SLOTTED WAVEGUIDE ANTENNAS FOR PRACTICAL RADAR SYSTEMS

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Abstract

This paper summarizes recent results on the development, fabrication, and application of slotted waveguide antenna systems for practical radar systems, including Ka-band helicopter collision avoidance and weather radar, Ku-band surveillance and tracking radar, and X-band airborne SAR system. The corresponding design solutions, antenna characteristics, and test results are presented and discussed.

Keywords: Slot antennas, Aircraft antennas, Antenna array feeds

1. INTRODUCTION

Recently, several novel slotted waveguide antenna arrays (SWA) for radars operating in K_a-, K_u-, and X-bands have been developed at the Institute of Radio Astronomy of the National Academy of Sciences of Ukraine. Each of these antenna arrays has some specific design features, which were introduced to meet challenging operational requirements of the radars. In this paper, we review the corresponding design solutions, antenna characteristics, and test results.

In the next section, we describe an electrically switchable, K_a–band antenna system, which consists of four SWAs. This antenna system has been developed for a helicopter collision avoidance and weather radar intended to increase the flight safety of helicopters.

In Section 3, a K_u–band, circular-aperture SWA for a monopulse search and tracking radar is described. The SWA forms the antenna beam, which is inclined with respect to the antenna surface normal. This solution enables to reduce essentially the radar visibility in the direction of an illuminated target.

In the last section, a possibility of the development of wideband SWAs is demonstrated. This is confirmed by the development of an X-band SWA with the relative bandwidth of about 15%. This antenna is intended for a high resolution airborne SAR system to be produced at the institute.

2. ELECTRICALLY SWITCHABLE SLOTTED WAVEGUIDE ANTENNA SYSTEM

An electrically switchable, K_a-band antenna array system has been designed for airborne radar applications. The system consists of four identical SWA sections. The sections are connected to a radar transmitter/receiver by means of a high-power, multipole P-i-N switch. The SWA has been developed by using the conventional methods [1-3], modern antenna simulation techniques and original approaches to the antenna design described in [4]. The P-i-N switch used in the antenna system is the state-of-the-art device which is characterized by both a high commutated power – of about several kilowatts, and a rather low switching time – of about several microseconds.

The target antenna parameters are: the fan-like beam of the width of 2°×10°, the sidelobes level of -22 dB, the antenna gain of 30 dB and the VSWR of 1.2 or better in the operational bandwidth of 35±0.2 GHz.

Each individual section of the antenna system is produced as shown in Fig. 1. Radiating layer is a collection of nine identical nonresonant (travelling-wave) radiating arrays fed from one end and matched from another. The feeding layer is a single resonant (standing-wave) feeding array of inclined slots placed in the edge of the antenna.

According to [5], we synthesize the radiation pattern in both planes by using the following amplitude distribution:

$$U_n = \mu + \left(1 - \alpha\beta\left(\frac{n-N-1}{N}\right)^2\right) \cdot \exp\left(-\beta\left(\frac{n-N-1}{N}\right)^2\right),$$

where U_n is the normalized amplitude at the n-th slot, $2N-1$ is the number of slots, $\mu=0.8, \alpha=2.3, \beta=0.85$. This Gauss-Bessel distribution

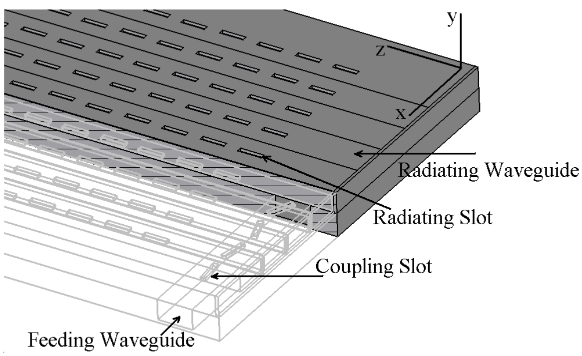


Fig. 1. Antenna construction

enables for the realization of radiation patterns having both maximal gain and minimal sidelobe level. In contrast to the standard distributions, like Tchebyshev distribution, this distribution has no unrealizable amplitude jumps at the end elements in the case of a large number of elements.

It should be noted that the aperture distribution is separable here. Moreover, the aperture distribution in the H-plane is determined by only the single linear radiating array, and that in the E-plane is determined be the feeding array. The mutual coupling between the radiating and feeding arrays is weak, because they are displaced one from another and the radiating arrays are designed to minimize backward reflections inside the working bandwidth.

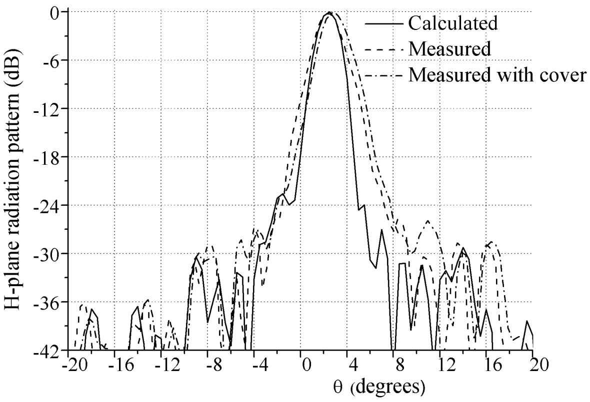
The designed antenna sections have been fabricated by using metal coating, milling, electric-sparking, and laser welding technologies. These technologies allow for producing such antennas with rather high reproducibility of the antenna characteristics. We have also observed a rather high degree of compliance of the measured and simulated results. In Fig. 2, the corresponding comparison is shown for the radiation patterns in both planes.

Fig. 3 plots and compares the dependence of the VSWR on the operating frequency obtained from the theoretical and experimental results. The antenna demonstrates a rather low value of the VSWR in the prescribed frequency band what simplifies its matching with the radar transmitter and receiver.

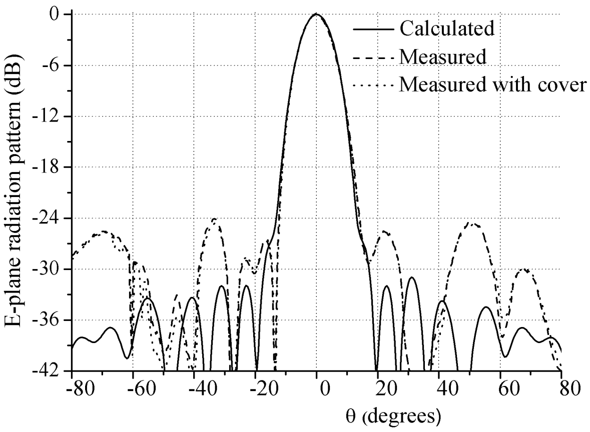
In order to protect the antenna from dust and moisture, a radome coating has been designed and introduced. The radome is made of a 4 mm foam sheet placed directly on the antenna radiating surface. The sheet is stabilized by means of 50 μm lavsan film. As it can be seen from Fig. 2, the radome exerts a rather small influence on the radiation pattern.

The main lobe of the pattern measured in the H-plane is a little wider (below the 3 dB level) than the calculated one. It is because of phase errors associated with the finite tolerance of the antenna fabrication. The level of sidelobes is as low as -23 dB what satisfies the design goal as well.

The complete antenna system consists of four independent slotted waveguide sections, which are shown



(a)



(b)

Fig. 2. Calculated and measured radiation pattern for the designed SWA, a) H-plane; b) E-plane.

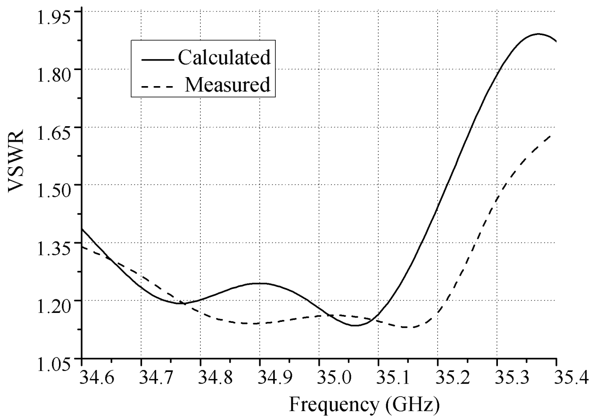


Fig. 3. Calculated and measured VSWR

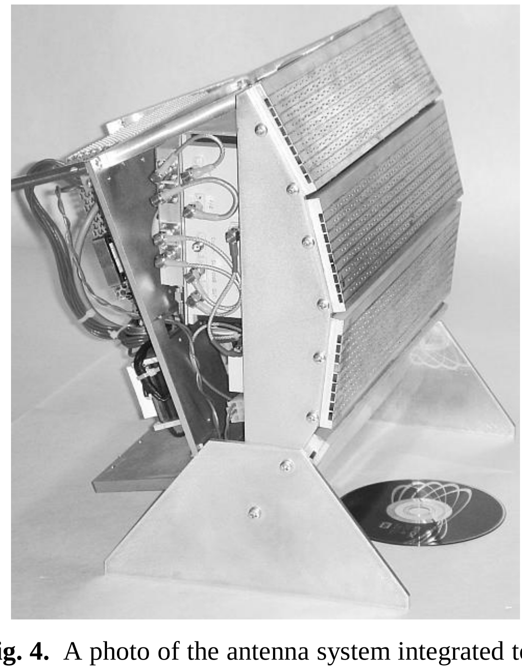


Fig. 4. A photo of the antenna system integrated to a transmitter/receiver module

in Fig. 4 integrated to the transmitter/receiver module of the airborne radar. The section dimensions are 310×72×9 mm^3. The antenna beams are displaced with the step of 16º in the elevation plane providing the total observation sector of about 60º. The sections are switched electrically by using an original high power reciprocal SP4T switch based on P-i-N diodes. The switch is based on three waveguide Y-junctions connected as a binary tree.

The developed and produced antenna system along with other hardware and software solutions has enabled for achieving rather attractive characteristics of the complete radar system, which is the helicopter collision avoidance, surveillance, and weather radar [6].

3. CIRCULAR SWA WITH INCLINED BEAM

In this section, we describe a K_u–band, circular-aperture SWA for a monopulse search and tracking radar. In order to decrease the radar visibility of the antenna in the direction of an illuminated target, the antenna beam is inclined with respect to the antenna surface normal.

The target antenna parameters are: the pencil-like beam with the width of 5°, the beam inclination angle of 15° in the E-plane, the sidelobes level of -22 dB, null depth of the difference pattern in the H-plane of -30 dB, the antenna gain of 29 dB and the VSWR of 1.2 or better in the bandwidth 16.75±0.25 GHz.

A SWA made of rectangular waveguides has been selected in order to satisfy the above formulated requirements. The antenna configuration is shown in Fig. 5.

The antenna has a circular aperture and consists of radiating and feeding layers. We use nonresonant feeding waveguides to incline the antenna beam. However, each radiating waveguide is a resonant device. The antenna consists of two separate radiating semicircles, and it is able to produce sum and difference patterns.

The phase distribution at the aperture should be specially selected in order to incline the antenna beam at a value larger than the antenna beamwidth. It has appeared that the standard feeding layer design with single feeding waveguide for each of the antenna halves is not valid. The problem is that in this case, it is needed to use feeding waveguides operating very closely to their cut-off frequency, or close to a high-order mode cut-off. To solve the problem, we have proposed to use the feeding layer with pair-waveguides to feed the both halves of the antenna. In this design, the first waveguide of the feeding pair feeds the odd radiating wave-

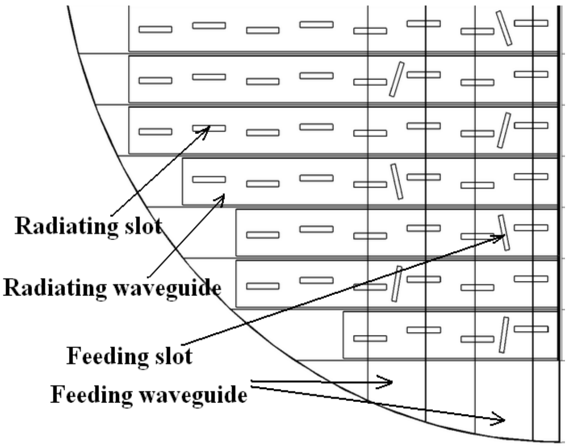


Fig. 5. Antenna design (quarter of the antenna is shown).

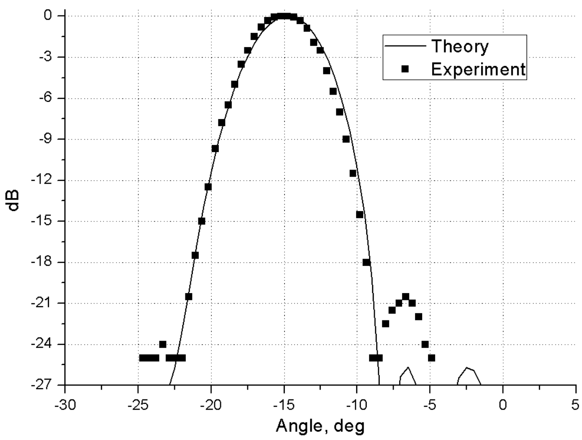


Fig. 6. Measured and simulated radiation pattern in E-plane.

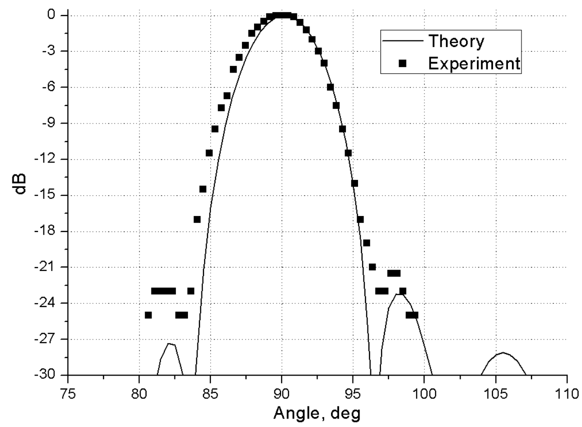


Fig. 7. Measured and simulated radiation pattern in H-plane.

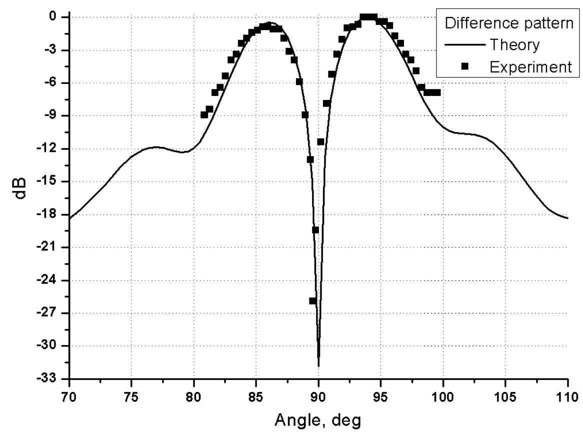


Fig. 8. Measured and simulated difference radiation pattern in H-plane.

guides, whereas the second waveguide feeds the even ones. A waveguide divider has been used to transmit signals with specified amplitudes and phases into the feeding waveguides

The synthesis of the aperture distribution is done by using the Taylor circular aperture distribution with $\bar{n} = 4$ and the sidelobe level of -25 dB [7, 8]. The synthesis procedure is similar to that described in [9]. The energy method [3] is used to produce an initial approximation for the resonant subarrays of the radiating layer and the recurrence method [3] is used for the nonresonant feeding subarrays to account mutual coupling via the fundamental mode of the rectangular waveguide.

A compact waveguide comparator is designed to feed the both halves of the antenna via the pairs of the feeding waveguides. This comparator is based on a magic tee unit, and it contains a very compact waveguide system. The magic tee unit is matched by means of a stepped post in the internal cavity of this unit and an iris in its difference channel. Parameters of these matching elements have been numerically optimized to minimize the VSWR at the sum port. The VSWR at this port is less than 1.09 in the operating frequency range of 500 MHz. The comparator combines the halves of the antenna to produce the sum pattern with the inclined beam and the difference pattern in the H-plane.

The simulation of the complete structure of the antenna has been performed. The structure contains both radiating and feeding layers and the waveguide comparator. Results of the computer simulation of the antenna are presented in Figs. 6, 7, and 8. The designed antenna has been fabricated of aluminum. Milling, conductive-epoxy bonding, and silver-plating technologies have been used in the fabrication process. A photo of the antenna is shown in Fig. 9.

The radiation pattern of the antenna has been measured. Sum pattern cuts in both E- and H-planes of the antenna along with a H-plane cut of the difference pattern are presented in Figs. 6, 7, and 8 respectively.

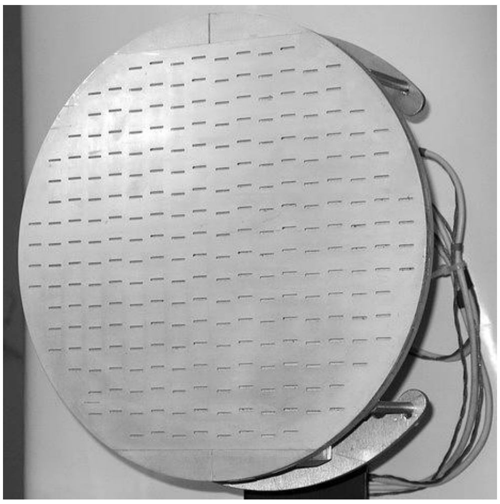


Fig. 9. Photo of the designed antenna.

Our analysis of the obtained results indicates that the target characteristics of the antenna have been achieved. The measurement results are in rather good agreement with the simulated ones.

4. WIDEBAND SWA FOR HIGH-RESOLUTION SAR SYSTEMS

SWAs due to their planar form, strength of the construction, and high efficiency are attractive candidates for applications in airborne and spaceborne SAR systems. But the typical bandwidth of practical SWAs is usually of about few percents what limits their applications in high-resolution radars. Potential radar applications call for the bandwidth of about 10% and higher, to achieve, for example, the spatial range resolution of about 20 cm with X-band radars.

Recent studies [10]-[14] have demonstrated that there are promising approaches to the extension of the bandwidth of conventional resonant SWAs. We have studied these and some other approaches to the extension of the bandwidth of such type of antennas. These results are applied to the development of a novel X-band SWA with the relative bandwidth of about 15% and with a 4°×6° antenna beam.

It is well known that the bandwidth of such arrays is determined by both the resonant properties of individual slots and the bandwidth of the waveguide structure.

The frequency bandwidth of slots can be extended by reducing the waveguide wall thickness and/or increasing the slot width. The application of slots of special forms, e.g., dumbbell slots [11], is another way to solve this problem. But such slots are hard-to-manufacture and they provide a high level of cross-polarization components.

It should be also reminded that conventional longitudinal slots themselves demonstrate a rather large bandwidth under a proper choice of their parameters. Our simulations have shown that the bandwidth of about 20% can be easily achieved.

In order to increase the bandwidth of a SWA, wideband waveguides are used and/or the antenna array is divided on short sections (subarrays) with individual feeding. The usage of broad rectangular waveguides is the simplest way to extend the frequency bandwidth. However, such waveguides are only useful in the case of linear arrays. For planar arrays, this solution results in the appearance of intensive grating lobes. Evidently, the interelement spacing can be reduced by using dielectrically filled waveguides, but this approach is not too practical. Actually, the same factor limits the application of wideband ridged waveguides [12], [14]. The subarraying technique is considered now as the most effective and preferable approach to the extension of the antenna bandwidth.

A rectangular array of radiating slots has been selected. Such aperture is separable one [7], so it is possible to use linear aperture distributions to form independently the radiation pattern with different values of the beam width in the antenna principal planes. The 20 dB Chebyshev amplitude distribution for linear arrays has been used for this purpose. To realize such distribution in the antenna aperture, the antenna is designed in the manner shown in Fig. 10, where two “building” blocks: *Left* and *Right*, from total 16 are shown. There are two radiating subarrays in each block.

The wideband slots and the waveguide described above have been used in the antenna design. The antenna contains two main layers: radiating and feeding ones (see Fig. 10). The radiating layer consists of 32 slotted subarrays with longitudinal slots (16 in each half). A center-feed design is used here. The feeding of the radiating layers is organized by means of crossed feeding arrays, which are coupled with radiating ones via inclined slots. The feeding arrays are end-fed, and the number of slots was selected to be equal two per subarray. Due to the subarraing used, the feeding layer has 16 individual inputs (8 in each half), and a feeding network is assumed.

The feeding network for the 16 inputs of the antenna feeding layer is of a parallel type based on matched E-plane T-junctions. It is organized identically for each 8 inputs of both antenna halves in the manner shown in Fig. 11. The feeding networks of the antenna halves are joined by an additional E-plane T-junction. The distribution of the subarray feed amplitudes A_i $(i=1, 2,...8)$ approximates the required aperture distribution, and the $\Delta\phi$ is a deliberately introduced phase shift. This phase shift is the sum of phase shifts in each branch of the feeding tree (see Fig. 11). The phase distribution inside each block is constant. So, the phase is changed discontinuously from one block to another.

The reason for the introduction of the phase shift $\Delta\phi$ is as following. In the case of in-phase antenna feeding ($\Delta\phi = 0$), reflections from the all inputs are summarized and the overall VSWR can be high. In order to prevent this effect, we introduce this phase distortion in the antenna E-plane phase distribution. To suppress completely the reflection and to achieve the ideal case of VSWR=1, the phase shift should be equals 45°, which is determined as 360° divided on the number of the building blocks.

However, such phase shifts results in some distortions of the antenna radiation pattern, like inclination of

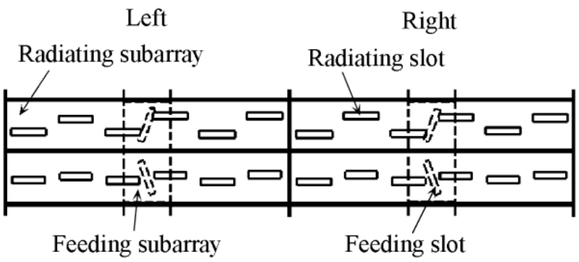


Fig. 10. Two building blocks (*Left* and *Right*) of 16 of the SWA

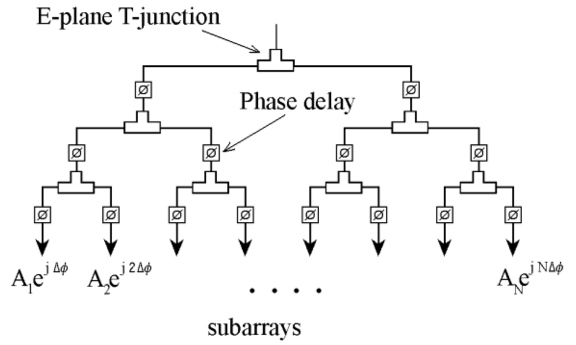


Fig. 11. The structure of the feeding network for the antenna half.

the antenna beam and growth of the side lobes. To reduce these distortions, the phase shift should be minimized. So, some compromise should be found for this shift. In our case, this compromise value is 30°, when the VSWR is less than 1.4 in the operating frequency band, and the distortions have acceptable values.

To validate the antenna design, an FDTD simulation of the complete antenna has been performed. The simulation has confirmed that the beam of 4°×6° is formed. The antenna gain, calculated by taking into account the feeding network, in the operating frequency band is shown in Fig. 12. It is seen that the gain is around 30 dB, and it has a small variations (±0.5 dB) within the bandwidth of about 1.7 GHz.

Simulation results on the VSWR are illustrated in Fig. 12. It is seen that this value is less than 1.4 in the frequency band from 9.15 GHz to 10.85 GHz, which is larger as compared to the required frequency band. It should be stressed that this result is due to the usage of the introduced phase shifts between the feeding blocks.

The phase shifts, as it was noted above, may cause some antenna pattern distortions in the E-plane. This pattern is shown in Fig. 13a for various values of the frequency. It is seen that there is a beam inclination of about 3°, which slightly depends on the operating frequency. The beam width in this plane is 4°.

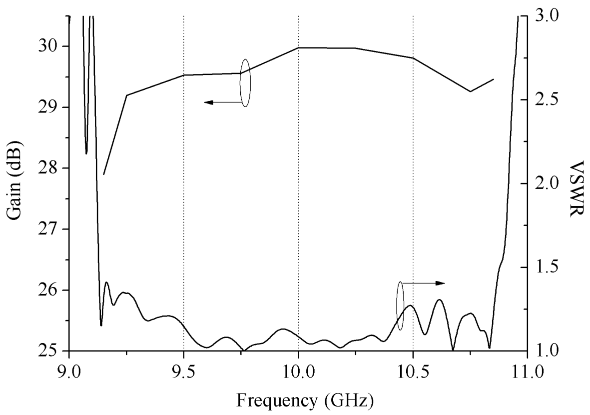


Fig. 12. Gain and VSWR of the designed antenna with the matched feeding network vs. the frequency.

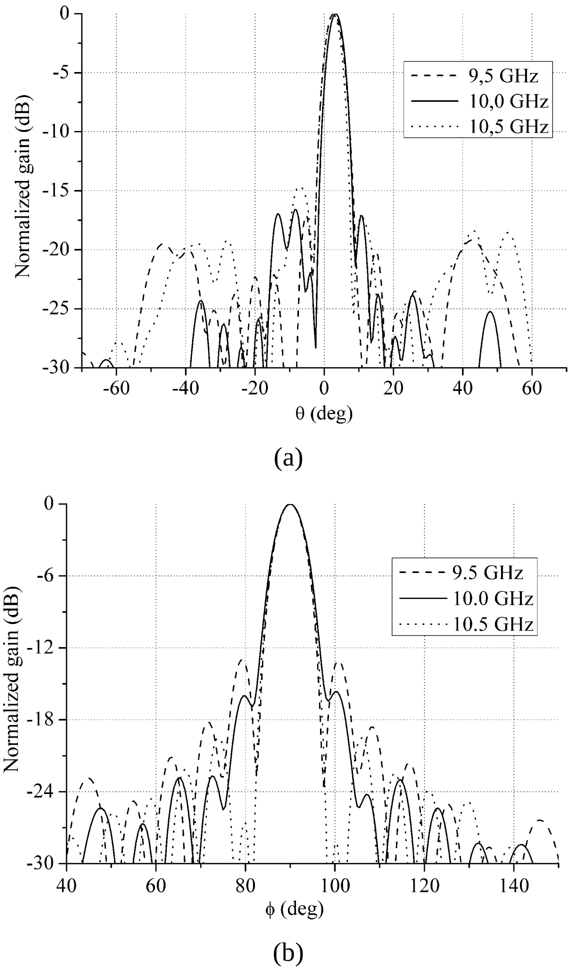


Fig. 13. Simulated radiation pattern of the designed antenna: a) E-plane; b) H-plane

The radiation pattern in the H-plane is illustrated in Fig. 13b. There is no beam inclination because of the homogeneous phase distribution in this plane. However, the frequency value has a rather pronounced effect on the level of sidelobes.

Simulation results confirm that the designed antenna complies with the formulated requirements. The dimensions of the antenna are 365×260×34 mm^3 what makes it attractive for applications in airborne SAR and other radar systems.

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