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Compact CRLH-SIW Based LWA Array with Periodical Loading for Ku-Band Applications

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Abstract—A novel compact composite right/left-handed (CRLH) substrate integrated waveguide (SIW) based leaky wave antenna (LWA) is proposed. Mushroom-inspired unit cell is utilized to achieve CRLH transmission property as well as energy leakage. Periodically loaded metallic vias, which act as an internal 1 : 2 power divider, are along the center line of the SIW structure, leading to a compact antenna size. The LWA can be regarded as an antenna array whose two elements are excited by two newly produced quasi-TE_{10} modes, respectively, and therefore, the antenna peak gain is enhanced. Good agreements are obtained between the simulated and measured results. Continuous beam scanning feature indicates that the proposed design is a balanced frequency scanning work operating in Ku-band.

1. INTRODUCTION

In recent years, leaky wave antennas (LWAs) have received considerable attentions in radar system and satellite communication fields for its frequency-scanning capability and wide bandwidth feature [1]. However, due to the absence of the left-handed (LH) characteristics, conventional leaky wave antennas can only work in the right-handed (RH) frequency region and scan their beams in forward direction, which greatly limits their applications in practical use [2].

Recently, there has been increasing interest in the composite right/left-handed (CRLH) SIW based leaky wave antennas for supporting both backward and forward wave propagations in their right- and left-handed regions [3–8]. In [3], a family of CRLH SIW and half-mode substrate integrated waveguide (HMSIW) leaky-wave structures is proposed. Four types of leaky-wave antennas that use interdigital slots are implemented and analyzed. Continuous beam-steering capabilities are achieved. Several one-dimensional CRLH LWAs consisting of new unit cells based on a modified mushroom cell are presented in [4]. By using multiple vias to take advantage of the inductance dependence on the diameter, a scanning range of -60° to $+66^\circ$ is achieved. Multiband LWAs were also investigated, including dual-band LWA [5] and tri-band LWA [6]. Moreover, a CRLH ridge substrate integrated waveguide (RSIW) is proposed in [7] and applied to slot array antennas for sidelobe reduction. In addition to linearly polarized LWAs, CRLH-SIW based LWAs can also be used in circularly polarized antennas, such as the design in [8, 9].

In this communication, a novel compact CRLH-SIW based LWA is proposed and designed. Mushroom-inspired radiators, composed of a square patch and four grounded vias, are used to obtain the left-handed transmission feature as well as energy leakage. Periodic vias are introduced as an internal 1 : 2 power divider, and two array elements, located at two sides of the loaded vias, are excited in-phase by two quasi-TE_{10} modes. Therefore, antenna gain enhancement is achieved. Due to the absence of external feeding network, the proposed LWA is compact in size and easy to be integrated. Both simulated and measured results show that the proposed antenna is a balanced LWA operating in Ku-band. The antenna in this communication is suitable for Ku-band applications where a compact LWA with continuous beam scanning capability is desired.

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2. ANTENNA DESIGN

The unit structure is given in Fig. 1(a) and Fig. 1(b) while the proposed LWA is presented in Fig. 1(c). The SIW unit cell is made of inexpensive FR4 with relative permittivity 4.4. The mushroom-inspired radiator used in this design is composed of two parts, a square ring and four grounded vias. Series capacitor is due to the capacitive coupling between the radiator and the SIW while grounded vias contribute to shunt inductor, leading to the left-handed wave propagation. Two radiators, separated by periodically loaded vias, are located symmetrically with respect to longitude center line.

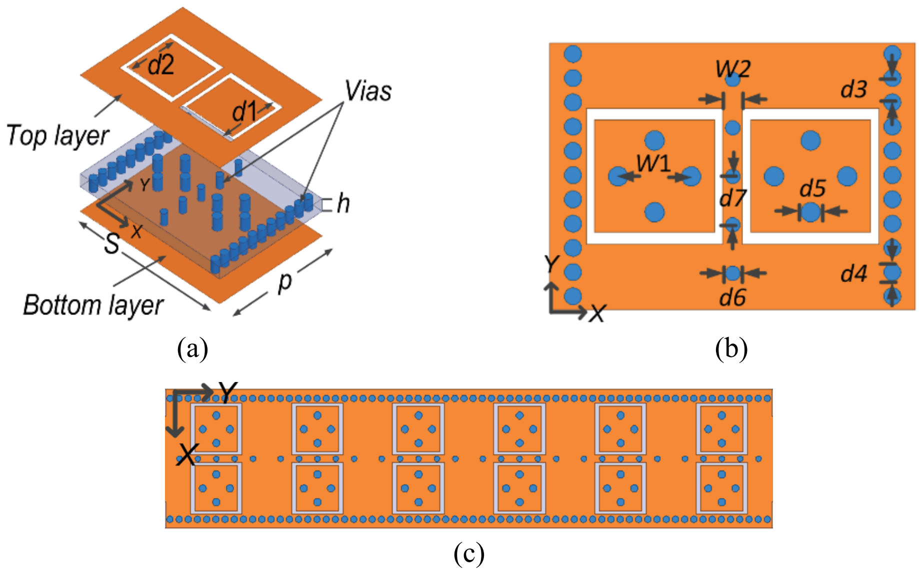

Figure 1. (a) 3-D view of the unit cell. (b) Top view of the unit cell. (c) Top view of the antenna array. The parameter values are: $S = 11.1\,\text{mm}$, $p = 11\,\text{mm}$, $h = 1\,\text{mm}$, $d1 = 5.4\,\text{mm}$, $d2 = 4.7\,\text{mm}$, $d3 = 1\,\text{mm}$, $d4 = 0.7\,\text{mm}$, $d5 = 0.8\,\text{mm}$, $d6 = 0.6\,\text{mm}$, $d7 = 2\,\text{mm}$, $W1 = 3\,\text{mm}$, $W2 = 0.8\,\text{mm}$.

2.1. Dispersion Features

A single unit cell is analyzed firstly to obtain its dispersion characteristics. Driven mode method is utilized with the help of Ansys Electronics Desktop 2021 to get the unit S-parameters [10], from which

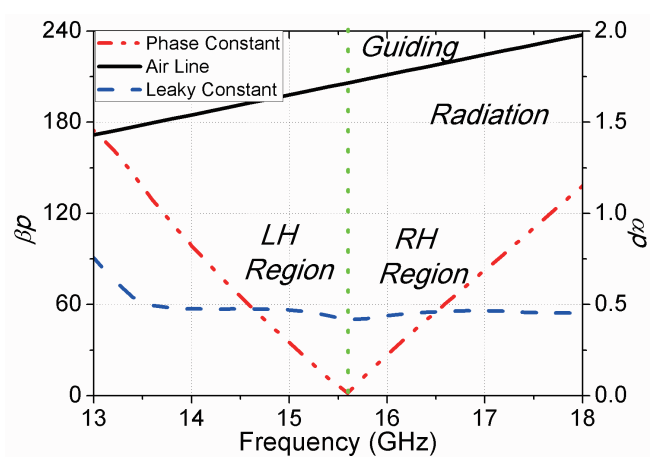

Figure 2. Calculated dispersion feature of the proposed LWA unit.

the ABCD matrix can then be obtained. By solving Equation (1) for the complex propagation constant γ, the leaky constant α and phase constant β can be calculated by the relationship $\alpha = \mathrm{real}(\gamma)$ and $\beta = \mathrm{imag}(\gamma)$.

$$e^{\gamma p}\left(AD - BC\right)e^{-\gamma p} - (A + D) = 0 \tag{1}$$

The radiation angle of the main beam can then be straightforwardly determined by the following equation

$$\theta = \sin^{-1}\left[\frac{\beta(\omega)}{k_0}\right] \tag{2}$$

where k_0 is the wavenumber in vacuum.

The calculated dispersion properties are shown in Fig. 2. As can be seen, the transition between the right- and left-handed regions occurs at ~ 15.53 GHz where $\beta = 0$, and the broadside radiation is expected to occur. The low radiation boundary is at about 13 GHz, and the radiation region is in the Ku-band, which predicts the potential of the antenna for Ku-band applications. Good transition from the LH region to the RH region is obtained.

2.2. Performance of the LWA

LWA with 6 unit cells are used in this paper to demonstrate the design concept. The simulated S-parameters of the proposed antenna are shown in Fig. 3. Good impedance matching is achieved from 13 GHz to 18 GHz, within which acceptable energy leakage is also achieved as $|S_{21}|$ is less than -20 dB. To clarify the frequency-scanning ability of the proposed LWA clearly, the directions of the main beam versus frequency obtained by both Eq. (2) and simulation are given in Fig. 4. Continuous beam scanning from about $-60°$ to $30°$ is achieved in the interested frequency band, indicating that the proposed antenna is a balanced LWA.

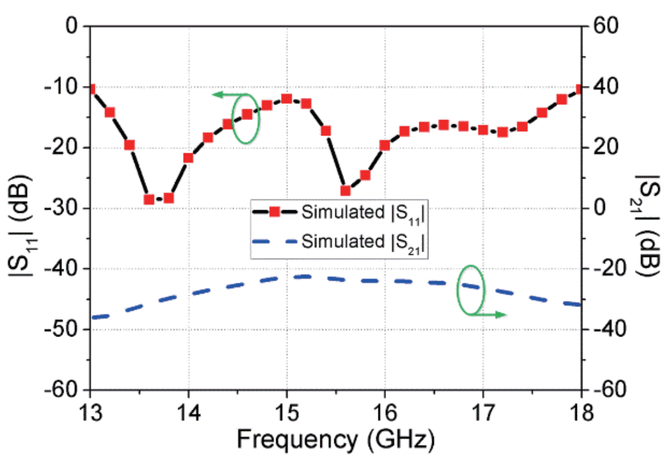

Figure 3. Simulated S-parameters of the proposed LWA with 6 unit cells.

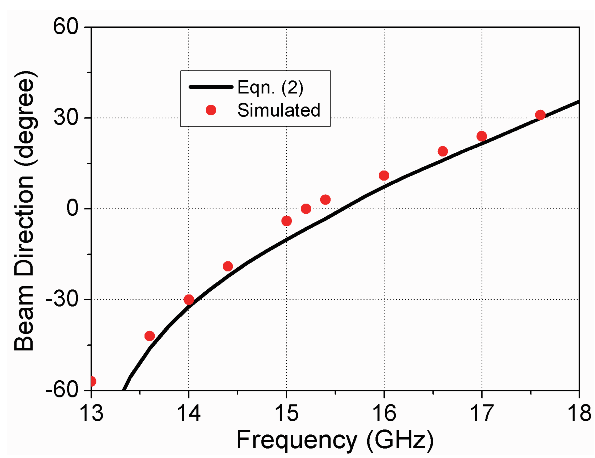

Figure 4. Main beam directions of the proposed LWA versus frequency.

2.3. Clarification of Gain Enhancement and Size Reduction

The proposed LWA shown in Fig. 1(c) can be considered an LWA array with two elements shown in Fig. 5. Usually, external feeding network is needed for an antenna array to excite the elements, which makes the antenna system complicated. Inspired by the work in [11], periodic metallic vias are introduced in the conventional SIW structure working in TE_{10} mode to form a modified CRLH-SIW based LWA with gain enhancement shown in Fig. 1(c). The electric field distributions in conventional SIW and modified SIW are shown in Fig. 6(a) and Fig. 6(b), respectively. Due to the presence of the loaded vias, the TE_{10} mode existing in conventional SIW is divided in two quasi-TE_{10} modes, by which two array elements are excited respectively as shown in Fig. 6(c). Therefore, the antenna gain in main

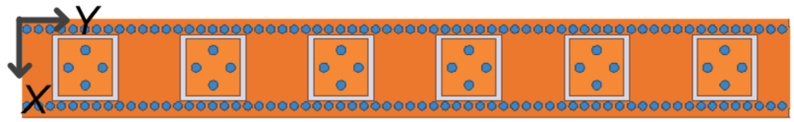

Figure 5. Geometry of the array element of the proposed LWA.

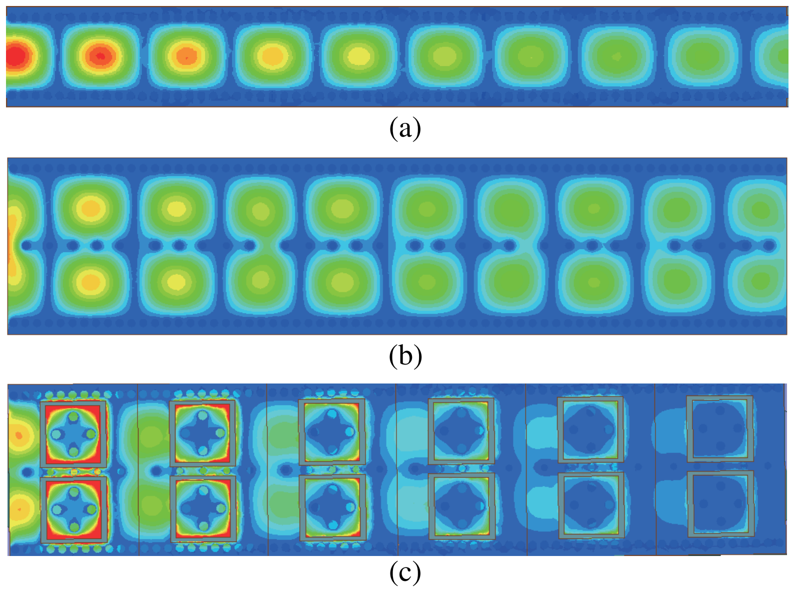

Figure 6. Electric field distribution in different structures. (a) Electric field distribution in conventional SIW. (b) Electric field distribution in modified SIW. (c) Electric field distribution in the proposed LWA array.

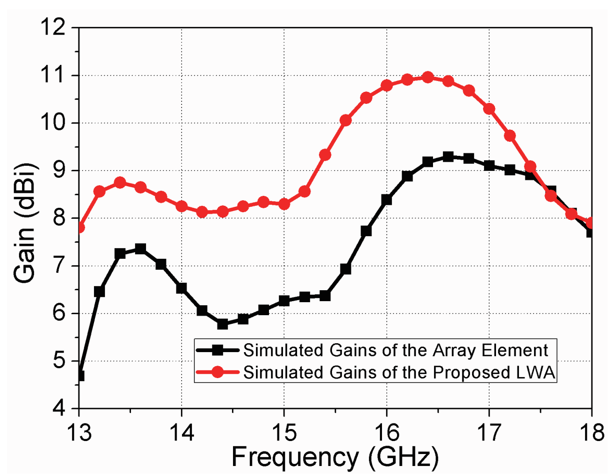

Figure 7. Gain comparison between the LWA array and its element.

beam direction is expected to be enhanced due to the in-phase excitation of the array elements. It should be noted that the proposed LWA can be considered as an array without any external feeding networks, which makes the proposed LWA compact and easy to integrate.

An array element given in Fig. 5 is simulated to clarify the gain enhancement effect, and the result is plotted in Fig. 7. An average gain enhancement about 2 dBi is obtained within 13–17.4 GHz, which is in accord to what is discussed above.

2.4. Measured Results of the Proposed Antenna

The proposed LWA is fabricated and measured to demonstrate the antenna design analyzed in previous sections. The prototype of the proposed antenna and its measured S-parameters are presented in Fig. 8. Acceptable agreements are obtained compared with the simulated results. The normalized radiation patterns are given in Fig. 9. Continuous beam scanning ability is observed with transition frequency at 15.2 GHz, and low cross polarizations less than -30 dB are also achieved in the scanning plane. The measured peak gain is 9.7 dB with variations less than 3 dBi across the working band. Table 1 shows the comparison of the proposed antenna with some existing works, and it can seen that our design in this paper has a relative higher antenna gain with less unit number and smaller radiation aperture.

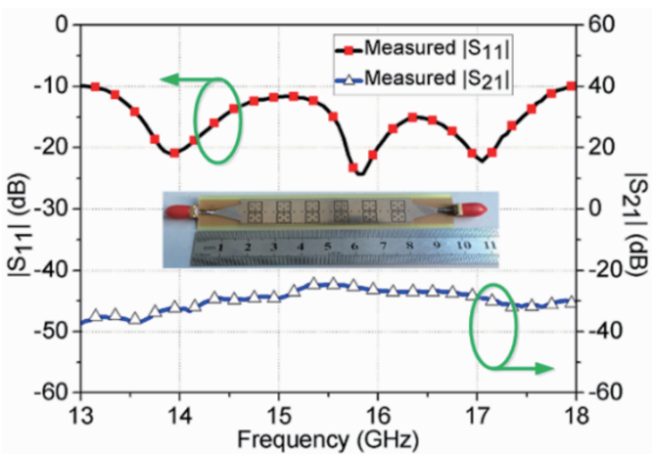

Figure 8. Measured S-parameters of the proposed LWA with 6 unit cells.

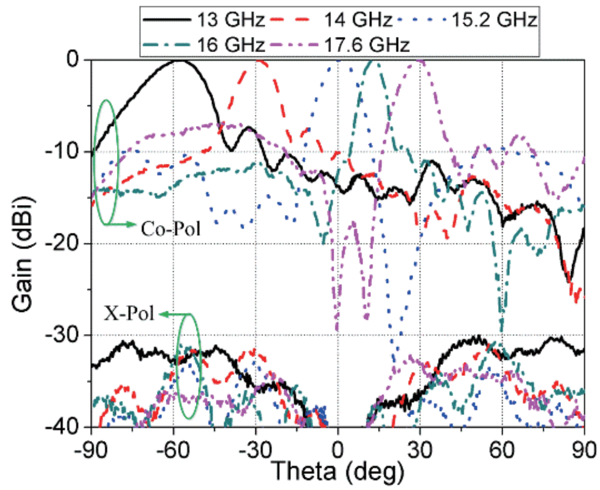

Figure 9. Measured radiation patterns of the proposed LWA.

Table 1. Comparison of the proposed antenna with some existing antennas.

Reference	Antenna type	Scanning range	Unit Number	Antenna Length	Maximum gain (dBi)
[3] (Single-sided)	Single-layered	$-70°$–$+60°$	15	$\approx 4.4\lambda_0$	10.8
[12]	Single-layered	$-19° - +84°$	14	$3.8\lambda_0$	8.95
[13]	Single-layered	$-65°$–$+65°$	9	$4.92\lambda_0$	9
[14]	Single-layered	$-57°$–$+30°$	6	$3.44\lambda_0$	9.2
Our work	Single-layered	$-60°$–$+30°$	6	$3.3\lambda_0$	9.7

3. CONCLUSION

A novel CRLH-SIW based LWA with gain enhancement for Ku-band applications is proposed in this letter. The proposed antenna can be considered as a small LWA array with two elements. External feeding network is avoided due to the loaded periodic vias located along the center line of the SIW structure, and the conventional TE_{10} mode is divided into two quasi-TE_{10} modes, by which two array elements are excited simultaneously. The antenna gain in main beam direction is enhanced due to the in-phase excitation. Due to the absence of the external feeding network, the proposed antenna array is compact in size and is suitable for Ku-band applications where balanced LWA with high antenna gain is desired.

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