Composite Right/Left-Handed Substrate Integrated Waveguide Leaky-Wave Sparse Array Antenna With Low Sidelobe Level

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***Abstract*—As the frequency response of the CRLH antenna array is sensitive to parameters of every unit cell, changing parameters of each element to realize a tapered distribution array and low sidelobe level (SLL) performance will be difficult. In this paper, sparse array synthesis theory is applied to optimize composite right/left handed (CRLH) substrate integrated waveguide (SIW) leaky-wave antenna (LWA) to achieve low SLL. With the sparse array synthesis method, the low SLL can be achieved without amplitude and phase weighted. And all antenna elements are all the same except cell spacing. A 15-unit-cell CRLH SIW leaky-wave sparse array antenna in KU-band with low SLL is designed and simulated as an example. The SLLs are approximately -15dB in the left handed region while below -16dB in the right handed region corresponding to the scanning angle from -3.6° to 7.6°.**

Keywords—Composite right/left handed (CRLH) ; leaky-wave antenna (LWA) ; substrate integrated waveguide (SIW) ; sidelobe level (SLL) ; sparse array

I. Introduction

Composite right/left-handed (CRLH) metamaterials have demonstrated unique and advantageous features when employed in microwave and millimeter-wave circuits and systems[1]-[4]. Permittivity and permeability of left handed (LH) material are both negative. LH material has specific electromagnetic properties which is relative to right handed (RH) material, such as negative refraction, evanescent wave amplification effect, inverse Doppler effect, inverse Cerenkov radiation effect, perfect lens effect and so on[5]. Because of these special properties, LH material is widely applied in communication especial in antenna design. Antenna designed with LH material can realize negative angle scanning. There are two types of structure to realize LH properties, metal resonance structures and unresonance structures. Smith construction composed of rod and SRR is the most typical structure of metal resonance structure while CRLH transmission line composed of interdigital capacitor and vias is the most typical structure of unresonance structure[6].

In [7], an interdigital capacitor structure that presents CRLH properties is proposed in X-band. The SIW LWA composed of this unit cell can realize backfire-to-endfire wide angle beam-scanning performance. For the low SLL CRLH LWA, investigations of the weighting amplitude array have been presented in [8] and [9]. In [8], an 8 cell SIW LWA was designed and fabricated. The middle two unit cells were widened to realize low SLL. Comparing with the conventional antenna, the proposed tapered antenna shows -15.02 (LH region) and -14.37dB (RH region) SLLs. In [9], another structure composed of 12 tapered microstrip interdigital unit cells was proposed. For this structure, it realized -20.6dB SLL at center frequency. As tapering radiation of the unit cell will lead to the change of RH and LH regions, frequency response of each unit cell will be different. To keep a balanced frequency response, other parameters of each cell should be optimized, which is a complicated work.

Sparse array synthesis theory has been researched for decades. According to [10], sparse linear array is a linear array whose cell spacings are needed to be optimized based on the optimization criterion. Using the sparse array synthesis theory, it can achieve low SLL without amplitude and phase weighted.

In this paper, the sparse array method has been investigated to achieve the CRLH antenna's low SLL. CRLH SIW sparse LWA has been given as an example. In this antenna array, elements are all the same except element spacing. With this arrangement of elements, the low SLL performance has been achieved.

II. Theory of CRLH Transmission Line and Sparse Array

A. CRLH Transmission Line

The CRLH transmission line represents a transmission line having both LH and RH region. Basically, each unit cell in this periodic structure consists of LH shunt inductance (L_L) and LH series capacitance (C_L) as well as parasitic RH series inductance (L_R) and RH shunt capacitance (C_R). In Fig.1, it displays the structure of one unit cell of CRLH SIW LWA. The corresponding equivalent circuit is given in Fig.2. The dispersion relation of the CRLH-TL based on the equivalent

This work was supported by the National Natural Science Foundation Project (61301024) the Foundation of NJUST under the Grant XKF09010, the postdoctoral science foundation of China and the postdoctoral science foundation of Jiangsu province.

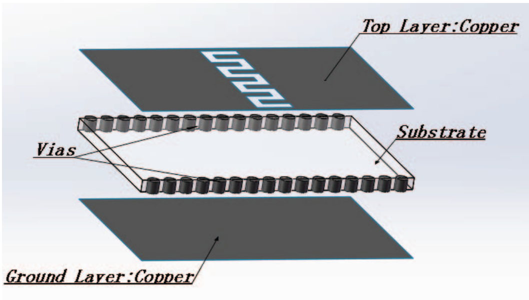


Fig.1 Structure of one unit cell of CRLH SIW LWA.

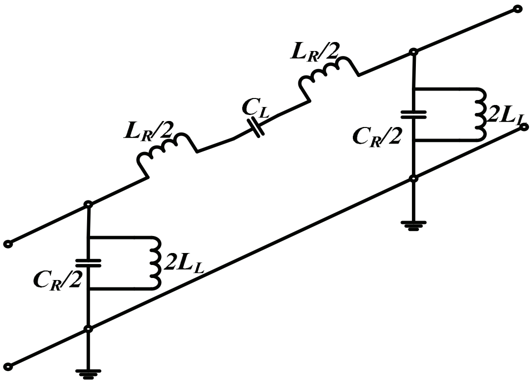


Fig.2 Equivalent circuit model for CRLH SIW unit cells.

circuit of one unit cell can be calculated from S parameters [11][12].

$$\beta d = \cos^{-1}\left(\frac{1 - S_{11}S_{21} + S_{12}S_{21}}{2S_{21}}\right) \quad (1)$$

The dispersion curve can be broken down into three regions, respectively are RH region ($\beta>0$), bandgap region ($\beta=0$) and LH region ($\beta<0$) [13]. Notice that these three regions are bounded by the following four frequencies.

The series resonant frequency $f_{se} = \dfrac{1}{2\pi\sqrt{L_R C_L}}$,

The shunt resonant frequency $f_{sh} = \dfrac{1}{2\pi\sqrt{L_L C_R}}$,

The RH region cutoff frequency $f^{c}{}_{RH} = \dfrac{1}{\pi\sqrt{L_R C_R}}$,

The LH region cutoff frequency $f^{c}{}_{LH} = \dfrac{1}{4\pi\sqrt{L_L C_L}}$.

There is no bandgap region only if $f_o = f_{se} = f_{sh}$ so that a seamless transition from the LH to the RH region [14]. f_o is the transition frequency. For the frequency above f_o, LC series circuit presents inductive character while LC parallel circuit presents capacitive character, the unit cell presents RH properties. On the contrary, the unit cell presents LH properties in the frequency below f_o.

B. Sparse Array

Sparse array synthesis based on genetic algorithm (GA) to lower SLL has been widely used. From the previous work, sparse array can realize low SLL without amplitude and phase weighted [10]. There are two ways to optimize sparse antenna array. One is to constrain the minimum and maximum element spacing. The beamwidth is not certain as the aperture of the array is not decided. Another way is to constrain the aperture of array and the minimum element spacing. The beamwidth is certain with the given aperture [15][16]. In this paper, the second constraint condition has been used to optimize the CRLH SIW LWA.

For element location synthesis of sparse array with the design constraint of minimum element spacing, an improved genetic algorithm (IGA) [17] has been presented to define the element location. The steps of IGA is shown in Fig.3. This method can effectively achieve low SLL with the adjustable minimum element spacing on the condition of given array aperture and element number.

III. DESIGN OF CRLH SIW LOW SIDELOBE LEVEL LEAKY-WAVE ANTENNA

A. Design of Unit Cell

In Fig.1, it shows the configurations of one CRLH SIW element. The prototype is built on the substrate of Rogers 5880 with a permittivity of 2.2, a loss tangent of 0.001 and a thickness of 0.508 mm. The vias used in the models share a common diameter of 0.5 mm and a center-to-center spacing around 0.73 mm. The key sizes of the unit cell are displayed in Fig.4 and Table 1. In Fig.5, it plots the dispersion curve of the balanced unit cell used in sparse array. The transition frequency f_o is 16GHz.

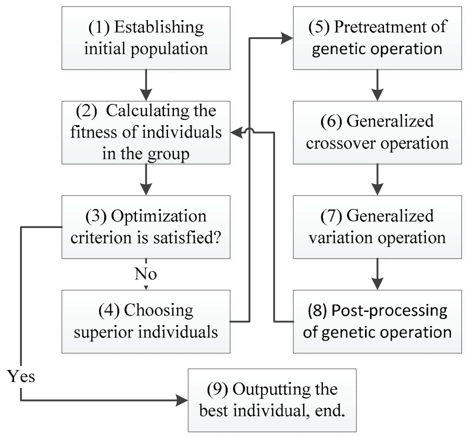


Fig.3 The steps of improved genetic algorithm(IGA)

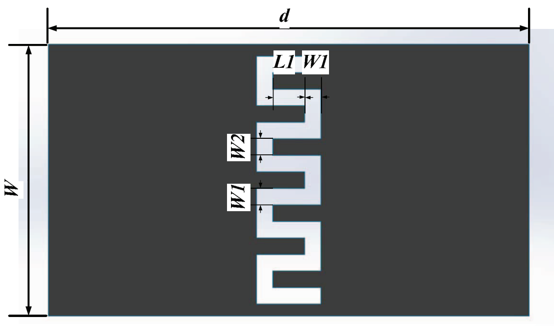


Fig.4 Detailed configuration of one unit cell

TABLE I. Key sizes of the unit cell

Parameter	*Size(mm)*
W	6.50
d	7.20
W1	0.40
W2	0.39
L1	0.63

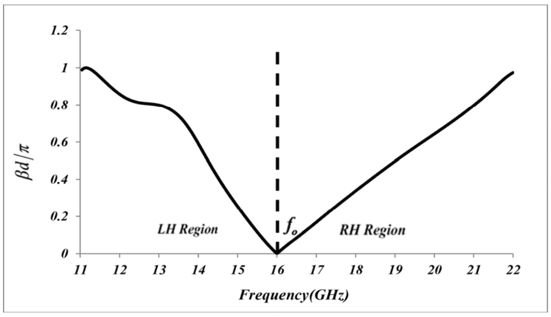


Fig.5 Dispersion curve of the unit cell used in CRLH LWA

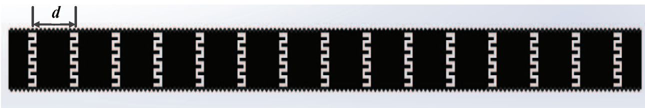


Fig.6 Configuration of the proposed CRLH SIW conventional array leaky-wave structure.

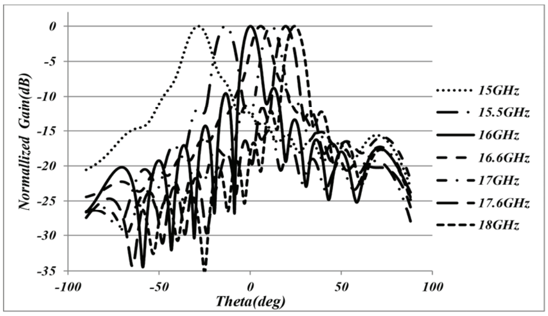


Fig.7 The simulated 2-D radiation patterns of conventional array at different frequencies

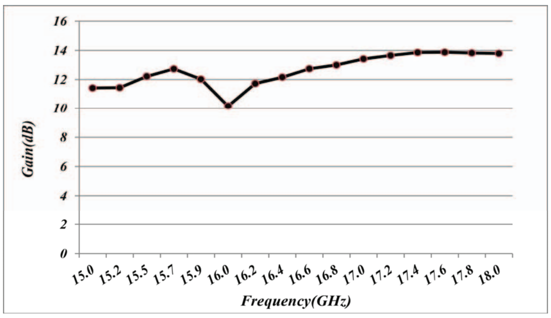


Fig.8 The simulated antenna gains of conventional array at different frequencies

B. Conventional Antenna Array

In Fig.6, it shows the configuration of conventional CRLH array antenna. The array is composed of 15 designed unit cells and element spacings are all the same. The element spacing is *d*=7.2mm. The simulated 2-D radiation patterns at different frequencies are displayed in Fig.7 and the antenna gain is given in Fig.8. It is seen that this antenna realized wide-angle scanning performance in 15GHz~18GHz. There exists a slight decrease of gain in the transition frequency. However, for the conventional array, the SLL performance is unsatisfactory.

C. Sparse Array Antenna with Low Sidelobe Level

To realize low SLL, the spacings between each two adjacent elements are optimized with sparse array theory. Firstly, the constraint conditions including number of elements, minimum element spacing and array aperture are given. Then IGA is applied to optimize the unit distribution under these constraint conditions. The initial population is 200, crossover probability is 0.5, mutation probability is 0.01 and the maximum generation is 300.

In Fig.9, it shows the configuration of sparse array. Taking the center of the first element as origin, the specific positions of each element are displayed in Table 2. The full-wave simulation is performed using the CST Microwave studio.

In Fig.10, it shows the simulated S-parameters of this leaky-wave antenna. The simulated 2-D radiation patterns at different frequencies are given in Fig.11. In Fig.12, it shows the simulated antenna gain of sparse array. It is seen that, when the frequency is increased, the main beam direction moves from the backfire towards the endfire direction. But most importantly, the sparse array antenna realized a low SLL. The SLL is approximately -15dB in LH region while below -16dB in RH region in the frequency span of 15.9GHz~16.7GHz corresponding to the scanning angle from -3.6° to 7.6°. Compared with conventional CRLH SIW array, the application of sparse array to lower SLL is effectual. However, the SLL performance is unsatisfactory at the wide scanning angle region as shown in Fig.11 (b). It should be investigated further.

Fig.9 Configuration of the proposed CRLH SIW sparse array leaky-wave structure.

TABLE II. Positions of each element

NO.	*Position(mm)*	*NO.*	*Position(mm)*
1	0.0	9	50.9
2	8.2	10	56.4
3	16.2	11	62.8
4	23.6	12	68.8
5	29.0	13	75.7
6	34.6	14	85.8
7	40.0	15	100.8
8	45.4		

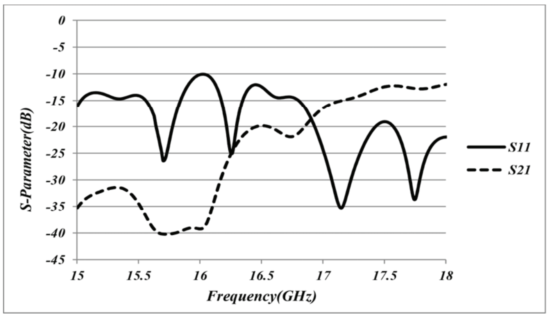
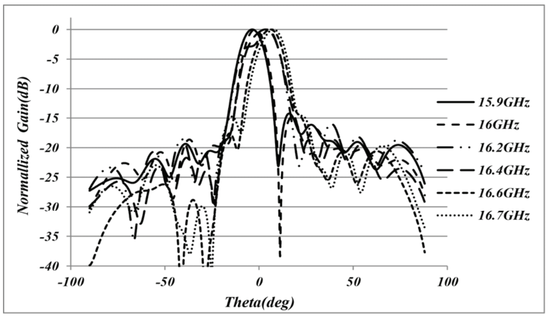
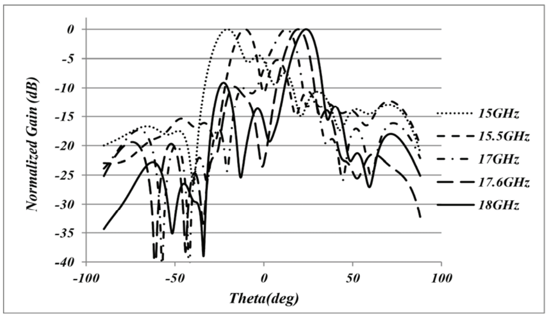


Fig.10 The simulated S-parameters of proposed sparse array antenna.



(a)



(b)

Fig.11 The simulated 2-D radiation patterns of saprse array at different frequencies

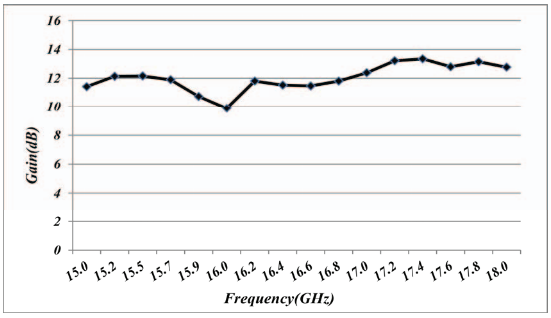


Fig.12 The simulated antenna gains of sparse array at different frequencies

IV. CONCLUSION

A CRLH SIW LWA sparse array antenna with low SLL has been presented. Using the sparse antenna synthesis method, it avoids weighting each element results in the balanced unit cells in RH and LH region. Element spacing is the only parameter that needs to be optimized. Comparison has been made between the conventional CRLH SIW LWA and the sparse one. The sparse array realized SLL below -15dB in the frequency span of 15.9GHz~16.7GHz where the scanning angle is from -3.6° to 7.6°. To optimize the SLL performance at the whole scanning angle should be investigated further.

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