards propagation [1]-[4].

These characteristics are obtained through the periodic arrangement of unit cells, called "meta-atoms", which have the size smaller than the incident electromagnetic wavelength. Thus, through the flexible and intentional engineering of the structures, dimensions, and arrangement of constituent meta-atoms, electromagnetic metamaterials are able to function as efficient electromagnetic devices to control the amplitude and phase of the electromagnetic (EM) waves so that the response regarding scattering, absorption and dispersion of EM waves can be easily manipulated [2], [5], [6].

Consequently, they have been studied and applied in many areas, as: optics, electromagnetism, electronics, machinery, wireless power transfer systems, acoustics, and communications [7]-[11].

Due to these particular characteristics, metamaterials can be applied in different fields such as: perfect lenses, optical coating, and microwave antenna. Perfect absorber metamaterials that absorb electromagnetic waves can be applied to plasmon sensors, solar cells, photo-detectors, thermal emitters or thermal imagers. By blocking the electromagnetic wave generated in Wi-Fi, mobile phones and home appliances, the absorber metamaterials can protect the body against harmful electromagnetic waves [12]-[16].

Researches in the field of metamaterials have mobilized a wide range of scientific communities, including physics, electrical engineering, materials science, chemistry and mathematics, and have now expanded into the communications society to advance the Internet of Things.

In this paper, a review of the state of research and development of metamaterials is made, highlighting the new challenges and ways to improve and to apply these new synthetic structures in electromagnetics and optics.

The paper provides a more comprehensive understanding of how to design and make metamaterials, highlighting new trends in applications with this category of synthetic materials.

II. METAMATERIAL HISTORY AND TRADITIONAL CLASSIFICATION

The beginning of artificial electromagnetic media can be considered the year 1898, when Sir J. C. Bose published his work on the rotation of the polarization plane through twisted structures created by man.

Then, in the first half of the twentieth century, there were some investigations on obtaining new properties with electromagnetic artificial environments.

In the years 1950s and 1960s, artificial dielectrics were explored for light-weight microwave antenna applications.

Metamaterial structures were first predicted by Veselago in 1968 [17], and the interest in metamaterials was resurrected in the years 1980s and 1990s, with new investigations of microwave radar absorbers for stealth applications.

Since Sir John Pendry proposed to realize negative permittivity using periodic structure of thin wires in 1996 [18], modern metamaterials have received great progress in the past 20 years and are still in the frontiers of physics, chemistry, material, and information societies.

But investigations intensified in the early 2000s when there have been highlighted the opportunities offered by metamaterials for manipulating electromagnetic waves using controlled wave-matter interactions, which sparked a new revolution in materials science and engineering [6]-[8].

Landy in 2008, introduced a new function for metamaterials. He proposed a perfect absorber by utilizing the loss characteristic of the metamaterial substrate. Light weight, low profile and easy fabrication compared to traditional absorbers caused the rapid development of metamaterial perfect absorber, and different applications have been exploited for metamaterial absorbers in various frequency ranges from microwave to terahertz [19]-[21].

Metamaterials consist of ordered repetitive structures called "periodic unit cell" or "cell". The cell structure, differing in the shape, arrangement, and geometry, manipulates the electromagnetic wave propagation inside the metamaterials. Just like atoms or molecules of natural materials, the structure of the repetitive unit cells determines the properties of the metamaterials [13], [21].

In most cases, the metamaterial consists of a periodic network of identical meta-atoms, analogous to the crystalline structure. Random or irregular arrangements are less often considered and are analogous to the structure of amorphous substances. Consequently, metamaterials represent the second level of structural organization and hence the name of meta (beyond) - materials.

The behaviour of the metamaterial to the action of the incident electromagnetic wave can be described by the material parameters: electric permittivity, respectively magnetic permeability.

But the material parameters depend on the scale on which they are considered [13]:

- If the incident wavelength is much larger than the atomic dimensions and inter-atomic distances, then the atomic behaviour is collective and average material parameters can be introduced, replacing a huge number of separate contributions of the components. In this case, the metamaterials are quite analogous to the conventional ones and the same methods of analysis can be applied;
- When the incident wavelength is comparable to the scale of the dimensions of the structure, complex diffraction and scattering phenomena occur and there is no way to establish the average material parameters. Consequently, in this case, metamaterials can hardly be treated as continuous media;
- For waves with a much smaller length than the size of the constituent elements, the material characteristics are determined by the nature and density of the constituent atoms, with which the electromagnetic quantums interact in a completely independent way. Thus, the concept of metamaterials loses its meaning and can no longer be applied.

Thus, a traditional definition of metamaterials is related to the existence of meta-atoms with dimensions and arrangements of the structure smaller than the incident electromagnetic wavelengths. In this case, the behaviour of the metamaterial can be described mathematically by the effective characteristics of the proposed structure:

$$B_{av} = \mu_0 \mu_{reff} H_{av} \tag{1}$$

$$D_{av} = \varepsilon_0 \varepsilon_{reff} E_{av} \tag{2}$$

where B_{av} is the average magnetic flux density, μ_{reff} is the effective magnetic permeability of the medium, μ_0 is the free space permeability, H_{av} is the average magnetic field

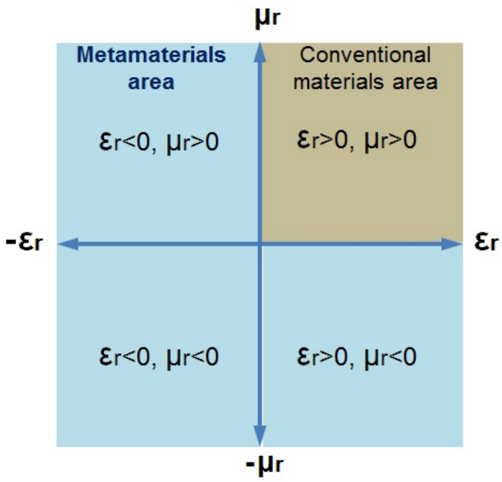


Fig. 1. Traditional classification of electromagnetic materials (after [21])

intensity, D_{av} is the average electric flux density, ε_{reff} is the effective permittivity of the medium, ε_0 is the free space permittivity, and E_{av} is the average electric field intensity.

In general, because H and B, respectively, E and D, are asymmetric and inhomogeneous quantities along the propagation of the resulting electromagnetic wave, the parameters permittivity and permeability will be altered [16].

The concept of simultaneous negative permittivity and permeability was postulated by Veselago in 1968 [7] but it came into existence in 2000 when there was proposed a composite medium based on a periodic array of interspaced conducting nonmagnetic split ring resonators and continuous wires that exhibits a frequency region in the microwave regime with simultaneously negative values of effective permittivity and permeability [9], [22], [23].

Thus, in function of different structure and excitation frequencies, the metamaterials can be with one negative parameter (Fig. 1) or with double negative parameters [21]. In Fig. 1, a conventional classification of the metamaterials is shown, where permittivity and permeability are both positive, this area represents conventional materials area; the other areas, where either one of parameter - permittivity or permeability are negative, or where permittivity and permeability are both negative, represent metamaterial area [21], [24].

The earlier study of metamaterials has focused on homogeneous situations with extreme effective medium parameters (e.g. negative permittivity, negative permeability, and zero index of refraction).

Metamaterials with negative permittivity and negative permeability can be made by properly artificial structures designing, typical being two structures:

- the negative permittivity was achieved by using a periodic thin rod structure;
- the negative permeability was achieved using a periodic split ring resonator structure.

Metamaterials are generally comprised of nano-resonators, scatterers and meta-molecules of different size, shape, geometry, orientation, and arrangement.

In the next section the typical investigations on the structure of metamaterials are reviewed.

III. Specific Configurations of Metamaterials

Through flexible and intentional engineering of the structures, dimensions, and arrangement of constituent meta-atoms, electromagnetic metamaterials, obtained by structuring natural materials (metals, semiconductors and insulators), are able to function as efficient electromagnetic devices to control the amplitude and phase of the EM wave.

Different configurations of metamaterials have been proposed to meet lots of applications, for wavefront control, and/or for obtaining perfect absorption.

A. Split Ring Resonator Structures

Current research, inspired by Pendry's proposal in the 2000s to make a material with a negative index, has led to the creation of metamaterials with split-ring resonant (SRR) structures [23].

An image of the split ring resonator (SRR) type structure is shown in Fig. 2(a). This is a planar array with a periodic configuration of the unit cells.

The unit cell of the structure consists of a SRR core, made of gold, considered as a perfect electrical conductor in the THz range, provided with a gap-size *S*. This SRR core is repeatedly arranged on a film fabricated on polyethylene naphthalate with thickness of 100 μm.

The split-ring resonator SRR subwavelength structure acts as an *LC* resonator circuit with resonance frequency:

$$\omega = \frac{1}{\sqrt{LC}} \qquad (3)$$

where inductance *L* is mainly related to the effective enclosed area of the SRR, and capacitance *C* is largely determined by the gap size and the surrounding medium.

It can predict that the increase in the gap size *g* will decrease the capacitance *C* of the resonator, thus leading to the resonance frequency blue shift. This is observed in Fig. 2(b), in which are simulated the wave transmission in metamaterial samples, with a core size of 40 μm and gap size changing from 4, 6, 8 to 10 μm (SRR 1, 2, 3, and 4).

The authors also propose a SRR hybrid structure consisting of four SRR cells with uniform core length and width, but with different dimensions for the gap antenna. The simulation of wave transmission is shown in Fig. 2(c) and Table I.

TABLE I.
Resonance frequency and Transmission

Characteristics	Uniform SRR structure	Hybrid SRR structure
Resonance frequency [THz]	0.83	0.79
Transmission [dB]	-11.1	-39.8

It is observed that the hybrid SRRs structure has a broader and stronger resonance peak as compared with that of the uniform SRR structure. The simulation shows that the increase of the resonator density in each unit cell will determine a broader bandwidth with resonance enhancement.

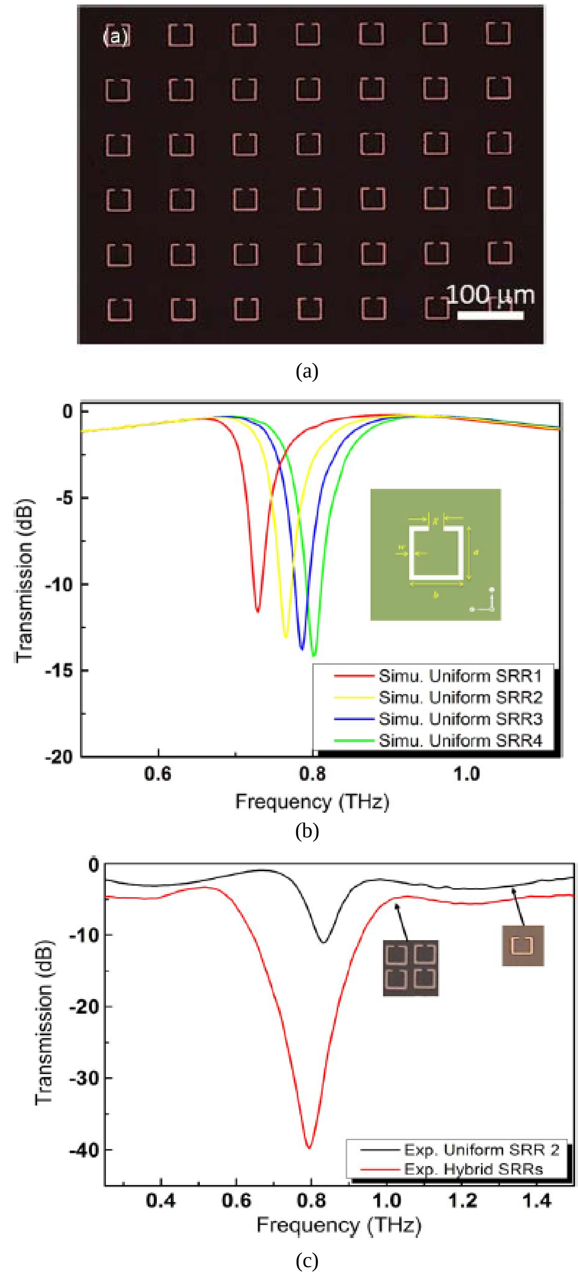


Fig. 2. Microscopic image of the planar array structure (a), simulation of transmission spectra for uniform SRR structures (b), simulation of transmission spectra for the hybrid SRRs sample as compared with uniform SRR structures (after [23])

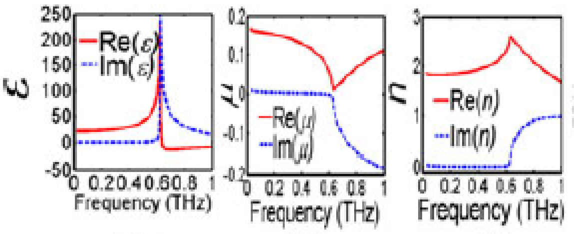
B. Single and Multi-Layer Structures

Many metamaterial structures have been proposed with strongly multilayer coupled unit cells.

By drastically increasing the effective permittivity by means of intense capacitive coupling and reducing the diamagnetic effect using a thin metamaterial structure, a peak refractive index of 70-80 at the resonance was obtained for a single-layer thin ring terahertz metamaterial.

Thus, in [25] different brick shape metallic patch symmetrically embedded in a dielectric material have been proposed.

(a)



(b)

Fig. 3. Unit cell configuration for uniform single layer metamaterial (a), permittivity, permeability and refraction index obtained in THz domain (b) (after [25])

In Fig. 3(a) is shown a top view of the cells of uniform single layer metamaterial, with different cell configurations: thin brick shape metallic patch; thin ring shaped patch; thin window-type; and crossed I-shaped patch, which are symmetrically embedded in a dielectric material. By experimental and theoretical investigations, the authors demonstrated a polarization-dependent and anisotropic extremely high index of refraction in the terahertz region.

The case analyzed by the authors is that of a simple cubic array structure of metal cubes with the period of array abut p = 60 µm, which is much smaller than the wavelength of electromagnetic waves in THz (which is about λ = 300 µm). Thus, the repetition period of the array is sub-wave length relative to the incident electromagnetic wave. Because these cubic arrays have bulk properties when the distance between the elements is much less than the incident wavelength, it is possible to extract their effective constitutive parameters. Different methods are applied to retrieve the constitutive parameters of metamaterial: by numerically calculating the ratios of the electromagnetic fields, by some approximate analytical models or by using the reflection and transmission coefficients (*S* parameters)**.**

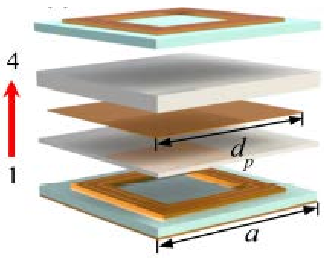
In Fig. 3(b) for this simple cubic array, the dependence of the real and imaginary parts of permittivity ε_r, permeability μ_r and index of refraction n on the frequency in the THz domain, extract with method of transmission coefficients, is shown.

Having in view that the electromagnetic properties of this structure is isotropic permittivity and permeability are scalar quantity and have been extracted with relationships:

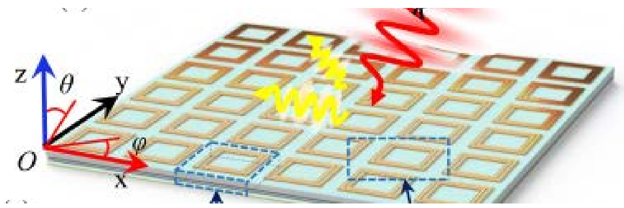
$$\varepsilon_r = n \cdot \frac{z_0}{z(\omega)} \tag{4}$$

$$\mu_r = n \cdot \frac{z(\omega)}{z_0} \tag{5}$$

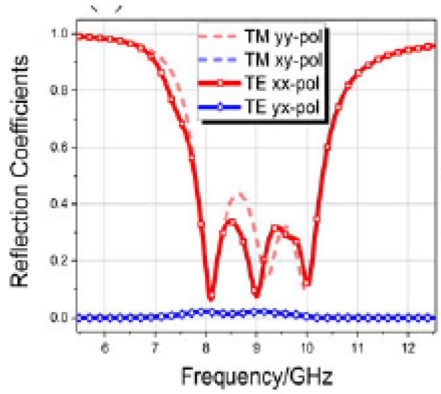
$$n(\omega) = \sqrt{\varepsilon_r(\omega) \cdot \mu_r(\omega)} \tag{6}$$



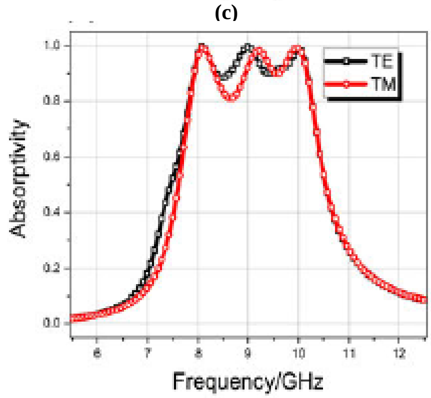
(a)



(b)



(c)



(d)

Fig. 4. The structure of unit cell for multilayer hybrid metamaterial structure (a), sample view of multilayer hybrid metamaterial structure (b), numerically simulation of the reflection coefficient (c) and absorption (d) of the metamaterial in Te and TM excitations (after [24]).

where z (ω) is structure impedance and z_0 is the impedance of free space. The specific values obtained and shown in Fig. 3(b) are: ε_{max} = 250; μ < 0.16 and n< 2.5 for resonance frequency f_{rez} = 0.6 THz.

To increase the performances of EM wave control, many multilayer hybrid structures have been proposed [24]. In Fig. 4(a), spatial detailed cell geometry in a vertical expanded view of a multilayer hybrid structure is shown. Unit cell is comprised of a back metal layer of full copper foil, an insulator layer of Rogers 5880, a five-metal resonant square-loop, a flexible adhesive layer of

PDMS, a sputtered aluminium layer, another PDMS layer, and a flame-retardant FR4 layer.

The overall prototype consists of 15 x 15 cells of elements, with a 12 x 12 cm^2 area, as shown in Fig. 4(b).

For this multi-layer metamaterials, the authors [24] considered the correlations between layer thicknesses, bandwidths, absorptions, and the composite-substrate thickness in determination of the device flexibility.

The absorption level of the metamaterial can be represented as:

$$A(\omega) = 1 - R(\omega) - T(\omega) \qquad (7)$$

where $R(\omega)$ and $T(\omega)$ are the reflectivity and transmittance of the EM wave, respectively. $T(\omega)$ is close to zero when the back of the metamaterial is metallic foil, so the absorption is related only to the reflection coefficients.

The proposed structure presents many bandwidth and absorptivity advantages.

As observed in the reflection-coefficient characteristics at a working band range of 5.5-12.5 GHz, shown in Fig. 4(c), the trends are in connection with the absorbing energy transformation. The anisotropy of different materials at high frequencies leads to tight deviations, and reflection-coefficient in the cross-polarization direction converge nearly to zero, which indicates that the EM wave was absorbed by the proposed structure, rather than the wave transformation.

The absorptivity of the proposed metamaterial is shown in Fig. 4(d), when TE (transversal electric mode of excitation) and TM (transversal magnetic mode of excitation) waves normally propagate to the proposed structure. The absorption in the TE and TM incident waves is almost uniform, and only a slight discrepancy is observed at 8.8 GHz because the electric-dipole absorption is stronger than the magnetic absorption of the multi-layer structure.

C. Multi-Layer Metamaterials with Graphene

Recent, different configurations of absorbers are proposed using the advantages of graphene, to have the band gap of greater than 0.5 eV, which facilitate the applications with tunable sub-wavelength devices [26]-[29].

Thus, in [26] there are proposed dual band absorbent structures, insensitive to polarization, in the THz domain, which are based on the unit cell of the graphene / SiO_2 / Au.

The structures shown in Figs. 5(a) are composed of a graphene layer, of different shapes (cross-shaped, disk or combined shape), which is placed on top of a gold layer, separated by a thick layer of SiO_2. The bottom Si substrate is used to protect the entire structure against mechanical damage.

For Structure I, in Fig. 5(b) it can be seen that for wavelength range from 30 to 100 μm, at normal incidence of EM wave, there are two higher absorption peaks in the considered wavelength range, but they cannot reach nearly unity at the same time. With the increasing of the wing length *S*, the long wavelength absorption peak is firstly blue-shifted and then red-shifted, and the change trend of the short wavelength absorption peak is just opposite.

For the case of Structure II shown in Fig. 5(c), one can see that there is only one absorption peak, and the spectral line has an obvious red-shift with the increasing of radius *r*.

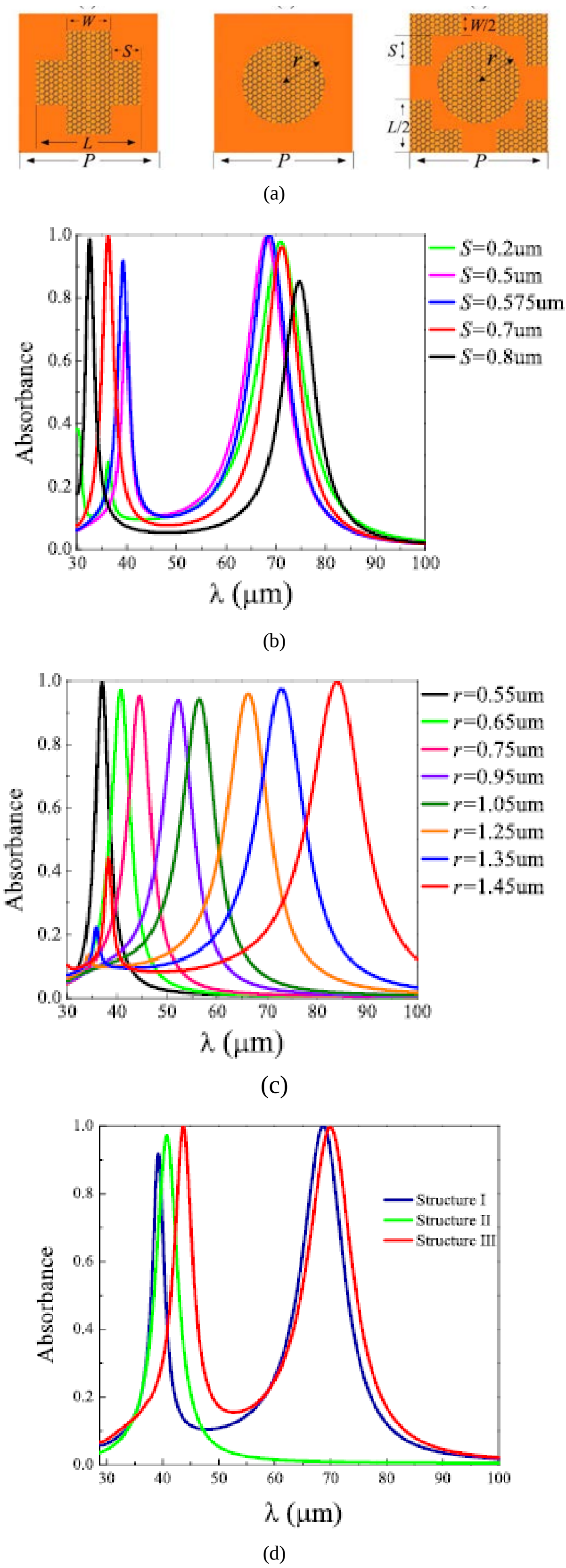


Fig. 5. Proposed multi-layer structures with cross-shaped graphene (Structure I), disk-shaped graphene (Structure II), and both cross- and disks shaped graphene (Structure III) (a), Absorption spectra of Structure I for the different wing length *S* (b), Absorption spectra of Structure II for different radius *r* (c), Absorption spectra in the wavelength range from 30 to 100 μm at normal incidence, for the Structures I, II and III (after [26])

The authors proved that by combination of these structures, one can obtained two absorption peaks occurring at λ = 69.94 and 43.747μm in the absorption spectrum, with the absorbance of the two peaks close to 100%. The optimal geometry parameters are L = 2.35 μm, S = 0.575 μm, and r = 0.65 μm, and other parameters are the same as those in the figures above.

D. *Multi-Layer Multi-Functional Metamaterials*

A lot of investigations proposed the composite multilayer structures of metamaterials which have two operation functions, for instance, to assure the transparency to visible light and absorbance [20], [30] or application as absorber and polarization converter [5], [21].

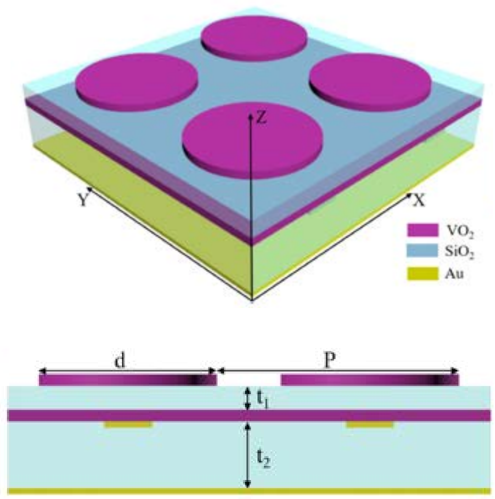
Many papers proposed multi-layer structures which include vanadium dioxide (VO_2) which undergoes a structural transformation from a monoclinic phase to a tetragonal phase around 340 K. Through the phase transition, the conductivity and permittivity of VO_2 vary significantly, which can be applied to control the electromagnetic properties of metamaterial structures.

Phase transition in VO_2 can be caused by external electrical, optical, or thermal excitation.

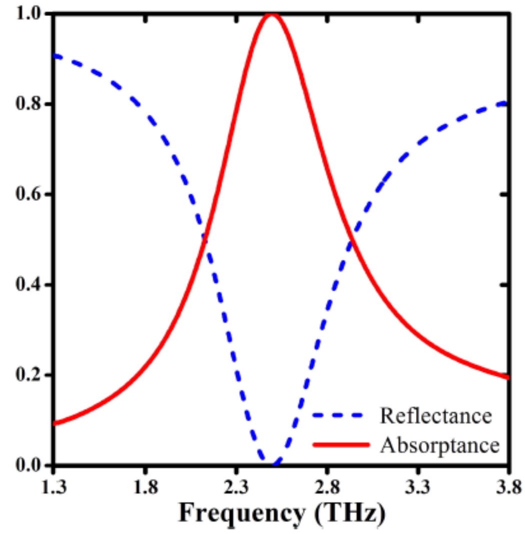
In [5], the proposed structure of the layers includes: VO_2 disks, silica (SiO_2) layer, VO_2 film, metallic strip, SiO_2 layer, and a metallic film (Fig. 6(a)). The dimensions are of order of micrometers, and repetition period is P= 40 μm.

In this case, the thermal excitation is used.

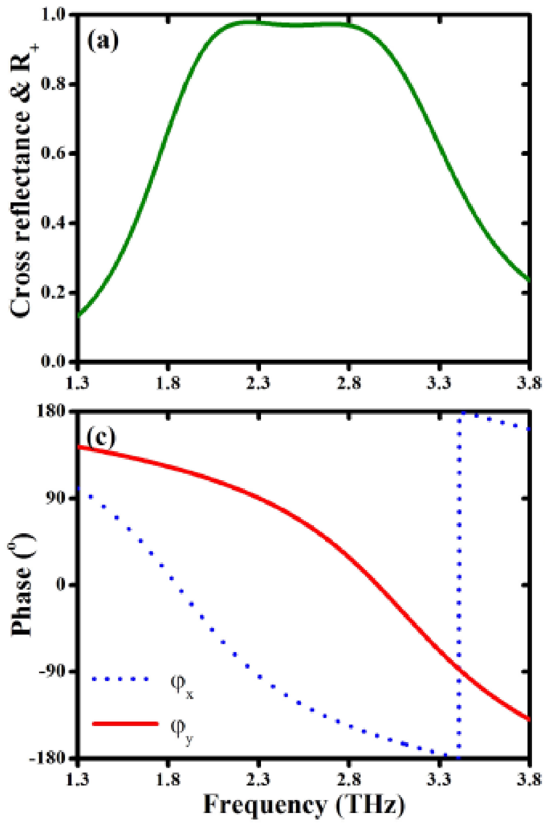
- When VO_2 is in the metallic state (at the room temperature of 20^{o}C), the designed configuration behaves as a perfect single-band absorber based on two-dimensional arrays of VO_2 disk on a VO_2 film. The performance of absorption is polarization-insensitive and angle-independent (Fig. 6(b));
- When VO_2 is in the insulating state (over the phase transition point of 68^{o}C), the designed configuration behaves as an efficient cross polarization converter working in the reflective mode at terahertz frequencies. It can convert a linear-polarized wave to its orthogonal direction. Because of the subwavelength size of the unit cell, the efficiency of cross polarization is higher than 90% from 2.0 THz to 3.0 THz under normal incidence (Fig. 6(c)).



(a)



(b)



(c)

Fig. 6. Geometric parameters of the structure with VO2 (a); Simulated reflectance and absorptance under normal incidence at normal temperature (b); Reflectance of cross-polarized wave and phases for x and y-polarized waves. The incident electric field is decomposed into two orthogonal components along the x- and y-axes and reflected electric field is rotated by 90^o (c) (after **[**5**]).**

Another two-functional structure of metamaterial based on VO_2 is proposed in [21], which allow obtaining a broadband switchable absorber.

The composite resonant structure consists of a criss-cross structure and four square patches of tantalum nitride (TN), with thickness of 21 μm, a multi-layer dielectric plate (foam layer, VO_2 layer, SiO_2 layer), and a gold ground plane.

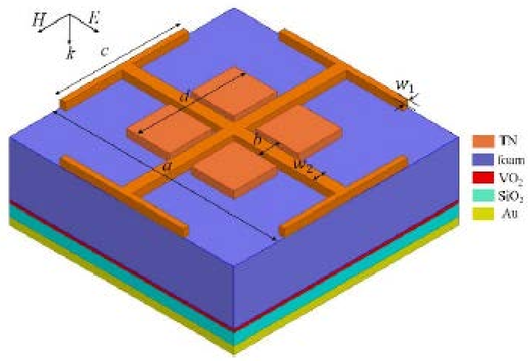


Fig. 7. Schematic of unit cell of the switchable broadband absorber (after [21])

The switch function is realized by controlling the operation temperature, and the absorber can be switched in a broadband ranging from 0.32 THz to 0.56 THz to another broadband ranging from 0.356 THz to 0.682 THz with an absorptivity of over 90%.

IV. New Steps in Metamaterial Development

Research to date has shown that metamaterials have great capability and flexibility in controlling electromagnetic waves, because theirs subwavelength meta-atoms can be designed and customized in the desired ways.

But, for the metamaterials presented so far, it is characteristic that once manufactured, these metamaterials will have fixed functions, i.e. they are passive metamaterials [31].

In order to dynamically control the EM waves, several ways have been proposed, among which, the integration in meta-atoms of different active devices, so that active metamaterials have been obtained.

Recently, a special kind of active metamaterials - digital coding and programmable metamaterials - has been proposed, which can realize a large number of distinct functionalities and switch them in real time with the aid of field programmable gate array (FPGA).

In Fig. 8 the steps of metamaterial development are pointed, having in view the capabilities and flexibilities in controlling electromagnetic waves.

From the perspective of achievable functions, the first step was the development of passive metamaterials, composed of structures specially designed in periodic or non-periodic arrays of sub-wavelength unit cells, to obtain homogeneous or inhomogeneous material parameters that do not exist in nature or are difficult to achieve in practice. Numerous structures of passive metamaterials have been proposed, in the 3D version and in the 2D version, with applications in microwave and optical frequency bands. But, the disadvantage of passive metamaterials is that, once these structures are manufactured, their functionality will be fixed, without being able to react dynamically to the action of incident waves.

The second step in the development of metamaterials to achieve dynamic control of electromagnetic waves was the fabrication of the active metamaterials, by integrating active devices.

In the active metamaterials, the unit cells consist of meta-atoms and active devices (e.g. PIN diodes, varactors, amplifiers, semiconductors, micro-fluids, and VO_2) to their EM responses under the external excitations.

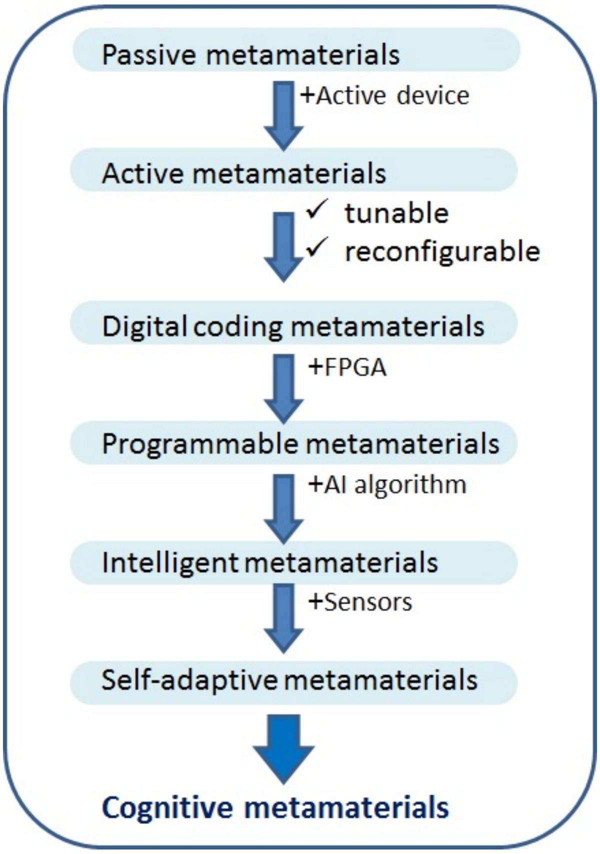


Fig. 8. Steps of metamaterial development (processed after [31])

Traditionally, the active metamaterials include tunable metamaterials and reconfigurable metamaterials (Fig. 8). The tunable metamaterials usually realize similar functions (such as shifting the resonance peaks and perfect absorptions) by tuning the active devices. For reconfigurable metamaterials, which can have significantly different functions (such as changing polarization states and working bandwidth control) by switching active devices, the number of functions is very limited.

The third stage of metamaterial developments is that of digital metamaterials, obtained by representing the digital coding of meta-atoms [24], [31]. By integrating the digital coding metamaterial with the field programmable gate array (FPGA) a programmable metamaterial is obtained.

The development of metamaterials which are programmable in the field is a major breakthrough in the development of metamaterials, as a single programmable metamaterial can perform many distinct functions (eg, single-beam radiation, different multi-beam radiation, beam scanning, wave diffusion, vortex beam generation etc.). All these functions are switched in real time by changing the digital states and sending the instructions by the FPGA.

Thus, the introduction of digital code representation of metamaterials makes it possible to connect the digital world with the physical world, so that metamaterials process digital information directly, resulting in informational metamaterials.

New steps are predicted by applying artificial intelligent (AI) and including specific sensors to obtain intelligent metamaterials, self-adaptive metamaterials and the highest level of cognitive metamaterials.

There are already a multitude of applications, from which three areas are well developed: in optics (for birefringence modification), in wireless power transfer (to increase the efficiency of power transfer), and in the realization of electromagnetic absorbers in the THz domain (to increase the absorption coefficient close to 100%).

V. Conclusions

The field of metamaterials has been progressing rapidly in the past years, showing that the conventional limitations of modern technologies can be overcome using the advanced knowledge in electromagnetism and in nanofabrication techniques.

The traditional metamaterial classification, with the criterion of the values of permittivity and permeability, is no longer sufficient. Current advances in the field have imposed the new classification of metamaterials in which the criterion of capability and flexibility of dynamic control of electromagnetic waves is considered.

Thus, depending on the types of functionalities that can be achieved, metamaterials are classified into passive and active metamaterials. Active metamaterials can be tunable and reconfigurable. Some active metamaterials are programmable and, by adding the appropriate software, could become information metamaterials.

Advances in understanding the processes that take place in metamaterials, and progress in their realization with modern micro- and nano-technologies show that nowadays the characteristics of these synthetic materials for realization of new generation of communication systems are possible to be explored.

Source of research funding in this article: Research program of the Transilvania University of Braşov.

Contribution of authors:
First author – 70%
First co-author – 30%

Received on June 25, 2020
Editorial Approval on November 02, 2020

References

[1] J. Zhang, J. Tian, and L. Li, “A Dual-Band Tunable Metamaterial Near-Unity Absorber Composed of Periodic Cross and Disk Graphene Arrays,” *IEEE Photonic Journal,* vol. 10, 2, April 2018.

[2] W. Wang, F-P. Yan, S-Y. Tan, H-S., et all., “Numerical Analysis of Magnetic Plasmonic Resonance Modes in Three-Dimension Split Ring Resonator Metamaterials,” *IEEE Photonics Journal,* vol. 11, 4, 2019.

[3] W. Ai, P. Zhou, R. Sun, Y. Liu, et al.**, “**Control of Resonance Absorption Modes for Broadband Infrared Metamaterial Absorber,” *IEEE Photonic Journal*, vol. 11, 1, February 2019.

[4] A. Hoque, M. T.ariqul Islam, A.F. Almutairi, et all, “SNG and DNG meta-absorber with fractional absorption band for sensing application,” *Scientific Reports*, 10 (1), art. 13086, 2020.

[5] M. Zhang, J. Zhang, A. Che, and Z. Song, “Vanadium Dioxide-Based Bifunctional Metamaterial for Terahertz Waves,” *IEEE Photonics Journal,* vol. 12, 1, 2020.

[6] Z. Yangjian, F. Chuhuan, L. Qi, S. Xin, and Y. Hongbin, “Dynamic Reflection Phase Modulation in Terahertz Metamaterial,” *IEEE Photonics Journal,* vol. 11, 4, 2019.

[7] H. Kwon, D.L. Sounas, A. Cordaro, A. Polman, and A. Alù, “Nonlocal Metasurfaces for Optical Signal Processing,” *Physical Review Letters*, vol. 121, 17, 173004, October 24, 2018.

[8] B. Gao, M.F. Yuen, and T. Ye, “Ferrite Film Loaded Frequency Selective Metamaterials for Sub-GHz Applications*,” Materials*, vol. 9, 1009, 2016.

[9] R. Deng, M. Li, B. Muneer, et.al., “Theoretical Analysis and Design of Ultrathin Broadband Optically Transparent Microwave Metamaterial Absorbers,” *Materials* vol. 11, 107, 2018.

[10] Y. Cho, S. Lee, D-H Kim, H. Kim, et.al., “Thin Hybrid Metamaterial Slab With Negative and Zero Permeability for High Efficiency and Low Electromagnetic Field in Wireless Power Transfer Systems,” *IEEE Transactions on Electromagnetic Compatibility*, vol. 60, 4, pp. 1001-1009, August 2018.

[11] D.C. Brooke, O. Umnova, P. Leclaire, and T. Dupont, “Acoustic metamaterial for low frequency sound absorption in linear and nonlinear regimes,” *Journal of Sound and Vibration*, 485, 115585, 2020.

[12] F. Costa, and A. Monorchio, “Multiband electromagnetic wave absorber based on reactive impedance ground planes,” *IET Microw. Antennas Propag*., vol. 4, 11, pp. 1720–1727, 2010.

[13] A. Dubey, and T.C. Shami, “Metamaterials in Electromagnetic Wave Absorbers,” *Defence Science Journal*, vol. 62, 4, pp. 261-268, July 2012.

[14] D. Hu, H-Y. Wang, and Q-F. Zhu, “Design of Six-Band Terahertz Perfect Absorber Using a Simple U-Shaped Closed-Ring Resonator,” *IEEE Photonics Journal*, vol. 8, 2. 2016.

[15] H. Liu, K. Luo, S. Tang, et all., “An Ultra-Wideband THz/IR Metamaterial Absorber Based on Doped Silicon,” *Materials*, 11, 2590, 2018.

[16] M. Amiri, F. Tofigh, N. Shariati, J. Lipman, and M. Abolhasan, “Wide-angle metamaterial absorber with highly insensitive absorption for TE and TM modes,” *Scientific Reports* 10 (1), art. no. 13638, 2020.

[17] V.G. Veselago, “The electrodynamics of substances with simultaneously negative values of permittivity and permeability.” *Sov. Phys. Uspekhi*, 1968, 10, 509–514.

[18] J.B. Pendry, A.J. Holden, W.J. Stewart, I. Youngs, “Extremely low frequency plasmons in metallic mesostructures.” *Phys. Rev. Lett*., 76, 4773–4776, 1996.

[19] N.I. Landy, et al., “Perfect Metamaterial Absorber.“ *Phys. Rev.Lett.*, 100.20, 207402, 2008:

[20] G. Deng, Y. Lu, Z. Yin, et.al., “A Tunable Polarization-Dependent Terahertz Metamaterial Absorber Based on Liquid Crystal,” *Electronic*s, vol. 7, 27, 2018.

[21] H-E. Su, J-L. Li, and L. Xia, “A Novel Temperature Controlled Broadband Metamaterial Absorber for THz Applications,” *IEEE Access*, vol. 7, 2019.

[22] Y. Hollander, ant R. Shavit, “Constitutive parameter extraction and experimental validation of single and double negative metamaterials,” *IET Microw. Antennas Propag.* vol. 5, 1, pp. 84–94, 2011.

[23] Z.Y. Pan, P. Zhang, Z.C. Chen, G. Vienne, and M.H. Hong, “

[24] J. Cui, H. Xu, X. Yu, G. Shao, and H. Sun, “A Novel Encoding Strategy of Enhanced Broadband and Absorption Conformable Metamaterial for MW Applications,” *IEEE Access*, vol. 8, pp. 100458-100468, 2020.

[25] X. Jing, X. Gui, R. Xia, and Z. Hong, “Ultrabroadband Unnaturally High Effective Refractive Index Metamaterials in the Terahertz Region,” *IEEE Photonics Journal*, vol. 9, 1, 5900107, 2017.

[26] J. Zhang, J. Tian, and L. Li, “A Dual-Band Tunable Metamaterial Near-Unity Absorber Composed of Periodic Cross and Disk Graphene Arrays,” *IEEE Photonic Journal,* vol. 10, 2, April 2018.

[27] H. Liu, K. Luo, S. Tang, et all., “An Ultra-Wideband THz/IR Metamaterial Absorber Based on Doped Silicon,” *Materials*, 11, 2590, 2018.

[28] K.T. Lin, H. Lin, T. Yang, and B. Jia, “Structured graphene metamaterial selective absorbers for high efficiency and omnidirectional solar thermal energy conversion,” *Nature Communications*, 11:1389, 2020.

[29] M. Biabanifard, A. Arsanjani, M.S. Abrishamian, and D. Abbott, “Tunable Terahertz Graphene-Based Absorber Design Method Based on a Circuit Model Approach,” *IEEE Access,* vol. 8, 2020.

[30] T. Liu, and S.S. Kim, “Ultrawide Bandwidth Electromagnetic Wave Absorbers Composed of Double-Layer Frequency Selective Surfaces with Different Patterns,” *Scientific REporTS*, 8:13889, 2018.

[31] T.T. Jun Cui, "Information Metamaterial Systems,” *iScience*, 23, 101403, August 21, 2020.

[32] J. Shabanpour, S. Beyraghi, and H. Oraizi, “Reconfigurable honeycomb metamaterial absorber having incident angular stability,” *Scientific Reports*, 10:14920, 2020.