Broadband CRLH Beam Scanning Leaky-Wave Antenna Designed on Dual-Layer SIW

Mohsen Niayesh [1] and Zahra Atlasbaf [2]

[1] Department of Electrical and Computer Engineering
University of Tehran, Iran
mohsenniayesh@ut.ac.ir

[2] Faculty of Electrical and Computer Engineering
University of Tarbiat modares, Iran
atlasbaf@modares.ac.ir

Abstract **─** This paper presents a broadband Composite Right/Left Handed (CRLH) leaky-wave antenna operating above the cutoff frequency based on the substrate integrated waveguide (SIW) is introduced. The proposed antenna consists of two dielectric layers, as the host of the structure, an interdigital capacitor radiation slot and a pair of twisted inductive post. The beam scanning capability of the leaky wave antennas will be achieved using CRLH, which allows radiation both in RH and LH regions. The design procedure begins with designing a unit-cell and evaluated with dispersion diagram. Based on the proposed unit-cell, the antenna structure consists of 10 units-cells, is developed at the X-band. The bandwidth of 66% has been obtained beside 105° of the beam steering angle both in the RH and LH regions, while the frequencies change from 6.5 GHz up to 9.5 GHz. The proposed antenna could be used in radar and imaging systems.

Index Terms **─** Beam scanning, Composite Right/Left Handed (CRLH), leaky-wave antenna, metamaterial, Substrate Integrated Waveguide (SIW).

I. INTRODUCTION

Many researchers have been interested in the concept of composite right left handed based antenna due to posing outstanding features beside the fabrication process in the comparison with other metamaterial structures introduced yet, which makes such structures more practical. By using CRLH, backward waves could be obtained based on its left hand properties [1]. Using the CRLH in the leaky-wave antennas, which are categorized in traveling wave antennas, could enhance the performance of these antennas including the beam steering capability [2], [3].

Many approaches are available to design balanced CRLH above the cutoff frequency and appropriate to be used as an antenna, but the most common way, is using the advantages of rectangular waveguide. Many researchers have been through the concept of CRLH based on the rectangular waveguide like [4-6]. Although these structures provide high power capability, but such structures are bulky and costly. Also, non-negligible losses will be imposed due to the nature of the waveguide. However, the proposed antenna in [4] could scan 76°, but since the proposed structure uses short stub to provide the negative permeability and consists of 20 unit-cells in rectangular waveguide structure, it becomes so massive, which makes it unable to be applicable structure.

With emerging the substrate integrated waveguide (SIW) technology, a new horizon in the microwave and antenna engineering has been evolved [7]. These structures synthesized on a planar dielectric with periodic arrays of metallic vias. This technology has desirable features such as low profile, low cost, and easily integrated with planar circuits maintaining the advantageous characteristics of conventional rectangular waveguide. Using the concept of substrate integrated waveguide (SIW) technique gives us the ability to overcome some of the limitations we are dealing with in the microwave and antenna engineering, such as high price and heavy constructed structure with waveguide technology, which is the reason why it becomes popular in recent years.

Leaky-wave antennas (LWA) uses traveling waves that radiates along a guiding structure in order to produce radiation. One of the features of LWA is the ability to beam scanning. With particular development in the recent years being directed toward planar LWAs, which have the advantage of being low profile an easy to fabricate, which has been facilitated with SIW technology.

In [8], benefiting from the concept of CRLH and

Submitted On: November 8, 2015
Accepted On: February 26, 2016

LWA, a prototype antenna is reported, which provides the bandwidth of 4.3 GHz with 15 unit-cells. Although a beam steering angle of 130° has been achieved during the frequency scan, but the radiation parameters, i.e., SLL has been dramatically changed, hence a poor performance for the practical application has been achieved.

In this paper the proposed antenna possesses the advantages of low-profile, low-cost and wideband, besides the radiation properties of the antenna will not affect the performance of the antenna. A comparison between the proposed structure with the most recent relevant aforementioned has been summarized in Table 1.

Table 1: Comparison between the reported antenna designs in literature and the proposed antenna

Ref.	Bandwidth (GHz)	Beam Scans (°)	Backward Radiation
[3]	2.9	76	No
[9]	-	40	No
[8]	4.2	130	Yes
This design	6	105	Yes

II. DESIGN PROCEDURE

A low profile antenna is proposed with a wide coverage at the X-band frequencies and also the ability to change the direction of the main lobe, which yields to have a beam scanning antenna. The proposed structure consists of three major sections, which are discussed more in details in the following. It is worthwhile to mention that the main lobe radiation angle of a leaky-wave antenna is straightforwardly determined by Equation (1). Due to the dispersion diagram of a CRLH leaky-wave antenna, such antenna theatrically could scan from the backfire (θ = -90) to endfire (θ = +90), and broadside radiation (θ = 0) is also possible and the stop band problem does not occur in such structure [10]. Figure 1 indicates the radiation angle of the main lobe when port 1 is excited and port two is terminated to the matched load which is the measurement scenario.

$$\theta(\omega) = \arcsin\left(\frac{\beta_0(\omega)}{k_0}\right). \tag{1}$$

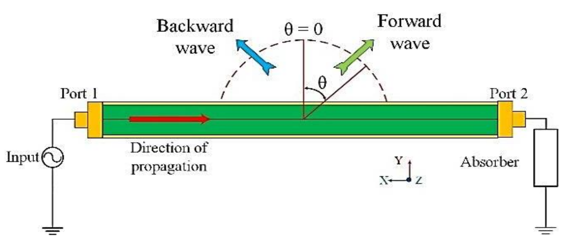

Fig. 1. The measurement, obtaining scenario for the radiation angle of the main lobe. Showing side view of the antenna including the SMA connectors.

A. SIW

In order to reduce the undesirable losses and miniaturizing the structure, the advantages of SIW technology are used in the proposed structure. The Equation (2) is used to calculate the width of the SIW [11]:

$$a_{SIW} = a_{eq} + \frac{d^2}{0.95h}. \tag{2}$$

In the Equation (2), a_{eq} is the equivalent waveguide width which is chosen as 12.13 mm with respect to the substrate of Rogers 4003c with ε_r = 3.55 and height of 0.813 mm for X-band, and d indicates the diameter of the metallic vias of the SIW. The SIW design parameters of the unit-cell with respect to Fig. 2 and Fig. 3, can be found in Table 2.

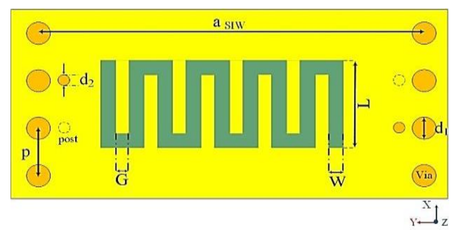

Fig. 2. Top view aspect of the proposed unit-cell structure.

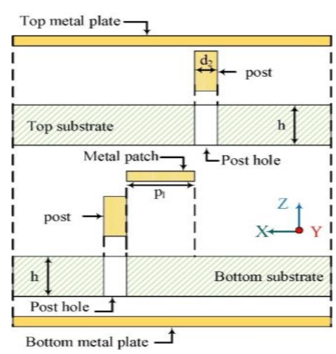

Fig. 3. Side view of the proposed unit-cell which shows the twisted post configuration.

Table 2: Design parameters of the proposed unit-cell

Quantity	Value (mm)	Description
a_{SIW}	12.736	Width of SIW
p	8.00	Adjacent via center-to-center space
d_1	0.80	Via diameter
d_2	0.50	Post diameter
Pl	0.80	Patch length
Pw	0.50	Patch width
L	3.00	IDC length
W	0.50	IDC width
G	0.50	Width of finger
h	0.813	Substrate high

B. Radiation slot

Since we are dealing with a leaky-wave antenna, and in this type of antennas the propagation occurs while the wave inside the structure travelling from the excited port to the terminated one, thus it is in need of some radiation aperture to form the leaked power. It should be noticed that the parameters of the interdigital capacitor (IDC) slots is not independent with the SIW host and the inductive posts. The schematic of the radiation slot with the design parameters are shown in Fig. 2. Using the IDC as radiation slots not only give us the controllability of the leaked power but also the balanced frequency. By increasing the length of the IDC slots (L), the provided capacitance was increased, thus the balanced frequency would be decreased. On the other hand, this capacitance decreases as the slot is widened, by increasing the W.

C. Post

Increasing the total inductance of the structure is a way to tackle the existence of band gap at the operational bandwidth of the antenna. In this way the balanced conditions will be satisfied in a higher frequency, so the left handed region will be extended. Using inductive elements to increase the inductance of the structure much more than what is provided by the nature of waveguide, is obtained with a twisted post which is realized with two metallic vias in the top and bottom substrate and are connected with each other using a metal patch etched to the top surface of the bottom substrate. Figure 3 illustrates the metallic posts and the metal patch in order to obtain the twisted post. It should be noticed that in Fig. 3 the side wall vias of the SIW are not shown for the better view of the post.

The equivalent circuit model for the proposed unit-cell could be found at Fig. 4. This circuit model consists of a series inductor (L_R) and shunt capacitor (C_R) which dictate the properties of the dielectric including the permeability and permittivity respectively. The right handed capacitor (C_R) which was used in conventional right handed circuits, is now parallel with the capacitance of the twisted post and forms a total capacitance of (C') as (3). The same procedure has been applied to the shunt inductance of the left handed inductor (L_L) and makes (L') as (4).

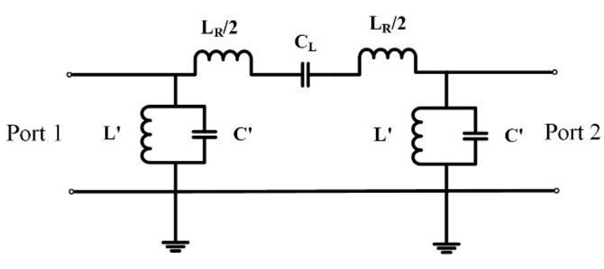

Fig. 4. Equivalent circuit model for the proposed unit-cell.

$$C' = \frac{C_R}{2} + \frac{C_P}{2} = \frac{C_R + C_P}{2}, \tag{3}$$

$$L' = \frac{L_L + L_P}{2 L_L L_P}. \tag{4}$$

III. SIMULATED AND MEASURED RESULTS

The proposed structure is simulated using finite element method in a full wave simulation, to obtain the dispersion diagram of the unit-cell and also the scattering parameters of the antenna.

The dispersion diagram of the proposed unit-cell calculated and depicted as Fig. 5. The balanced condition satisfied at 6.8 GHz. The band below this frequency would be named as the left handed area. Another band which is above the balanced frequency named as Right Handed (RH) band indicated in Fig. 5. Also the airline is separated the operating region into the two separate bands, which are radiating and guiding region. The region, above the airline is the radiation region, which is ideal for antenna applications. On the other hand, the region below the airline indicates the guiding region which is used for the guiding applications. Figure 5 clarifies that the proposed unit-cell is appropriate to the antenna application.

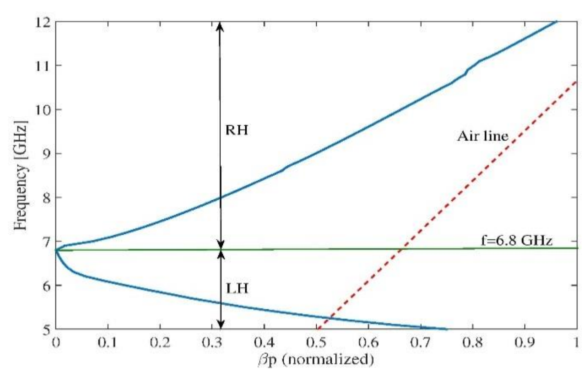

Fig. 5. Dispersion diagram of proposed the unit-cell.

Base on the unit-cell, which is discussed above, the antenna consists of 10 units-cells, is designed. The scattering parameters of the antenna are depicted in Fig. 6. Since the antenna is a leaky-wave antenna based on the mechanism of the operation, while the S_{11} is less than -10 dB and also the S_{21} is kept above -3 dB, are the ideal cases for operating the LWA. The proposed antenna provides 66% as the fractional bandwidth, based on the measurement data.

A wide variety of techniques are available to feed SIW structures, one of the popular and easiest way to design the feeding, is using the tapering transition from microstrip to SIW structure technique. Figure 7 shows the schematic of the designed tapering transition used in the proposed antenna. The dimensions used to design the tapering transition are as: l_1=5.1 mm, l_2=5 mm, w_1=7 mm, w_2=3 mm.

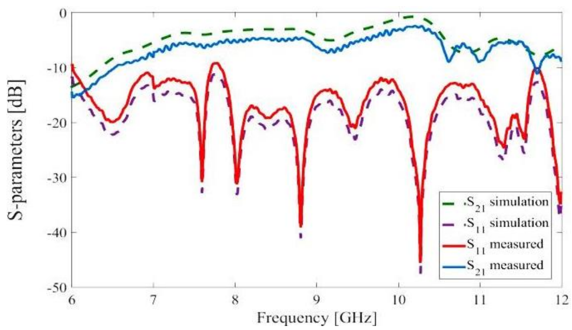

Fig. 6. Simulated and measured scattering parameters of the proposed antenna containing 10 unit-cells.

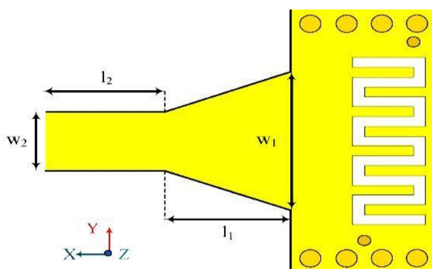

Fig. 7. Microstrip to SIW transition for feed the proposed antenna.

One of the dominant features of proposed antenna beside the wide coverage in the X-band frequency, is the ability to do the beam sweep while changing the operating frequency. The radiation pattern of the proposed antenna contains 10 unit-cells, for the simulation and measurement are depicted in Fig. 8 and Fig. 9 respectively. As it is observed, the proposed antenna can change the direction of the main lobe from -34° up to +72° angle including the broadside obtained from measurement.

On the other hand, other parameters of the antenna will be changed when the operating frequency changes and exactly this is where a tradeoff between bandwidth and the gain of the antenna should be taken into the account. The other parameters of the proposed antenna including the realized gain and side lobe level of the antenna at different frequencies could be found in Table 3. It is worthwhile to mention that another feature of the proposed structure which made it distinguishable from other similar works is the low sensitivity of the radiation parameters with respect to changing the operating frequency, that they are not affected, as it is obvious in Table 3.

The antenna is fabricated using the substrate of Rogers 4003c with ε_r = 3.55 and height of 0.813 mm. The total physical dimension of the antenna is 100.2 mm×13.53 mm×1.69 mm. The fabricated antenna can be found in Fig. 10.

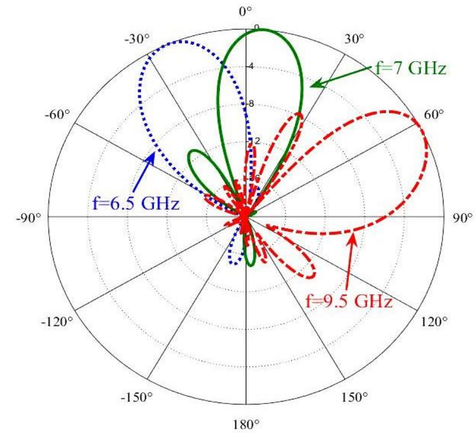

Fig. 8. The Simulated normalized radiation pattern.

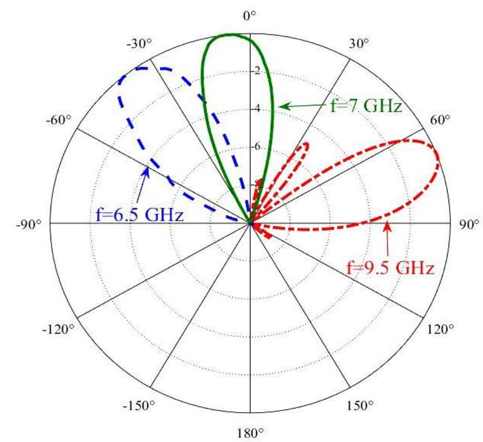

Fig. 9. Normalized radiation pattern. The radiation pattern is measured at the frequencies 6.5, 7, 9.5 GHz.

Table 3: The obtained CRLH LWA antenna radiation properties

Quantity/Freq. (GHz)	6.5	7	8	9	9.5
Simulated Gain (dB)	14.37	15.47	10.1	13.15	12.41
Measured Gain (dB)	14.18	15.28	9.95	12.72	11.18
Simulated SLL (dB)	-12.1	-13.5	-10	-11	-6.1
Measured SLL (dB)	-10.26	-11.41	-8	-9.15	-5.5
Simulated HPBW (°)	28	25.9	25.11	24.6	26.3
Measured HPBW (°)	31.79	28.2	27	26.8	28.2

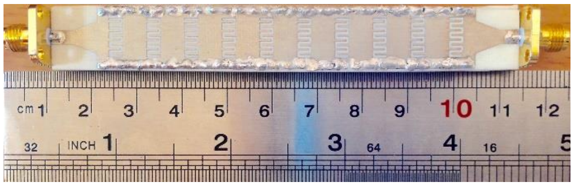

Fig. 10. Fabricated CRLH leaky-wave antenna based on SIW containing 10-unit-cells.

IV. CONCLUSION

A CRLH leaky-wave benefiting from the SIW technology, which operates above the cutoff frequency was presented. The proposed unit-cell for the antenna consists of two inductive twisted posts and an interdigital capacitor (IDC) radiation slot. The unit-cell has been evaluated with the dispersion diagram and then a 10 unit-cell antenna has been designed. The antenna has the ability to change the direction of its' main lobe continuously from -34° up to +72° besides obtaining the bandwidth of 66% according to the measurement, and there is a decent agreement between the simulation and measured results.

REFERENCES

[1] A. Grbic and G. V Eleftheriades, "Experimental verification of backward-wave radiation from a negative refractive index metamaterial," *J. Appl. Phys.*, vol. 92, no. 10, 2002.

[2] C. Caloz and T. Itoh, *Electromagnic Metamaterials: Transmission Line Theory and Microwave, The Engineering Approach*., Wiley-IEEE Press, 2005.

[3] K. Hosseini and Z. Atlasbaf, "Analysis and synthesis of singly-curved microstrip structures utilizing modified Schwarz-Christoffel transformation," *IEEE Trans. Antennas Propag*., vol. 61, no. 12, pp. 5940-5947, 2013.

[4] D.-J. Kim and J.-H. Lee, "Beam scanning leaky-wave slot antenna using balanced CRLH waveguide operating above the cutoff frequency," *IEEE Trans. Antenna Propag.*, vol. 61, no. 5, pp. 2432-2440, 2013.

[5] D.-J. Kim and J.-H. Lee, "Broadband left-handed rectangular waveguide using a shorted stub and twisted E-plane posts," *Microw. Opt. Technol. Lett.*, vol. 55, no. 4, pp. 835-840, 2013.

[6] T. Ikeda, K. Sakakibara, T. Matsui, N. Kikuma, and H. Hirayama, "Beam-scanning performance of leaky-wave slot-array antenna on variable stub-loaded left-handed waveguide," *Antennas Propagation, IEEE Trans.*, vol. 56, no. 12, pp. 3611-3618, 2008.

[7] D. Deslandes and W. Ke, "Integrated microstrip and rectangular waveguide in planar form," *Microw. Wirel. Components Lett. IEEE*, vol. 11, no. 2, pp. 68-70, 2001.

[8] D. Yuandan and T. Itoh, "Composite right/left-handed substrate integrated waveguide and half mode substrate integrated waveguide leaky-wave structures," *Antennas Propagation, IEEE Trans.*, vol. 59, no. 3, pp. 767-775, 2011.

[9] J. Tanabe, "Dual-band Composite Right/Left Hand Substrate Integrated Waveguide Leaky Wave Antenna Phased Array Design," *Ph.D.*, UCLA: Electrical Engineering, 2013.

[10] D. Yuandan and T. Itoh, "Substrate integrated composite right-/left-handed leaky-wave structure for polarization-flexible antenna application," *Antennas Propagation, IEEE Trans.*, vol. 60, no. 2, pp. 760-771, 2012.

[11] D. Deslandes and W. Ke, "Design consideration and performance analysis of substrate integrated waveguide components," in *Microwave Conference, 2002, 32nd European*, pp. 1-4, 2002.

Mohsen Niayesh was born in Tehran, Iran in Jan. 1989. He received the Bachelor's degree in Electrical Engineering specialized in Communication Engineering from the Islamic Azad University, Tehran, Iran in May 2012 and the Master's degree in Electrical Engineering major in Communication Engineering from the University of Tehran, Tehran, Iran, in Feb. 2015.

His main areas of interest in research are Metamaterial, Microstrip antenna, Radio wave propagation, Radar, On-body communication, Microwave circuits and Mobile communication.

Since early 2014 he has been with the University of Tehran as Research Assistance.

Zahra Atlasbaf (M'08) received the B.S. degree in Electrical Engineering from the University of Tehran, Tehran, Iran, in 1993, and the M.S. and Ph.D. degrees in Electrical Engineering from the University of Tarbiat Modares, Tehran, Iran, in 1996 and 2002, respectively.

She is currently an Associate Professor with the Faculty of Electrical and Computer Engineering, Tarbiat Modares University. Her research interests include numerical methods in electromagnetics, theory and applications of metamaterials, radar, mobile communications, microwave and antenna design.