Received: 30 August 2018 | Revised and accepted: 3 November 2018
DOI: 10.1002/mmce.21611

WILEY INTERNATIONAL JOURNAL OF RF AND MICROWAVE COMPUTER-AIDED ENGINEERING

RESEARCH ARTICLE

Eighth-mode SIW based compact high gain leaky-wave antenna

Anirban Sarkar | Abhishek Sharma | Animesh Biswas | Mohammad Jaleel Akhtar

Department of Electrical Engineering, Indian Institute of Technology Kanpur, Kanpur, Uttar Pradesh, India

Correspondence
Anirban Sarkar, Department of Electrical Engineering, Indian Institute of Technology Kanpur, Kanpur, Uttar Pradesh, India.
Email: anirban.skr227@gmail.com

Abstract

In this article, a novel electrically small eighth-mode substrate integrated waveguide (EMSIW) based leaky-wave antenna (LWA) in planar environment is presented. The proposed antenna uses 1/8th mode SIW resonator which helps to improve compactness of the design while maintaining high gain and increased scanning angle. The proposed SIW cavity is excited by a 50 Ω microstrip line feeding to resonate at dominant TE_{110} mode in X-band. The dimensions of the resonators are adjusted to keep resonant mode at same frequency. The fabricated prototype is approximately $5\lambda_0$ long. Measured results show that the proposed leaky-wave antenna is able to operate within frequency range of 8-10 GHz with beam scanning range of 51° and maximum gain of 13.31 dBi.

KEYWORDS

eighth-mode substrate integrated waveguide, leaky-wave antenna, frequency beam scanning

1 | INTRODUCTION

Over the last few years, the use of substrate integrated waveguide (SIW) in microwave and millimeter wave integrated circuits has increased extensively due to its advantages of being light weight, low cost, low loss and convenient integration with planar circuits.[1,2] Recently, SIW based leaky-wave antennas (LWAs)[3,4] opens a new avenue for antenna design due to their high efficiency, high gain, narrow elevation beamwidth and beam-scanning ability. Several LWAs based on SIW and other planar environments have been proposed.[5–9] Also, half-mode SIW (HMSIW) and quarter-mode SIW (QMSIW)[10] based resonators are used for realization of compact antennas.[11–14] More compactness can be achieved by eighth-mode SIW (EMSIW)[15–17] which is realized by bisecting the QMSIW. EMSIW is almost 1/8th of the full mode SIW resonator and it preserves the similar electric and magnetic field distribution at same resonant frequency.

In this article, an electrically small EMSIW resonator is employed for the realization of efficient and compact LWA at X-band. The open sides of the EMSIW are used as leakage slots. For the periodic leaky-wave antennas, dominant mode is a slow wave and does not radiate. So $n = 0$ spatial harmonic is excited for fast wave radiation mainly by using periodic perturbations. The proposed antenna is fed by simple microstrip feed line through its radiating edge. The performance of the proposed LWA is optimized using HFSS and validated by experiments. Dispersion properties are studied with various parameters of the antenna to show the control of the antenna leakage rate and its effect on radiation. The use of eighth-mode SIW enhances the radiation intensity per unit cell significantly resulting into gain enhancement. Its scanning angle can be varied from 37° to 88° by varying frequency from 8 to 10 GHz. This design provides more compact size compared with other reported designs in 1D LWA[5,8,14] with good scanning capability of 51°. The designed prototype is fabricated, tested and analyzed. To the best of author's knowledge, such type of gain enhancement technique to design SIW based compact leaky-wave antenna with larger beam scanning ranges has not been earlier proposed in literature.

2 | LEAKY-WAVE ANTENNA USING TILTED EMSIW RESONATOR

2.1 | Tilted EMSIW resonator unit-cell

Firstly, eighth-mode SIW is developed where a square SIW resonator is divided across the perfect open symmetry plane

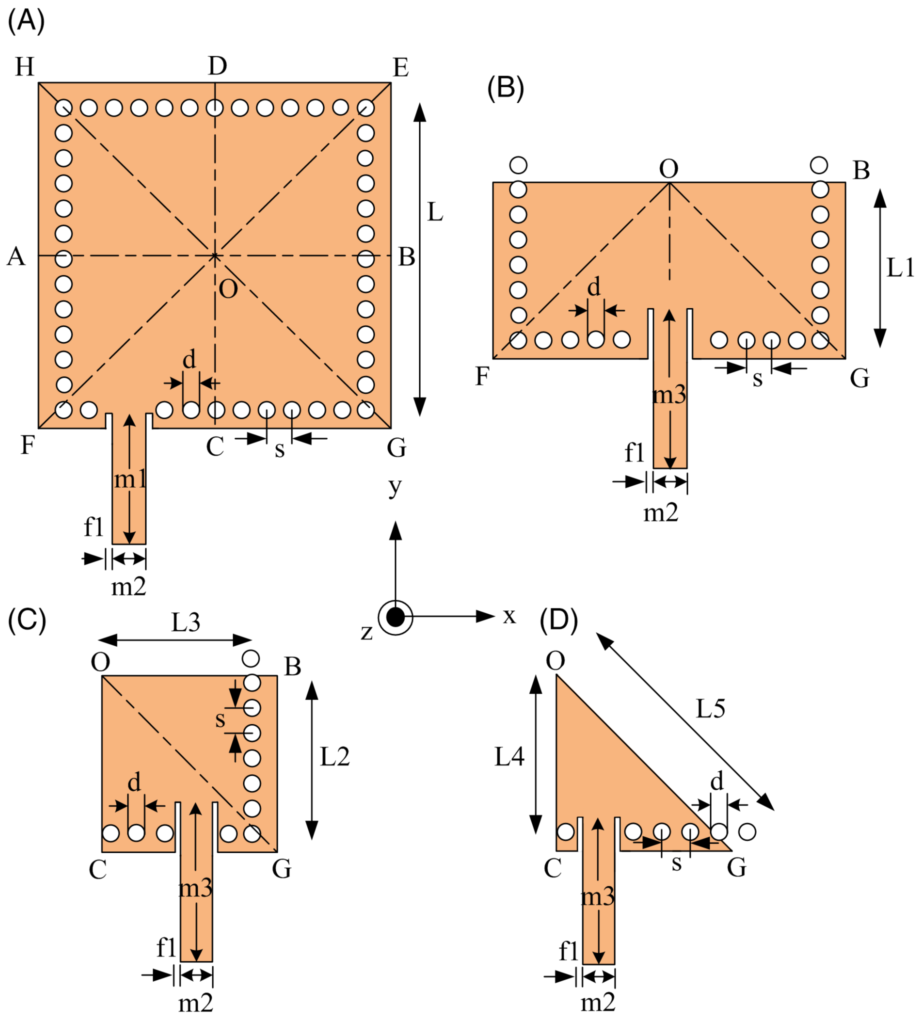

FIGURE 1 Transformation from square SIW full-mode cavity to eighth-mode cavity

(fictitious magnetic wall) and is shown in Figure 1. Simulated and measured reflection coefficient response of EMSIW cavity, in Figure 2, shows similar resonance condition with full-mode SIW cavity. EMSIW has two radiating edges and one bounded via edge. The electric and magnetic field components for dominant TE_{110} mode are described in Ref. 15. Several designs of EMSIW resonator with various feeding mechanisms such as gap coupled microstrip line to either of the radiating edges,[15,16] diagonal microstrip feeding,[18] etc, are reported in recent years. However, for periodic leaky-wave antenna applications, in the proposed design, the eighth-mode SIW resonator unit cell is designed in such a way that $n = 0$ space harmonic is lied in the fast wave region that is, over frequency range 8-10 GHz. In this article, EMSIW unit cell is slightly tilted at an angle ζ with proper feeding line position (Figure 3A) to satisfy the above mentioned condition of unit cell for realization of leaky-wave antenna as shown in Figure 4. The electric field and surface current distributions are shown in Figure 3B,C, respectively. The tip of the open edge of tilted EMSIW resonator has the maximum magnitude of electric field which implies larger accumulation of electric charges and causes disturbances of surface current and as a result a small radiation occurs. Moreover, the parameter $m1$, corresponding to the microstrip feeding line position also has a very crucial role to optimize the tilted EMSIW unit cell. If "$m1$" is varied from 1.5 mm (ie, close to the via wall) to 2.9 mm (ie, close

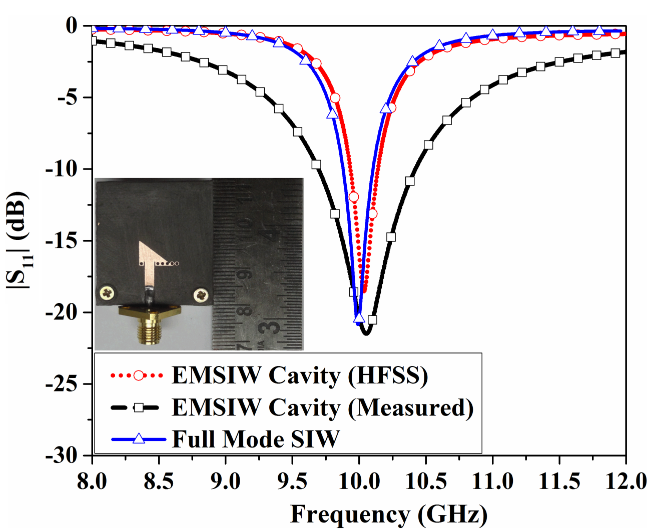

FIGURE 2 Simulated and measured reflection coefficient against frequency of the EMSIW cavity (1(d)) with full-mode SIW (1(a))

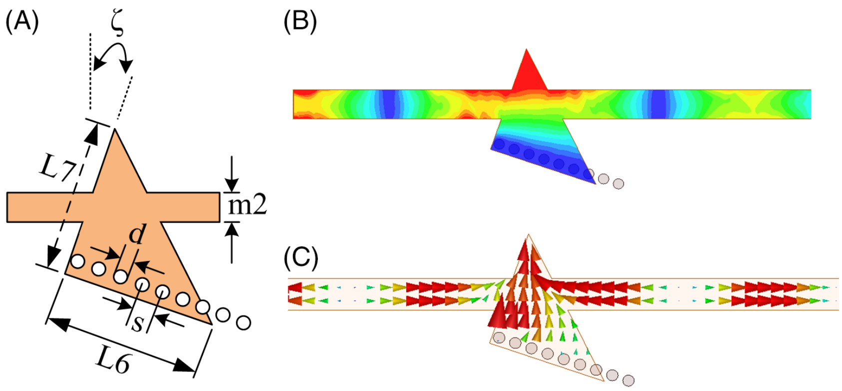

FIGURE 3 Tilted EMSIW resonator unit cell with proposed feeding technique (A) HFSS model of EMSIW resonator, (B) E-field distribution, and (C) surface current distribution

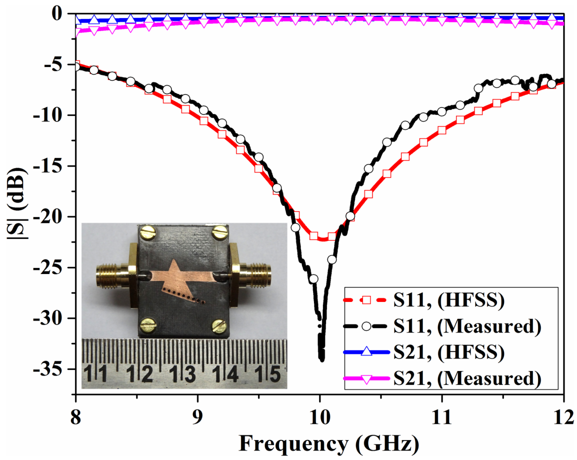

FIGURE 4 Comparison of simulated and measured reflection coefficients against frequency of tilted EMSIW resonator (fabricated unit-cell is in inset)

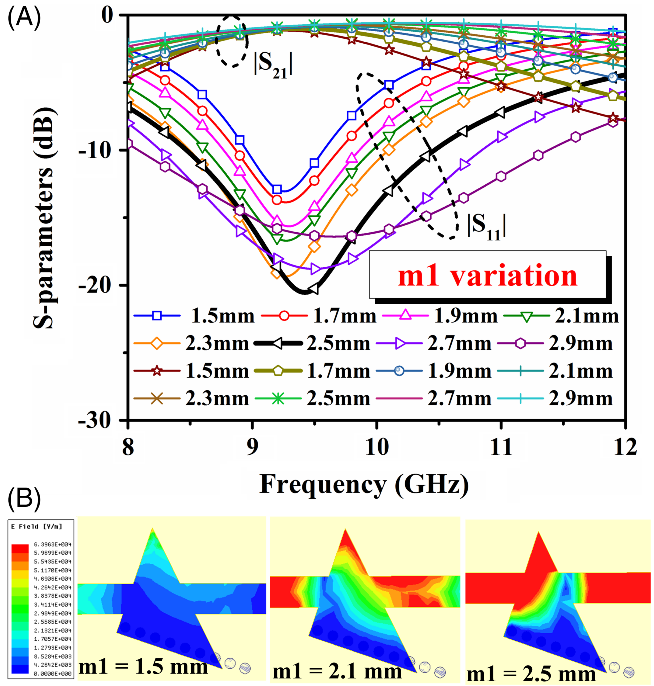

FIGURE 5 A, Variation of reflection coefficient for the corresponding variation of $m1$ for the tilted EMSIW cavity; B, variation of E-field magnitude for different values of $m1$

to tip of the resonator), the reflection coefficient changes and it shows favorable response for $m1 = 2.5$ mm as shown in Figure 5. Moreover, the suitable E-field distribution on the top of the tilted EMSIW for desired radiation mechanism is also shown in Figure 5 where the induced E-field is maximum having good reflection characteristics at $m1 = 2.5$ mm. The responses of full-mode EMSIW and tilted EMSIW are validated by experimental results.

2.2 | Leaky-wave antenna design

The unit cell shown in Figure 3A is placed periodically with the periodicity p in such a manner that the scanning range of the LWA will be in the fast wave region (8-10 GHz) where nth space harmonic phase constant is less than the free space wave number that is, $\beta_n < k_0$ (for our case $n = 0$) which is necessary radiation condition of LWA. Figure 6A shows the layout of the LWA with tilted EMSIW resonator (unit cell is in inset). The dispersive nature of the antenna is studied using Ansoft HFSS and are also extracted from measured scattering parameters of the antenna. Retrieved normalized phase constant and attenuation constant due to leakage from measured response are shown in Figure 7A,B, respectively. From the figure it is clear that proposed antenna is able to scan in forward quadrant of the visible space within the frequency range of 8-10 GHz that is in fast wave region ($\beta_n < k_0$). Beyond the aforementioned frequency range, β_0 is greater than k_0, that is, antenna goes to slow wave region and the contribution of proper bound wave effect becomes dominant which degrades the radiation performance. Also, above 10 GHz, the $n = 1$ spatial harmonic starts radiating which is backward in nature and its presence causes undesired higher side-lobe level. Moreover, the tilt angle of the cells and feeding position of the microstrip line controls the radiation characteristics as well as the scanning range of the antenna. Effect of these parameters on dispersion properties of the proposed antenna is studied later. The effect on beam scanning range of the proposed LWA due to tilt angle variation is shown in Figure 8 and its effect on dispersion

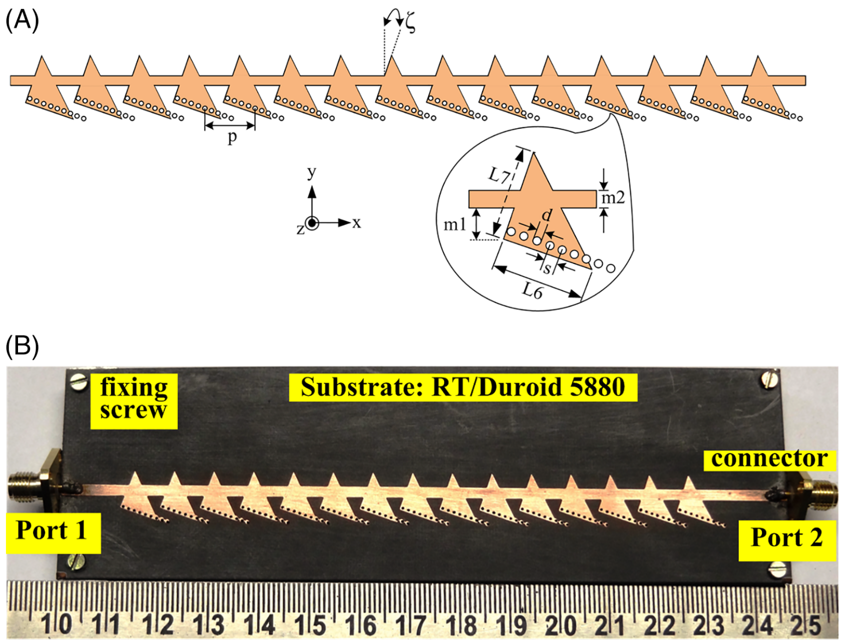

FIGURE 6 Proposed leaky-wave antenna where (A) layout of LWA with unit cell (inset) and (B) fabricated prototype of proposed leaky-wave antenna

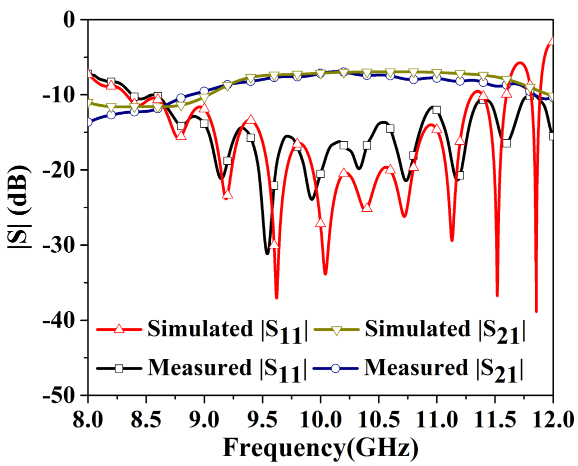

FIGURE 7 Variation of normalized wave number with frequency from the measured radiation pattern of the proposed antenna with tilt angle (ζ) = 19° (A) phase constant and (B) attenuation constant

characteristics of the antenna are shown in Figure 9. It is clear that when tilt angle increases, normalized phase constant (β) increases while attenuation constant (α) decreases. It is also observed that deviations of β and α (for each ζ variation) are more prominent in lower frequencies than the higher end with tilt angle variation. This causes larger shift of main beam toward the end fire direction at lower frequencies with smaller value of tilt angle while at higher frequency main beam remains almost stationary (Figure 8). From Figure 8 it is clear that when till angle changes from $\zeta_1 = 19°$ to $\zeta_2 = 40°$, then the radiated main beam at lowest frequency shifts toward endfire. As a result beam scanning range is decreased from $\Delta\theta_1 = 51°$ to $\Delta\theta_2 = 27°$. Similar effect is observed with feeding positions and is shown in Figure 10. The phase constant of the nth spatial harmonic β_n determines the direction of the main beam measured from broadside direction (θ_m) which is calculated from Equation (1) given below

$$\theta_m = \sin^{-1}\frac{\beta_n}{k_0} = \sin^{-1}\left(\frac{\beta_0}{k_0} + \frac{n\lambda_0}{p}\right) \tag{1}$$

where, k_0 and λ_0 are the wave number and wavelength in free space, respectively. β_0 is the fundamental space harmonic propagation constant. The leakage constant α is calculated following the procedure described in Ref. 3. The optimized dimensions are given by: $s = 1.2$ mm, $d = 0.8$ mm, $m2 = 2.32$ mm, $L6 = 8.51$ mm, $L7 = 8.41$ mm, $\zeta = 21.5°$, $P = 8$ mm, $m1 = 2.5$ mm, $m3 = 7.8$ mm, $f1 = 0.2$ mm, $L3 = 7.9$ mm, $L1 = 7$ mm, $L5 = 10.75$ mm, $L2 = 6.41$ mm, and $L4 = 6.61$ mm.

3 | RESULTS AND DISCUSSIONS

The proposed leaky-wave antenna is fabricated on Rogers RT/duroid 5880 substrate having dielectric constant (ε_r) of 2.2, loss tangent (tanδ) of 0.0009, and thickness (t) of 0.787 mm which is shown in Figure 6B. The simulations have been done in Ansoft HFSS. Proposed antenna has 15 unit cells of tilted EMSIW resonator with a total dimension of 46.8 mm × 147 mm (~$5\lambda_0$ long) which is much more compact than the previously reported designs and has advantages over scanning range, gain and bandwidth. The attenuation constant (α) due to leakage from the measured S-parameters is also calculated and is shown in Figure 7B. It is clear that when wave travels through the structure, the loss factor α which is responsible for leakage gradually decreases with frequency and produces long effective aperture. Also above 10 GHz $n = 1$ starts

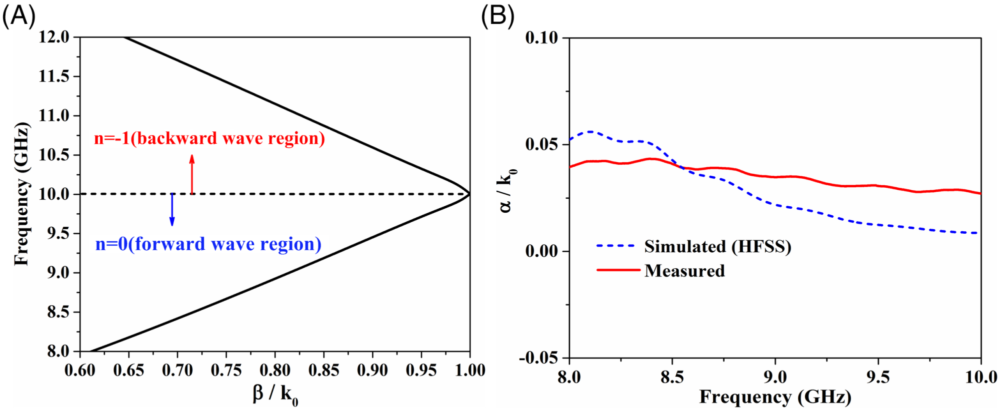

FIGURE 8 A, The effect of tilt angle variation (ζ); B, its effect on beam scanning range of the proposed leaky-wave antenna where $\zeta_1 = 19°$, $\zeta_2 = 40°$, $\Delta\theta_1 = 51°$, and $\Delta\theta_2 = 27°$

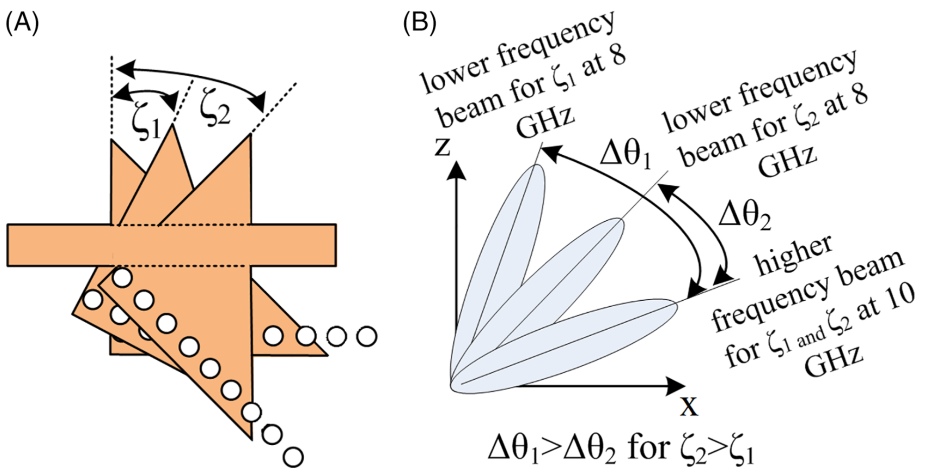

FIGURE 9 Normalized wave number for different tilt angle (ζ) variation where solid lines indicate attenuation constant and dashed lines indicate phase constant

appearing as backward spatial harmonic. The simulated and measured impedance bandwidths (S_{11} < 10 dB) of proposed LWA can be found from Figure 11. These are 3.27 GHz covering the frequency range 8.33-11.6 GHz and 3.17 GHz covering 8.53 11.7 GHz, respectively. The measured data for S_{21} are a little lower than the simulated results. This might be due to increased conductor loss[19] in the measurement. Nevertheless, the simulated results are close agreement with measured results. Figure 12 shows the normalized radiation patterns in xz-plane. The

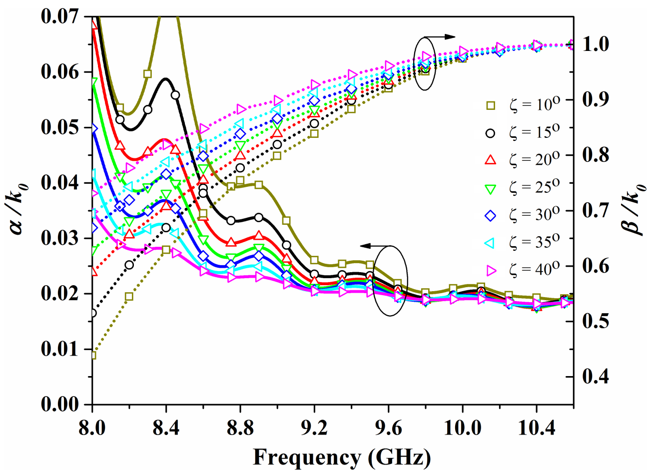

FIGURE 10 Normalized wave number for different microstrip line positions (*m*1) variation where solid lines indicate attenuation constant and dashed lines indicate phase constant

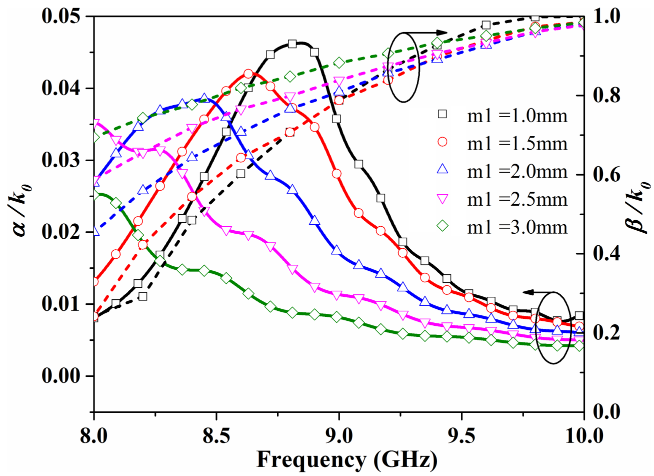

FIGURE 11 Comparison between simulated and measured S-parameters versus frequency of the proposed leaky-wave antenna

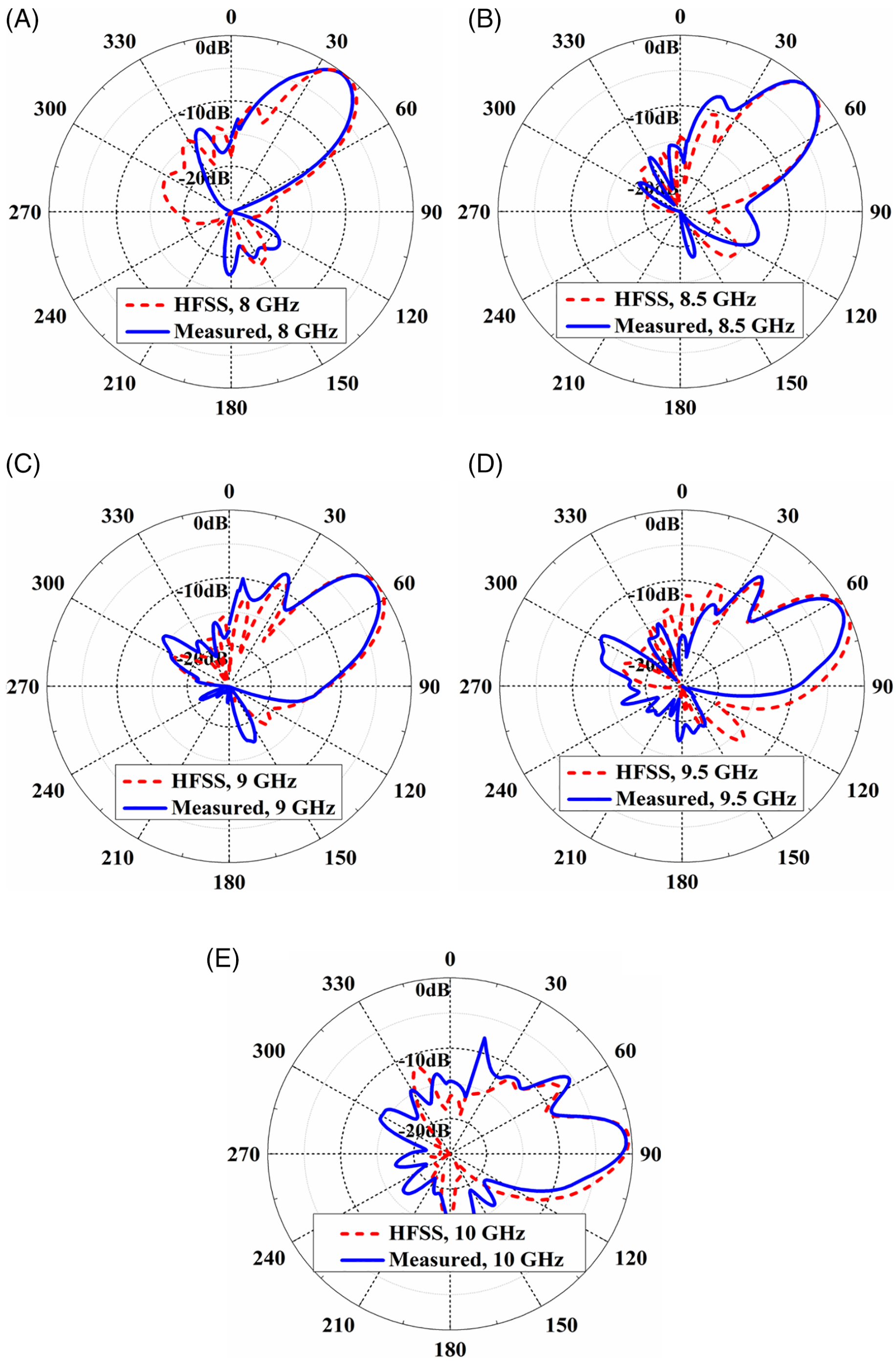

FIGURE 12 Comparison of simulated and measured radiation pattern in x–z plane (A) at 8 GHz (θ_m = 37°), (B) at 8.5 GHz (θ_m = 46°), (C) at 9 GHz (θ_m = 54°), (D) at 9.5 GHz (θ_m = 65°), (E) at 10 GHz (θ_m = 88°)

measured forward quadrant scanning range ($\Delta\theta$) of the antenna is 51° (37° 88°). At higher frequency range the radiation pattern distorts with higher side-lobe level and gain is reduced due to the proper bound wave mode propagation as the β_n space harmonic is gradually comparable with free space wave number, that is, it tends to move in slow wave region and $n = 1$ backward space harmonic starts radiating. The radiation patterns in yz-plane are also shown in Figure 13 for the minimum and maximum beam locations due to the operating frequencies 8 and 10 GHz, respectively.

The variation of peak gain is shown in Figure 14. The simulated and measured peak gain varies from 9.054 to 13.31 dBi and 8 to 11.84 dBi, respectively. The comparative study is shown in Table 1. It is also noticed that the gain is reduced at high frequencies as leakage loss is decreased with frequencies. The gain can be further increased by increasing number of cells but by compromising the size of the design. The beam pointing angle cannot reach close to endfire direction as second higher order mode will be a fast wave and will participate in radiation which results undesired grating lobes. The simulated and measured radiation efficiencies are

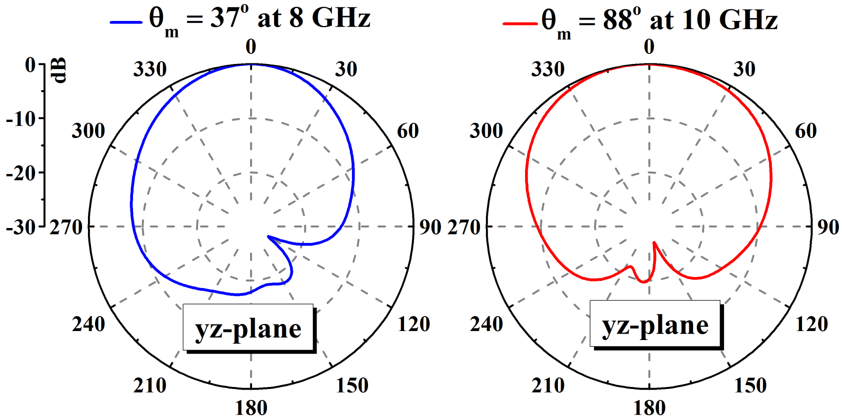

FIGURE 13 yz-plane fan beam radiation patterns at 8 GHz (left) and 10 GHz (right)

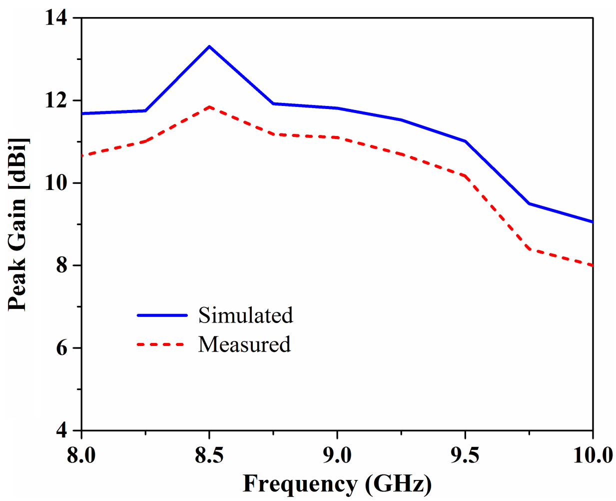

FIGURE 14 Variation peak gain (simulated and measured) with frequency

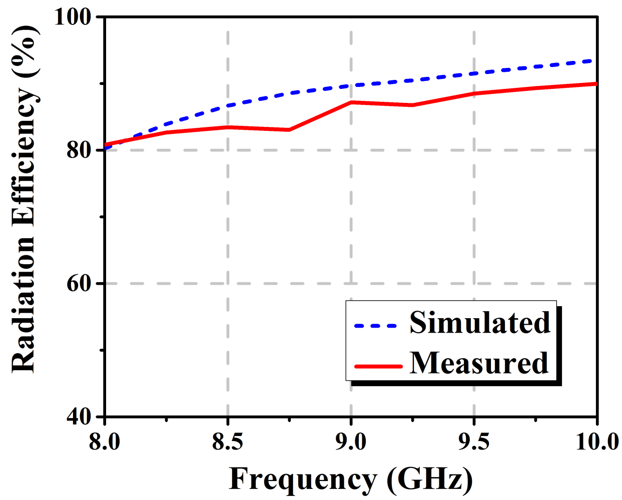

FIGURE 15 Comparison of simulated and measured radiation efficiency of the proposed antenna

calculated and depicted in Figure 15. The maximum simulated and measured radiation efficiencies are obtained of 95% and 90.8%, respectively. A little discrepancy between simulated and measured results is observed due to the measurement and fabrication tolerances.

4 | CONCLUSION

A compact leaky-wave antenna based on EMSIW resonator has been presented at X-band. Good agreement between simulated and measured radiation patterns ensure the efficient design methodology of the prototype leaky wave antenna and the setup used in the far-field measurements. With the efficient tuning of tilt angle of the resonator as well as position of microstrip line, a frequency scanning range of 51° has been achieved within 8-10 GHz. The measured peak gain of the proposed antenna varies from 8 to 11.84 dBi. Having the advantages of being compact, light weight, and high gain with simpler feeding mechanism, the proposed antenna could be the potential candidate for several microwave applications at X-band.

TABLE 1 Comparative study of proposed LWA with other designs

Properties	Liu et al.[5]	Conventional half-width MLWA[8]	Lee et al.[14]	Proposed design
Operating frequency range (GHz)	~10.2–11.9	~4.5–7	~2.5–15.4	8–10
Bandwidth (%)	15.38	43.47	20.78	29.41
Number of cells/slots/unit cells	Series of periodic transverse slots	–	15	15
Overall dimensions (mm^2)	~$0.4\lambda_0 \times 9\lambda_0$ (280 mm long)	260 mm long	~$4.2\lambda_0 \times 15.8\lambda_0$	~$1.56\lambda_0 \times 4.9\lambda_0$ (147 mm long)
Peak gain (dBi)	~14 dBi	~13 dBi	13.17 dBi	13.31 dBi
Scanning range (deg)	Near broadside to near forward endfire	42°	28°	51°

ORCID

Anirban Sarkar https://orcid.org/0000-0003-2592-8967
Abhishek Sharma https://orcid.org/0000-0001-8026-9752

REFERENCES

1. Deslandes D, Wu K. Integrated microstrip and rectangular waveguide in planar form. *IEEE Microw Guided Wave Lett*. 2001;11:68-70.
2. Deslandes D, Wu K. Accurate modeling, wave mechanisms and design considerations of a substrate integrated waveguide. *IEEE Trans Microw Theory Tech*. 2006;54:2516-2526.
3. Oliner AA, Jackson DR. Leaky-wave antennas. In: Volakis JL, ed. *Antenna Engineering Handbook*. 4th ed. New York, NY: McGraw-Hill; 2007.
4. Mohammad-Ali-Nezhad S, Mallahzadeh A. Periodic ridged leaky-wave antenna design based on SIW technology. *IEEE Antennas Wirel Propag Lett*. 2015;14:354-357.
5. Liu J, Jackson DR, Long Y. Substrate integrated waveguide (SIW) leaky-wave antenna with transverse slots. *IEEE Trans Antennas Propag*. 2012;60:20-29.
6. Mohtashami Y, Rashed-Mohassel J. A butterfly substrate integrated waveguide leaky-wave antenna. *IEEE Trans Antennas Propag*. 2014;62:3384-3388.
7. Martinez-Ros AJ, Gomez-Tornero JL, Goussetis G. Conformal tapered substrate integrated waveguide leaky-wave antenna. *IEEE Trans Antennas Propag*. 2014;62:5983-5991.
8. Yang ST, Ling H. Two-section half-width microstrip leaky wave antenna. *IEEE Trans Antennas Propag*. 2014;62:4988-4996.
9. Lai Q, Fumeaux C, Hong W. Periodic leaky-wave antennas fed by a modified half-mode substrate integrated waveguide. *IET Microw Antennas Propag*. 2012;6:594-601.
10. Memon MU, Lim S. Frequency-tunable compact antenna using quarter-mode substrate integrated waveguide. *IEEE Antennas Wirel Propag Lett*. 2015;14:1606-1609.
11. Xu J, Hong W, Tang H, Kuai Z, Wu K. Half-mode substrate integrated waveguide (HMSIW) leaky wave antenna for millimeter-wave applications. *IEEE Antennas Wirel Propag Lett*. 2008;7:85-88.
12. Henry R, Okoniewski M. A broadside-scanning half-mode substrate integrated waveguide periodic leaky-wave antenna. *IEEE Antennas Wirel Propag Lett*. 2014;13:1429-1432.
13. Jin C, Li R, Alphones A, Bao X. Quarter-mode substrate integrated waveguide and its application to antennas design. *IEEE Trans Antennas Propag*. 2013;61:2921-2928.
14. Lee D, Lim S. Leaky-wave antenna design using quarter-mode substrate-integrated waveguide. *Microw Opt Technol Lett*. 2015;57:1234-1236.
15. Sam S, Lim S. Electrically small eighth-mode substrate-integrated waveguide (EMSIW) antenna with different resonant frequencies depending on rotation of complementary split ring resonator. *IET Microw Antennas Propag*. 2013;61:4933-4939.
16. Kang H, Lim S. Electrically small dual-band reconfigurable complementary split-ring resonator (CSRR)-loaded eighth-mode substrate integrated waveguide (EMSIW) antenna. *IEEE Trans Antennas Propag*. 2014;62:2368-2373.
17. Sarkar A, Biswas A. Compact and high gain leaky-wave antenna using eighth-mode sicc based resonator. In 2016 Asia-Pacific Microwave Conference (APMC), New Delhi, 2016, pp. 1–4.
18. Mujumdar M, Alphones A. Eighth mode substrate integrated resonator antenna at 2.4 GHz. *IEEE Antennas Wirel Propag Lett*. 2016;15:853-856.
19. Bhartia P, Bahl IJ. *Millimeter Wave Engineering and Applications*. New York, NY: John Wiley and Sons, Inc.; 1984.

AUTHOR BIOGRAPHIES

Anirban Sarkar received the BTech degree in Electronics and Communication Engineering from Hooghly Engineering and Technology College, Kolkata, India, in 2011 and ME degree in Microwave Communication from Indian Institute of Engineering Science and Technology, Shibpur, India in 2013. Currently, he is pursuing the Ph.D degree from Indian Institute of Technology Kanpur, Kanpur, India. He has authored/co-authored 8 peer-reviewed journals and 10 international conference articles. His current research interests include SIW based circuits, leaky wave antennas, and diversity antennas. Mr. Sarkar is a student member of IEEE and has served as webmaster of IEEE APS Student Branch Chapter, IIT Kanpur. He currently holds the position of Vice-Chair in IEEE APS Student Branch Chapter, IIT Kanpur and secretary in IEEE MTT-S Student Branch Chapter, IIT Kanpur.

Abhishek Sharma received the BTech degree in Electronics and Communication Engineering from Shri Mata Vaishno Devi University, Jammu, India, in 2010 and MTech degree in RF and Microwave Engineering from AIACTR, New Delhi, India, in 2013. Currently, he is pursuing the PhD degree from Indian Institute of Technology Kanpur, Kanpur, India. He has authored/co-authored 13 peer-reviewed journals and 18 international conference articles. His current research interests include dielectric resonator antennas, MIMO antennas and SIW based leaky wave antennas. He is a Graduate student member of IEEE and student member of European Microwave Association. Mr. Sharma has served as Treasurer and Chapter Chair of IEEE MTT-S Student Branch Chapter, IIT Kanpur, in 2015 and 2016, respectively.

Animesh Biswas received the MTech degree in microwave and radar engineering from the IIT Kharagpur, India, in 1982, and the PhD degree in electrical engineering from the IIT Delhi, New Delhi, India, in 1989. From 1989 to 1990, he was a Post-Doctoral Fellow with Oregon State University, where he was involved in characterizing multi-conductor lines in layered medium. He is currently a Professor with the Department of Electrical Engineering, IIT Kanpur, Kanpur, India. He has served as a technical consultant for M/S COMDEV Europe, and was involved in development of multimode DR filters and diplexers. His current research includes modeling of microwaves circuits, RF integrated circuits (RFICs), and numerical methods for solving electromagnetic problems. He has authored or co-authored over 195 articles in various peer-reviewed international journals and conference proceedings. Prof. Biswas is a Fellow of the Institution of Electronics and Telecommunication Engineers, India and senior member of IEEE, USA.

M. Jaleel Akhtar received the PhD degree in electrical engineering from the Otto-von-Guericke University of Magdeburg, Magdeburg, Germany, in 2003. He was a Scientist with the CEERI, Pilani, India, from 1994 to 1997. From 2003 to 2009, he was a Post-Doctoral Research Scientist and a Project Leader with the Institute for Pulsed

Power and Microwave Technology, Karlsruhe Institute of Technology, Karlsruhe, Germany. In 2009, he joined the Department of Electrical Engineering, IIT Kanpur, Kanpur, India, where he is currently an Associate Professor. He has authored two books, two book chapters, and has authored or co-authored over 200 articles in various peer-reviewed international journals and conference proceedings. He holds two patents on RF sensors for testing of solid and liquid sample, and one patent on nanomaterial integrated RF sensor for detection of harmful gases in the environment. His current research interests include microwave and THz imaging, microwave nondestructive testing, metamaterial inspired RF sensors, SIW based RF devices and sensors, RF energy harvesting, UWB antennas for imaging, and design of RF filters and components using the electromagnetic inverse scattering. Dr. Akhtar is a fellow of the Institution of Electronics and Telecommunication Engineers, New Delhi, India, and a Life Member of the Indian Physics Association and the Indo-French Technical Association.

How to cite this article: Sarkar A, Sharma A, Biswas A, Akhtar MJ. Eighth-mode SIW based compact high gain leaky-wave antenna. *Int J RF Microw Comput Aided Eng*. 2019;29:e21611. https://doi.org/10.1002/mmce.21611