

A Beam Steerable CPW-CTS Antenna Array using Reconfigurable Metamaterial-based Phase Shifters for Cognitive Radio Applications

*Yue Li^{*1}, Zhijun Zhang¹, Zhenghe Feng¹, and Magdy F. Iskander²*

¹State Key Laboratory on Microwave and Digital Communications, Tsinghua University, Beijing, 100084, China,
lyee@tsinghua.edu.cn, zjzh@tsinghua.edu.cn, fzh-dee@tsinghua.edu.cn

²Hawaii Center of Advanced Communication, University of Hawaii at Manoa, Honolulu, HI, 96822, USA,
iskander@spectra.eng.hawaii.edu

Abstract

In this paper, a coplanar waveguide (CPW) fed continuous transverse stub (CTS) antenna array with beam steering capability is proposed and validated for cognitive radio applications. A novel reconfigurable negative reflect index (NRI) phase shifter is integrated with the CTS element to provide continuous phase states. The proposed phase shifter is based on CPW transmission line and consists of a series capacitor and two groups of shunt inductors. The continuous switching mechanism is achieved by adopting two groups of pin diodes and one varactor. A three-stage reconfigurable NRI phase shifters are integrated with the CPW-CTS antenna array, and a beam steering range of 81°-107° is achieved with stable gain.

1. Introduction

With the progress of wireless communication, phased arrays with continuous switchable beam steering angles have been widely studied and adopted. Such beam reconfigurable phase array is able to provide dynamic coverage to mitigate multi-path fading, increasing the spectrum efficiency.

Continuous transverse stub (CTS) antennas have firstly been invented in 1990s [1] and widely adopted in the wireless communication systems. The CTS antennas are with the merits of compact dimension, low cost, high directivity, low loss and low cross polarization. In recent literatures [2-8], different kinds of CTS antenna arrays are studied and developed, such as the coaxial transmission line based CTS antenna array [2-4], and the co-planar waveguide (CPW) transmission line based CTS antenna array [5-6]. In order to enhance the performance for CTS array application, our group has proposed a new CTS element with extra connecting patches added at both ends to reduce the mutual coupling in the array [7-8]. Using the new CPW-CTS element, the CTS array is able to become a good candidate of beam steering operations for cognitive radio applications.

In this paper, we have proposed a novel reconfigurable NRI phase shifter based on the work of [9-10], and can be adopted in the CTS array for beam steering. The NRI phase shifter is composed by two groups of shunt inductors controlled by two groups of pin diodes and a series varactor. The reconfigurable operation states are controlled continuously by the pin diodes. The proposed NRI phase shifter is integrated with a three-element CPW-fed CTS antenna array for cognitive radio applications. A beam steering range of 81°-107° is achieved with a stable gain. The simulated results are demonstrated to verify the antenna design, which is with an excellent performance in reconfigurable configuration.

2. Reconfigurable NRI Phase Shifter

In order to achieve beam steering capability of the CTS antenna array, the NRI phase shifter studied in the reference [9-10] is adopted and integrated with the feeding CPW transmission line. As shown in Fig. 1, the CPW-based NRI phase shifter consists of a series capacitor C_0 , and two symmetrically arranged shunt inductors L_0 . In order to examine the phase shift, a one-stage NRI phase shifter integrated onto CPW transmission line is simulated. The length (d) is 78 mm, approximately 35/36 of wavelength of the CPW on the substrate (FR4, $\epsilon_r=4.4$, $\tan\delta=0.02$) at 2.4 GHz. As a result, the phase difference between the two ports is -10.2° without using any phase shifter. The phase lags by using different NRI phase shifters (different values of C_0 and L_0) are illustrated in Fig. 2(a). With the smaller values of the components, bigger phase lag is achieved in the band of 2.4-2.48 GHz. In order to achieve good impedance matching, a relationship between C_0 and L_0 must be fulfilled [9-10]. With different values of L_0 , C_0 must be varied accordingly.

However, the impedance matching of CPW transmission line deteriorates with smaller values, as shown in Fig. 2(b). Therefore, a tradeoff between impedance matching and phase lag must be considered while choosing the values of the NRI phase shifter.

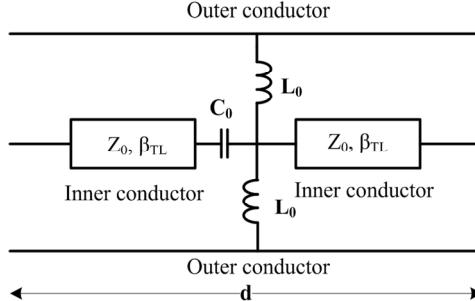


Fig. 1. One-stage NRI phase shifter integrated with the CPW (inner and outer conductors), consisting of a series capacitor and two shunt inductors.

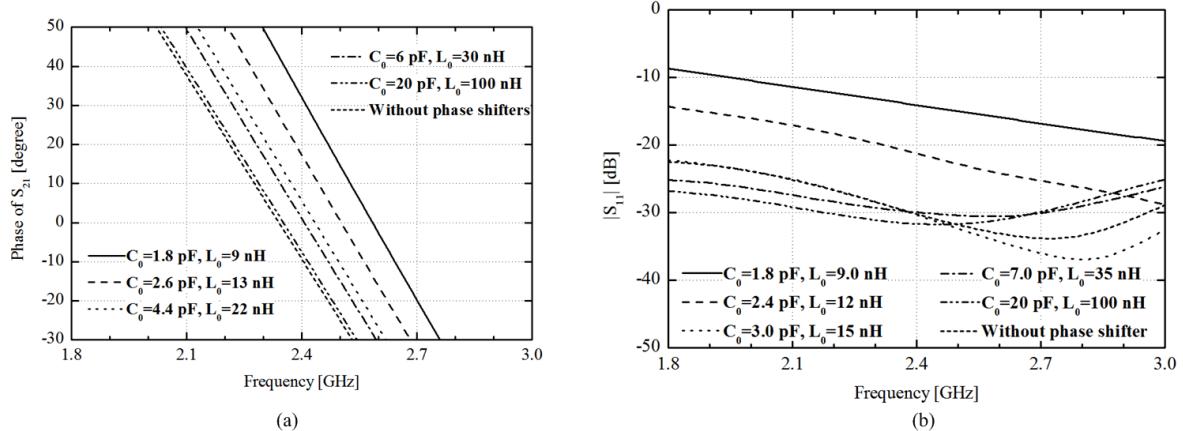


Fig. 2. (a) Simulated phase of S_{21} and (b) Simulated $|S_{11}|$ of 1-stage NRI phase shifter in Fig. 1 with different values of C_0 and L_0 .

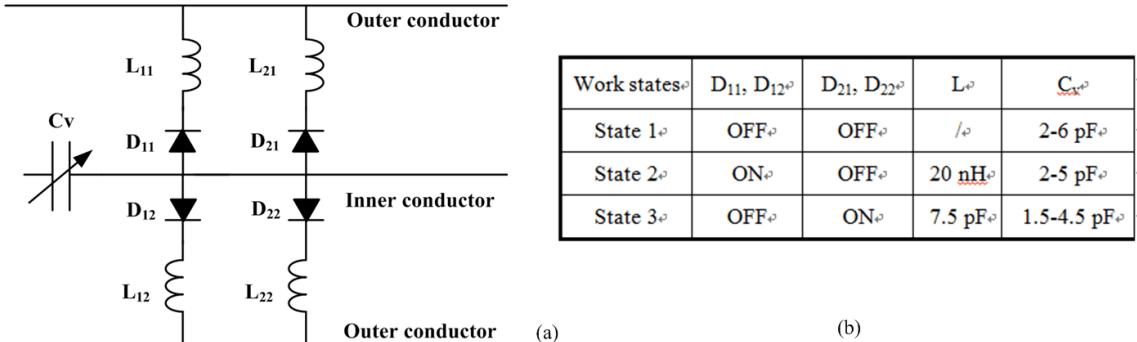


Fig. 3. (a) 1-stage reconfigurable NRI phase shifter integrated with CPW transmission line, consisting of a series varactor, four shunt inductors and four pin diodes; (b) Operation summary using the reconfigurable NRI phase shifter in (a).

We aim to achieve a continuous phase variation from the NRI phase shifter. A reconfigurable mechanism based on Fig. 1 is proposed and shown in Fig. 3(a). We use two groups of pin diodes to control the values of the shunt inductors, and a varactor providing accordingly capacitance with the inductance. For the NRI phase shifter used in this paper, $L_{11}=L_{12}=15$ nH, $L_{21}=L_{22}=15$ nH. The operation states are listed in TABLE I. For State 1, D_{11} and D_{12} are “OFF”, while D_{21} and D_{22} are “OFF”, no shunt inductors are connected to the CPW transmission line, the varactor changes from 2 pF to 6 pF. For State 2, D_{11} and D_{12} are “ON”, while D_{21} and D_{22} are “OFF”, the shunt inductance is 20 nH, the varactor changes from 2 pF to 5 pF. For State 3, D_{11} and D_{12} are “OFF”, while D_{21} and D_{22} are “ON”, the shunt inductance is 7.5 nH, the varactor changes from 1.5 pF to 4.5 pF. Therefore, a continuous phase variation is achieved by using the proposed reconfigurable schemes of the NRI phase shifter.

3. Application on Beam Steering Phased Array

We have integrated the proposed reconfigurable NRI phase shifter to a three-element CPW-CTS antenna array to validate the design strategy. The geometry and dimensions of the proposed CPW-CTS array are shown in Fig. 4(a). A three-stage reconfigurable NRI phase shifter is used between two CTS elements. Figs. 4(b) and (c) show the top view and side view of the proposed antenna array, respectively. The CPW-CTS antenna element is supported by an FR4 substrate ($\epsilon_r=4.4$, $\tan\delta=0.02$ and thickness is 1 mm). The dimension of CPW is designed to achieve 50 ohm at the input and output ports. Three new CTS elements [7-8] are located on the front side of the substrate and fed by the CPW transmission line. The stubs of CTS element are tilted with the angle of 45° , as shown in Fig. 4(c). The structure of the stub is tuned to control the emission rate of the input energy. In order to achieve a uni-directional radiation pattern, an 8×6 -element mushroom-typed EBG structure is used as the back cavity, as shown in Fig. 4(c). The EBG is placed at a distance of 30 mm, approximately a quarter of wavelength in free space at 2.4 GHz. The array consists of three CTS elements, with the distance of 95mm, approximately 0.77 wavelengths in free space at 2.4 GHz.

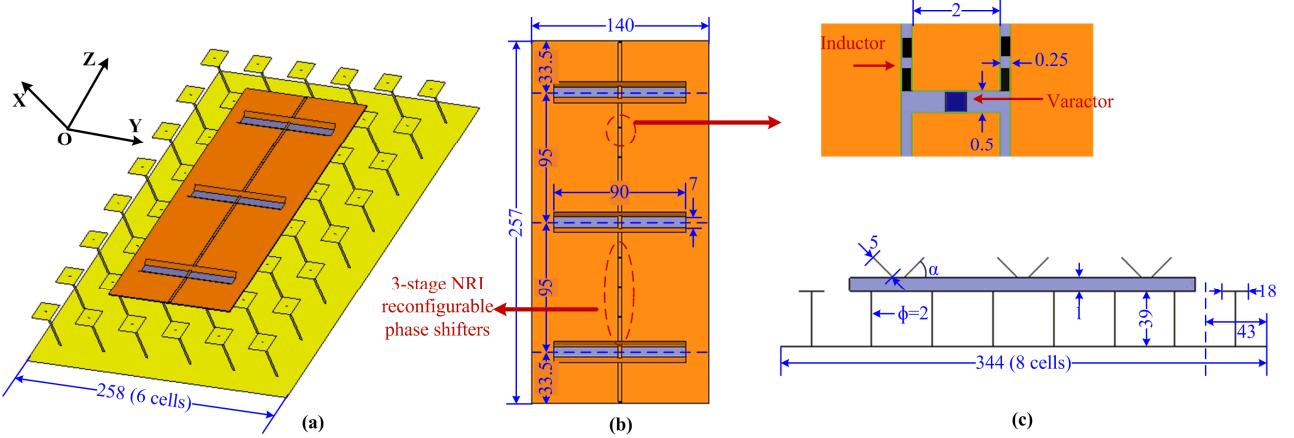


Fig. 4. Antenna geometry and dimensions (Unit: mm): (a) 3-D view with mushroom-typed EBG ground, (b) top view with two sets of three-stage NRI phase shifters, (c) side view of antenna array.

The series CPW-fed CTS antenna array with the proposed reconfigurable NRI phase shifter is simulated using the software of Ansoft High-Frequency Structure Simulator (HFSS). The radiation patterns of different operating states (as summarized in Fig. 3(b)) are illustrated in Fig. 5. For the State 1 in Fig. 5(a), the beam steering angle changes from 81° to 92° , with the capacitance from 2 pF to 5 pF. For the State 2 in Fig. 5(b), the beam steering angle changes from 87° to 98° , with the capacitance from 2 pF to 5 pF. For the State 3 in Fig. 5(c), the beam steering angle changes from 95° to 107° , with the capacitance from 1.5 pF to 4.5 pF. By combining all the operating states, the overall steering angle is from 81° to 107° ; and the gain is stable and better than 12 dBi.

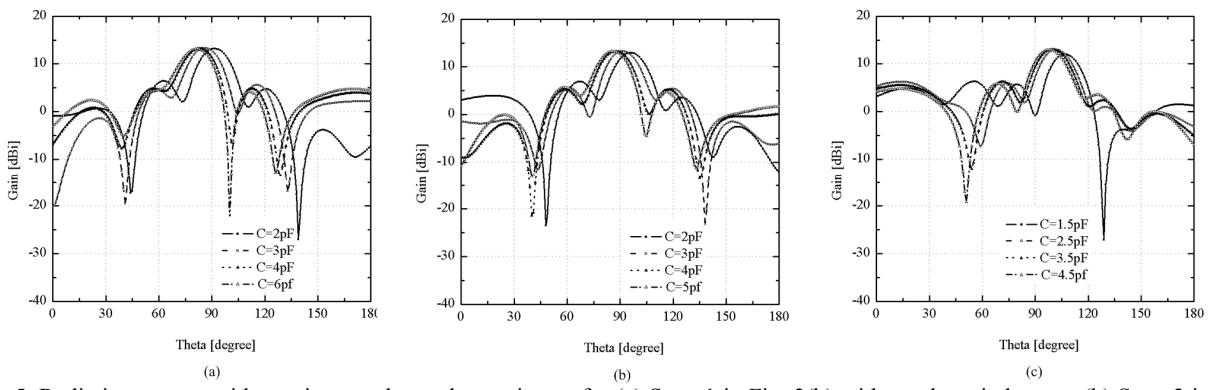


Fig. 5. Radiation pattern with continuous changed capacitance for (a) State 1 in Fig. 3(b) with no shunt inductors; (b) State 2 in Fig. 3(b) with shunt $L=20$ nH; (c) State 3 in Fig. 3(b) with shunt $L=7.5$ nH.

4. Conclusion

In this paper, a beam steerable CPW-CTS antenna array is proposed for beam steering in 2.4-GHz cognitive radio applications. We also have proposed a CPW-based reconfigurable NRI phase shifter, which can be easily integrated with the CTS antenna array for the element phase tuning. The NRI phase shifter is composed by two sets of shunt inductors, controlled by two sets of pin diodes and a series varactor. A mushroom-typed EBG structure is utilized as the back ground to achieve uni-directional radiation pattern of the proposed CPW-CTS antenna array, without the deterioration of impedance bandwidth and gain. Three continuous phase states can be provided with different operating configurations. A beam steering angle range of 81° - 107° is achieved with stable gain better than 12 dB. The proposed antenna array shows the potential application in cognitive radio.

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