A Shunt-capacitance-aided Composite Right/Left-handed Leaky Wave Antenna with Large Scanning-range/Bandwidth Ratio

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Abstract—In this paper, we propose an improved shunt-capacitance-aided composite right/left-handed (CRLH) leaky wave antenna (LWA) with large beam-scanning-range (BSR)/bandwidth ratio based on substrate integrated waveguide (SIW) structure. The CRLH LWA is constructed by etching interdigital capacitor on the waveguide surface, which behaves as the series capacitor for left-handedness as well as radiating cell. Two longitudinal slots locate at upside and downside of the interdigital capacitor, respectively, which are working as the aided shunt capacitance to achieve large BSR/bandwidth ratio. An X-band LWA composed of 15 CRLH cells is fabricated. The simulated results of $S$-parameters and radiation patterns are presented. Compared with other frequency scanning CRLH LWAs reported before, this LWA has the advantage of large BSR from $-57^\circ$ to $+65^\circ$ within a fractional bandwidth of 28% (from 9.2 GHz to 12.2 GHz).

1. INTRODUCTION

Metamaterial LWAs based on CRLH transmission lines (TLs) have been studied intensively for its outstanding advantage of continuous BSR from backfire to endfire [1], which can be used in modern radar system for frequency scanning application. Many researches on SIW structure CRLH TLs with the application in LWA have been reported [2, 3]. However, the required frequency scanning bandwidths of the before proposed CRLH SIW LWAs are usually as large as 40% fractional bandwidth or even larger in order to achieve certain BSR of $[-60^\circ, +60^\circ]$ [2, 3]. A large BSR/bandwidth ratio is usually preferred for radar systems with high performance beam scanning characteristic required. In this paper, we propose a shunt-capacitance-aided CRLH LWA using SIW structure so as to achieve wide continuous scanning range within a narrow fractional bandwidth.

Three sections are contained in the main body of this paper. In Section 2, we show the LWA configuration and discuss the leaky wave principle. The dispersion of this CRLH cell is analyzed in Section 3. In Section 4, the $S$-parameters and radiation patterns of the LWA are presented.

2. CONFIGURATION & LEAKY WAVE PRINCIPLE

A LWA is basically a uniform or periodic waveguiding structure that possesses a mechanism that permits it to leak power all along its length. Our design is based on the substrate of Rogers 5880 with a permittivity of 2.2, loss tangent of 0.0009 and thickness of 0.508 mm. The unit cell and the LWA configurations are shown in Figure 1. Interdigital slots are etched on the surface of the SIW CRLH cell, which behave as series capacitors as well as leaky wave unit. The via-holes adopted in our SIW structure acting as the shunt inductors have the same dimension with a radius of 0.35 mm and a center-to-center distance of 1.35 mm between neighboring via-holes. Two longitudinal slots locate at upside and downside of the interdigital capacitor, respectively, which are working as the aided shunt capacitances which help to achieve large BSR/bandwidth ratio. The bottom of the substrate is covered by copper so as to act as ground plane.

In a LWA, the free space wave number $k_0$ corresponds to radiation direction of the main beam, and can be decomposed into longitudinal ($x$) and transversal ($z$) components, as indicated in Figure 1(b). The longitudinal component is

$$k_x = \beta(\omega) - j\alpha(\omega)$$

where $\beta(\omega)$ and $\alpha(\omega)$ are the phase factor and the leaky factor, respectively. The transversal component $k_z$ depends on both $\beta(\omega)$ and frequency (via $k_0$)

$$k_z = \sqrt{k_0^2 - \beta^2}$$

If $|\beta| > k_0$ (phase velocity $v_p < c$, slow wave), $k_z$ is imaginary, and the field will be exponentially decaying along $z$, which means the wave is completely guided. If $|\beta| < k_0$ ($v_p > c$, fast wave), $k_z$ is real, therefore leakage radiation occurs.
Figure 1: Figuration of the proposed (a) SIW CRLH cell & its equivalent circuit, (b) LWA.

The radiation angle of the main beam is straightforwardly determined by Figure 1(b) as \[ \theta(\omega) = \sin^{-1} \left( \frac{\beta(\omega)}{k_0} \right) \] (3)

which shows a beam steering can be achieved by frequency scanning.

3. DISPERSION ANALYSIS

A CRLH TL is commonly constructed by embedding repetition of series capacitance and shunt inductance into a traditional right-handed (RH) TL which exhibits left-handed (LH) property at low frequency band and RH property at high frequency band. Because of the effect of parasitic series inductance and shunt capacitance, a pure LH TL cannot exist physically, even if we intentionally provide only series capacitance and shunt inductance, thus the CRLH model represents the most general structure.

In original SIW cell, the top and the ground metal surfaces behave effectively as a two-wire TL with distributed series inductance and shunt capacitance. The short-circuit via-holes can be regarded as shunt inductance, so for the CRLH model, just series capacitance is needed, which can be realized by the interdigital slots. The equivalent circuit of the proposed CRLH cell is shown in Figure 1(a), where \( C_R \) and \( L_R \) represent the distributed series inductance and shunt capacitance, while \( C_L \) and \( L_L \) represent the interdigital slots and via-holes, respectively. The two longitudinal slots are equivalent to the shunt admittance of \( G + jB \) [5]. This is similar to the longitudinal slot on the broad wall of a rectangular waveguide. When the slot length is smaller than the resonant length, \( B > 0 \) can be achieved, thus the longitudinal slot will work as an extra shunt capacitor \( C_{slot} \).

In the CRLH model of Figure 1(a), a balanced condition can be achieved if the series and shunt resonant frequencies are equal with each other or equivalently

\[ L_R C_L = L_L C_R \] (4)

Under this balanced condition, the propagation constant \( \beta \) can be simply expressed as the sum of
a (linear and positive) RH TL and a (negative and hyperbolic) LH TL [1]

\[ \beta = \beta^{RH} + \beta^{LH} = \frac{\omega}{p \sqrt{L_R C_R}} - \frac{1}{\omega p \sqrt{L_L C_L}} \]  

(5)

The propagation constant \( \beta \) exhibit zero at the frequency called the transition frequency:

\[ \omega_0 = \frac{1}{\sqrt{L_R C_R L_L C_L}} \]  

(6)

According to (5), the sensitivity of propagation constant with frequency can be obtained by

\[ \frac{d\beta}{d\omega} = \frac{1}{p} \left( \sqrt{L_R C_R} + \frac{1}{\omega^2 \sqrt{L_L C_L}} \right) \]  

(7)

From (7), we can see the aided shunt capacitor \( C_{slot} \) will enlarge the RH capacitor \( C_R \), thus the sensitivity of propagation constant \( d\beta/d\omega \), which means this CRLH cell has a narrower fast wave region compared to that does not has the aided longitudinal slots. In our CRLH cell design, the interdigital capacitor parameters are chosen as: finger length \( l_c = 2.8 \) mm, finger width \( w_c = 0.3 \) mm, space between neighboring fingers \( w_s = 0.35 \) mm. The length and width of the longitudinal slot are chosen to be 5.5 mm and 0.45 mm, respectively. Now, let’s compare the dispersion curves of the novel cell and that proposed in [2], as depicted in Figure 2. It is shown that both of them are balanced at 10 GHz approximately, and the fast wave region of the new cell is much narrower than that of the cell in [2]. The difference between the airlines of the two CRLH cells is due to the different lengths of unit cells. It is to say the proposed CRLH cell can be a good candidate to LWA for achieving large BSR/bandwidth ratio. Based on this CRLH cell, a LWA composed of 15 cells is designed and simulated in Section 4.

Figure 2: Dispersion of CRLH, red real line: cell in [2]; blue dashed line: cell in this work.

Figure 3: Simulated S-parameters of the shunt-capacitor-aided LWA.

Figure 4: E-plane radiation patterns of (a) LH region, (b) RH region, (c) transition frequency.
4. SIMULATION RESULTS OF THE LWA
The designed LWA is realized by cascading 15 identical CRLH cells. Two taper lines are adopted in the two ends of the LWA for impedance matching to 50 Ω, as shown in Figure 1(b). The simulated S-parameters of the LWA using CST Microwave Studio are shown in Figure 3. A bandwidth of $S_{11} < -10$ dB is achieved from 9.5 GHz to 11.2 GHz. The $E$-plane radiation patterns at different frequencies are simulated, as shown in Figure 4. A BSR of $[-57^\circ, +65^\circ]$ is achieved within a bandwidth from 9.2 GHz to 12.2 GHz and the maximum gain of 13 dBi is obtained in the broadside radiation.

5. CONCLUSIONS
A shunt-capacitor-aided CRLH LWA with large BSR/bandwidth ratio is proposed in this paper. Simulation results of $S$-parameters and radiation patterns are presented. The BSR can be from $-57^\circ$ to $+65^\circ$ within a fractional bandwidth of 28% (from 9.2 GHz to 12.2 GHz). The performance of BSR/bandwidth ratio is better than that of the LWA reported in [2], which has a fractional bandwidth of 40% (from 8.6 GHz to 12.8 GHz) for achieving a BSR of $[-70^\circ, +56^\circ]$.

REFERENCES