

Frequency-Fixed Beam-Scanning Leaky-Wave Antenna Using Electronically Controllable Corrugated Microstrip Line

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Abstract—An electronically controllable microstrip leaky-wave antenna (LWA) to steer the radiations at a fixed frequency is presented. The proposed LWA is composed of a corrugated microstrip line loaded by the varactor diodes with triangular-modulated surface impedance. Due to the periodical modulation of the surface impedance, the guided waves can be converted into the leaky-wave radiations efficiently with frequency-scanning property. Furthermore, the surface impedance of the LWA can be reconfigured by changing the capacitance of the varactor diode through dc bias voltage, which will make the radiation beam steer in a large angle range accordingly at a fixed frequency. Both numerical simulations and experimental results show that the radiation beams can be controlled for continuously steering at each frequency from 5.5 to 5.8 GHz by changing the dc bias voltage from 0 to 20 V, in which the scanning angle can reach as high as 45°.

Index Terms—Electronically controlled beam scanning, leaky-wave antennas (LWAs), surface impedance modulation.

I. INTRODUCTION

LEAKY-WAVE antennas (LWAs), which are kinds of travelling-wave antennas, have attracted much attention due to their unique advantages, such as low profile, high gain, and low cost. The concept of leaky wave was first proposed by Hansen [1] through slit slots on a waveguide. Thereafter, many LWAs based on different wave-guiding structures have been proposed, including microstrip line [2], coaxial cable [3], substrate integrated waveguide [4], [5], composite right/left-handed transmission line (CRLH TL) [5], [6], and spoof surface plasmon polariton waveguide [7]–[9]. Generally, LWAs can be divided into two categories according to their working principle. One is the quasi-uniform LWAs, whose periodic corrugations have a period

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lower than half-wavelength, and these kinds of LWAs usually have the limitation of frequency scanning in the front quadrant [4]. The other is the periodic-modulated LWAs, which have a period in the order of half-wavelength, and the $n = -1$ space harmonic is designed to make a radiation which allows for backward-to-forward radiation [10], [11]. However, the periodically modulated LWAs usually suffer from the open-stopband (OSB) at broadside [12]. The LWAs based on the CRLH TL also allow for backward-to-forward scanning from the $n = 0$ space harmonic using metamaterial unit cells without OSB effect [13].

The real-time manipulation of leaky-wave steering at a fixed frequency has always been a hot topic in the area of LWAs [14]–[18]. Based on the type of quasi-uniform LWAs, a 1-D Fabry–Perot (FP) LWA has been reported to achieve electronic scanning from 9° to 30° at 5.6 GHz in the front quadrant by using tunable high impedance surface [14], and then the scanning angle was enlarged to 29° at 6 GHz by independently controlling the connection of loaded capacitor in each unit cell of a half-width microstrip LWA [15] at the price of much more complicated bias circuit. In order to obtain the continuous beam scanning from backward-to-forward direction, another FP LWA has been presented by using a central feed to obtain a continuous electronic scanning from –25° to 25° at 5.5 GHz [16]. It was also reported that 17.5° beam scanning could be achieved from backward-to-forward direction at a fixed frequency by changing the bias voltage of loaded-varactor in CRLH structure [17]. Based on periodically modulated LWA, an electronically tunable LWA was proposed to realize fixed-frequency beam scanning in the forward quadrant based on sinusoidal modulations of reactance surface [18]. However, it is difficult to place varactor diodes and add dc bias in practice, and hence only simulation results were presented in [18].

In this paper, we propose an electronically controllable LWA using corrugated microstrip line (CML) with triangular modulation of surface impedance to control the leaky-wave steering in real time at a fixed frequency. The LWA consists of a corrugated metallic strip decorated with periodically modulated subwavelength grooves and a metal ground spaced by a substrate dielectric. Due to the periodic modulation of the surface impedance by changing the groove depth, one can efficiently modulate and convert the guided waves to the leaky-wave radiations with frequency-scanning properties,

and the radiation direction is dependent on the modulation of surface impedance [7], [19], [20]. However, under the passive condition, the radiation direction of the leaky wave cannot be controlled at a fixed frequency once the design is completed. In order to realize fixed-frequency beam scanning, varactor diodes are added in the LWA to provide reconfigurable surface impedance since their capacitances can be easily changed through the bias voltage. Then, the radiation direction of the leaky wave can steer in a programmable way at a fixed frequency. Finally, we design, fabricate, and measure the electronically controllable LWA, in which the measured results have good agreements with numerical simulations. We show that the scanning range of leaky-wave radiations can reach 45° at every frequency from 5.5 to 5.8 GHz. Moreover, the OSB effect has been discussed and solved by adding a matching stub (MS) in each period of the LWA, and the simulation results show that the radiation efficiencies are improved significantly at broadside radiation.

II. THEORIES AND SIMULATIONS

According to knowledge of the LWA, the guided waves can be converted to leaky-wave radiations if the surface impedance of the transmission line (TL) is modulated sinusoidally [7], [19], [20]

$$Z_s(x) = jX_s \left[1 + M \cos \left(\frac{2\pi x}{P} \right) \right] \quad (1)$$

in which X_s is the average surface reactance, M is the modulation factor, and P is the modulation period. The first harmonic, which is the first radiating harmonic, is usually designed to generate the leaky-wave radiation, whose radiation angle can be calculated as

$$\theta_{-1} = \arcsin \left(\sqrt{1 + X'^2} - \frac{2\pi}{k_0 p} \right) \quad (2)$$

in which $X' = X_s/\eta_0$ is the average surface reactance, η_0 is the free-space wave impedance, and k_0 is the free-space wavenumber.

In this designing, the LWA is realized by choosing a CML with triangular-modulated surface impedance for simplifying the model of the varactor diodes loaded CML, whose surface impedance is written as

$$Z_s(x) = \begin{cases} jX_s \left(1 + \frac{2M}{P}x - \frac{M}{2} \right) & \text{if } 0 \leq x \leq \frac{P}{2} \\ jX_s \left(1 - \frac{2M}{P}x + \frac{3M}{2} \right) & \text{if } \frac{P}{2} \leq x \leq P \end{cases} \quad (3)$$

where X_s , M , and P are the same as those in (1). We remark that the radiation angle of the beam based on the triangular modulation also can be calculated by using (2) [21].

The schematic of the LWA with triangularly modulated surface impedance is demonstrated in Fig. 1, which is composed of a corrugated metallic strip and a metal ground spaced by a dielectric substrate of F4BK350 with relative permittivity 3.5 and loss tangent 0.001. The thicknesses of dielectric substrate and covering copper are 3 and 0.018 mm, respectively, and the total length of the LWA is 330.8 mm. The dimensions shown in Fig. 1 are $d = 4.708$ mm, $a = 0.6d$,

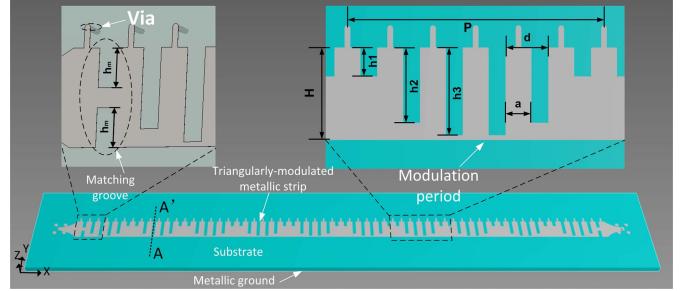


Fig. 1. Schematic of triangularly modulated LWA using CML.

$H = 10$ mm, $P = 6d = 28.248$ mm, and the groove depths are h_1 , h_2 , and h_3 , respectively. At each terminal of the LWA, a notch groove with dimension of 4×1.8832 mm² is used for impedance matching between the terminal and the corrugated metallic strip.

The dispersion curves of the unit cell with different groove depths are simulated by using full-wave commercial software, CST Microwave Studio, and shown in Fig. 2(a) with solid lines. Then, the surface impedance of the LWA can be calculated as

$$Z_s = j\eta_0 \sqrt{(k_x/k_0)^2 - 1} \quad (4)$$

in which k_x is the wavenumber of the LWA along the propagating direction. The finally calculated surface impedance (Z_s) versus the wavenumber (k_x) is demonstrated as the dashed lines shown in Fig. 2(a).

The radiation angle of the leaky-wave beam is related to both the modulating period (P) and the average surface reactance (X_s) according to (2), while the modulating period of $P = 28.248$ mm is always fixed in this design, so the radiation angle of the beam only depends on X_s . For example, if we design a radiation beam directing to $\theta_{-1} = 16^\circ$ at 5.6 GHz, then $X_s = 726.3$ Ω can be obtained from (2). The surface impedance ranges from the minimum value of 435.7 Ω to the maximum value of 985.6 Ω as the groove depth changes from 1 to 9.5 mm, as shown in Fig. 2(a). Hence, we choose $M = 0.37$ to make the range of the surface impedances as large as possible and consequently obtain highly efficient radiation. Then, the groove depths of the triangularly modulated LWA can be finally determined according to the relationship between Z_s and h at 5.6 GHz, as is shown by the red dashed lines in Fig. 2(a). The finally calculated groove depths are $h_1 = 3.137$ mm, $h_2 = 8.164$ mm, and $h_3 = 9.51$ mm. Fig. 2(b) demonstrates the simulated power-density distributions in the plane of $y = 0$ and the cross section of AA' (inset at the upper left corner) at 5.6 GHz, which show that the EM energy is mainly confined on the upper surface of the corrugated metallic strip and radiates to the direction of $\theta = 15.5^\circ$. Fig. 2(c) shows the simulated 3-D far-field radiation pattern at 5.6 GHz with the main beam directing to 15.5° , which agrees well with the theoretical calculation. The radiation angles of the beam at other frequencies can also be calculated from (2), whose simulated far-field radiation patterns are shown in Fig. 2(d), which are consistent very well with the calculation results given in Table I. We remark that

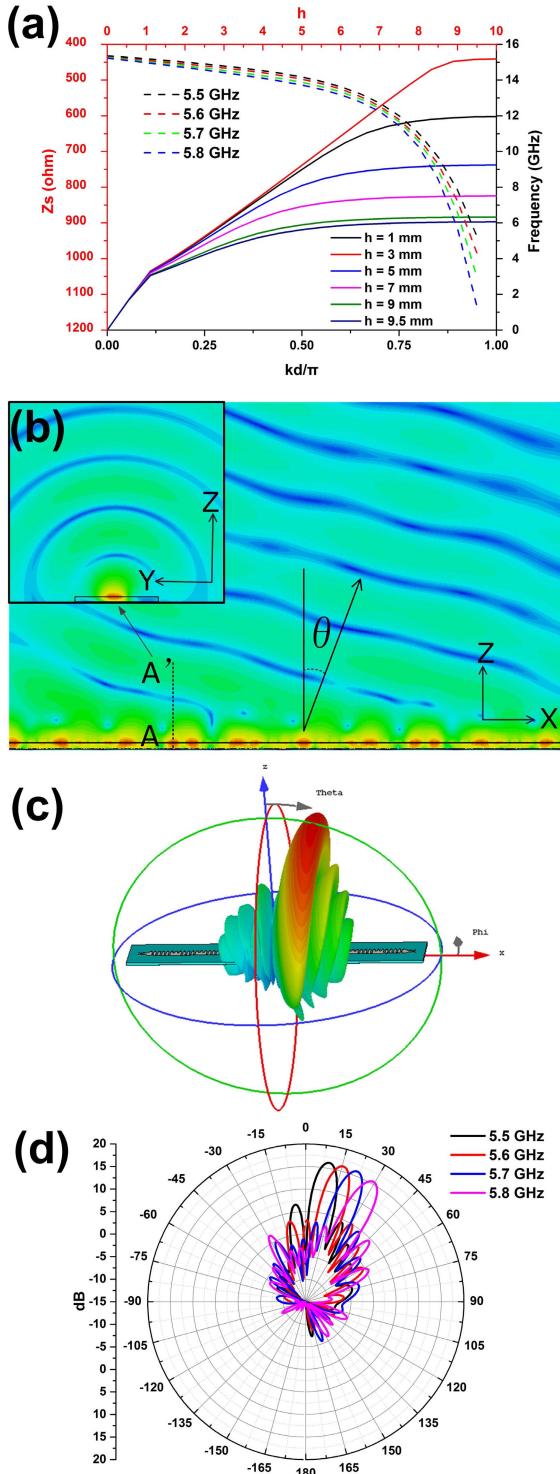


Fig. 2. Dispersion curves and the simulation results of the LWA. (a) Dispersion curves and the surface impedances of the unit. (b) Power-density distributions in the plane of $y = 0$ and the cross section of AA' (inset at the upper left corner) at 5.6 GHz. (c) 3-D far-field radiation patterns at 5.6 GHz. (d) 2-D far-field radiation patterns when frequency changes from 5.5 to 5.8 GHz.

the radiations are linearly polarized transverse electromagnetic waves with electric-field vector paralleling to the xoz plane.

However, from above discussions, the radiation beam can steer as frequency changes but becomes nonsteerable at a

TABLE I
CALCULATED AND SIMULATED RADIATION ANGLES OF THE BEAM AT DIFFERENT FREQUENCIES

Freq./GHz	5.5	5.6	5.7	5.8
Cal.	10.2°	16.0°	23.2°	32.2°
Sim.	10.0°	15.5°	22.3°	29.5°

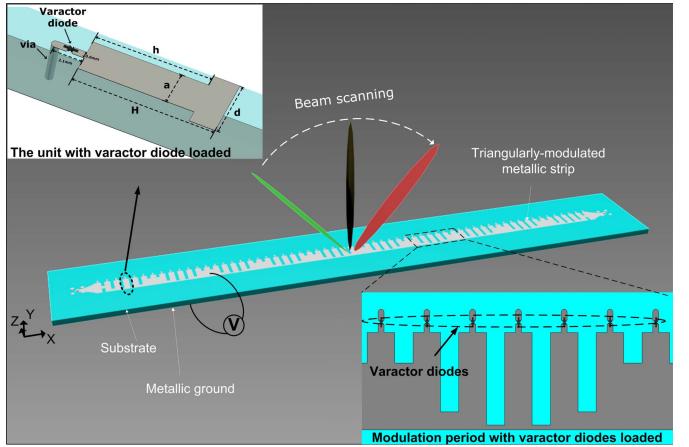


Fig. 3. Schematic of the LWA loaded with varactor diodes.

fixed frequency. In order to realize fixed-frequency beam scanning, we add varactor diodes to the design of LWA, which are connected between the grooves of the corrugated metallic strip and the metal ground through via holes, as shown in Fig. 3. When the bias voltage applied between the corrugated metallic strip and the metal ground, the capacitance value of the varactor diodes can be tuned accordingly. In this way, the surface impedance of the LWA can be reconfigured at a fixed frequency, and then the radiation beam can be steered correspondingly.

In order to predict accurate radiation direction of the beam with different capacitance values of the loaded-varactor diode, we should first obtain the relationship between the capacitance and the surface impedance Z_s from simulations. However, the lumped capacitor cannot be added in the Eigenmode Solver of CST Microwave Studio. To solve the problem, we use an equivalent model of parallel-plate capacitor to replace the lumped capacitors in the Eigenmode simulations. The equivalent model is a sandwiched structure composed of two metallic slabs spaced by a dielectric block, as shown in Fig. 4(a). Hence, the initial permittivity of the dielectric block can be simply calculated as $\epsilon_c = \epsilon_0 \cdot L_2 \cdot C / (W_1 \cdot W_2)$, in which C is the capacitance of the lumped capacitor, and W_1 , W_2 , and L_2 are the geometrical parameters as shown in Fig. 4(a). However, this formula is only suitable for an ideal model of parallel-plate capacitor, and hence ϵ_c must be optimized to make sure the model shown in Fig. 4(a) is exactly equivalent to the lumped capacitor with the capacitance C . For instance, if the lumped capacitor with capacitance of C is loaded in the LWA, then we obtain the accurate radiation angle θ_1 of the beams directly from the full-wave simulation by the loaded lumped capacitor based on the model shown in Fig. 3. On the other hand, the lumped capacitor with the capacitance C can

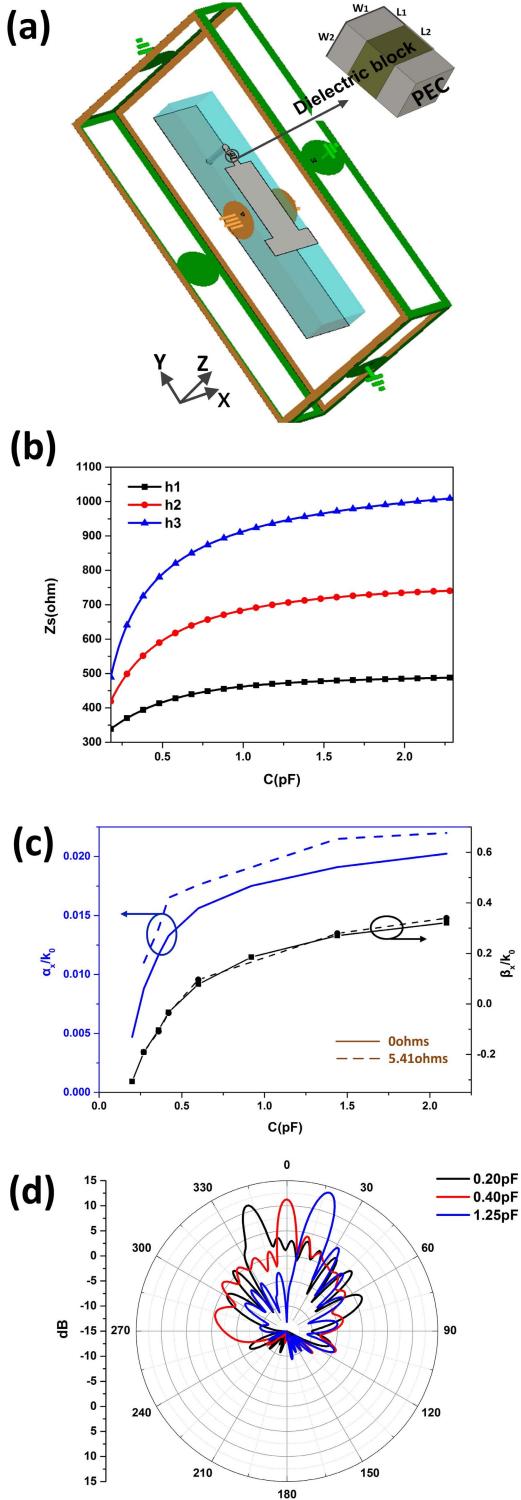


Fig. 4. Equivalent model of the capacitor-loaded unit cell and the related calculation and simulation results at 5.8 GHz. (a) Equivalent model of the unit cell in Eigenmode simulation environment. (b) Curves of surface impedance (Z_s) with respect to capacitance value for groove depth of $h_1 = 3.137$ mm, $h_2 = 8.164$ mm, and $h_3 = 9.51$ mm, respectively. (c) Normalized attenuation constant α_x/k_0 and phase constant β_x/k_0 . (d) Full-wave simulated 2-D far-field radiation patterns with loaded capacitances of 0.20, 0.40, and 1.25 pF, respectively.

be equivalent to the abovementioned parallel-plate capacitor with an initial permittivity ϵ_c , so the propagating constants k_x for different groove depths can be obtained by using

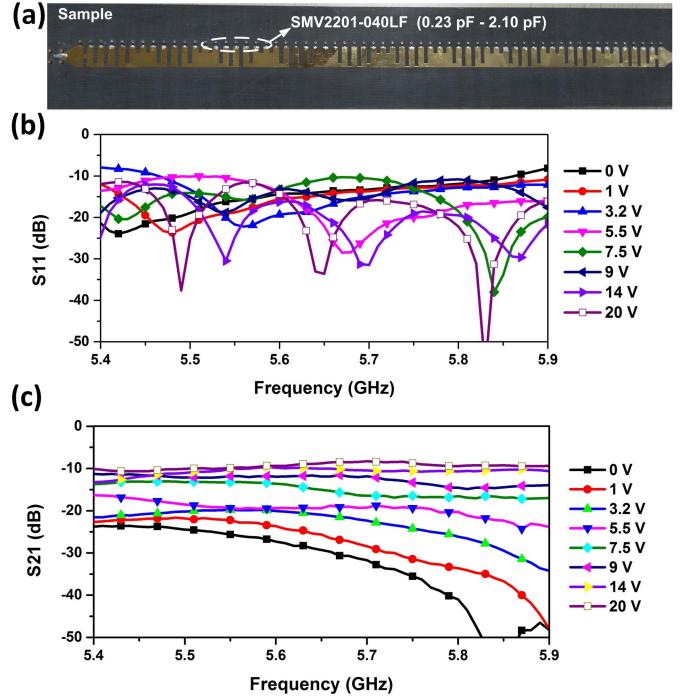


Fig. 5. Experimental sample of LWA and the measured S-parameters with different bias voltages loaded. (a) Experimental sample. (b) Measured reflection coefficients (S_{11}). (c) Measured transmission coefficients (S_{21}).

the eigenmode simulation as shown in Fig. 4(a), and then a radiation angle (θ_2) of the beam can be calculated theoretically from (2)–(4). To make sure the theoretical calculations are consistent with the full-wave simulations, the permittivity ϵ_c of the equivalent model must be optimized to make $\theta_2 = \theta_1$. Then, the surface impedances Z_s of the unit cells can be calculated from (4) by using the optimized equivalent model. The final Z_s - C curves of the unit cells with different tooth depths ($h_1 = 3.137$ mm, $h_2 = 8.164$ mm, and $h_3 = 9.51$ mm) at 5.8 GHz are demonstrated in Fig. 4(b) by sampling capacitances of $C = 0.23, 0.27, 0.36, 0.42, 0.60, 0.92, 1.44$, and 2.10 pF.

Furthermore, based on the Z_s - C curve, the leaky-wave rate α and the phase constant β can be theoretically calculated [19] as shown in Fig. 4(c) with the solid lines. The normalized attenuation constant α_x/k_0 , and it increases gradually from 0.0035 to 0.021 as the capacitance changes from $C = 0.2$ pF to $C = 2.1$ pF at 5.8 GHz, which implies that the higher radiation efficiency and gain will be achieved as the capacitance increases. The normalized β_x/k_0 increases from -0.3 to 0.32 as capacitance changes from $C = 0.2$ pF to $C = 2.1$ pF. Since the radiation angle of leaky waves can be approximately obtained by $\sin\theta \approx \beta_x/k_0$, the main beam of the leaky wave can be qualitatively predicted to scan from backward quadrant to forward quadrant continuously at 5.8 GHz by changing the capacitance of varactor diodes from 0.2 to 2.1 pF. It should be noted that the above α_x and β_x are calculated based on the lossless varactor diodes, assuming that the parasitic resistance (R) is 0Ω . However, the parasitic resistance of the varactor diode is unavoidable in practical applications, so we further calculate the α_x/k_0 and β_x/k_0 with $R = 5.41 \Omega$ as

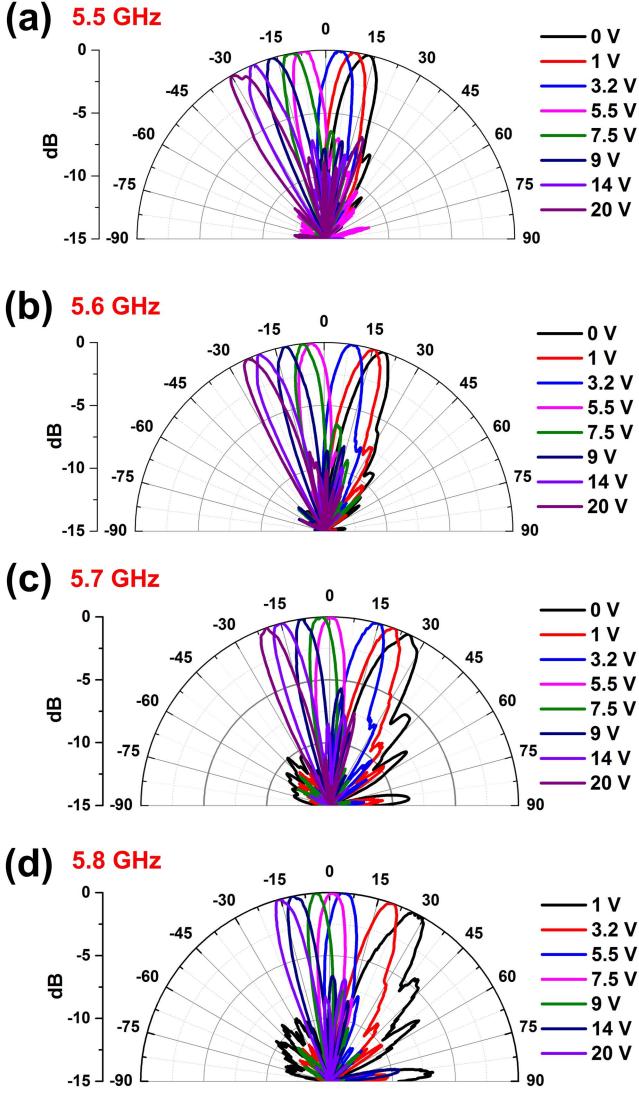


Fig. 6. Measured far-field radiation patterns with different bias voltages loaded. (a) 5.5 GHz. (b) 5.6 GHz. (c) 5.7 GHz. (d) 5.8 GHz.

shown in Fig. 4(c) with the dashed lines [22]. We remark that $R = 5.41 \Omega$ is consistent with parasitic resistance of varactor diode (SMV2201-40LF) used in the following experiment. The results show that the parasitic resistance has little influence on the β_x/k_0 but the α_x/k_0 is increased, which means the direction of the radiation beam is not influenced, but the radiation power is partially consumed by the ohmic dissipation.

According to the Z_s-C curves shown in Fig. 4(b), the radiation angle of the beam radiated by the LWA loaded with any capacitance can be predicted accurately by using (2)–(4). For example, when $C = 0.2 \text{ pF}$, which is not included in above capacitance sampling values, the calculated radiation angle is -17.4° at 5.8 GHz, which is very close to the full-wave simulated radiation angle of -16.2° [see the black solid line shown in Fig. 4(d)]. When the capacitance is increased to 0.4 and 1.25 pF , the radiation beam will steer and direct to $0^\circ / -1.1^\circ$ (simulation/calculation) and $18.9^\circ / 17.3^\circ$, respectively, as demonstrated in Fig. 4(d), showing a good agreement between the calculation and the simulation. However, because

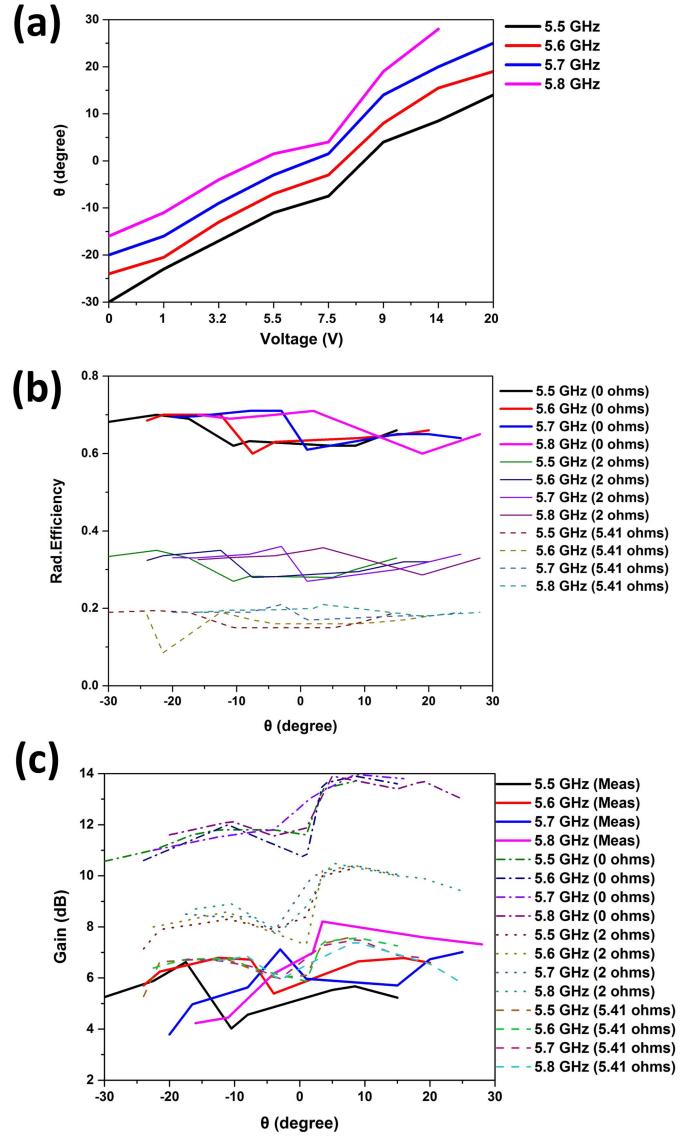


Fig. 7. Simulation and measurement results at different frequencies. (a) Measured scanning angle versus control bias voltage. (b) Simulated radiation efficiency versus pointing angle for different parasitic resistances. (c) Simulated and measured gain versus pointing angle for different parasitic resistances.

the equivalent model is not wideband, the radiation angles of the beams must be recalculated by using the above steps when the frequency changes. In theory, the largest scanning range of the beam can reach about 55° at 5.8 GHz if the loaded capacitance is varied from 0.15 to 10 pF.

III. FABRICATION AND EXPERIMENT

We design and fabricate the electronically controllable LWA, as shown in Fig. 5(a), which is composed of a metallic corrugated strip and a metal ground spaced by a dielectric substrate with permittivity 3.5 and loss tangent 0.001. The type of loaded-varactor diode we choose is SMV2201-040LF, whose capacitance values are relative to the voltages, as shown in Table II. We remark that the parasitic resistance of the varactor diode SMV2201-040LF is 5.41Ω and a BIAS-TEE

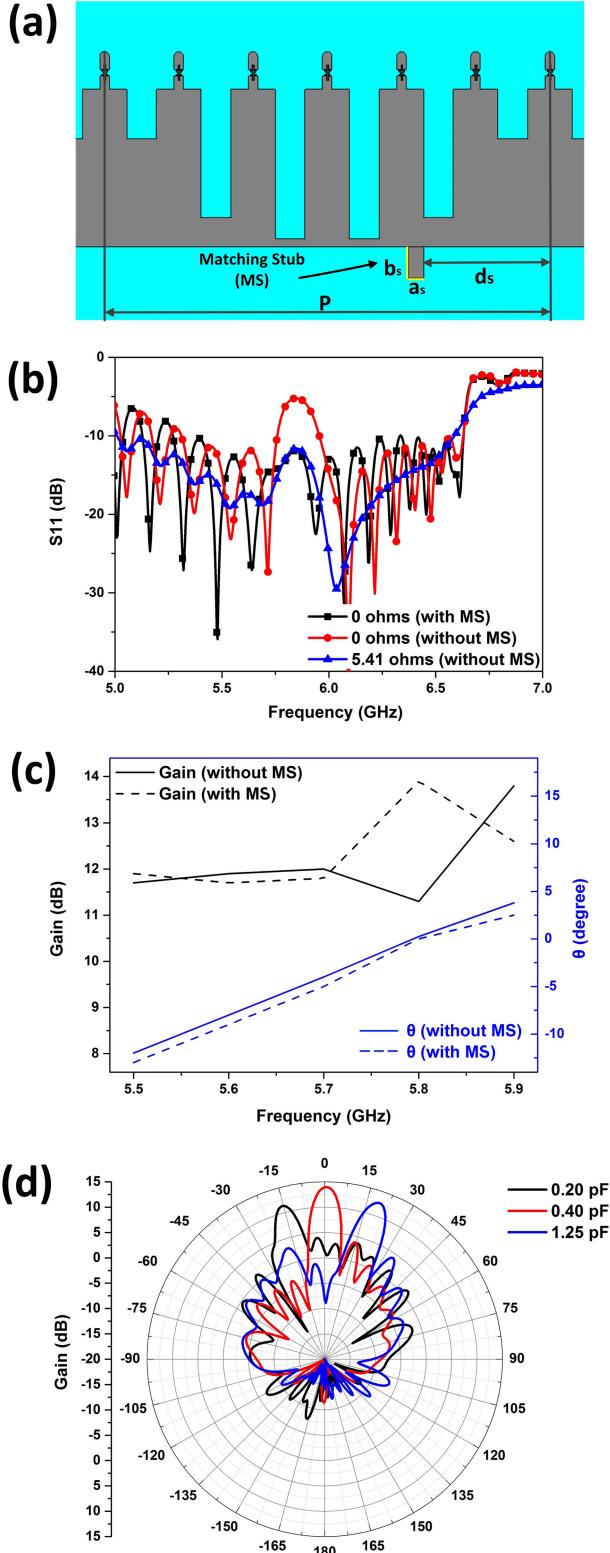


Fig. 8. Model of LWA loaded with a matching stub in each period and the simulation results. (a) Period of LWA loaded with a matching stub. (b) S_{11} . (c) Gain and scanning angle. (d) Far-field radiation patterns at 5.8 GHz with loaded capacitances of 0.20, 0.40, and 1.25 pF, respectively.

has been used as the bias network to load voltage and radio frequency signals to the LWA. The measured S-parameters of the LWA are presented in Fig. 5(b) and (c), showing that

TABLE II
RELATIONSHIP BETWEEN THE CAPACITANCES AND BIAS VOLTAGES FOR VARACTOR DIODE OF SMV2201-040LF

Vol. (V)	0	1	3.2	5.5	7.5	9	14	20
Cap. (pF)	2.10	1.44	0.92	0.60	0.42	0.36	0.27	0.23

TABLE III
RADIATION ANGLES OF THE BEAM AT 5.8 GHz ACHIEVED FROM CALCULATIONS, SIMULATIONS, AND EXPERIMENT, RESPECTIVELY

	0.23 pF (20 V)	0.27 pF (14 V)	0.36 pF (9 V)	0.42 pF (7.5 V)	0.6 pF (5.5 V)	0.94 pF (3.2 V)	1.44 pF (1 V)
Cal	-14°	-11°	-3°	0°	6°	14°	19°
Sim	-14°	-10°	-3°	1°	6°	14°	20°
Exp	-16°	-11°	-3°	1°	5°	19°	27°

both reflection (S_{11}) and transmission (S_{21}) coefficients are lower than -10 dB as the bias voltage changes from 0 to 20 V. Then, we measure the far-field radiation patterns of the beam controlled by the bias voltage at different frequencies, as demonstrated in Fig. 6. We note that the large scanning angle of the beam reaches 43° , 44° , 47° , and 45° at 5.5, 5.6, 5.7, and 5.8 GHz, respectively, by changing the bias voltage from 0 to 20 V. We compare the measured results with the calculated and simulated ones at 5.8 GHz, as listed in Table III, which have good agreements with each other.

Fig. 7(a) shows the measured radiation angle of the beam versus bias voltage at different frequencies, which show that the beams can be controlled to steer from backward quadrant to forward quadrant continuously. It should be noted that the increase of the parasitic resistance of the varactor diodes in the experiment has little influence on the radiation angle as shown in Fig. 7(a), but brings in a great influence on the radiation efficiency and gain, as shown in Fig. 7(b) and (c), which have a good agreement with the calculated attenuation constant α and the phase constant β demonstrated in Fig. 4(c). When the parasitic resistance increases from 0 to 5.41Ω , the radiation efficiency declines from about 68% to 20% [Fig. 7(b)] and the gain decreases from about 12 to 6 dB [Fig. 7(c)]. We remark that the measured gains are consistent very well with the simulated ones if the 5.41Ω parasitic resistance is added into the varactor diodes. From above discussion, we can conclude that the low radiation efficiency and gain of the designed LWA in the experiment are mainly caused by the large parasitic resistance of the varactor diode SMV2201-040LF. As a result, low-loss varactor diode can be applied to replace the SMV2201-040LF diodes in this design to effectively improve the radiation efficiency and gain.

IV. DISCUSSION OF OPEN-STOPBAND EFFECT

The periodically modulated LWAs usually suffer from an OSB at broadside radiation with low radiation efficiency [12], [23]–[25]. In order to investigate the OSB effect of the LWA proposed in this paper, we first analyze the S-parameters of the waveguide, as shown in Fig. 8(b). We assume that the loaded capacitance is $C = 0.4$ pF, when the parasitic resistance is 5.41Ω , which is the same

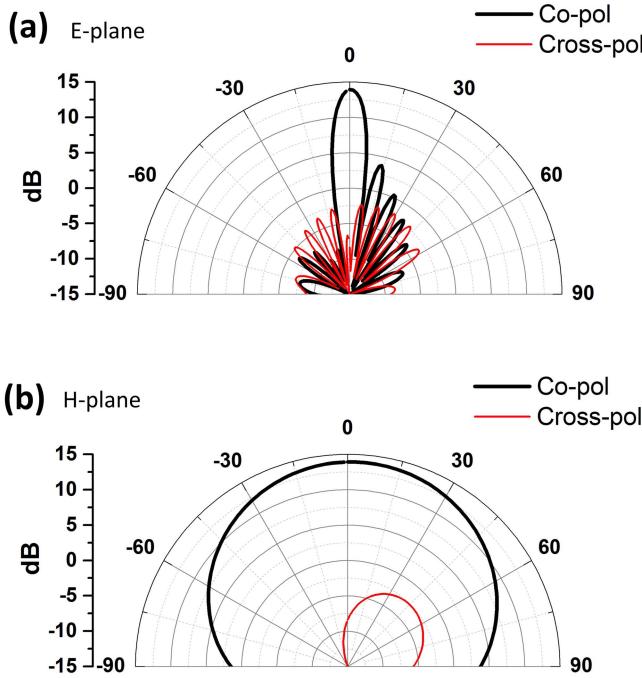


Fig. 9. Simulated far-field radiation patterns of the LWA at 5.8 GHz with loaded capacitance of 0.40 pF. (a) E-plane. (b) H-plane.

as that of the varactor diode SMV2201-040LF used in the experiment, the OSB effect still can be observed from the S_{11} parameter, as shown by the solid blue line in Fig. 8(b). However, the level of S_{11} is lower than -10 dB in the whole frequency range, which is mainly due to the large loss of the parasitic resistance introduced by the varactor diode SMV2201-040LF. So, the radiation efficiency is decreased greatly within the whole band and the OSB effect cannot be clearly observed from the radiation efficiency and gain as demonstrated in Section III. When the parasitic resistance is decreased to 0 (lossless), the OSB effect can be observed obviously from the sudden rise of the reflection coefficient (S_{11}) at broadside radiation around 5.8 GHz, as shown by the red solid line in Fig. 8(b), and the gain has a sudden decrease as shown by the black solid line in Fig. 8(c).

In order to improve the radiation efficiency at broadside radiation, we add a MS in every period of the original LWA to reduce the reflection [24] as shown in Fig. 8(a), in which the MS is located at $d_s = 14.7$ mm away from the end of each period with the size of $a_s \times b_s = 1$ mm \times 2 mm. The reflection coefficients of the lossless LWA with MS can be decreased greatly at broadside radiation (5.8 GHz) as shown by the red solid line in Fig. 8(b), and the gain can be increased from 11.6 to 13.7 dB at 5.8 GHz compared to the original LWA without MS as shown in Fig. 8(c), while the radiation angles are slightly influenced as shown by the blue lines in Fig. 8(c). Fig. 8(d) shows that the radiation beam steers from backward quadrant (-15°) to forward quadrant (17°), passing through broadside (0°), when the capacitance of the loaded-varactor diode changes from 0.2 to 1.25 pF at 5.8 GHz,

in which the gain is increased obviously at broadside radiation compared to that shown in Fig. 4(d). Hence, the OSB can be suppressed effectively by adding the MS into the LWA, and the highly efficient backward-to-forward continuous scanning can be achieved by the designed electronically controllable LWA if varactor diodes with small or near-zero parasitic resistance can be found to replace the high-loss varactor diodes SMV2201-040LF in the experiment.

Furthermore, the simulated far-field radiation patterns of the LWA with MS at broadside are plotted in Fig. 9, which show a narrow beam and a wide beam in E-plane (xoz plane) and H-plane (yoz plane) with low cross-polarization level, respectively.

V. CONCLUSION

We proposed a kind of electronically controllable LWA, which can control the radiation direction of the leaky wave in real time with a wide scanning angle at a fixed frequency by changing the bias voltages of varactor diodes. The surface impedance of the proposed LWA is modulated triangularly by designing the groove depths of the corrugated metallic strip. Infinite space harmonics are generated by the LWA, in which the one-order space harmonic is chosen to obtain a single-beam radiation. However, the radiation direction of the leaky-wave beam only steers as the frequency changes, which cannot continuously scan at a fixed frequency. In order to realize continuous beam steering at a fixed frequency, we added the varactor diodes in designing the LWA to reconfigure its surface impedance by changing the dc bias voltage, so that the beam can steer continuously as the bias voltage increases or decreases gradually. Finally, we designed, fabricated, and measured the electronically controllable LWA, in which the measured results have good agreements with the calculations and simulations, showing that the radiation beam can scan continuously in a wide range (about 45°) by changing the bias voltage from 0 to 20 V at each frequency from 5.5 to 5.8 GHz. We also provided a solution to improve the OSB effect at broadside radiation. However, due to the ohmic losses of the varactor resistance, the designed LWA suffers from low radiation efficiency (20%) and thus low-loss varactor diodes are needed for more efficient designs of this electronically controlled LWA.

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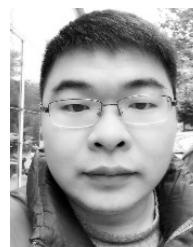
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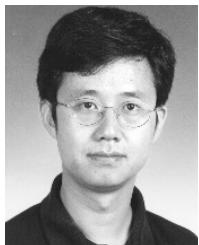
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