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Composite Right/Left-Handed Substrate Integrated Waveguide Leaky-Wave Antennas

Yuan Dan Dong and Tatsuo Itoh

Department of Electrical Engineering, University of California, Los Angeles
405 Hilgard Avenue, Los Angeles, CA 90095, USA

yddong@ee.ucla.edu
itoh@ee.ucla.edu

Abstract **— Leaky-wave antennas based on composite right/left-handed (CRLH) substrate integrated waveguide (SIW) are investigated and presented in this paper. By introducing series interdigital capacitors, which are realized by etching slots on the waveguide surface, a balanced CRLH waveguide leaky-wave antenna with a continuous beam-steering capability has been implemented. The backfire radiation is obtained when the waveguide is operated below its characteristic cutoff frequency while the broadside radiation is achieved at the balancing frequency point. By embedding the series interdigital capacitors in both the top surface and the ground of the SIW, a frequency-scanned leaky-wave antenna characterized by double-side radiation or a quasi-omnidirectional feature is achieved. The measured results show that the proposed antennas offer a scanning angle covering almost backfire-to-endfire directions with relatively high gains.**

Index Terms **— Composite right/left-handed (CRLH), substrate integrated waveguide (SIW), leaky-wave antennas**

I. INTRODUCTION

A leaky-wave antenna is a radiating transmission line (TL) structure, either in uniform or periodic configurations, which have been widely studied and found a variety of applications. They essentially offer a relatively high gain with a low profile of the structure. However, due to the nature of forward-wave propagating within the antenna structure, the conventional leaky-wave antennas suffer from major limitations in their scanning capability. Composite right/left-handed (CRLH) metamaterials, which support the backward-wave propagation, have paved the way for novel perspectives of leaky-wave antennas [1]. Since its ever introducing, various CRLH leaky-wave antennas based on different technologies have been investigated and implemented [2-6]. They all exhibit the beam-steering ability through the frequency scanning. Substrate integrated waveguide (SIW), which is synthesized on a planar substrate with linear periodic arrays of metallic vias using printed circuit board (PCB) technology, has provided a very attractive platform to design low-cost and highly integrated waveguide components. Substrate integrated waveguide leaky-wave antennas were discussed and investigated in [6-8]. A design with transverse slots etched on the waveguide surface which are bridged by metallic strips located in a plane slightly below the surface is adopted in [6] to achieve a CRLH structure. It requires a multi-layer PCB process and is rather complicated to realize. By increasing the period length between the vias or making use of the open side of the half mode SIW to achieve single-side edge-radiating, conventional leaky-wave antennas which are not CRLH types are also attainable as shown in [7], [8].

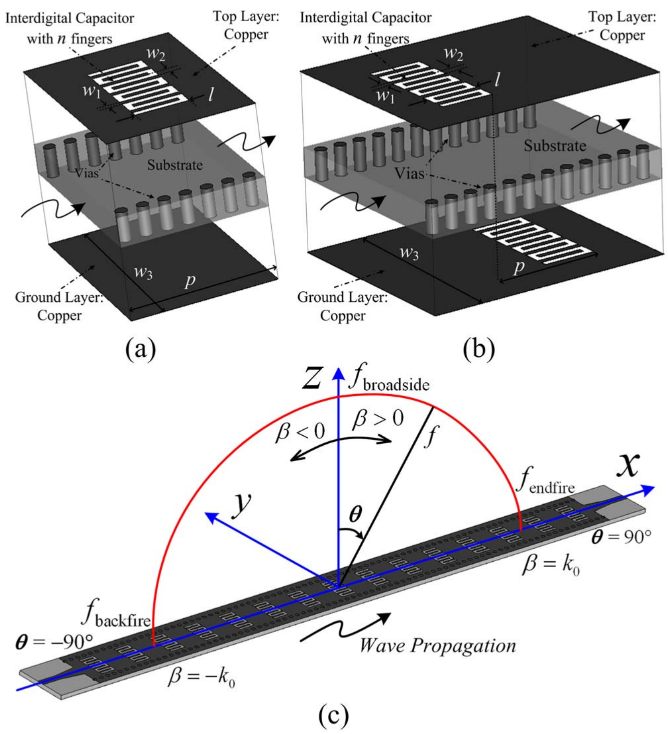

Fig. 1. Configuration of the proposed structures (a) Single-Side radiating element, (b) Double-Side radiating element and (c) Overall leaky-wave antenna prototype.

This paper presents two novel leaky-wave antennas based on the CRLH and SIW technologies. Compared with those previous designs, the antennas proposed here offer continuous beam-scanning performance as well as an extremely easy way for realization. The present designs also allow obtaining a relatively high gain with only a small number of unit cells. They are achieved simply by etching interdigital slots on the metal surface and the ground of the waveguide. It is known that waveguide has an inherent shunt inductance. The slots act like a series capacitor, which, along with the shunt inductance,

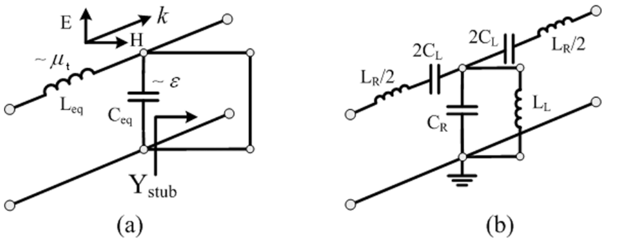

Fig. 2. Equivalent circuit models for (a) SIW TL unit cell and (b) CRLH SIW leaky-wave radiating element.

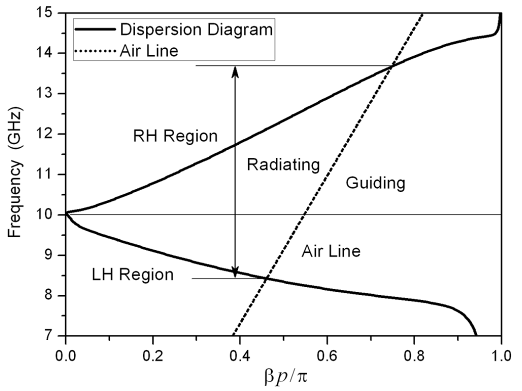

Fig. 3. Dispersion diagram of the CRLH SIW unit cell shown in Fig. 1(a). The parameter values are: $w_1 = 0.33$ mm, $w_2 = 0.45$ mm, $w_3 = 9.2$ mm, $n = 9$, $p = 8.2$ mm, $l = 3.3$ mm.

creates the necessary condition to support backward-wave radiation. Also, since the backward-wave propagation is operated below the waveguide cutoff, the antenna miniaturization is then achieved. Their dispersion relation and radiation mechanism are discussed. Their backfire-to-endfire beam scanning performance is confirmed by measuring and comparing the radiation patterns at different frequencies. We also give the transmission and antenna gain response, which are compared with the simulated results.

II. One Period Design of The CRLH-SIW Element

The CRLH-SIW leaky-wave antennas are designed at the X-band. Fig.1 (a) and (b) present the configurations of the one period element, while the prototype of the whole leaky-wave antenna with its orientations in the coordinate systems is illustrated in Fig. 1(c). For the first resonator as shown in Fig. 1(a), the slot is etched on the surface and it is grounded by a solid metallic plane. For the second resonator shown in Fig. 1(b), both the surface and the ground are embedded by interdigital slots with a period distance of p. All the structures are synthesized on the substrate of Rogers 5880 with a thickness of 0.508 mm and a relative permittivity of 2.2. And all the metallic via holes have a diameter of 0.8 mm and a center-to-center spacing around 1.6 mm.

Fig. 2(a) presents the equivalent circuit model for the original SIW unit cell without the slots, which is similar to the traditional rectangular waveguide. The metal surface and the ground can be modeled as a two-wire TL with distributed series inductance and distributed shunt capacitance which are associated with the permeability and permittivity of the substrate, respectively. It is important to bear in mind that the input impedance of a short circuited stub (via-walls) after a piece of TL appears as inductive. Compared with the standard circuit model of a CRLH structure only the series capacitance is absent and needs to be added. Fig. 2(b) depicts the circuit model of the unit cells shown in Fig. 1(a), which are symmetrical. The interdigital capacitor has been introduced into the model as C_L to form a CRLH structure. L_L represents the inductance generated by the via-walls. They make the left-handed (LH) contribution. Right-handed (RH) contribution comes from the distributed shunt capacitance C_R and the distributed series inductance L_R. Note that the series slot also plays the role of radiating element for the leaky-wave antenna. Increasing the width and the length of the slots will make the radiation more efficient. Also bear in mind that increasing the slot width leads to the decrease of C_L while increasing the slot length results in the rise of C_L. Thus enhancing the radiation does not conflict with achieving a balanced case (The balanced case is obtained when the relation $L_R \times C_L = L_L \times C_R$ is satisfied [1]).

Fig. 3 presents the dispersion curve for the CRLH SIW unit cell shown in Fig. 1(a) with the main parameter values shown in the caption. It is clearly seen that a balanced case is achieved with the balancing point located at about 10 GHz, which ensures a seamless transition from the LH to the RH band. The airline is also plotted which gives rise to the two distinct regions: the radiating region above the line and the guiding region below the airline.

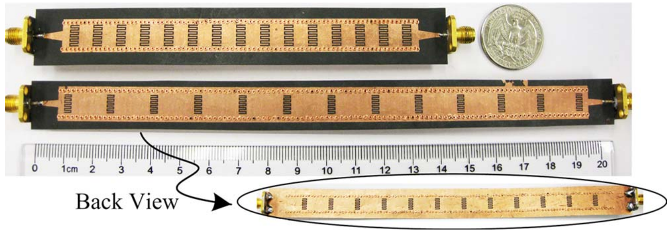

Fig. 4. Photograph of the two fabricated leaky-wave antennas.

III. Experiments

Here two CRLH SIW leaky-wave antennas are designed and fabricated using the substrate of Rogers 5880 with a thickness of 0.508 mm. The first leaky-wave antenna is one-side radiating while the second one is a double-side radiating antenna which is realized by etching slots on both the surface and the ground. Fig. 4 shows the photograph of the fabricated antennas. Their performance will be discussed in the following part of this section.

A. One-Side Radiating Leaky-Wave Antenna

The first antenna has 15 identical elementary cells. The dispersion relation and parameter values for the unit cell have

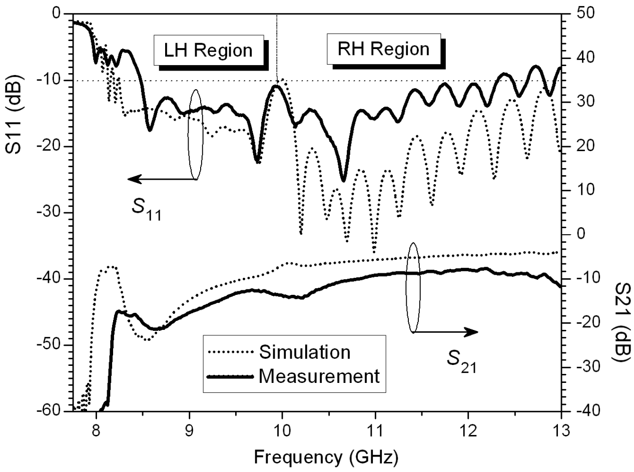

Fig. 5. Measured and simulated *S*-Parameters for the one-side radiating leaky-wave antenna.

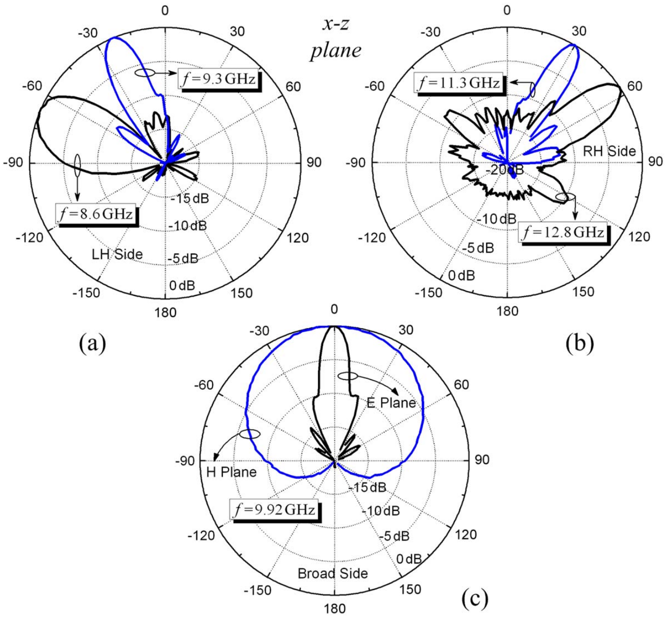

Fig. 6. Measured antenna radiation patterns (a) E-plane (*x*-*z* plane) in the LH region, (b) E-plane (*x*-*z* plane) in the RH region and (c) Broadside radiation patterns in the E-plane (*x*-*z* plane) and H-plane (*y*-*z* plane).

already been presented in the above section. Fig. 5 shows the measured and simulated *S*-parameters of this leaky-wave antenna, which show good consistency. A satisfactory return loss below -10 dB in the band of interest (from 8.5 GHz to more than 12 GHz) is achieved. The insertion loss is almost below -10 dB, which indicates good leakage radiation. The curve also shows that in the LH region, the radiation is more effective compared with radiation in the RH region.

Fig. 6 shows the normalized radiation patterns measured at different frequencies. The E-plane radiation patterns at 8.6 GHz and 9.3 GHz in the LH region is given by Fig. 6(a). We find that at 8.6 GHz the beam angle θ is about -70°, very close to backfire. Fig. 6(b) presents the E-plane radiation patterns in the RH region. It is found that at 12.8 GHz the beam angle θ switches to approximately 60°. Fig. 6(c) displays the measured broadside radiation patterns in the E-plane and H-plane. Fig. 7 shows antenna gain response. We find a discrepancy around 2 dB between the simulated and measured results, which is acceptable due to the extra loss in the measurement. The backfire-to-endfire beam-steering ability by the way of frequency scanning is confirmed with an average gain of approximately 10.5 dBi for this antenna.

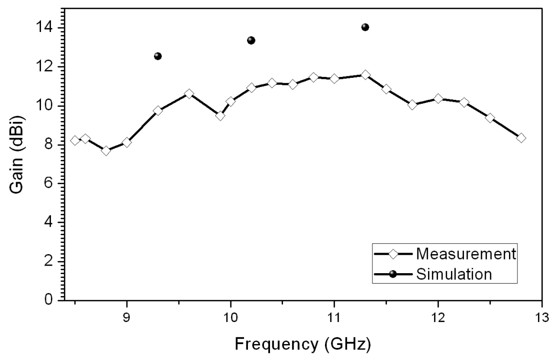

Fig. 7. Measured and simulated antenna gain.

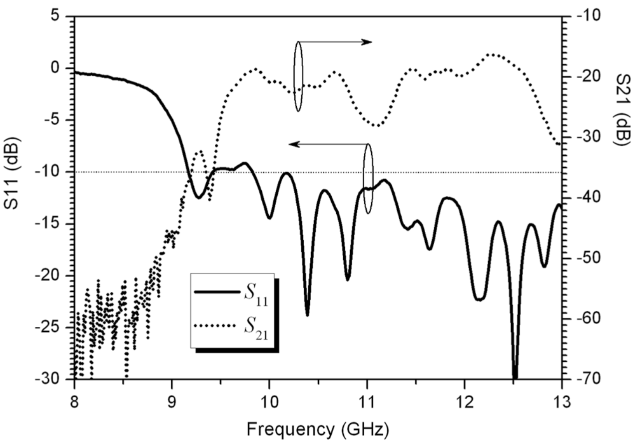

Fig. 8. Measured *S*-Parameters of the double-side radiating leaky-wave antenna. The parameter values are: $w_1 = 0.32$ mm, $w_2 = 0.33$ mm, $w_3 = 8.6$ mm, $n = 9$, $p = 7.45$ mm, $l = 2.6$ mm.

B. Double-Side Radiating Leaky-Wave Antenna

The double-side leaky-wave antennas have a total number of 25 interdigital capacitors etched on the surface and the ground of the SIW. The measured transmission response with detailed parameter values are shown in Fig. 8. Still, a balanced case is designed in order to obtain continuous beam-steering function. The observed low S_{11} and S_{21} indicate a good matching and a good radiation performance.

Fig. 9(a) and (b) shows the measured E-plane radiation patterns in the LH and RH regions, respectively. Fig. 9(c) gives an overall view about the radiation characteristics

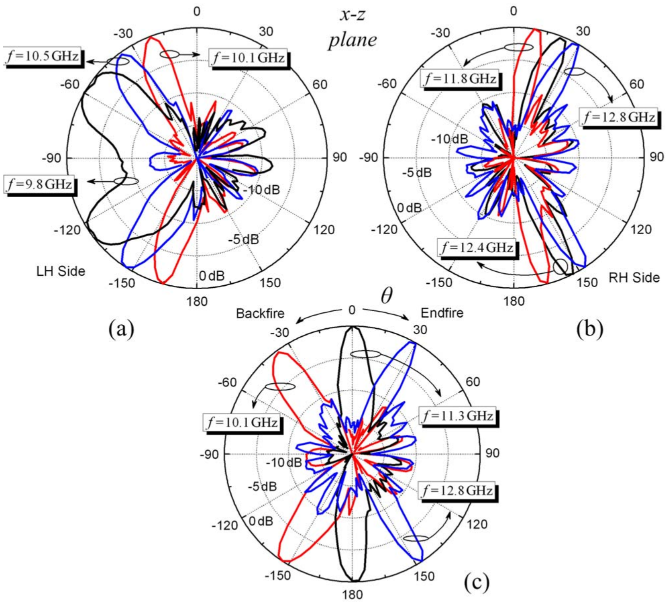

Fig. 9. Measured antenna radiation patterns (a) E-plane (*x-z* plane) in the LH region, (b) E-plane (*x-z* plane) in the RH region and (c) Overview of E-plane (*x-z* plane) patterns including the broadside radiation pattern.

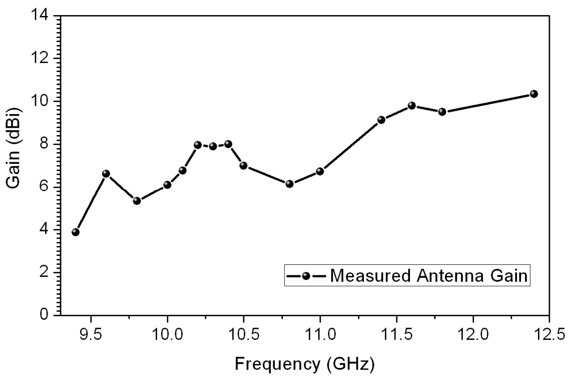

Fig. 10. Measured gain for the double-side radiating leaky-wave antenna.

including the backward, broadside and forward radiation patterns. These E-plane patterns are similar to the inline element arrays while for the latter beam-steering is usually achieved by phase control which is very difficult to realize. We also find that the beam for this antenna is sharper compared with the first antenna. This is due to the reason that the distance between the unit cells on one side is increased for the second antenna, which results in the decrease of the beamwidth according to the arrays theory. This also explains that the beamwidth in the LH region (at low frequency) is larger than that in the RH region (at high frequency which corresponds to smaller wavelength). Fig. 10 shows the measured antenna gain. Taking its double-side radiating nature into account, the gain for this antenna should be 3 dB less than the first antenna in theory.

IV. Conclusion

Two novel frequency-scanned CRLH-SIW leaky-wave antennas have been developed. They are realized using the normal PCB process. Their working principles have been illuminated. Their one-side or quasi-omnidirectional radiating characteristics have been analyzed and presented. We demonstrated their ability of backfire-to-endfire continuous beam scanning due to the employment of a balanced CRLH design. We also showed that an average antenna gain as high as 11 dBi for the first antenna and 9 dBi for the second antenna is achieved due to the introducing of a waveguide leaky-wave structure.

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