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Planar SIW Leaky Wave Antenna With Electronically Reconfigurable E- and H-Plane Scanning

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ABSTRACT This paper reports on a novel technique of switching radiation characteristics electronically between E- and H-planes of planar Substrate Integrated Waveguide Leaky Wave Antennas (SIW-LWAs). The leaky wave mode is achieved through increasing the pitch of bounding metallic via posts on one side of SIW transmission section. The radiation switching is achieved by extending the top and bottom metallic planes to a distance of 1 mm along the leakage side. The extended section acts as a parallel plate section which is conveniently connected or disconnected from the leaking side of SIW through PIN diodes. The 'ON' state of PIN diodes extends the metal guides and results in the H-plane leakage whereas 'OFF' state of PIN diodes truncates the extended metal earlier and alter the leakage line boundary condition towards E-plane. The whole concept is validated by series of simulations followed by the realization and testing of the SIW-LWA. The measured radiation pattern scans about 54° in the E-plane between 10.0 GHz to 11.7 GHz, and 58° in the H-plane from 9 GHz to 10.6 GHz. The proposed topology is a suitable candidate for remote sensing and airborne applications.

INDEX TERMS E-plane, H-plane, leaky wave antenna (LWA), reconfigurability, substrate integrated waveguide (SIW), and travelling wave antennas.

I. INTRODUCTION

Substrate Integrated Waveguide (SIW) technology has gained considerable attention by researchers exploring microwave and millimeter (mm) waves applications because of its compact and rapid realization. Introducing periodic or non−periodic perturbations in the transmission line section of Substrate Integrated Waveguides (SIWs) results in travelling wave non−resonant radiating structures which are classified as Leaky Wave Antennas (LWAs) [1]–[3]. These types of antennas are useful in many scanning applications such as remote sensing, radio astronomy, and satellite communication due to their beam scanning capability over a frequency band along with high directivity [4]–[7].

In SIW-LWA antenna, frequency driven beam scanning characteristics can be obtained either in E-plane or H-plane by applying different techniques in periodic and non-periodic fashion. For instance, in [8], beam scanning from −40° to 35° in the E-plane is achieved by introducing both longitudinal and transverse slots in conventional SIW antenna topology. Henry *et. al.* proposed half-mode SIW-LWA architecture using antipodal tapered slots for the broadside scanning [9]. A SIW-LWA inspired with Composite Righ/Left Handed (CRLH) structure is proposed in [10] for radiation

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leakage in the E-plane from −25° to 26°. CRLH cell structure composed of interdigital slots in SIW-LWA is discussed in [11] for achieving three bands having beam scan angle from −78° to 78°, −40° to 20°, and 22° to 54° at first, second, and third band respectively. Similarly, a butterfly like configuration is incorporated in SIW-LWA for the E-plane beam scanning from 12° to 45° [12]. Also, beam scanning in E-plane is achieved by proposing uniform slots on the top wall of SIW-LWA in [13].

On the other hand, a LWA with only H-plane beam scanning is achieved by inserting sparse row of metallic posts on one side of SIW structure [14]. Similarly, a LWA using spoof surface plasmon excitation having single beam scanning capability of 43.5° over frequency range from 10 GHz-13 GHz in the H-plane is discussed in [15]. Moreover, Ros *et. al.* proposed a double-sided SIW-LWA having beam scanning in the H-plane with an increased directivity in the E-plane [16].

There has been limited use of inherent leaky nature of SIW-LWA ([8]–[16]) because of frequency bands assigned by the regulatory authorities. Therefore, there is a great need of investigating pattern reconfigurable SIW-LWAs [17]. In this context, a one dimension (1D) SIW-LWA at a fixed frequency 5.5 GHz has been reported using two control lines in a two layer design with ground plane in the middle layer to achieve pattern reconfiguration [18]. Also, in [19], E-plane scanning and H-plane sectorization have been achieved using the electronic reconfiguration.

It can be observed from the aforementioned work that beam scanning in SIW-LWA is either reported in the E-plane or H-plane by incorporating structural modifications on the top surface without disturbing fundamental TE_{10} mode. Moreover, pattern reconfiguration of SIW-LWA have also been proposed only at fixed frequency with restriction either in the H-plane or E-plane scanning which therefore limits the flexibility of leaky-wave antennas. Therefore, a SIW-LWA having flexibility of radiation leakage control in both planes using electronic switching can be used to address the complexity of propagation channels.

This paper presents a SIW-LWA structure having flexibility of the E-plane and H-plane beam scanning reconfigurability, achieved by the incorporation and switching of PIN diodes on top and bottom plane. A layout of the proposed design is shown in Figure 1. The ‘OFF’ state of PIN diodes creates a longitudinal slot in the proposed structure between SIW width (a_{eff}) and extended metallic section (a_0), that alters β_{10eff} caused by an Electromagnetic (EM) wave travelling in the y-direction. This arrangement results in radiation leakage in the E-plane from nearly broad side to nearly endfire but not exactly at endfire because of the finite ground plane [13]. However, PIN diodes ‘ON’ state provides a connection of SIW section with the extended metal section placed at a distance of 1 mm from the sparsely placed metallic vias and produces radiation leakage and beam scanning with respect to frequency in H-plane.

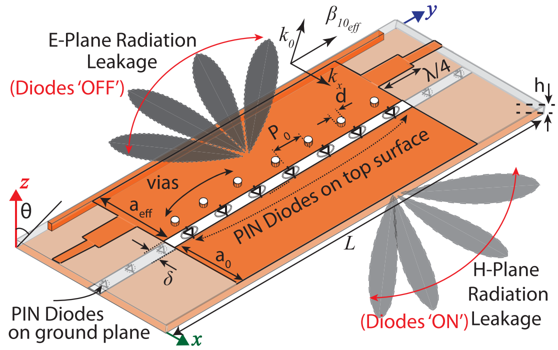

FIGURE 1. Layout of the proposed SIW-LWA design with PIN diodes to achieve E- and H-plane radiation leakage. Optimized dimensions in mm are: $a_{eff} = 15$, $a_0 = 17.5$, $\delta = 1$, $P_0 = 8$, $d = 1.5$, $h = 1.524$ and $L = 130$.

II. DESIGN APPROACH OF RECONFIGURABLE E- AND H-PLANE SIW-LWA

Initially, a simple SIW transmission line is designed on Rogers RO4003 substrate ($\epsilon_r = 3.55$, $h = 1.524$ mm, $tan\delta = 0.0027$) using basic design equations [20]. To minimize the radiation losses and leakage losses, via diameter $d = 1.5$ mm, and period $P_o = 2$ mm is used in the initial design. The structure is modeled in Ansys HFSS [21] by creating 1 mm thick solid Perfect Electric Wall (PEC) on one side and metallic via holes on the other side having period P_o to generate TE_{10} mode having 8 GHz cut-off frequency.

The structure is then widened by introducing the extended metallic section with width a_o on the top and bottom layers and etching a 1 mm longitudinal slot on both sides for the incorporation of PIN diodes, as shown in Figure 1. In the modified design, the period (P_o) of the metallic via posts is increased to convert the proposed topology in leaky wave regime [1], [2]. It was observed that for an optimized period of $P_o = 8$ mm, TE_{10} mode is perturbed and radiation leakage occurs in the structure. In order to maximize the radiation power of the proposed SIW-LWA, a_{eff} is kept at 15 mm with the cut-off frequency of 8 GHz. The leakage rate α came out to be 8.5 m^{-1} for the radiation efficiency of 90 %. The length of the antenna is calculated using $L = -ln[1-\eta]/2\alpha$.

The longitudinal slot of $\delta = 1$ mm between the effective SIW width (a_{eff}) and the extended metallic section (a_0) appears as a discontinuity when PIN diodes are in the ‘OFF’ state. This situation results in a wave ($e^{-j\beta_{10eff}y}$) faster than the velocity of light ($\beta_{10eff}/k_0 < 1$) for radiation leakage [22], [23], where β_{10eff} is the effective phase constant of the dominant perturbed TE_{10} mode because of the introduced longitudinal slot (δ) and extended metallic section (a_0). k_0 is the free space wave number. Also, following relationship holds for the dielectric-air interface at the longitudinal slot along x-axis having snell’s law condition with the angle of refracted wave (θ') $\sqrt{\epsilon_r} sin(\theta) = sin(\theta')$ [23]:

$$k_x{}^2 = k_0{}^2 - \beta_{10eff}{}^2, \quad (1)$$

where, k_x is the wave number along x-axis, k_0 is free space wave number, and β_{10eff} is the phase constant. Eq. (1) also

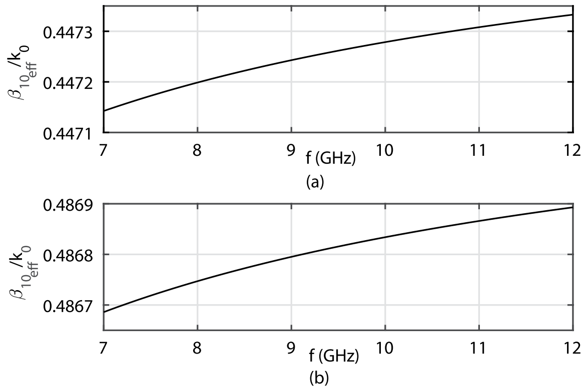

FIGURE 2. Dispersion relation of the proposed SIW-LWA having leaky wave in the E- and H-plane (a) β_{10eff}/k_0 vs frequency graph showing leaky wave regime of the proposed layout with PIN diodes 'OFF' state and (b) β_{10eff}/k_0 plot validating leaky wave in the H-plane for PIN diodes 'ON' state.

confirms that only leaky wave will generate along x-axis for real value of k_x. The β_{10eff} for the x-directed leaky wave due to surface truncation at the longitudinal slot in the 'OFF' state of PIN diodes is:

$$\beta_{10eff} = \left(\omega^2\epsilon\mu - \left(\frac{\pi}{a_{eff} + \delta + a_0}\right)^2\right)^{\frac{1}{2}}, \tag{2}$$

where, $\epsilon = \epsilon_0\epsilon_r$, $\mu = \mu_0\mu_r$, a_{eff} is the width of the top and lower metal surfaces, δ is width of the longitudinal slot, and a_0 is the width of the the top and bottom extended metal surfaces. The leaky wave condition judging rule $\beta_{10eff}/k_0 < 1$ is plotted in Figure 2 (a) and it confirms that proposed structure with longitudinal slots i.e. in the PIN diodes "OFF" state will have a leaky-wave in z-direction. Moreover, dependence of β_{10eff} on frequency steers the beam from broadside towards endfire at higher frequencies than the cutoff frequency of the dominant mode [23], [24]. However, frequency scan angle $\theta = sin^{-1}\left(\beta_{10eff}/k_0\right)$ of the leaky wave can be approximated as:

$$\theta = sin^{-1}\left(\frac{\lambda_0\left(\omega^2\epsilon\mu - \left(\frac{\pi}{a_{eff}+\delta+a_0}\right)^2\right)^{\frac{1}{2}}}{2\pi}\right), \tag{3}$$

where θ is maximum scanned angle measured from the broadside. Eq. (3) shows that scanning range from the broadside to the end fire can be achieved by changing the phase constant β_{10eff}. Eq. (3) also indicates that the scan angle θ is dependent on the values of a_{eff}, δ, and a_0. Thus, for PIN Diodes 'OFF' state, a separation through a longitudinal slot of 1 mm (δ) exists between the metallic surface a_{eff} and the extended metallic surface a_0 on the top and bottom sides of the proposed SIW-LWA. This arrangement alters leaky line boundary condition and the proposed SIW-LWA results in the E-plane radiation leakage for PIN diodes 'OFF' state. In simulation environment, the PIN diodes are modeled using lumped RLC boundary conditions and 20 PIN diodes are used in total (10 on ground plane and 10 on top plane) for providing continuous current path in 'ON' state and isolation in 'OFF' state [25].

The phenomenon of radiation leakage in the E-plane is further validated by observing magnitude of E-field distribution in the E-plane and H-plane. It can be seen in Figure 3 (a) that maximum E-field is in the E-plane (yz plane) of SIW because of the existence of a longitudinal slot for PIN diodes 'OFF' state. The presence of the longitudinal slot and increase in period directs the leakage in the E-plane for a guided wave having perturbed TE_{10} mode travelling in y-direction. Thus, magnitude of the E-field distribution depicted in Figure 3 (a) further validates the design procedure and leakage characteristics of the proposed SIW-LWA in the PIN diodes 'OFF' state.

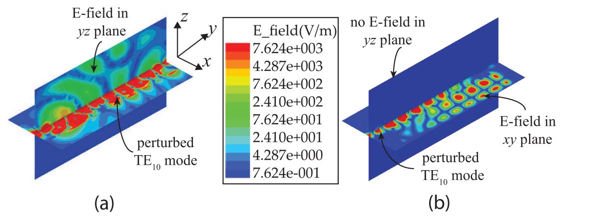

FIGURE 3. (a) Magnitude of E-field distribution in the E-plane of SIW-LWA having perturbed TE_{10} mode showing radiation leakage in the E-plane and (b) magnitude of E-field distribution validating the radiation leakage in the H-plane with no radiation leakage in the E-plane.

Contrarily, 'ON' state of PIN diodes in the proposed structure provides a continuous path towards the extended metallic surfaces having width a_0. The judging rule of the leaky wave ($\beta_{10eff} < k_0$) using the phase constant expression of (2) having slot width $\delta = 0$ mm (because of PIN diodes 'ON' state that connect metallic surface a_{eff} and extended metallic surface a_0) plotted in Figure 2 (b) confirms that wave is leaked in the H-plane.

Moreover, for verification of the H-plane radiation leakage and confirmation with the theoretical procedure, magnitude of the E-field distribution is also plotted in the H-plane (xy plane) and is shown in Figure 3 (b). Concretely, the 'ON' state of PIN diodes creates a continuous current path and results in radiation leakage in the H-plane. In addition, vector components for the E- and H-fields in both E- and H-plane have also been observed to verify the design procedure and are shown in Figures 4 (a-b) and 5 (a-b). It can be observed from Figure 4 that E- and H-vector distribution is maximum in the E-plane when PIN diode are in 'OFF' state, whereas, 'ON' state of PIN diodes electronically switch the E- and H-vector distribution to the H-plane and resulting in the radiation leakage in the H-plane, as shown in Figure 5 (a-b).

III. RESULTS AND DISCUSSION

In order to validate the theoretical design procedure and simulation results, the proposed SIW-LWA shown in Figure 1 is fabricated on a commercial substrate Rogers RO4003. The S-parameters of the prototype with PIN diodes 'OFF' and 'ON' state were measured using a Performance Network Analyzer (N5242A). Whereas, the radiation patterns of the prototype with PIN diodes 'OFF' and 'ON' state were measured in a well calibrated full anechoic chamber. A standard gain wideband horn antenna has been used as

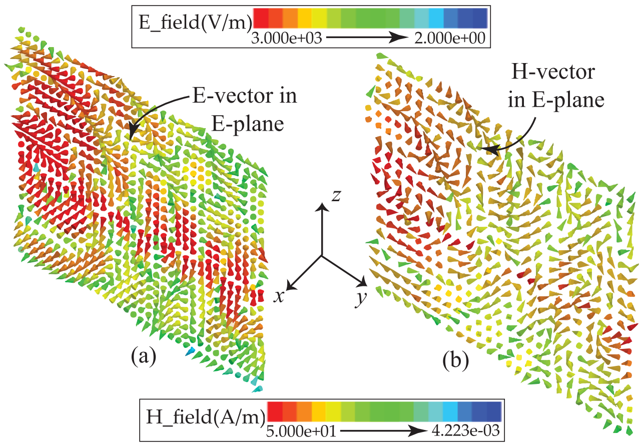

FIGURE 4. (a-b) E-field and H-field vector components showing radiation leakage of SIW-LWA in the E-plane for PIN diodes 'OFF' state.

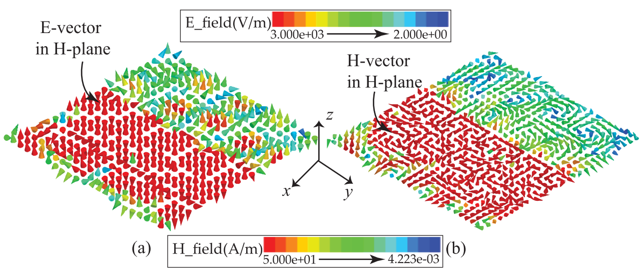

FIGURE 5. (a-b) E-field and H-field vector components showing radiation leakage of SIW-LWA in the H-plane for PIN diodes 'ON' state.

a transmitter and the leaky wave antenna is fixed on the rotating platform as a receiving antenna. The measured results are then compared with the simulated results to verify design procedure. A photograph of the fabricated prototype during the measurements in the anechoic chamber is shown in Figure 6. The PIN diodes are manufactured by Skyworks [27] (SMP 1322), whereas RF chokes used for the isolation of RF and DC current are manufactured by Mini-Circuits [28] (ADCH-80A).

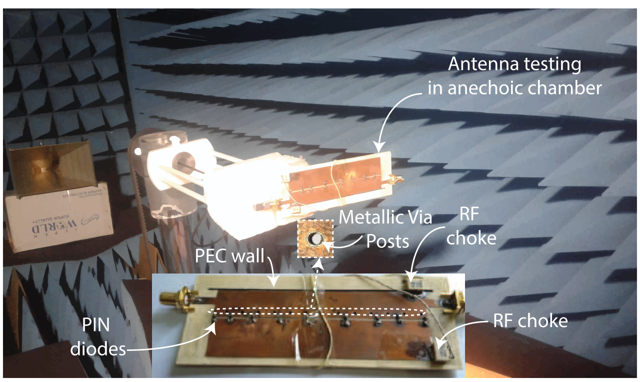

FIGURE 6. Photograph of the fabricated prototype mounted on the turn-table during radiation pattern measurements in an anechoic chamber.

A. S-PARAMETERS RESULTS

Figures 7 and 8 depict the simulated and measured $|S_{11}|$ and $|S_{21}|$ results of the prototype shown in Figure 6. It can be observed from the S-parameter results shown in Figure 7

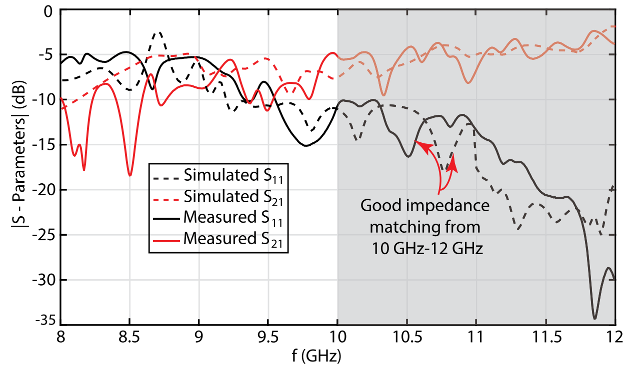

FIGURE 7. Simulated and measured magnitude of the S-Parameters of the proposed SIW-LWA scheme when PIN Diodes are in 'OFF' state.

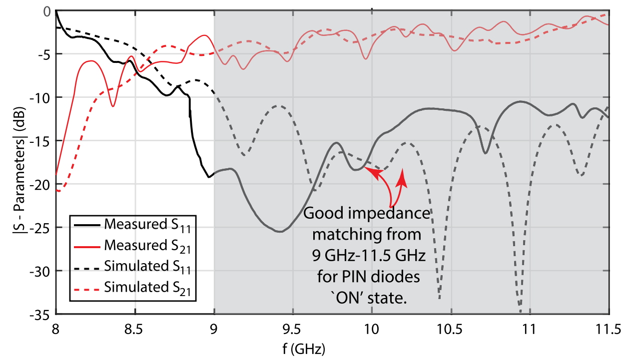

FIGURE 8. Simulated and measured magnitude of the S-Parameters of the proposed SIW-LWA scheme when PIN Diodes are in 'ON' state.

that a good impedance match exists over frequency range from 10 GHz to 12 GHz when PIN diodes are in 'OFF' state. Whereas, PIN diodes in 'ON' state lowered the cutoff frequency of the proposed SIW-LWA and good impedance is achieved at lower frequency range from 9 GHz to 11.5 GHz, as shown in Figure 8. It can also be observed in the Figure 7 that $|S_{21}|$ less than -3 dB depicts good load efficiency [29] over the frequency range from 10 GHz to 11.7 GHz. Beyond 11.7 GHz, proposed SIW-LWA antenna with PIN diodes 'OFF' state scans very close to the endfire direction. Hence, more and more power are transmitted to the terminated end instead of radiating into the space.

On the other hand, 'ON' state of PIN diodes directed the leaky wave in the x-direction and resulted in good impedance match from 9 GHz to 11.5 GHz, as seen from $|S_{11}|$ results of Figure 8. Moreover, $|S_{21}|<-3$ dB validated that maximum power is leaked into the space. Whereas, an increase in $|S_{21}|$ beyond 10.6 GHz showed that more power is transmitted to the terminated end rather than leaking into the H-plane for PIN diodes 'ON' state. Overall, a fair agreement is observed between the simulated and measured S-parameter results. A small discrepancy between the simulated and measured results is due to PIN diodes [25], [30], conductor losses [13], [31], and fabrication errors.

B. RADIATION CHARACTERISTICS

Radiation leakage characteristics (normalized far field radiation patterns) of the final SIW-LWA scheme for PIN diodes

'OFF' state are plotted for the performance demonstration. It can be seen in Figure 9 (a) and (b) that when PIN diodes are switched 'OFF', proposed SIW-LWA structure has radiation leakage in the E-plane. The designed scheme has radiation leakage from an angle of 10.0° in the E-plane at the operating frequency of 10 GHz and continues to scan till 64.0° at 11.7 GHz. Overall, 54.0° scan angle in the E-plane (*yz* plane) with respect to the operating frequencies from 10 GHz to 11.7 GHz is obtained when PIN diodes are switched 'OFF' with maximum gain of 6.5 dBi.

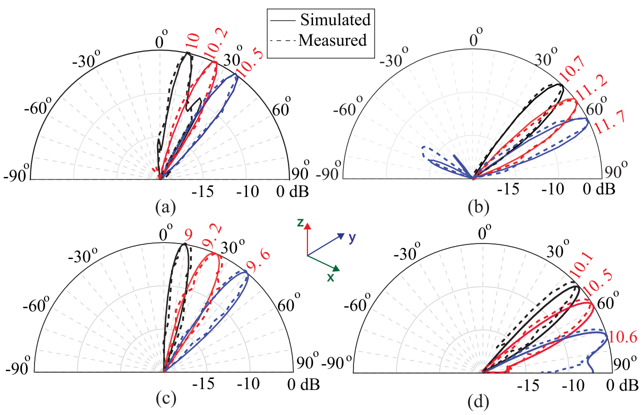

FIGURE 9. Normalized patterns of SIW-LWA design; (a) normalized radiation pattern in the E-plane at 10 GHz, 10.2 GHz, and 10.5 GHz for PIN diodes 'OFF' state, (b) normalized radiation pattern in the E-plane at 10.7 GHz, 11.2 GHz, and 11.7 GHz for PIN diodes 'OFF' state, (c) normalized radiation pattern in the H-plane at 9 GHz, 9.2 GHz, and 9.6 GHz for PIN diodes 'ON' state, and (d) normalized radiation pattern in the H-plane at 10.1 GHz, 10.5 GHz, and 10.6 GHz for PIN diodes 'ON' state.

On the other hand, when PIN diodes are switched to 'ON' state, the radiation leakage occurred in the H-plane, as depicted in Figures 9 (c) and (d). The proposed structure is able to scan in the H-plane (*xy* plane) from 8.0° to 66.0° for the operating frequencies from 9 GHz to 10.6 GHz, respectively. It can also be observed from Figures 9 (c) and (d) that the proposed SIW-LWA has 58.0° scan angle in the H-plane for the operating frequencies ranging from 9 GHz to 10.6 GHz having maximum gain of 6.0 dBi. In addition, Co- and Cross-Polarization results presented in Figure 10

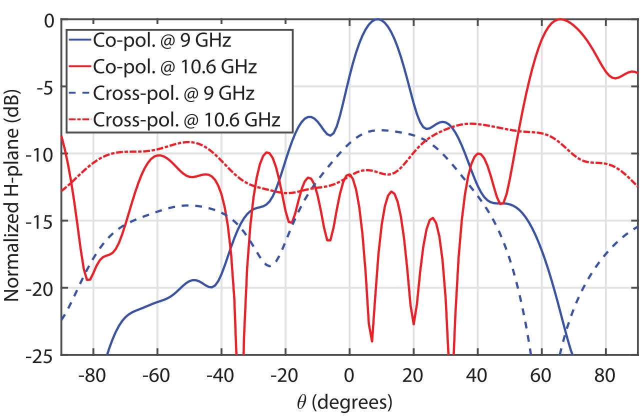

FIGURE 10. Co- and Cross-Polarization levels for PIN diodes 'ON' state at 9 GHz and 10.6 GHz.

show that maximum cross polarization level is at least 7 dB less than the co-polarization beam. A degradation in the maximum gain is attributed to the incorporation of PIN diodes and biasing circuitry. A 3-D radiation pattern of the proposed SIW-LWA for the PIN diodes 'OFF' state showing radiation leakage in E-plane at 10.0 GHz, 10.5 GHz, and 11.7 GHz is presented in Figure. 11. Whereas, 3-D radiation pattern results shown in Figure 12 confirm that proposed SIW-LWA has radiation in the H-plane when PIN diodes are in the 'ON' state.

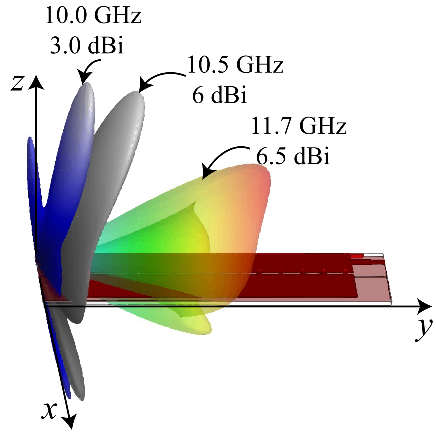

FIGURE 11. 3D patterns of SIW-LWA design in the E-plane at 10.0 GHz, 10.5 GHz, and 11.7 GHz for PIN diodes 'OFF' state.

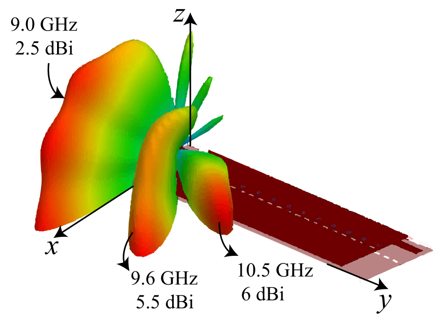

FIGURE 12. 3D patterns of SIW-LWA design in the H-plane at 9.0 GHz, 9.6 GHz, and 10.5 GHz for PIN diodes 'OFF' state.

Furthermore, a comparison of our proposed work with other reported SIW-LWAs is given in Table 1. It can be inferred from Table 1 that most of the research in SIW-LWA domain is on achieving either E- or H-plane radiation leakage with flexible control of complex propagation constant. However, electronic reconfiguration at fixed frequency in SIW-LWA using varactors diodes is only realized in simulations [17]. According to Table 1 and to the best of authors' knowledge, electronic reconfiguration from the E- to H-plane and vice versa using PIN diodes in SIW-LWA having a beam scan angle of 54.0° in E-plane and 58.0° scan angle in H-plane is reported for the first time in this paper. It is applicable to remote sensing and airborne systems, where target object may change its plane i.e. E-plane or H-plane simultaneously. The proposed SIW-LWA is capable of producing beam steering with respect to frequency scan in both planes using electronic switching that makes it a very suitable candidate for the above mentioned and relevant applications.

TABLE 1. Comparison of proposed work with other reported SIW-LWAs.

References	Design Topology	Beam scanning	Advantage(s)	Limitation(s)
[32]	Composite Right/Left Handed (CRLH) structure incorporating varactor diodes for single frequency voltage-controlled operations.	E-plane scanning from 50.0° to −49.0° at 3.33 GHz.	Additional benefit of half-power beamwidth variation upto 200 %.	Complicated design because of the use of CRLH unit cell, series, and shunt varactor diodes.
[4]	Fifteen slots radiating elements with one microstrip feed line	E-plane scanning over operating bandwidth from 2.7 GHz to 3.2 GHz	Reduced beam squinting.	Inflexibility in the design for beam direction.
[5]	Liquid crystal based X-band leaky wave antenna.	Frequency/Pattern reconfiguration only in the E plane.	Replacement of frequency sweep characteristics of conventional LWA with liquid crystal material.	Gain fluctuation during tuning and design complexity.
[17]	Double layer designs having ground plane in middle and use of varactor diodes to connect High Impedance Surface (HIS) posts on top layer with tuning stubs in bottom layer.	E-plane beam scanning from 15.0° to 35.0° at 5.5 GHz.	Independent biasing of PRS and HIS provide electronic control over radiation angle and beamwidth of scanned fan beam.	Design is only realized in simulation environment. Also, dispersion curves and fabrication complexities are still unknown.
[8]	Periodic SIW-LWA with longitudinal and transverse slots.	E-plane beam scanning having −40.0° at 9 GHz to 35.0° at 14 GHz.	A non-cutoff SIW supporting backward to forward beam scanning.	Provides beam scanning only in E-plane.
[12]	Periodic SIW-LWA with 8-winged butterfly structure.	E-plane beam scanning from 12° to 45° from 9.9 GHz to 10.5 GHz.	8-winged butterfly designs with higher gain values at lower elevation angles than uniform counterpart leaky wave antennas.	Frequency shift of 300 MHz exists between the simulated and measured radiation patterns with poor radiation performance.
[14]	A SIW with replacement of lateral wall with partial reflecting walls for H-plane radiation leakage.	H-plane radiation leakage from 10.0° to 50.0° is reported with three different prototypes having different values of width a_{eff} and period P_0.	At 15 GHz, operating principle of SIW-LWA having variable beamwidth control from 5° to 20° is discussed.	Beam scan angle of a single design in H-plane having constant value of width a_{eff} and period P_0 is not reported.
[Proposed work]	Incorporation of PIN diodes to control leaky line boundary conditions for E- and H-plane radiation leakage.	54.0° scan angle from 10.0° at 10.0 GHz to 64.0° at 11.7 GHz in PIN diodes 'OFF' state. Whereas, 58° scan angle in H-plane from 8.0° at 9 GHz to 66.6° at 10.7 GHz.	Provides flexibility of achieving E- or H-plane radiation leakages electronically.	Effect of PIN diodes and biasing circuitry on beamwidth, directivity, and gain [25].

IV. CONCLUSION

In this paper, fully reconfigurable E- to H-plane radiation leakage characteristics have been demonstrated in SIW-LWA by incorporating PIN diodes on the top surface and ground plane. The SIW is realized with a wall of PEC at one side and via posts having period of 8 mm at the other side. An extended metallic surface with 1 mm gap is placed on the ground plane and top layer. The extended portion on the top and bottom layer is shorted using PIN diodes. It is shown successfully that in the proposed design topology, the E-plane radiation leakage is obtained when PIN diodes are in 'OFF' state. Whereas, radiation leakage in the H-plane is obtained when PIN diodes are in 'ON' state. The results show that the scan angle is 54° in the E-plane from 10.0 GHz to 11.7 GHz, whereas, 58° scan angle is achieved from 9 GHz to 10.6 GHz in the H-plane. The validation of the design topology and electronic reconfiguration of SIW-LWA establishes that the proposed structure is a suitable candidate for the multi-beam frequency dependent scanning in remote sensing applications and airborne systems.

REFERENCES

[1] F. Xu and K. Wu, "Guided-wave and leakage characteristics of substrate integrated waveguide," *IEEE Trans. Microw. Theory Techn.*, vol. 53, no. 1, pp. 66–73, Jan. 2005.

[2] D. Deslandes and K. Wu, "Substrate integrated waveguide leaky-wave antenna: Concept and design considerations," in *Proc. Asia–Pacific Microw. Conf.*, Dec. 2005, pp. 346–349.

[3] A. A. Oliner and D. R. Jackson, "Leaky-wave antennas," in *Antenna Engineering Handbook*, J. L. Volakis, Ed., 4th ed. New York, NY, USA: McGraw-Hill, ch. 11, Jun. 2007.
[4] Y. Hou, Y. Li, Z. Zhang, and Z. Feng, "Dual-beam periodic leaky-wave antenna with reduced beam squinting," *IEEE Antennas Wireless Propag. Lett.*, to be published, doi: 10.1109/LAWP.2019.2942723.
[5] D. Jiang, X. Li, Z. Fu, P. Ran, G. Wang, Z. Zheng, T. Zhang, and W.-Q. Wang, "Liquid crystal-based wideband reconfigurable leaky wave X-band antenna," *IEEE Access*, vol. 7, pp. 127320–127326, 2019.
[6] Y. Hou, Y. Li, Z. Zhang, and Z. Feng, "High-gain leaky-wave endfire antenna based on Hansen–Woodyard condition," *IEEE Antennas Wireless Propag. Lett.*, vol. 18, no. 10, pp. 2155–2159, Oct. 2019.
[7] D. Zheng, Y.-L. Lyu, and K. Wu, "Longitudinally slotted SIW leaky-wave antenna for low cross-polarization millimeter-wave applications," *IEEE Trans. Antennas Propag.*, to be published, doi: 10.1109/TAP.2019.2940469.
[8] Y.-L. Lyu, X.-X. Liu, P.-Y. Wang, D. Erni, Q. Wu, C. Wang, N.-Y. Kim, and F.-Y. Meng, "Leaky-wave antennas based on noncutoff substrate integrated waveguide supporting beam scanning from backward to forward," *IEEE Trans. Antennas Propag.*, vol. 64, no. 6, pp. 2155–2164, Jun. 2016.
[9] R. Henry and M. Okoniewski, "A broadside scanning substrate integrated waveguide periodic phase-reversal leaky-wave antenna," *IEEE Antennas Wireless Propag. Lett.*, vol. 15, pp. 602–605, 2015.
[10] H. Lee, J. H. Choi, C.-T. M. Wu, and T. Itoh, "A compact single radiator CRLH-inspired circularly polarized leaky-wave antenna based on substrate-integrated waveguide," *IEEE Trans. Antennas Propag.*, vol. 63, no. 10, pp. 4566–4572, Oct. 2015.
[11] S. S. Haghighi, A.-A. Heidari, and M. Movahhedi, "A three-band substrate integrated waveguide leaky-wave antenna based on composite right/left-handed structure," *IEEE Trans. Antennas Propag.*, vol. 63, no. 10, pp. 4578–4582, Oct. 2015.
[12] Y. Mohtashami and J. Rashed-Mohassel, "A butterfly substrate integrated waveguide leaky-wave antenna," *IEEE Trans. Antennas Propag.*, vol. 62, no. 6, pp. 3384–3388, Jun. 2014.
[13] J. Liu, D. R. Jackson, and Y. Long, "Substrate integrated waveguide (SIW) leaky-wave antenna with transverse slots," *IEEE Trans. Antennas Propag.*, vol. 60, no. 1, pp. 20–29, Jan. 2012.
[14] A. J. Martinez-Ros, J. L. Gomez-Tornero, and G. Goussetis, "Planar leaky-wave antenna with flexible control of the complex propagation constant," *IEEE Trans. Antennas Propag.*, vol. 60, no. 3, pp. 1625–1630, Mar. 2012.
[15] S. Ge, Q. Zhang, C. Chiu, Y. Chen, and R. D. Murch, "Single-side-scanning surface waveguide leaky-wave antenna using spoof surface plasmon excitation," *IEEE Access*, vol. 6, pp. 66020–66029, 2018.
[16] A. J. Martinez-Ros, M. Bozzi, and M. Pasian, "Double-sided SIW leaky-wave antenna with increased directivity in the *E*-plane," *IEEE Trans. Antennas Propag.*, vol. 66, no. 6, pp. 3130–3135, Jun. 2018.
[17] Y. J. Guo, J. L. Gómez-Tornero, R. Guzmán-Quirós, and A. R. Weily, "Reconfigurable leaky wave antennas," in *Forum Electmag. Res. Methods Appl. Technol. (FERMAT)*, vol. 1, Feb. 2014, pp. 1–11.
[18] A. J. M-Ros, J. L. G-Tornero, and G. Goussetis, "Broadside radiation from axial arrays of substrate integrated leaky-wave antennas," in *Proc. 6th Euro. Conf. Antennas Propag. (EUCAP)*, Mar. 2012, pp. 252–254.
[19] M. García-Vigueras, R. Guzmán-Quirós, and J. L. Gómez-Tornero, "Beamwidth control of 1D LWA radiating at broadside," in *Proc. 5th Euro. Conf. Antennas Propag. (EUCAP)*, Apr. 2011, pp. 252–254.
[20] T. Djerafi, A. Doghri, and K. Wu, "Substrate integrated waveguide antennas," in *Handbook of Antenna Technologies*. Singapore: Springer, Sep. 2015, pp. 1–60.
[21] *ANSYS HFSS: High Frequency Electromagnetic Field Simulation Software*. Accessed: Aug. 2017. [Online]. Available: http://www.ansys.com
[22] J. Ghalibafan and S. M. Hashemi, "Leaky-wave centerline longitudinal slot antenna fed by transversely magnetized ferrite," *IEEE Trans. Magn.*, vol. 52, no. 1, Jan. 2016, Art. no. 4000104.
[23] F. Xu and K. Wu, "Understanding leaky-wave structures: A special form of guided-wave structure," *IEEE Microw. Mag.*, vol. 14, no. 5, pp. 87–96, Jul./Aug. 2013.
[24] F. Xu, K. Wu, and X. Zhang, "Periodic leaky-wave antenna for millimeter wave applications based on substrate integrated waveguide," *IEEE Trans. Antennas Propag.*, vol. 58, no. 2, pp. 340–347, Feb. 2010.
[25] A. Iftikhar, J. Parrow, S. Asif, J. Allen, M. Allen, and B. D. Braaten, "Improving the efficiency of a reconfigurable microstrip patch using magneto-static field responsive structures," *Elect. Lett.*, vol. 52, no. 14, pp. 1194–1196, Jul. 2016.
[26] I. J. Bahl and K. C. Gupta, "Design considerations for leaky-wave antennas," *Proc. IEEE*, vol. 123, no. 12, pp. 1302–1306, Dec. 1976.
[27] Skyworks. *Low Resistance, Plastic Packaged PIN Diodes*. Accessed: Aug. 2017. [Online]. Available: http://www.skyworksinc.com
[28] *Mini-Circuits*. Accessed: Aug. 2017. [Online]. Available: http://www.minicircuits.com
[29] J. Liu, X. Tang, Y. Li, and Y. Long, "Substrate integrated waveguide leaky-wave antenna with H-shaped slots," *IEEE Trans. Antennas Propag.*, vol. 60, no. 8, pp. 3692–3697, Aug. 2012.
[30] M. S. Khan, S. Asif, A. Capobianco, B. Ijaz, D. E. Anagnostou, and B. D. Braaten, "Frequency reconfigurable self-adapting conformal array for changing surfaces," *IET Microw., Antennas. Propag.*, vol. 10, no. 8, pp. 897–901, Jun. 2016.
[31] M. S. Khan, A.-D. Capobianco, A. Iftikhar, S. Asif, B. Ijaz, and B. D. Braaten, "A frequency-reconfigurable series-fed microstrip patch array with interconnecting CRLH transmission lines," *IEEE Antennas Wireless Propag. Lett.*, vol. 15, pp. 242–245, 2016.
[32] S. Lim, C. Caloz, and T. Itoh, "Metamaterial-based electronically controlled transmission-line structure as a novel leaky-wave antenna with tunable radiation angle and beamwidth," *IEEE Trans. Microw. Theory Techn.*, vol. 53, no. 1, pp. 161–173, Jan. 2005.

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