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Improving the performance of SIW-based leaky wave antenna using the creation of an entrance hole

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ABSTRACT

In this paper, the effect of input holes on the performance of leaky wave antennas(LWA) is investigated by presenting two designs based on the substrate integrated waveguide(SIW) structure. Both antennas are made of unit cells with transverse and longitudinal slots, the main difference being the placement of holes in the input ports of one of the designs. The results of experiments of both antennas under the same conditions show that adding holes in the input ports significantly improves the qualitative and quantitative radiation characteristics of the antenna. The simulation, fabrication and measurement processes for both LWAs confirm these findings. The antenna equipped with the hole in the input port achieves a bandwidth of 6.7 GHz with a minimum return loss of +10 dB over this entire bandwidth, focusing at a frequency of 12.8 GHz and a reflection coefficient of -48.5 dB. The antenna is capable of beam scanning from -66° to +5° and from +20° to +73° with a cross-polarization level of more than -45 dB over the entire frequency scan range. The final antenna has a maximum gain of 16.7 dB in the 7.9–14.6 GHz frequency band with 52% of the normalized bandwidth relative to the center frequency. Overall, the findings emphasize that the inclusion of input holes in LWA designs significantly enhances the antenna radiation performance and highlight their potential for optimizing SIW-based antennas in various applications.

1. Introduction

Leaky Wave Antennas (LWAs) are a family of traveling wave antennas and generally radiate over a wide bandwidth and have the ability to scan a portion of space. These antennas are divided into two main types: integrated and intermittent. In frequency-scanned leaky wave antennas, the main beam angle of radiation changes with frequency change relative to the line perpendicular to the antenna plane. On the other hand, substrate integrated waveguide (SIW) structures have been widely used in recent years in literature and industry due to their ease of manufacture, cost-effectiveness, planar structure, and other advantages over other transmission lines. Due to the advantages of this type of waveguide, their use in the design and construction of wave antennas has become very common. This antenna operates in a specific bandwidth and leaks into space through the slots created in the upper surface of the SIW waveguide and creates beams in specific directions[15]. This structure makes the antenna work more effectively and is used in specific applications such as curved antennas. Leaky wave antennas control the direction of the beam in a specific bandwidth due to their phase dependence on frequency. Due to their unique features and numerous advantages, this type of antenna has attracted a lot of attention. Low specifications, narrow beam width, high directivity and

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simple feeding capability at specific frequencies have made leaky wave antennas widely used in various applications such as broadband wireless communications, sensors and FMCW radar systems [1], [2]. These antennas can be used in various antenna applications and their design and performance depend on the cross-sectional dimensions of the waveguide [3]–[14]. This technology is known as one of the key techniques in the design of LWA antennas. These antennas are divided into several categories:

1. Uniform SIW antennas [3], [4]: This type of antenna is designed based on a waveguide or transmission line with regular slots that operate based on resonance at specific frequencies. These antennas produce maximum voltage in the receiving mode. The gain of the structure affects the coverage and uniformity of the signal, such that increasing the gain increases the coverage but reduces the uniformity.

2. Quasi-uniform SIW antennas [5]–[6]: This type of antenna is formed with a combination of regular and irregular slots and operates in a specific bandwidth and is mostly built based on regular or serrated waveguides. One of the characteristics of these antennas is the phase dependence on frequency.

3. SIW periodic antennas [7]–[8]: These structures have a slow wave fundamental space harmonic and its period is approximately equal to the guided wavelength over a wide range of frequencies. Their important features include high gain, suitable beam width and robust structure. Some models of this type of antenna have special capabilities such as folding and light weight.

4. CRLH (compound right/left) antennas [9]–[13]: These antennas use both right/left handed properties to achieve various capabilities and are made of meta-material structures. They are of great interest due to their special capabilities such as wide frequency coverage and small dimensions. The design and analysis of these antennas can be complex, but structures based on SMT components are simpler. CRLH antennas are used in various applications and are also used in the design of low-pass filters. Left-right-left hybrid meta-material structures allow for backward propagation of waves in addition to normal propagation. These types of structures are used in leaky wave antennas to obtain backward radiation. They can also be used in substrate integrated waveguide structures.

Leaky wave antennas are also used in frequency scanning applications. The direction of the main beam of these antennas changes with frequency, so that with increasing frequency, the radiation beam moves from side-to-front in right-handed leaky wave antennas and from back-to-front in combined left-handed leaky wave antennas (CRLH).

In previous research, in particular in [8], a slotted LWA-SIW has been introduced that allows back-to-front beam scanning, but this design takes up a lot of space. In the present study, two types of LWA-SIWs were designed and fabricated, both structures are similar in terms of substrate material, physical dimensions, and details, and the only difference between the two antennas is the hole created in the input ports of one of the antennas, which leads to a change in the antenna radiation results. The initial design without holes with a bandwidth of 2 GHz with a minimum return loss of +10 dB in this bandwidth and focusing at a frequency of 12.8 GHz with a reflection coefficient of -26 dB did not perform well, while the antenna with an input hole, with a bandwidth of 6.7 GHz with a minimum return loss of more than +10 dB, provides good radiation performance and is optimized at a frequency of 12.8 GHz with a reflection coefficient of -48.5 dB. Simulation and measurement results show that the antenna is capable of scanning the beam from -66° to $+5^{\circ}$ and from $+20^{\circ}$ to $+73^{\circ}$ in the frequency range of 7.9-14.6 GHz with a maximum gain of 16.7 dB. The improved antenna performance shows that this design can effectively meet the needs of various applications, especially in areas that require high-frequency performance and efficient signal transmission. The presence of holes in the input ports in the antenna design helps to improve its performance characteristics and allows for better control over the structure's propagation pattern.[15] These findings indicate the potential for further optimization of LWA-SIW antennas by exploring different geometries and configurations, ultimately leading to more versatile and efficient antenna solutions for modern communication systems. Overall, the integration of innovative design elements, such as entry holes, into LWA-SIW antennas represents a step forward in antenna technology and paves the way for improved performance in a wide range of applications, including telecommunications, radar systems, and other high-frequency devices.

2. Structure

2.1. Substrate Integrated Waveguide

SIW is a type of waveguide structure specifically designed for transmitting electromagnetic signals at microwave and millimeter wave frequencies. This structure has many advantages, such as reduced size, lower cost, and ease of integration with other electronic components, due to the combination of the characteristics of waveguides and integrated circuits. In SIW, the dielectric acts as the main core and its top and bottom surfaces are covered with metal plates. These metal plates help create confined electromagnetic fields and cause signals to be retained inside the structure. Also, metal vises on both edges of the waveguide help control and regulate surface currents caused by electromagnetic radiation. The openings between the two sides of this structure, known as SIW holes, are designed to create minimal disturbances in surface currents while maintaining maximum electromagnetic fields inside the structure[15]. These characteristics make SIW a suitable choice for various applications including filters, amplifiers, and other RF and microwave components [15].

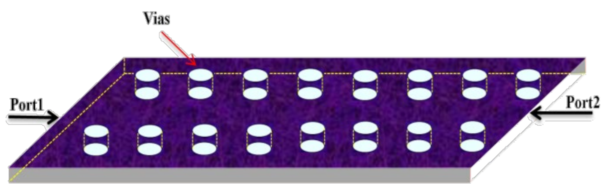


Fig. 1. Substrate integrated waveguide structure.

2.2. Leaky Wave Antenna

The initial and final proposed leaky-wave antennas without and with holes is shown in Fig. 2(a) and (b), respectively.

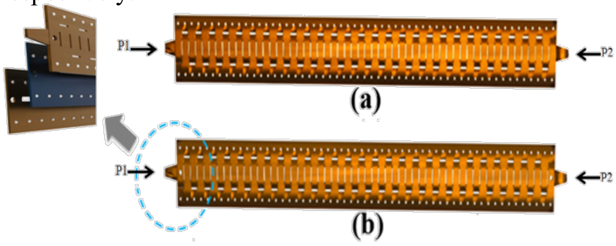


Fig. 2. (a) Leaky wave antenna without a hole (b) Leaky wave antenna with a hole at the input.

The antenna consists of 28 units, each with a period or length of 6.5 mm. The substrate used is Rogers 5880 with a relative permittivity of 2.2 and a thickness of 0.79 mm. The antenna performs scanning from back to front using electromagnetic waves, making it impossible to perform continuous beam scanning in the width direction, so there is no radiation in the wide side. The antenna structure is designed and built based on an array of impedance-matched unit cells. Each cell consists of two transverse and longitudinal slots. The transverse slot of the unit cell introduces the series Z impedance and the vertical slot introduces the parallel Y admittance in the equivalent circuit model shown in Fig. 3.

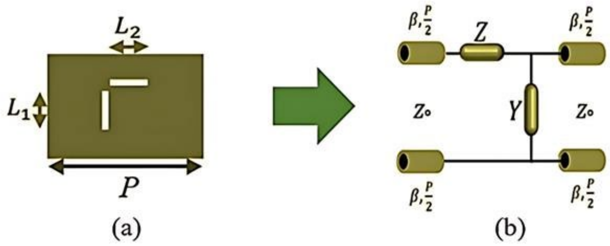


Fig. 3. The unit cell of proposed leaky-wave antenna (a) geometrical structure (b) equivalent circuit.

Longitudinal slots disrupt the transverse flow of the waveguide. In other words, they can change the electrical current pattern inside the antenna and lead to different impedances. These changes can affect the radiation and performance of the antenna. On the other hand, the transverse slots act as capacitors and organize the disturbances caused by the longitudinal slots. By creating capacitance, these slots help to adjust and optimize the impedance and increase the efficiency of the antenna. By changing the length and position of both types of slots, various antenna parameters can be adjusted and lead to desirable results in terms of radiation, accuracy and efficiency. The information on the physical parameters of the antenna in Fig. 4 is given in Table 1 as an important reference for evaluating and performing the antenna in different conditions[15].

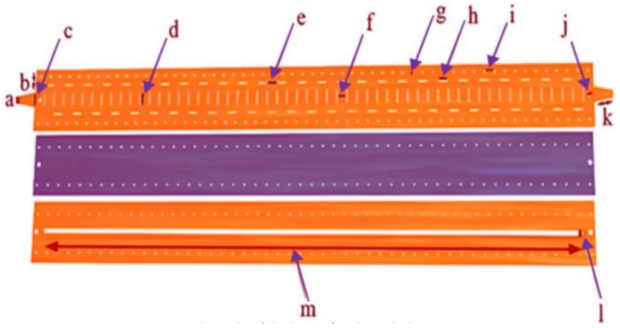


Fig. 4. 2D schematic of the layers forming a leaky wave antenna.

Table 1. Parameters for the unit cell in Fig. 2b.

Parameter	Value(mm)	Parameter	Value(mm)
a	3.1	h	6.5
b	12.56	i	1.6
c	4.7	j	2
d	4.5	k	15
e	6.5	l	3
f	6.5	m	266.5
g	0.8	n	0.79

3. Data Analysis

The photograph of the fabricated LWA without holes is shown in Fig. 6. The length of this antenna is 317 mm.

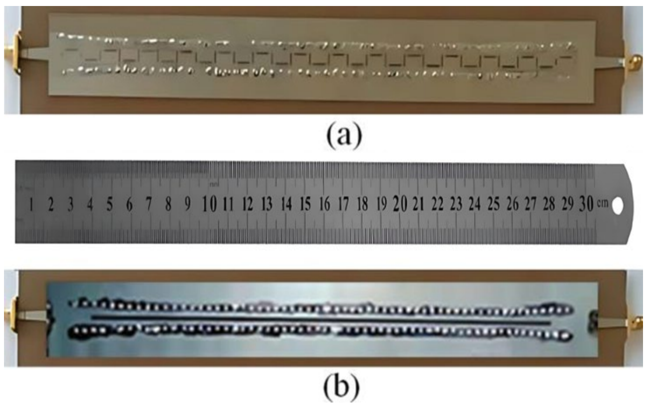
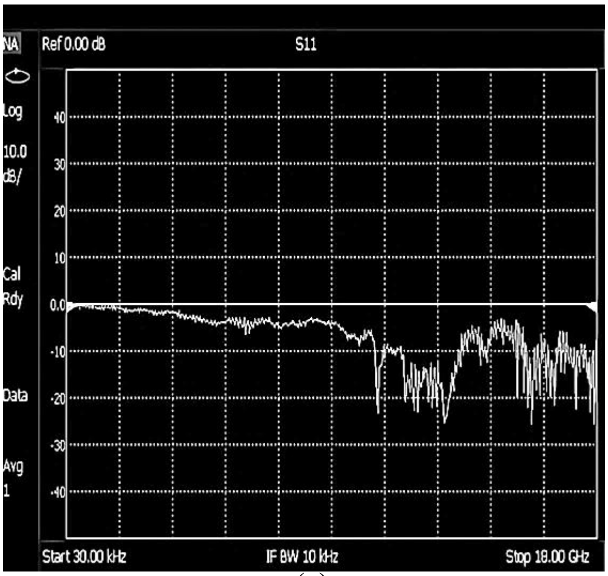
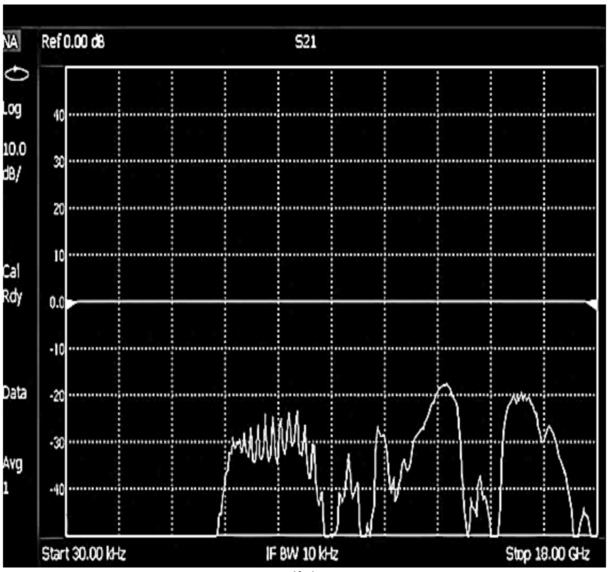


Fig. 5. Proposed leaky wave antenna (a) front view with length size of L=317mm (b) back.

Fig. 6 shows the reflection coefficients S_{11} and transmission coefficients S_{21} for the antenna without holes. The 2 GHz bandwidth, focusing at 12.8 GHz with a radiation coefficient of -26 dB, shows that the original antenna does not perform well. To improve the performance and achieve a better design, a new antenna is fabricated with the same material and physical dimensions, except that two holes are applied on both ports of the original LWA.



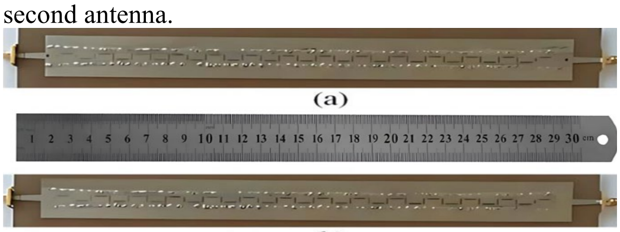
(a)



(b)

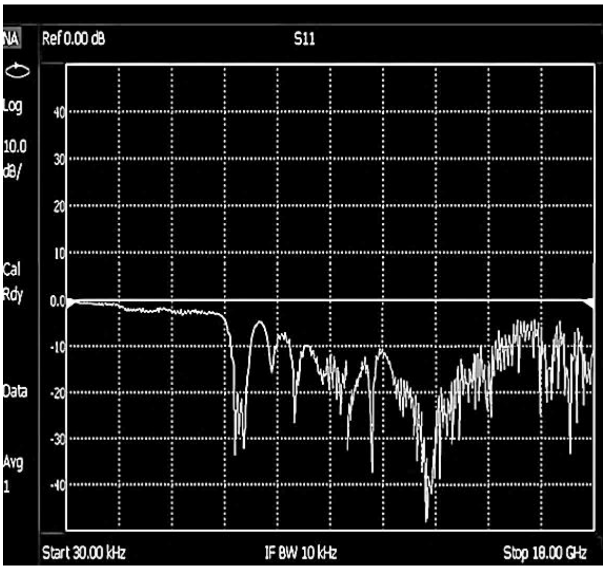
Fig. 6. The measured (a) $\mathbf{S_{11}}$and (b) $\mathbf{S_{21}}$ of the first antenna.

The geometry of this LWA is shown in Figure 2b. An example of the implemented and measured antenna is shown in Figure 7a. According to this figure, it can be confirmed that the dimensions of the final antenna are the same as the original antenna. The holes made on both sides play a very effective role in improving the performance of the antenna. Fig. 8 show the reflection coefficient S_{11} and the transmission coefficient $S_{21}$for the second antenna.



(b)

Fig. 7. Comparing the dimensions of the final antenna with the initial antenna (L=317 mm) (a) the final antenna (b) initial antenna.



(a)

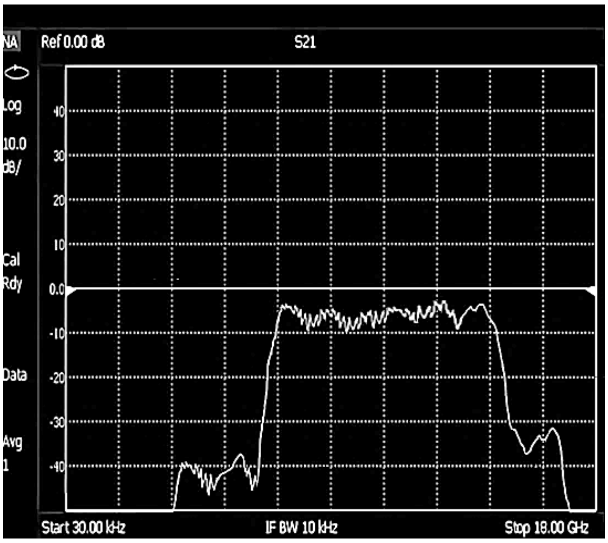


Fig. 8. The measured (a) $\mathbf{S_{11}}$and (b) $\mathbf{S_{21}}$ of the second antenna.

In Fig. 8, the S_{11} and S_{21} parameters of the antenna are shown in a wide frequency range. The bandwidth of this antenna is 7.6 GHz with a return loss coefficient of +10 dB over the entire width. This antenna works with a focus at a frequency of 12.8 GHz with a reflection coefficient of -48.5 dB. The increase in the bandwidth of this antenna compared to the prototype allows the use of a wider range of frequencies.

Table 2 shows the percent radiation efficiency at several frequencies in the antenna operating range.

Table 2. Radiation efficiency of the proposed leaky wave antenna.

Frequency (GHz)	Radiant Efficiency Percentage	Frequency (GHz)	Radiant Efficiency Percentage
11.200	27.80	12.800	23.14
12.200	94.00	14.000	36.15
12.600	48.52	17.300	23.50

ecreasing the value of S_{11} or increasing the value of S_{21} can lead to an increase in the radiation efficiency of the antenna. Therefore, the antenna design should be such that it has low reflection and high transmission to provide optimal performance. At a frequency of12.8 GHz the S_{21} parameter is about -5 dB(Fig.8a) and the S_{11} parameter is about -48.5 dB(Fig.8b). These results show that the transmission to radiation ratio is approximately 10 to 1, which confirms the favorable performance of the proposed leaky wave antenna. Also, the stable return coefficient of the second antenna (+10 dB) over the entire bandwidth indicates that 90% of the power penetrated the antenna and was transmitted through the structure's fins to the next antenna, and only about 10% of this power was radiated, which on the one hand highlights the leakage state in the antenna and on the other hand indicates impedance matching along the structure. The VSWR value also reached an order of magnitude less than two(Fig.9). Considering that one of the goals of this research is the use in areas such as tunnels that require maximum power transfer to the next antenna in the form of a relay and with much less radiation in the antenna's field of view, the holes embedded in the antenna input have had a positive effect on its performance characteristics.

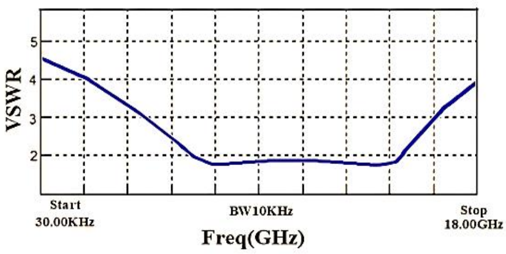


Fig. 9. The VSWR changes of the second antenna.

Fig. 10 shows the normalized, simulated, and measured radiation patterns of the optimized antenna. The observed difference between the simulated and measured gain values can be attributed to the insertion losses associated with the SMA connector and the measurement inaccuracy in the out-of-band frequency range from 8 to 18 GHz. The data show that the radiation efficiency in the operating band varies from about 30% to 60%. This relatively low efficiency is primarily due to material losses in the conductors, especially copper. To increase the overall efficiency of the antenna, it may be beneficial to use substrates with lower tangential losses or to choose conductors with higher conductivity. Furthermore, the results show that the antenna is capable of scanning the beam in two ranges from -66° to +5° and from +20° to +73°, in the frequency range of 7.9–14.6 GHz. Fig. 11 confirms the antenna radiation range with the hole in the opposite direction, these beams effectively cover two distinct areas, which are shown in red. This feature is effective for applications that require focused signal transmission and reception and shows the potential of the antenna to communicate in targeted directions. The dual radiation beams of the antenna not only increase its coverage in the lower frequency range, but also enable effective signal propagation in both directions. This feature is especially useful for deployment in environments with high signal loss, such as tunnels. By using two radiation beams, the distance between the antennas can be increased while maintaining acceptable performance levels. This strategic placement can lead to reduction in the overall number of antennas required, which is beneficial for both cost and installation efficiency. Fig. 12 shows the surface current variations for both the antennas with and without holes.

Figure 12 shows the surface current distribution in both antennas (with and without an inlet hole). In the primary antenna, where there is no input hole, the surface current distribution is irregular. When the antenna input port is excited, minimal current enters the antenna and most of it returns to the antenna input, which leads to a decrease in its reflection coefficient and an increase in return loss, which consequently negatively affects the antenna performance. In contrast, the hole embedded in the secondary antenna creates a match at the antenna input opening and, in addition to increasing the amount of current at the antenna surface, gives a certain order to this current and causes it to move flatly along the antenna longitudinal axis. This improvement contributes to the desired S_{11} state and allows matching of impedance and radiation characteristics. The uniform current distribution enables the antenna to radiate with a constant radiation pattern. Furthermore, when ports 1 and 2 of the antenna are excited at different frequencies in the Ku-band, the structure can effectively radiate at both frequencies without interference. This capability not only enhances the antenna performance but also allows for the creation of a multi-band communication system. In this regard, the surface current of the desired antenna with holes in the input ports is investigated in phase in Figure 13. In order to better illustrate the surface current variations on the antenna, the images are shown in different phases (frequency of occurrence relative to the zeroth second (at zero phase). The surface current variations in different phases are logarithmic. It is expected that the surface currents at different lengths (e.g. 1/12, 1/8, 1/6, etc.) are similar to ensure the stability of the frequency response and antenna performance under different conditions. The similarity of the current distributions at 0 degrees and 180 degrees indicates that the system follows the phase of the input signal and produces the correct phase output, which leads to phase synchronization. Therefore, by controlling the phase, interference is avoided and the system capacity is increased. On the other hand, precise control of the surface currents can help in the seamless transfer of the current from back to front, thereby increasing the gain stability factor at different frequencies and minimizing unwanted changes in the antenna performance. Fig. 14 shows the role of the entrance hole in improving the gain in two antennas with and without holes.

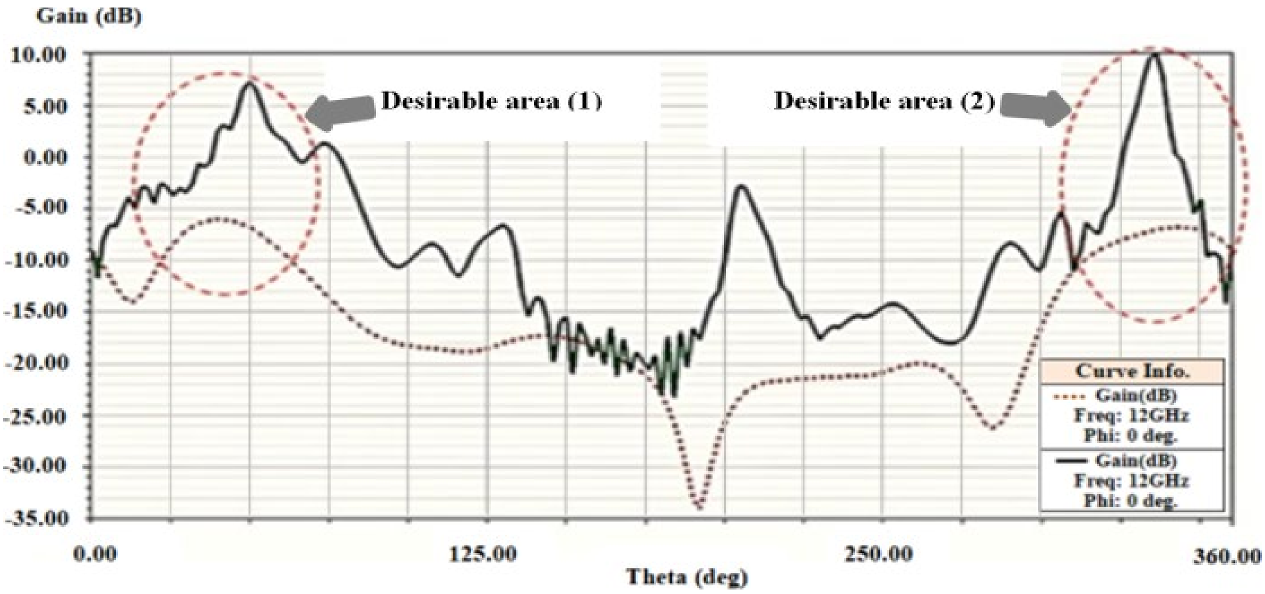


Fig. 10. Simulated normalized radiation patterns of the proposed LWA at the angles φ = 0 and φ = 90 degrees.

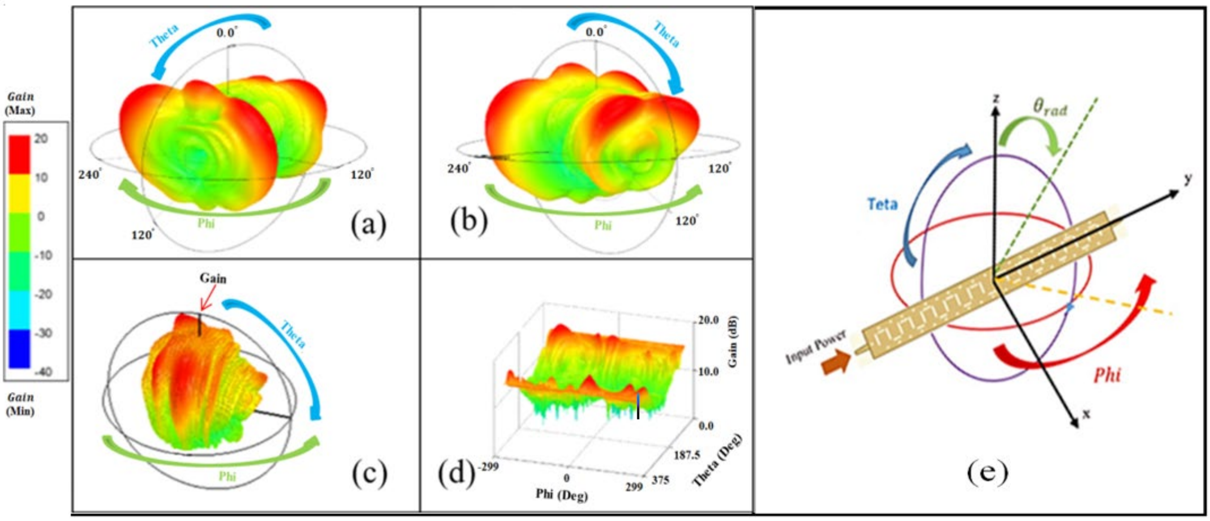


Fig. 11. 3D far field radiation (a), (b), (c) polar device (d) coordinate device (e) Antenna orientation in spherical coordinates.

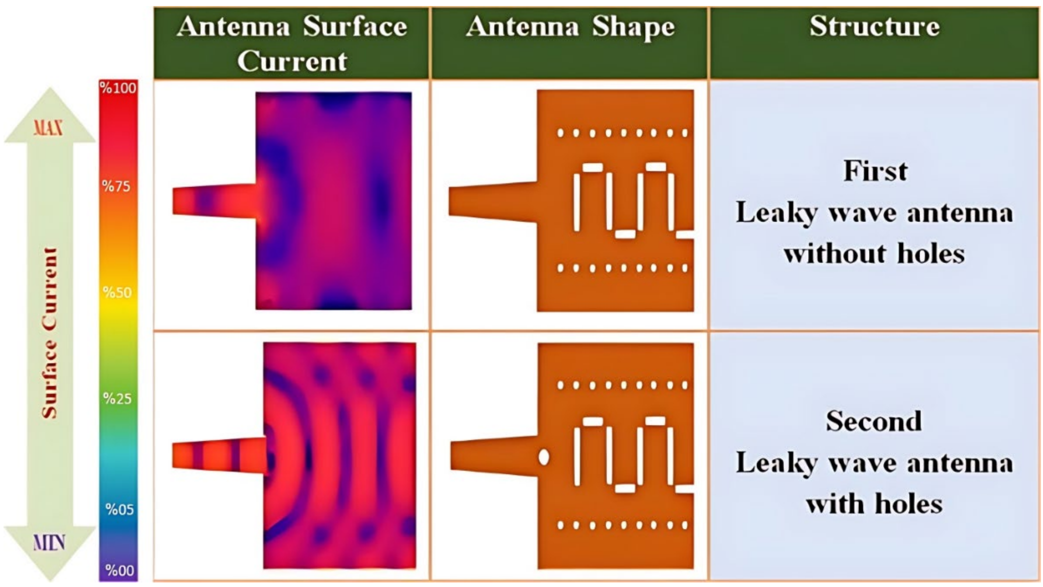


Fig. 12. The effect of the hole on the antenna surface current distribution.

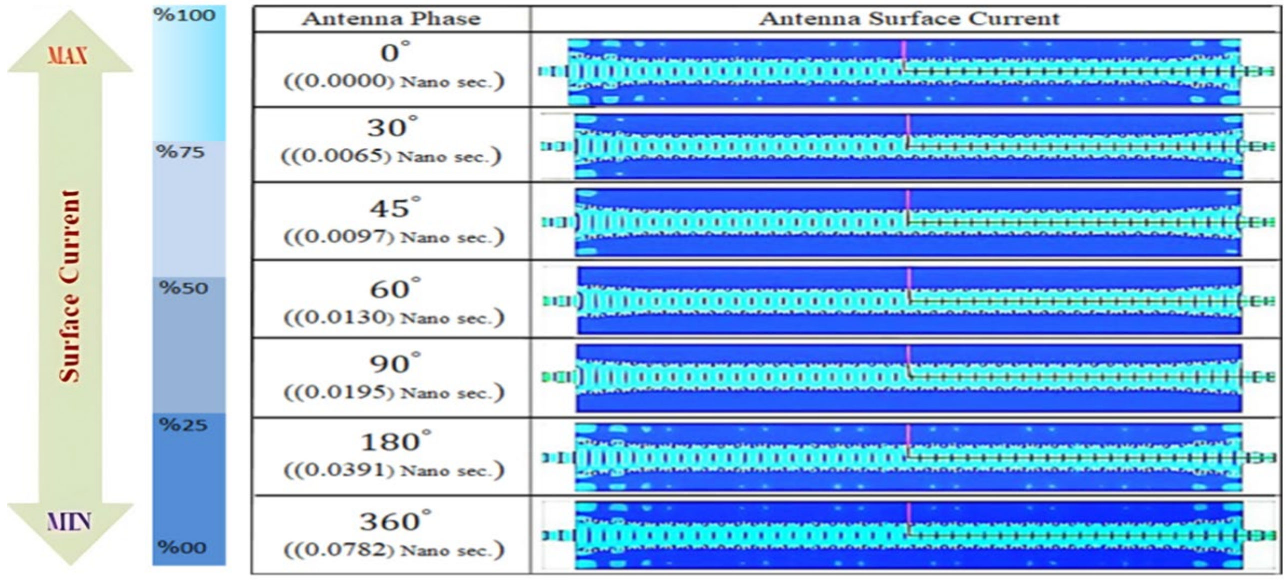
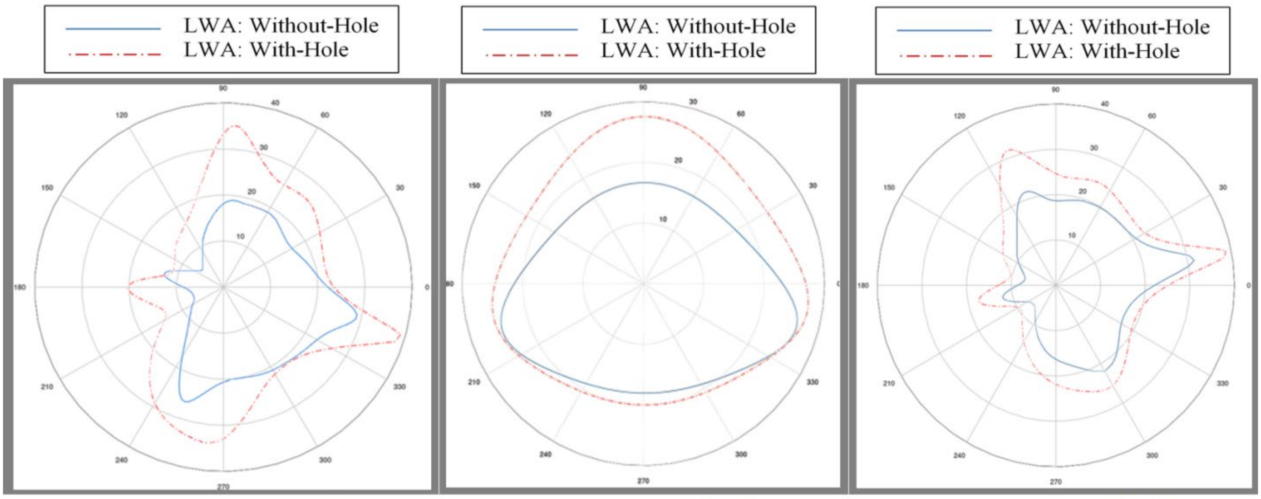


Fig. 13. Surface current flowing on the antenna with hole in differen phases.



(a)The Horizontal gain versus φ = 0 at z=0. (b)The Vertical gain versus θ = 0 at x=0. (C)The Vertical gain versus θ = 0 at y=0.

Fig. 14. Gain and antenna alignment (with and without holes).

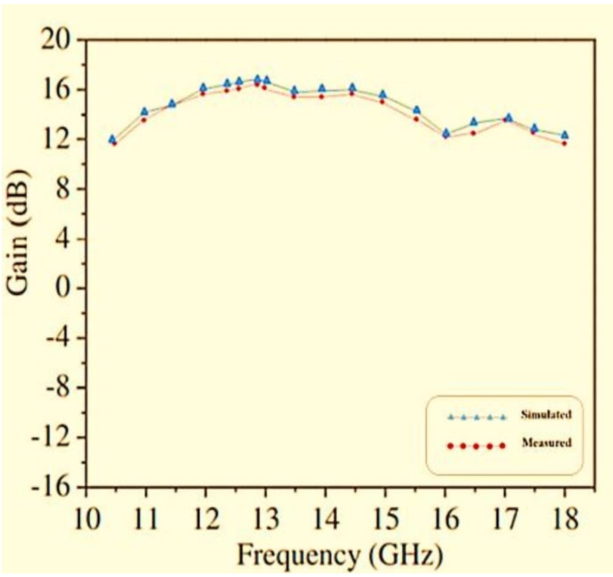


Fig. 15. Measured and simulated gain of the antenna with hole.

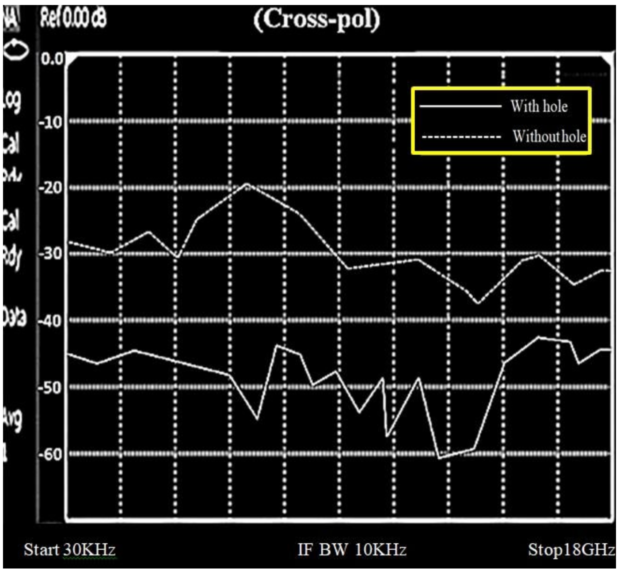


Fig. 16. X-pols levels for antennas(with and without holes)

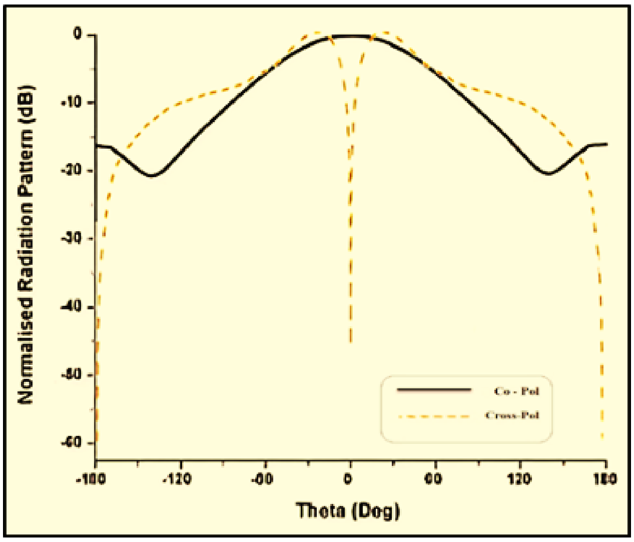


Fig.17. Measured copolarization(co-pol) and crosspolarization (cross-pol) patterns in the H-plane at broadside frequency.

The horizontal gain of the antenna with holes has increased by 8 dB in the φ direction (Z=0) compared to its original type. The gain in the vertical direction in the θ direction (x=0 and y=0) has also increased by 5 dB, which has led to an improvement in the radiation performance of the antenna. The measured and simulated gain of the antenna is shown in Fig. 15. The measured results are well agreed with the simulated result for the maximum gain of 16.7 dB. Radiation efficiency is also above 66% throughout the operating band. Fig. 16 shows the X-pol variations in the antennas with and without holes. The second antenna with a hole in the input port has a more balanced structural symmetry than the original antenna, as confirmed in Fig. 16. The increased symmetry not only minimizes cross-polarization but also leads to variations in gain across the frequency spectrum, which shows a more accurate and balanced radiation pattern, while the asymmetry keeps the gain constant and leads to an increase in the X-pol level.

In this case, the antenna suffers from more cross-polarization interference, which can affect the overall signal quality and performance in practical applications. In the original antenna, the X-pol levels are -19 dB across the main band and more than -30 dB in the bandwidth range of 11.4–13.4 GHz. While the antenna with a hole in the input port has -42 dB across the main band and more than -45 dB in the bandwidth range of 7.9-14.6 GHz. These findings indicate that the antenna designed with the hole-in-the-input technique, which has increased structural symmetry, can effectively enhance the antenna performance by reducing unwanted cross-polarization while potentially optimizing the gain characteristics in different frequency ranges. Fig. 17 shows the X-pol and coupler patterns in the H-plane at broadband frequencies. It can be seen that the symmetry in the structure has balanced the radiation pattern and has somewhat reduced the polarization interference problem.

Table 3 shows the comparison of the performance of published articles and the proposed LWAs in this work. The study presented in this paper explores an innovative technique for enhancing the radiation performance of periodic Leaky Wave Antennas (LWAs) utilizing substrate integrated waveguide (SIW) technology. The introduction of holes in the antenna inputs has been identified as a significant factor contributing to improved propagation parameters. This modification leads to enhanced S-parameters and optimized surface current distribution along the antenna structure, ultimately resulting in better radiation characteristics.

A comparative analysis of two LWA prototypes, one featuring the hole and one without hole, demonstrates the efficacy of this approach. The results indicate that the antenna with the input hole exhibits superior cross-polarization rates during radiation compared to the design referenced in [14]. Furthermore, when compared to the antenna discussed in [8], the modified design not only achieves better cross-polarization but also offers an expanded operational bandwidth. To validate this method, both LWA samples were fabricated with identical dimensions, differing only in the presence of the hole at the input of one antenna, as depicted in Fig.7. The antennas were fed through SMA connectors via a micro strip transition, and the prototypes were constructed using Rogers 5880 material (with a relative permittivity of $\varepsilon_r = 2.2$). The dispersion parameters were accurately measured using a microwave vector network analyzer, with results illustrated in Fig. 6 and 8.

Table 3. Comparison with other continuously scanning planar LWAs.

Reference	Antenna type	Beam at broadside	Scanning range	Frequency Band (GHz)	Ratio of normalized Bandwidth to center frequency(%)	Cross Polarization (dB)
[7]	CRLH-SIW	Yes	-70°to +60°	8.6-12.8	39	-20
[12]	CRLH-SIW	Yes	-17°to +13°	24-27	12	-15
[11]	CRLH-SIW	Yes	-57°to +30°	13.5-17.8	28	-27
[10]	Ridged-SIW	Yes	-	-	-	-43
[8]	Periodic-SIW	Yes	-74°to +45°	7.6-11	37	-20
[14]	Periodic-SIW	Yes	-28°to +30°	9.5-15.2	49	-40
First work	Periodic-SIW	Yes	-	11.4-13.4	16	-30
Final work	Periodic-SIW	Yes	-66°to +5° & +20°to +73°	7.9-14.6	52	-45

4. Conclusion

In this study, two LWAs-SIW were designed, fabricated, and tested: one with and another without entrance holes. Both antennas had transverse and longitudinal slots to enhance their performance. The initial design without holes did not perform well with a bandwidth of 2 GHz with a minimum return loss of +10 dB over the entire bandwidth and focused at a frequency of 12.8 GHz with a reflection coefficient of -26 dB. While the antenna with an entrance hole, with a bandwidth of 6.7 GHz and a minimum return loss of +10 dB over the entire bandwidth of interest and focused at a frequency of 12.8 GHz with a reflection coefficient of -48.5 dB, provided good radiation performance. Simulation and measurement results show that this antenna is capable of beam scanning from -66° to +5° and from +20° to +73°, in the frequency range of 7.9–14.6 GHz, with a maximum gain of 16.7 dB. The improved antenna performance shows that, this design can effectively meet the needs of various applications, especially in areas that require high-frequency performance and efficient signal transmission. The presence of holes in the input ports in the antenna design helps to improve its performance characteristics and allows for better control of the structure's propagation patterns. These findings indicate the potential for further optimization of LWA-SIW antennas by exploring different geometries and configurations, ultimately leading to more versatile and efficient antenna solutions for modern communication systems.

Overall, the integration of innovative design elements, such as entry holes, into LWA-SIW antennas represents a step forward in antenna technology and paves the way for improved performance in a wide range of applications, including telecommunications, radar systems, and other high-frequency devices. The obtained radiation patterns show that the optimal radiation performance occurs at a frequency of 12.8 GHz, which is characterized by the open radiation angle. This angle, which represents the area in which electromagnetic radiation from the antenna is emitted into the surrounding environment, can have a large impact on signal quality and area coverage, helping the antenna to provide optimal coverage for different areas. This finding highlights the potential for incorporating strategic design modifications, such as inlet holes, to enhance the overall performance of LWAs in SIW configurations.

5. Acknowledgement

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