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Research Article

Low Sidelobe Level Pattern Synthesis of 2-D Slot Array Antenna Based on Ridged Waveguide

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Slotted waveguide antennas have received much attention due to features such as low loss, high efficiency, and high power capacity. In this article, a 2-D slot array antenna based on a ridged waveguide with a low level of side lobe is synthesized. The antenna consists of four slotted ridged waveguides, each of which consists of eight slots as the radiating elements. A fast and easy way is proposed to synthesize the aperture distribution in the H-plane. Further, a corporate feed network based on ridged waveguide is designed to feed the antenna. The feed network is designed such that the desired aperture distribution in the E-plane is achieved. A prototype of the antenna is fabricated and measured. The measured sidelobe levels in the H- and E-planes are, respectively, -24.5 dB and -23.9 dB, and the reflection coefficient of the antenna is -19 dB at the design frequency, indicating the accuracy of the design procedure. The measured antenna gain is approximately 20.4 dBi at the entire frequency band. The stable radiation pattern of the antenna makes the antenna suitable for radar applications.

1. Introduction

Slotted waveguide antennas (SWAs) have been employed in many applications such as radar, space, and wireless communications for decades due to their interesting features such as low loss, high power capacity, and high efficiency [1–7]. A conventional slotted waveguide array antenna consists of a series of shunt slots displaced on alternate sides of the centerline of the broad wall of a waveguide having a standard width of $0.7\lambda_0$. This structure has some drawbacks such as high cross polarization, a second-order beam, and a limited E-plane scanning angle which degrades the antenna efficiency [8, 9]. In this regard, many researchers try to propose different designs of SWAs such as design with corrugated narrow walls [10], SWA with untilted slots on the narrow wall [11], or designs using the irises close to slots [12]. However, these structures are difficult to demonstrate. Moreover, synthesis of the aperture distribution is not easy in these structures. It is shown that using the ridge inside the waveguide can improve the performance of SWA [13, 14]. It is shown that a ridged waveguide can decrease the width of the SWA to $0.5\lambda_0$. Therefore, apart from decreasing the SWA dimensions, the scanning angle up to the endfire position can be achieved without producing grating lobes [15, 16]. Moreover, it is shown that using a ridge inside the waveguide causes a better radiation pattern where low level of sidelobes is desired. Hence, the 1-D slot array antenna based on ridged waveguide has attracted a lot of attention in recent years [17–22]. In 2-D type, however, there has not been any literature, and thus, the 2-D type design is deprived of the proposed attractive features. It is of note that the available literature on conventional 2-D SWA, without utilizing ridge, is composed of some SWAs placed next to each other and fed through a series feed network [23] or a corporate one [25–27]. However, as illustrated in [24, 25], a corporate feed network can provide better impedance bandwidth than series one. In this article, a 2-D slot array antenna based on a ridged waveguide with a low level of side lobe is synthesized. A corporate feed network based on a ridged waveguide is designed to feed the antenna which is designed such that the desired aperture distribution in the vertical plane is achieved.

Apart from offering a 2-D ridged SWA with low sidelobe level (SLL), a fast and easy synthesis method is presented based on which the aperture distribution in the horizontal plane is synthesized. It is of note that, according to the previous literature, two methods are utilized to synthesize the low SLL pattern. The first one is obtaining the conductance for each slot offset, then satisfying the impedance matching subject to the desired aperture distribution such as [17, 21, 26]. The second method is obtaining the radiated power, and consequently, the voltage amplitude for each slot offset such that the desired distribution is achieved [28]. It can be mentioned that all the methods are time-consuming because the designer must obtain an iterative procedure for each slot offset, which takes a lot of time. Through the proposed approach, all offset slots are linked to the first slot. Therefore, obtaining the desired aperture distribution is subject to determining the offset of the first slot. This, effectively, reduces the simulation time. In the following section, the proposed 2-D ridged SWA together with the proposed synthesis procedure is presented and discussed.

2. Fundamentals of Slotted Ridged Waveguide Antennas

A conventional slotted waveguide antenna is formed by etching arrays of longitudinal slots normally on the broad wall of a waveguide. The slots have the length of $\lambda_0/2$ and are located on the alternate sides of the waveguide centerline. Further, they are placed by $\lambda_g/2$ from each other, where λ_g is the guide wavelength. This structure has a limited scanning angle due to the waveguide width of about 0.7 λ_0. The offsets of the slots from the waveguide centerline control the excitation magnitude of the slots. By proper design of the offsets, a desired aperture distribution is achieved. To obtain an aperture distribution with a desired SLL, the appropriate offsets, O_i, for the slots are obtained by [1]

$$O_i = \left(\frac{W}{\pi}\right) \sin^{-1}\left(\sqrt{\frac{g_i}{G}}\right). \tag{1}$$

$$G = 2.09\left(\frac{a\lambda_g}{b\lambda_0}\right) \cos\left(\frac{\pi\lambda_0}{2\lambda_g}\right)^2. \tag{2}$$

From (1) and (2), one can synthesize a slotted waveguide antenna to achieve a desired SLL. By inserting a ridge inside the waveguide, the fundamental mode of the waveguide excites at a lower frequency due to the increase in λ_g. This causes a wide scanning angle in the E-plane due to the reduction of the waveguide width to 0.5 λ_0. The electromagnetic field distribution inside the waveguide is significantly altered due to the coupling between the ridge and the slot. This makes the synthesis of the desired aperture distribution a difficult task. The conventional way of synthesizing the antenna is found in [21] where the conductance of the slot relative to its offset is calculated utilizing a full-wave simulation software. This, however, is a time-consuming task. In the next section, the proposed 2-D slotted ridged waveguide antenna is explained. Further, our synthesis procedure to design such a 2-D slot array is discussed.

3. Design Principles for the Proposed 2-D Slot Array Antenna

The structure of the proposed 2-D slot array antenna based on the ridged waveguide is shown in Figure 1(a). As shown, the structure consists of two parts: the 2-D slotted ridged waveguide antenna and the corporate feed network. The slot array antenna consists of four slotted ridged waveguides, each of which consists of eight slots. The corporate feed network is a four-way power divider that splits the input signal of the structure into four output signals, which feed the slot array antenna with minimum losses. The output signals are unequal in amplitude but equal in phase. Our aim is to achieve a low SLL radiation pattern in both the H and E-planes. The low SLL pattern in the H-plane is realized through proper design of the slotted ridged waveguides, whereas in the E-plane this is obtained by appropriate design of the corporate feed network. In the following subsections, the design of both parts is illustrated. It is of note that the design frequency of the proposed antenna is 8.75 GHz and the operation bandwidth is 8.5-9 GHz. Further, the simulations were performed by the well-known package CST microwave studio.

3.1. Design of the Slotted Ridged Waveguide Antenna. As depicted previously, the proposed antenna consists of four similar ridged waveguides, each contains of eight radiating elements. The geometry of a 1×8 slotted ridged waveguide is shown in Figure 1(b). The waveguide has a width of $W = 19$ mm and a height of $H = 10$ mm. As shown in Figure 1(b), the ridge has a uniform profile along the antenna, which has the height h_r and the width w_r. The dimensions of the ridge are chosen such that the dominant TE_{10} mode is excited at 5.2 GHz. To this end, the value of h_r and w_r is considered 5.8 mm and 3 mm, respectively. The radiating slots in Figure 1(b) have the length $L = \lambda_0/2$ and are located on alternate sides of the waveguide centerline. Further, to feed the slots with equal phase, they are placed by $\lambda_g/2$ from each other, where λ_g is the guide wavelength. Such dimensions make the antenna radiates at broadside. From this figure, each slot has the offset O_i ($i = 1, 2, \ldots 8$) from the waveguide centerline. The values of O_i determine the aperture distribution of the antenna. It is of note that to have a symmetrical pattern, the slots' offsets must have a symmetrical value relative to the waveguide center. Therefore, $O_i = O_{9-i}$. The objective is to determine the values of O_i to achieve a radiation pattern with -25 dB SLL. In this paper, we use a new method to determine the offset values.

According to the well-known Chebyshev distribution, to achieve -25 dB SLL, an eight-element array must have the amplitude distribution shown in Figure 2. Considering the first element as the reference, the amplitude of the others can be interpreted relative to this element. For example, the second element has an amplitude of 1.54 relative to the reference element. The third and

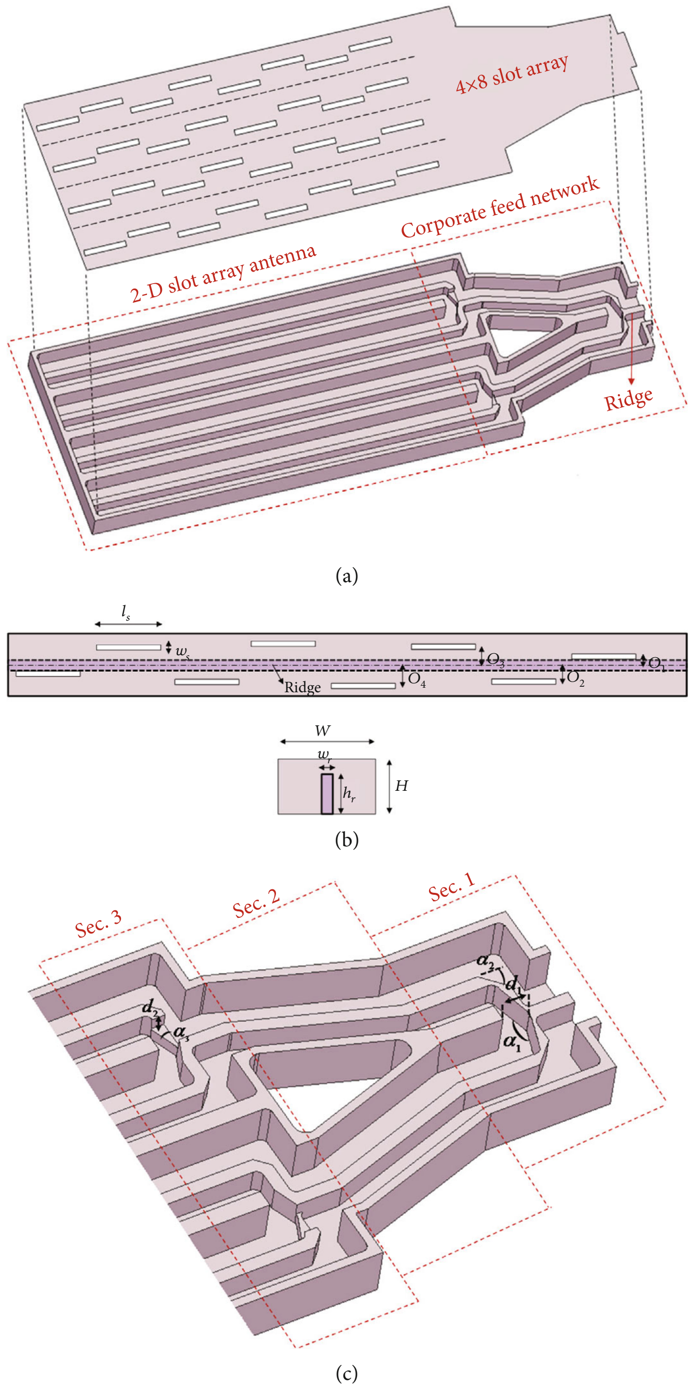

Figure 1: The configuration of the proposed 2-D slotted ridged waveguide antenna. (a) 3-D view of the structure. (b) Details (the top and the cross-section view) of a 1 × 8 slotted ridged waveguide and (c) Details of the corporate feed network.

fourth elements have relative amplitudes of 2.23 and 2.64, respectively.

Next, using the CST software, a family of slotted ridged waveguide antennas is simulated in which the slots' offsets are varied from 0 to 9 mm. In each case, a field-measuring probe is placed in the center of a slot through which the electric field is probed. The results (normalized form) of the proposed parametric study are provided in Figure 3. From this figure, a nonlinear relation between the offset value and the electric field intensity can be observed. Utilizing the curve-fitting approach, the following relation can be written between the slot offset and the electric field intensity:

$$E = 0.98 \sin (165.3\, O). \tag{3}$$

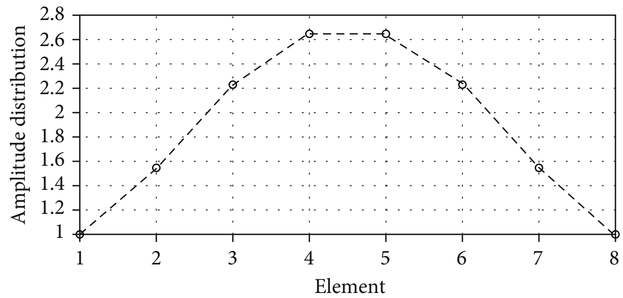

Figure 2: The relative amplitude distribution of the elements in eight-element array to achieve -25 dB SLL.

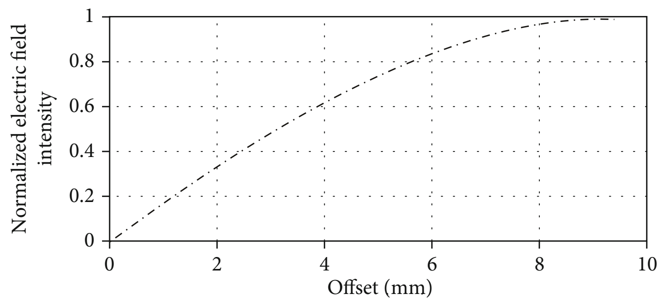

Figure 3: The relation between the electric field intensity within the slot and the slot offset.

It is of note that (3) is established for each element of the proposed array. Therefore, (3) can be written in the following general form:

$$E_i = 0.98 \sin\left(165.3\, O_i\right). \tag{4}$$

Now, regarding Figure 2 in relative amplitude distribution of the elements, one can find the following relations for the second, the third and the forth slot:

$$\frac{E_2}{E_1} = \frac{\sin\left(165.3 O_2\right)}{\sin\left(165.3 O_1\right)} = 1.55, \tag{5a}$$

$$\frac{E_3}{E_1} = \frac{\sin\left(165.3 O_3\right)}{\sin\left(165.3 O_1\right)} = 2.23, \tag{5b}$$

$$\frac{E_4}{E_1} = \frac{\sin\left(165.3 O_4\right)}{\sin\left(165.3 O_1\right)} = 2.65. \tag{5c}$$

Through the above relations, the offset of each slot relative to the first slot can be found as

$$O_2 = 0.006 \sin^{-1}\left(1.55 \sin\left(165.3 O_1\right)\right), \tag{6a}$$

$$O_3 = 0.006 \sin^{-1}\left(2.23 \sin\left(165.3 O_1\right)\right), \tag{6b}$$

$$O_4 = 0.006 \sin^{-1}\left(2.65 \sin\left(165.3 O_1\right)\right). \tag{6c}$$

According to the above relation, once the first offset is determined, the others can be obtained. Our strategy is that the first offset is varied in the interval (0, 1.5 mm); then the reflection coefficient of the antenna is observed to reach a predetermined value. Once the desired reflection coefficient

Table 1: The values of O_i.

i	1	2	3	4
O_i (mm)	1.1	1.8	2.8	3.3

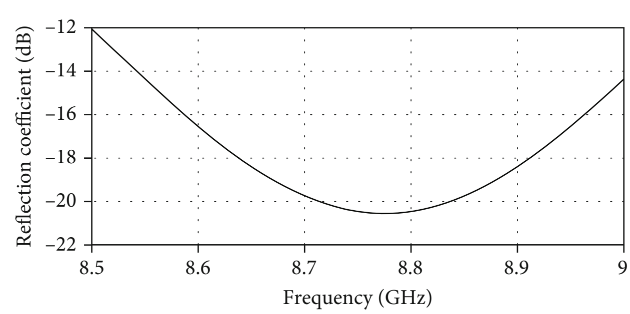

Figure 4: The reflection coefficient of the synthesized eight-element array.

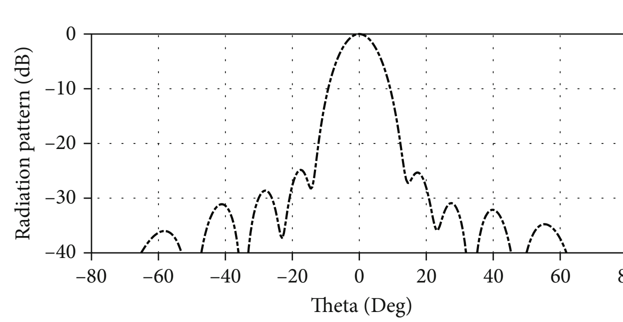

Figure 5: The H-plane radiation pattern of the synthesized slotted ridged waveguide antenna.

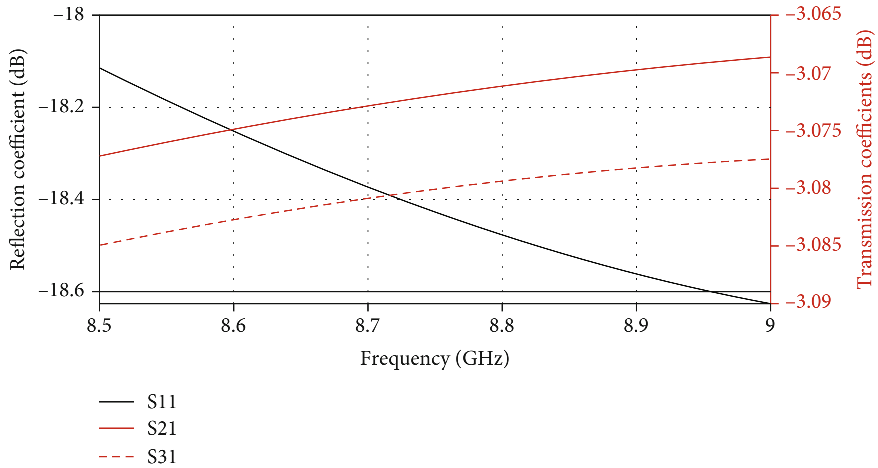

Figure 6: The reflection and transmission coefficients of the first section of the proposed feed network.

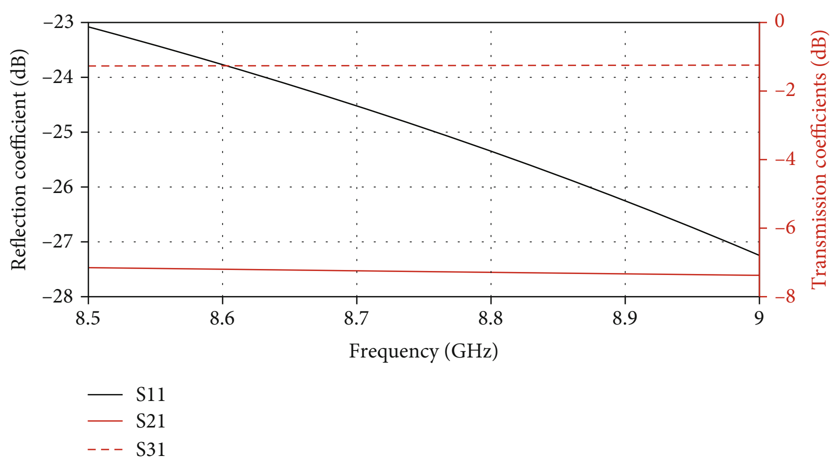

Figure 7: The reflection and transmission coefficients of the third section of the proposed feed network.

is achieved, the solution is terminated. The procedure is performed over the well-known genetic algorithm tool in CST software. The offset values produced through the proposed method are listed in Table 1.

Figure 4 shows the reflection coefficient of the synthesized eight-element slot array antenna. As can be seen, at the design frequency of 8.75 GHz, the antenna has the reflection coefficient of -20.4 dB which indicates that the goal of optimization has been achieved. From the figure, the reflection coefficient is well below -10 dB at the desired frequency band of 8.5-9 GHz.

Figure 5 shows the H-plane radiation patterns of the synthesized slotted ridged waveguide antenna. As can be seen, the H-plane SLL of the synthesized antenna is -24.8 dB, indicating the accuracy of the proposed synthesis procedure. Finally, the 2-D slot array antenna is formed by placing four antennas next to each other. It is of note that the synthesis of the E-plane pattern is realized through the proper design of the corporate feed network which is portrayed in the next section.

3.2. Design of the Corporate Feed Network. As mentioned previously, by properly feeding the four-port slot array antenna, the low SLL pattern in the E-plane is realized. This is achieved through the proper design of the corporate feed network. Our aim is to divide the input signal such that the four ports of the proposed 2-D antenna are fed by the amplitude coefficients 0.48 : 1 : 1 : 0.48. These amplitudes result in a radiation pattern with a -25 dB SLL, according to the Chebyshev distribution. The desired feed network consists of three sections. The first section, as shown in Figure 1(c), is a two equal way power divider which produces the output signals with minimal losses. In this case, by adjusting the angles α_1 and α_2 and the distance d_1, good reflection coefficient together with 3 dB power division is achieved. The values of α_1, α_2 and d_1 are, respectively, 148°, 45° and 7.8 mm. It is of note that the height and the thickness of the ridge along the network are the same as depicted in Figure 1(b). Figure 6 shows the reflection and transmission coefficients of this section. From this figure, it can be seen that the 3 dB power

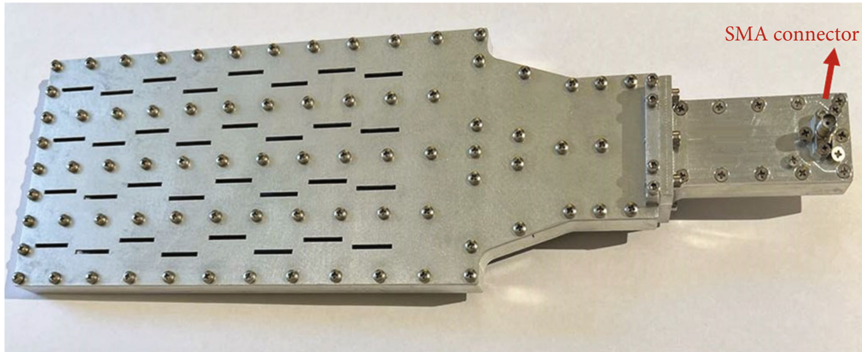

Figure 8: Photograph of the proposed fabricated antenna.

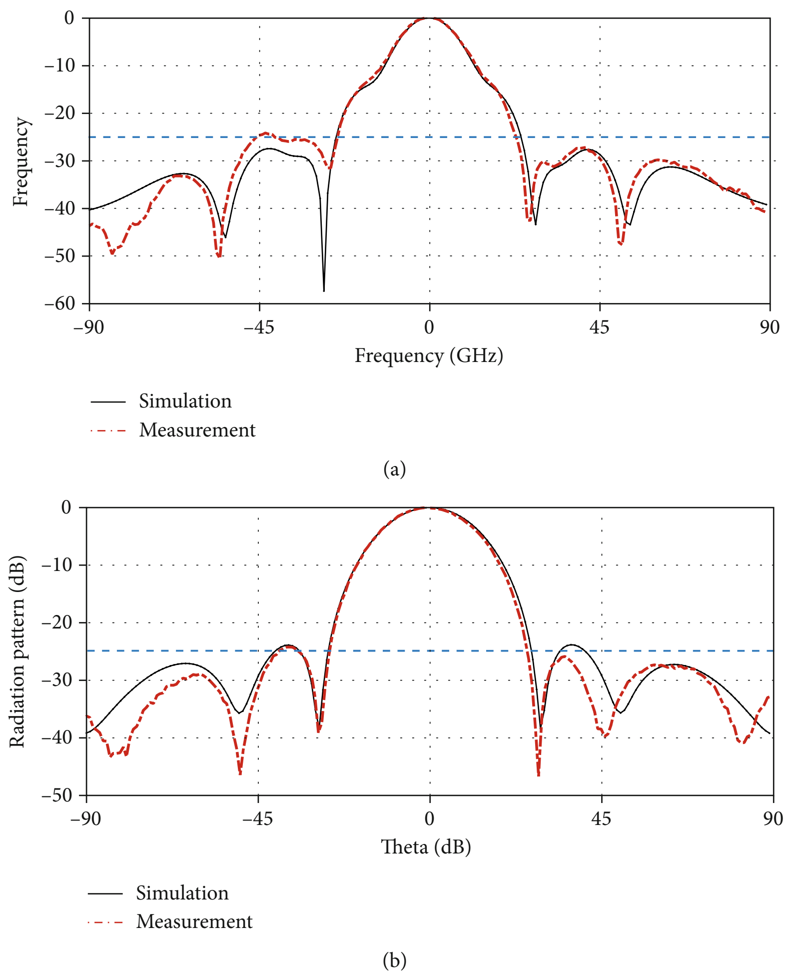

Figure 9: The simulation and measurement radiation patterns of the proposed slot array antenna at the design frequency of 8.75GHz. (a) H-plane pattern. (b) E-plane pattern.

division is well realized with a good reflection coefficient (below -18 dB).

The second section is a ridged waveguide transmission line which transmits the power between the first section and the third one. The third section divides the input signal at a ratio of 0.48 : 1. It is of note that this section is responsible for acquiring the required amplitude coefficients. The determining parameters for the proper working of this section are the angle α_3 and the distance d_2. The appropriate values for these parameters are $\alpha_3 = 22.6^o$ and $d_2 = 3$ mm. The reflection and transmission coefficients of this section are shown in Figure 7. From this figure, the desired power division can be seen. The reflection coefficient is below -23 dB.

As mentioned before, the proposed three sections form the corporate feed network which feeds the antenna array

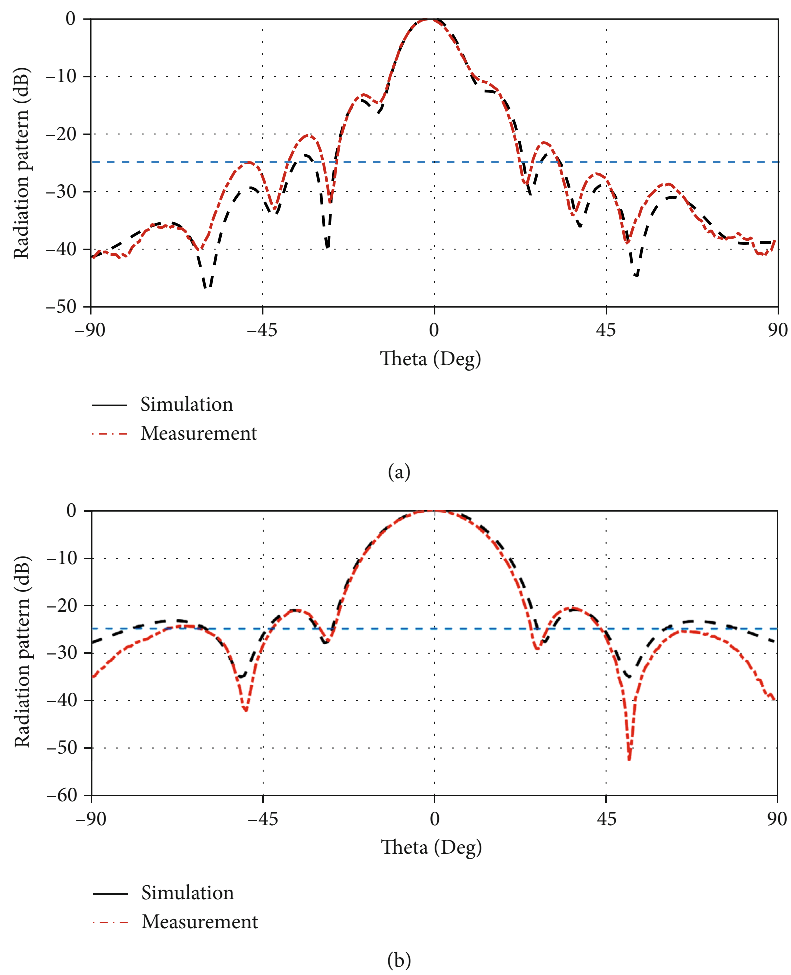

FIGURE 10: The simulation and measurement radiation patterns of the proposed slot array antenna at 8.5GHz. (a) H-plane pattern. (b) E-plane pattern.

such that the desired aperture distribution in the E-plane is achieved. At this point, the antenna array is synthesized in both the E- and H-planes. In the next section, the radiation characteristics of the proposed 2-D antenna are discussed. The measurement results are also presented.

4. Simulation and Measurement Results

Based on the principles illustrated previously, the proposed 2-D slotted ridged waveguide antenna is simulated and a prototype of the antenna is fabricated and measured. It is of note that a simple coax-to-ridge waveguide transition as depicted in [29] is designed to feed the antenna. Figure 8 shows the fabricated antenna. The simulated and measured radiation patterns at the design frequency in both the H- and E-planes are provided in Figure 9. From Figure 9, the simulated radiation patterns are in good agreement with the measured ones. As depicted in Section 3, the low SLL pattern in the H-plane is realized through the proper design of the slots' offsets. This is obtained through the proposed synthesis procedure. The measurement SLL of the H-plane pattern (Figure 9(a)) is -24.5 dB, indicating the accuracy of the proposed synthesis procedure.

From Figure 9(b), the measurement SLL of the E-plane pattern is -23.9 dB. This indicates that the proposed corporate feed network feeds the antenna array over the desired amplitude coefficients, resulting in the desired radiation pattern in the E-plane. The simulation and measurement radiation patterns of the antenna at 8.5 GHz and 9 GHz are plotted in Figures 10 and 11. From this figure, it can be found that the antenna has a stable radiation pattern over the entire frequency band. The simulation and the measurement patterns are in good agreement.

The gain of the antenna is measured over the operating frequency band. The results are provided in Figure 12. From the figure, the difference between the simulation and the measurement results is below 0.6 dB. This difference is due to the fabrication process. Further, the antenna gain is approximately 20.4 dBi at the entire frequency band. The stable radiation pattern of the antenna makes the antenna suitable for radar applications.

The simulated and measured reflection coefficient of the proposed 2-D antenna is shown in Figure 13. As mentioned before, the little difference between the simulation and measurement results is due to the fabrication procedure. From this figure, the measured reflection coefficient

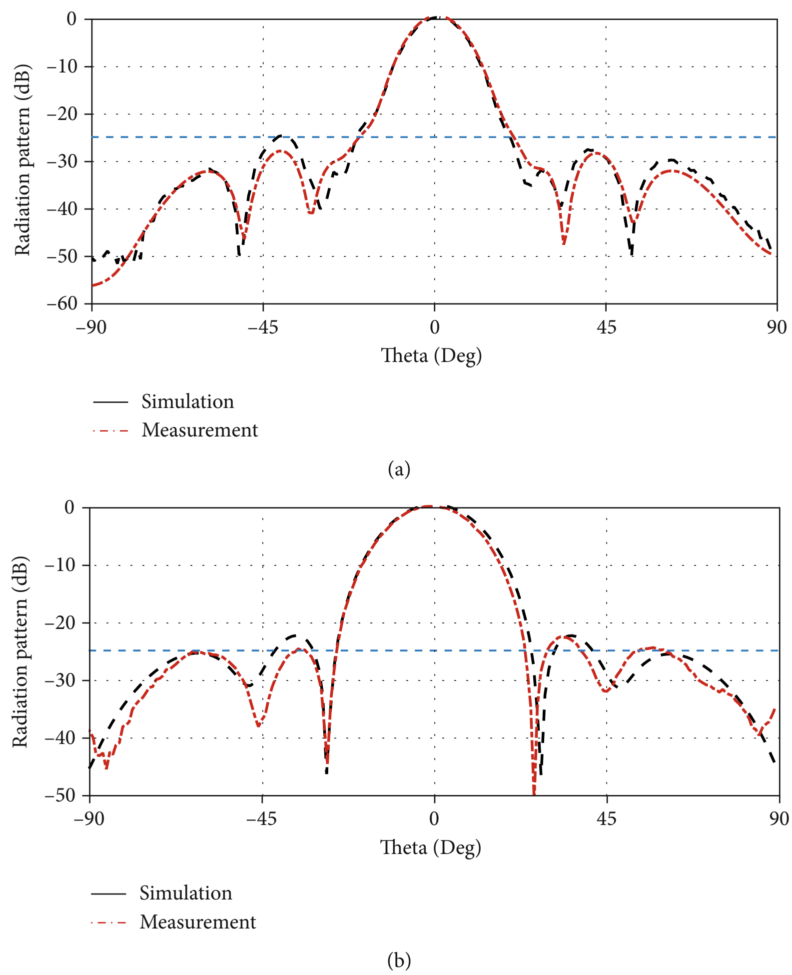

FIGURE 11: The simulation and measurement radiation patterns of the proposed slot array antenna at 9GHz. (a) H-plane pattern. (b) E-plane pattern.

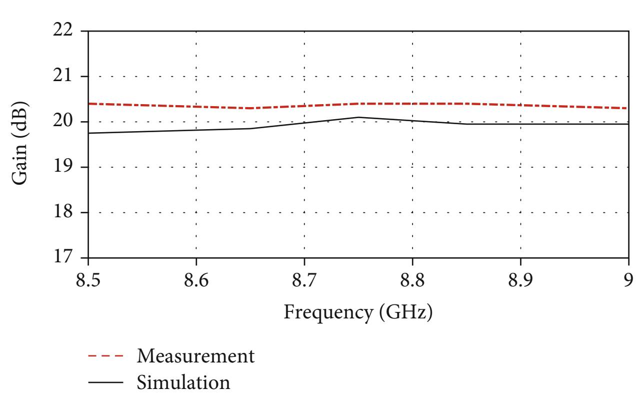

FIGURE 12: The simulation and measurement gains of the proposed slot array antenna at the operating frequency band.

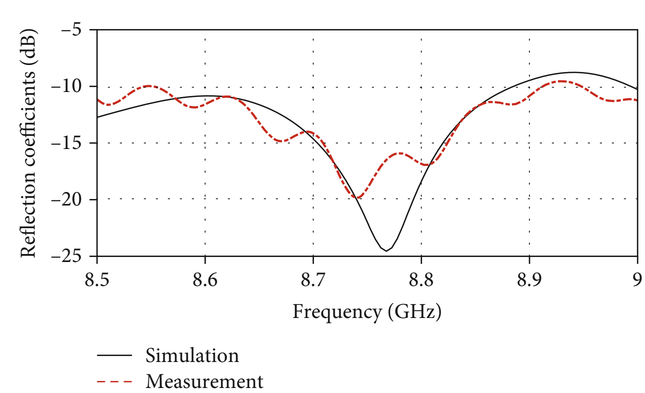

FIGURE 13: The simulation and measurement reflection coefficients of the proposed slot array antenna.

has a value of −19 dB at the design frequency of 8.75 GHz, making the antenna suitable for use in radar systems. Finally, it has to be mentioned that due to using the ridge inside the waveguide, the dimensions of the antenna have been reduced by 20% compared with a conventional 2-D slot array antenna.

5. Conclusion

A 2-D slot array antenna based on a ridged waveguide to achieve low sidelobe level (SLL) is proposed. The structure consists of two parts: the 2-D slotted ridged waveguide antenna and the corporate feed network. The low SLL pattern in the H-plane is achieved by properly determining the slots' offsets. A fast and easy way is proposed to determine the offset values. Considering the required aperture distribution and following the relationship between the electric field intensity within the slot and its offset, all offsets are described relative to the first one. Therefore, obtaining the desired H-plane aperture distribution is subject to determining the offset of the first slot. Therefore, the offset value of the first slot is optimized to achieve a reflection coefficient below the predetermined value of -15 dB.

The low SLL pattern in the E-plane is realized by properly designing the corporate feed network which is based on ridged waveguide. A prototype of the antenna is fabricated and measured. The measured H- and E-plane sidelobe levels are, respectively, -24.5 dB and -23.9 dB. The reflection coefficient of the antenna is measured which is -19 dB at the design frequency, indicating the accuracy of the design procedure. The measured antenna gain is approximately 20.4 dBi at the entire frequency band. The stable radiation pattern of the antenna structure makes the antenna suitable for radar applications.

Data Availability

No underlying data was collected or produced in this study.

Conflicts of Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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