Development of a new type of metamaterial and its application in antenna technology

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Abstract. In this paper, we consider a method for creating left-sided metamaterials. We select a method for creating metamaterials from a system with distributed parameters that are non-resonant structures. The equation of a discrete transmission line is solved taking into account the conditions for creating a metamaterial. The resulting solution in the form of effective permittivity shows that such a medium really has a double negative value of both the dielectric and magnetic permittivity. A generalized scheme of a universal method for searching for creating metamaterials is considered.

1. Theoretical part
This part summarizes the method for creating left-sided metamaterials, and selects a method for creating metamaterials from a system with distributed parameters that are non-resonant structures. The equation of a discrete transmission line is solved taking into account the conditions for creating a metamaterial. The resulting solution in the form of effective permittivity shows that such a medium really has a double negative value of both the dielectric and magnetic permittivity. A generalized scheme of a universal method for searching for creating metamaterials is considered.

The principal possibility of creating superdirectional antennas appeared after the creation of artificial materials with unique electrophysical characteristics ($\varepsilon(\omega)$, $\mu(\omega)$) – metamaterials (MTM).

![Figure 1. Elements of the metastructure cell (a), a piece of a broken single-wire communication channel (1), a metal rod (2), a dielectric filler (3); an elementary metastructure cell(b).](image_url)
Metamaterial creation can be attributed to nonlinear dynamic phenomena, since the "medium" of the metamaterial must have dispersion properties ($\varepsilon(\omega)$, $\mu(\omega)$), moreover, the higher the frequency of irradiation, the easier it is to create a metamaterial. On the other hand, it is shown below that a metamaterial appears exclusively in an open system when all elements of the metasystem are interconnected, and therefore there is a connection between the output and input of the system. It is shown below that creating a metamaterial using an open communication line is of great importance in antenna theory. Thus, the creation of a metamaterial is really a dynamic process of exposure to electromagnetic radiation with metamaterial [5]. Note that the metamaterial is located in the near zone of electromagnetic radiation for the manifestation of meta-properties.

In this paper, in contrast to [1], we draw up a diagram of elementary cells (figure 1). The scheme is voluminous, so for simplicity of calculations, an equivalent system is shown only on the z axis.

In the diagram in figure 2 the metastructure is created from pieces of a copper tube of a certain length, a single-wire cable communication line, where copper cylindrical conductors are used as metal "rods" (figure 1a), and the conductors are located strictly parallel, which again simplifies model calculations. Cylindrical segments made of polyvinyl chloride are considered as an effective medium. Since the "medium" must be continuous, all segments of the cable line and polyvinyl chloride are fixed with a silicone-based glue, which has $\varepsilon_0$ very close to $\varepsilon_0$ polyvinyl chloride.

Consider a system in the form of a metamaterial consisting of elements of a long transmission line, where there are also traveling waves and reverse waves. Following the work [2], we can associate the effective parameters of the "medium" with the average values of electric and magnetic fields.

Model calculations are made using the following formulas, which are consistent with the theory of the effective medium [3, 4, 5, 6, 7]:

$$\vec{D} = \varepsilon_{eff} \vec{E}; \quad \varepsilon_{eff} = \frac{Z_0^2}{Z^2};$$

$$Z(\omega) = \sqrt{\frac{\mu_{MTM}(\omega)}{\varepsilon_{MTM}(\omega)}} = Z_0 \sqrt{\frac{1 + \mu_{MTM}(\omega)}{\varepsilon_{MTM}(\omega) + \varepsilon_{eff}}},$$

Figure 2. Principal (a) and equivalent (b) scheme of the metamaterial.
\( n_{\text{eff}}(\omega) = \sqrt{\varepsilon_{\text{eff}}} + \sqrt{\left(\varepsilon_{\text{eff}}(\omega) + \mu_{\text{MTM}}(\omega)\right)\left[1 + \mu_{\text{MTM}}(\omega)\right]} \).

From these equations we find
\[
\begin{align*}
\mu_{\text{MTM}}(\omega) &= \frac{1}{\sqrt{\varepsilon_{\text{eff}}(\omega)}} - 1, \\
\varepsilon_{\text{MTM}}(\omega) &= \varepsilon_{\text{eff}}(\omega)\mu_{\text{MTM}}(\omega)
\end{align*}
\] (2)

The formula from the works of Nader Engheta (2) [8] is remarkable in that, as we show, it allows us to transfer the effective environment method for systems with distributed parameters (back-wave) (figures 1–2).

For a single-wire line, as we have shown [3], the following results can be obtained, summarized in table 1.

| Conditions | \( e^a = b + \sqrt{b^2 - 1} \) | \( e^a = b + \sqrt{b^2 - 1} \) | \( e^a = b - \sqrt{b^2 - 1} \), | \( e^a = b - \sqrt{b^2 - 1} \), |
|------------|-----------------|-----------------|-----------------|-----------------|
| \( \omega > 2\omega_p \) | \( \omega < 2\omega_p \) | \( \omega > 2\omega_p \) | \( \omega < 2\omega_p \) |
| Values of \( \omega \) | \( \omega = 2.2\omega_p \) | \( \omega = 1.7\omega_p \) | \( \omega = 2.2\omega_p \) | \( \omega = 1.1\omega_p \) |
| Values of \( |e_{\text{eff}}^a| \) | 0.21 | 0.49 | 1.21 | 0.5 |
| \( \mu(\omega) \) | 1.18 | 0.42 | -0.09 | 0.41 |
| \( \varepsilon(\omega) \) | 0.25 | 0.21 | -0.11 | 0.205 |

Table 1 shows that \( \omega > 2\omega_p \) a meta-environment with two negative parameters is formed \( \mu(\omega) = -0.09 \), \( \varepsilon(\omega) = -0.11 \).

In contrast to the work [6], we made an elementary cell (figure 1) and an electrical equivalent circuit (figure 2). The distinctive feature of this scheme is that it is not a resonant structure, where there are traveling and reverse electromagnetic waves and their interaction.

Note that the properties of a metamaterial are manifested when exposed to external electromagnetic influence. Therefore, as a rule, the "metasredu" is located near the transmitting antenna (in the near field) with a frequency of at least 10 MHz and higher.

In the equivalent scheme (figure 2b), there is a phase shift (along the "y" axis), between the rows of the "x" axis and the "y" axis, located in parallel (figure 1a).

Find the total resistance \( Z(\omega) \) for the equivalent circuit (figure 2b):

1) Serial connection \( Z(\omega) \) on the "x" axis (figure 2):

\[
Z(\omega) = \sum_{i=1}^{9} Z_i = 9jX_L.
\]

If you consider the capacity between \( Z_i \)

\[
Z_{ic} = 9j\left(\frac{X_L - \frac{1}{\omega C_d}}{\omega C_d}\right),
\]

where \( C_d \) is the dielectric constant of polyvinyl chloride.
Since \( \frac{1}{\omega C_a} \ll \omega X_L \) we will not consider the member \( \frac{1}{\omega C_a} \) further.

\[ Z^x_{\text{eff}}(\omega) = 9jX_L = 9Z_1. \]

2) Parallel connection on the “y” axis

Then find the value \( Z^y_{\text{eff}}(\omega) \) by

\[ Z^y_{\text{eff}}(\omega) = \left| Z^y_{xy}(\omega) \right| = \frac{1}{Z_L} \gg Z_C \]

\[ |Z^y_{xy}(\omega)| = \sqrt{(Z^y_{1x}(\omega))^2 + (Z^y_{2x}(\omega))^2 + \cdots + (Z^y_{9x}(\omega))^2}. \]

For our case \( |Z^y_{xy}(\omega)| = 5.24Z_C \).

3) Parallel connection on the “z” axis:

[Figure 3. On the left the metastructure (figure 2), on the right, the value of the total resistance relative to the “xyz” axis.]

For the first layer \( Z^y_{1z}(\omega) = |Z^y_{xy}(\omega)| = 5.24Z_C \).

\[ Z^y_{2z}(\omega) = \frac{Z^y_{xy}(\omega)Z^y_{2x}(\omega)}{Z^y_{1x}(\omega) + Z^y_{2x}(\omega)} = \frac{5.24Z_C \cdot 5.24Z_C}{10.48Z_C + 5.24Z_C} = 2.62Z_C, \]

\[ Z^y_{3z}(\omega) = \frac{Z^y_{xy}(\omega)Z^y_{3x}(\omega)}{Z^y_{2x}(\omega) + Z^y_{3x}(\omega)} = \frac{2.62Z_C \cdot 5.24Z_C}{5.24Z_C + 5.24Z_C} = 1.7Z_C, \]

\[ Z(\omega) = |Z^y_{\text{eff}}(\omega)| = \left[ \left( Z^y_{1z}(\omega) \right)^2 + \left( Z^y_{2z}(\omega) \right)^2 + \left( Z^y_{3z}(\omega) \right)^2 \right]^{1/2} = 6.1Z_C. \]  

(3)

Next we find \( |\varepsilon_{\text{eff}}| \) the entire metamaterial

\[ |\varepsilon_{\text{eff}}| = \left| \left( \frac{1 + \frac{\omega^2}{2X(\omega)C_0}}{0.25\frac{\omega^2}{\omega_0^2} - 1} \right)^2 \right|. \]  

(4)

For our case when \( Z(\omega) = 6.1Z_C \) we find the value \( |\varepsilon_{\text{eff}}| \)

\[ |\varepsilon_{\text{eff}}| = \left| \left( \frac{1 + 0.08\frac{\omega^2}{\omega_0^2}}{0.25\frac{\omega^2}{\omega_0^2} - 1} \right)^2 \right|. \]  

(5)
When $\frac{\omega}{\omega_p} = 2.2$ we find the value $|\varepsilon_{\text{eff}}|$

$$|\varepsilon_{\text{eff}}| = 9.16.$$  

Then using the formula (2) we find the values $\mu_{\text{MTM}}(\omega)$ и $\varepsilon_{\text{MTM}}(\omega)$

$$\begin{align*}
\mu_{\text{MTM}}(\omega) &= -0.67 \\
\varepsilon_{\text{MTM}}(\omega) &= -6.1 
\end{align*}$$

**Figure 4.** Graphs of dependences of: a) magnetic permeability; b) dielectric permittivity on frequency for an equivalent circuit (figure 2).

Figure 4 shows the graphs of theoretical calculated dependences of a) magnetic permeability and b) dielectric permittivity on frequencies according to the formulas (3), taking into account (2).

It can be seen that the calculated data give double negative values ($\mu<0$, $\varepsilon<0$), which indicates the possibility of creating a metamaterial in the entire assumed frequency range.

**2. Practical part**

During the experimental part of the work, a sample of metamaterial was created using the dynamic-evolutionary method from the elements of the communication line. The main metal element is copper. Copper tubes with a diameter of 0.6 cm are cut into parts of 0.4 cm, which are put on the communication line (figure 5b, 5c), then the elements are cut longitudinally in order to get an open communication line. The next element is a system of conductors acting as the main potential line and insulation in the form of polyvinyl chloride to create an open capacitor. The next step is to combine elements to create a metastructure with a common surface of 5.5x8.5 sm² (figure 5a).

The elements of the metamaterial must be arranged symmetrically and the places of breaks are located with a turnover of 180⁰ between them. This is done in order to achieve phase variability. Next, a regular communication line (without a metaelement) and a line with metaelements are alternately assembled in one row. The metamaterial is made in three rows, and the order of the set of elements changes in each row. This is done in order to achieve phase variability. All elements of the metamaterial are connected with each other using a silicone-based glue.

When creating a metamaterial, you must strictly observe symmetry and order, and only in this case can you achieve maximum efficiency of the metamaterial.
Figure 5. a) Metamaterial in the form of a piece of cable line with $Z_0 = 50 \, \Omega$; b) metamaterial element in the form of a longitudinally cut piece of cable line top view; c) metamaterial element side view.

The installation corresponds to the schematic experiment (figure 6) in the sense that the signal generator is taken as a generator of the Rohde company & The Schwarz SM 300, which operates in the frequency range from 3 KHz to 3 GHz.

Figure 6. Installation assembled to study the effectiveness of metamaterial relative to antenna feeder devices.

When measuring, special attention should be paid to the location of the metamaterial between the transmitting and receiving antenna. When making measurements follow the following rules:

1. First of all, all elements (generator, antennas, and portable frequency analyzer) are connected using a cable ($Z_0 = 50 \, \Omega$) with appropriate connectors.
2. The system of communication at close distances is initially adjusted without MM, to the maximum sensitivity of the receiver, in order to observe all changes when using the metamaterial.
3. Between the antennas of the transmitter and receiver is the MM without any sources connected to the MM.
4. At the same time, the metamaterial must be installed in such a way as to achieve maximum efficiency. Observations have shown that the distance from the transmitting antenna to MM varies at different frequencies.
5. We determine the signal parameters (field strength, signal strength) in a wide frequency range, first without metamaterial and then with metamaterial.

The main measured characteristic of MM is the relationship between the signal level and frequency, the intensity of the electric (or magnetic) field with a frequency in the entire measured range of waves of the transmitter from 0.6 to 2.4 GHz (figure 7), which shows the dependence of the amplified signal on the frequency of the transmitter.

Let's look at these charts in more detail:

– figure 7 shows the dependence of the signal level with frequency in the frequency range $0.6 \div 2.4 \text{GHz}$ with a frequency range of 0.1 GHz. When comparing the amplified signal from the presence of MM, it can be seen that in the frequency range $0.6 \div 1.2 \text{GHz}$ and $1.7 \div 2.4 \text{GHz}$, the transmitter signal is actually amplified when present, and these amplifications reach the maximum value at frequencies $2.2 \div 2.4 \text{GHz}$.

![Figure 7. Results of experimental works: the solid line, the medium with the metamaterial, the dashed line environment without metamaterial.](image)

The average gain of the transmitter is 4 dBμV/m (decibel microvolts per meter), the maximum value at 2.24 GHz is about 7 dBμV/m. Note that the gain is achieved in a wide range of frequencies $0.6 \div 1.2 \text{GHz}$ and $1.7 \div 2.4 \text{GHz}$.

Experimental results are given for the selected model method in the frequency range of the generator $450 \div 3\text{GHz}$. The main thing: the metamaterial is not connected to any electrical circuits, and the distance between the transmitting and receiving antenna is selected, so as to get the maximum signal gain. In this research work, the signal gain of the order of more than 7 dBμV/m was obtained.

References

[1] Panchenko B A and Nefedov E I 1986 *Microstrip antennas* (Moscow: Radio i svyaz’)

[2] Machulyansky A, Verbitskiy V and Yakimenko Y 2016 *Proc. of the IEEE 36th Int. Sci. Conf. Electronics and Nanotechnology* (Kiev) p 140–43
[3] Salakhitdinov A N and Mirzokulov Kh B 2019 *Dynamics of systems, mechanisms and machines* 7 2

[4] Yashin M M, Yurasov A N, Ganshina E A, Garshin V V, Semenova D V, Mirzokulov Kh B and Danilov G E 2019 *Herald Of the Bauman Moscow state technical university* **83** 5

[5] Yurasov A, Yashin M, Ganshina E, Granovsky A, Garshin V, Semenova D and Mirzokulov Kh 2019 *J. of Phys.: Conf. Ser.* **1389** 012113

[6] Panchenko B A and Gizatulin M G 2010 *Nano antennas* (Moscow: Radiotekhnika)

[7] Marqués R, Martín F and Sorolla M 2008 *Metamaterials with Negative Parameters: Theory, Design and Microwave Applications* (USA: Wiley)

[8] Engheta N and Ziolkowski R W 2006 *Metamaterials: Physics and Engineering exploration* (USA: Wiley-IEEE Press)