METAMATERIALS ON ANTENNA SOLUTIONS

Slyusar V.I.

Central Research Institute of Armaments and Military Equipment of Ukraine's Armed Forces, Kiev, Ukraine
E-mail: swadim@inbox.ru

Abstract

This report describes the theory of metamaterials and its utilization for antenna's techniques. Metamaterials exhibit qualitatively new electromagnetic response functions that can not be found in the nature. The present report reviews basic historical aspects of the meta-environments theory development. Also the role of Veselago, the well-know theorist of negative refraction index metastructures whose 80 anniversary is celebrated in present year is emphasized as well as the role of other scientists.

Keywords: Metamaterial, left-handed materials (LHM), path antenna, split ring resonators (SRR), double negative (DNG), Composite Right/Left-Handed (CRLH), negative refractive index (NRI)

Metamaterials exhibit qualitatively new electromagnetic response functions which can not be found in the nature.

The prefix "meta-" has the Greek origin and is translated as *"outside of"* that allows to interpret the term "metasubstances" as structures whose effective electromagnetic behavior falls outside of the property limits its forming components.

The analysis of publications on various aspects of metamaterials technology allows to classify all variety of artificial environments depending on their effective values of permittivity (ε) and magnetic permeability (μ) according to the classification diagram presented in fig. 1.

One of the first records of this term belongs to release of 1999 news by a forum of industrial and applied physics (FIAP) the American physical community (APS), which announced the series of reports on section "Metasubstances" in the program of APS session in March, 2000 [1]. Among report sections included in the program the performance of Rodger M. Walse's [2] (Texas State University in Austin) was distinguished by others. R. Walse is also the author of the term "metasubstance". However, simultaneously with him the similar concept has been applied by Eli Yablonovitch whose report title at the mentioned forum contained a word "Meta-Materials" [3].

With regard to historical aspects of the metaenvironment theory development it should be noted that the modern science gradually approached to understanding of DNG environment physics that required significant amount of time. History of metamaterial development can be divided on three stages.

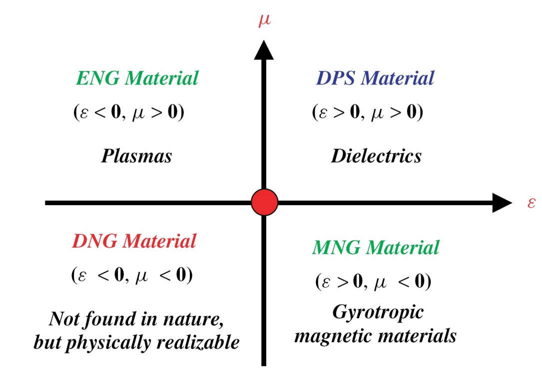

Fig. 1. Classification of physical environments depending on its effective values of permittivity (ε) and magnetic permeability (μ) [4].

The first stage of the DNG modern representation formation is connected with the development of the backward wave's theory. In this theory one of key concepts was negative group wave speed. English physicist Franz Arthur Friedrich Schuster (1851-1934) can bear palm of superiority in practical statement of the question about wave's existence with negative group speed. But this fact was noted by the English mathematician and hydrodynamicist Horace Lamb (1849 - 1934) in his publication [5] dated by February, 11, 1904.

Owing to A. Shuster, the assumption about opportunity of negative refraction (Fig. 2) has appeared in the physical literature for the first time. However, it has not been detailed what could be characteristic properties of the corresponding environment in the case of its existence.

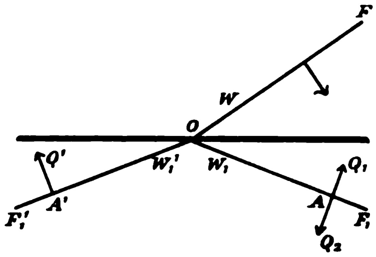

Fig. 179.

Fig. 2. A.Shuster's illustration from [6], (WF -front of an incident wave, $W_1^{'}F_1^{'}$ - front of the refracted wave in the usual environment, W_1F_1 - front of the refracted wave in the environment with negative group speed).

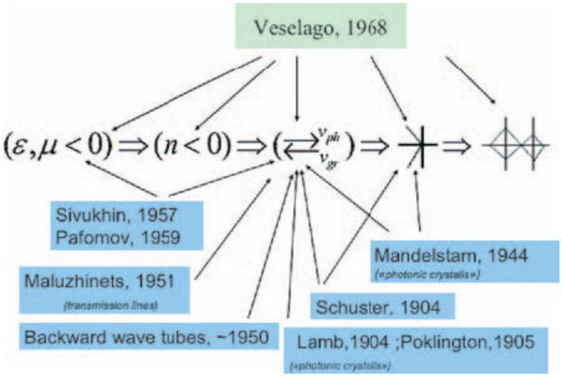

Fig. 3. The basic milestones of the first two stages of DNG theory formation [9].

Generally, the practical application of the found effects was unobvious, and the interest of researchers strongly decreased for some decades which determined a boundary between the first and the second stages of the theory DNG evolution.

When in 40th years the first microwave frequencies-devices using backward waves appeared, theories of backward waves that were already thoroughly forgotten have reappeared for physicists. The formal beginning *of the second stage* of the DNG-environment's theory can be considered from the L.I.Mandelshtam's (1879-1944) lectures [7] in optics dated by 1944.

The most developed theory of substances with negative factor of refraction within the limits of the second stage was offered in [8] by Soviet physicist Victor Georgievich Veselago who was born in 06.13.1929 in Ukraine. Now he is a doctor of physical and mathematical sciences, the professor, the Honored scientist of the Russian Federation, the Winner of the State premium of the USSR.

In the survey report are considered a historical aspects of development of the metaenvironments theory. In Figure 3 the basic moments of DNG theory development [9] are briefly illustrated within the limits of its first two stages.

Among the second stage publications it is necessary to distinguish R.A. Silin's works [10, 11] where in 1970th years he has described optical properties of the artificial dielectric materials and has investigated the features of the plainly-parallel lens made from a metamaterial with a negative index of refraction.

John Pendry's publication [12] should be noted as a new stimulus to development of the given direction and the beginning of a modern *third stage* in the formation of theoretical representations about DNG-materials. In his publication he offered to use a special design possessing negative effective values of dielectric permittivity (ε) and magnetic permeability (μ). John Pendry's idea was reduced to the mass structure application from tiny split ring resonators (SRR) and linear pieces of wire.

For the solution of a narrow passband's problem many variants of the elements having the shape of spirals and the «omega» Greek symbol were offered to researchers. The problem of a narrow passband can be solved to some extent by the geometrical sizes optimization of SRR-resonators. For example, in the work for rectangular SRR [13] the bandwidth was 11,2 % that corresponded to a frequency band 10,57 - 11,82 GHz that in 2,3 times better than an initial variant. For retrieval of an optimum combination of the geometrical parameters CST Microwave Studio software (www.cst.com) was used.

Evidently, further for the shape optimization of the specified elements it is expedient to use genetic [14, 15] and ant algorithms of optimization [16]. With reference to multifrequency decisions it is meaningful to apply fractal's frameworks Serpinsky on the basis of Kokh's broken line or others fractal's decisions [17] instead of cutting ring or square SRR. Similar fractal's designs should be involved instead of rectilinear conductors. The most adapted for investigation of metamaterial properties is the HFSS package standing out from all antennas modeling packages at present. In this case it is reasonable to lead modeling of electromagnetic properties of new metamaterials in HFSS program model if these metamaterials use fractal's elements.

The use of the ideal metaenvironment without losses and frequency dispersion provides essential dilation of passband electrically small antennas (ESA) in comparison with Chu's limit and lower values of reactance factor, than it follows from his fundamental limit. However, transition to the real metaenvironment designs possessing frequency dispersion and losses leads to catastrophic degradation of ideal aerial properties based on metamaterials. Therefore, the primary goal of metastructure perfections is synthesis of such environments that would possess the minimal losses and dispersive properties.

The basic metamaterial applications in engineering are:

1) manufacturing of substrates in path antenna for achievement of band width and the radiator size reduction;

2) indemnification of electrical small antennas reactance in a wide strip of frequencies including those exceeding a fundamental Chu’s limit [18];

3) formation of narrow beams by the elementary radiators submerged on metamaterial;

4) utilization of metamaterials for manufacturing superficial wave antennas;

5) decrease of mutual coupling between elements of antenna array.

Below we review the achieved results guided by characteristic examples of a corresponding meta-antennas design.

Utilization of metastructures as *substrates for printed antennas* creates an opportunity to subsequent shortening of the radiator sizes, increase in their passband and efficiency of radiation. The structure of the metasubstance forming a substrate can be either homogeneous or composite (formed by several environment types). So, in [19] is described the variant of homogeneous MNG-substrate utilization (Fig. 1) which is generated from cutting square SRR submerged in dielectric pillow (Fig. 4). The similar decision is also possible on the basis of DNG-environment [20].

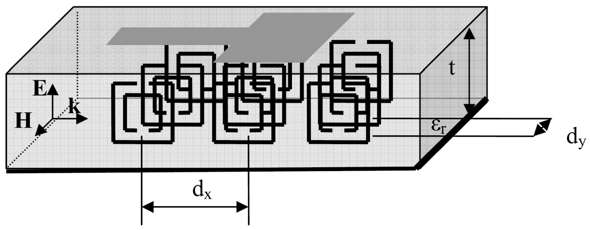

Fig. 4. The printed antenna with a substrate from MNG [19].

Among composite substrates the most widespread structures are those combining right-handed and link sided segments. One of the attractive properties of such hybrid decisions is opportunity to realize a frequency's selective factor of refraction in it. For example, in a low-frequency band the composite substance CRLH (Composite Right/Left-Handed) has a negative refraction index, and after increasing of some frequency boundary - positive. Size selection of the Right- and Left-Handed segments makes it possible to regulate a resonance frequency of a printed antenna.

One of the first examples of metamaterial practical use for serial manufacturing printed antennas is the Rayspan’s antenna array design (http://www.rayspan.com) used by company Netgear in MIMO-routers WNR3500 and WNDR3300 supporting specifications 802.11n Draft 2.0. Details of the respective technical decisions which have underlain in a basis of a meta-antennas design can be found in descriptions of Rayspan applications of the American patents for inventions [21], [22]. The main idea is the use of printed antenna for manufacturing of a composite CRLH structure on the basis of an interval transmitting with a negative refraction index.

A new type of antennas insignificantly differs from the printed prototypes by appearance; however, the achieved results exclude skeptics doubts in perspective of similar decisions. In particular, on the basis of metamaterials it was possible to reduce dimensions of MIMO antenna array radiators that have allowed lowering of its mutual coupling. The electric length of the printed meta-antenna can be reduced up to 0,1λ that is less than known restriction in a half-wave length. Thus the work is provided in two frequency bands (in area of 2,4 GHz and 5,2 GHz), and the antennas passband is increased by 15 %.

For electrically small antennas (ESA) reactance decrease in a wide strip of frequencies in [23] is offered to use metashell from ENG-material substances (Fig. 5, 6). Therefore, metashell thickness can be less than 100-th portion of wave length in free space that does not lead to appreciable signal attenuation of electromagnetic fields. Simulation results published in [23] display the increase in power of monopole's radiation under resonance conditions which forms 60 - 65 dB in the case of insignificantly small losses compare to a variant with the absence of ENG covering.

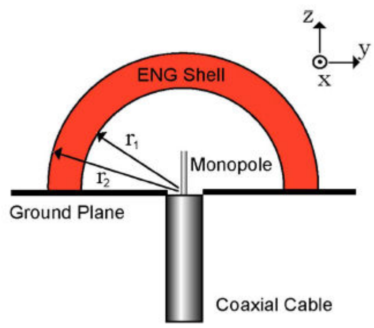

Fig. 5. The general view of ESA design in the structure of monopole and ENG-environments [23].

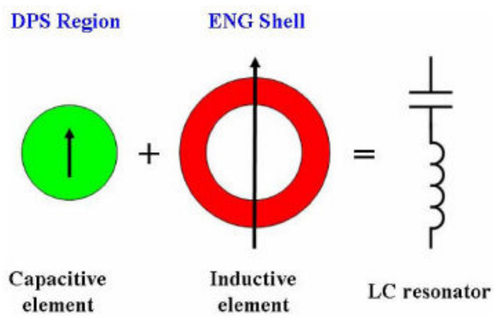

Fig. 6. A principle of ESA reactance indemnification by a metashell [23].

The most important author’s conclusion [23] is the statement that considered ESA created from the accessible metamaterials, possesses the expressed superiority over a limit of Chu. In particular, for the levels of losses and dispersion used in calculations the achievable size of reactance factor Q exceeds a limit of Chu in 1,583 times. It is essential that for ENG-material it is possible to achieve resistance nearby 50 Ohm on a resonance frequency, almost zero the antenna reactance and efficiency nearby 98 – 99 %.

The similar idea can be also used in the case of DNG-environments which allow reducing the shell sizes (thickness and radius) in comparison to an ENG-covering. The utilization of environment with μ <0 is equivalent to capacity entering simultaneously with the dipole capacity that reduces summed ESA size and require less of compensating inductance.

The evidence of the effects described in [23] are experimental results [24] obtained for electrically small dipole plunged in the plasma discharge in gas. In the described experiment the plasma was formed in a vacuum tube with the continuous discharge on a direct current. The increase in electric field intensity handling plunged in plasma ESA (l/λ << 10^{-3}) was more than 100 times in comparison to the same dipole at free space.

The given phenomenon can be easily explained considering the vibrator electrodynamics properties in a cover of ENG structures. The similar effect can be applied, for example, for the problem solution of long-wave communication with a landing spacecraft. In this case parameters' selection of ESA allocated on a spacecraft should be carried out by taking into consideration of all resonance phenomena in the plasma environment described above.

By the present time many experimental confirmations have been obtained describing the occurrence effect of the directed emanation at the elementary monopole placed on DNG-environment. One of such experiments on measurement of the vibrator diagram is described in work [25]. The vibrator is located inside of a metamaterial formed by square SRR and the connection strips. The depicted metamaterial has shown the negative factor of refraction in a band of 10,3 - 10,8 GHz in the limited spatial sector. The general view of the respective research facility scheme is demonstrated on Figure 7.

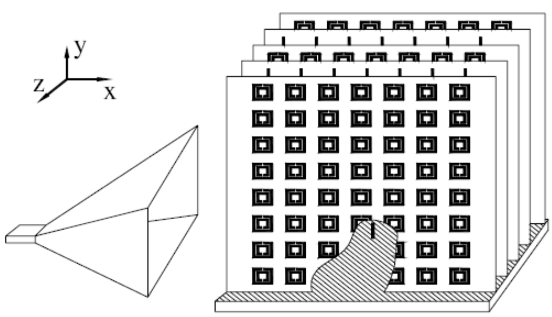

Fig. 7. The experiment scheme used for taking of the monopole orientation diagram submerged in the DNG-environment [25].

Results of the vibrator diagram orientation measurement are presented on Figure. 8, where the plane is parallel to horizontally located screen (x-z). The dashed line corresponds to the freely located vibrator, and a continuous line corresponds to the monopole submerged in metamaterial.

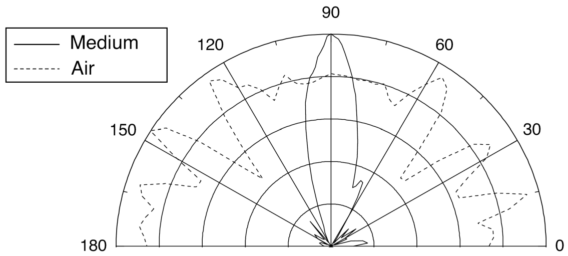

Fig. 8. The normalized diagram of a monopole orientation in a plane xz under frequency of 10,6 GHz [25].

For comprehensive investigation of vibrator diagram sharpening effect in the metaenvironment the experiment discussed in [25] should be necessary supplemented with an estimation of the direction's diagram width monopole dependence from overall metashell sizes. It would allow to obtain the persuasive answer on stated in [26] assumption that the angular sizes of the direction diagram of the vibrator surrounded by the metamaterial are determined by its aperture's area.

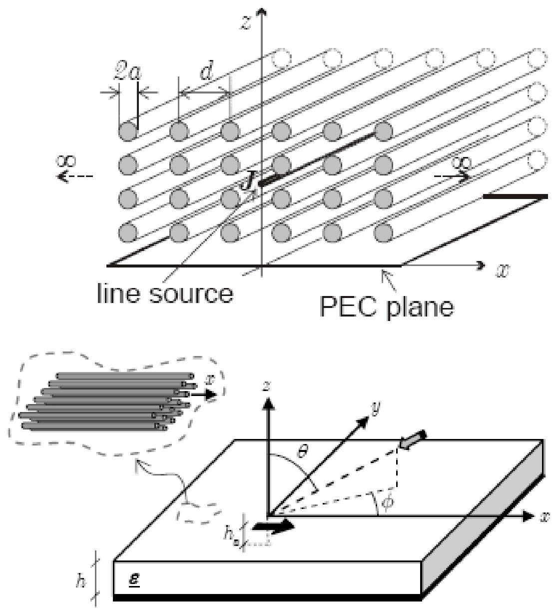

Fig. 9. The vibrator built in an ENG-plate [27].

Besides, for similar structures a performance of the reciprocity theorem for functional modes of transmittion and reception requires an additional check. Since the concerned metamaterial is made of homogeneous periodic structures some researchers hypothesize that the flat wave in a mode of reception can be directed by a metashell under other angle than in a transmitting mode. The example of the reciprocity theorem infringement reviewing the antenna shells of the radar station made from a metamaterial is presented in [27].

The ENG-environment of parallel conductors (Fig. 9, 10) [28] can be also applied for the location of elementary radiator direction diagrams.

In summary, it is necessary to highlight that the analysis of known research directions which have issued in the theory of metamaterials now, allows to predict the occurrence of antenna designs based on the active and nonlinear metastructures. But the theory and techniques are still developing.

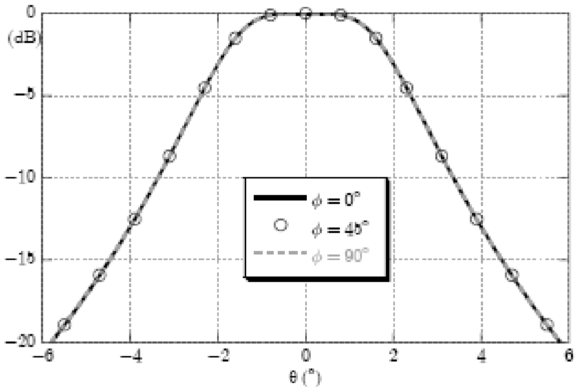

Fig. 10. The direction diagram of the vibrator in a wire metaplate [27].

It is quite possible that in this process can be involved chiral metaenvironments [29], substances with artificial magnetic response, metamaterials with a strong spatial dispersion used to create optical devices with the sanction exceeding the diffraction limit. Reviewing the successful beginning of metamaterials era in the technical antennas equipments accompanied by opening of many remarkable effects we can hope for its continuation.

For more information about problems of metamaterials theory please look in [30].

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