# Half Mode Substrate Integrated Waveguide Leaky Wave Antenna with Broadside Gain Enhancement for Ku-Band Applications

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***Abstract.*** *A miniaturized frequency scanned leaky wave antenna (LWA) based on half mode substrate integrated waveguide (HMSIW) with open stop-band suppression is proposed. The modified cross-slot is etched on the top of HMSIW as the radiating element. The folded and unfolded ground plane designs of the proposed HMSIW LWA are compared and analyzed with respect to their Bloch impedance characteristics and it is found that further miniaturization and gain improvement at broadside by ~ 2 dBi are achieved for folded ground plane design. The proposed LWA scans a region from –40° to +24° as the frequency range increases from 12 to 17 GHz with broadside at 15.5 GHz. The HMSIW LWA with folded ground plane is fabricated and its performance is experimentally measured showing the close agreement between the simulation and the measured results.*

## Keywords

Miniaturization, folded ground plane, half mode substrate integrated waveguide, broadside gain enhancement, leaky wave antenna

## 1. Introduction

Microwave and millimeter wave systems are widely designed on rectangular waveguides due to their high quality factor and high power handling capacities. However, with the development in satellite communications, antennas with compact size, low profile, high gain, specific radiation patterns and easy integration with planar circuits are more favorable. As a solution to this problem, substrate integrated waveguide (SIW) is being preferred which is a planar waveguide technology suitable for millimeter-wave applications because of its ease to manufacture, low cost, small size, low loss, and easy integration with planar circuits [1].

For the purpose of miniaturization, half mode substrate integrated waveguide (HMSIW) on the transverse side was proposed while maintaining the fabrication complexity at the same level [2]. Since its introduction, it has gained enormous interests particularly in the antenna field due to its open geometry. The size of the HMSIW is almost half compared to SIW while maintaining all the advantages of the SIW. The HMSIW is considered as a variant of SIW. The different variations of HMSIW are also available in the literature like truncated HMSIW [3], truncated HMSIW with infinite ground planes [4] (baffles) and the variation of SIW with longitudinal slot closed to one via wall. The variation with longitudinal slot provides extra degrees of freedom to control the leakage of the structure [5]. The propagation constant for HMSIW can be calculated using equivalent model of HMSIW proposed in [6]. Based on the phase constant $\beta$ of the HMSIW, it can operate either in fast wave region ($\beta \leq K_0$) and slow wave region ($\beta > K_0$).

The major problem in the conventional periodic LWA is open stop-band (OSB) in the scanning frequency range [7]. The OSB occurs because the reflected waves of each unit cell are in phase at the frequency of broadside radiation. With the advent of metamaterials, leaky wave antennas (LWA) have regained interest because of their backward to forward beam scanning capabilities through broadside [8]. In CRLH LWA (unit cell length, $P < \lambda_g/4$), OSB is suppressed by achieving the balance condition. Various structures of composite right/left handed (CRLH) LWAs on the SIW technology have been proposed [9–12]. In periodic SIW LWAs ($P \sim \lambda_g$), the problem of OSB is solved by mainly three techniques, namely, reflection cancellation [13], impedance matching [14] asymmetric technique [15], [16]. However, the frequency-scanning capability of SIW based LWAs is not suitable for more common fixed-frequency applications because of its closed geometry. However, on the other side, the tuning elements can be loaded very easily on the open side of the HMSIW that will result in the electronically scanned LWA [17]. Therefore, HMSIWs have become popular in the design of LWAs over the past years.

In [18], a novel HMSIW based LWA is proposed with quasi-directional radiation patterns. A circularly po-

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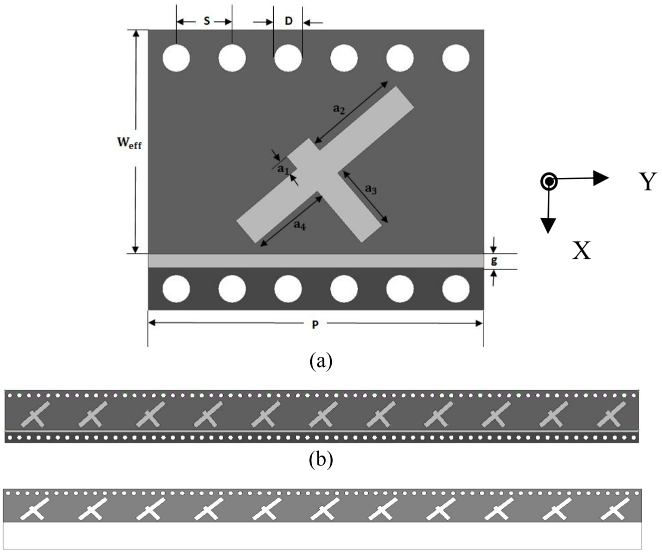
larized CRLH based HMSIW LWA with interdigital slots is proposed with OSB suppression in [19]. Two half-mode structures are combined for high gain and a meandered line is inserted between the two elements for increasing the scanning rate sensitivity of the whole LWA [20]. A folded ground plane technique is applied for gain enhancement and further miniaturization in CRLH based HMSIW LWA [21]. The combination of transverse and longitudinal slots as the radiating elements is used for OSB suppression in HMSIW LWA [22]. In [23], a compact CRLH based HMSIW LWA with spiral slots for gain enhancement and radiation efficiency improvement is presented. The main idea is similar to the previously developed HMSIW P-LWA but with the use of folded ground plane, the gain is enhanced by ~2 dBi with OSB suppression. The folded ground plane technique is applied for the CRLH HMSIW LWA [21] but it is not capable of continuous beam scanning through broadside while in the presented HMSIW LWA the continuous beam scanning is obtained.

In this paper, a new periodic LWA based on the HMSIW for Ku-band applications is presented for OSB suppression and miniaturization on the transverse side. Two designs of presented HMSIW LWA with folded and unfolded ground plane are also compared and concluded. The folded configuration of HMSIW LWA is capable of continuous beam steering from –40° to +24° with broadside gain of ~12 dBi.

This paper is organized as follows: The unit cell is analyzed for folded configuration with respect to their dispersion characteristics. The LWAs are designed with folded and unfolded ground planes and are compared in the second section. The experimental results confirm the continuous beam scanning characteristics of presented HMSIW LWA with good impedance matching characteristics and are discussed in the third section and finally the conclusion is drawn in the last section.

## 2. Antenna Designing and Analysis

The unit cell design of the proposed HMSIW LWA with folded ground is shown in Fig. 1(a). The complete LWA designs of folded and unfolded ground are shown in Fig. 1(b), (c). The proposed structures are designed using RT/Duroid 5880 substrate with dielectric constant $\varepsilon_r = 2.2$ and height of 0.787 mm and loss tangent tan $\delta = 0.0009$. The unit cell of the SIW LWA proposed in [16] is converted into HMSIW LWA unit cell by bisecting it through the central line of symmetry. The width for the HMSIW is chosen according to the equations in [6]. The parameters $D$, $S$, $W_{\text{eff}}$ denote via diameter, via period and HMSIW effective width, respectively.



(a)

(b)

(c)

**Fig. 1.** (a) Unit cell design with folded ground. (b) HMSIW LWA with folded ground. (c) HMSIW LWA with unfolded ground.

| Parameters | Values (mm) |
|---|---|
| $W_{\text{eff}}$ | 8.52 |
| $D$ | 1 |
| $S$ | 2 |
| $g$ | 0.5238 |
| $a_1$ | 1.11 |
| $a_2$ | 4.15 |
| $a_3$ | 2.99 |
| $a_4$ | 3.39 |
| $P$ | 12 |
| $W_{\text{f}}$ | 10.5 |
| $W_{\text{uf}}$ | 14.5 |
| $L$ | 132 |

**Tab. 1.** Design parameters of unit cell with folded ground configuration.

The unit cell of the HMSIW LWA is studied and the period $P$ is taken approximately equal to the guided wavelength $\lambda_g$. The cross slot used in the design consists of longitudinal and transversal components for achieving continuous beam scanning. Initially the slots are designed according to our broadside frequency and their lengths are taken as $\lambda_b/4$ and $\lambda_b/2$ for transverse and longitudinal direction respectively, and width of the slot is taken as $\sim\lambda_b/20$ where $\lambda_b$ is the wavelength at broadside frequency. The width of the slots is taken as approximately 1 mm. The slot parameters ($a_1$–$a_4$) are optimized to achieve continuous beam scanning and for the maximum radiation. For the folded ground design of proposed HMSIW LWA, another via-wall covered by a strip on the top is placed beside the open boundary of the HMSIW with a small gap $g$. This via-wall is used to reduce the energy leakage from the open boundary and increases the gain at broadside. It can be viewed as folded ground which helps in further miniaturization in the transverse side [21]. The optimized parameters for the unit cell are shown in Tab. 1.

The OSB suppression in the unit cell can be explained with the help of unit cell's dispersion graph. Attenuation constant, $\alpha_{\text{eff}}P$ and phase constant, $\beta_{\text{eff}}P$ are calculated using the formula mentioned in [14]. Figure 2 shows the dispersion graph for a unit cell consisting of the cross slot. The dispersion graph of the proposed unit cell shows that $\alpha_{\mathrm{eff}}P$ is almost zero in operating band and $\beta_{\mathrm{eff}}$ is zero at single frequency unlike at a band of frequency which confirms the OSB suppression for HMSIW LWA unit cell. Therefore, unit cell with longitudinal slot and transversal slots can scan seamlessly from backward to forward through broadside. Decreasing and increasing nature of the phase constant shows the backward and forward frequency scanning ranges. The broadside or transition point is around 15.5 GHz.

The real and imaginary parts of the Bloch impedance curve of the HMSIW periodic LWA with both folded and unfolded configurations consisting of 11 unit cells are shown in Fig. 3. These curves are compared with the input impedance for matching purpose. From Bloch impedance curve it is clear that for a folded ground plane design there is only a slight variation of real part of Bloch impedance around the broadside compared to the unfolded ground plane design. Therefore it is anticipated that the gain of the folded design will be more at broadside. The simulated gain patterns for the folded and unfolded configurations are shown in Fig. 5. It is clearly depicted in the figure that broadside gain is enhanced by ~2 dBi at the broadside for the folded ground plane design. The Bloch impedance curve rotates around the input impedance confirming impedance matching for the LWA.

The surface current at 15.5 GHz is plotted at the unit cell to understand the polarization behavior of the proposed LWA as shown in Fig. 4. The surface current distributions are cancelled out at 90° and 180° phase difference. From these figures, one can observe that the antenna possess the elliptical polarization which is inherent due to the presence of series and shunt radiating elements [24]. Asymmetry of the cross slots can be controlled for making it a circular polarization.

In order to complete our understanding on the OSB, the influence of different geometrical variations of the design parameters ($a_1$, $a_2$, $a_3$ and $a_4$) on the behavior of the

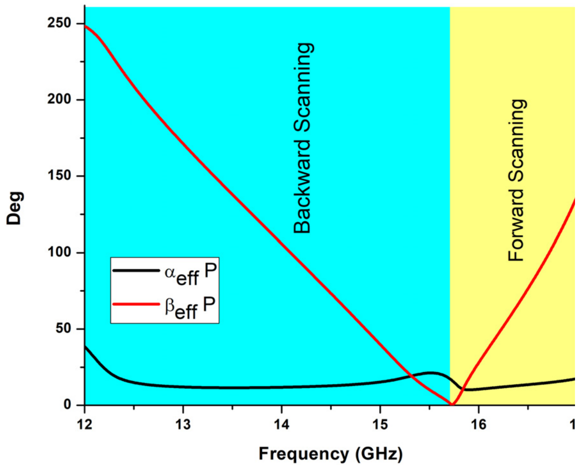


**Fig. 2.** Normalized dispersion diagram of unit cell with folded ground plane.

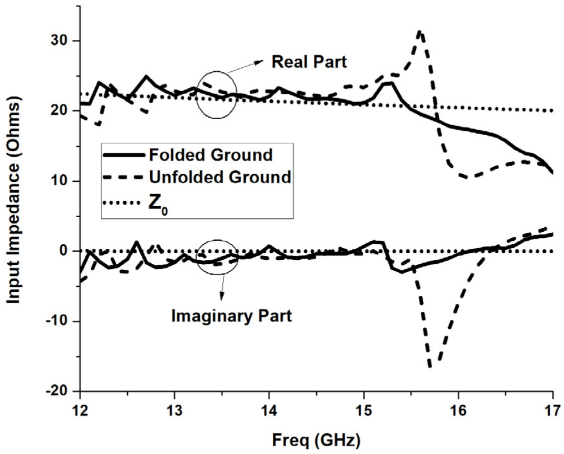
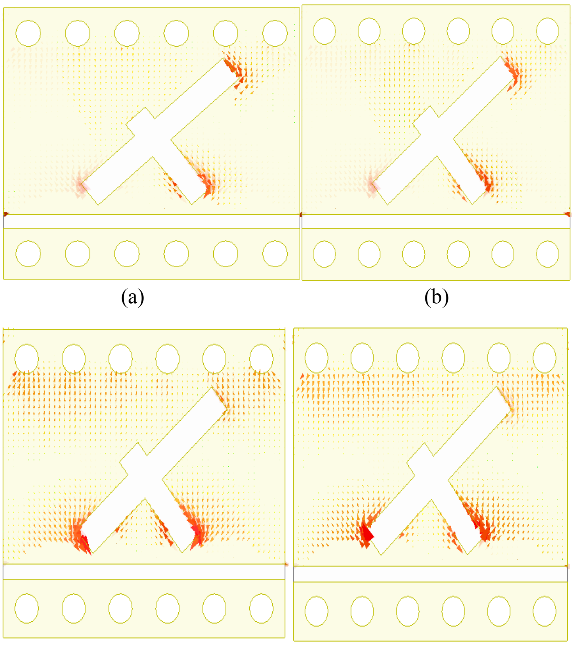


**Fig. 3.** Bloch impedance of HMSIW LWA with folded and unfolded ground plane designs.



(a) (b)

(c) (d)

**Fig. 4.** Surface current distibutions (15.5 GHz) on the unit cell at phase of (a) 0°, (b) 270°, (c) 90°, (d) 180°.

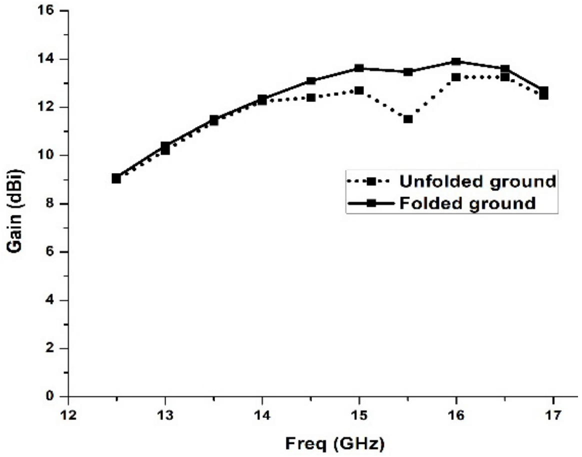
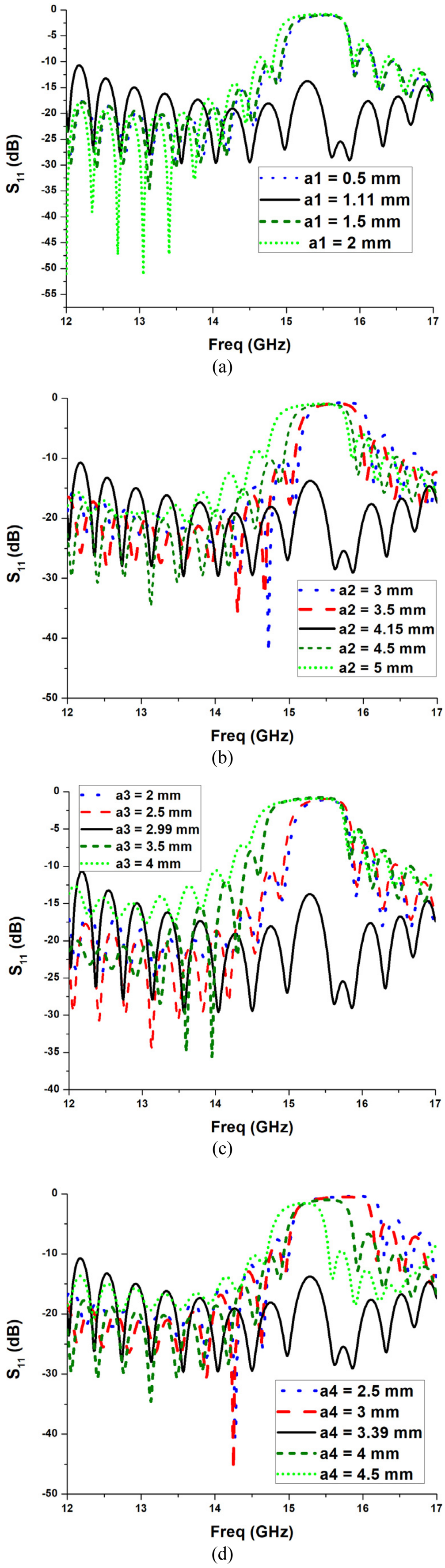


**Fig. 5.** Gain comparison for folded and unfolded ground plane designs of HMSIW LWA.



(a)

(b)

(c)

(d)

**Fig. 6.** OSB parametric study of the folded design by varying parameters (a) $a_1$, (b) $a_2$, (c) $a_3$ (d) $a_4$ .

folded design of the periodic LWA is studied using full wave simulation with Ansys HFSS software package. All the parameters are very crucial in suppression the OSB. The reflection coefficient ($S_{11}$) is displaced by varying $a_1$–$a_4$ is shown in Fig. 6(a)–(d). Larger and smaller values of $a_1$–$a_4$ introduce the OSB due to the radiating power disturbance of the series and shunt elements.

## 3. Experimental Results

For verification purpose, a HMSIW LWA with folded ground plane design is fabricated and is shown in Fig. 7. This prototype is fed by SMA connectors through microstrip-to-SIW transitions. The tapered sections are used with tapered width equal to 3.4 mm for broadband impedance matching. The S-parameters are measured using a microwave vector network analyzer (VNA), and the results are depicted in Fig. 8 together with the simulation results. The parameters are all lower than –10 dB in the 12 GHz to 17 GHz frequency range. Due to additional reflections caused by the SMA connectors and potential production variations, the measured $S_{11}$ spectrum presents shallower resonance dips compared to the simulated spectrum. Hence, the measured magnitude of the $S_{21}$ prototype's spectral response is also deviating from the corresponding simulated $S_{21}$ spectrum due to the worsened $S_{11.}$ The fraction of the input power that should go to the output connector can be inferred from the plot of radiation efficiency as shown in Fig. 9. The radiation efficiency is not uniform all over the frequency range and there is little bump at the broadside. The efficiency of the LWA varies from 75 to 95 percentage.

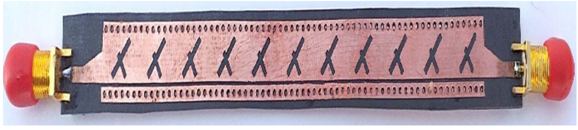


**Fig. 7.** The fabricated prototype of HMSIW LWA with folded ground plane.

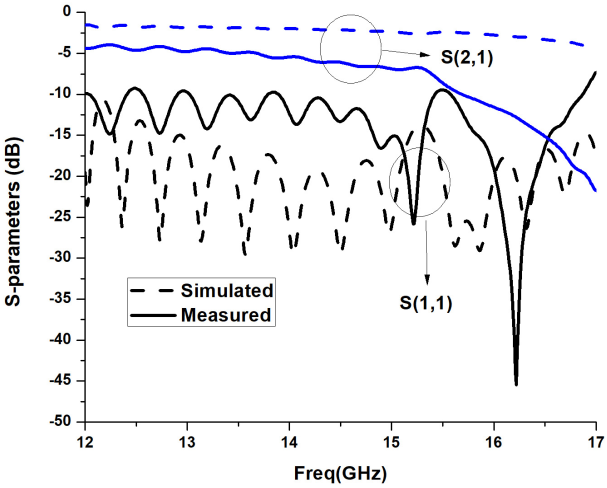


**Fig. 8.** S-parameters of HMSIW LWA with folded ground plane.

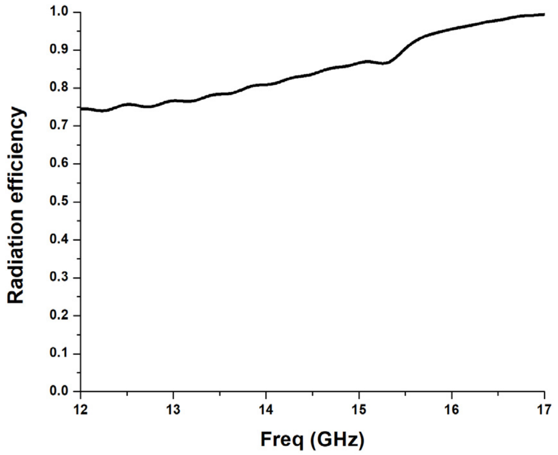


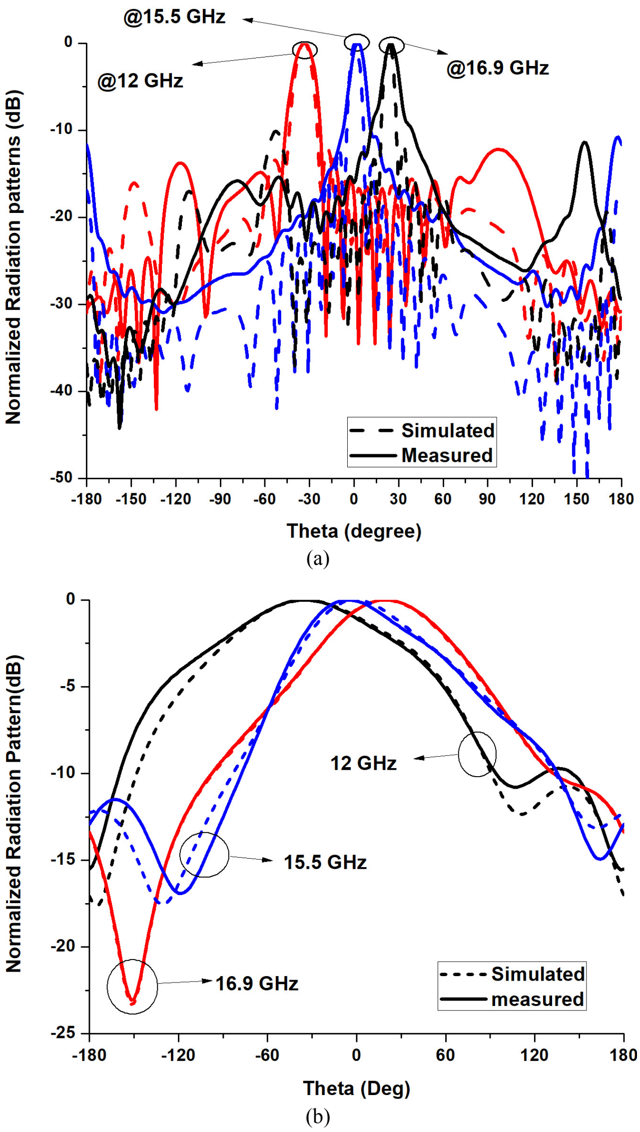
**Fig. 9.** Radiation efficiency of the LWA.

Figure 10 presents the experimental radiation patterns measured through far-field measurement system in an anechoic chamber. The far-field radiation pattern of this antenna indicates a directional patterns characteristic in E plane (Y–Z). Both E-plane and H-plane radiation patterns at 12 GHz, 15.5 GHz (broadside) and 16.9 GHz are shown in Fig. 10(a), (b).The well agreed measured and simulated results demonstrate that the main radiation beam of the prototype scans from −40° at 12 GHz to +24°at 16.9 GHz with smooth transition through broadside at 15.5 GHz.

The E-and H-plane patterns constitute a frequency-dependent scanning, with maximum radiation in the broadside. The measured and simulated gain patterns for folded configuration are shown in Fig. 11. The maximum gain realized for the scanning range for the prototype is ~12 dBi. A dip in the gain at broadside is seen which is a result of poor matching at the broadside point. The similar reported works are shown in Tab. 2. The presented HMSIW LWA has unit cell length $P$ approximately equal to the guided wavelength $\lambda_g$ whereas the structures based on CRLH technology have a unit length $P < \lambda_g/4$, which increases their numerical and fabrication complexity. Thus, the proposed HMSIW LWA is easy to fabricate as compared to other contemporary antennas, which proves its novelty. Also, Table 2 reveals that the proposed antenna is compact as compared to other periodic HMSIW based LWA antennas.

## 4. Conclusion

A miniaturized frequency scanned LWA based on HMSIW for the Ku-band with OSB suppression is proposed. Miniaturization is achieved on the transverse side using HMSIW technology compared to the LWAs based on SIW technology. The unfolded and folded ground configurations are compared and it is concluded that further miniaturization by 4 mm and gain improvement at broadside of nearly 2 dBi is achieved for folded ground plane design. This folded ground plane design of LWA is capable of scanning the beam from –40° to +24° with broadside at 15.5 GHz with the maximum gain of 12 dBi.



(a)

(b)

**Fig. 10.** (a) Normalized E plane (Y–Z plane) and (b) H-plane (X–Z plane) radiation patterns of HMSIW LWA with folded ground.

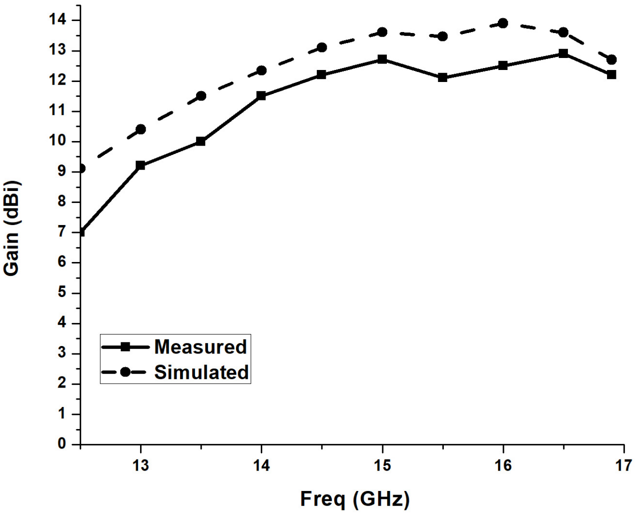


**Fig. 11.** Simulated and measured gain of HMSIW LWA with folded ground plane.

| Ref | Antenna type | Radiator length | Scanning freq. range (GHz) | Designing and fabrication complexity | Backward to forward beam scanning | Pol | Peak gain (dBi) |
|---|---|---|---|---|---|---|---|
| [19]<br>2014 | CRLH HMSIW LWA<br>($P <<< \lambda_g$) | ~6.25$\lambda_0$ | 7.4 to 13.5 | Complex | Yes (–70° to +70°) | CP | ~12 dBi |
| [21]<br>2011 | CRLH HMSIW LWA<br>($P<<< \lambda_g$) | ~5$\lambda_0$ | 8.5 to 12 | Complex | No (–35° to +37°) | LP | ~10 dBi |
| [25]<br>2018 | Periodic HMSIW LWA<br>($P \sim \lambda_g$) | ~8$\lambda_0$ | 10 to 14 | Simple | Yes (–27° to +23°) | LP | ~11.5 dBi |
| [23]<br>2018 | CRLH HMSIW LWA<br>($P <<< \lambda_g$) | ~4.85$\lambda_0$ | 13.5 to 17.8 | Complex | Yes (–66° to +20°) | NA | ~16 dBi |
| [26]<br>2015 | Periodic HMSIW LWA<br>($P \sim \lambda_g$) | ~10$\lambda_0$ | 32 to 46 | Simple | No (–44° to +77°) | NA | ~13 dBi |
| This work | Periodic HMSIW LWA<br>($P \sim \lambda_g$) | ~7.5$\lambda_0$ | 12 to 16.9 | Simple | Yes (–40° to +24°) | EP | ~12 dBi |

**Tab .2.** Comparison with other reported HMSIW LWA design.

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