Equivalent Circuit Model for Varactor-Loaded Reconfigurable Intelligent Surfaces

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***Abstract*— Reconfigurable intelligent surfaces (RIS) have gained a lot of attention due to its ability to perform low-cost beam steering for applications in emerging smart radio environments. An equivalent circuit model for a varactor-loaded microstrip RIS element, covering a wide tuning range and providing accurate physics-based circuit model for both reflection phases and magnitudes for a normal incidence is developed and presented. The circuit model facilitates system level study of RIS-based wireless communication networks with realistic analytical RIS responses as parameter inputs.**

I. Introduction

Communication channels have been characterized as random for the past generations of wireless communication networks. The channel noise, path fading, and distortion usually cannot be modified within the channel but can only be compensated for at the transmitter or receiver end of the communication system. However, current research seeks to control the communication channel using an adaptive thin composite material sheet capable of modifying the radio waves impinging upon it. The RIS can be designed having an array of these sheets, which can control the beamforming and steering in desired locations.

The phase shifts of the unit elements for passive reflecting surface are closely related to the beamforming patterns and angles, while the reflection coefficient magnitude models the losses introduced by the unit elements. In recent articles studying RIS-enhanced wireless communication systems [1,2], the RIS elements are modeled as ideal phase shifting elements with unit reflection magnitude and arbitrary phase shift angles. This ideal model facilitates the optimal system performance outcome. However, it also suffers from the shortcoming of being non-realistic and non-physical. In this paper, we consider a practical RIS element design with realistic varactor loads, and investigate its phase shifting response as well as associated losses. An equivalent circuit is developed to model the continuous operation of the RIS unit element, offering a physics-based analytical model for system level analysis and optimization.

II. Varactor-Loaded RIS Element

RIS elements with low loss and wide phase tuning range play an essential role in the RIS operation. In this paper, a simple varactor-loaded unit cell is developed for the phase shifting analysis and response modeling. Fig. 1 shows a unit cell which consists of a rectangular microstrip radiating patch mounted on a substrate with a ground plane underneath. The varactor diode connected to the radiating patch controls the phase response of the radiating element as depicted in Fig. 1. A pin diode can also be used as reported in [3]. In our application, we choose a varactor because of its ability to give a continuous phase response in contrast to the discrete states offered by the pin diode. In the proposed model, the substrate is 1.52 mm thick, with a relative permittivity of 3.66, and the patch size is 15.2×18.21 mm^2, which is primarily resonant around 5.5 GHz. Full wave simulations with periodic boundaries are employed to calculate the phase shifting of the unit elements.

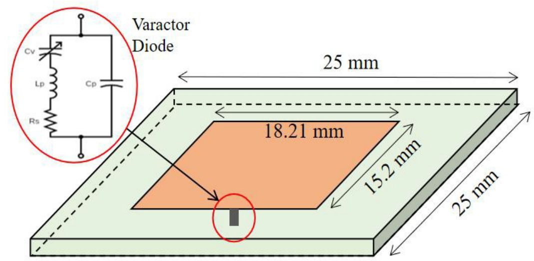

Figure 1. A simple varactor-loaded RIS unit cell.

Changing the capacitance of the varactor affects the surface response of the radiating patch to the impinging electromagnetic waves, and thus results in different phase shifts. The varactor is placed at the radiating edge of the patch element to maximize the impact of the loading for phase shifting. As shown in the equivalent circuit model of the varactor in Fig. 1, C_v is a variable term standing for the variable capacitance. The varactor chosen for this study is the MV319110-89 which has a variable C_v ranging from 0.2 pF to 2 pF as used in [4].

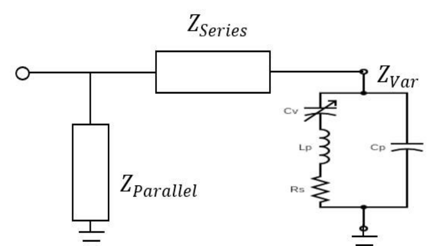

Figure 2. Equivalent circuit model for the varactor-loaded RIS element.

III. Equivalent Circuit Model for RIS Elements

An equivalent circuit model for the RIS element is proposed and shown in Fig. 2. $Z_{Parallel}$ and Z_{Series} represent the RIS unit cell connected to a varactor diode Z_{Var}. Equations (1) and (2) are the equations characterizing the impedance $Z_{Parallel}$ and Z_{Series} respectively. The total surface impedance of the RIS surface is given in (3). Z_{Air} represents the intrinsic impedance of air. The total reflection coefficient of the RIS unit cell is calculated from (4).

$$Z_{Parallel} = j\omega L_1 + R_1 + \frac{1}{j\omega C_1} \quad (1)$$

$$Z_{Series} = j\omega L_2 + \frac{1}{j\omega C_2} \quad (2)$$

$$Z_{Surface} = \frac{1}{\frac{1}{Z_{P} + Z_{S}} + \frac{1}{Z_{Var}}} \quad (3)$$

$$\Gamma = \frac{Z_{Surface} - Z_{Air}}{Z_{Surface} + Z_{Air}} \quad (4)$$

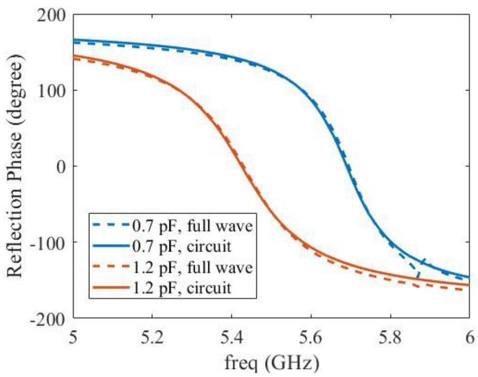

Figure 3. The equivalent circuits are fitted for two distinct states (C_v=0.7 pF and C_v=1.2 pF) simultaneously. Dashed lines are full wave responses, and the solid lines are circuit responses.

Since the proposed circuit model is expected to work for a wide tuning range, the specific circuit components are optimized for two states (C_v=0.7 pF and C_v=1.2 pF), simultaneously. Figure 3 illustrates the phase response of the two states using full wave simulation and the optimized circuit simulation. Clearly the equivalent circuit model approach yields the same results as the full wave simulation approach.

The above synthesized circuit model is then applied to various tuning states, with C_v varying from 0.4 pF to 2.0 pF, with a step of 0.2 pF. Fig. 4 (b) shows the phase response of the multiple states covering a wide phase shifting range (from 180 to -116 degrees at the design frequency of 5.5 GHz). Fig. 4 (a) shows the corresponding reflection magnitude of the RIS element at different states. The solid lines and dashed lines represent circuit model and full wave simulation respectively and can be seen to follow each other very closely, validating the proposed equivalent circuit model.

IV. Conclusion

In this paper, an equivalent circuit model for varactor-loaded RIS elements is developed and presented. The developed circuit model accurately models both the phase shift and the reflection magnitude of the multiple states of the varactor-loaded microstrip RIS element, providing a physics-based model for future study of RIS-based wireless communication systems considering hardware limitations.

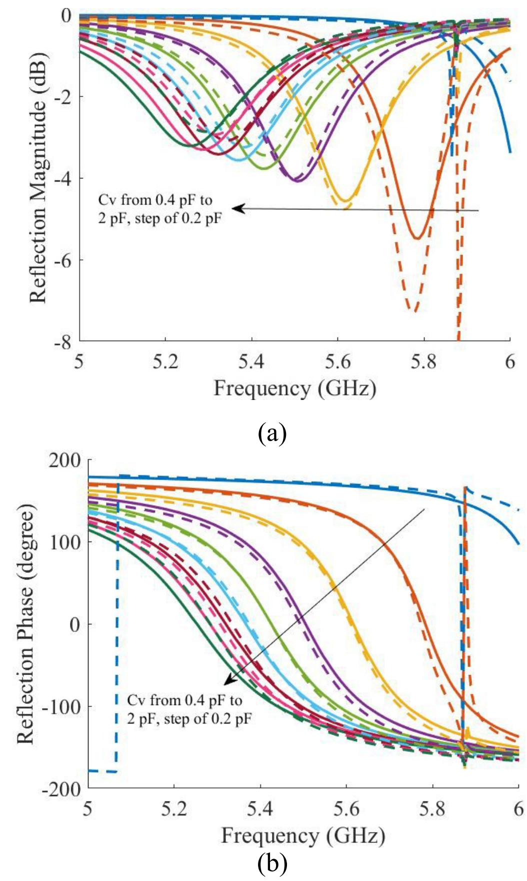

Figure 4. (a) the magnitude response for various states; (b) the corresponding phase responses. C_v ranges from 0.4 pF to 2 pF with a step of 0.2 pF. (Dashed lines are full wave simulation results, and solid lines are circuit responses.)

Acknowledgement

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