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Metamaterials an electrically small antennas and radar technology

Abstract. This paper analyzes the results of recent years on the creation and use of metamaterials in the field of telecommunications and radar technology. Prospects for the use of so-called left-hand materials (LHM) in antenna technology to improve in a wide range of frequencies of electromagnetic waves from 24 MHz to 30 GHz with the possibility of additional signal amplification (up to 20 dB) and the creation of electrically small transmitting or receiving antennas with linear dimensions significantly smaller than the wavelength of the transmitter. This is illustrated by the technology of manufacturing such antennas and graphs showing minimization (in some cases, full compensation). In particular, the equivalent scheme of such a "non-absorbing" filter is shown.

Keywords**:** metamaterial, left-handed material, antenna, telecommunication, radar technology.

In the last 10 years, a powerful scientific direction has been formed – the search and study of MM, which requires the joint efforts of theorists, experimenters and technologists working in various fields of electrodynamics, radiophysics in electrical and optical communication, nanotechnology and materials science.

At present, a sufficient number of review papers [1-4] devoted to electrophysics and electrodynamics of MM are published. Therefore, in contrast to them, in this work we focus on the applied aspects of M, in relation to telecommunications and telecommunication devices.

Metamaterials are artificially created composite materials with unique electrophysical, radiophysical and optical properties that are absent in natural materials. Theory, prerequisites and properties of MM were predicted by V. G. Veselago [1], confirmed by I. B. Pendry et al. [5], experimentally developed by D. R. Smith et al. [6].

The uniqueness of the electrophysical properties of MM) $\varepsilon' < 0, \mu' < 0$ the so-called left-hand materials (LHM - left-hand materials) or double negative media (DNGM - double negative media) is explained by the first and second Maxwell equation:

$$rot\vec{H} = i\omega\vec{D}; rot\vec{E} = -i\omega\vec{B} \qquad (1)$$

where $\vec{E}, \vec{H}$ – vectors of electric and magnetic fields; $\vec{D}, \vec{B}$ – vectors of electric and magnetic induction.

Solution (1) we are looking for in the form of a plane wave

$$\vec{E} = E_0 \cdot \exp^{-i\vec{k}\vec{r}} \cdot \vec{a}_x; \vec{H} = H_0 \cdot \exp^{-i\vec{k}\vec{r}} \cdot \vec{a}_y \qquad (2)$$

where $\vec{k}$ is the wave number, $\vec{r}$ is the radius vector. As a result of solution (1) and (2) we come to RHM (right-handed materials) $\varepsilon' > 0, \mu' > 0$ and LHM connection to the following relations:

$$\left[\vec{k} \cdot \vec{E}\right] = \omega\vec{B} = \begin{cases} +\omega|\mu|\vec{H}, \mu > 0 \\ -\omega|\mu|\vec{H}, \mu < 0 \end{cases},$$
$$\left[\vec{k} \cdot \vec{H}\right] = \omega\vec{D} = \begin{cases} -\omega|\varepsilon|\vec{E}, \varepsilon > 0 \\ +\omega|\varepsilon|\vec{E}, \varepsilon < 0 \end{cases}, \qquad (3)$$

The Poynting vector $\vec{\Pi} = \left[\vec{E} \cdot \vec{H}\right]$ is written the same for both RHM and LHM; its direction coincides with the group velocity of the electromagnetic wave $\vec{V}_{гр}$. In Fig.1a. the vectors $\vec{E}, \vec{H}$ and $\vec{k}$ form a right-handed (RH), and Fig.1b. left (LH). In Fig.2 boundary conditions are clearly presented for field components and wave numbers.

$$\varepsilon_1' \vec{E}_{1n} = \varepsilon_2' \vec{E}_{2n}; \mu_1' \vec{H}_{1n} = \mu_2' \vec{H}_{2n}; \quad \arg(\hat{n}_2) = -\arg(\hat{n}_1) \qquad (4)$$

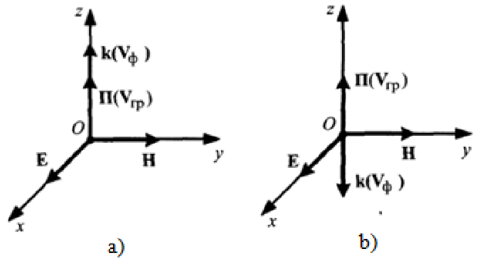


Fig.1. Mutual orientation of vectors for RHM and LHM.

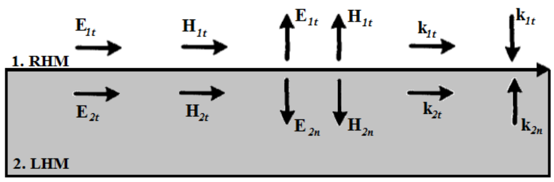


Fig.2.Boundary conditions on the LHM–LHM interface.

When the electromagnetic wave normally falls on the interface (z=0) RHM–LHM, the following conditions are met:

$$\vec{\Gamma}(0) = \frac{Z_C^{LHM} - Z_C^{RHM}}{Z_C^{LHM} + Z_C^{RHM}} \qquad (5)$$

where, $Z_C^{RHM} = \sqrt{|\mu_1| / |\varepsilon_1|}, Z_C^{LHM} = \sqrt{|\mu_2| / |\varepsilon_2|}$.

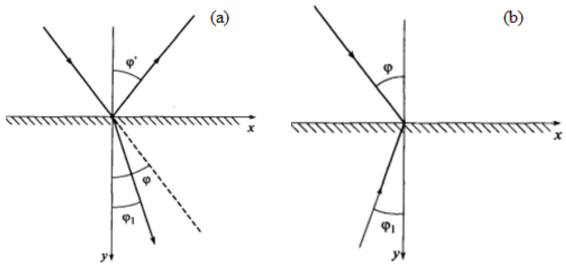


Fig.3. Proposed by L. I. Mandelstam scheme of reflection and refraction of the incident plane wave at the boundary with the usual medium (a) and metamaterial (b).

Thus, it follows from the ratio (5) that the reflection coefficient of electromagnetic waves from the interface is zero or the reflected beam is absent (this formula is conditionally contrary to the Snellius law). It is interesting that this dependence was immediately used by the military: aircraft coating MM becomes “invisible” to enemy radars.

Telecommunication and antenna technology using MM

Let’s look at the most important work on the application of MM in telecommunication, for miniaturization of the size of the antennas, the gain of the signal in the middle of the action, for the desired changes and control their radiation pattern.

In the work of Seleznev A.D., Pachurin G. V. and Galkin A. G. [10] an electrically small antenna with the use of metamaterial was developed: the elementary cell has the form of a U-shaped open resonator. To create a MM at a frequency of 300 MHz, resonators were filled with a thin layer of silicone, the agreement of electromagnetic waves at a frequency of 300 MHz is small enough, tgδ is approximately 10^{-4}. Then the resulting metamaterial was applied to the strip antenna. The distance between the emitter and receiving antennas was chosen 6 meters. This distance is justified by the range of the information transmission zone. In Fig. 5. experimental data of the manufactured receiving-transmitting antenna are presented.

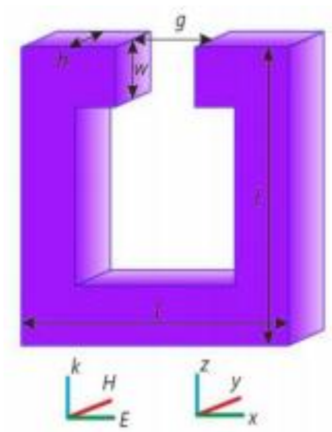
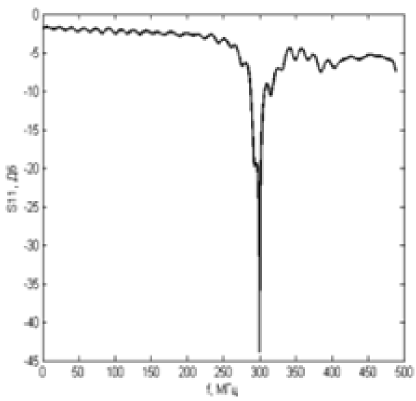
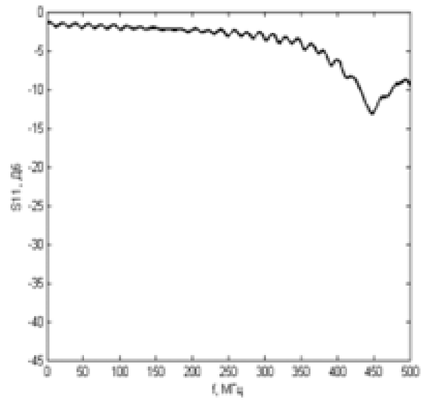


Fig.4. U-shaped open resonator – as an element of the electromagnetic cell of the metamaterial.

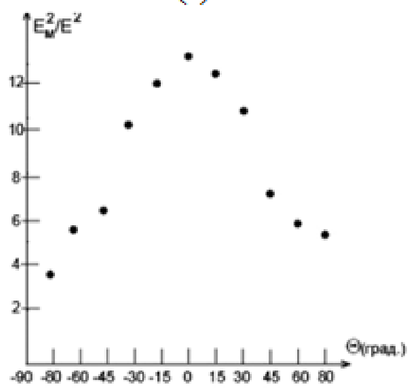
With the rapid development of wireless communications, microstrip antennas integrated with MM, have the advantages of broadband, multi-function, with the property of amplification and the ability to scan the radar beam needed in various communication systems.



(a)1



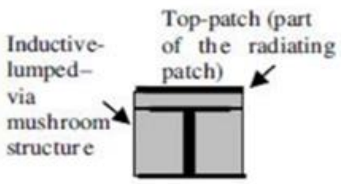
(a)2



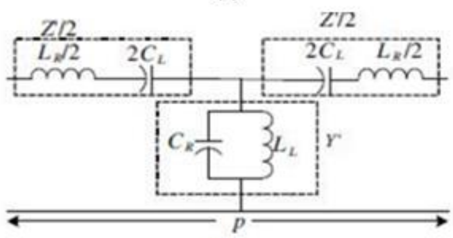
(b)

Rice.5. a – frequency dependence of the reflection coefficient of the antenna: 1 – using MM; 2 – without it. b – antenna radiation pattern, covered with a layer of MM.

In particular, in [11,12] it was shown that MM with different periodic structures have unusual electromagnetic properties, in particular in the microwave range in antennas systems are used to improve the gain levels of the lower lobes of the radiation pattern and better isolation between the elements of the array cell.



(a)



(b)

Fig.6. a) EM cell of the transmission line; b) the corresponding equivalent circuit.

In [13] the theory of right/left (LHM/LHM) transmission lines for the analysis of frequency characteristics of mushroom type antennas is considered (Fig.6.). On the basis of the electromagnetic cell Fig.5a is designed multiband, multimode and multi-polar antenna type LP/CP are designed.

Additionally, [13] considers the question of the peculiarities of the diagram of radiation of electromagnetic waves at frequencies of 5.1 and 8.3 GHz with the gain $g_n = 6,2 - 10dB.$

To increase the range of scanning and amplification Similar to [13], [14] proposed to improve the radiation pattern microstrip patch antennas due to the use of MM.

Four types of different MM are used as a flat lens in front of the MPA that is configured for a resonance frequency of 12 GHz (Ku-band). Unlike [14], [15] uses the results of modeling a resonator with separate rings for two different substrate thicknesses: in the range from 0.05 to 2 mm. When ε=1÷14 is changed, while maintaining the substrate thickness, the resonance frequency decreases from 16 to 6 GHz. In the second case, the resonance frequency is reduced from 13.2 to 9.2 GHz. In other words, this work shows that the properties of MM can be effectively changed with the change in the thickness of the substrate.

In [16], a broadband microstrip antenna with an operating frequency of 14.14 – 8.65 GHz was developed, and the electromagnetic cell has the shape shown in Fig.7. The antenna has a minimum size of 28x32 mm^2. This antenna meets all the requirements for size and price, as well as bandwidth. Therefore, they can be used in the fields of microwave and optics.

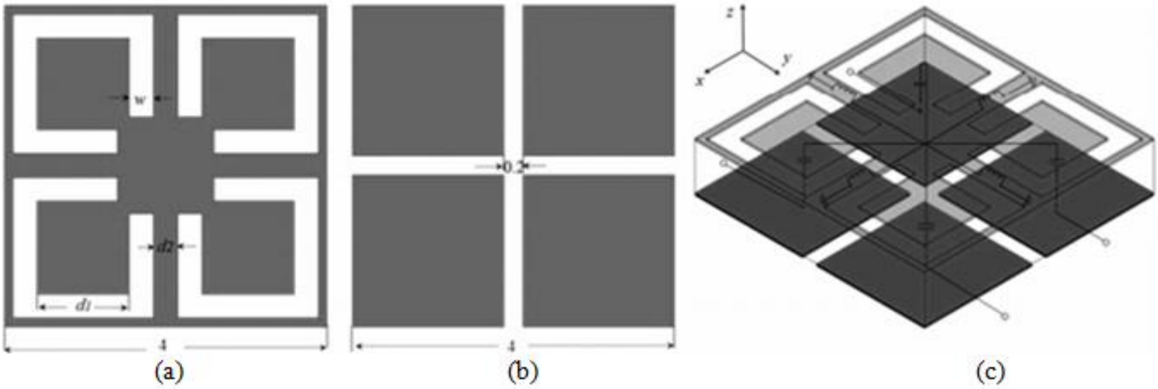


Fig.7. The proposed structure of the 2D negative refractive index: (a) the upper layer; (b) the lower layer; (c) the unit cell.

Mohamed-Ali Boujemaa [17] and others offer an ultra-wideband antenna (UWB). Electromagnetic cells are in the form of meander-lines (Fig.8) and placed into the antenna aperture to improve the polar pattern. The antenna operates at a frequency of 1.3-12 GHz with a gain of about 10 dB.

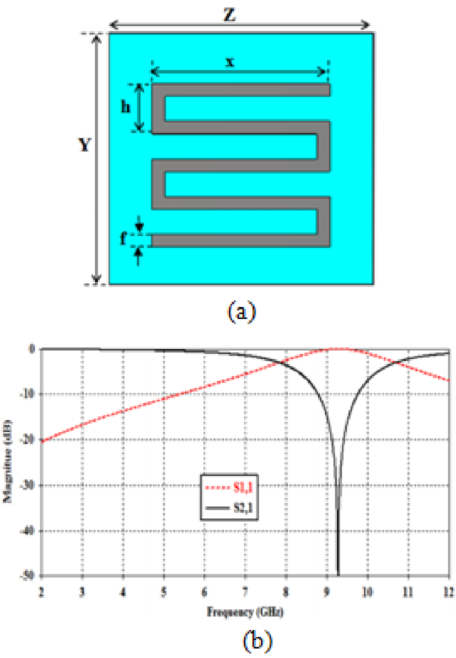


Fig.8. (a) the structure of the cell MM; (b) S Unit cell parameters.

Similar to [17], in [18] the absorption characteristics of a three-layer MM developed for the purpose of reducing the radar cross-section of the slit radio antenna are demonstrated by the modeling method. The cross-section of the antenna with MM is reduced at frequencies of 3.9÷18 GHz.

Finally, in [19], we analyzed the ability of MM “epsilon-near-zero” (ENG, MTN) to reduce the mutual relationship between densely packed elements of array cells. To verify and confirm the simulation results manufactured and tested prototypes of the proposed ENZ structure with a characteristic with parameters: frequency range of 10.5-to 27.7 GHz; reducing a mutual influence of the cells of the array 20 dB; the total size of the patch antenna of 2.66·λ·L×1,75·λ·L×0,05·λ·L.

References

[1] Veselago V.G. Elektrodinamika veshestv s odnovremenno otritsatelnim znacheniyami ε i μ (The electrodynamics of substances with simultaneously negative values of ε and μ), Uspexi fizicheskix nauk, (1967), 92 (7), pp. 517–526.

[2] Lagarkov A.N., Kisel V.N., Sarichev A.K., Semenenko V.N. Elektrofizika i elektrodinamika MM (Electrophysics and electrodynamics MM) Institut teoreticheskoy I prikladnoy elektrodinamiki OIVT RAN (ITPE RAN) (Institute of theoretical and applied electrodynamics JIHT RAS (ITAE RAS), Moscow, 2010.

[3] Slyusar B. Metamateriali v antennoy texnike: istoriya I osnovnie prinsipi (Metamaterials in antenna technology: history and basic principles), Electronics, (2009), 7, pp.70–79.

[4] Engheta N. and Ziolkowski R.W. Metamaterials: Physics and Engineering Explorations, Wiley-IEEE Press, (2006).

[5] Pendry J.B., Holden A.J., Robbins D.J., and Stewart W.J. Magnetism from conductors and enhanced non-linear phenomena, IEEE Trans. Microwave Theory Tech, (1999), 47, pp.2075.

[6] Smith D.R., Padilla W., Vier D.C., Nemat-Nasser S.C., and Shultz S. Composite Medium with Simultaneously Negative Permeability and Permittivity, Phys. Rev. Lett, 2000, 84, pp. 4184.

[7] Shelby R.A., Smith D.R., Schultz S. Experimental Verification of a Negative Index of Refraction, Science (2001), 292 (5514), pp. 77–79.

[8] Sivuxin D.B. Ob energii EM polya v dispergirueshix sredax (On EM field energy in dispersible media), Optics and spectroscopy, 1957, 3 (4).

[9] Agranovich V.N., Ginzburg V.L., Krisstalooptika s uchyotom prostranstvennoy dispersii I teorii eksitonov (The crystal optics with account of spatial dispersion and theory of excitons) Moscow: Nauka, (1965).

[10] Seleznev A.D., Pachurin G.V., Galka A.G. Razrabotka elektricheski malix antenn s primeneniyem metamateriala (Development of electrically small antennas using metamaterial) Mejdunarodniy jurnal prikladnix I fundamentalnix issledovaniy (2017), (9).

[11] Caloz C., Itoh T. Electromagnetic metamaterials Transmissons Line Theory and Microwave Applications, IEEE press, (2005).

[12] Sievenpiper DF. Superluminal waveguides based on non-Foster circuits for broadband leaky-wave antennas. IEEE Antennas Wireless Propagation Letters, (2011), 10, pp. 231-234.

[13] Wenquan Cao, Zuping Qian and Bangning Zhang. Applications of Metamaterials-Based Microstrip Antennas. 3rd Asia-Pacific Conference on Antennas and Propagation. (2014).

[14] Tutuncu B., Torpi H., Bulent U. A comparative study on different types of metamaterials for enhancement of microstrip patch antenna directivity at the Ku-band (12 GHz), Turkish Journal of Electrical Engineering & Computer Sciences, (2018), 26 (1171).

[15] Zhongyan Sh., Vasundara V.V. Tuning the effective properties of metamaterials by changing the substrate properties. Journal of Applied Physics (2007), 101 (014909).

[16] Han Xionga, Jing-Song Honga. A wideband endfire directional microstrip antenna with metamaterials. IETE Journal of Research (2013) 59, 2, (150).

[17] Mohamed-Ali Boujemaa, Rabiaa Herzi, Fethi Choubani, Ali Gharsallah. UWB Antipodal Vivaldi antenna with higher radiation performances using metamaterials, Applied Physics A. (2018), 124 (714).

[18] Qiang FU, Cheng-Li FAN, Si-Jia LI, Gang WANG, Xiang-Yu. Ultra-Broad Band Radar Cross Section Reduction of Waveguide Slot Antenna with Metamaterials. Radioengineering, (2016), 25(2).

[19] Mohammad H., Mazaheri A.J. A broadband array antenna using epsilon-near-zero metamaterials for MIMO applications International Journal of RF and Microwave Computer-Aided Engineering, (2018), https://doi.org/10.1002/mmce.21475.

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Метаматериалы электрически малые антенны и радиолокационная техника

Аннотация. В статье анализируются результаты последних лет по созданию и использованию метаматериалов в области телекоммуникаций и радиолокационной техники. Перспективы использования так называемых левосторонних материалов (ЛСМ) в антенной технике для улучшения в широком диапазоне частот электромагнитных волн от 24 МГц до 30 ГГц с возможностью дополнительного усиления сигнала (до 20 дБ) и создания электрически малых передающих или приемных антенн с линейными размерами, существенно меньшими, чем длина волны передатчика. Это иллюстрируется технологией изготовления таких антенн и графиками, показывающими минимизацию (в некоторых случаях полную компенсацию). В частности, показана эквивалентная схема такого "не поглощающего" фильтра.

Ключевые слова: метаматериал, левосторонний материал, антенна, телекоммуникация, радиолокационная технология.