

Ultra-low SLL slotted waveguide antenna array using Chebyshev aperture distribution function for MM-wave tracking radar applications

Basma M. Yousef^a, Allam M. Ameen^{b,*}, Ayman Elboushi^{b,c}

^a Delta Higher Institute for Engineering and Technology, Mansoura, Egypt

^b Microstrip Department, Electronics Research Institute, Cairo, Egypt

^c PSDSARC, Riyadh, Kingdom of Saudi Arabia

ARTICLE INFO

Keywords:

Slotted waveguide antennas (SWAs)
Radar Antennas system
Rectangular Waveguide
Side Lobe Level (SLL)
Controlled beam-width antennas

ABSTRACT

A non-uniform aperture distribution slotted waveguide antenna is presented. The slotted waveguide antenna array is chosen for its ease for aperture distribution control and the flexibility of gain adjustment. Multiple aperture distribution functions, including uniform, binomial, Chebyshev, and Blackman, have been extensively investigated to achieve the best possible side lobe suppression. These distribution functions have been converted to slot displacement from the center line of the antenna. Number of slots in the proposed array is chosen to be eight to satisfy the required gain for mm-wave radar tracking application. The proposed antenna is simulated and optimized using the full wave simulator package (CSTMWS). Rounded edge slots are adapted instead of the sharp ones, as they are more applicable for the CNC fabrication process. An eight-slot waveguide antenna is fabricated and gold-plated, considering the Chebyshev distribution approach. The proposed design achieves very stable radiation characteristics and performance over the operating bandwidth, which extends from 33.6 GHz up to 35.9 GHz. At 35 GHz, the total realized gain of the overall antenna is found to be 13.4 dBi, with an overall radiation efficiency of 95.21 %. An obvious low SLL of -30 dB is obtained at the frequency of 35 GHz. The low side lobe level parameter is very crucial for radar applications as it enhances the overall target SNR and reduces false target observations. The pre-stated antenna characteristics make it a good candidate for mm-wave radar applications and point-to-point communications (P2P).

1. Introduction

One of the most important systems that plays an important role in many applications such as aviation, navigation, CubeSat, military, and commercial applications is the radar system [1–4]. Transmitted and received antennas are the key components of any radar system [5]. Antennas that are used in these applications are illustrated as having a high-power microwave (HPM), a low side-lobe level, and a high-power handling capacity. It is also required to have a high gain, a compact, lightweight, tightly controlled beamwidth, and a well-directed pattern [6].

Slotted waveguide antennas (SWAs) with their ability to transfer the signals point-to-point and having the majority of the requirements, especially the HPM handling capacity and high performance, are suitable to be used [7–9]. SWA is made up of a rectangular waveguide with slots etched on its walls (either the broad or narrow wall of the waveguide) that correspond to the desired energy and radiated field [10].

Vertical polarization occurs when the slots are in the board wall; otherwise, horizontal polarization occurs when the slots are in the narrow wall [11]. Standing wave antennas and travelling wave antennas are the two most frequent forms of SWAs, however they may be categorised into many other categories. Both resonant and non-resonant antennas are other names for them [12,13]. The short-circuit termination of standing wave antennas boosts their effectiveness [12]. Although it has a smaller frequency range, its primary beam is not reliant on the resonance frequency. The traveling-wave antennas, on the other hand, contain a matched load that lowers efficiency but is utilised to stop wave reflections. They also have a larger bandwidth. SWAs have other advantages, such as a small volume, being simple to fabricate, having a high reflection coefficient, and being easy to mount. One of the main merits of SWAs according to slot position is that the side-lobe level (SLL) can be controlled [14]. In [15], a novel approach using meta-surface technology is presented to decrease mutual coupling between waveguide slot array (WSA) antennas. The two WSA antennas are separated

* Corresponding author.

E-mail addresses: basmanyousef@gmail.com (B.M. Yousef), allamameen@eri.sci.eg (A.M. Ameen).

<https://doi.org/10.1016/j.asej.2023.102582>

Received 12 May 2023; Received in revised form 2 October 2023; Accepted 21 November 2023

Available online 6 December 2023

2090-4479/© 2023 THE AUTHORS. Published by Elsevier BV on behalf of Faculty of Engineering, Ain Shams University. This is an open access article under the CC BY-NC-ND license (<http://creativecommons.org/licenses/by-nc-nd/4.0/>).

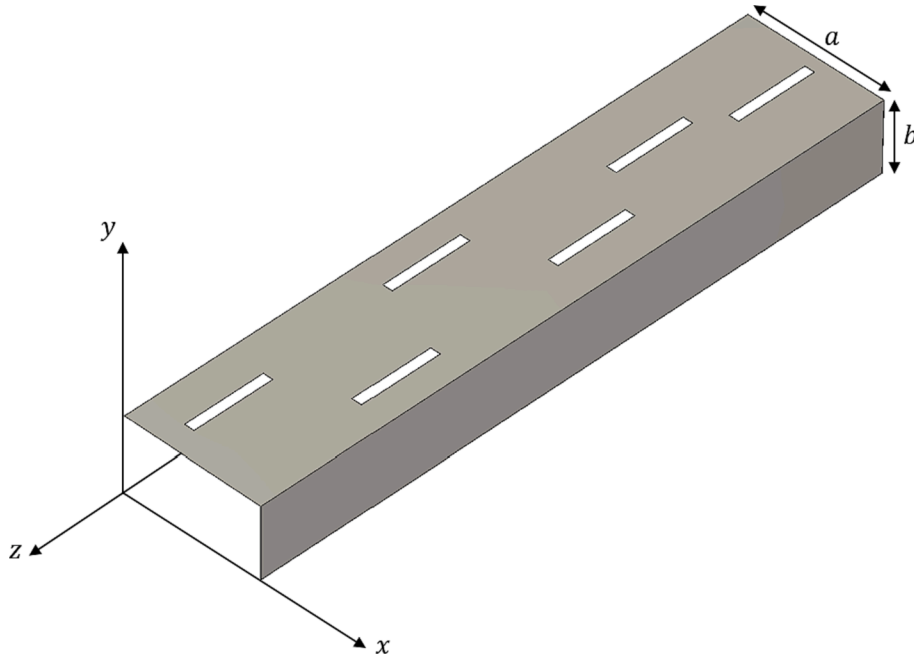


Fig. 1. Schematic diagram of the basic slotted waveguide antenna array.

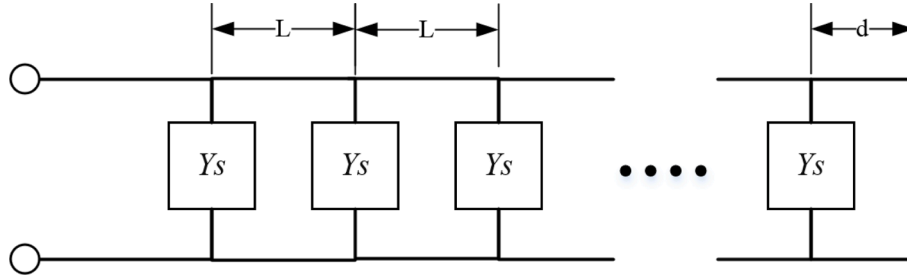


Fig. 2. Circuit model of slotted waveguide antenna [31].

from one another by a meta-surface bulkhead. Another technique for a different type of mutual coupling is obtained and discussed in [16–18]. This technique is applied to slotted antenna array based on substrate integrated waveguide (SIW). In [19,20], a survey describes the results of a study on enhancing the performance characteristics of a new antenna for on-chip implementation for millimeter-wave and terahertz integrated-circuits, such as the impedance bandwidth, radiation gain and efficiency, as well as decreasing substrate loss.

The design of resonant antennas is based on the equations and steps introduced by Stevenson and Elliot [10,21,22]. This procedure tends to the waveguide end bring short-circuited at a distance of a $\lambda_g/4$ from the center of the last slot, and the inter-slot distance is $\lambda_g/2$. The slot length should be have $\lambda/2$, if it has a rectangular shape. Planar slotted waveguide antennas (SWA) with controllable side lobe level are also introduced in [23], in which optimization of non-uniform displacement slots is obtained. A dual-band mm-wave SWA applied to 5G applications at high band frequencies (28 and 38 GHz) is discussed [24]. The creation and improvement of a slotted waveguide array with a central feed and low side-lobes fed from one end and shorted from the other [25]. In [26], a complementary-split-ring SWA applied to a land vehicle is presented. In [27], a simple inventive procedure for the design of broad-wall SWAs with low SLLs is presented. A slotted waveguide antenna with inclined slots based on the narrow wall of a circular waveguide has been presented [28]. A highly directive 3D-printed dual-beam directional waveguide slotted antenna designed at 28 GHz is introduced [29]. Longitudinal slots have been made on both broad walls of the SWA. A

new technique to enhance the directivity of SWAs using metamaterial parasitic elements with discrete dipole approximation is applied in [30].

2. Slotted waveguide antennas

Any radar system's most important component is its antenna. The effectiveness of the radar system as a whole depends on the antenna selection. Slotted waveguide antennas are a common kind of antenna used in high-frequency systems such as radar and navigation. They emit linear polarization with little cross-polarization, are easy to make, and have minimal loss (high antenna efficiency) as they are being created. These antennas may also be engineered to adapt to the surface on which they are installed, making mounting them quite simple. We'll suppose that the waveguide's slots are somewhat narrow in comparison to the operational wavelength. The bandwidth grows as the breadth does (recall that a wider antenna frequently has a higher bandwidth). Larger widths come at the cost of more cross-polarization. For narrow slots, the fractional bandwidth might be as low as 3–5 %. A FBW in the range of 75 % is possible for wide slots. The dimensions of a slotted waveguide array are illustrated in Fig. 1 (length and breadth). The slots' direction, location, and form will all affect how they radiate. The waveguide's design and operating frequency will also be very important.

The last slot is separated from the end by d (which is short-circuited, as appeared in Fig. 2) [31], and the slot components are spaced apart by L . λ_g depends on the waveguide's width a and the wavelength of free space λ . The guiding wavelength for the dominating TE_{01} mode

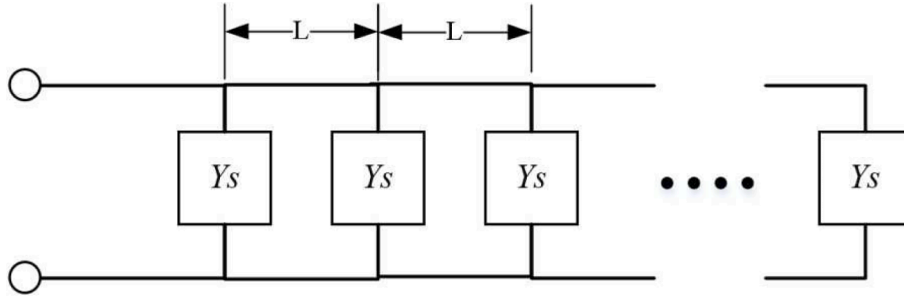


Fig. 3. Circuit model of slotted waveguide using quarter-wavelength transformation.

Table 1
Specification Requirements.

Parameter	Specification
Frequency Range	ka-band, 33–36 GHz
Coupling between TX and RX Antennas	< −30 dB
Gain	> 10 dB
Input Match	SWR < 2:1
Input Maximum Power	37 dBm (5 Watts)
Polarization	Vertical
Beam Shape	Fan Beam
Azimuth Beamwidth	70° minimum
Elevation Beamwidth	14° minimum
Azimuth Side-lobe Level	< −20 dB
Feeding Requirement	Single Direct Feed through WG-to-Coax Adapter

excitation is provided by:

$$\lambda_g = \frac{\lambda}{\sqrt{4a^2 + \lambda^2}} \quad (1)$$

For maximum power coupling, it is common practice to select a quarter-wavelength as the distance between the final slot and the finish, where the end of the waveguide is shorted. Half a wavelength is selected as the distance between the centers of any two slots that come after one another. According to transmission line theory, an open circuit has an impedance of one short circuit travelling a quarter wavelength along a transmission line (i.e. the short circuited load is transferred to be an open circuited load). Hence, it is possible to simplify the model in Fig. 3 to the one displayed there.

All of the slots in the waveguide slot antenna can be seen as being parallel if it is constructed in this way. As a result, it is simple to determine the input admittance and input impedance of an element slotted array:

$$Y_{in} = N * Y_s \quad (2)$$

$$Z_{in} = \frac{1}{Y_{in}} \quad (3)$$

where, Y_s is the slot admittance at the center frequency of the operation.

3. Antenna design

We will focus mainly on the slotted array design procedure, objectives, Side Lobe Level reduction (SLL) techniques, fabrication technology intended to be used, and simulation results of the proposed array prototype. The required design should meet the following specifications mentioned in Table 1.

In order to achieve the required gain, the number of radiating slots in the antenna array is found to be eight slots. The distance between each slot from center to center is chosen to be $\lambda/2$ at the center frequency of the operating band and the distance from the center of the last slot to the waveguide short end is considered to be $\lambda/4$ for achieving best coupling scenario. Later, these dimensions are optimized using optimization tool in CSTMW studio to reach the best performance.

3.1. Synthesis of the array pattern

According to the required design parameters stated in Table 1. The operating resonance frequency is chosen to be 35 GHz. Although the design and fabrication of millimeter wave (MMW) structures come with big challenges in terms of small dimensions and high sensitivity of the fabrication tolerance, operating around such frequencies becomes mandatory in order to satisfy an appropriate Radar Cross Section (RCS) from the bullet. The number of the slots in the rectangular waveguide is chosen to be eight slots, after multiple simulations trails, to meet the targeted Half Power Beam Width (HPBW). Fig. 4 shows the primary model schematic diagram of the slotted waveguide antenna built with CSTMWS. The waveguide employed in this design (WR-28) has a major length of $a = 7.11\text{mm}$ and minor length $b = 3.56\text{mm}$. The distance between the last slot and the end $d = 3.7\text{mm}$. All the slots have a length of

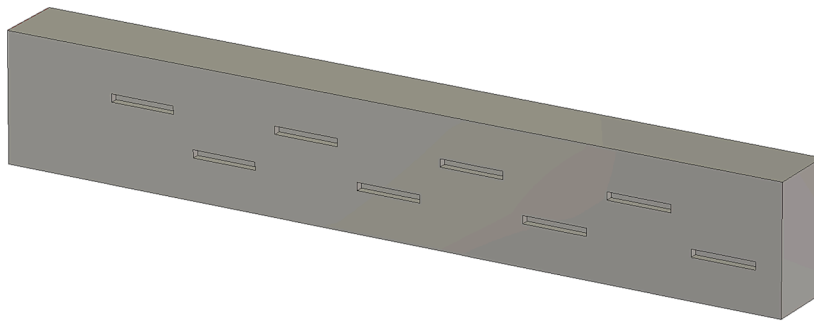


Fig. 4. Primary CSTMWS Model for the slotted waveguide array.

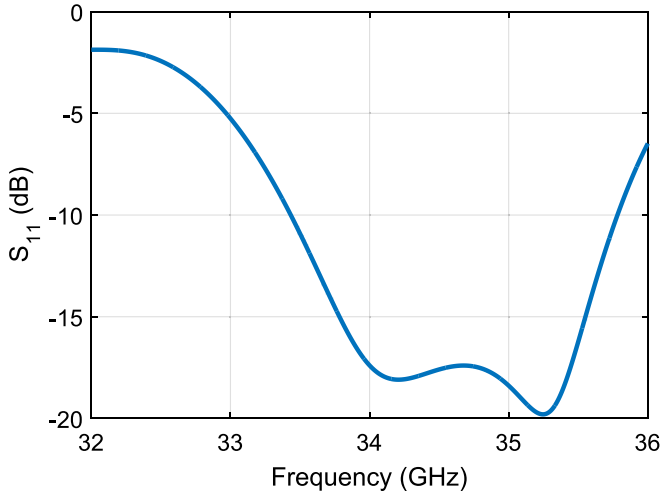
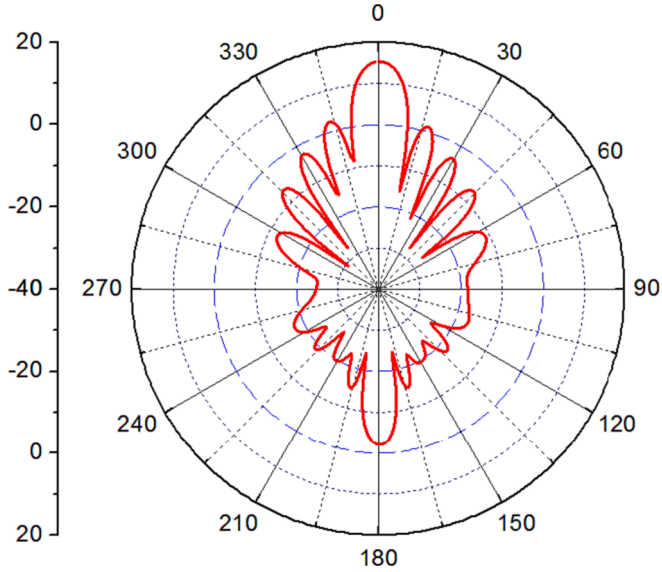
Fig. 5. The reflection Coefficient S_{11} of the primary design.

Fig. 6. The azimuth radiation pattern at 35 GHz.

4.1mm, and width of 0.5mm. The distance between the centers of two successive slots L is chosen to be 5.4mm, and the displacement for all the slots from the waveguide center is 2.4mm. The reflection coefficient of the primary model S_{11} is illustrated in Fig. 5. The proposed design shows an operated bandwidth of 6.66 % extends from 33.4 GHz to 35.7 GHz.

The slotted waveguide array shows a remarkable radiation performance. Both azimuth and elevation radiation patterns of the proposed design are demonstrated in Figs. 6 and 7 respectively. The total realized gain of the proposed design is 15.4 dB, however the azimuth SLL is around -13 dB.

3.2. Azimuth plane SLL reduction

Although, applying uniform feeding for the radiating slots results in a good realized gain (around 15.4 dB), it introduces higher SLL in the azimuth plane (around -13 dB). This SLL can be considered suitable enough for some communication applications, however in radar applications it cannot be tolerated. One of the possible solutions for this problem can be achieved by applying non-uniform slot excitation or tapered feeding. Many mathematical functions can be used for realizing

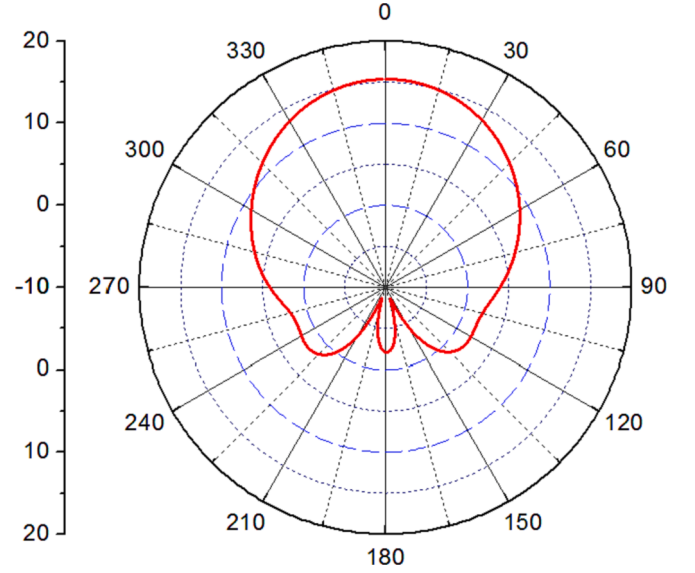


Fig. 7. The elevation radiation pattern at 35 GHz.

Table 2
Mathematical distribution models and their parameters.

Distribution	Coefficients C_n s	Displacements d_n (in mm)	SLL (in dB)	HPBW (in degrees)	Gain
Uniform	1	2.4	-13	10.2	15.4
	1	2.4			
	1	2.4			
	1	2.4			
	1	2.4			
	1	2.4			
	1	2.4			
Binomial	0.0078	0.2899	-22.2	15.3	13.7
	0.0546	0.7804			
	0.1640	1.4156			
	0.2734	1.9394			
	0.2734	1.9394			
	0.1640	1.4156			
	0.0546	0.7804			
Chebyshev	0.0078	0.2899	-21.6	14.7	14
	0.0078	0.2911			
	0.0548	0.7818			
	0.1641	1.4159			
	0.2731	1.9379			
	0.2731	1.9379			
	0.1641	1.4159			
Blackman	0.0078	0.2911	-22	15.4	13.5
	0	0			
	0.0307	0.5801			
	0.1561	1.3761			
	0.3130	2.1319			
	0.3130	2.1319			
	0.1561	1.3761			
	0.030	0.5801			
	0	0			

such feeding mechanism, including binomial distribution, Blackman Harris distribution, Chebyshev, etc.

These mathematical models can be implemented as different slot displacements from the center line of the waveguide, the displacement of the n^{th} slot is related to the normalized conductance g_n can be given by [4]-[6]:

$$d_n = \frac{a}{\pi} \sin^{-1} \sqrt{\frac{g_n}{2.09 \cdot \frac{\lambda_g}{\lambda_0} \cdot \frac{a}{b} \cos^2(\frac{\pi \lambda_0}{2 \lambda_g})}} \quad (4)$$

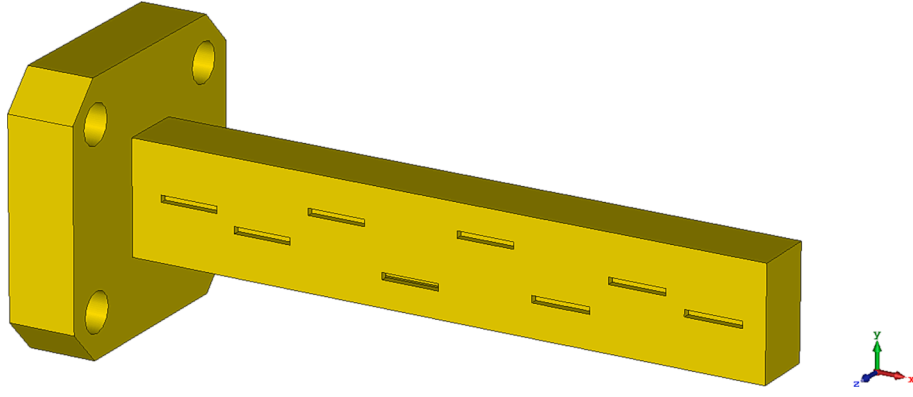


Fig. 8. Realistic antenna model.

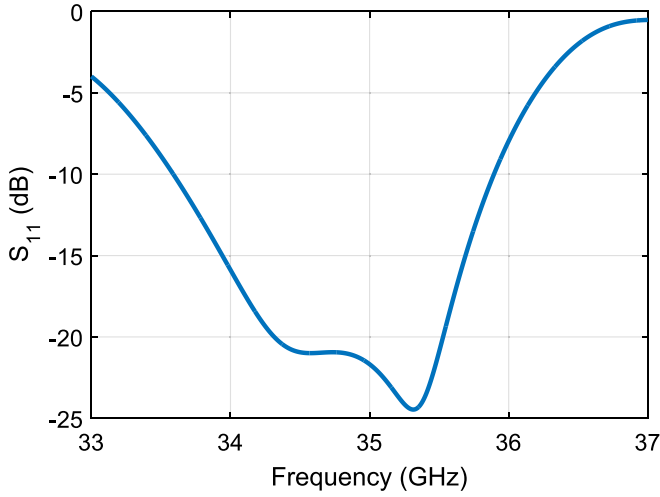
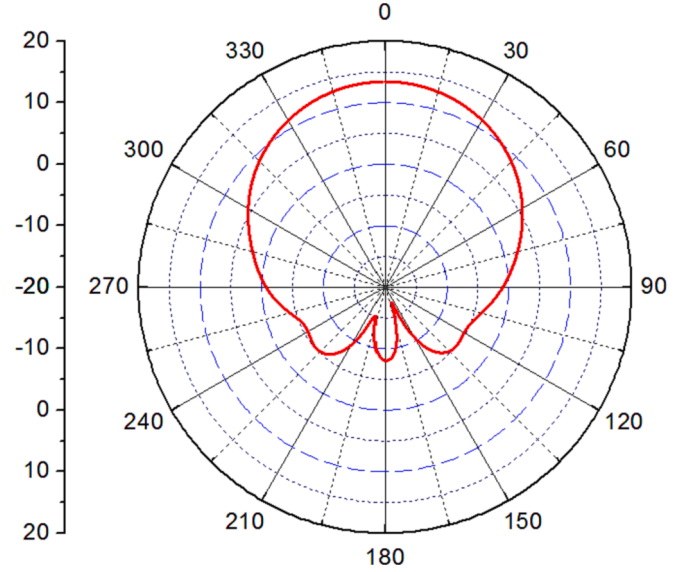
Fig. 9. The reflection Coefficient S_{11} of the practical design.

Fig. 11. The elevation radiation pattern at 35 GHz for the realized model.

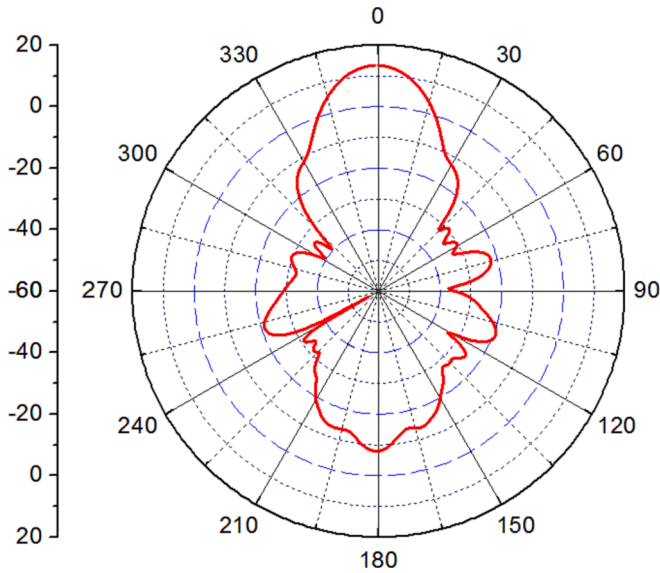


Fig. 10. The azimuth radiation pattern at 35 GHz for the realized model.

$$g_n = \frac{c_n}{\sum_{n=1}^N c_n} \quad (5)$$

Where, N is the number of the slots, c_n s are the distribution coefficients of the mathematical functions.

In our study, multiple simulations have been carried out to investigate the effect of different mathematical distributions on the HPBW and the SLL. Table 2 lists the coefficients, practical displacement of each slot, SLL, HPBW, and realized gain associated with every mathematical distribution.

As a compromise between the realized gain and the SLL, Chebyshev distribution is considered as the optimal solution for SLL reduction.

3.3. Realistic antenna modelling

In order to obtain more accurate results, a new model based on a practical WR-28 waveguide with a brass flange is considered in the CSTMWS simulation. In Fig. 8, the proposed design's schematic diagram is displayed. A 5 mm separation distance is added between the slots and the waveguide flange because the manufacturing company requests it. Fig. 9 shows the reflection coefficient of the realistic structure. Regarding the reflection coefficient, there is no big change in the operating bandwidth. The proposed design exhibits an operating band of 6.6 % that extends from 33.6 GHz up to 35.9 GHz. The design achieves a SLL of -21.4 dB in azimuth plane. When the metallic losses of the brass

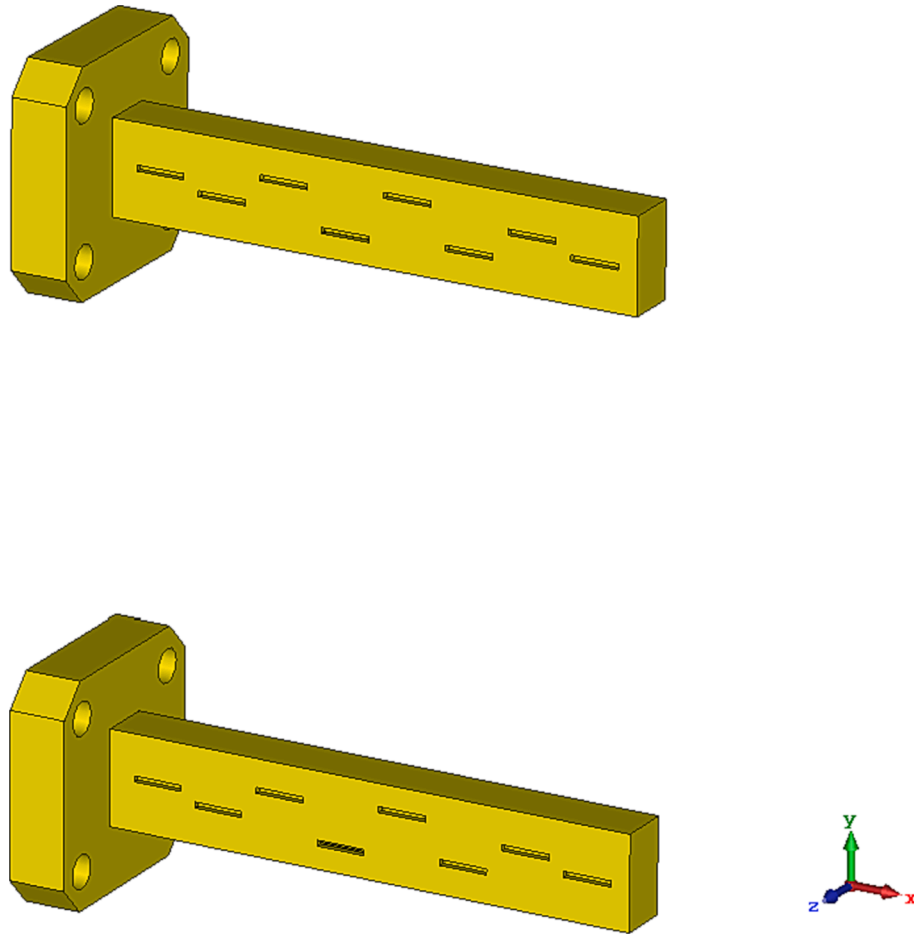


Fig. 12. Two adjacent antennas side-by-side for mutual coupling study.

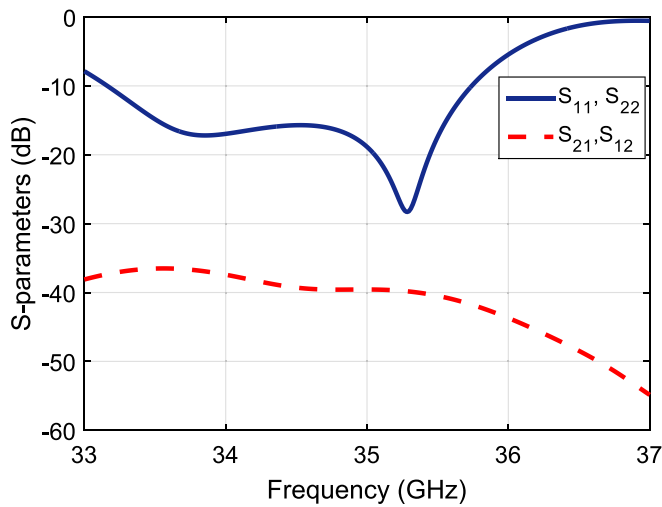


Fig. 13. S-parameters for two adjacent antennas separated by 5 cm.

waveguide are taken into account, the overall realized gain is 13.4 dBi. The azimuth and elevation radiation patterns of the design are illustrated in Figs. 10 and 11, respectively.

3.4. T_X - R_X antenna coupling

As the antennas employed in the proposed radar system consist of multiple antennas (one transmitter and three receivers), mutual

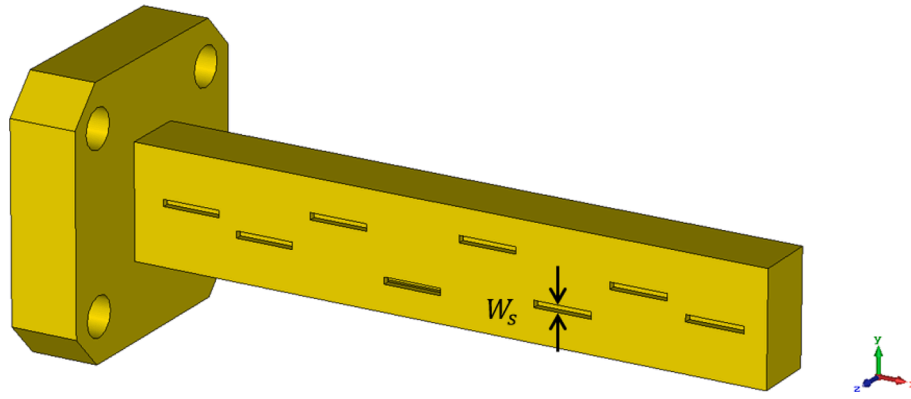
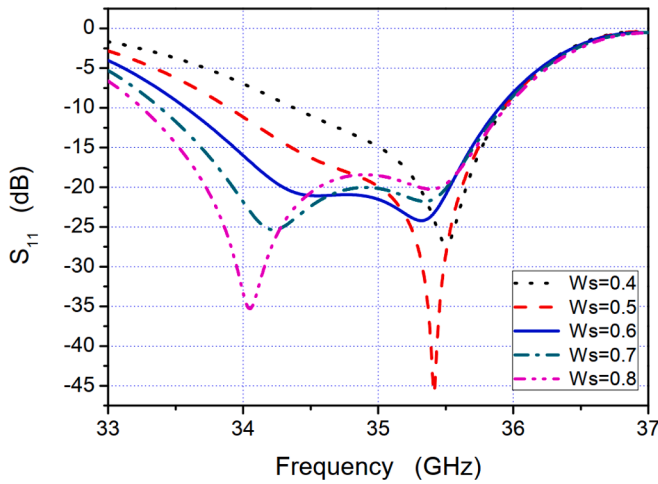
coupling between the transmitter and receivers becomes an important issue. The main reason for that is that power leakage from the transmitter toward the receiving antennas can deteriorate the radar's detection abilities. A mutual coupling study has been carried out in order to investigate the mutual coupling effect. As illustrated in Fig. 12, two adjacent antennas separated by 5 cm are simulated in CSTMWS. According to the S-parameter measurements, the mutual coupling (S_{21}) between the two antennas is around -40 dB and gets worse as the frequency increases, whereas the reflection coefficient (S_{11}) for both antennas has an undetectable impact. Fig. 13 shows the simulation's S-parameters.

4. Machining considerations and requirement

Working in MMW frequency ranges usually comes with big challenges in terms of the small dimensions and the associated fabrication tolerance. This tolerance mainly relies on the fabrication technology used. There are two main fabrication techniques for such structures. The first one is by using precise laser cutting which can have a precision tolerance of 5 to 10 μm while the second is based on mechanical cutting using fine cutting tools which have a tolerance ranges from 5 to 20 μm depending on the quality of the cutting tools and the cutting machine. In this work, the second technique is adopted. However, the drawback of this fabrication technique is the higher expected fabrication tolerance.

4.1. Tolerance analysis

In order to estimate the effect, the fabrication tolerance on the antenna performance, multiple simulation have been carried out. Form the

Fig. 14. Slot width effect (W_s).Fig. 15. S_{11} variation as a function of (W_s).

design point of view, the main critical dimensions that may results in a significant impact on the array performance are the slot width (W_s), the slot length (L_s), and the slots' main symmetrical line shift (SH).

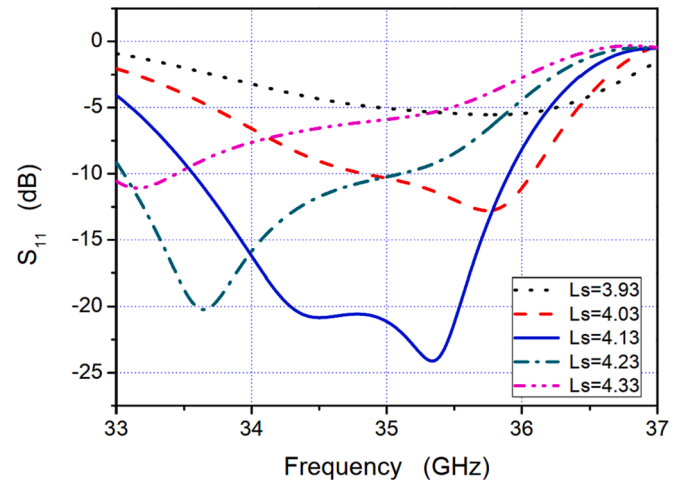
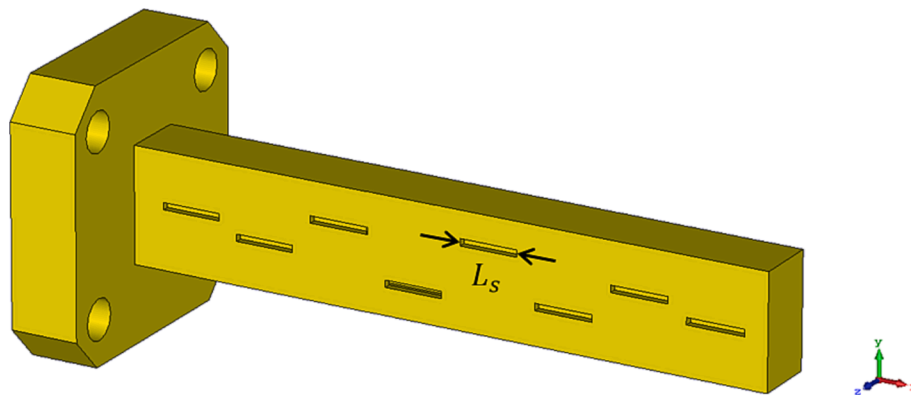
As shown in Fig. 14, the slot width is considered one of the most critical parameters, where it has a clear effect on antenna matching and the operating bandwidth adjustment. Fig. 15 shows the S_{11} variation as a function of W_s . The optimal slot width is chosen to be 0.6 mm.

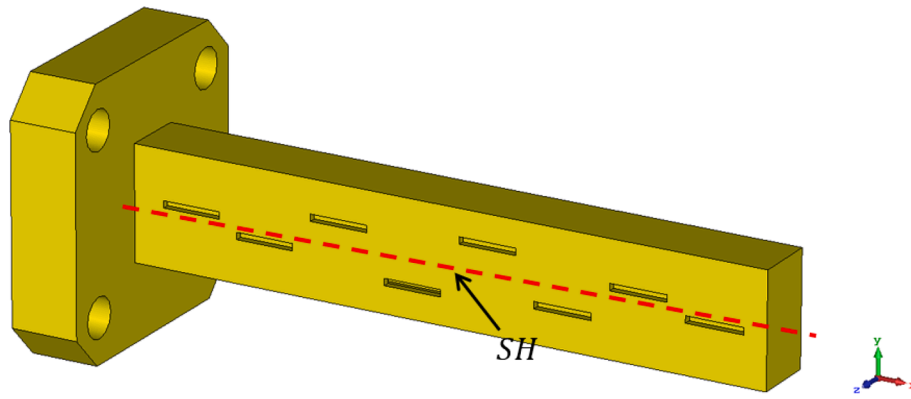
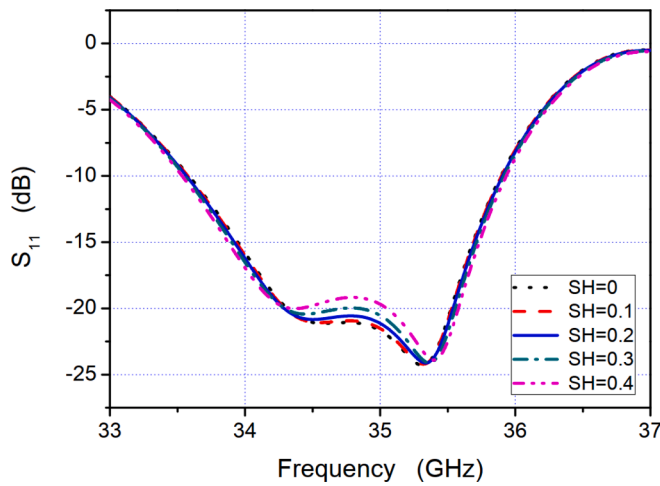
The slot length (L_s) illustrated in Fig. 16 is very critical parameter in terms of selecting the band of operation. Fig. 17 shows the S_{11} variation as a function of L_s . The optimal slot length is chosen to be 4.13 mm. As a fabrication expected error, an axial shift (SH) from the center line of the

slots, shown in Fig. 18, may be occur. Fig. 19 shows the variation in S_{11} according to the variation in SH . The optimal axial shift is chosen to be 0.2 mm.

4.2. Rounded edges modification

In all previous designs, the slots were treated as having a rectangular shape. Given that the dimensions of the slots are very small and that it is practically difficult to implement them in a sharp rectangular shape and that rounding of the edges must occur during the manufacturing process, this was taken into account during the simulations. Fig. 20 shows the

Fig. 17. S_{11} variation as a function of (L_s).Fig. 16. Slot width effect (L_s).

Fig. 18. Slot width effect (SH).Fig. 19. S_{11} variation as a function of (SH).

new rounded edges modifications.

The modified slot length ($L_{s-round}$) illustrated in Fig. 20 is very critical parameter in terms of selecting the band of operation as discussed before, so a parametric study is presented. Fig. 21 shows the S_{11} variation as a function of $L_{s-round}$. As observed, there is a large difference between the two values of L_s and $L_{s-round}$ which illustrates the significant effect of rounded edges on the results. The optimal rounded slot length is chosen to be 3.73 mm.

5. Experimental results and discussions

The proposed slotted waveguide antenna with a non-uniform aperture distribution is designed, simulated and fabricated to verify the simulation results. This waveguide is designed to operate at a wide range from 33.4 GHz to 35.7 GHz. Fig. 22 shows the fabricated waveguide antenna model. In Fig. 23, a comparison between both measured and simulated reflection coefficient (S_{11}) is presented. As shown, the measured bandwidth of the fabricated waveguide is started from 33.2 GHz up to 35.6 GHz which means that good agreement is achieved

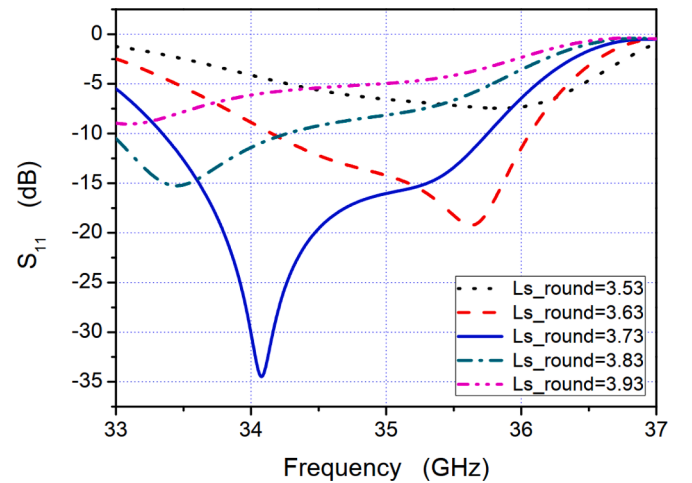
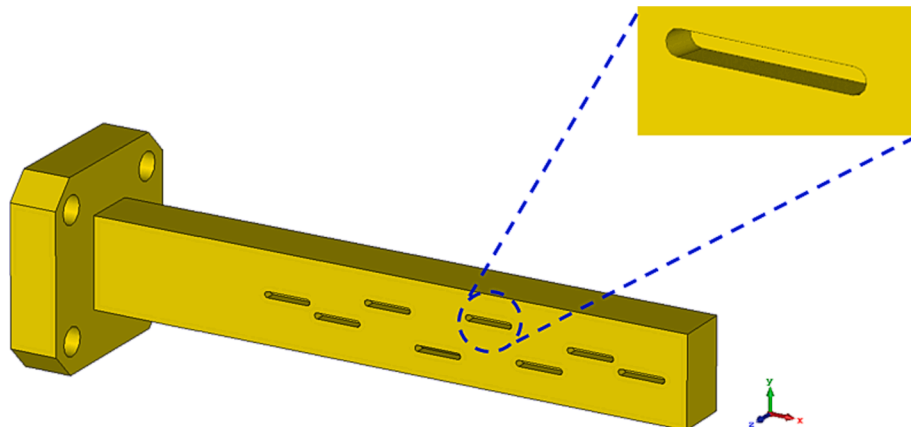
Fig. 21. S_{11} variation as a function of ($L_{s-round}$).

Fig. 20. Rounded edges modification.

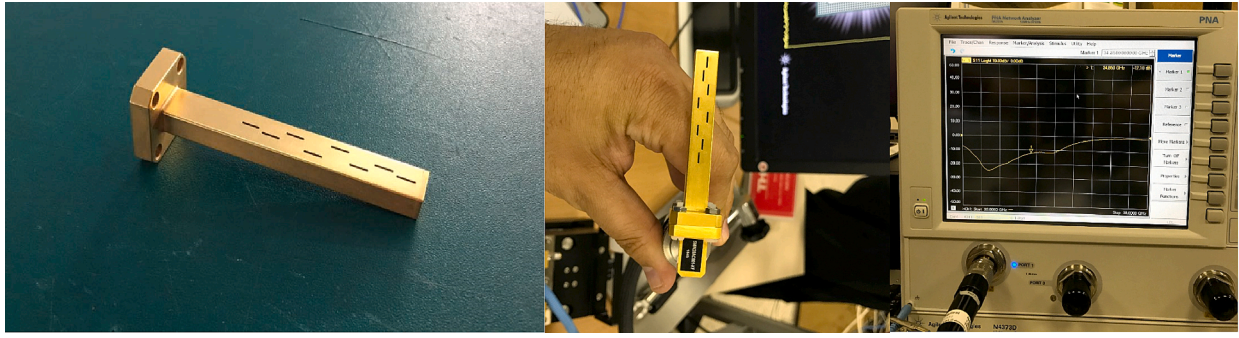


Fig. 22. The fabricated antenna model.

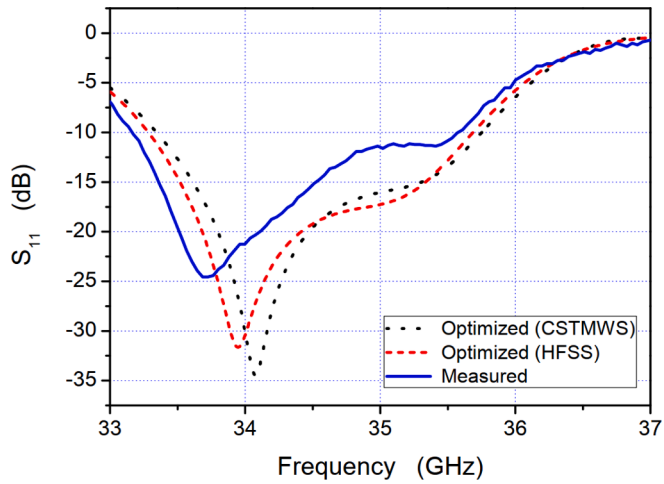
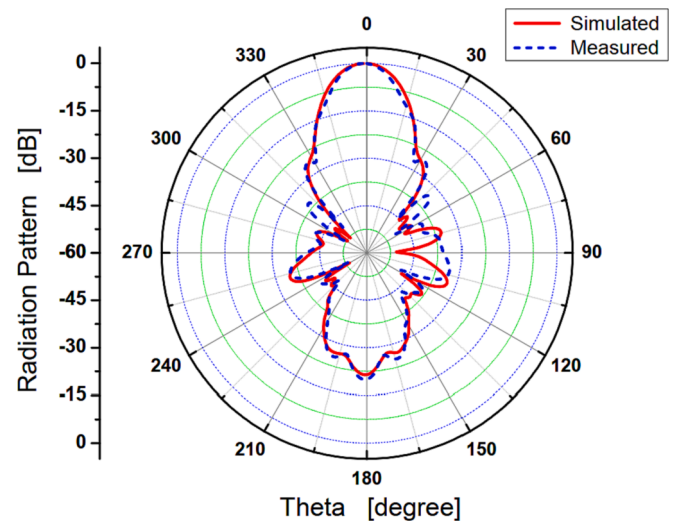
Fig. 23. S_{11} comparison between CSTMWS, HFSS, and the experimental results.

Fig. 25. The 35 GHz azimuth radiation pattern, both the measured and simulated.

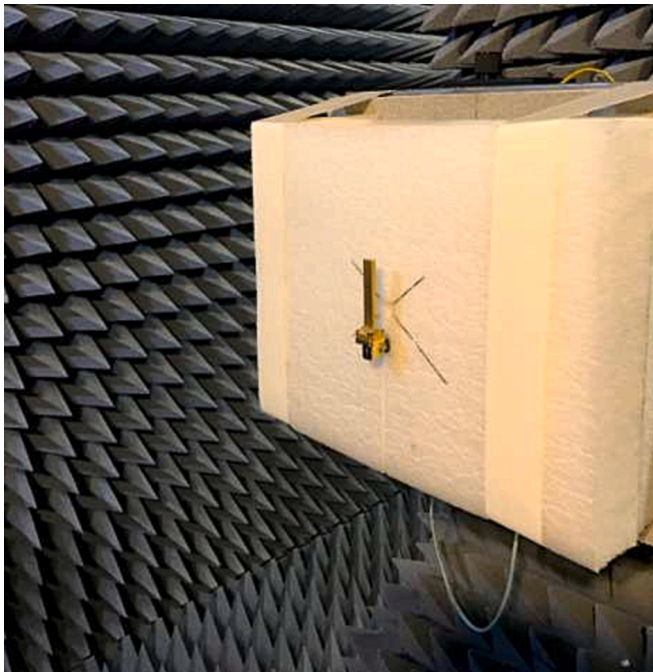


Fig. 24. The setup of the antenna model's radiation pattern measurement.

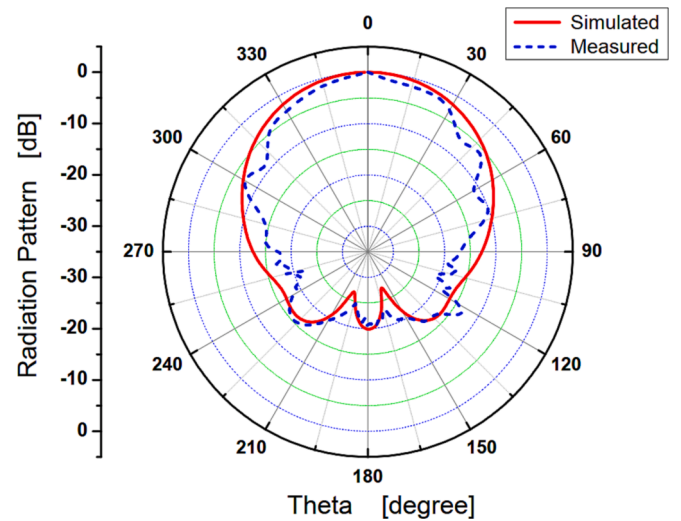


Fig. 26. The 35 GHz elevation radiation pattern, both the measured and simulated.

between them.

The radiation pattern of the proposed waveguide antenna is measured. Fig. 24 shows the setup configuration of the antenna during radiation pattern measurement. In Fig. 25, the comparison between both measured and simulated radiation pattern for both azimuth and elevation plans is introduced. The results from simulation and measurement are in good agreement. Fig. 26.

6. Conclusion

In this paper, a slotted waveguide antenna with a non-uniform aperture distribution is introduced. To obtain the optimal side lobe suppression, different types of aperture distribution functions, including uniform, binomial, Chebyshev, and Blackman, have been thoroughly studied. The slot displacement from the antenna center line has been converted from these distribution functions. Number of slots in the proposed array is chosen to be eight to satisfy the required gain for mm-wave radar tracking application. Instead of sharp edges, rounded edge slots are used since they are more suited for CNC construction. Incorporating the Chebyshev distribution strategy, a gold-plated, eight-slot waveguide antenna is produced. Over the operational bandwidth, which ranges from 33.6 GHz to 35.9 GHz, the suggested design provides highly steady radiation characteristics and performance. The total realized gain of the whole antenna is determined to be 13.4 dBi, and an overall radiation efficiency of 95.21 % at 35 GHz. At the frequency of 35 GHz, an obviously low SLL of -30 dB is achieved. As it improves the total target SNR and lowers false target observations, the low side lobe level parameter is essential for radar applications. It is an excellent choice for point-to-point communications and mm-wave radar applications due to the pre-stated antenna properties (P2P).

Declaration of Competing 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.

References

- [1] Kuo F-Y, Hwang R-B. High-isolation x band-marine radar antenna design. *IEEE Trans Antennas Propagat* 2014;62(5):2331–7.
- [2] Oktafiani F, Saputera YP, Wahyu Y. Lightweight and compact antenna design for navigation radar application. In: *International conferences on Information Technology, Information Systems and Electrical Engineering (ICITISEE)*, pp. 106–110, 2017.
- [3] Wahab M, Wahyu Y, Saputera YP. Small antenna using transmission line uniform for X-band navigation radar. In: *International Workshop on Antenna Technology (iWAT)*; 2015. p. 309–12.
- [4] Rahmat-Samii Y, Manohar V, Kovitz JM, Hodges RE, Freebury G, Peral E. Development of highly constrained 1 m Ka-band mesh deployable offset reflector antenna for next generation CubeSat radars. *IEEE Trans Antennas Propagat* 2019; 67(10):6254–66.
- [5] Lo YT, Lee SW. *Antenna Handbook: theory, applications, and design*. Springer Science & Business Media; 2013.
- [6] Misilmani El, Hilal M, Al-Husseini M, Kaban KY. Design procedure for planar slotted waveguide antenna arrays with controllable sidelobe level ratio for high power microwave applications. *Eng Rep* 2020;2(10):1–15.
- [7] Mailloux RJ. *Phased array antenna handbook*. Artech House 2017.
- [8] Volakis, John L. *Antenna engineering handbook*, Waveguide slot antenna arrays. McGraw-Hill Education, 2007.
- [9] Casula GA, Mazzarella G, Montisci G, Muntoni G. A review on improved design techniques for high performance planar waveguide slot arrays. *Electronics* 2021;10 (11):1311.
- [10] Stevenson AF. Theory of slots in rectangular wave-guides. *J Appl Phys* 1948;19(1): 24–38.
- [11] Enjiu RK, Perotoni MB. Slotted waveguide antenna design using 3D EM simulation. *Microwave J* 2013;56(7):e72.
- [12] Elliott R, Kurtz L. The design of small slot arrays. *IEEE Trans Antennas Propagat* 1978;26(2):214–9.
- [13] Elliott R. On the design of traveling-wave-fed longitudinal shunt slot arrays. *IEEE Trans Antennas Propagat* 1979;27(5):717–20.
- [14] Ripoll-Solano L, Torres-Herrera L, Sierra-Pérez M. Design, simulation and optimization of a slotted waveguide array with central feed and low sidelobes. In: *IEEE-APS Topical Conference on Antennas and Propagation in Wireless Communications (APWC)*; 2018. p. 886–9.
- [15] Alibakhshikenari M, Virdee BS, Khalily M, See CH, Abd-Alhameed R, Falcone F, & Limiti E. A new study to suppress mutual-coupling between waveguide slot array antennas based on metasurface bulkhead for MIMO systems. In: *Proceedings of the 2018 Asia-Pacific Microwave Conference (APMC)*, pp.500–502, November 6–9, 2018, Kyoto, Japan.
- [16] Alibakhshikenari M, Virdee BS, See CH, Abd-Alhameed R, Falcone F, & Limiti E. Mutual-Coupling Reduction in Metamaterial Substrate Integrated Waveguide Slotted Antenna Arrays Using Metal Fence Isolators for SAR and MIMO Applications. In: *2018 12th International Congress on Artificial Materials for Novel Wave Phenomena (Metamaterials)*, pp. 13–15, 27 Aug.-1 Sep. 2018, Espoo, Finland.
- [17] Alibakhshikenari M, Virdee BS, Khalily M, See CH, Abd-Alhameed R, Falcone F, & Limiti E. New Approach to Suppress Mutual Coupling Between Longitudinal-Slotted Arrays Based on SIW Antenna Loaded with Metal-Fences Working on VHF/ UHF Frequency-Bands: Study, Investigation, and Principle. In: *Proceedings of the 2018 Asia-Pacific Microwave Conference (APMC)*, pp. 1564–1566, November 6–9, 2018, Kyoto, Japan.
- [18] Alibakhshikenari M, Virdee BS, See CH, Abd-Alhameed R, Falcone F, & Limiti E. A New Waveguide Slot Array Antenna with High Isolation and High Antenna Bandwidth operation on Ku- and K- bands for Radar and MIMO Systems. In: *Proceedings of the 48th European Microwave Conference (EuMC)*, pp. 1421–1424, 25–27 Sep. 2018, Madrid, Spain.
- [19] Alibakhshikenari M, Ali EM, Soruri M, Dalarsson M, Naser-Moghadasi M, Virdee BS, et al. A comprehensive survey on antennas on-chip based on metamaterial, metasurface, and substrate integrated waveguide principles for millimeter-waves and terahertz integrated circuits and systems. *IEEE Access* 2022; 10:3668–92.
- [20] Alibakhshikenari M, Virdee BS, Althwayb AA, Aissa S, See CH, Abd-Alhameed RA, et al. Study on on-Chip Antenna Design Based on Metamaterial-Inspired and Substrate-Integrated Waveguide Properties for Millimetre-Wave and THz Integrated-Circuit Applications. *Journal of Infrared, Millimeter, and Terahertz Waves* 2021;42(1):17–28.
- [21] Elliott R. An improved design procedure for small arrays of shunt slots. *IEEE Trans Antennas Propagat* 1983;31(1):48–53.
- [22] Elliott R, O’Loughlin W. The design of slot arrays including internal mutual coupling. *IEEE Trans Antennas Propagat* 1986;34(9):1149–54.
- [23] Misilmani El, Hilal M, Al-Husseini M, Kaban KY. Design procedure for planar slotted waveguide antenna arrays with controllable sidelobe level ratio for high power microwave applications. *Eng Rep* 2020;2(10):e12255.
- [24] da Costa IF, Arismar Cerqueira S, and Spadoti DH. Dual-band slotted waveguide antenna array for adaptive mm-wave 5G networks. In: *11th European Conference on Antennas and Propagation (EUCAP)*, pp. 1322–1325, 19–24 March 2017.
- [25] Ripoll-Solano, Lácides, Luis Torres-Herrera, and Manuel Sierra-Pérez. Design, simulation and optimization of a slotted waveguide array with central feed and low sidelobes. In: *IEEE-APS Topical Conference on Antennas and Propagation in Wireless Communications (APWC)*, pp. 886–889, 10–14 September 2018.
- [26] Pan X, Christodoulou CG. A narrow-wall slotted waveguide antenna array for high power applications. In: *IEEE Antennas and Propagation Society International Symposium (APSURSI)*, pp. 1493–1494, Memphis, 2014.
- [27] El Misilmani HM, Al-Husseini M, Kaban KY. Design of slotted waveguide antennas with low sidelobes for high power microwave applications. *PIER C* 2015; 56:15–28.
- [28] Tan L, Zhang J, Wang W, Jinping Xu. Design of a W-band one-dimensional beam scanning slotted waveguide antenna with narrow beam and low side lobe. In: *Progress in Electromagnetics Research Symposium-Spring (PIERS)*; 2017. p. 3625–8.
- [29] Sabri MW, Murad NA, Rahim MKA. Highly directive 3D-printed dual-beam waveguide slotted antennas for millimeter-wave applications. *Micro & Optical Tech Letters* 2019;61(6):1566–73.
- [30] Pulido-Mancera LM, Zvolensky T, Imani MF, Bowen PT, Valayil M, Smith DR. Discrete Dipole Approximation Applied to Highly Directive Slotted Waveguide Antennas. *Antennas Wirel Propag Lett* 2016;15:1823–6.
- [31] Pozar DM. Chapter 2, Transmission line theory. In: *Microwave Engineering*. Hoboken, NJ, USA: John Wiley & Sons; 2012. p. 56–63. 4th edition.



Allam Mohammed Ameen received a B.Sc. degree in Electronics and Communication Engineering Department, Faculty of Engineering, Zagazig University, Zagazig, Egypt in 2009. He was awarded the M.Sc. degree in Electrical Engineering from Faculty of Engineering, Zagazig University, Zagazig, Egypt in 2016. His M.Sc. area was in the design, simulation, fabrication, and measurement of microstrip patch antennas applied to mobile handset systems for 4G applications. He received a Ph.D. degree in the area of design and implementation of wideband MIMO antenna systems applied to intelligent transportation systems (ITS) and connected vehicles (V2V) at Ain Shams University, Cairo, Egypt. Currently, he is a Researcher at the Microstrip Department, Electronics Research Institute, Cairo, Egypt. He has joined the Electronics Research Institute (ERI) since 2016 as an Assistant Researcher. He is awarded several prizes such as Award of the sixth place in 2019, fourth place in 2020, sixth place in 2021, and first place in 2022 for the Best Researcher in Electronics Research Institute. His research interests include the design, simulation, and fabrication of microstrip antenna array for wideband applications in the microwave band. Also, he interests in antenna mutual coupling reduction using EBG and DGS, leaky wave antennas, RFID, and MIMO antenna systems.