K-Band Frequency-Scanned Leaky-Wave Antenna Based on Composite Right/Left-Handed Transmission Lines

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***Abstract*—A frequency-scanned leaky-wave antenna at K-band is proposed, which is based on two composite right/left-handed (CRLH) transmission lines with a virtual ground in between and composed of two identical RT 5880 substrates. The main beam of the proposed leaky-wave antenna scans from $-25°$ to $+50°$, i.e., from backfire to endfire, as the frequency varies from 20 to 30 GHz. The highest antenna gain reaches 14 dB at a backfire direction. The proposed antenna has no vias. Its dimensions are 155×34 mm^2.**

***Index Terms*—Composite right/left-handed (CRLH), K-band, leaky-wave antenna.**

I. Introduction

FREQUENCY-SCANNED leaky-wave antennas based on microstrip structures have been proposed decades ago [1]–[3]. They have simple structures and are easy to be fabricated, which leads to a great demand in many applications. A conventional leaky-wave antenna uses the first higher-order mode to realize a high antenna gain. Its main beam may scan to endfire directions, which is limited by the nature of conventional transmission lines, i.e., right-handed transmission lines.

Left-handed (LH) materials have a few unique characteristics [4]–[10]. One of the most remarkable characteristics is its simultaneously negative permittivity and permeability. Due to their unprecedented performance, left-handed materials have spurred considerable interest throughout the last decades [11]–[13]. Conventional leaky-wave antennas based on composite right/left-handed (CRLH) transmission lines (TLs) are very interesting and allow a beam to scan from backfire to endfire [11], [12], [14]. They usually contain vias and/or interdigital structures as required by CRLH transmission lines, which limit their applications. A novel frequency-scanned leaky-wave antenna from CRLH TLs is proposed in this letter, which enables the main beam scans from endfire to backfire. This antenna has a self-integrated balun, no vias, and operates in K-band from 20 to 30 GHz.

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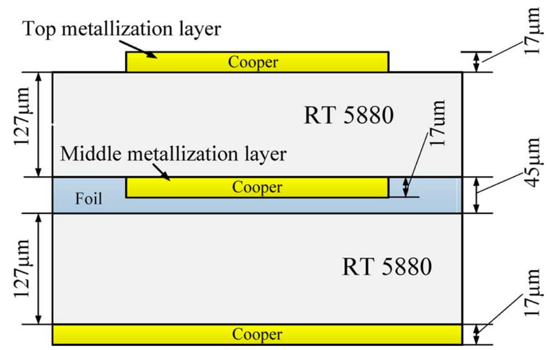

Fig. 1. Cross section of the leaky-wave antenna with a total thickness of 0.3 mm.

II. Antenna Design

A. Fundamental

A left-handed transmission line supporting backward waves consisting of series capacitance and shunt inductance was proposed in [15]. The propagation constant of the left-handed transmission line is $\beta_{\rm L}(\omega) = -1/\omega\sqrt{L_{\rm L}C_{\rm L}}$, where $L_{\rm L}$ and $C_{\rm L}$ are the inductance and capacitance per unit length, respectively. Its equivalent permittivity and permeability are both less than zero. Thus, the equivalent refraction index is less than zero as well, which shows its left-handed nature. With this, radiation to backfire is possible from a left-handed transmission line.

The structure mentioned above cannot avoid the right-handed (RH) characteristic in general. Thus, the structures are CRLH transmission lines. The propagation constant becomes $\beta_{\rm C} = \omega\sqrt{L_{\rm R}C_{\rm R}} - 1/\omega\sqrt{L_{\rm L}C_{\rm L}}$, where $L_{\rm R}$ and $C_{\rm R}$ are the series inductance and shunt capacitance per unit length, respectively [16]. A CRLH transmission line is dominant LH mode while $f < f_0$, RH mode while $f > f_0$, and with infinite wavelength while $f = f_0$ [17]. $\beta_{\rm C}$ varies from negative to positive with the increase of frequency. Then, a leaky-wave antenna based on CRLH transmission lines operated in dominant mode scans from backfire to endfire.

B. Antenna Structure

The layered structure of the proposed leaky-wave antenna is shown in Fig. 1, in which there are two substrates and three metallization layers. Microstrip elements are placed on the top and middle metallization layer, respectively, and the ground is on the bottom metallization layer, while a bonding foil layer is between the two substrates. The antenna was fabricated on Rogers RT5880 substrates with dielectric constant of 2.2 and

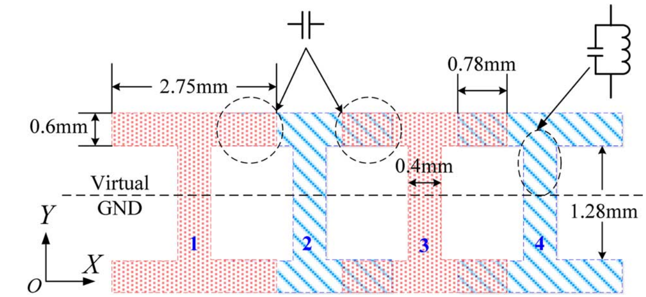

Fig. 2. Structure and dimension of the coupled CRLH transmission lines.

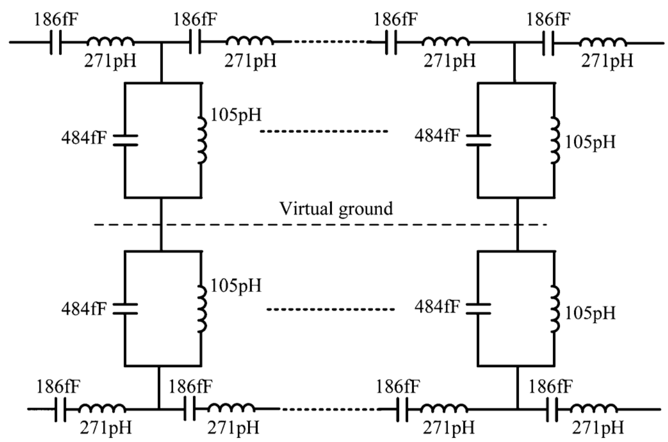

Fig. 3. Equivalent circuit of the coupled CRLH transmission lines.

thickness of 0.127 mm. The foil layer has a dielectric constant of 2.0 and a thickness of 0.045 mm.

As shown in Fig. 2, there are two symmetrically coupled CRLH transmission lines to form the antenna, which requires a balanced feeding. A few CRLH elements at the beginning of the two coupled CRLH transmission lines operate as a self-integrated balun, as we have previously presented in [6]. Thus, it has a naturally integrated build-in balun.

The microwave leaky-wave antenna consists of two coupled CRLH transmission lines. They are connected together symmetrically to form a virtual ground in between. Fig. 2 shows the layout of the arrangement. The microstrip elements in areas with odd numbers are on the top metallization layer, and those in areas with even numbers are on the middle metallization layer. The series capacitances are formed by the overlapping microstrip structures between the top-two metallization layers. The shunt inductances are realized by the narrow vertical microstrip lines. Series inductances and shunt capacitances result from the normal transmission-line behavior of the finite size structure. The symmetric plane of the two coupled CRLH transmission lines is a virtual ground at balanced feeding. The length of the overlapping part is 0.78 mm, and each element is 3.98 mm apart (center to center) from its neighbor. The equivalent circuit obtained from parameter extraction of the two coupled CRLH transmission lines is shown in Fig. 3, and Fig. 4 shows the balanced dispersion diagram of the CRLH transmission line from simulation.

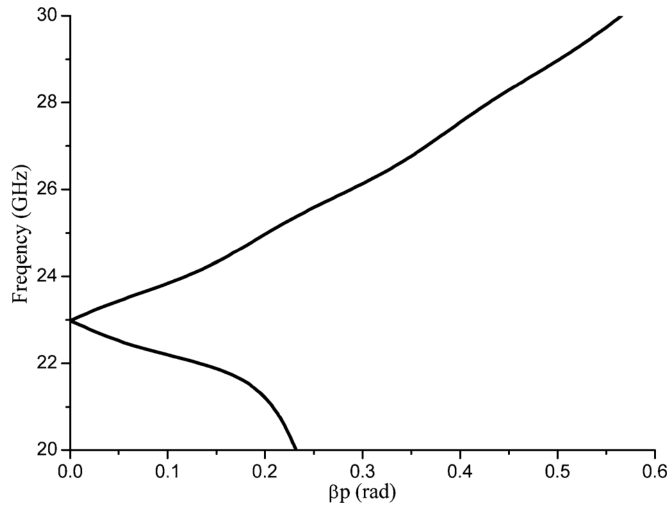

Fig. 4. Simulated dispersion diagram of a CRLH unit cell.

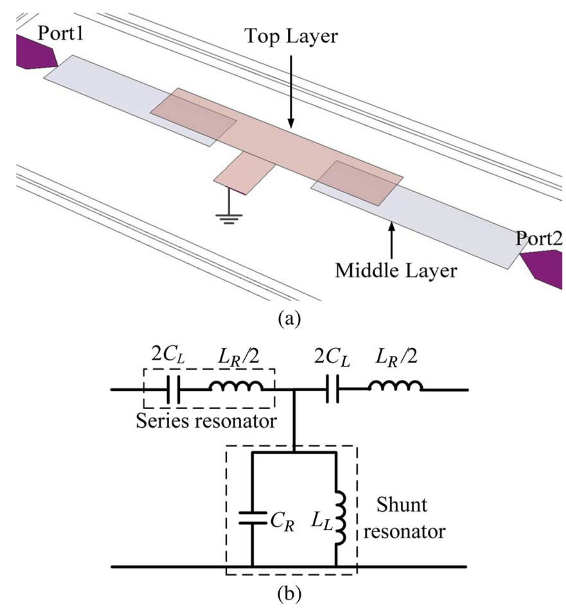

Fig. 5. (a) CRLH microstrip unit cell for parameter extraction. (b) Equivalent circuit of a CRLH microstrip unit cell model.

TABLE I
EXTRACTED CRLH UNIT CIRCUIT PARAMETERS

L_R(pH)	C_L(fF)	L_L(pH)	C_R(fF)
542	93	105	484
$Z_L(\Omega)$	$Z_R(\Omega)$	ω_{se}(GHz)	ω_{sh}(GHz)
23.7	23.7	22.4	22.3

C. Parameter Extraction

The parameters of the equivalent circuit are extracted. Fig. 5 shows the CRLH microstrip unit-cell model, in which the reference plane of both ports have been shifted to the overlapping regions. The admittance matrices of the unit CRLH cell are obtained from the simulated scattering parameters at frequencies near the center frequency. Then, the circuit parameters of series LC and shunt LC of the unit CRLH cell are achieved. The extracted circuit parameters for the CRLH structure are given in Table I.

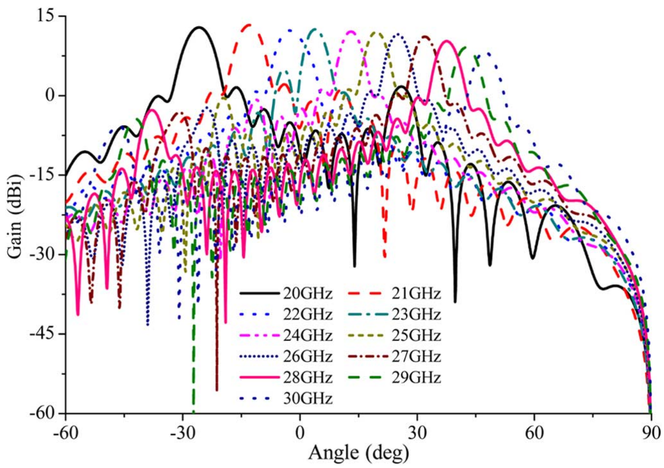

Fig. 6. Simulated H-plane (xoz-plane) radiation patterns of the antenna from 20 to 30 GHz.

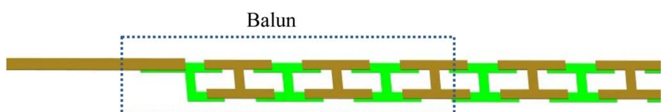

Fig. 7. Layered structure of the leaky-wave antenna with an unbalanced microstrip feedline.

The results from full-wave and equivalent circuit simulation are compared. ω_{se} and ω_{sh}, the resonant frequency of the series and shunt resonators, are close to the center frequency. The phase shift of a CRLH microstrip unit cell is simulated by the IE3D and compared to the results from the equivalent circuit model. The two results are close to each other, which indicates the extracted parameters are valid.

III. Simulated and Measured Results

A K-band frequency-scanned leaky-wave antenna was designed with the electromagnetic (EM) simulation software IE3D. The leaky-wave antenna works from 20 to 30 GHz with a return loss greater than 15 dB. The center frequency of the antenna is 22.2 GHz. The H-plane radiation patterns at various frequencies are shown in Fig. 6. The antenna main beam scans from backfire to endfire, i.e., from -25° to $+50^\circ$. The simulated antenna gain is higher than 10 dB from 20 to 28 GHz. At high frequencies, the current distribution is not as uniform as at low frequencies, which leads to a drop of the antenna gain.

There are 33 microstrip unit elements on either the top or the middle metallization layer. The first several elements form a balun and result in a self-integrated balun [6], as shown in Fig. 7. The fabricated frequency-scanned leaky-wave antenna is shown in Fig. 8. Its dimensions are $155.5 \times 34.5\ \mathrm{mm}^2$. There are no vias in the proposed leaky-wave antenna, which means that it is easy to be fabricated and is suitable for higher-frequency applications.

There is a 100-Ω chip resistor at the end of the fabricated leaky-wave antenna. It absorbs the microwave power that is not radiated by the antenna. The radiation efficiency of the frequency-scanned leaky-wave antenna is $\eta = P_{\mathrm{R}}/P_{\mathrm{IN}}$, where

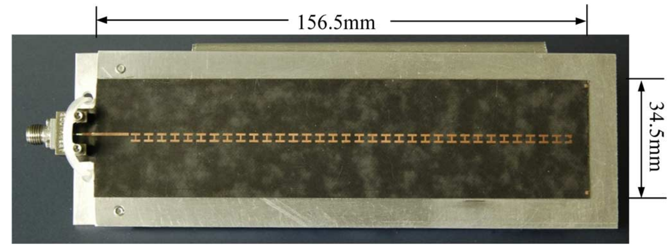

Fig. 8. Fabricated frequency-scanned leaky-wave antenna. A 2.92-mm end-launch connector is applied as the feeding port.

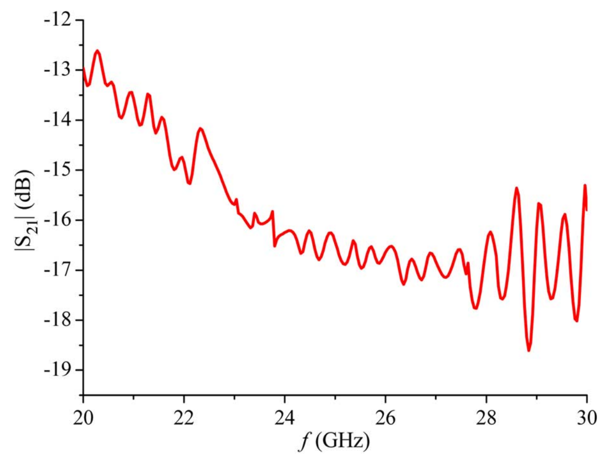

Fig. 9. $|S_{21}|$ of the input port and the 100-Ω termination.

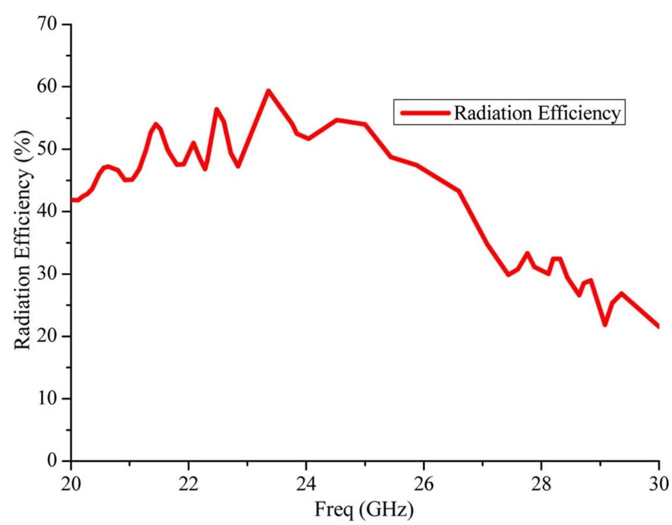

Fig. 10. Radiation efficiency of the leaky-wave antenna.

P_{IN} is the input power and P_{R} is the radiation power of the antenna. The power loss of the antenna mainly includes the dielectric loss, metal loss, surface wave, and the power that is absorbed by the 100-Ω termination. Microwave power will be reflected back to the antenna and disturb the radiation patterns without the termination. There is less than 5% of the input microwave power reaches at the end of the antenna from the simulation. The $|S_{21}|$ between the input port and the 100-Ω termination is shown in Fig. 9. Thus, the 100-Ω termination leads to a slight drop of the antenna radiation efficiency. The simulated radiation efficiency of the antenna is shown in Fig. 10.

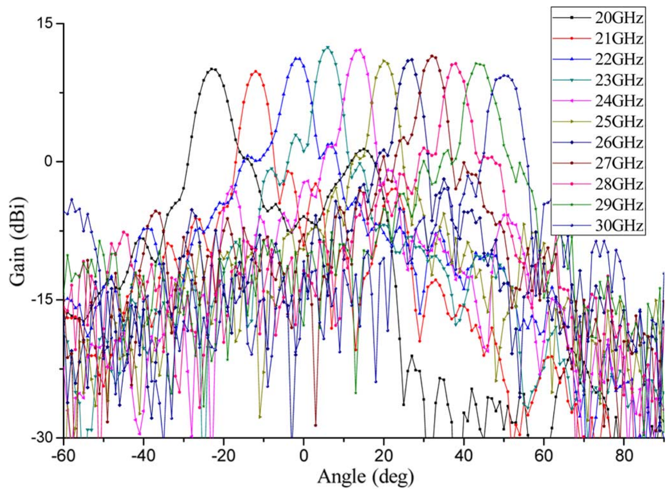

Fig. 11. Measured H-plane (xoz-plane) radiation patterns of the antenna from 20 to 30 GHz.

The radiation patterns have been measured and are shown in Fig. 11. The measured and simulated results agree well. Compared to the simulated results, the measured antenna main beam scans from backfire to endfire with the angle from $-25°$ to $+50°$ at frequency from 20 to 30 GHz as well. The measured antenna gain is higher than 10 dB at the LH band (20–22.2 GHz), and the highest gain reaches 14 dB at 23 GHz (RH mode). At higher frequencies, i.e., in RH band, there is a drop of antenna gain due to the nonuniform current distribution among microstrip unit elements. The fabrication errors, e.g., the shift between the top and middle metallization layer, play an important role in the difference between measured and simulated results.

IV. Conclusion

In this letter, a novel frequency-scanned leaky-wave antenna based on a pair of coupled CRLH transmission lines is presented. The main beam of the proposed leaky-wave antenna scans from backfire to endfire with an angle range from $-25°$ to $+50°$ at the frequency from 20 to 30 GHz. The proposed leaky-wave antenna is based on a pair of coupled CRLH transmission lines to form a virtual ground. Thus, there are no vias in the leaky-wave antenna. Moreover, there is a build-in balun at the beginning of the antenna, which is directly formed by the CRLH transmission lines. The self-integrated balun shares the same microstrip elements as those in the CRLH transmission lines. The proposed leaky-wave antenna is easy to be fabricated and is suitable for applications at higher microwave frequencies.

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