# A Low-Profile Hollow Waveguide Slot Array Antenna with Full-Corporate Feeding Network at K-Band

**Yunus Emre Yamaç[1], Alper Çalışkan[2], Ahmet Serdar Türk[2], and Ahmet Kızılay[2]**
[1]The Scientific and Technological Research Council of Turkey, Informatics and Information Security Research Center, 41400, Kocaeli, Turkey
[2]Department of Electronic and Communication Engineering, Yildiz Technical University, 34220, Istanbul, Turkey

Corresponding author: Alper Çalışkan (e-mail: alperc@yildiz.edu.tr)

**ABSTRACT** A hollow waveguide slot array antenna with a total volume of $338\times106.5\times28.9$ mm$^3$ is proposed as a sensor for millimeter-wave short-range radar applications at K-band. The proposed antenna consists of a radiating slot plate with $8\times32$ slots, a middle plate with 64 cavities and apertures, and a full-corporate-feeding network. The antenna structure is fabricated with these three parts in which the sub-array feeding technique is employed. The proposed antenna accomplishes high gain and efficiency with a straightforward fabrication, and it operates between $23.72-25.30$ GHz frequencies with 6.45% bandwidth. The measured directivity is 32.1 dBi, and the realized gain of the antenna is attained as 30.84 dBi at 24.5 GHz center frequency with 74.8% total efficiency. In spite of fabrication imprecision and connector losses, these measurements are obtained sufficiently consistent with simulations.

**INDEX TERMS** Full-corporate feeding network, K-Band, Waveguide slot array.

## I. INTRODUCTION

HOLLOW waveguide slot array antennas (WSAAs) can be commonly employed for military and civil radar applications requiring high gain and high power due to their low loss and sidelobes, together with their low profile structure. However, conventional WSAAs are deficient in bandwidth [1] and show beam distortions in wideband operation [2] and require an increasingly complex feeding network design to make a two-dimensional array [3]. The main point of designing a WSAA with a good radiation performance is contriving a suitable and low-profile feeding network. Various feeding structures to increase the bandwidth and prevent distortions in the antenna beam have been presented in the literature to provide appropriate phase and amplitude distribution [4]–[6]. In addition, alternating phase-fed WSAAs have been affected by long feed lines while increasing array size, and some cavity-backed methods have needed constant element spacing to avoid grating lobes in some studies [7]–[13].

A full-corporate feed network is proposed for WSAAs to remedy these problems by a sub-array feeding technique [14], [15]. Also, this feeding network has been arranged to employ an amplitude-tapering with Taylor synthesis to obtain better sidelobes [16], [17]. Uniform radiating beams in broadband have been assured through these antenna structures with full-corporate feeding networks [18], [19]. Moreover, the polarization has been easily altered by adding a new plate above the apertures of the antenna [20]–[22], as well as EBG-integrated ridged waveguides have also been utilized at high frequencies for fabrication to achieve high efficiency and low-cost [19].

Herein, an antenna design is performed at K-band for short-range surveillance radar systems for which the full-corporate-feed network with cavities is chosen and designed to reach desired radiation pattern performance due to the above reasons and system requirements of radar application. In order to prevent the profile of the antenna from increasing, the antenna structure is made up of only three essential parts: the radiating slot plate, the aperture and cavity plate, and the feeding network. These three layers are produced by appropriate methods, thus achieving the desired antenna gain and efficiency with a low-profile antenna. The antenna acquires a compact structure with reasonable bandwidth, and therefore WSAA is suitable for communications and radar system applications where compact size and wide bandwidth are required [23], [24].

## II. ANTENNA DESIGN AND FABRICATION

In this study, the full-corporate feeding method encountered in some studies in the literature was used to obtain the desired bandwidth and antenna radiation pattern. This design method can significantly improve the impedance bandwidth and sidelobe levels (SLLs) of traditional WSAA designs through subarray feeding. The antenna structure based on this feeding method is depicted in Fig. 1. Here, the power has to be divided six times to feed each $2\times2$ slots, and this power distribution is accomplished by the E-plane T-junctions where all septums are tuned and optimized to achieve the desired

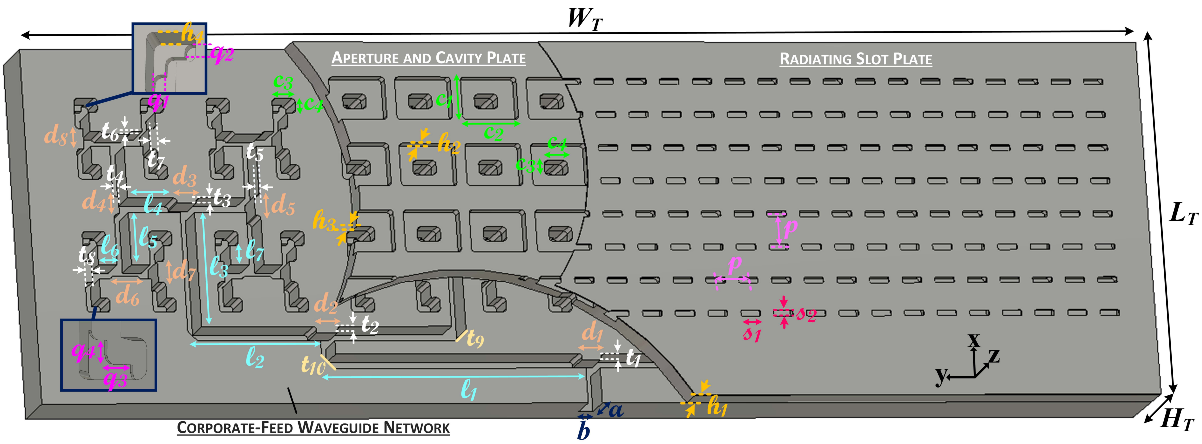


**FIGURE 1.** Configuration parameters of the proposed WSAA.


**FIGURE 2.** Fabricated plates of the WSAA prototype.

bandwidth. All power dividers are on the same layer in the feeding network, and an input feeding connector is placed on the side of the antenna. The antenna thereby acquires a lower profile structure, and the power has been distributed to every four slots with the dividers by ensuring optimal impedance matching for the operation band. The subarray is extended to the whole array antenna through the T-junction power dividers and hollow waveguides. The designed power dividers feed the array elements with uniform amplitude and phase. In our previous work, an antenna structure which is consist of the unit cell of this WSAA design has been studied in [15]. The main radiating structure of the antenna is inspired from our previous study in [15], and all parameters are tuned manually in achieving the final structure of the proposed antenna in this paper. As seen in Fig. 1, the design parameters are tuned step by step, starting from the unit cell to achieve wide bandwidth and high gain performance. Besides, it should be noted that the inter-element spacing between the slots is 10 mm to accomplish a formal array factor without grating lobes and the best possible gain.

As mentioned earlier, in order to fabricate, the WSAA is divided into three layers: the feeding plate, apertures and cavities plate, and radiating slots plate. These three plates are mounted together by screws, the distances between the screws are shortened to prevent possible wave leakage between the radiating slot and cavity plates. The design parameters of the WSAA are given in Fig. 1 and the production prototype in Fig. 2. Therefore, the total size of the antenna is $338 \times 106.5 \times 28.9$ mm$^3$, and the parameters are as follows: $W_T = 338$, $L_T = 106.5$, $H_T = 28.89$, $a = 10.668$, $b = 4.318$, $c_1 = 12.8$, $c_2 = 16.93$, $c_3 = 7$, $c_4 = 4.318$, $d_1 = 7.736$, $d_2 = 8.342$, $d_3 = 7.745$, $d_4 = 7.139$, $d_5 = 7.612$, $d_6 = 9.925$, $d_7 = d_8 = 8.086$, $h_1 = 9.72$, $h_2 = 3.8$, $h_3 = 5.32$, $h_4 = 8.523$, $l_1 = 80$, $l_2 = 40$, $l_3 = 34.341$, $l_4 = 13.9685$, $l_5 = 15.682$, $l_6 = l7 = 5.682$, $p = 10$, $q_1 = 1.65$, $q_2 = 1.796$, $q_3 = 2.668$, $q_4 = 2.522$, $s_1 = 5.927$, $s_2 = 1.796$, $t_1 = 1.767$, $t_2 = 1.813$, $t_3 = 1.515$, $t_4 = t_5 = 1.616$, $t_6 = 0.968$, $t_7 = t_8 = 2.197$, $t_9 = 4.046$, $t_{10} = 5.34$ (All in mm).

The excitation of the antenna has been realized with a WR42 waveguide adapter. The dimensions of the feeding structure are also compatible with the WR42 standard dimensions (10.668–4.318 mm). For production, the slot aperture's edges are rounded with a radius of 0.1 mm for the laser cutting machine's sensitivity, where it should be noted that the wall thickness of the radiating plate is 0.6 mm, and this plate is made of stainless steel. The feeding network and the plate of the cavities and apertures have been fabricated using a computerized numerical control (CNC) milling machine, and these parts are aluminum. Also, one millimeter rounding is employed at the corner of these structures to tolerate errors due to the CNC machine's fabrication sensitivity.

## III. RESULTS AND DISCUSSION

The designed WSAA was produced as two prototypes, and one of the prototypes inside the measurement environment is

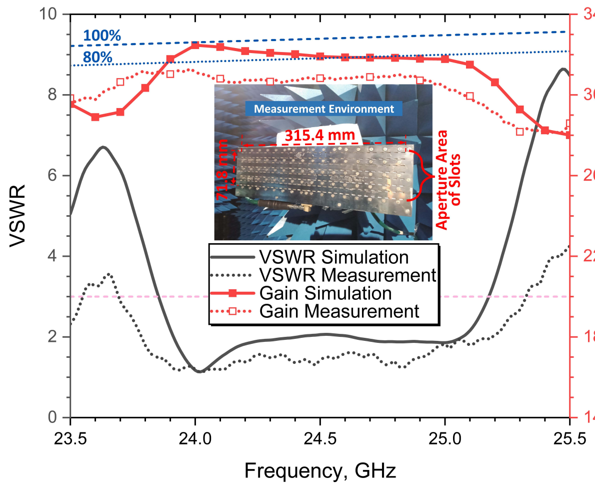


FIGURE 3. VSWR and realized gain characteristics of the antenna.

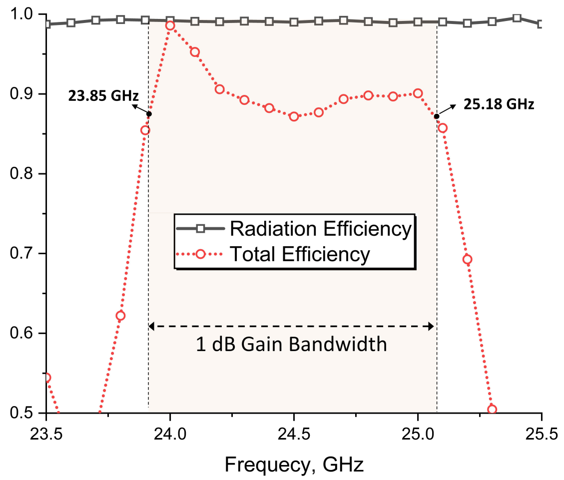


FIGURE 4. Numerical results of radiation and total efficiency as a function of frequency.

represented in Fig. 3. The reflection coefficient and pattern measurements were carried out in TUBITAK's antenna technologies and measurement systems laboratory. According to the simulation results, the operating frequency range of the antenna for the reference value of the VSWR is below 3 between 23.85 and 25.18 GHz frequencies. Also, according to the measurement, these frequencies are 23.72 and 25.3 GHz, respectively.

The reflection coefficients of the simulation of the antenna and the measurement of the fabricated prototype are compatible, as shown in Fig. 3. Therefore, the relative impedance bandwidth of the antenna in the simulation and measurement is 5.42% and 6.45%, respectively. However, the simulation and measurement results of the frequency-dependent gain changes of the antenna are also shared in Fig. 3. As easily can see from the figure, 1-dB gain bandwidths of the antenna agree well with the impedance bandwidths. Besides, the simulated radiation and total efficiencies are demonstrated in Fig. 4. As can be seen in this figure, the antenna exhibits a very high radiation efficiency due to its metallic structure, and the 1-dB gain bandwidth of the antenna agrees well with the impedance bandwidth. Furthermore, it can be useful to mention that all simulations are performed by time domain solver in the CST Microwave Studio Suite program. The simulation of the antenna takes 4.5 hours for about 33 million meshes with 128 GB RAM and AMD Ryzen 3900x processor.

Moreover, the minimum distance of the far-field region of the proposed WSAA is approximately 18 meters. The antenna has a linear polarized propagation, and also, the antenna's beam is relatively narrow. Taking into account all of these, the antenna pattern should be measured precisely. For this purpose, 3-D patterns at 24.5 GHz have been measured in an anechoic chamber using a commercially available spherical near-field measurement system. The antenna's directivity is achieved utilizing this 3-D pattern measurement. Then, the

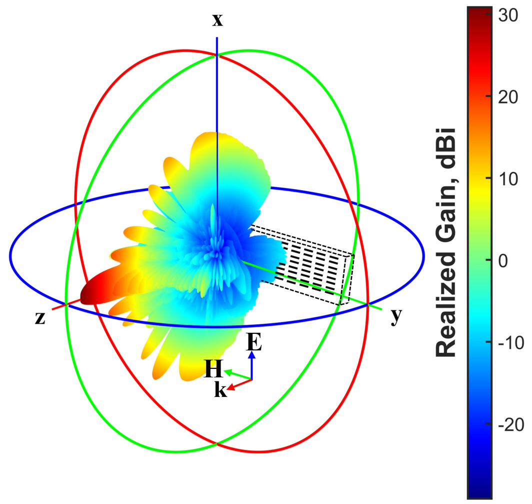


FIGURE 5. Measured 3-D pattern of the antenna at 24.5 GHz.

realized gain value of the antenna has been calculated by means of a reference antenna. The co-and cross-polarization patterns of the antenna have also been evaluated employing vertical and horizontal E-field probes. TUBITAK's antenna technologies and measurement systems laboratory carried out these measurements. The measurement result of the 3-D radiation pattern of the WSAA is shown in Fig. 5. The E- and H-plane patterns of the antenna at operating frequency are also given in Fig. 6 and Fig. 7, respectively. The exact numerical values of the radiation performance of the antenna are given by comparing with the simulation results in Table I. As can be seen from these results, the measurement results of the antenna are in perfect harmony with the simulations.

The proposed design is also compared in Table II with similar studies in the literature. The proposed antenna achieves a considerable gain and efficiency, as seen from the table. In addition, the SLL of the antenna is also adequate. On the

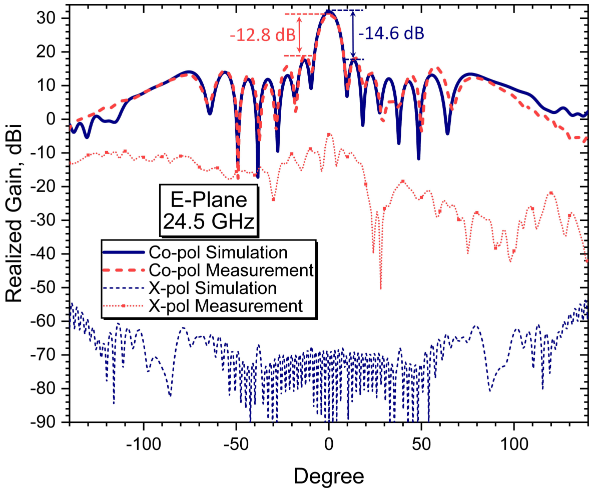


FIGURE 6. Simulated and measured E-plane radiation patterns of the antenna at 24.5 GHz.

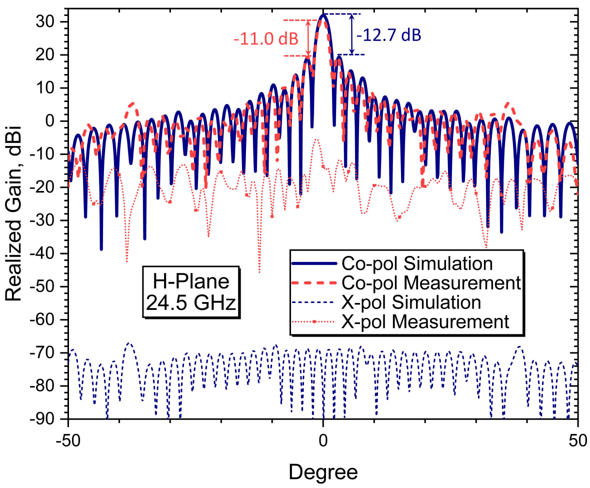


FIGURE 7. Simulated and measured H-plane radiation patterns of the antenna at 24.5 GHz.

other hand, some of the losses in the measurement results may be due to the connection points, manufacturing errors, material losses, and primarily because of not using more screws on the radiating slot plate to avoid wave leakage. Also, the measured SLL in Table I, is slightly different from the simulation due to the large size of the screw heads. Antenna performance can be improved with better and more precise manufacturing. Nevertheless, the results are still reassuring.

As a result, the manufacturing technique of the WSAA is quite simple, whereas the performance results are satisfactory. Also, the results can be improved with better and more precise production. If desired, thanks to the flexibility of this antenna structure, the upper frequency can be increased up to 27 GHz, sidelobe suppression can be applied by changing the power division ratios in the feeding structure, and the polarization can also be changed by adding an extra layer above the slots.

TABLE I. Comparison of the simulation and measurement of the proposed antenna for 24.5 GHz.

| Antenna parameters | Simulation | Measurement |
|---|---|---|
| Directivity | 32.50 dBi | 32.10 dBi |
| Realized Gain | 31.89 dBi | 30.84 dBi |
| Total Efficiency | 86.9% | 74.8% |
| HPBW | E-plane: 8.6°<br>H-plane: 1.90° | E-plane: 9.4°<br>H-plane: 1.77° |
| SLL | E-plane: -14.6 dB<br>H-plane: -12.7 dB | E-plane: -12.8 dB<br>H-plane: -11.0 dBi |

TABLE II. Comparison of the proposed antenna with previous studies.

| Ref. | Total Aperture Dimensions | Slot Numbers | Freq. (GHz) | 1dB Gain BW (%) | Gain (dBi) | Tot. Aper. Eff. (%) |
|---|---|---|---|---|---|---|
| [7] | $17.8\lambda_0 \times 14.3\lambda_0$ | 320 | 24.45 | 3.54 | 30.5 | 35 |
| [10] | $16.0\lambda_0 \times 16.0\lambda_0$ | 304 | 25.33 | 2.52 | 31.7 | 46 |
| [25] | $12.9\lambda_0 \times 5.2\lambda_0$ | 36 | 28.6 | 0.95 | 24.8 | 36 |
| This Work | $27.6\lambda_0 \times 8.7\lambda_0$ | 256 | 24.5 | 5.59 | 30.8 | 40 |

## IV. CONCLUSION

In this paper, a low-profile hollow WSAA with the full-corporate feeding network at K-band has been presented for surveillance radar applications. The 256-slot WSAA was designed in the 24-25 GHz range, and its performance has been demonstrated both in simulation and experimentally. The measured results were well consistent with the simulations. The proposed antenna's efficiency, gain, and 1-dB gain bandwidth are satisfactory. The available bandwidth and SLL of the proposed antenna have been deemed adequate as a short-range radar application. Also, the antenna has been designed to be produced rapidly without additional effort. This means that the proposed design and manufacturing method can provide low-cost and high efficiency at the millimeter-wave band for surveillance radar applications. Since the proposed antenna stays within the 5G frequency band and has the advantage of its low-profile structure, it can also be used in such applications with a few minor modifications. Also, proposed antenna operates within the New Radio band, defined as n258 in FR2 (24.25 to 27.50), with an impedance bandwidth more than 1 GHz.

## ACKNOWLEDGMENT

This work was supported by the Scientific and Technological Research Council of Turkey (TUBITAK) under Project Number 114E241.

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