Horn antenna with integrated metamaterial for beam steering

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Abstract. The paper presents a design of pyramidal horn antenna with an active metamaterial integrated in its structure, which allows controlling the direction of antenna radiation in the frequency range from 10.5 to 11 GHz while maintaining a high level of antenna performance and directivity. Pin diodes are used as switching devices located at the nodes.

1. Introduction

The use of antennas with metamaterial structures integrated into their design is an attractive solution, since it is not required to change the physical characteristics of the antenna itself to control the characteristics. It is only necessary to commute the lines of the metamaterial structure or use various combinations of such structures. The use of metamaterials for horn antennas is studied in [1-4, 5], for printed antennas in [6, 7, 8, 10]. At the same time, modern metamaterial structures make it possible to improve the MIMO antennas characteristics [7, 8, 10].

In [1] the authors investigate a circular-section horn antenna designed to work with circular polarization. At the same time, a metamaterial was integrated into the design. It serves as a lens and is designed to improve the axial ratio, the quality of the pattern, and the front of the wave passing through it.

In [2] the authors consider the possibility of controlling the horn antenna directional pattern by integrating a metamaterial structure into the design. So, by using various types of metamaterials, it was possible to achieve a narrowing of the main lobe of the directional pattern or its bifurcation when using cross polarization.

In [3] the authors consider a pyramidal horn antenna with split-ring resonators (SRR) integrated into the horn of the metamaterial cell. This made it possible to increase the antenna directivity as well as to form a more clearly defined main antenna lobe.

In [4] the authors consider an antenna array which is built on the basis of four pyramidal horn antennas with an integrated metamaterial. When using the proposed design, it was possible to improve the directivity as well as the efficiency of the horn antenna aperture. This resulted in a serious narrowing of the operating frequency range.

In [5] the authors consider a metamaterial, which is integrated into the "pyramidal horn – Luneburg lens" system. The proposed solution made it possible to achieve an improvement in the directional pattern characteristics (an increase in the directivity and a narrowing of the main lobe).

In all the considered works passive metamaterials are used, the control of which is possible only by changing their geometric characteristics. This article discusses an active metamaterial that can be controlled by switching elements of the metamaterial structure.
2. The main characteristics of the proposed design
A pyramidal horn antenna with a double-layer metamaterial integrated in its aperture was chosen as the structure under study (Figure 1).

![Figure 1. The 3D view of the investigated pyramidal horn antenna.](image)

The metamaterial is a structure consisting of two layers of thin metal conductors placed in the antenna aperture. The first layer contains 77 metamaterial lines (the length of each metal conductor is 3.5 mm, the distance between the conductors in the layer is 0.65 mm, which corresponds to the length of the housing of switching pin diodes, the distance between the lines is 1 mm). At a distance of 7 mm the second metamaterial layer consisting of 67 lines with similar geometric parameters is placed deep in the aperture. The use of the second layer is due to provide better field attenuation in the switched zone. The introduction of additional metamaterial layers leads to a serious drop in the antenna efficiency as well as to significant field distortion caused by a gradual decrease in the horn aperture. The design under study is completely symmetrical in the h-plane of the horn. Node switching was performed using the SPICE model of the BAR 65-02 L pin diode.

In the course of the study, it was found that the directional pattern can be controlled at frequencies of 10.5-11 GHz covering a wide range of changes in the direction angle while maintaining the efficiency level above 60%. The characteristics of the directional diagrams for all the considered cases are shown in table 1.

3. Study of the influence of line switching in metamaterial on the antenna radiation direction
When performing switching in the lines of the metamaterial the electromagnetic field is blocked while the horn antenna sections with missing switching freely pass the electromagnetic wave. Thus, it makes possible to control the antenna directional pattern by switching. Figure 2 shows the E-field patterns in the main plane of the horn antenna for the case when there is no switching in the metamaterial and when half of the metamaterial lines are commutated.
Figure 2. E-field patterns (f = 10.75 GHz). The E-field is passing through the horn antenna: a) – without switching; b) – switching has been done in half of the layers.

Radiation control can be carried out in the frequency range from 10.5 GHz to 11 GHz, and it is necessary to switch the two layers of metamaterial synchronously, since this will ensure that the electromagnetic field is blocked in sufficient intensity to avoid side radiation. The simplest type of switching is the inclusion of half of the metamaterial, while the rotation of the directional pattern occurs in the horn antenna H-plane.
Figure 3. Radiation pattern for the case when half of vertical lines are switched: a) – view of switched lines; b) – 3D radiation pattern (f = 10.75 GHz).

From the obtained radiation patterns, it can be seen that when switching the layers of the metamaterial in the configuration shown in Figure 3-A the main lobe of the radiation pattern is deflected only in the H-plane. To rotate the radiation pattern in the opposite direction, it is necessary to switch the other side of the metamaterial, and in view of the symmetry of the structure under consideration, the obtained values will be similar.

When switching lines diagonally (Figure 4A), a narrowing of the antenna main lobe is observed, and in this case the switching of the upper and lower diagonals on one side leads to a complete coincidence of the directivity diagrams in both planes, and the switching of the metamaterial nodes in the opposite side will only lead to a change in the direction of radiation to the opposite.
According to the results obtained, it can be seen that the main lobe deflection at frequencies of 10.75 GHz and 11 GHz occurs in both horn antenna planes, while, in contrast to switching of half of the metamaterial (Figure 3A), the width of the main lobe in the H-plane is less than 36°. A distinctive feature of this line switching type is an increase in the antenna efficiency with increasing frequency, in contrast to the case with switching half of the lines in the antenna.
Table 1. Characteristics of radiation patterns depending on the switching type.

| Characteristic | No switching (Figure 1) | Switching half of the lines (Figure 3) | Diagonal switching (Figure 4) |
|----------------|-------------------------|----------------------------------------|-----------------------------|
| Directivity    | 13.3                    | 12.7                                   | 11.3                        |
| Radiation direction | 0                      | 32                                     | 8                           |
| Main lobe width | 33.8                    | 57                                     | 35.5                        |
| Direction of radiation | 0                    | 0                                      | 0                           |
| Antenna efficiency | 86                    | 77                                     | 66                          |
| Directivity    | 12.8                    | 13.2                                   | 11.9                        |
| Main lobe width | 37                      | 52.1                                   | 30.4                        |
| Direction of radiation | 0              | 2                                      | 2                           |
| Antenna efficiency | 86                    | 76                                     | 77                          |
| Directivity    | 12.4                    | 13.5                                   | 11                          |
| Radiation direction | 0                | 25                                     | 10                          |
| Main lobe width | 44.7                    | 46.5                                   | 33.5                        |
| Radiation direction | 0            | 0                                      | 7                           |
| Antenna efficiency | 84                    | 72                                     | 82                          |
4. Conclusion
The paper proposes an active metamaterial, which is integrated into a pyramidal horn antenna. Switching at the nodes of the metamaterial makes it possible to control the radiation pattern while maintaining a high level of efficiency and it is possible to control within a fairly wide range. So, the application of the proposed two-layer metamaterial construction enables to achieve a change in the patterns of the electromagnetic field passing through the waveguide. In this case, an increase in the number of metamaterial layers leads to additional reflection losses, significant field distortion, since the antenna aperture narrows due to the peculiarity of the pyramidal horn design.

Thus, the metamaterial makes it possible to achieve control of the radiation pattern by switching lines without changing the geometric characteristics of the antenna, which is the main advantage in the use of metamaterials in antennas.

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