A Miniaturized Polarization-Insensitive Reconfigurable Intelligent Surface for Beam Steering Applications

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Abstract—**In this work, a miniaturized RIS design is presented for phase switching which is not only polarization-insensitive, but also achieves angular stability for both TE and TM polarized signals. A wide phase switching is obtained (-160° to +160°) by using varactor diodes, as well as high angular stability is achieved up to 50° with an operating frequency centered at 3.5 GHz. The full wave simulation results are presented and corroborated with the equivalent circuit model (ECM) response. It is hoped that this design would lead to the development of more robust and practical RIS structures for beam-steering applications.**

Index Terms—**Reconfigurable intelligent surfaces, metasurface, beam steering, polarization-insensitivity, angular stability**

I. INTRODUCTION

Reconfigurable intelligent surfaces (RISs) have assumed an important role in the development of the backbone of new communication standards. Their ability to dynamically cause a change in the propagation characteristics of the incoming signal, coupled with their small size and inexpensive nature, has led to their accelerated adoption across the new-age network infrastructure for purposes such as establishing a secure link between the source and the receiver, dynamic switching to the least path-loss transmission path, and so on. However, most of the existing studies in this area are restricted in their applicability due to one or more of the following design limitations - (a) lack of four-fold symmetry for achieving polarization-insensitive behavior, (b) limited phase tunability, and (c) low angular stability concurrently for TE and TM polarized wave. Recently, a polarization-insensitive structure exhibiting a wide phase tunability has been proposed [1], however, it is angularly stable for only TE polarized wave, owing to its large unit cell size.

In this project, the proposed RIS design aims to address the design limitations of the previous works. By incorporating the concept of miniaturization, the structure achieves angular stability for both TE and TM polarized signals, while maintaining polarization-insensitive and low absorption characteristics. The design achieves wide phase tunability from -160° to +160° at the operating frequency of 3.5 GHz, as well as, is angularly stable up to 50° for both TE and TM polarized signals.

II. STRUCTURE DESIGN

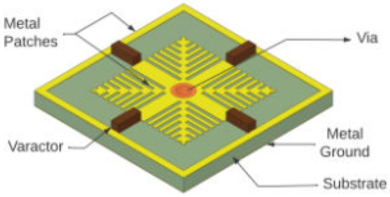

Fig. 1. Design sketch of the proposed RIS

The proposed RIS unit cell design assumes a square geometry with a metal pattern etched on the top surface of a dielectric substrate. The bottom surface is completely covered with a metal sheet to allow for complete reflection of the impinging signal. Figure 1 depicts the unit cell design across different views. FR4 (ϵ_r = 4.4 and tanδ = 0.030) is used as the substrate. The structure exhibits a four-fold symmetricity, which imparts its polarization-insensitive nature and results in identical responses for both TE and TM polarized waves under normal incidence.

A fundamental aspect of this structure is that it uses the concept of miniaturization [2] to achieve similar phase characteristics while concurrently improving the response of the structure for TM polarized wave. To achieve miniaturization, two design aspects are incorporated in this structure. First, convoluted slots in the square metal patch are introduced in the structure and second, the overall dimensions of the structure are scaled down. Due to the scaling down of the structure dimensions, the net capacitance and inductance offered by the geometry decreases. This in turn causes an increase in the operating frequency and reduces the bandwidth of the response [3]. To compensate for these effects, convoluted slots are made. These convoluted slots provide high equivalent capacitance, and the metal strips provide high equivalent inductance [4]. This is a direct result of the approximate first-order equations of the capacitance and inductance of a wire grid [5].

For dynamic tuning of phase characteristics, four varactor diodes modeled after Infineon BB-857 (equivalent series resistance = 1.5 Ω, tuning range from 0.45 pF to 6.0 pF, corresponding to a reverse bias voltage of 28 V and 1 V, respectively) are used with a symmetrical arrangement. A via at the center of the unit cell is also provided to bias the varactors concurrently with a common ground. The optimal parameters for the structure may be looked up from the associated conference publication [6].

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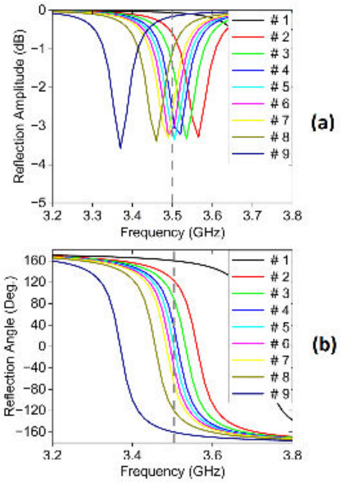

Fig. 2. Reflection characteristics at different incident angles for TM polarized signal at the operating frequency of 3.5 GHz: (a) amplitude plot and (b) phase plot.

III. Simulation Results

Full-wave simulations of the proposed structure are performed in Ansys HFSS software. For analysis, a single unit cell is characterized with appropriate boundary conditions to simulate the behavior of an infinite array of RIS unit cells. A floquet port is implemented on the top-facing side to accurately simulate the incidence and reflection of the EM wave. The varactors are modeled by an equivalent capacitance, following the datasheet specifications. The amplitude and phase characteristics can be observed in Fig. 2. The entire phase response is bifurcated into nine equispaced coding states (from #1 to #9) at the operating frequency of 3.5 GHz, which provides a wide phase tunability from -160° to +160°. It is to be noted that the low amplitude loss and wide phase spread for different coding states is obtained, thus reflecting on the desired characteristics of the RIS.

The reflection characteristics observed for different incident signals with varying polarization angles are depicted in Fig. 3. The high degree of overlap obtained for different plots that correspond to the different polarization angles of the incident signal across different coding states signifies that the structure is insensitive to the polarization angles of the incident signal.

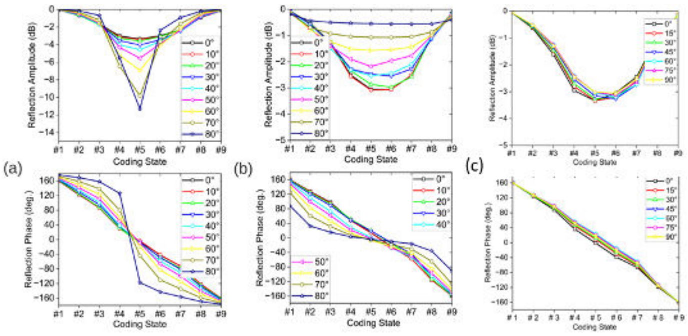

Fig. 3. Reflection characteristics for different (a) polarization angles, (b) incident angles for TE polarized signal and (c) incident angles for TM polarized signal at 3.5 GHz (Top image - Amplitude variation; Bottom image - Phase variation

The angular stability of the structure has also been studied via the simulations for both TE and TM polarized signals. This is done by varying the angle of incidence (measured from the plane normal to the surface of the unit cell) of the impinging signal. The simulated characteristics for TE and TM polarized signals can be observed from Fig. 3. The phase and amplitude response starts deviating from the reference response at 0° as the angle of incidence is increased, but remains largely stable up till 50°. Beyond this angle of incidence, the deviation from the ideal response becomes quite substantive leading to high absorption loss and constricted tuning ability of the phase angle.

IV. Conclusion and Future Career Plans

The proposed RIS geometry has various characteristics that makes it suitable for use in beam-steering applications, such as wide phase tunability, polarization-insensitivity and angular stability for TE and TM polarized signals under oblique incidence. It is expected that this work will prove to be instrumental in developing practical RIS structures with characteristics that are robust to different variations in the incident signals. In follow up to this study in the future, it is aimed to prototype this design and use it to create intelligent surfaces for beam-steering, wherein each unit cell can be controlled intelligently to make the phase angles of the signals impinging on them interfere constructively in a single direction of choice.

This work has been presented in the 2023 IEEE Microwaves, Antennas, and Propagation Conference (MAPCON) [6] in the form of an oral presentation. Support provided by the MTT-S Undergraduate Scholarship has been crucial in performing this project and presenting it in the IEEE conference, and is sincerely acknowledged. Further, the scholarship has motivated me to gain a more holistic understanding of the microwave industry, not merely from the technical side but from the practical aspect as well.

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