Waveguide phase shifter based on controlled metamaterial

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Abstract The paper present study of the opto-controlled metamaterial integrated into the waveguide design to control the phase of the flowing electromagnetic wave. A change in the metamaterial characteristics occurs when we switching nodes of a system consisting of thin metal conductors. In the course of the study a computer simulation of an electrodynamic system was carried out. It consists of a waveguide with dimensions of 26.4x10.62x200 mm and a metamaterial integrated into the structure, as a result of which, the flowing electromagnetic wave images, phase graphs $S_{21}$ of the waveguide parameters were obtained.

1. Introduction

In existing studies phase shifters are a mechanical structure that changes either the geometric characteristics of the structure where the electromagnetic wave flows or, if the control occurs in the optical range, the permeability of the medium. In well-known papers [1-7] phase shifters are studied for various problems that are solved in electrodynamics. In [1,3] a waveguide with a variable geometry is investigated, which leads to a phase shift of the passing electromagnetic wave; in [4] the phase shifter of the terahertz range is considered; in [2,5-7] planar structures that perform the phase shifter function are considered.

In [1] a model for controlling the phase shift of a wave in a waveguide by introducing an anisotropic material into the waveguide is proposed. It changes its degree of overlap, and therefore changes the pattern of the passing electromagnetic field. The proposed concept is based on the Maxwell equations and validated by the finite element method simulation.

In [2] the authors propose a design of a waveguide phase shifter integrated on a dielectric substrate, operating in the frequency range from 27.4 to 28.6 GHz. The phase shift of the electromagnetic wave occurs with a change in the physical position of the structure in the waveguide.

In [3] a mechanical phase shifter, which changes the overlap of the waveguide channel is presented. The phase shift of the output wave occurs while changing the flow pattern of the electromagnetic wave.

In [4], a phase shifter for terahertz antennas is presented. The phase delay occurs by connecting different sections of the circuit that have different lengths, which leads to wave delays when passing through the entire section.

In [5] the authors developed a phase shifter for a waveguide integrated into a dielectric substrate for operation in the frequency ranges that relate to 5G. The application of the proposed design allows you to change the main lobe of the radiation pattern direction.
In [6] the authors study a scanning antenna array constructed using planar technology, in which control is performed by changing the wave phase in a waveguide that is integrated in a dielectric substrate.

The authors of [7] study the phase shifter which is formed on a dielectric substrate in the frequency range from 1.9 to 2.1 GHz. Thanks to the proposed design it is possible to achieve a wide range of the electromagnetic wave phase changes.

However, in all the proposed works the phase change requires either a mechanical change in the channel of the wave flow or a pre-formed wave delay line, which leads to a design complication. In this paper we consider a system that is based on an active metamaterial, the switching of nodes in which is performed using pin-diodes, while no change in the geometric parameters of the structure is required.

2. The main characteristics of the considered metamaterial and waveguide
The active system is a metamaterial, which consists of thin cylindrical copper conductors with a length of 4.5 mm and a radius of 0.05 mm from which a multilayer structure was formed, which is shown in Figure 1.

![Figure 1. The 3D model of controlled metamaterial.](image)

The metamaterial is installed in a rectangular waveguide with a wall size of 26.4 by 10.62 mm and a length of 200 mm, which allows the active system to be completely located inside, in which pin-diodes will be switched (spice models of the pin-diode BAR65-02L were used in the simulation process). Figure 2 shows the waveguide in the section, so you can see it installed inside the metamaterial.
3. Investigation of the effect of metamaterial line switching on the phase shift in the waveguide
When switching in the nodes of the metamaterial is performed, the resistance of the waveguide section changes so that the passing electromagnetic wave encircles it. In this case there is a change in the waveguide line characteristics, namely a change in the scattering matrix characteristics (S-parameters). The proposed design of the metamaterial assumes the possibility of closing four lines, since when switching a larger number of lines, a narrowing occurs. It does not allow the penetration of electromagnetic waves at lower frequencies. In accordance with the selected waveguide dimensions, in the absence of switching in the metamaterial, the line cutoff frequency is $f_c = 5.68$ GHz, and the operating frequency range is 7.09-10.73 GHz. Figure 3 shows the graph $S_{21}$ of the waveguide parameters for all the studied cases.

![Figure 2. The waveguide with integrated metamaterial.](image)

**Figure 2.** The waveguide with integrated metamaterial.

![Figure 3. $S_{21}$ waveguide parameters during switching of various metamaterial layers.](image)

**Figure 3.** $S_{21}$ waveguide parameters during switching of various metamaterial layers.
As can be seen from the obtained graphs, when the number of active layers in the metamaterial increases, the frequency range at which the wave can penetrate the structure narrows. In this case the form of switching that ensures the smoothest passage of the electromagnetic wave is shown in Figure 4.

**Figure 4.** The view of switched metamaterial lines.

When a wave flows through the proposed layers, in addition to changing the operating frequency range of the waveguide, a phase shift of $S_{21}$ parameters occurs. Figure 5 shows the phases of $S_{21}$ parameters when switching different layers of metamaterial.

**Figure 5.** The phases $S_{21}$ of waveguide parameters for different types of metamaterial switching.
As can be seen from the obtained graphs, the phase shift of the electromagnetic wave occurs when switching layers. On the basis of the obtained data Table 2 was formed. It shows the maximum values of the phases $S_{21}$ of the parameters as well as the frequency at which they occur. The frequency range from 8.45 to 9.6 GHz is considered, since at lower frequencies when switching four lines the electromagnetic wave does not penetrate the output of the waveguide.

Table 1. Phase maxima $S_{21}$-waveguide parameters with indication of their observation frequencies.

| The number of performed switching of the metamaterial | 0  | 1  | 2  | 3  | 4  |
|-----------------------------------------------------|----|----|----|----|----|
| The maximum phase value, °                          | 179.2 | 179.88 | 178.07 | 179.12 | 179.39 |
| The maximum observation frequency, GHz              | 8.52 | 8.55 | 8.67 | 8.96 | 9.29 |
| Phase shift ($f=9.66$ GHz), °                       | 0   | 10.51 | 36.42 | 105.4 | 114.86 |

As can be seen from the results obtained, the phase shift of the electromagnetic wave occurs. When switching the first line, the phase shift occurs by 9.5° relative to the situation without performed commutations; when switching the second line, the phase shift is 46.07°; when switching the third line, the phase shift is 138.27°; when switching the fourth line, the phase shift is 243°.

In the entire investigated frequency range, the deviation from the phase shift at a frequency of 9.66 GHz is not more than 5%.

Figure 6 shows the flowing electromagnetic wave images for the case when there was no commutation, when three lines of metamaterial were combined. It demonstrates the principle of the proposed design operation.

As can be seen from the image, when switching the metamaterial lines, the wave goes around the activated zone, due to which it passes a longer path, and therefore the phase shift of the wave at the output occurs.
Figure 6. The image of the flowing electromagnetic wave in the waveguide: a) – in the absence of switching of the metamaterial lines; b) – switching of three lines is performed.

4. Conclusion

This paper proposes study of the active metamaterial which performs the function of a waveguide phase shifter, while it is not necessary to change the geometric dimensions of the waveguide channel, but only to perform switching of various lines of the active structure. The proposed design is built directly into the waveguide and consists of thin conductors. Pin-diodes are used to control the metamaterial characteristics.

Thus, the metamaterial is a more promising way to control the electromagnetic wave characteristics, since it is not necessary to change the geometric characteristics of the structure itself.
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