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RESEARCH ARTICLE

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TE_{20} mode substrate integrated waveguide based high gain eight-beam leaky-wave antenna for multi-directional radiation coverage

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Abstract

In this article, a TE_{20} mode substrate integrated waveguide (SIW) is utilized to design a leaky-wave antenna (LWA) which is capable to scan all the four directions (eight quadrants) simultaneously. With the eight radiated main beams, frequency beam scanning range of the proposed antenna is 56° in all the eight quadrants. By exploiting co-axial probe feeding and step impedance transformer, four ways microstrip power divider is designed which is further exploited to feed all the four TE_{20} mode SIW sections containing microstrip-coupled slotline-SIW transitions. For radiation, ±45° rectangular slots are systematically placed on the top as well as bottom plane of the structure. The proposed antenna is working within the frequency range of 10-11.7 GHz having the maximum peak gain of 14 dBi. The proposed design is verified by experimental results which are in good agreement with the simulation. Along with the utilization of higher order mode of SIW to achieve compactness and design simplicity, the four directional frequency beam scanning capability makes it a promising candidate in various microwave circuits and several beam-scanning applications including navigational and surveillance purpose.

KEYWORDS

frequency beam scanning, leaky-wave antenna, TE_{20} mode substrate integrated waveguide (SIW)

1 | INTRODUCTION

Substrate integrated waveguide (SIW) has been extensively used in several microwave and mm-wave applications due to its alluring features such as light weight, low loss, low cost, ease of fabrication and integration with MMICs.[1–3] The utilization of higher order mode of SIW in designing antenna array makes the design compact and also reduces the fabrication cost.[4,5] Besides this, the rapid growth in wireless communications and other surveillance applications demand a new standard having maximum beam-scanning coverage area, compactness, fair gain and so forth. These systems often demand simultaneous multiple beams and beam steering capabilities. To achieve the said characteristics, the leaky-wave antenna (LWA) appears to be an appropriate choice. LWA belongs to the traveling wave antenna family, having unique feature of frequency beam-scanning.[6–8] Over the past few years, one major aspect of research has been focused on designing LWA using the SIW technology.[9] Several SIW based LWAs have been proposed in past. For example, in Refs. 10,11, transverse slots are etched on the broad wall of SIW in designing forward quadrant beam scanning LWA. In Ref. 12, slot apertures are varied sinusoidally to achieve LWA having lower side-lobe level. In Refs. 13,14, a wider scanning has been achieved by utilizing CRLH TLs. More recently, the higher order TE_{20} mode of SIW has also been utilized to design high gain and compact LWA.[5]. In Ref. 15, high impedance surface has been used to design multibeam antenna for full azimuth coverage. A multibeam antenna based on homogeneous ellipsoidal lens fed by circular array[16] and a multibeam antenna based on SIW technology for MIMO wireless communications[17] have been designed to achieve full azimuth coverage.

However, the structure proposed in Ref. 15, employs rotational beamforming networks and microstrip patch array-based HIS which leads to a complicated antenna design without covering the lower half of the radiation space. It is also noted that though the LWA presented in Ref. 5 shows larger

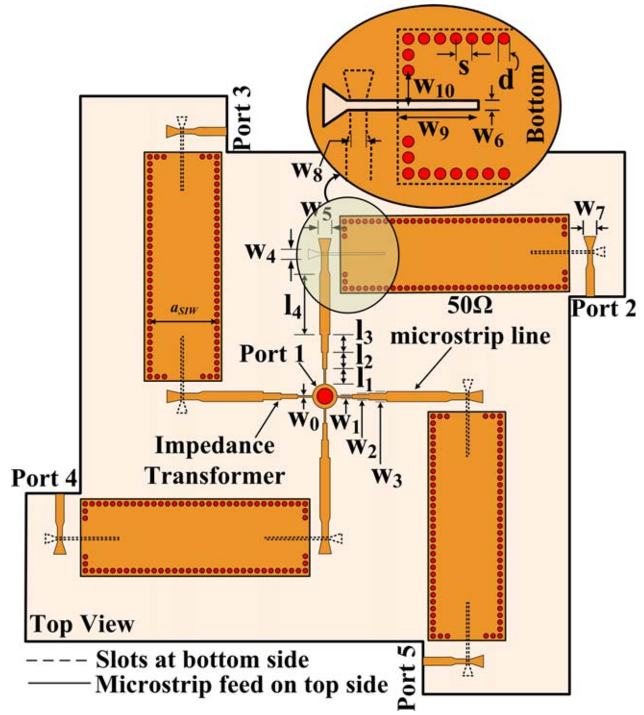

FIGURE 1 Layout of the four way TE_{20} mode SIW power divider having coaxial probe feed-microstrip power divider-slot line transition

radiation coverage with frequency beam scanning capabilities using TE_{20} mode of SIW technology but it still uses a dual beam to facilitate only two quadrant beam scanning. At a fixed frequency, the dual radiated main beam scans only in 1st and 4th quadrant of a particular elevation plane. Considering the aforementioned facts, it can be inferred that most of the earlier proposed SIW based leaky-wave structures have limited capability to facilitate high gain with larger frequency beam scanning area. To the best of author's knowledge, such type of SIW based multibeam LWA with larger beam scanning ranges maintaining high gain has not been earlier proposed in literature.

In this article, a simplified single layered LWA which can facilitate frequency beam scanning in all the eight quadrants of the radiation space is proposed and investigated. The proposed structure is based on TE_{20} mode SIW incorporating with a novel co-axial probe fed microstrip power divider. The radiating slots are placed systematically on the top as well as bottom wall of the SIW according to the electric field of the transmission line (TL). The geometry is capable to radiate eight beams simultaneously to scan four directions with frequencies. All the output ports are terminated into the 50Ω matched load. The full wave simulations are performed in HFSS and the prototype of same is built and verified experimentally.

2 | PROPOSED GEOMETRY AND OPERATING PRINCIPLE

2.1 | Power divider design

The layout of the microstrip line based TE_{20} mode SIW power divider is depicted in Figure 1. The 50Ω co-axial probe feeding is used at the input port to feed the four way microstrip power divider which are connected to transitions through step impedance transformers. This power divider is used as a feeding circuitry for TE_{20} mode SIW TL and width of the TE_{20} mode SIW can be calculated from Equation 1.[4]

$$a_{\mathrm{SIW}} = \frac{c_0}{f_{c(\mathrm{TE}_{20})}\sqrt{\varepsilon_r}} + \frac{d^2}{1.1s} + \frac{d^3}{6.6s^2} \tag{1}$$

Further, microstrip power divider to slot line transition and slotline to SIW transitions are used at the input of the transmission line. By using slotlines, 180° out-of-phase but equal in magnitude electric fields are formed automatically on both sides of the symmetric plane of slot line (electric wall) as shown in Figure 2. Figure 3 shows the S-parameter responses of the power divider where the reflection coefficient (S_{11}) is almost below −20 dB and uniform distribution of the power

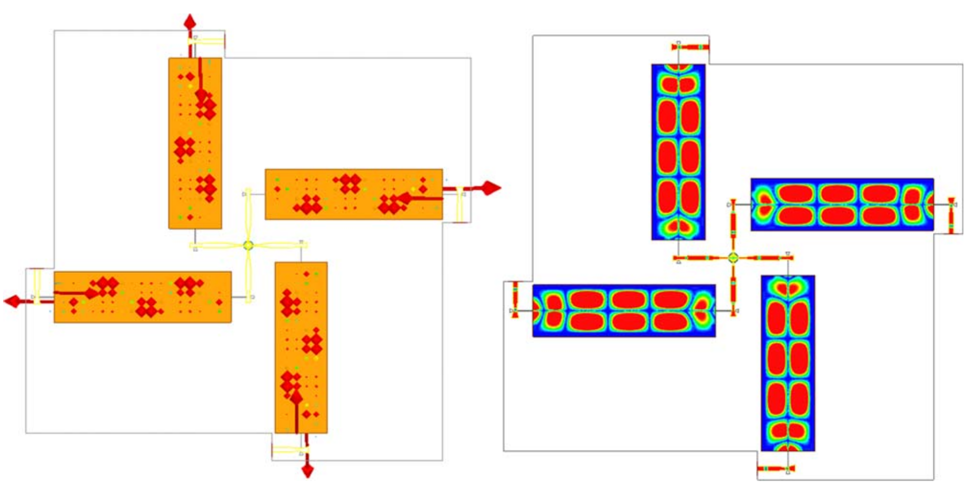

FIGURE 2 E- field vector and magnitude distributions of the power divider

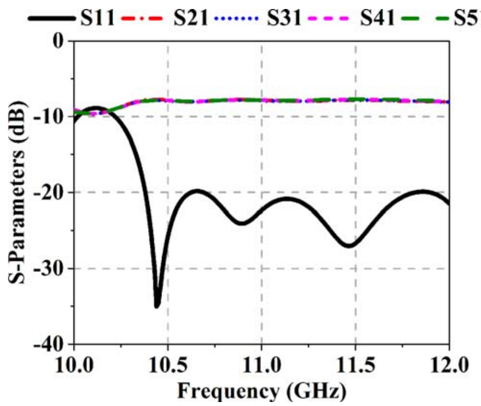

FIGURE 3 S-parameter responses with frequencies of the power divider

in all the four TL's reveal a good matching for the designed power divider. The magnitude of electric field distribution and electric field vector distribution are also shown in Figure 2.

2.2 | Design procedure and parameter selection of the power divider network

2.2.1 | Selection of the parameters diameter of vias, inter-via spacing and width of TE_{20} mode SIW

Since many years, various regions in the plane of d/λ_c, p/λ_c for SIW are well defined by the researchers. There is a region in the plane where the SIW is equivalent to a conventional rectangular waveguide that has negligible leakage losses and does not present any bandgap in its operating bandwidth. From Refs. 4, [18], the diameter of the metallic via, the spacing between vias and equivalent width of TE_{20} mode SIW are determined. In our design purpose, the cut-off frequency is chosen as $f_c = 9.22$ GHz. The basic parameters for TE_{20} mode SIW are obtained as $a_{SIW} = 22.33$ mm, $d = 0.8$ mm, and $s = 1.6$ mm as shown in Figure 4A.

2.2.2 | Selection of the parameters for the transition between coaxial probe and 4-way μ-strip power divider

From Figure 4B, it is clear that the input power is fed by coaxial probe to feed the microstrip power divider which is further used to feed the TE_{20} mode SIW sections. Step impedance transformer with quarter wavelength is used for impedance matching between coaxial probe and 50Ω microstrip line. The values of l_1, l_2, l_3, w_0, w_1, w_2, and w_3 are optimized based on the number of steps and by satisfying the criteria $l_1 + l_2 + l_3 \sim \lambda_g/4$. λ_g is the guided wavelength. The number of steps is varied from one to three and in our design, three steps are chosen due to good impedance matching. The improvement of matching with the variation of number of steps is shown in Figure 5. The optimized dimensions are: $w_0 = 0.4$ mm, $w_1 = 0.8$ mm, $w_2 = 1.4$ mm, $w_3 = 2.32$ mm, $l_1 = 2.87$ mm, $l_2 = 3$ mm, $l_3 = 2.8$ mm.

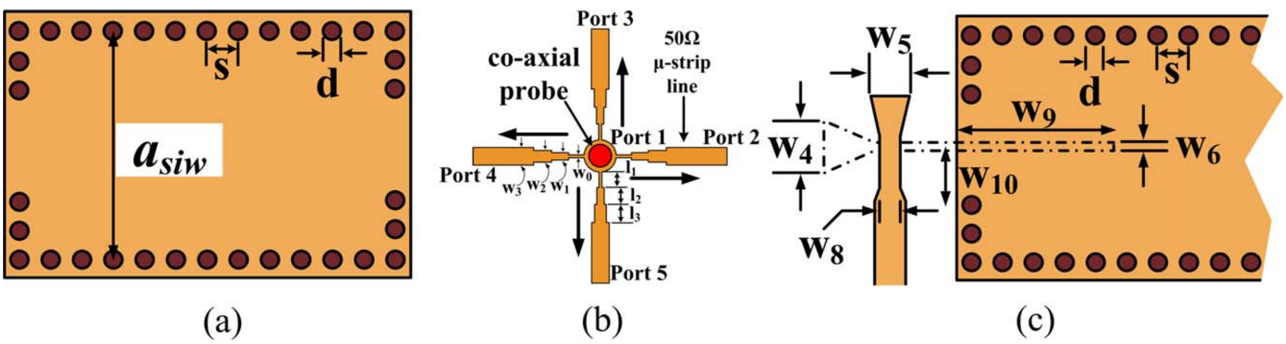

FIGURE 4 (A) TE_{20} mode SIW section, (B) Transition between coaxial probe and 50Ω microstrip power divider through step impedance transformer with 3-steps (C) Transition between microstrip power divider section and TE_{20} divider with matching ground slot

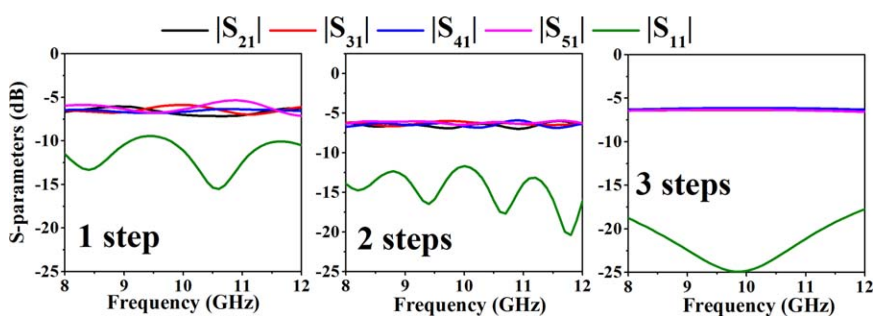

FIGURE 5 Variation of S-parameters with step numbers of the matching section for better impedance matching

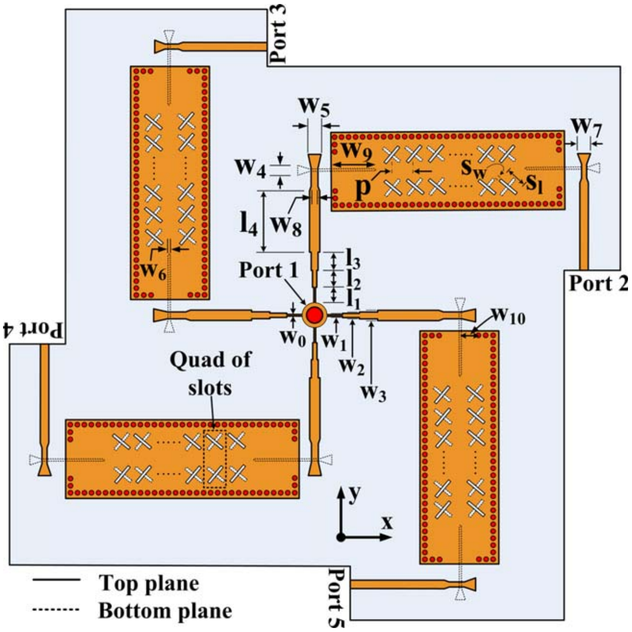

FIGURE 6 Layout of proposed LWA

2.2.3 | Selection of the parameters for the transition between 4-way μ-strip power divider to TE_{20} mode SIW sections

To realize the wideband TE_{20} mode excitation, the transition from microstrip power divider section to SIW section is realized by two step transitions. One acts as a mode converter between the slotline and the higher order mode SIW as elaborately mentioned in Ref. 4. When the electromagnetic field is fed into the SIW from the slotline, the horizontally polarized electric field of the slotline would be converted to the vertically polarized field of the SIW. The symmetric plane of the slotline is an electric wall, and thus the excited electric fields at both sides of the slotline in the SIW are automatically 180 out-of-phase. The extended portion of slotline w_9 is kept as $\lambda_g/2$ to make it resonate. The highest amplitude part exists at the center of the half wavelength resonator, i.e., quarter-wavelength

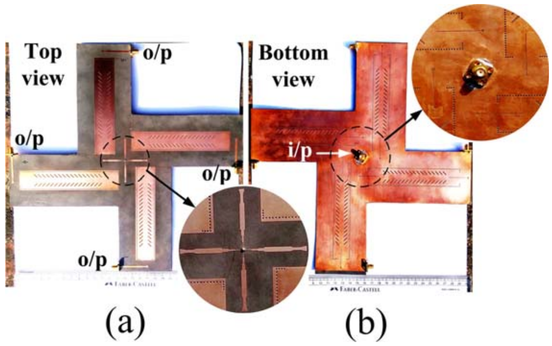

FIGURE 8 Fabricated prototype of the proposed antenna (A) Top view, (B) Bottom view

away from the shorted termination and inside the SIW. Hence, high coupling is achieved between slot line and SIW. Couple of matching vias is placed at the edge of SIW section for better impedance matching. For fine tuning, w_4 and w_5 are optimized and w_6 is kept as minimum as possible as per the fabrication facility available in our laboratory for minimizing any potential radiation loss during slotline to SIW transition. Another transition is microstrip to ground slotline where the length of the triangular microstrip stub shown in Figure 4C is set to be a $\lambda_g/4$ to ensure a high coupling between the microstrip line and slotline resonator. The optimized dimensions are $l_4 = 12$ mm, $w_4 = 1.8$ mm, $w_5 = 2.7$ mm, $w_6 = 0.2$ mm, $w_7 = 3.5$ mm, $w_8 = 1.6$ mm, $w_9 = 15.23$ mm, and $w_{10} = 7.21$ mm.

2.3 | Leaky-wave antenna design

To realize LWA, ±45° tilted slots are systematically etched on the broad walls of SIW. The slots are placed according to the electric field distribution of SIW and therefore the slots are oriented orthogonally in top and bottom of four waveguide sections. The periodicity of the slots are maintained by taking care about the homogeneity condition, i.e., $p \ll \lambda_g$.[19] To demonstrate the effectiveness of the concept, a finite lossless structure having 17 quad of slots (for each SIW section) is designed and

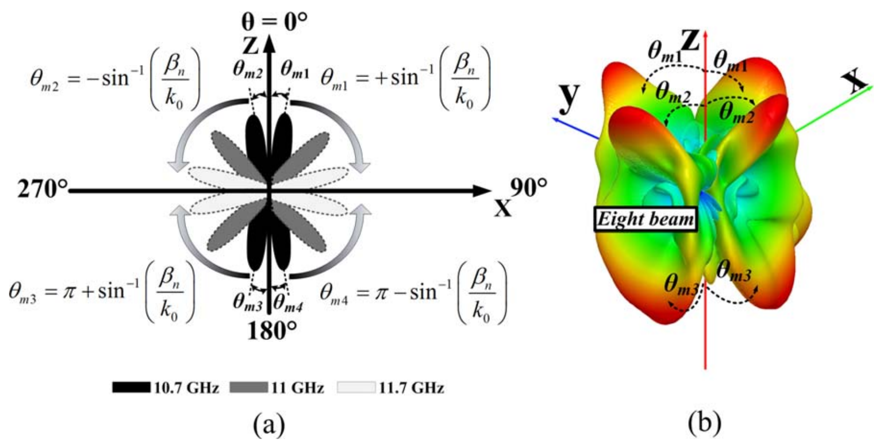

FIGURE 7 (A) Working mechanism of four quadrant scanning by the proposed structure, (B) 3D radiation pattern of the proposed leaky-wave antenna

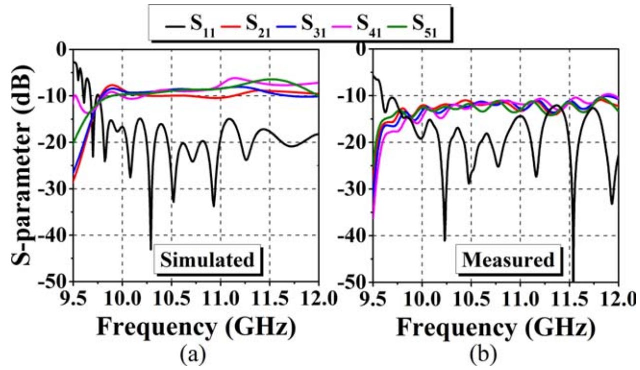

FIGURE 9 S-parameter responses of the proposed leaky-wave antenna, (A) Simulated, (B) Measured

optimized by full wave simulation using Ansys HFSS. The layout of the proposed LWA is shown in Figure 6. The scanning angle of the proposed antenna depends on the n^{th} spatial harmonic β_n and the free space wave number k_0. The antenna is working in fast wave region where $\beta_n \ll k_0$ having forward quadrant scanning capability. The direction of maximum radiation from z-axis can be determined as (2)[8]

$$\theta_{m1,2} = \pm \sin^{-1}\left(\frac{\beta_n}{k_0}\right) = \pm \sin^{-1}\left(\frac{\beta_0}{k_0} + \frac{n\lambda_0}{p}\right)$$
$$\theta_{m3,4} = \pi \pm \sin^{-1}\left(\frac{\beta_n}{k_0}\right) = \pi \pm \sin^{-1}\left(\frac{\beta_0}{k_0} + \frac{n\lambda_0}{p}\right) \tag{2}$$

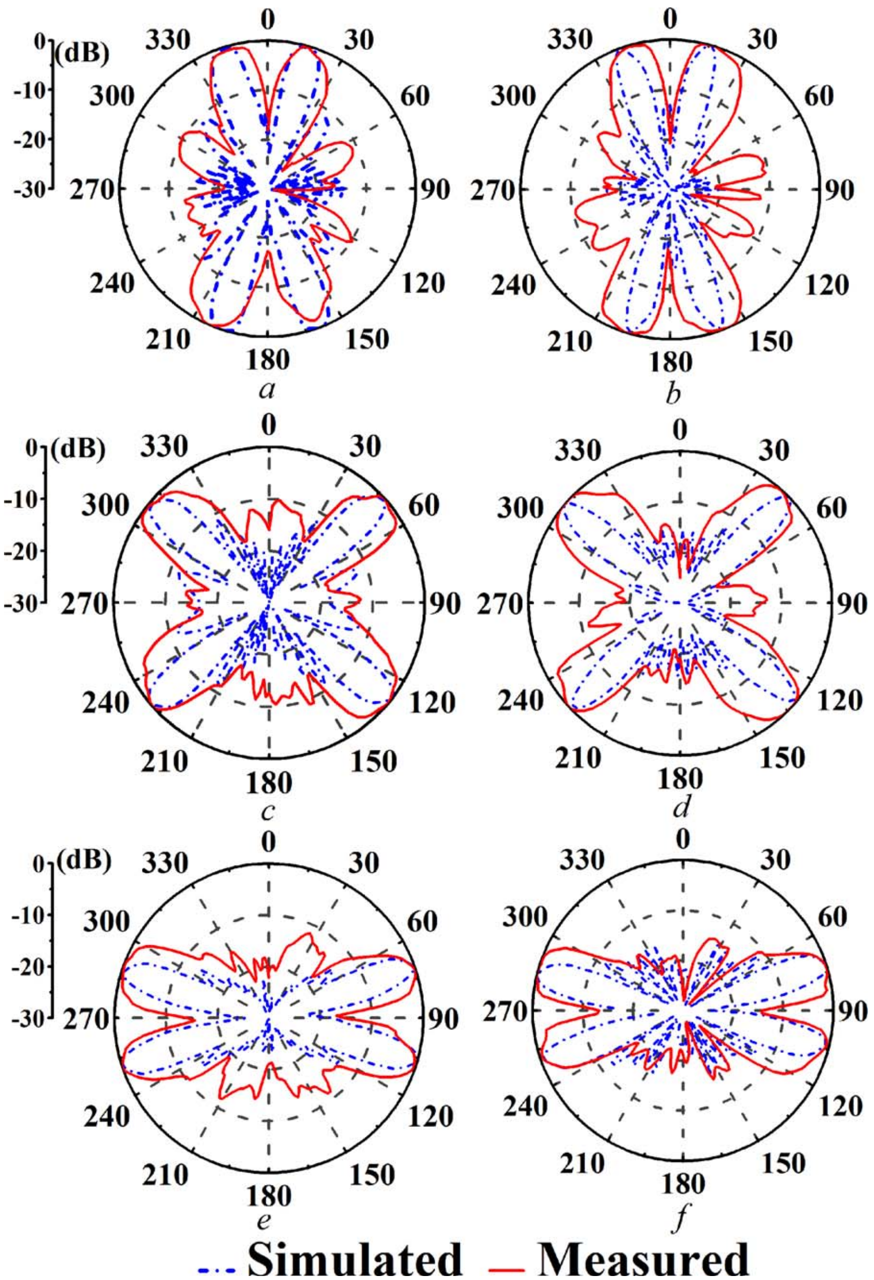

FIGURE 10 Normalized radiation pattern of the proposed leaky-wave antenna, (A) at 10 GHz in xz-plane, (B) at 10 GHz in yz-plane, (C) at 11 GHz in xz-plane, (D) at 11 GHz in yz-plane, (E) at 11.7 GHz in xz-plane, (F) at 11.7 GHz in yz-plane

where, $\theta_{m1,2}$ represents the radiated beam direction in 1st and 2nd quadrants and $\theta_{m3,4}$ for 3rd and 4th quadrants, β_0 is the fundamental spatial harmonic, k_0 is the free space wave number, p is the periodicity and n is an integer number referring to the order of the space harmonic. In our design purpose $n = -1$ is chosen. From Equation 2, it can be concluded that a full space scanning (0° to 360°) can be achieved if β_n varies with the range (0, k_0). The layout of four quadrant beam scanning and four directional radiation coverage are shown in Figure 7A,B. The optimized dimensions of the LWA are: $p = \lambda_g/6$, $S_w = 0.8$ mm, $S_l = \lambda_0/(4.4.\varepsilon_r^{1/2})$.

3 | RESULTS AND DISCUSSIONS

To validate the proposed concept, a prototype is built using Rogers RT/Duroid 5880 having relative permittivity of 2.2, thickness of 0.787 mm and tanδ of 0.0009. The top and bottom view of the fabricated prototype are shown in Figure 8A,B respectively. The proposed antenna is operating within the frequency range of 10–11.5 GHz ($|S_{11}| < -10$ dB) as depicted in Figure 9. As the ±45° tilted radiating rectangular slots are etched on the top as well as bottom of the TE_{20} mode SIW, the resultant electric field exhibits horizontal polarization for each SIW section. Hence, during measurement, linearly polarized horn is used for measuring the radiation patterns in xz-plane and yz-plane. A comparison between the simulated and measured normalized radiation patterns at xz-plane and yz-plane with different frequencies are shown in Figure 10A-F where the measured maximum radiated beam directions in xz-plane are 16°, 50°, and 72° at 10 GHz, 11 GHz, and 11.7 GHz, respectively having the angular deviation of 0°, 2°, and 2° respectively as compared to simulated results. Similarly, in yz-plane, measured maximum radiated beam directions are 16°, 42°, and 74° at 10 GHz, 11 GHz, and 11.7 GHz, respectively having the angular deviation of 2°, 4°, and 2°, respectively as compared to simulated results. The antenna is capable to scan all the four directions simultaneously having the scanning range of 56° for each of the eight quadrants. The proposed antenna achieves the maximum measured gain of 14 dBi across the working frequency band. The slight discrepancies between simulated and measured results are due to the fabrication tolerances. The proposed multi-beam LWA can be a deserving candidate in many applications such as Development of adaptive cruise control (ACC) using intelligent transport systems (ITS), for tracking humans in perimeter security or through-wall surveillance, aircraft collision avoidance system (ACAS), noncontact vital sign monitoring system and so forth.

4 | CONCLUSION

In this article, a novel TE_{20} mode SIW based eight beam LWA for four directional radiation coverage has been proposed. In the proposed antenna, the radiating ±45° tilted slots have been placed systematically on the top and bottom wall of the SIW and the microstrip based power dividing network has been used to feed the antenna. The proposed antenna covers a beam scanning range of 56° in each of the eight quadrants with the maximum gain of 14 dBi. The proposed antenna is advantageous in terms of compactness, gain and scanning range compared to the conventional waveguide based designs. The measured performances have been found to match well with the corresponding simulated values. The antenna could be the potential candidate for several frequency beam scanning applications like collision avoidance radars, development of adaptive cruise control (ACC) using intelligent transport systems (ITS), traffic safety and so forth, and other X-band applications.

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