Substrate Integrated Waveguide based Leaky Wave Antenna

Ayushi$^{1,2}$  Ashutosh Tripathi$^{1,3}$  Areeba Nafis$^{1,4}$  Saksham Omer$^{1,5}$  and  Ruchi Agarwal$^{1,6}$

$^1$Department of Electronics and Communication Engineering, Galgotias College of Engineering and Technology, Greater Noida, India

$^2$shanayasingh2000lali@gmail.com,  $^3$ashutri04@gmail.com

$^4$areebanafis065@gmail.com,  $^5$sakshamomer08@gmail.com

$^6$ruchi.agarwal1987@gmail.com

Abstract. Leaky Wave Antennas (LWAs) allow electromagnetic wave to leak along its structure. LWAs being low profile have been effortless to fabricate. The SIW can be designed by inserting two rows of metallic via on a dielectric material which work as a wall to prevent the radiation. CRLH property can be generated by cutting the slot on the upper stub which provide the capacitance.

In this paper, a periodic CRLH based C-shaped SIW-LWA is proposed which operates in a single band between the frequencies of 13.2 to 15.5 GHz. With the help of SIW and CRLH property designed antenna scans in continuous backward to forward direction with suppressed stop band. This paper shows a substrate integrated waveguide (SIW) based on leaky wave antenna (LWA) including better gain, efficiency and backward to forward beam steering. The periodic C-shaped slot substrate integrated waveguide leaky wave antenna (SIW-LWA) are made-up and the calculated and replicated results acknowledges marvellously. It seems that there is a good contract between them. The beam steering of SIW-LWA is from -60 degree to 29 degree when frequency sweeps from 13.2 GHz to 15.5 GHz. The SIW-LWA offers the peak value of gain as 5.733 dB and peak value of efficiency are 77.545%. The broad side radiation will be at 14 GHz. Below 14 GHz the antenna works as a LH material and scans negative angles and above 14 GHz antenna works as RH material and scans positive angle.

This antenna, substrate integrated waveguide leaky wave antenna (SIW-LWA), is proposed only to obtained better beam steering so as to use for such application where beam scanning is used.

1. Introduction

Leaky-wave antennas (LWAs) exist since 1940 when the first LWA containing of an inserted rectangular waveguide was made. These antennas allow electromagnetic wave to leak along its structure [1]. LWAs being low profile have been effortless to fabricate [2]. LWAs can be seen as a dispersive metamaterial, whose response changes rapidly with frequency. LWAs are well liked in and above the microwave band, because they can achieve a high directivity without the complicated or costly feed network, they have the advantage of frequency beam scanning and permits for upgraded end fire scanning [3]. Also, frequently modern attention has been given to get on the better of the open stopband issue in order to do scans of the whole region starting from the backside, through broadside [4]. LWA is made on a leading design that transmits the given wave in one-direction, whether unidirectionally, in which an origin is set at particular point of the design or bidirectionally, in which an origin is transmits in the mid of the design. 1-D LWAs can further be designated in to two form as uniform and periodic [5]-[7]. LWAs generally
can't examine entire techniques to endfire because the emitting components like slots & stubs have a component pattern that forbidden this to happen [8] [9].

A substrate integrated waveguide is a technique which can be used to design the LWA antenna of low cost and having planar structure and can be designed on the PCB [10]. As a waveguide, it is the advantages of low loss, high Q factor, high power capability and small radiation and as a planar transmission line we can fabricate it at a relatively lower cost. The SIW can be designed by inserting two rows of metallic via on a dielectric material which work as a wall to prevent the radiation to lea [11].

The CRLH materials are known as the material which can deliver the property of both left hand (LH) and right hand (RH) material due to which antenna can scan both in backward (back fire) as well as in forward direction (end fire) and antenna also covers the negative angle of scanning in addition to positive angles. This CRLH property can be generated by cutting the slot on the upper stub which provide the capacitance [12].

In this paper, a periodic CRLH based C-shaped SIW-LWA is proposed which operates in a single band between the frequencies of 13.2 to 15.5 GHz. With the help of SIW and CRLH property designed antenna scans in continuous backward to forward direction with suppressed stop band.

2. Configuration and simulation of Antenna

To create the beam scanning leaky wave antenna, first we have designed the unit cell of C-shaped slot based SIW-LWA which is shown in figure 1(a). We have designed this unit cell to analyse the dispersion diagram of antenna which tells about the scanning range of the antenna from backward direction to forward direction.

The main beam direction of designed antenna can be given by the below expression

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

If the field traveling inside the waveguide structure leaks energy, the complex propagation wavenumber of the guided field is expressed by leakage constant \( \alpha \) and propagation constant \( \beta \). The frequency dependent propagation constant \( \beta(\omega) \) mainly dictates the beam-scanning angles and \( \alpha \) shapes the amplitude distribution of the antenna. The primary requirement in designing a leaky-wave antenna is therefore to ensure the waveguiding structure is operated in the fast-wave region (\( \beta / k_0 < 1 \)). To support wave propagation away from the interface, the antenna has to operate in the fast-wave regime where \( b(\omega) < k_0 \). The term “fast wave” describes the faster phase velocity of the wave traveling down the propagating direction (z-direction) relative to that of the speed of light: The main beam angle \( \theta \) of the leaky-wave antenna operating under the fast-wave condition is determined by the ratio between \( \beta(\omega) \) and \( k_0 \).

The measurements and parameters used in designing of the unit cell are given in the table 1.

| Boundary | Length (in mm) |
|----------|----------------|
| a        | 2              |
| b        | 6.4            |
| c        | 13             |
| d        | 3              |
| e        | 1              |
| f        | 5              |
| g        | 3.45           |
| h        | 0.45           |
| i        | 0.6            |
| j        | 29             |
| k        | 12             |
To improve the gain and efficiency of the designed unit cell we have created the array of four-unit cells of C-shaped SIW-LWA. To obtain the impedance matching of LWA a tapered feed line is attached at the both end of array. Figure 1(b) shows the perspective view and figure 1(c) shows the top view of array of C-shaped slot based SIW-LWA.

|   |   |
|---|---|
| L | 68 |
| l | 52 |
| t | 5  |
| s | 8  |

Material used: Rogers RT6010LM (lossy)
Figure 1. C-shaped slot based SIW-LWA. (a) Unit cell and (b) array of 4-unit cells (perspective view) (c) array of 4-unit cells (top view)

There are two software used for the simulation of this antenna. First is HFSS (high frequency structure simulator) which is used for calculating the dispersion diagram, and second software is CST MICROWAVE STUDIO which is used for calculating gain and efficiency of the antenna.

3. Results

3.1. Dispersion diagram

A layout of frequency map prefer as function of the phase constant beta $\beta$ is known as dispersion diagram. The reflection of the unit cell composing the planar periodic layout of the antenna was acquired utilizing the Eigen mode solver of the CST Microwave Studio environment. The acquired dispersion diagram of the unit cell of a proposed antenna is introduced in Fig. 2.

From the dispersion diagram, it discovered undoubtedly that the phase constant exchanges its value from backward to forward direction as frequency rise with transition at 14 GHz.

Figure 2. Dispersion graph
The dispersion diagram of unit cell of C-shaped slotted SIW-LWA is introduced in figure with in the range of 13.2 to 15.5 GHz. It talks about the frequency range over which antenna works in leaky mode i.e., leaks the power and scans from continuous backward to forward direction.

The above graph shows that the broad side radiation will be at 14 GHz. Below 14 GHz the antenna works as a LH material and scans negative angles and above 14 GHz antenna works as RH material and scans positive angle.

3.2. S-Parameters

Let’s discuss about the s – parameter of the periodic C-shaped slot SIW-LWA. We achieved excellence graph of the s – parameter of the periodic C-shaped slot SIW-LWA. As we can see graph given below which shows S11 and S21.

![Figure 3. S-parameters](image)

Fig 3 guides the S-parameters of the SIW LWA filled with C-slot. As it is notice that there is a contract between replicated and calculated values. There is slight change because of little modelling errors. The calculated scattering parameter S11 stays beneath -10dB level and S21 remains above -10dB within the scanning range.

As we can see in graph that the bandwidth we find from 13.2 GHz as its S11 is below -10 dB and at the same point S21 is above -10 dB (around -7 dB). Below -10 dB shows continuous wave till 15 GHz. This means not less than 90% input power is provided to device and reflected power is less than 10% which is applicable in any application.

3.3. Gain

Gain specifics how powerful signal a given antenna can transmit or receive in a particular direction. It is computed by collating the calculating power send or receive by the proposed antenna in a particular direction to the power send or receive by a hypothetical imaginary antenna in the identical circumstances. It has better parameters than directivity, like it utilizes significance all the losses.
\[ G = D \times E \]

Scientifically, the product of directivity (D) and efficiency (E) gives Gain (G). Where D is the calculated the attentiveness of an antenna’s radiation layout in a specific direction and efficiency significance for the losses of the antenna because of fabricating defects, surface coating irregularities, dielectric, resistance, VSWR, or any other factor.

![Gain graph](image)

**Figure 4.** Gain

Figure 4 guides the gain of the array of C-shaped slotted SIW-LWA. The maximum gain attained by the antenna is 5.733dB. Since there is some variation but still we can see that gain is increasing.

### 3.4. Efficiency

The ratio of power radiated (Prad) by the given antenna to the power supplied (Ps) to the given antenna is called as efficiency (E). The efficiency of proposed antenna is generally calculated in a unreverberant chamber here antenna is support with some power and the strength of the radiated electromagnetic field in nearby space is calculated.

100% efficiency is given by an ideal antenna i.e., it sends all the power fed to it. However in the reality, only 50 to 60% of power supplied is radiated by a good antenna.

\[
\text{Antenna Efficiency} = \frac{P_{\text{rad}}}{P_t} \%
\]

Figure 5 guides the efficiency of the array of C-shaped slotted SIW-LWA.
Since gain is better as it seems previously. Also, directivity is achieved better. This makes it achieved better efficiency almost 77.545% which is pretty good. No matter there is variation but peak value of efficiency of the periodic C-shaped slot SIW-LWA is better.

3.5. Beam Scanning

By changing the phase of the input signal on all radiating elements helps in achieving beam steering. Phase shifting enables the signal to be chose at a particular receiver. To steer a single beam in a particular direction an antenna needs employ radiating elements with a common frequency.

Figure 6 - 11 guides the Beam steering of the array of C-shaped slotted SIW-LWA. The beam steering of periodic C-shaped slot SIW-LWA is achieved from -60 degree to 29 degree when the frequency explores from 13.2 GHz to 15.5 GHz. Here we discussed few beam scanning of antenna.

3.5.1 At 13.2 GHz
Here we see that the beam starts from backward. As steering starts from -60 degree at 13.2 GHz.

3.5.2 At 13.8 GHz

![Figure 7. At 13.8 GHz](image)

Now, we see that beam steering move a little forward. Beam steering stops on -39 degree at 13.8 GHz.

3.5.3 At 14 GHz

![Figure 8. At 14 GHz](image)

Now, we move further and here we see that beam steering move a little forward. Now, steering stops on -31 degree at 14 GHz.
3.5.4 At 14.2 GHz

![Figure 9. At 14.2 GHz](image)

Now, we move further and here we see that beam steering move forward. This time beam steering stops in positive. Now, beam steering stops on 1 degree at 14.2 GHz.

3.5.5 At 15 GHz

![Figure 10. At 15 GHz](image)

Now, we move further and here we see that beam steering move a more positive. Now, steering stops on 9 degree at 15 GHz.
3.5.6 At 15.5 GHz

![Figure 11. At 15.5 GHz](image)

Now, we move further and reached at last bandwidth. Here we see that beam steering become a more positive. Now, beam steering stops on 29 degree at 15.5 GHz.

4. Comparison

Table 2 guided the contrast of the proposed antenna with SIW-LWA. The proposed antenna guides preferable outcomes on the subject of bandwidth, gain, efficiency and beam steering.

| S. No. | Paper | Antenna Type | Size of Antenna (L*W) | Operating Frequency Range(GHz) | Calculated Gain | Maximum Efficiency (%) | Beam Steering |
|--------|-------|--------------|-----------------------|-------------------------------|-----------------|------------------------|---------------|
| 1.     | [3]   | HW-MLWA      | 247*50                | 5.05 - 6.32, 8.77-10.28, 12.63-14.13 | 2.5 dB, 3.4 dB, 3.1 dB | 61.33                 | 30 to 64, -75 to -18, -19 to -4 |
| 2.     | [4]   | HM SIW       | 188*7.5               | 15 – 21                       | 15.9 dBi        | 68                    | -55 to -10    |
| 3.     | [15]  | Rigid SIW Horn | 121.3*56             | 6.6-18                        | 2.5 dB          | 71                    | No            |
| 4.     | This work | SIW-LWA     | 68*12                 | 13.2 – 15.5                   | 5.733 dB        | 77.545                | -60 to 29     |

5. Conclusion

The periodic C-shaped slot SIW-LWA has been demonstrated with forward as well as backward beam scanning along with good efficiency. The periodic C-shaped slot SIW-LWA has ability for many candidates to use as application where beam scanning is required. The periodic C-shaped slot SIW-LWA are very useful in radio system, radar system, communication, digital signal processing technology, optical systems, 5G technology. Also, the periodic C-shaped slot SIW-LWA has ability for many candidate to use as application where beam scanning is required.
The periodic C-shaped slot SIW-LWA is simulated at 13.2 to 15.5 GHz. The peak value of gain of the periodic C-shaped slot SIW-LWA is 5.733 dB. The peak value of efficiency of the periodic C-shaped slot SIW-LWA has 77.545%. To improve gain and efficiency just simply increasing unit cells. Beam steering of the periodic C-shaped slot SIW-LWA is calculated from -60 degree to 29 degree.

6. References

[1] David R. Jackson, “Recent advances in leaky-wave antennas”, in Proc. 2013 Int. Symp. Electromagnetic Theory, pp 9-12.

[2] Yunjie Geng and Junhong Wang, “A Novel Double-Layer Leaky-Wave Antenna Array for Radiation Efficiency Improvement Based on Substrate Integrated Waveguide”, 2017 Proc. IEEE, pp 837–838.

[3] Debabrata K. Karmokar, Y. Jay Guo, Pei-Yuan Qin, Karu P. Esselle, and Trevor S. Bird, “Forward and Backward Beam Scanning Tri-Band Leaky-Wave Antenna”, IEEE Antennas and Wireless Propagation lett. , 2017, pp 1-5, doi: 10.1109/LAWP.2017.2685439.

[4] Xin Gu, Leilei Liu, Jian Wang and Jianing Cai, “A space Harmonic Leaky-Wave Antenna based on Half Mode Substrate Integrated Waveguide”, IEEE, 2018.

[5] Ratnesh Ranjan and Jayanta Ghosh, “SIW Based Leaky-Wave Antenna Supporting Wide Range of Beam Scanning through Broadsides”, IEEE Trans. Antennas and Propagation, 2019, doi: 10.1109/LAWP.2019.2897836.

[6] Aparna Vashishtha, Akriti Yadav and Dhruv Chaudhary “A Review of 1-Dimensional and 2-Dimensional Leaky Wave Antenna and Recent Advancements in LWAS”, Int. J. of Computer Applications (0975 – 8887), vol. 155, no. 9, pp 7-12, Dec. 2016.

[7] M. K. Mohsen, M.S.M. Isa, A.A.M. Isa , M.S.I.M.Zin, S.Saat, Z.Zakaria, I.M.Ibrahim, M.Abu, A.Ahmad and M.K. Abdulhameed, “The Fundamental of Leaky Wave Antenna”, J. Telecommun. , Electron. And Comput. Eng. , vol. 10, no. 1, pp 119-127, 31 Jan 2018.

[8] Miguel Poveda-Garcia, David Cañete-Rebenaque, George Goussetis, and José Luis Gómez-Tornero, “Coupling Substrate-Integrated Waveguides to Increase the Gain Bandwidth of Leaky-Wave Antennas”, IEEE Trans. Microw. Theory and Techn. , 2018.

[9] Yujian Li and Junhong Wang, “Dual-Band Leaky-wave Antenna Based on Dual-Mode Composite Microstrip Line for Microwave and Millimetre-Wave Applications”, IEEE Trans. Antennas and Propagation, 2018, doi: 10.1109/TAP.2018.2800705.

[10] M. Bozzi, A. Georgiadis, and K. Wu, “Review of substrate-integrated waveguide circuits and antennas,” Microwaves, Antennas Propagation, IET, vol. 5, no. 8, pp 909–920, 2011.

[11] Kumar, Arvind and Singaravelu, Raghavan, “A Review: Substrate Integrated Waveguide Antennas and Arrays” 2016 8.

[12] C. Caloz, T. Itoh, and A. Rennings, “CRLH metamaterial leaky-wave and resonant antennas,” IEEE Antennas Propag. Mag., vol. 50, no. 5, pp 25–39, 2008.

[13] F. Nazarzadeh, Mohammad H. Neshati, and Seyed. M.S. Majedi, “Leaky Wave Antenna Based on Quasi-TEM Mode of Substrate Integrated Waveguide”, Presented at the 2015 23rd Iranian Conf. on Electrical Eng. (ICEE), pp 493-496.

[14] Enrico Massoni, Maurizio Bozzi and Ke Wu, “Increasing Efficiency of Leaky-Wave Antenna by Using Substrate Integrated Slab Waveguide”, IEEE Trans. Antennas and Propagation, 2019, doi: 10.1109/LAWP.2019.2924727.

[15] Y. Zhao, Z. Shen and W. Wu, “Wideband and low-profile H-plane ridged SIW horn antenna mounted on a large conducting plane,” IEEE Trans. Antennas Propag., vol. 62, no. 11, pp 5895–5900, Nov 2014.