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A Beam Scanning Leaky-Wave Slot Antenna With Enhanced Scanning Angle Range and Flat Gain Characteristic Using Composite Phase-Shifting Transmission Line

Wenquan Cao, Zhi Ning Chen, Wei Hong, Bangning Zhang, and Aijun Liu

***Abstract*—In this communication, a planar beam scanning substrate integrated waveguide (SIW) slot leaky-wave antenna (LWA) is proposed for enhancing scanning range and gain flatness using a modified composite right/left-handed transmission line (CRLH TL) structure. The curved phase-shifting characteristics of the modified CRLH TLs positioned between the radiation slots are adopted to increase the scanning range of the proposed antenna. Compared with conventional SIW CRLH LWAs, this antenna offers less gain variation due to its better balance between left-handed and right-handed bands and less sensitivity to its geometrical dimensions. The proposed antenna operating at the center frequency of 25.45 GHz is designed and experimentally verified for an automotive collision avoidance radar. The results show that the antenna achieves a twofold improvement in beam scanning ability with identical overall size.**

***Index Terms*—Beam-scanning, composite right/left-handed transmission line, leaky-wave antenna, substrate integrated waveguide.**

I. INTRODUCTION

With attractive properties such as low profile, compact structure, wideband performance and frequency beam scanning capabilities, planar leaky-wave antennas (LWAs) have received much attention for applications of automotive collision avoidance radar (ACAR) and satellite communication systems. However, the conventional LWAs achieve limited scanning range only along the forward direction [1]. Recently, there has been an increasing interest in the composite right/left-handed (CRLH) metamaterial-based antennas for supporting both the backward and backward wave propagation in their right and left-handed (LH) regions. Such a propagation feature can be used to achieve wider scanning range by their continuing back-fire, broadside, and end-fire radiations [2]–[10]. However, the performance of the CRLH LWA degrades with frequency, especially at the millimeter-wave frequency range because of its distributed capacitance and inductance.

With features of low-profile, low cost, and easy integration with planar circuits while maintaining the advantages of conventional rectangular waveguide, substrate integrated waveguide (SIW) has been widely used as a planar guided-wave structure over the past decade, particularly for designing waveguide-slot antennas at microwave and

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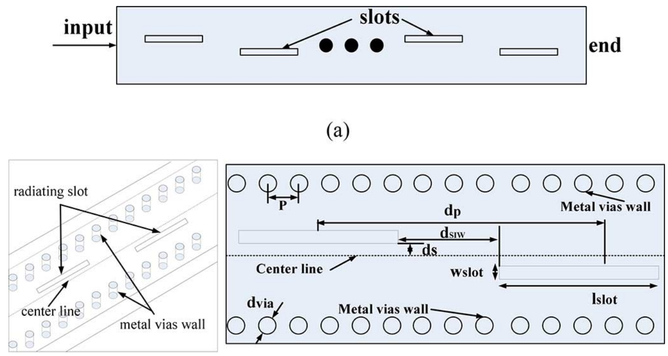


Fig. 1. (a) Top view of the conventional waveguide slot array antenna, (b) 3-D and top views of two adjacent unit elements of the SIW slot array antenna, where $l_{\rm slot}$ and $w_{\rm slot}$ are the length and width of the slot, respectively.

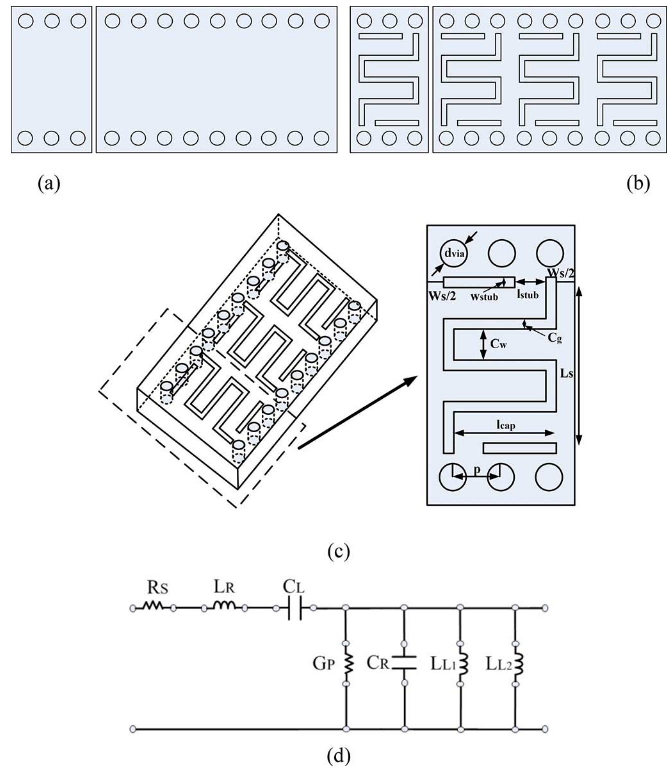


Fig. 2. The two unit cell types for TL, (a) one (left) and three (right) unit cells for Type A, (b) one (left) and three (right) unit cells for Type B. (c) The structure of Type B unit cell, (d) the equivalent-circuit model for Type B, L_{L1} and L_{L2} represent the inductance effect for the loading copper strips of $l_{\rm stub} \times w_{\rm stub}$ and $W_s \times w_{\rm stub}$, respectively.

millimeter-wave bands [11]–[13]. T. Itoh and his group invented a family of CRLH SIW and HMSIW leaky-wave structures by etching interdigital slots on the top metal surface and the ground of the waveguide [14]. Then, a CRLH LW structure based on the SIW was developed for the polarization-agile antenna application [15]. Most of the proposed metamaterial-based structures suffer from either a complicated structure or difficulty in maintaining balance between different frequencies due to the high sensitivity of the dimensions of the CRLH TLs. Therefore, to realize consistent gain over the beam scanning range is challenging since boresight radiation is very sensitive to the balanced condition and usually drops down with lower gain at the balanced point nearby. Recently, a multi-layer SIW LWA with a CRLH behavior was also presented with improved boresight gain at the balanced condition frequency [16]. Actually after Itoh *et al.* proposed the concept of CRLH TL, many CRLH TL-based microwave components and antennas have been reported [17]–[22]. However, the balance between LH and RH bands is sensitive to the dimensions so that it is difficult to design arbitrary phase response by adjusting the length of CRLH TLs. This situation had not been changed until Lin *et al.* proposed a compact CRLH structure [23]–[25]. The proposed structure can be easily controlled by adjusting the shunt inductance and series capacitance to produce different LH properties and meet the balance condition $L_R C_L = L_L C_R$ naturally.

This communication proposes a CRLH TL with curved phase-shifting characteristics to increase the scanning angle range of the LWA. The proposed CRLH TL is used as a transmission element rather than a radiating element. Based on the CRLH TL proposed in [23], a modified structure is proposed here for increasing the beam scanning angle range.

II. Theoretical Analysis

The proposed LWA is a modification of a conventional SIW longitudinal slot array antenna [26], [27]. Fig. 1 shows the top view of the conventional LWA and the 3-D and top views of two adjacent unit elements. When all slots with the element separation of one guided wavelength are excited in-phase at the center frequency, broadside radiation can be achieved. However, once the operation frequency deviates from the center frequency, the phase difference between any two of adjacent slots results in beam steering. The relationship between the angle of beam steered from normal ($\Delta\theta$) and phase difference between any two of adjacent slots ($\Delta\varphi$) can be obtained as follows:

$$\Delta\theta = \sin^{-1}\frac{\Delta\varphi}{\beta_0 d_p}, \Delta\varphi = \beta_{\rm SIW} \bullet d_{\rm SIW} \tag{1}$$

where β_0 is the propagation constant of free space, d_p is the physical distance between any two of adjacent slots, $\beta_{\rm SIW}$ is the propagation constant of the SIW and $d_{\rm SIW}$ is the current path distance of SIW that connecting any two adjacent slots.

From (1), it is found that:

1) For a fixed operation frequency range, the maximum steering angle can be increased by either reducing d_p or increasing $\Delta\varphi$.
2) Reducing d_p can be achieved by increasing the permittivity of dielectric in an SIW.
3) $\beta_{\rm SIW}$, the propagation constant of TE10 mode of the SIW, is unchanged when the center operating frequency and the fabrication material are fixed. Thus increasing $d_{\rm SIW}$ is the only option to increase $\Delta\varphi$ for larger beam steering angle. The linear phase response was realized in [28] by meandering entire structure but keeping a separation of about $1/2\lambda$ at the expense of larger size.
4) $\beta_{\rm SIW}$ is variable if modified TLs such as CRLH TLs are introduced. CRLH TL may increase $\Delta\varphi$ by tuning the propagation constant $\beta_{\rm SIW}$ without changing $d_{\rm SIW}$ and d_p.

The TLs between the radiating slots affect $\Delta\varphi$ and thus $\Delta\theta$. In this work, an SIW CRLH TL is used only as a transmission structure without any radiation to enhance the phase slope within the desired operation frequency range.

Two types of TL unit cells are under discussion, as shown in Fig. 2: namely, TL A, a conventional SIW; and TL B, the type proposed in this work. Fig. 2(c) shows the details of the proposed composite phase-shifting TL unit cell. The unit cell consists of series interdigital capacitors and two coupling stub inductors connected to the sides of the two linear arrays of metallic vias. $l_{\rm cap}, l_{\rm stub}$ and $w_{\rm stub}$ indicate the length of the interdigital capacitor, the length and the width of the shorted stub, respectively.

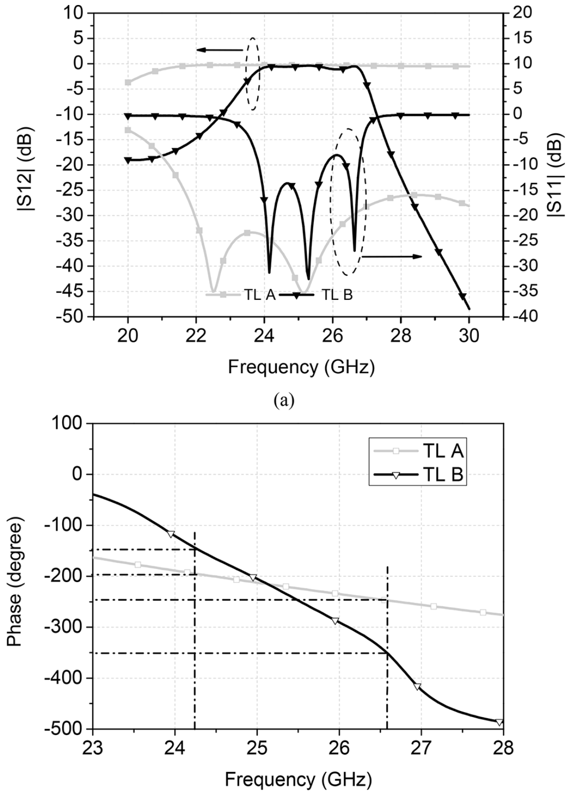


Fig. 3. Properties of the two TL unit cell types, (a) amplitudes and (b) phase of S-parameters.

We optimized the parameters of the two types of TLs with passbands with the fixed operation frequency range for comparison. From the S-parameters and phase response of the two types of TLs as shown in Fig. 3, it can be concluded as follows:

1) With the identical unit dimensions, the optimized two types of TLs operate in the desired frequency range of 24.25–26.65 GHz.
2) TL A can be considered as a highpass filter as its operating band is higher than TE_{10} mode. Although the insertion loss in the passband is low, the phase slope of TL A is only 22.42°/GHz, much smaller than that of TL B.
3) The proposed TL B is the modification of the CRLH TL [23]. The equivalent-circuit model for the unit cell of Type B is described in Fig. 2(d). The shunt capacitance C_R and series inductance L_R, the series interdigital capacitor C_L and the shunt stub inductor L_L produce LH and RH behaviors of the line, respectively. R_S and G_P refer to the loss of structure. Such lumped parameters can be retrieved using S-parameters [29]. With the copper strip added, the value of L_L decreases to

$$L_L = 1/\left(1/L_{L1} + 1/L_{L2}\right) \tag{2}$$

and the passband range is narrowed. Nevertheless, the phase slope is enhanced in a large-scale with about 90.2°/GHz which could increase the antenna beam scanning ability. The properties of the two types of TLs are also compared in Table I.

Then the radiating slot is added into the TL part as an antenna unit cell and the cell dispersion diagram is described for better understanding the working mechanism. As shown in Fig. 4, both the two types of TLs have a fast-wave property which ensures the radiation

TABLE I
PROPERTIES OF THE TWO TYPES OF TL WITH THREE UNITS

	Unit Length (mm)	Phase Variation	Phase Slope	With Ripples
TL A	2.55	53.8°	22.42°/GHz	No
TL B	2.55	216.5°	90.2°/GHz	minor

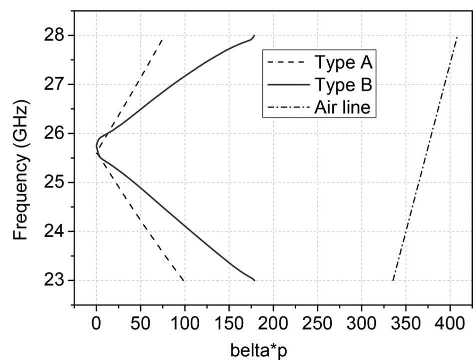


Fig. 4. The dispersion diagram of the antenna unit cell including both the TL and the radiating slot part.

capability. However, the phase slope range of Type B is larger than that of the Type A in the desiring working band which contributes to the enhanced scanning angle range. And the phase slope variation of Type B is less than that of Type A in the transition frequency band, which means flatter gain characteristic. The required circuit condition for smooth transition of the radiation loss and constant radiation rate can be found in [16], [30]–[32].

From the comparison, it is expected that the LWA based on TL B can improve scanning range and gain flatness.

III. SIW CRLH TL LWAs

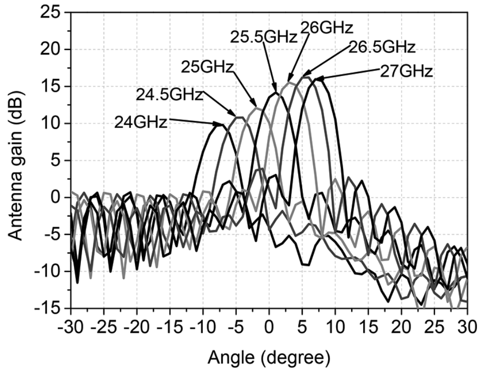
The proposed 12-cell SIW LWA is designed based on CRLH TL (TL B) while the 12-cell conventional SIW LWA is designed based on RH TL (TL A). Both have the same radiating elements and are fabricated on the substrate of Rogers 5880 with $\varepsilon_r = 2.2, \tan\delta = 0.001$ and thickness $h = 0.508$ mm. The two antennas have the same overall dimensions. The full-wave simulation was performed using the Ansoft's High Frequency Structure Simulator (HFSS) software package. The design procedure includes three steps as follows.

First, the design of the TL part is based on the method given in Section II and optimized for a wide passband and large phase slope.

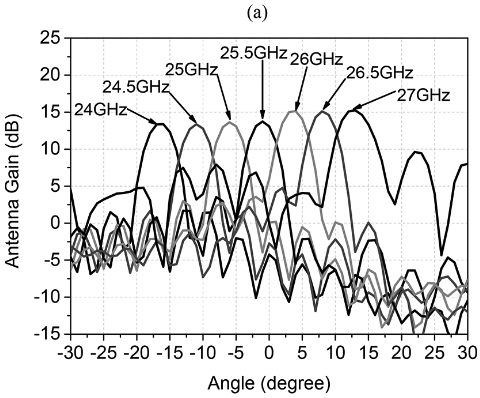
Second, both the TL and the radiating part of the antennas are co-designed in the simulation. Since the dimensions of the TLs are fixed in the former step, tuning the radiating slot size and the offset distance *ds* is adopted for good impedance matching.

Last, the input impedance matching and the output resistor load are taken into account. A taper line is used at the two ends of the LWA [33] and the output end is terminated by 50 Ω.

The simulated radiation patterns for the two antennas with the frequency varying from 24 GHz to 27 GHz with a step of 0.5 GHz are shown in Fig. 5. It can be found that the scanning range has increased from $-6^\circ \sim +6^\circ$ for the conventional antenna to $-14^\circ \sim +12^\circ$ for the proposed antenna. The simulated peak gain variation of the proposed antenna is less than 2 dB while the gain variation for the conventional antenna is 6 dB. Furthermore, less gain ripples are found across the operating bandwidth.



(a)



(b)

Fig. 5. Simulated radiation patterns for (a) conventional SIW LWA and (b) the proposed SIW CRLH TL LWA with the frequency varying from 24 GHz to 27 GHz with step of 0.5 GHz.

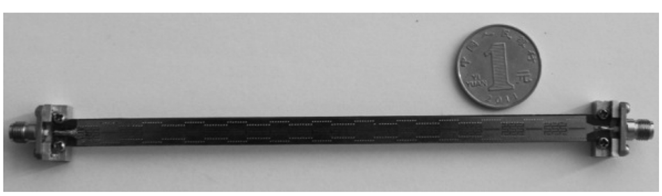


Fig. 6. The photograph of the proposed antenna.

TABLE II
THE PARAMETERS OF THE ANTENNAS (UNIT: mm)

d_s	d	w_{slot}	l_{slot}	p	d_{via}	h_1
0	12.15	0.2	4.6	0.8	0.4	0.508
l_{stub}	w_{stub}	C_w	l_{cap}	L_s	W_s	C_g
0.6	0.1	0.7	1.7	3.3	0.4	0.1

IV. RESULTS AND DISCUSSION

The proposed antenna shown in Fig. 6 was fabricated and measured for verification. The optimized parameters of the antenna are given in Table II.

The S-parameters were measured using an Agilent N5230A network analyzer. Fig. 7 compares the measured and simulated S-parameters of the antenna, which are in good agreement. The measured $|S_{11}| < -10$ dB bandwidth is from 23.95 GHz to 27.725 GHz which completely covers the bandwidth of ACAR system completely. The insertion loss is almost 10 dB, which indicates good leakage radiation. The discrepancy between the simulation and measurement is due to the increase of reflection, the loss from the SMA connectors and probably the increased conductor loss and dielectric loss which can also be found in [14], [15].

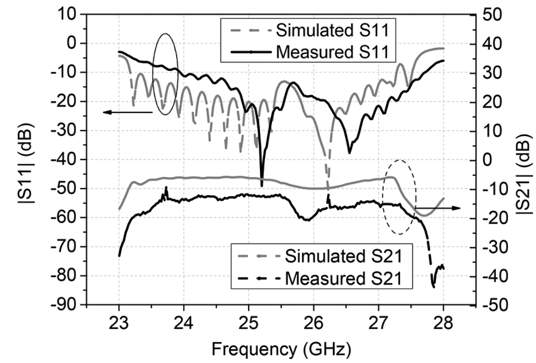


Fig. 7. The measured and simulated S-parameters of the proposed antenna.

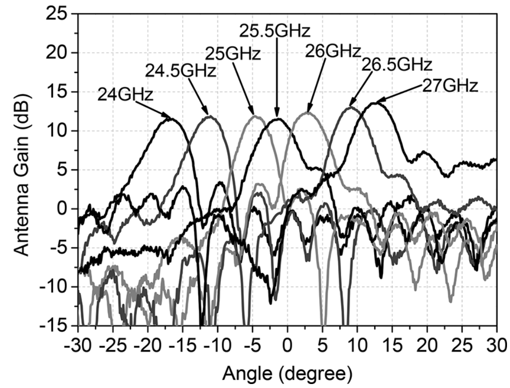


Fig. 8. Measured radiation patterns for the proposed antenna.

Fig. 8 shows the measured radiation patterns for the proposed antenna with a frequency ranging from 24 GHz to 27 GHz with a step of 0.5 GHz. Its beam-steering performance by frequency scanning is verified experimentally. The scanning range of the proposed antenna is $-17^\circ \sim +13^\circ$ from 24 GHz to 27 GHz. Comparing with the simulated radiation patterns given in Fig. 4(b), the gain decrease is about 1.5 dB for the measured results during the scanning range which may be attributed to the loss from the SMA connectors and the conductor. However, less gain variation has been realized and a twofold increase in antenna beam scanning ability than the conventional type is achieved without size increase. Thus the measured results confirm the theory analysis and the simulation results.

V. CONCLUSION

An SIW LWA with enhanced frequency beam-steering capability has been presented where the proposed SIW CRLH TL has been used as a transmission element. Compared with a conventional SIW CRLH LWA, the antenna gain does not vary significantly with frequency due to its improved balance between LH and RH frequency bands. This structure has shown the potential for automotive collision avoidance radar or wireless communication applications for its advantages of the simplicity in design, low-cost fabrication, and beam-steering and flat gain property.

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