A New Low Cost Leaky Wave Coplanar Waveguide Continuous Transverse Stub Antenna Array Using Metamaterial-Based Phase Shifters for Beam Steering

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***Abstract*—In this paper, we have proposed a new leaky-wave coplanar waveguide (CPW) continuous transverse stub (CTS) antenna array with metamaterial-based phase shifters for beam steering applications. The array integrates three CTS elements and two 6-stage negative reflective index (NRI) phase shifters, and is fed by CPW transmission line. Beam steering capabilities are achieved by tuning the values of the NRI phase shifters. The proposed CPW-CTS array is fabricated for 2.4-GHz wireless local area network (WLAN). The measured data, including S parameters, radiation patterns and gain, agree well with the simulation results. A scan-angle range from 58° to 124° of unidirectional radiation pattern is measured in the E-plane with good impedance matching (−10 dB). Designs incorporating continuous beam steering using tunable NRI metamaterial phase shifters are also discussed.**

***Index Terms*—Beam steering, CPW-CTS antenna array, leaky wave antenna, material-based phase shifter.**

I. Introduction

CONTINUOUS transverse stub (CTS) antennas have been invented in 1990s at Hughes Aircraft Company [1] and widely adopted in modern wireless communication systems. The CTS antennas have the advantages of compact dimension, low cost, high directivity, low loss and low cross polarization. In recent literatures [2]–[7], different kinds of CTS antenna arrays are researched and developed. The coaxial transmission line based CTS antenna array is proposed for omni-directional radiation pattern [2], [3], and also achieved for multiple band applications [4]. In order to design unidirectional radiation pattern, a co-planar waveguide (CPW) transmission line based CTS antenna array is developed in [5]–[7]. In an attempt to incorporate beam steering capabilities, an integrated CPW-CTS phased antenna array with ferroelectric materials as phase shifters was proposed [7]. 40° and 30° scan-angle ranges are achieved with thinner and thicker ferroelectric substrates, respectively. However, the phased CPW-CTS array in [7] suffers from relatively high substrate loss, and biasing the Ferroelectric material presents a challenge.

In recent publications, a series of phased antenna arrays with beam steering capabilities are designed [8]–[11]. In [8], varactor-tuned high-electron mobility transistor (HEMT) voltage-controlled oscillator (VCO) is employed to control the beam angle, with a scan-angle range from 24° to 46°. Backfire-to-broadside beam–scanning is achieved in [9] by adopting a periodic offset microstrip array. More integrated phase shifters are employed in different kinds of antenna arrays including those described in [10], [11], and scan-angle ranges of 21° and 38° are achieved. From the above discussion, it may be seen that the design of phased antenna array with integrated phase shifters and wider scan-angle range continues to be a challenge.

In this paper, a leaky wave CPW-CTS antenna array with beam steering capabilities is proposed for 2.4-GHz WLAN applications. Three new CTS antennas are used as the array element. Compared with the traditional ones in [5]–[7], extra connecting patches are added at both ends to reduce the mutual coupling for the array design. In order to adjust the phase difference among the three elements, two 6-stage NRI phase shifters [12], [13] are utilized and can be easily integrated into the proposed CPW-CTS antenna array. A series of static NRI phase shifters with different values are integrated with the proposed new CTS antenna array. A scan-angle range of 66° (58°–124°) of unidirectional radiation pattern is achieved in the E-plane. A prototype of the proposed CPW-CTS antenna array has been built and tested to validate the design strategy.

II. Array Design With NRI Phase Shifters

Fig. 1 shows the geometry and the dimensions of the proposed leaky wave CPW-CTS antenna array. As shown in the 3-D view in Fig. 1(a), the antenna array consists of three CTS elements, two 6-stage phase shifters and a metallic reflector for unidirectional radiation pattern. The three CTS elements are fed by a 50

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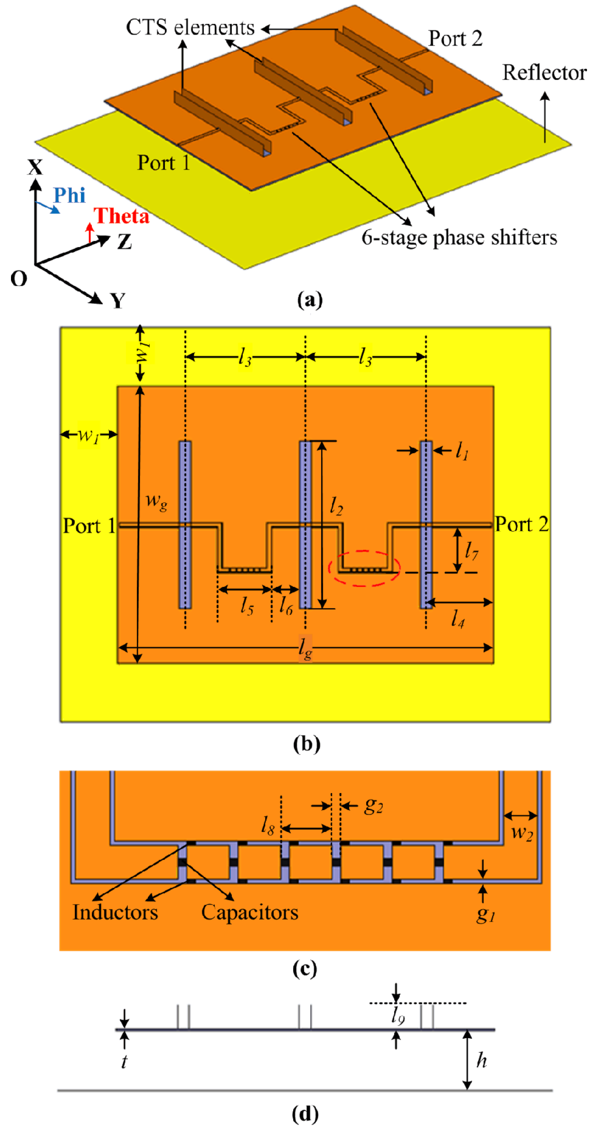

Fig. 1. Geometry and dimensions of the proposed antenna array: (a) 3-D view, (b) top view, (c) detailed view of 6-stage phase shifter, (d) side view.

Ohm CPW transmission line. The CPW-CTS antenna array is supported by an FR4 substrate board ($\varepsilon_r = 4.4$, $\tan\delta = 0.02$), with a thickness $t = 1$ mm. As shown in the top view in Fig. 1(b), three CTS elements are positioned with the distance of $l_3 = 61$ mm, approximately half wavelength in free space at 2.4 GHz ($\lambda_0 = 125$ mm). Two 6-stage phase shifters are integrated onto the meandered parts of the CPW transmission line between the CTS elements. The overall dimension of the FR4 substrate board is $l_g \times w_g = 18.8 \times 14\ \mathrm{cm}^2$. The detailed view of the phase shifter is shown in Fig. 1(c), 6-stage phase shifters are positioned periodically with the distance of $l_8 = 3$ mm. Each stage phase shifter is composed of two shunt inductors and a series capacitor. In order to achieve the unidirectional radiation pattern with higher gain than the bidirectional and omnidirectional radiation patterns, the reflector is employed at the back side of the proposed antenna array. As shown in Fig. 1(d), air substrate ($\varepsilon_r \approx 1$) is used between the proposed antenna array and the reflector and the effect of the 1 mm thick FR4 board was neglected. With this approximation, a distance of $h = 30$ mm, approximately a quarter of wavelength in free space at 2.4 GHz ($\lambda_0 = 125$ mm), is used. The dimension of each stub of CTS element is $l_2 \times l_9 = 85 \times 8\ \mathrm{mm}^2$. The proposed leaky wave CPW-CTS antenna array is fed through Port 1. In order to avoid standing wave on the feeding line, a 50-Ohm load is used at Port 2. In final implementation of the proposed integrated designs, clearly more elements would need to be used to minimize the lost power at the end load. The values of each parameter are optimized by using the Ansoft High-Frequency Structure Simulator (HFSS) software. The detailed values are listed in Table I.

TABLE I
DETAILED DIMENSIONS (UNIT: mm)

Parameter	l_1	l_2	l_3	l_4	l_5	l_6
Value	6	85	61	33	28	13.5
Parameter	l_7	l_8	l_9	h	w_1	w_2
Value	23	3	8	1	30	2
Parameter	l_g	w_g	g_1	g_2	t	
value	188	140	0.25	0.5	1	

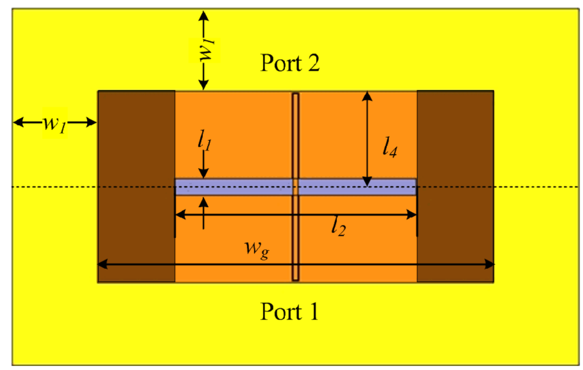

Fig. 2. Top view of the proposed new CPW-CTS element.

A. CPW-CTS Element Design

A new CPW-CTS antenna element is adopted in the proposed leaky wave antenna array design. Compared with the traditional open-ended ones discussed in [5]–[7], two connecting patches are added at both ends of the CTS element, as shown in the shadow areas of Fig. 2. For the open-ended CTS element, high mutual coupling exists among the elements in the leaky wave antenna array design. Therefore, the performances of single element and array are different, making the array design more complicated. Based on simulation results, we identified the fact that considerable portion (main part) of the mutual coupling actually comes from the extended open ends of the ground plane in the coplanar CTS design. For the new short-ended CTS element, the connecting patches are employed to prevent such mutual coupling from the open ends of the extended ground plane, and the resulting array functions as coupling between the radiating elements, rather than the cuts/ discontinuities in the ground plane was hence achieved. Therefore, the connecting patches played an important role of stabilizing the performance of the CTS array. The short ends also provide path for the return current thus maintaining the leaky transmission line-type mode of operation.

The simulated optimized S parameters of a single short-ended CTS element are shown in Fig. 3. The -10 dB reflection coef-

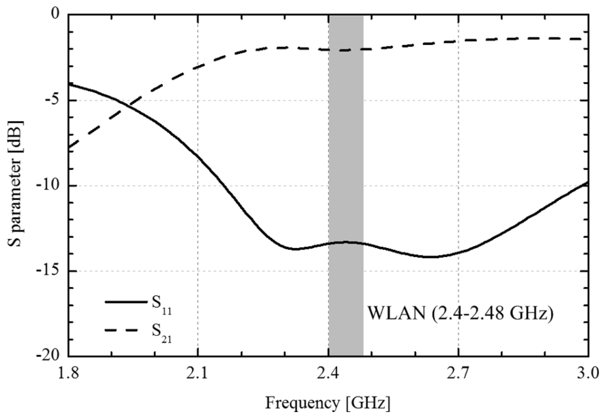

Fig. 3. Simulated S parameters of the new CPW-CTS element.

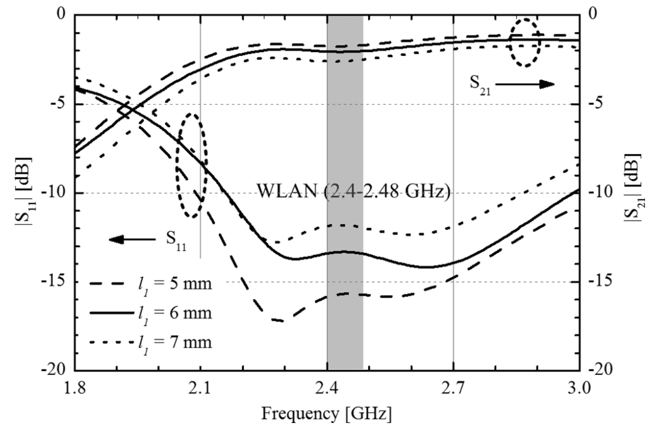

Fig. 4. Simulated $|S_{11}|$ and $|S_{21}|$ with different l_1.

ficient bandwidth is from 2.16 GHz to 2.98 GHz. In the WLAN band of 2.4–2.48 GHz, the S21 fluctuates from -2.05 dB to -2.09 dB. The radiated power ratio is approximately 35% for the single element at 2.4 GHz, calculated based on (1) [5]

$$Pwr_{rad} \approx (1 - Pwr_{refl} - Pwr_{trans}) \times 100\% \qquad (1)$$

where Pwr_{reft} and Pwr_{trans} are the reflected power and the transmit power relative to the incident power, and can be calculated using the data in Fig. 3.

For the series-fed leaky wave antenna array, more elements can be added easily to achieve higher gain. For large number of elements, the radiated power ratio of each element is expected to be reduced. Each element radiates relatively equal energy, and with small effect to the traveling wave in the feed line. Therefore, the radiated power ratio of each element needed to be carefully controlled to emphasize and better evaluate the proposed integrated CTS-NRI design. The width l_1 of CTS element is tuned to control the radiated power ratio. As shown in Fig. 4, when l_1 increases, more energy is radiated. With different l_1 values of 5 mm, 6 mm and 7 mm, the radiated power ratios from the three elements were approximately 30%, 35% and 39% at 2.4 GHz. For design simplicity, however, we used 3 elements in leaky wave antenna array, and chose an average value of $l_1 = 6$ mm for all the elements. The length l_2 of CTS antenna is tuned to control the operating frequency. The value of l_2 equals to one wavelength on the substrate, and half wavelength for each arm. The connecting patches used at both ends are metallic boundaries, and equal to virtual metallic boundaries to the CPW transmission line after an electrical length of half wavelength. Therefore, the CPW transmission line is able to feed a leaky wave antenna array. As shown in Fig. 5, the half wavelength mode of the electric field distribution appears in each arm. The length l_9 of the CTS stub is different from the ones discussed in [2]–[7]. For the open-ended CTS element, the length of the stub is approximately a quarter of wavelength due to the equally open-circuit boundary condition. For the shorted-ended CTS element, the stubs operate as loaded capacitor. As shown in Fig. 6, the impedance bandwidth can be optimized by tuning l_9. The value of w_g determines the front-back ratio of the radiation pattern. With the increasing w_g, the front-back ratio in-

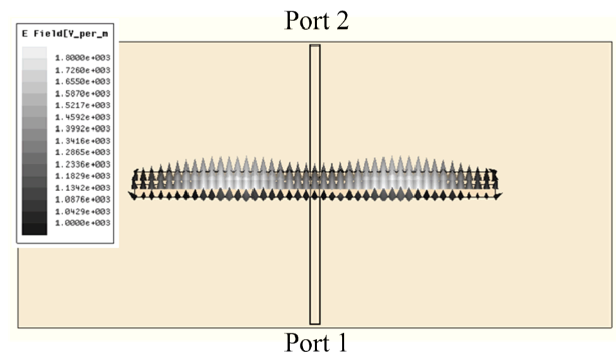

Fig. 5. Electric field distribution in CTS at 2.4 GHz.

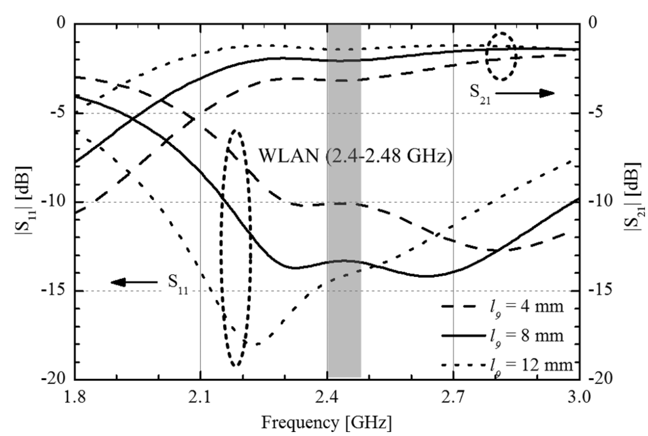

Fig. 6. Simulated $|S_{11}|$ and $|S_{21}|$ with different l_9.

creases. When w_g is larger than 140 mm, the front-back ratio almost stays the same. Therefore, $w_g = 140$ mm is selected. As discussed above, due to the connecting patches, the parameter tuning method of a single CTS element can be adopted for the CTS antenna array.

B. NRI Phase Shifter

In order to achieve beam steering at a fixed single frequency, the NRI phase shifter discussed in [12], [13] is adopted and integrated onto the feeding CPW transmission line. The NRI phase shifter is a kind of metamaterial-based phase shifter, and systematically studied and discussion in [14]–[16], showing good

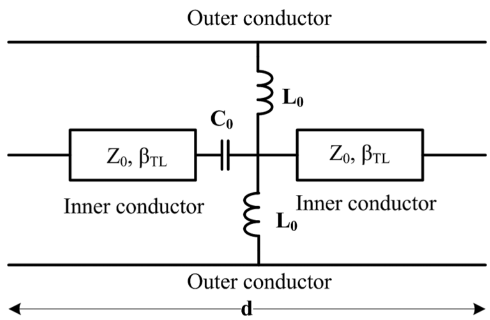

Fig. 7. 1-stage NRI phase shifter integrated with CPW transmission line.

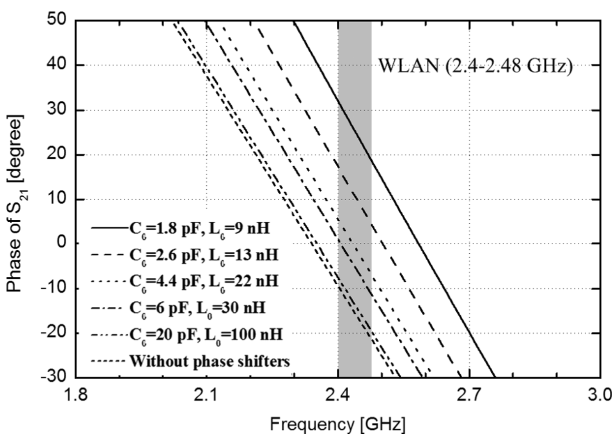

Fig. 8. Simulated phase of S_{21} of 1-stage NRI phase shifter with different values of C_0 and L_0.

performance in phased array design. The phases of each element can be controlled flexibly by employing the metamaterial-based phase shifter. As shown in Fig. 7, each unit cell of NRI phase shifter consists of a series capacitor C_0, and two symmetrically arranged shunt inductors L_0. As discussed in [11], using this structure, a stopband exists between two cutoff frequencies f_{c1} and f_{c2}. When L_0 and C_0 satisfy the matching condition of (2), the stopband closes with $f_{c1} = f_{c2}$.

$$Z_0 = \sqrt{\frac{\frac{L_0}{2}}{C_0}}. \quad (2)$$

In order to examine the phase shift based on (2), a 1-stage NRI phase shifter integrated onto CPW transmission line is simulated. The length (d) is 78 mm, approximately 35/36 of the wavelength of the CPW on the substrate. Therefore, -10.2° phase difference exists between two ports without using the phase shifter, as shown in Fig. 8. The phase lag by using different NRI phase shifters is illustrated in Fig. 8 and the detailed values are listed in Table II. With the smaller values of the components, more phase lag is achieved and is stable in the band of 2.4–2.48 GHz. However, the impedance matching of the CPW transmission line deteriorates with smaller values of the components, as shown in Fig. 9. The S21 of different phase shifters are all higher than -0.3 dB, which are not shown in the figures. There is, therefore, a trade off between impedance matching and phase lag while choosing the values of the phase shifter.

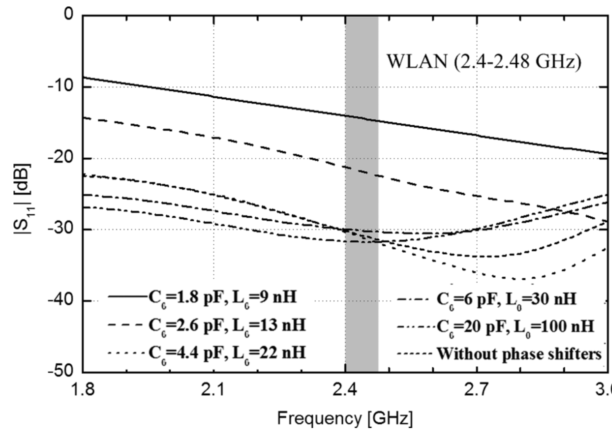

Fig. 9. Simulated $|S_{11}|$ of 1-stage NRI phase shifter with different values of C_0 and L_0.

TABLE II
PHASE LAG OF S_{21} WITH DIFFERENT PHASE SHIFTER AT 2.4 GHz

Capacitor C_0	1.8 pF	2.7 pF	4.4 pF	6 pF	20 pF	Without phase shifter
Inductor L_0	9 nH	13 nH	22 nH	30 nH	100 nH	
Phase of S_{21}	31.0°	17.3°	5.5°	1.0°	-8.4°	-10.2°
Phase Lag	41.2°	27.5°	15.5°	11.2°	1.8°	0°

C. Beam Steering Capabilities

By integrating the 6-stage NRI phase shifters with the 3-element CPW-CTS antenna array, beam steering capabilities are achieved. The beam steer angle scans in the xz-plane (E-plane), with $\varphi = 0^\circ, 0^\circ \leq \theta \leq 180^\circ$. As shown in Fig. 1(b), the overall length of CPW transmission line between two adjacent CTS elements is $l_3 + l_7 \times 2 = 107$ mm, approximately 4/3 of the wavelength of the CPW on the substrate at 2.4 GHz. The phase difference between adjacent CTS elements is 120°. Therefore, as shown in Fig. 10(a), the direction of the beam in the E-plane is 59°, 31° deviation from the broadside ($\theta = 90^\circ$).

By adding different static NRI phase shifters, different beam steering angles are achieved. Fig. 10 shows the radiation patterns in the E-plane with different NRI phase shifters at 2.4 GHz. As illustrated in Fig. 10(a), the smaller values of the components achieve larger beam steering angle. When $C_0 = 3.0$ pF and $L_0 = 15$ nH, the direction of the beam in the E-plane is 90° (broadside pattern). The direction of the beam in the E-plane is 122° by using the phase shifters of $C_0 = 1.8$ pF and $L_0 = 9$ nH. The detailed beam steering angles with different NRI phase shifters at 2.4 GHz are listed in Table III. It is clearly seen that a 63° beam-scanning angle is achieved in the E-plane with stable gain, which fluctuates between 11 dBi to 12.2 dBi. With the beam steering angle changing from 59° to 90°, the gain difference between the mainlobe and the sidelobe increases monotonously, from 6.5 dB to 21 dB. With the beam steering angle changing from 90° to 122°, the gain difference between the mainlobe and the sidelobe decreases monotonously, from 21 dB to 8.1 dB. This characteristic and based on a predetermined what is considered acceptable sidelobe level, the operating range of the steering angle could be determined. As

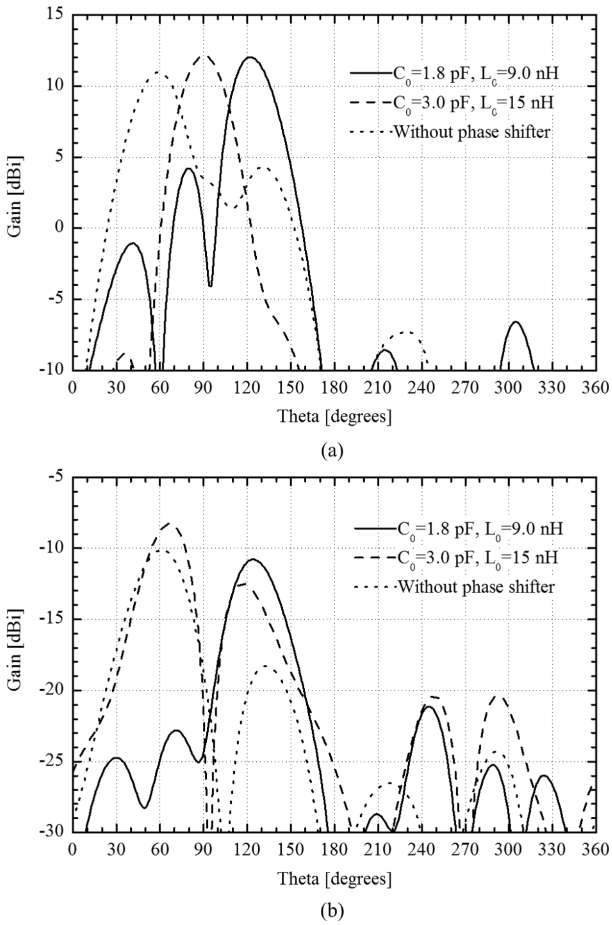

Fig. 10. Simulated E-plane radiation pattern with different values of C_0 and L_0 at 2.4 GHz, (a) co-polarization, (b) cross-polarization.

TABLE III
DIRECTIONS OF BEAM WITH DIFFERENT PHASE SHIFTERS

Capacitor C_0	1.8 pF	2.6 pF	4.4 pF	6 pF	20 pF	Without phase shifter
Inductor L_0	9 nH	13 nH	22 nH	30 nH	100 nH	
Beam steering	122°	109°	90°	79°	62°	59°

shown in Fig. 10(b), the cross-polarization level is more than 20 dB lower than the co-polarization.

Fig. 11 shows the 3-D radiation patterns of co-polarization for the leaky wave CPW-CTS antenna array with or without phase shifters. From the simulated results, the 3-dB beam width in the Y-direction at 2.4 GHz is 68°, with a cross-polarization level of -18 dBi. As listed in Table IV, in the WLAN band of 2.4–2.48 GHz, a stable beam scanning range of 63° is achieved by adding the NRI phase shifters of $C_0 = 1.8$ pF and $L_0 = 9$ nH.

III. EXPERIMENTAL RESULTS

To validate the design strategy, prototypes of the proposed CPW-CTS antenna array with and without the NRI phase shifters were built and measured. As shown in Fig. 12, the array prototype was fed by a 50-Ohm CPW transmission line, and supported by foam ($\varepsilon_r \approx 1, h = 30$ mm). Fig. 13 shows a clear view of the connecting patches of the proposed CTS antenna array. The stubs of CTS elements were made of copper tapes and also supported by foam. The reflector was made of alumina board with the thickness of 1.5 mm. Port 1 was connected to the feeding cable and Port 2 was loaded by 50 Ohm. Due to the parasitic parameters, the phase shifters are selected with the values of $C_0 = 1.8$ pF and $L_0 = 8.2$ nH for the desired phase shift. The antenna array was measured in the anechoic chamber of HCAC, University of Hawaii at Manoa.

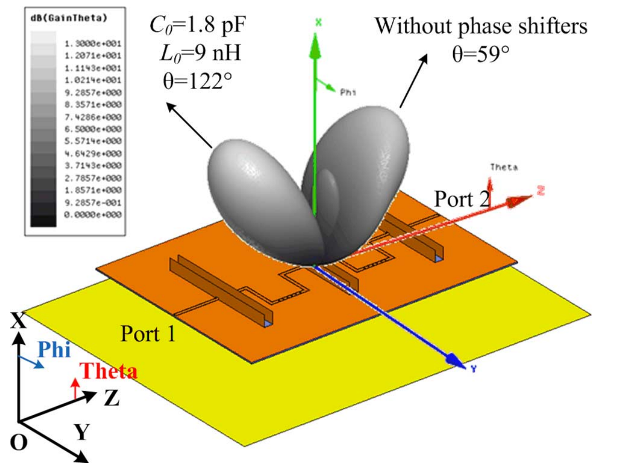

Fig. 11. Simulated 3-D radiation pattern (co-polarization) of the proposed CPW-CTS antenna array with and without phase shifters at 2.4 GHz.

TABLE IV
BEAM STEERING CAPABILITY AT DIFFERENT FREQUENCY WITH PHASE SHIFTER OF $C_0 = 1.8$ pF AND $L_0 = 9$ nH

Frequency	Without phase shifter	With phase shifter	Angle range
2.4 GHz	59°	122°	63°
2.44 GHz	57°	120°	63°
2.48 GHz	55°	118°	63°

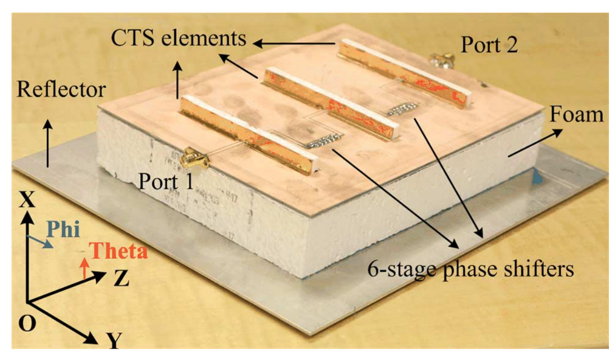

Fig. 12. Photograph of the proposed antenna array.

A. S *Parameters*

The measured results of S parameters are shown in Fig. 14, which agreed well with the simulated results. As shown in Fig. 14(a) and (b), the bandwidths of the $|S_{11}| < -10$ dB are 2.24–2.63 GHz for the array without phase shifters, and 2.28–2.71 GHz for the array with phase shifters, both covering the WLAN band of 2.4–2.48 GHz. In this desired band, the $|S_{21}|$ are lower than -5.5 dB and -8.2 dB, respectively. The

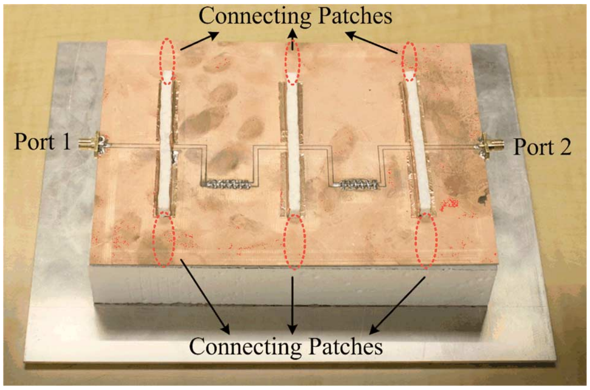

Fig. 13. Photograph of the connecting patches of the proposed antenna array.

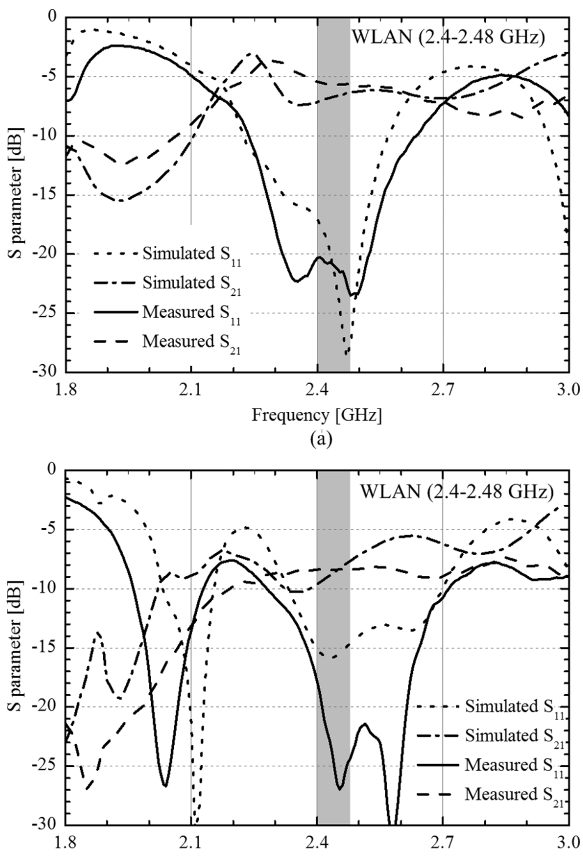

Fig. 14. Measured and simulated S parameters of the proposed CPW-CTS antenna array, (a) without phase shifters, (b) with phase shifters.

measured results show good impendence matching for both the arrays without and with the phase shifters.

B. Beam Steering Performance

The radiation patterns in the E-plane at different frequencies were measured with an angle step of 2°. The co-polarization and cross-polarization level are illustrated in Fig. 15(a) and (b). By using the NRI phase shifters of $C_0 = 1.8$ pF and $L_0 = 8.2$ nH, 66° measured scan-angle range is achieved in the entire WLAN band of 2.4–2.48 GHz, as listed in Table V. 3° angle difference

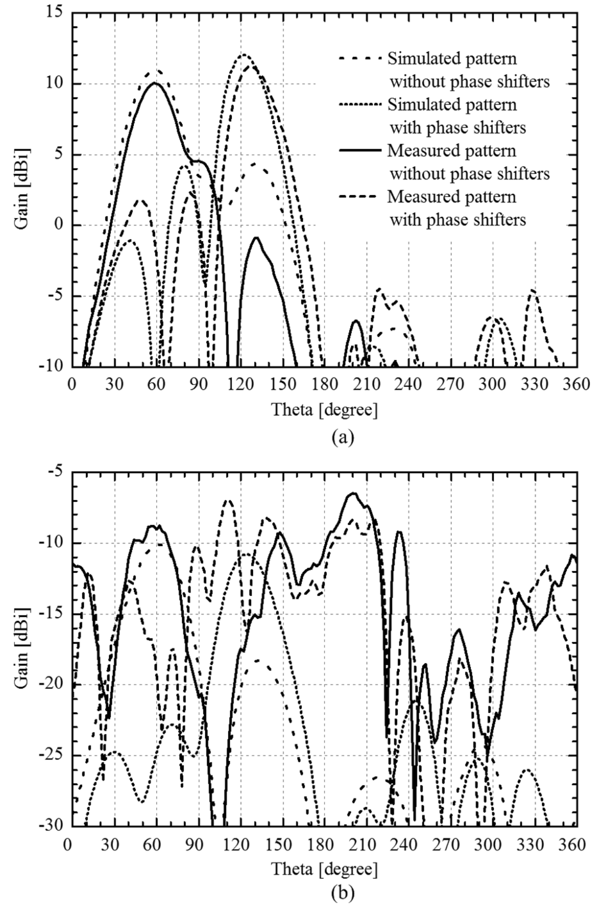

Fig. 15. Simulated and measured radiation patterns in E-plane at 2.4 GHz. (a) co-polarization; (b) cross-polarization. [(a) and (b) use the same legend].

exists, compared with the simulated results. Due to the undesired radiation and reflection from the feeding cable, the cross-polarization level is higher than the simulated results, but still 18 dB lower than the level of co-polarization. The difference between simulation and measurement, however, is considered acceptable given the small values of cross polarization powers.

The measured gains for the antenna array without and with the NRI phase shifters are shown in Fig. 16, compared with the simulated results. In the desired band of 2.4–2.48 GHz, the measured gains are better than 9.7 dBi for the array without phase shifters and 11 dBi for the array with phase shifters. The average gain losses between measurement and simulation are 1.1 dB and 0.7 dB, respectively. The difference is mainly from the parasitic lossy resistance of the lumped components and the error of the measurement system. From the simulation, we also know that the radiation efficiencies are 81% and 88% at 2.4 GHz for the proposed antenna array without and with phase shifters.

IV. Conclusion

This paper presents a new 3-element leaky wave CPW-CTS antenna array design with metamaterial-based phase shifters for beam steering. The CTS element employs two connecting patches at both ends, to help minimize mutual coupling in the array and achieve a consistent working principle by providing the return current for leaky transmission line arrangement. The NRI phase shifters are adopted to tune the phase difference

TABLE V
BEAM STEERING CAPABILITY AT DIFFERENT FREQUENCIES WITH PHASE SHIFTERS OF $C_0 = 1.8$ pF AND $L_0 = 8.2$ nH

Frequency	Without phase shifter	With phase shifter	Angle range
2.4 GHz	58°	124°	66°
2.44 GHz	56°	122°	66°
2.48 GHz	56°	122°	66°

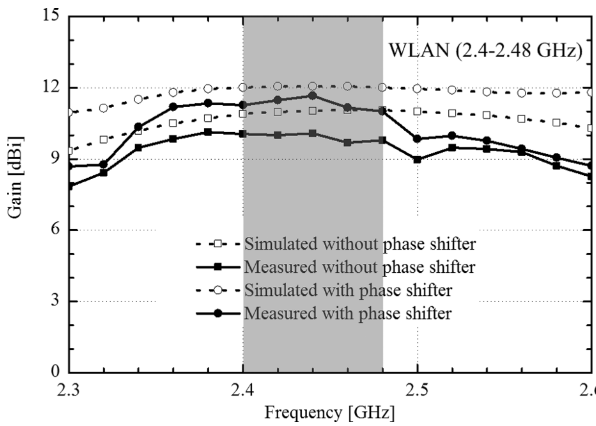

Fig. 16. Simulated and measured gains of the proposed antenna array.

between adjacent elements. The NRI phase shifters are easily integrated onto the CPW feeding line. A measured unidirectional scan-angle range of 66° (58°–124°) is achieved in the E-plane, wider than the designs in [7]–[11]. The S parameters and gain are also measured and compared with the simulated results. The proposed CPW-CTS antenna array is with the merits of low cost, low cross-polarization (less than -18 dB) and wide scan-angle range.

In the future work, we will focus on the tunable NRI phase shifters design for reconfigurable beam steering capability. In the reference of [17]–[19], the tunable metamaterial-based phase shifters are designed and integrated with series-fed arrays. The most important issue is the scan-angle range of the antenna array. For example, the scan-angle ranges are 49° (from $-27°$ to 22°), 49° (from $-21°$ to 22°) and 37.4° (from $-20°$ to 17.4°) for references of [17], [18] and [19], respectively. These works give us inspiration for the tunable NRI phase shifters design integrated with CTS antenna array. The idea that incorporating tunable NRI phase shifters (using switch and varactor elements in addition to the L/C circuits) has been proposed and primarily studied in [20]. The beam scan angle range and the complex bias circuits design are still challenges and will require additional research.

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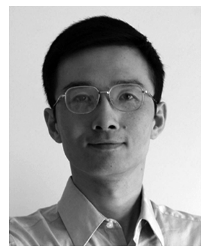

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