



Article

A 60 GHz Slotted Array Horn Antenna for Radar Sensing Applications in Future Global Industrial Scenarios

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Abstract: This paper presents the design of a 60 GHz millimeter-wave (MMW) slot array horn antenna based on the substrate-integrated waveguide (SIW) structure. The novelty of this device resides in the achievement of a broad impedance bandwidth and high gain performance by meticulously engineering the radiation band structure and slot array. The antenna demonstrates an impressive impedance bandwidth of 14.96 GHz (24.93%), accompanied by a remarkable maximum reflection coefficient of -39.47 dB. Furthermore, the antenna boasts a gain of 10.01 dBi, showcasing its outstanding performance as a high-frequency antenna with a wide bandwidth and high gain. To validate its capabilities, we fabricated and experimentally characterized a prototype of the antenna using a probe test structure. The measurement results closely align with the simulation results, affirming the suitability of the designed antenna for radar sensing applications in future global industrial scenarios.



Citation: Ma, B.; Li, J.; Chen, Y.; Si, Y.; Gao, H.; Wu, Q.; Li, M. A 60 GHz Slotted Array Horn Antenna for Radar Sensing Applications in Future Global Industrial Scenarios. *Micromachines* **2024**, *15*, 728. <https://doi.org/10.3390/mi15060728>

Academic Editor: Haejun Chung

Received: 11 May 2024

Revised: 29 May 2024

Accepted: 29 May 2024

Published: 30 May 2024



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Keywords: slot array; horn antenna; millimeter-wave; wide bandwidth coverage; high gain

1. Introduction

In recent times, there has been a notable surge in demand for radar sensors in the realms of automotive, industrial, and medical applications [1–3]. However, conventional radar sensors [4,5] are plagued by challenges including low operational frequencies, elevated costs, restricted bandwidth, and substantial form factors. To address these challenges, the 60 GHz frequency band emerges as a compelling solution due to its inherent broadband characteristics. Moreover, sensors operating in the 60 GHz band have the capability to capture rich and exceptionally accurate point cloud data [6,7], a critical factor for sustaining precision in measurements across a spectrum of applications within the global industrial radar sensing domain. Therefore, antennas characterized by both high gain and wide bandwidth [8,9] in this frequency band are poised as promising alternatives for advancing global industrial radar [10,11] sensing applications in the future. Currently, SIW technology [12–14] is gaining maturity within the high-frequency antenna domain [15]. An SIW represents a dielectric-filled metallic waveguide with a planar structure. In contrast to conventional metallic waveguides [16,17], an SIW offers distinct advantages such as a reduced profile, minimal signal loss, and seamless integration with planar circuits. As a result, SIW structures have found extensive utility in both circuit and antenna designs within the MMW frequency bands [18,19].

In 2015, S. Ramesh and his team conducted pivotal research in indoor radio link characterization for millimeter-wave wireless communications, utilizing dielectric-loaded

index-tapered slot antennas [20]. This design achieved a 3.33 GHz bandwidth, 6.45 dBi gain, and a maximum reflection coefficient of 21.31 dB. However, with the evolution of high-speed communication technology [21,22], its bandwidth and gain limitations became apparent, highlighting the need for more advanced designs. By 2019 [23], Nanda Kumar Mungaru and Thangavelu Shanmuganantham had addressed these limitations with a broadband H-spaced head-shaped slot antenna based on an SIW, specifically for 60 GHz wireless communication. This innovative antenna showed an impressive impedance bandwidth of 3.22 GHz, a reflection coefficient of -38.3 dB, and a gain of 6.812 dBi. In the same year, another significant advancement was a substrate-integrated waveguide-based slot antenna, also for 60 GHz applications [24]. It boasted a 3.64 GHz impedance bandwidth, a reflection coefficient of -21.31 dB, and a 6.812 dBi gain. Compared to S. Ramesh et al.'s earlier design, these newer antennas offered an improved bandwidth and reflection coefficient [25]. Moving to 2021, T. Shanmuganantham and colleagues analyzed a tree-shaped slotted impedance-matching antenna for 60 GHz femtocell applications. They achieved remarkable improvements in size, gain, and bandwidth, with a 7.46 dBi gain and a 9.7 GHz bandwidth, surpassing S. Ramesh's earlier design. Despite these advancements, the challenge of integrating these technologies into future radar sensing applications within the global industrial landscape remained formidable. In 2023, Manish Sharma introduced a Conformal ultra-compact narrowband 60.0 GHz four-port millimeter-wave MIMO antenna for wearable short-range 5G application [26]. This state-of-the-art design featured a compact size of $16 \times 16 \times 0.254$ mm³, a 1.735 GHz bandwidth, and a maximum reflection coefficient of -35.79 dB, exhibiting superior gain. However, the trade-off for this enhanced gain was a narrower bandwidth, potentially limiting its electrical performance stability near the central frequency [27].

Addressing the critical challenge of low gain and narrow bandwidth in antenna designs for radar industry applications, this paper introduces a novel 60 GHz slot array horn antenna based on an SIW structure. This design markedly enhances overall antenna performance by meticulously crafting the radiation band structure and gap array. The resultant antenna demonstrates exceptional capabilities, notably in terms of gain and bandwidth. The advanced performance of this antenna is pivotal for radar sensors, enabling them to achieve high accuracy and generate rich point cloud data. These attributes make the proposed antenna an optimal choice for future radar sensing applications across various global industrial scenarios. By overcoming the limitations of previous designs, this antenna stands as a significant step forward in the field, offering a robust solution tailored to meet the demanding requirements of modern radar technology.

2. Design and Simulation

In this study, we have developed an antenna substrate using Arlon AD255C (Chandler, AZ, USA), a high-frequency dielectric material, featuring copper layers on both the top and bottom surfaces to facilitate electromagnetic radiation. The copper layer of the metal substrate has a thickness (h_p) of 17.5 μ m and a conductivity (δ) of 5.8×10^7 s/m; its relative permittivity is 2.55, with a dielectric loss tangent of 0.0014, optimizing its performance for high-frequency applications. Additionally, our study employed Ansys Electronics Desktop 2022 R1 software for structural simulation. Comprehensive simulations and optimizations were conducted to refine the antenna's performance. The result is an SIW slot array [28,29] horn antenna, which notably achieves a bandwidth of 14.96 GHz, a gain of 10.01 dBi, and is tuned to a resonant frequency of 60 GHz. The detailed design and specifications of this antenna are illustrated in Figure 1.

Our study aims to iteratively refine and optimize the design of the antenna described above. Next, we will begin describing the following sections:

performance of the antenna is shown in Figure 3, and the antenna's bandwidth as designed in step 1 is 0.19 GHz.

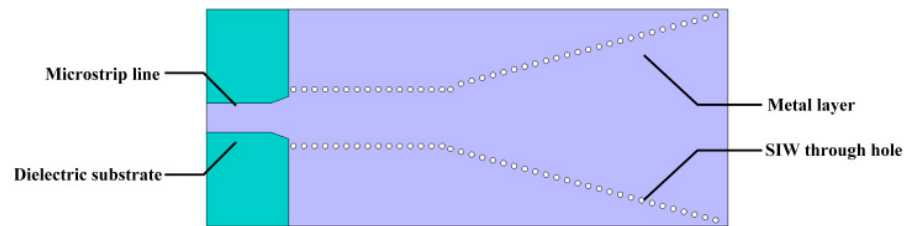


Figure 2. SIW horn antenna structure.

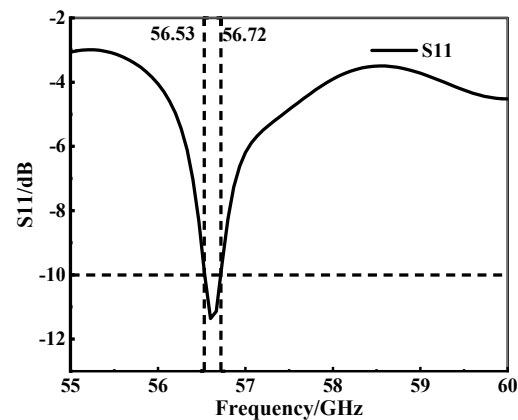


Figure 3. SIW horn antenna bandwidth performance.

2.2. Antenna Radiation Belt Design

The initial iteration of the SIW horn antenna, as developed through the aforementioned steps, exhibited a bandwidth of only 0.19 GHz. This was significantly narrower than the design requirements, with the center frequency and other parameters not aligning with our goals. To address this issue, we conducted an in-depth analysis of the antenna's electromagnetic radiation characteristics [34,35]. We discovered that the return loss at the transmitting end of a standard SIW horn antenna was notably high, negatively impacting its electromagnetic radiation, as depicted in Figure 4a. To optimize the electromagnetic performance of the antenna, we introduced a novel design element: the radiation belt, as illustrated in Figure 4b.

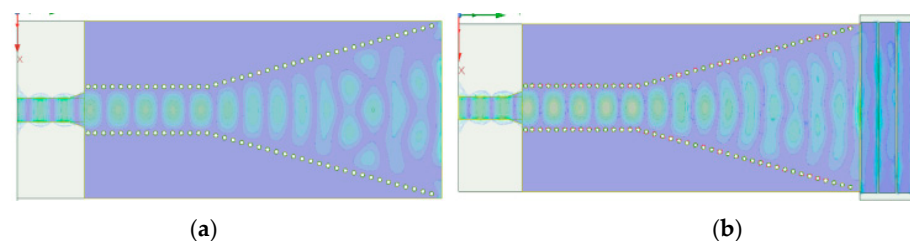


Figure 4. (a) Electromagnetic radiation without radiation belt; (b) electromagnetic radiation with radiation belt.

This strategic modification was found to not only optimize the electromagnetic radiation of the antenna but also substantially enhance its bandwidth performance. The improvements achieved through this design adjustment are clearly demonstrated in the parametric metrics shown in Figure 5. Most notably, the introduction of the radiation strip significantly expanded the antenna's bandwidth from a mere 0.19 GHz to an impressive 9.56 GHz. This dramatic increase marks a considerable advancement in the bandwidth performance of the antenna, aligning it more closely with the stringent requirements of high-frequency applications.

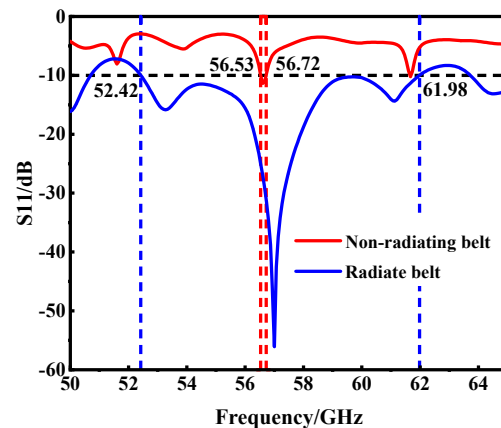


Figure 5. Results with or without radiation belt S_{11} .

2.3. Antenna Slot Array

Under the TE_{10} mode of a rectangular waveguide, opening narrow slots along the direction of current flow generally does not significantly affect the original mode. However, when etching slots on the metal surface, if the slots disrupt the original surface conduction current, displacement currents (i.e., time-varying tangential electric fields) will be induced on the aperture formed by the slots to maintain current continuity. In this case, the open slots are excited, leading to the radiation of electromagnetic energy into space.

According to the principle of electromagnetic equivalence, the radiation of an ideal slot with a length of L_c and a width of W_c ($L_c = \frac{\lambda}{2}$, $W_c \leq L_c$) is equivalent to a magnetic current source J_m . Following Babinet's principle, it complements a strip dipole with the same shape. Because the rectangular substrate-integrated waveguide (SIW) has transmission characteristics similar to those of traditional rectangular metal waveguides filled with dielectrics, the design methods for SIW slot antennas and traditional metal waveguide slot antennas are essentially the same. However, since the SIW is fabricated using PCB technology, its thickness is relatively thin, and the narrow sidewalls of the traditional metal waveguide are equivalent to the through-hole metallization of the SIW. Therefore, radiation can only be achieved by opening slots on the upper and lower metal surfaces of the SIW.

For the SIW operating in the TE_{10} mode, it exhibits three common types of slots based on their positions, as illustrated in Figure 6c. Slot 1 represents a longitudinal slot on the wide side, parallel to the propagation direction of the SIW. To cut off the current distribution, it needs to be offset from the centerline of the SIW by a certain distance. Slot 2 is a diagonal slot on the wide side, with its center located on the symmetrical centerline of the SIW and at an angle with respect to the propagation direction. Slot 3 is a transverse slot on the wide side, perpendicular to the propagation direction. Among these, the longitudinal slot array on the wide side is the most common type of SIW slot array. When the current is interrupted to open slots, energy leaks into space, thereby radiating electromagnetic waves. Therefore, by establishing a slot array, electromagnetic wave radiation can be controlled to achieve an increase in bandwidth.

In the quest to further augment the performance of the antenna, the concept of a slot array mode, as indicated in Reference [36], was incorporated in step 3 of our process. The SIW, fabricated using the PCB process [37], possesses a thin structure. This thinness is analogous to the narrow sidewalls of a traditional metal waveguide, achieved through metalized vias or holes. In the PCB design, electromagnetic radiation is primarily confined to the top and bottom wide edges of the SIW, where the metal layers are present. A critical aspect of this design is the presence of gaps within the SIW structure. These gaps disrupt the continuity of the transverse surface currents, leading to a distinct behavior. Specifically, the transverse surface currents are redirected towards the ends of these gaps. This redirection results in abrupt changes in the longitudinal currents along the propagation direction of the SIW, as detailed in References [38,39]. Consequently, the longitudinal slot on the wide side

of the SIW can be effectively modeled as an admittance in parallel with the transmission line. This concept is instrumental in establishing the equivalent circuit model, depicted in Figure 6a.

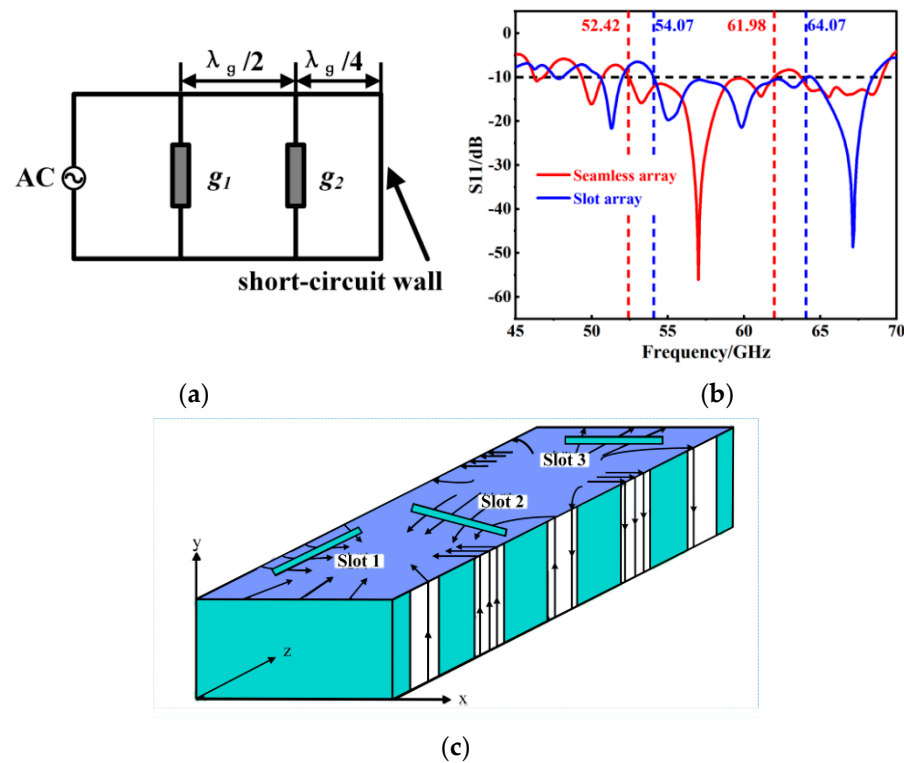


Figure 6. (a) Three slot types of the SIW TE₁₀ mold; (b) results with or without slot and S₁₁; (c) three types of slots under TE₁₀ mode in SIW.

When the wide-side longitudinal slot of the SIW is in resonance, Stevenson provided its normalized conductance as:

$$g = 2.09 \frac{W_i}{h} \frac{\lambda_g}{\lambda} \cos^2 \left(\frac{\pi \lambda}{2 \lambda_g} \right) \sin^2 \left(\frac{\pi \lambda}{W_i} \right) \quad (5)$$

Figure 6b illustrates the significant impact of implementing a slot array on the bandwidth of the antenna. This comparison clearly shows that introducing the slot array not only extends the bandwidth from 9.56 GHz to a remarkable 10 GHz, but also beneficially shifts the center frequency towards the higher frequency spectrum, moving from 57.2 GHz to 59.07 GHz. This shift brings the antenna's performance closer to the targeted center frequency of 60 GHz, aligning more closely with our design objectives.

In addition to the slot array modification, another critical strategy for optimizing the antenna's electromagnetic performance involves reducing the area of the metal layer. This is achieved by cutting the metal at specific angles, as discussed in Reference [40]. Reducing the metal layer area minimizes metal radiation and coupling effects, thereby enhancing the electromagnetic properties of the antenna. The simulations and comparisons of the S₁₁ results provide insightful evidence of this improvement. Notably, the bandwidth's left and right boundaries at the metal layer's tangent angle are expanded outwards, thereby broadening the overall bandwidth from the initial 10 GHz to an impressive 14.48 GHz. The culmination of these design modifications and optimizations is the finalized SIW slot array horn antenna, as showcased in Figure 7a. This design represents the integration of innovative techniques to significantly improve the antenna's bandwidth and electromagnetic performance, marking a substantial advancement in antenna technology for high-frequency applications.

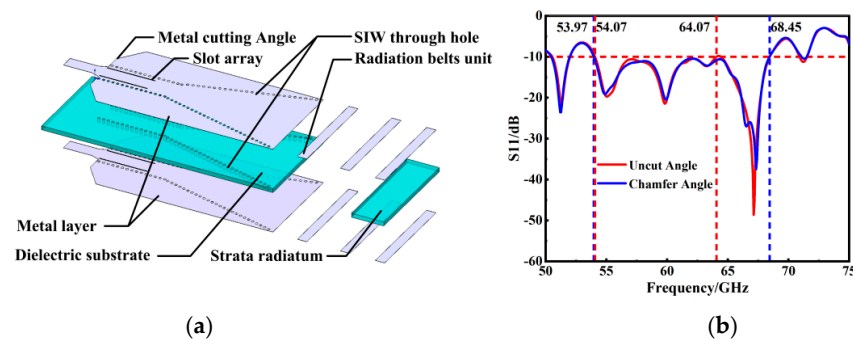


Figure 7. (a) Three-dimensional explosion diagram of the overall antenna structure; (b) results of cutting angle S_{11} with or without metal layer.

3. Analysis, Results, and Discussions

After the above three stages of the design process, the overall structure of the antenna is finally obtained. The effects of the geometric parameters are investigated in this part. The following parameters are selected for this study: the length (L_c) and width (W_c) of the slot array, the distance (P), length (L_f), and width (W_f) of the radiation belt unit, and the width (W_m) of the metal cutting angle. However, the parameters described above will exhibit a hierarchical relationship. The initial design parameters of the antenna are as follows (Table 1).

Table 1. Initial values of optimization parameters.

Symbol	Value (mm)	Description
W_m	2.735	Width of metal cut corners
P	0.150	Radiation belt unit spacing
W_f	1.000	Radiation band unit width
L_f	11.000	Radiation belt unit length
W_c	0.092	Width of slot array element
L_c	5.750	Length of slot array element

The scan optimization and discussion of the above parameters are as follows (Figure 8).

This part of the study focuses on the value of S_{11} under different W_m values. A step scanning optimization method was employed, incrementing W_m by 0.02 mm steps. The simulation results revealed that as W_m increased, the optimum value was identified at 2.835 mm. At this width, the antenna achieved its widest bandwidth, spanning 14.96 GHz (from 54.06 GHz to 69.02 GHz), with the maximum reflection coefficient reaching -39.27 dB. After careful analysis, a W_m of 2.835 mm was determined to be the most effective for achieving optimal bandwidth and reflection characteristics.

The study then analyzed the impact of varying the W_f on the antenna's performance, specifically looking at the S_{11} parameters. It was observed that the antenna's bandwidth shifted at both ends as W_f increased. The most favorable bandwidth expansion occurred at a W_f of 1.15 mm. Meanwhile, when W_f is set to 1.15 mm, the resonance frequency aligns well with the W_m at 2.835 mm, yielding optimal bandwidth. Consequently, an optimal antenna performance was achieved when the width of the W_f was set to 1.15 mm.

This part of the study examines the S_{11} results for different L_f values. The simulations indicate that the S_{11} reflection coefficient peaks at an L_f of 13 mm. However, the optimal length for L_f is determined to be 12 mm. At $L_f = 12$ mm, the length of the radiation belt closely aligns with the aperture of the SIW horn antenna, facilitating more effective radiation of electromagnetic waves. To minimize electromagnetic wave scattering, the width of the radiation belt is designed to be larger than the distance between the two metallized holes in the SIW horn antenna layer. The study further investigates how the variation in the P affects the antenna's reflection coefficients. It was observed that the antenna's bandwidth decreases as P increases, particularly when the band spacing exceeds 0.15 mm. The antenna

achieves its optimal impedance bandwidth of 14.96 GHz at $P = 0.15$ mm, marking this as the best value for antenna bandwidth performance.

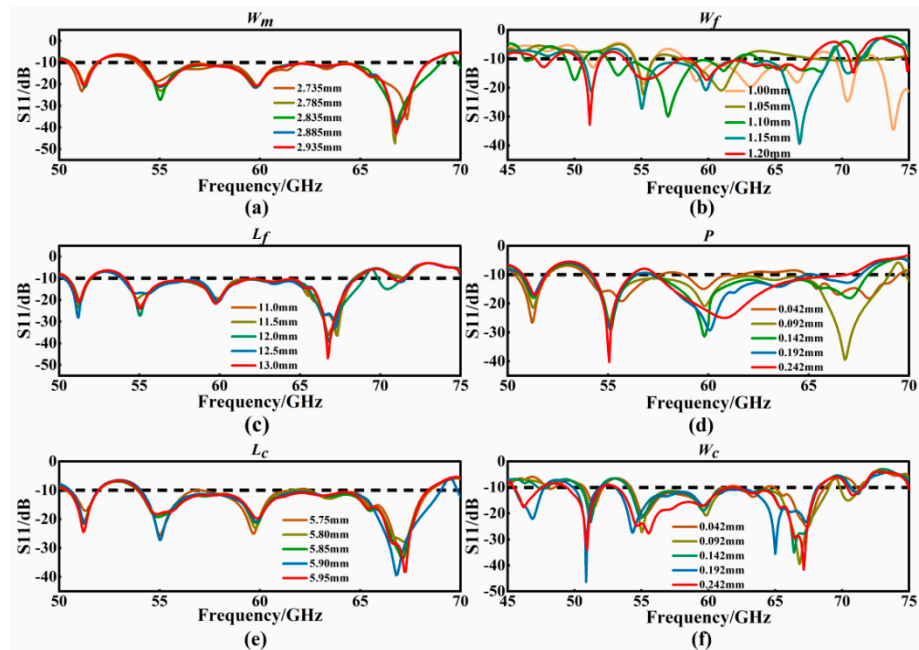


Figure 8. Antenna parameter optimization diagram. (a) the impact of the metal cutting angle width (W_m) on antenna performance. (b) the impact of the radiation belt unit width (W_f) on antenna performance. (c) the impact of the radiation belt unit length (L_f) on antenna performance. (d) the impact of the radiation belt unit distance (P) on antenna performance. (e) the impact of the slot array length (L_c) on antenna performance. (f) the impact of the slot array width (W_c) on antenna performance.

This segment of the study focuses on the influence of the L_c on the antenna's bandwidth. It was observed that the antenna's bandwidth reaches its maximum of 14.96 GHz when L_c is set to 5.90 mm. Consequently, an L_c of 5.90 mm was identified as the optimal length for maximizing the antenna bandwidth. The study then examines how varying the W_c affects the antenna's impedance bandwidth. The results show a gradual widening of the antenna's impedance bandwidth with an increase in W_c , with the maximum bandwidth of 15.15 GHz achieved at a W_c of 0.192 mm. Therefore, the optimal width for the slot array is determined to be 0.192 mm, as it yields the highest bandwidth performance.

Following the meticulous optimization of the core parameters of the antenna, we achieved notable results as depicted in Figure 9, which displays the gain exponent. The extensive simulation process culminated in the antenna achieving a significant bandwidth of 14.96 GHz along with a substantial gain of 10.01 dBi. These figures mark a considerable advancement in antenna performance, particularly in terms of bandwidth and gain. The detailed bandwidth simulation, showcasing these results, is presented in Figure 10b. This diagram illustrates the effective bandwidth coverage of the antenna, confirming its suitability for high-frequency applications. The substantial bandwidth, coupled with the high gain, indicates that the antenna is well-equipped to meet the demanding requirements of contemporary wireless communication systems. The specific size parameters of the designed 60 GHz SIW slot array horn antenna are given in Table 2:

The final design of the SIW slot array horn antenna, as depicted in Figure 10a, was meticulously crafted and manufactured based on the optimized parameters previously outlined. The antenna boasts a compact size of $32 \times 13 \times 0.543$ mm³, highlighting its small footprint and potential for seamless integration into various applications. The comprehensive simulation and validation results of this antenna are presented in Figure 10b. These results confirm its performance metrics and suitability for the intended high-frequency applications. The combination of its small size and the results from the simulation and

validation processes underscore the antenna's innovative design and its potential impact in the field of wireless communication.

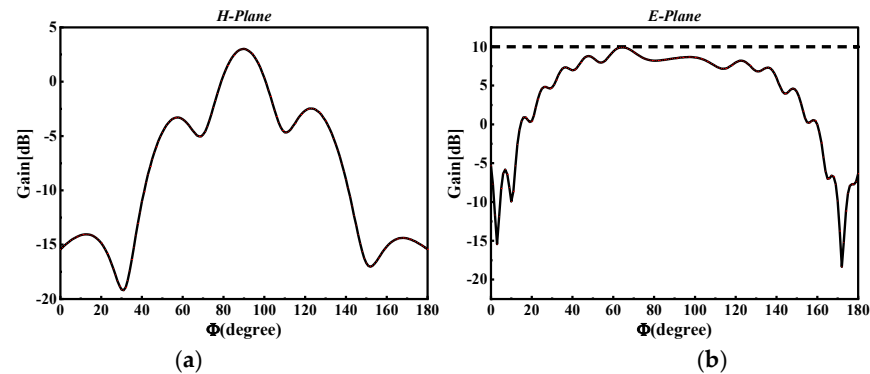


Figure 9. Radiation patterns of E and H planes of SIW slot array horn antenna; (a) H-plane radiation pattern; (b) E-plane radiation pattern.

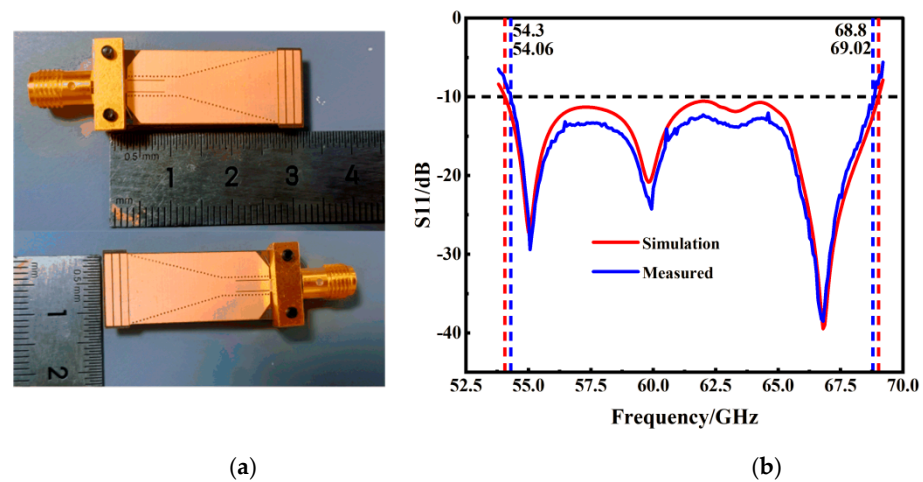


Figure 10. Antenna diagram and performance verification; (a) picture of real products; (b) analog and measurement bandwidth.

Table 2. Specific values of antenna design parameters.

Symbol	Value (mm)	Description
W	11.800	Antenna width
L_1	6.705	Transmission line and metal cutting length
L_2	21.795	Horn length
L_3	3.980	Radiation layer length
W_i	1.575	50 Ω feeder width
L_i	3.500	50 Ω feeder length
W_t	3.383	Metallized through hole row wide
L_t	8.405	Rectangular waveguide length
W_m	2.835	Width of metal cut corners
L_m	1.064	Conical corner length
W_f	1.150	Radiation band unit width
L_f	12.000	Radiation belt unit length
d	0.300	Metal through hole diameter
S	0.600	Metallized through hole aperture
P	0.150	Radiation belt unit spacing
W_c	0.192	Width of slot array element
L_c	5.900	Length of slot array element
W_0	13.000	Width of horn antenna output

The measurement results of the SIW slot array horn antenna revealed a bandwidth of 14.5 GHz and a reflection coefficient of -37.51 dB. These figures are largely in alignment with the theoretical predictions, affirming the success of the antenna design. However, a minor shift in frequency was observed, which warrants consideration.

This deviation from the theoretical values is likely attributable to a few key factors encountered during the manufacturing and testing phases. Firstly, errors in the positioning and sizing of the through-hole apertures during the manufacturing process could have contributed to these discrepancies. Secondly, the loss of joints in the measurement process is another potential source of variation. Lastly, environmental conditions [41] during testing may have had an impact on the results. These factors underscore the complexities involved in translating theoretical designs into practical applications. They highlight the need for precision in manufacturing and the influence of external conditions on the performance of high-frequency antennas.

4. Comparison

Table 3 presents a comprehensive comparison of the antenna's performance parameters across the three distinct design phases discussed in Section 2. This comparative analysis clearly illustrates that the antenna exhibits superior performance in the third phase compared to the first two phases. The enhanced performance in the final phase can be attributed to the strategic additions made to the antenna design, namely the incorporation of radiation bands and slot arrays. These modifications have proven to be effective in significantly improving both the bandwidth and gain of the antenna. This improvement highlights the importance of iterative design and optimization in antenna engineering, demonstrating how each phase of development contributes to the overall enhancement of antenna performance.

Table 3. Compares the performance of the three phases.

	Bandwidth (GHz)	Gain (dBi)	Maximum Reflection Coefficient (dB)
Phase 1	0.19	5.43	-11.35
Phase 2	9.56	10.56	-56.08
Phase 3	14.96	10.01	-39.47

Table 4 effectively compares the performance of the antenna developed in this paper with other antennas previously reported in the literature. The comparison is based on key parameters such as bandwidth, gain, size, and reflection coefficient. The findings indicate that the antenna designed in this study holds a distinct advantage in terms of bandwidth performance, surpassing most of the other antennas. Additionally, it demonstrates superior performance in terms of reflection coefficient, and its gain and size are also comparatively better than most of the antennas in the study.

The excellence in these performance metrics is particularly significant for industrial radar sensing systems. The wide bandwidth of the antenna contributes to a higher distance resolution, which is crucial in accurately determining the position of objects. Moreover, the center frequency of 60 GHz enhances the velocity resolution, enabling more stable detection of moving objects. The combination of a wide bandwidth and an optimal center frequency is vital for collecting rich and highly accurate point cloud data. This, in turn, facilitates the generation of high-resolution radar images, crucial for the efficacy of industrial radar systems.

Table 4. Comparison between the published SIW structural antennas at 60 GHz and our work.

Reference	Size (mm)	Gain (dBi)	Bandwidth (GHz)	Return Loss (dB)
[20]	$29.5 \times 8 \times 0.787$	10	3.33	−12.23
[23]	$14 \times 8 \times 0.381$	/	4.18	−33.95
[24]	$14 \times 8.4 \times 0.381$	/	3.5	−21.98
[25]	$7 \times 12 \times 0.508$	6.54	6.8	−36.35
[26]	$16 \times 16 \times 0.254$	10.56	1.73	<−50.0
[42] (simulation)	$17.5 \times 14.5 \times 0.42$	11.8	10	/
[43]	$13 \times 9 \times 0.381$	/	5.3	−29.6
This work	$32 \times 13 \times 0.543$	10.01	14.5	−37.51

5. Conclusions

This study focused on the development of a 60 GHz slot array horn antenna, leveraging an SIW structure. A key aspect of this design was the strategic control of electromagnetic radiation direction through the arrangement of apertures. Additionally, the antenna's bandwidth performance was optimized by incorporating a radiation band at the radiation front. The use of a slot array further expanded the working bandwidth of the antenna.

Experimental evaluations of the antenna demonstrated its exceptional performance, with a strong correlation between simulation predictions and actual measurement results. The antenna's impressive performance characteristics are pivotal for providing high-resolution radar imaging, crucial for accurate target detection and tracking in industrial applications. Moreover, the antenna's compact size contributes to cost reductions in the deployment of radar sensing systems in industrial settings.

In conclusion, the designed antenna, with its combination of excellent performance, high resolution, and cost-effectiveness, emerges as a promising alternative for future industrial radar sensing applications. Its innovative design and successful implementation mark a significant advancement in the field of radar technology.

Author Contributions: Conceptualization, B.M.; methodology, B.M. and J.L.; software, B.M.; validation, Y.S., H.G. and Y.C.; formal analysis, B.M. and Y.C.; investigation, B.M. and J.L.; resources, B.M.; data curation, B.M.; writing—original draft preparation, B.M. and J.L.; writing—review and editing, Y.C. and Y.S.; visualization, H.G. and Y.S.; supervision, Q.W.; project administration, Q.W. and M.L.; funding acquisition, M.L. All authors have read and agreed to the published version of the manuscript.

Funding: This research was funded by Double First-Class Talent Plan Construction (11012315); Double First-Class disciplines National first-class curriculum construction (11013168); Double First-Class Disciplines Construction (11013351); and the National Future Technical College Construction Project (11013169).

Data Availability Statement: The data that support the findings of this study are available from the corresponding author upon reasonable request.

Acknowledgments: Thank you very much for the support of the School of Instrument and Intelligent Future Technology of North University of China.

Conflicts of Interest: The authors declare no conflicts of interest.

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