Integration of decoupling capacitors in the structure of controlled metamaterial

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Abstract. The article studies a metamaterial placed in the aperture of a rectangular waveguide with dimensions of 36x18.1 mm to change the phase of the transmitted wave depending on the switched pin diodes. Since pin diodes are switched by supplying a constant voltage to them in the metamaterial structure, capacitors with a capacitance of 35 nF were installed, which make it possible to achieve separation of the constant component of the switching voltage from the alternating one, and, accordingly, ensure switching only in the required nodes. The simulation results contain S-parameters of the system, which prove the possibility of using the proposed metamaterial as a waveguide phase shifter.

1. Introduction
Metamaterials are widely used in modern electromagnetic devices, so antenna systems with controlled characteristics, waveguides with variable characteristics of a passing electromagnetic wave are built on their basis. Examples of such designs are investigated in scientific papers [1-10], and in [1-6] antenna systems controlled by commutation of metamaterials are considered, and in [7-10] waveguides with various types of metamaterials integrated into their design.

In work [1], the authors consider the possibility of controlling the orbital angular momentum of antenna study by performing commutation of pin diodes. With the help of commutation, it is possible to achieve a change in the type of circular polarization of the antenna from right to left. The proposed design made it possible to improve the noise characteristics of the communication channel. The pin diodes used in the design were replaced by an equivalent circuit, which is a series connection of a 2.1 Ohm resistance and an inductance of 0.6 nH.

In [2], the authors consider the use of various designs of metamaterials for wireless information transmission systems, which can improve the security of various household devices. The use of metamaterial made it possible to achieve a reduction in unnecessary radiation from antenna systems, and, accordingly, to lower the specific absorption rate of electromagnetic energy (SAR), since the leakage of magnetic and electrical energy during the transmission of electromagnetic waves was significantly reduced.

The work [3] considers absorbers of electromagnetic energy, built on the basis of metamaterial cells. The proposed design can be used in medical and military applications. Based on the obtained results of modeling and research of the layout of the proposed design, it was found that at the target frequencies, it is possible to achieve a high level of absorption of electromagnetic waves. The research results show a high correlation between simulation and experimental results.
In work [4], an antenna system with an integrated metamaterial is proposed, which makes it possible to control the characteristics of antenna elements without significantly complicating their design. In this case, the secrecy of the antenna system is improved, since the metamaterial acts as an absorber of electromagnetic energy.

In [5], the authors consider a rectangular patch antenna with an integrated metamaterial, which allows improving the radiation characteristics. At the same time, the simulation results showed a high correlation with the results of the experimental study of the antenna layout. Also, a feature of the proposed design is that it is made of completely biodegradable materials.

In [6], the authors propose a broadband antenna for the mm wavelength range. To improve the characteristics of the antenna system, a resonant metamaterial was integrated into the structure, which allows to achieve a decrease in losses during wave transmission, as well as to expand the operating frequency range.

In [7], various types of waveguide phase shifters are considered, which make it possible to achieve a change in the wave phase over a wide range. Different designs of the structures installed in the waveguide allow for different phase shifts. In [8], a complex design of the material of the phase shifter, which is placed in a waveguide, is considered. The incorporated design also allows the function of a bandpass filter.

In [9], a waveguide with a metamaterial integrated into its structure is considered, in which switching occurs using MEMS structures. During the simulation, the phases of the S-parameters of the waveguide were built, on which it was clearly seen how the wave phase shift occurs.

In [10], a multilayer metamaterial is considered, which, due to a change in resistance, makes it possible to change the characteristics of a wave flowing through it. In fact, the waveguide is narrowed down to complete blocking of the flowing waves.

### 2. Study of the characteristics of a metamaterial as a waveguide phase shifter

For the study, a metamaterial was chosen, which is a lattice of conducting cells in the center of which a capacitor with a capacitance of 35 nF was placed, which provided a minimum resistance at operating frequencies. The investigated construction of the metamaterial is shown in figure 1; lumped elements are integrated into the design, which replace capacitors with a capacitance of 35 nF.

![Figure 1. The studied design of the metamaterial.](image)

When switching, the central nodes in the crystal were closed, and the closing elements were equivalent pin-diode circuits, consisting of a series connection of a resistor with a resistance of 2.1 Ohm and an inductance of 0.6 H similar to those used in [1]. The switched nodes are highlighted in figure 2.
In accordance with the dimensions of the waveguide, the cutoff frequency was determined, which was 4.16 GHz. To investigate the possibility of using the proposed design as a waveguide phase shifter, let us consider the flow of the E-field through the structure, and also plot the phase diagrams of the S-parameters of the waveguide, and these parameters will be plotted for the case when the wave is supplied to only one power port – $S_{11}$ and $S_{21}$, at which this case, these parameters can be used for the situation of energy flow from the output to the input (in the opposite direction), while all the results obtained must be mirrored, since the counting of the switched lines goes relative to the input.

Pictures of the flowing E-field through the metamaterial are shown in figure 3 – in the absence of commutations, figure 4 – switching of the third line, figure 5 – switching of the seventh line, figure 6 – switching of the ninth line.

Figure 2. Switched metamaterial crystal nodes.

Figure 3. E-field pattern inside the metamaterial in case of absence of commutations.
Figure 4. E-field pattern inside the metamaterial in case of the third line is short-circuited.

Figure 5. E-field pattern inside the metamaterial in case of the seventh line short-circuited.

Figure 6. E-field pattern inside the metamaterial in case of the ninth line short-circuited.
The Weiland method was used to calculate the S-parameters of the waveguide, and the phases of these parameters are of particular interest for waveguide phase shifters, as in [9]. The $S_{11}$ phases are shown in figure 7, and for the convenience of their analysis, table 1 was formed. The graph shows the phases for all parameters during alternate switching of nodes, and the node with the completed switching corresponds to the graph index, so $S_{11,1}$ is the first line; $S_{11,2}$ – second, etc.

![Figure 7. Phases $S_{11}$ of the parameters of the studied metamaterial.](image)

**Table 1.** Maxima of phases $S_{11}$ of waveguide parameters with indication of frequencies of their observation.

| Closed lines | 0 | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 |
|--------------|---|---|---|---|---|---|---|---|---|---|----|
| **Phase peak, deg** | 179.8 | 179.6 | 179.64 | 179.9 | 179.9 | 179.4 | 178.9 | 179.9 | 178.6 | 177.9 |
| **Peak frequency, GHz** | 4.58 | 5.92 | 4.07 | 4.54 | 7.12 | 5.98 | 5.28 | 4.90 | 4.64 | 6.19 | 5.76 |

Parameter $S_{21}$ connects the input and output of the structure and allows you to determine the parameters of the wave when it passes from the input to the output. The resulting graphs are shown in figure 8, and the general data are summarized in table 2. Moreover, the figure shows the results at once for all cases of alternate switching of nodes in the metamaterial, for example, for the first line – $S_{21,1}$; second – $S_{21,2}$, etc.
Figure 8. Phases $S_{21}$ of the parameters of the studied metamaterial.

Table 2. Maxima of phases $S_{21}$ of waveguide parameters with indication of frequencies of their observation.

| Closed lines | 0  | 1  | 2  | 3  | 4  | 5  | 6  | 7  | 8  | 9  | 10 |
|--------------|----|----|----|----|----|----|----|----|----|----|----|
| Phase peak, deg | 179.7 | 179.3 | 179.5 | 179.4 | 179.7 | 179.8 | 179.9 | 179.7 | 179.9 | 179.0 | 178.9 |
| Peak frequency, GHz | 6.67 | 4.58 | 4.61 | 4.52 | 7.24 | 7.09 | 7.09 | 7.22 | 4.50 | 4.61 | 4.58 |
|                | 7.19 | 7.06 | 7.16 | 7.02 | 7.23 | 7.06 | 7.20 | 7.23 | 7.06 | 7.20 |

Thus, according to the data obtained, it can be seen that the proposed design makes it possible to change the phase of the electromagnetic wave passing through it, and the phase can be controlled by switching different lines that are part of the structure of the metamaterial.

3. Conclusion

According to the obtained results, it can be seen that the proposed design of the metamaterial can be used as a waveguide phase shifter, while controlling the wave phase, it is necessary to switch the lines in the metamaterial, and the switching is carried out by closing the nodes in the lattices with pin diodes, for which control it is required to apply a constant voltage. For the convenience of the implementation of this operation, capacitors were introduced into the design, which did not allow switching unnecessary nodes.

Thus, the use of a metamaterial makes it possible to control the characteristics of an electromagnetic wave without performing mechanical effects on the structure, and the use of pin diodes allows a rapid change in the characteristics of a metamaterial to achieve target values.

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