Reconfigurable Intelligent Surface Design for Enhanced Beam Steering in Communication Systems

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***Abstract*—** This paper presents a reconfigurable intelligent surface (RIS) design and simulation aimed at enhancing beamforming and beam steering capabilities for 5G and 6G mobile communications. The proposed design introduces a 2-bit unit cell design, having four distinct phase states that can be tuned by a single varactor diode. This configuration has a 5x5 array and provides efficient operation at 23.8 GHz within the 5G New Radio (NR) frequency range 2 (FR2). The proposed RIS design demonstrates unique beam steering capabilities ranging from $-60°$ to $60°$ in the azimuth plane which is crucial for extending coverage into the mm-wave coverage. The performance of the RIS is simulated using the CST 3D electromagnetic simulator, focusing on radar cross section (RCS) pattern for optimization. The simulation results reveal effective beam steering capabilities ranging from -10° to -60° and 10° to 60°, with a minimum scan loss of approximately 3 dB. The proposed RIS exhibits the high angular reciprocity that handles the incident waves up to $110°$ at an oblique $60°$ angle.

I. Introduction

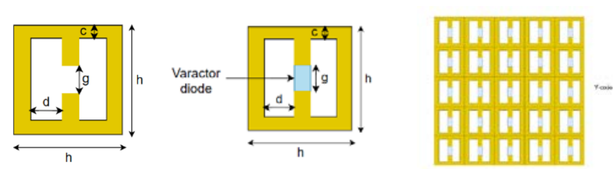
In recent years, the revolution of the wireless communication systems has been propelled by the development of novel technologies designed to enhance signal transmission, particularly in challenging environments. Among these emerging technologies, the Reconfigurable Intelligent Surfaces (RIS) have collected substantial interest due to their potential in revolutionizing wireless communications [1-2].

The focus of our work is the design and analysis of the of a varactor based 5x5 element RIS for mm-wave applications. The proposed RIS leverages the distinctive properties of metamaterials through split ring resonator (SRR)-based unit cells controlled by varactor diodes. The unique unit cell design offers an effective approach to beamforming and beam steering [3]. The design in this paper is optimized for the operational frequency at 23.8 GHz which is within the 5G New Radio (NR) frequency range and is particularly suited for enhancing mm-wave communication by extending coverage and improving signal quality in both indoor and outdoor environments for 5G and 6G communication systems.

In this paper, the proposed RIS design addresses the challenges associated with high-frequency signal propagation, such as path loss and blockages, and introduces an effective approach for improving the communication quality using a reconfigurable surface [4]. This is accomplished by manipulating electromagnetic waves using 2-bit SRR unit cells configured with a single varactor to provide four distinct phase states for controllability. A detailed analysis has been conducted and verification has been done using the 3D electromagnetic simulator, CST. It has been shown that the proposed RIS can enable beam steering between $-10°$ to $-60°$ and $10°$ to $60°$, with a minimum scan loss of approximately 3 dB. Furthermore, the proposed RIS exhibits the high angular reciprocity that handles the incident waves up to $110°$ at an oblique $60°$ angle. The results presented in this paper can be used for 5G communications systems and emerging 6G applications [5-6].

II. Design of SRR Unit Cell

The design and analysis of the SRR unit cell for the proposed RIS have been conducted using the CST 3D electromagnetic simulator to provide the desired operational characteristics at 23.8 GHz. The proposed unit cell is illustrated in Fig. 1. The outer boundary of the Split Ring Resonator (SRR) has a height (h) of 2.5mm, while the inner square side length (d) measures 1.8mm. Additionally, inside the ring of the unit cell structure, there is a cut (g) with a dimension of 0.3mm, and the height of the inner square (c) is 1.2mm. The substrate material is FR4, with a thickness of 3.0 mm, a relative permittivity of 2.65 and a dielectric loss of 0.002. A metallic ground plane exists on the bottom side of the SRR unit to guarantee absolute reflection which is a critical feature for RCS reduction.



(a) (b) (c)

Figure 1. Layout of the SRR unit cell (a) single element unit cell (b) Varactor diode with integrated with the unit cell (c) Layout of 5x5 array with the final unit cell

The varactor diode model used is the MAVR-00020-14110O from MACOM. The capacitance of this varactor diode ranges from 0.23 to 0.9 pF. The equivalent circuit of the diode used in the simulator has been modeled to reflect the lumped RLC boundary condition. The varactor diode is inserted at the main resonator arm of the FSS unit cell. This inclusion is crucial for tuning the resonance frequency of the unit cell to enable the reconfigurability feature of RIS.

III. RESULTS AND DISCUSSION

The simulation results in Fig. 2 represent the reflection amplitude as a function of frequency for different capacitance values of varactor diode based on the applied bias voltage for the 2-bit unit cell. The desired phase states are generated by using varactor diodes to present the equivalent capacitance from 0.23pF to 0.9 pF as shown in Fig. 2. The capacitor values corresponding to the four states are as follows: 0.9 pF in state 1 with and -180° phase, 0.38 pF in state 2 with and -90° phase, 0.31 pF in state 3 with and 0° phase, and 0.23 pF in state 4 with 90° phase. The reflection amplitude and phase for teach configuration state are illustrated in Fig. 3.

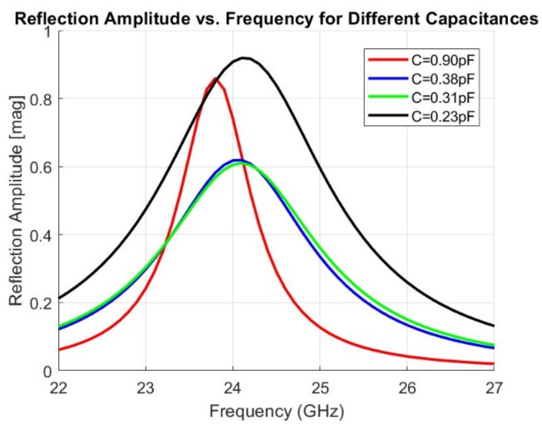
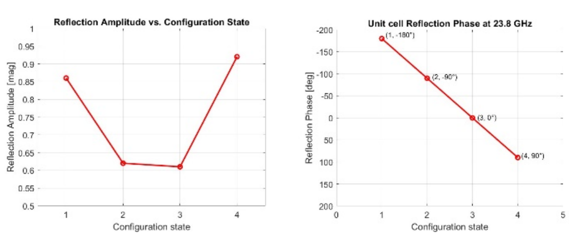


Figure 2. Reflection Coefficient Amplitude Response for Tuned Capacitance Values for 2-bit Unit Cell



(a) (b)

Figure 3. Reflection Coefficient Response for each State at 23.8 GHz for 2-bit Unit Cell (a) Amplitude (b) Phase

Figure 4 illustrates the RIS array factor for beam steering, comparing continuous and 2-bit phase control methods. It displays the amplitude in decibels (dB) against the angle theta in degrees. The continuous phase control (blue line) results in a smoother, more precise steering profile, while the 2-bit phase control (red line) shows a more discretized pattern with higher side lobes, indicating less precise beam control. The results in Fig. 4 affirm that the proposed RIS design provides phase distributions that produce the desired beam steering angle.

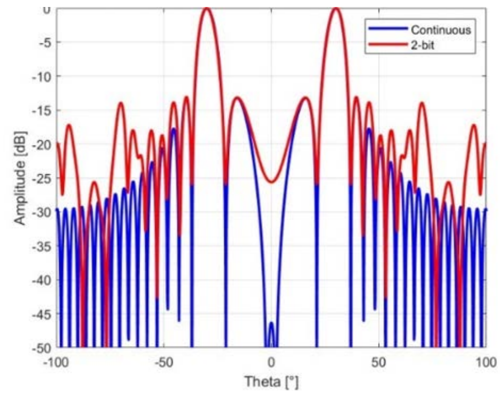


Figure 4. Comparison of Continuous and 2-Bit Phase Control for RIS Beam Steering at 23.8 GHz

IV. CONCLUSION

In this paper, design and simulation of a Reconfigurable Intelligent Surface (RIS) using 2-bit SRR unit cell is presented. The proposed design for the 2-bit Split Ring Resonator (SRR) unit cell enables four distinct states achieved by tuning a single varactor. This tuning allows for obtaining different capacitance values through the application of the required bias voltage. The RIS presented in this paper is configured using a 5x5 array featuring a unique Split Ring Resonator (SRR) unit cell. A detailed analysis has been conducted to obtain the reflection coefficient amplitude and phase response for four different states. It has been shown that the proposed RIS design can be used to effectively manipulate electromagnetic waves and provides tunability that allows for the desired beam steering and beamforming. The results in this paper can be used in enhancing the performance of wireless networks using the RIS configuration.

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