

Dual-Band, Circularly-Polarized Reconfigurable Intelligent Surfaces for Arbitrary Beam Shaping

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Abstract—This work introduces a dual-band, circularly-polarized reconfigurable intelligent surface that allows arbitrary beam shaping within the [4.35 GHz–4.5 GHz] and [11.8 GHz–12.3 GHz] frequency bands. Specifically, circular polarization is achieved through symmetrical structuring of the unit cells, while dual-band functionality is realized by stacking unit cells that are completely decoupled from each other and independently operate at their respective frequency ranges. Additionally, a genetic algorithm-based optimization technique is developed to enable arbitrary beam shaping with phase-only control. The versatility of the proposed approach is demonstrated through design examples that achieve (1) multi-directional beam steering and (2) sector beam formation within each frequency band.

I. INTRODUCTION

Over the past decade, reconfigurable intelligent surfaces (RISs) have gained significant attention as a key enabling technology for next-generation wireless communications. These surfaces typically consist of arrays of tunable, subwavelength-sized unit cells that can dynamically and locally control the scattered electromagnetic (EM) fields and generate desired radiation patterns. To date, numerous RIS designs have been reported based on this principle, with most studies focusing on redirecting incoming EM waves toward user-specified directions at specific operating frequencies (i.e., single-band beam steering). While such surfaces have proven effective in many practical scenarios, the evolving demands of wireless technologies now call for RISs with enhanced versatility, including improved spectral efficiency and the ability to dynamically and arbitrarily shape scattered EM fields beyond simple beam steering.

To meet these demands, this work presents a novel RIS that offers (1) dual-band functionality, (2) circular polarization (CP) operation, and (3) the ability to dynamically and arbitrarily shape the scattered EM fields, such as the generation of sector patterns. The proposed dual-band RIS unit cell provide continuous reflection phase control across each frequency band with a tuning range of 300° per band. In particular, the unit cell is precisely designed to offer completely independent reflection phase control within the frequency bands of [4.35 GHz–4.5 GHz] and [11.8 GHz–12.3 GHz]. With this phase-only control, arbitrary beam shaping is achieved (e.g., sector beams and dual beams) via a genetic algorithm (GA)-based beam synthesis technique. Furthermore, CP operation is achieved by symmetrically structuring the unit cell. The versatility of the proposed RIS and beam-synthesis method are demonstrated through examples of multi-directional beam steering and sector beam formation across two distinct frequency bands.

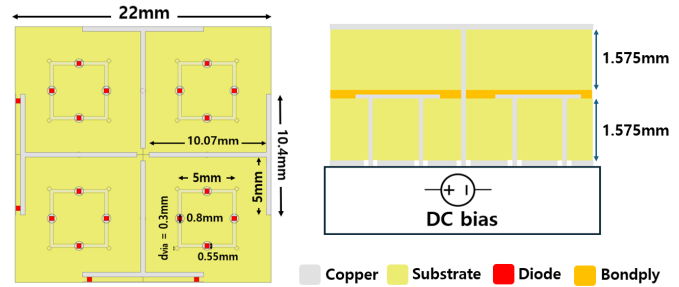


Fig. 1. Proposed metasurface unit cell design

II. DUAL-BAND RIS UNIT CELL DESIGN

Fig. 1 illustrates the proposed dual-band reconfigurable unit cell, which consists of cascaded sub-unit cells. Hereafter, we refer to the sub-unit cell at the bottom as Cell-B and the one at the top as Cell-T. Cell-T and Cell-B operate within the frequency band of [11.8 GHz–12.3 GHz] and [4.35 GHz–4.5 GHz], respectively. Each sub-unit cell has a compact size of 0.44λ (Cell-T) and 0.324λ (Cell-B) at their center frequencies. Additionally, four varactor diodes (MAVR-0110201411) are integrated into both Cell-T and Cell-B to attain the necessary tunability, and the unit cells are symmetrically structured to allow CP operation.

To ensure that the variation in Cell-T would not influence the operation of Cell-B and vice versa, a window-shaped structure is applied to Cell-T, thereby maximizing the distance between the current path (copper-patterns) of cell-T and Cell-B. Particularly, this decoupling of Cell-T and Cell-B is seen in Fig. 2, which plots the variation of the reflection coefficients of Cell-T (or Cell-B) when the capacitance of the diodes in Cell-B (or Cell-T) are changed. Here, C_t and C_b represent the capacitance of the varactor diodes mounted on Cell-T and Cell-B, respectively.

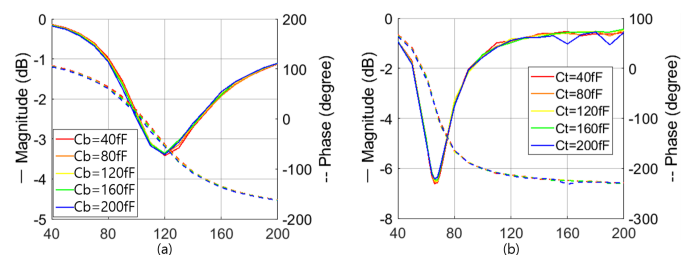


Fig. 2. Simulated magnitude and phase of the reflection parameter as a function of varactor capacitance at (a) 4.45GHz (b) 12GHz

It is clearly seen from Fig. 2 that the tuning of C_b (or C_t) does not affect the operation of Cell-T at 4.45 GHz (or Cell-B at 12 GHz). This implies that both cells are perfectly decoupled from each other, enabling reliable and effective band-independent operation of the dual-band reconfigurable unit cell. Specifically, at 4.45 GHz, the unit cell achieves a continuous reflection phase shift of 290° with a maximum loss of -3.4 dB. At 12 GHz, the unit cell induces a continuous reflection phase shift of 300° with a maximum loss of -6.5 dB, both of which are achieved by varying the bias voltage.

III. SYNTHESIS OF COMPLEX FAR-FIELD PATTERNS BASED ON GENETIC ALGORITHM

As an example of arbitrary CP beam shaping, we consider transforming two normally incident CP beams at the two frequency bands into (i) a dual-beam at 4.45 GHz and (ii) a sector pattern at 12 GHz that are directed at user-defined angles. For this purpose, we employ a GA-based optimization to determine the required reflection phase profiles along the proposed RIS. Specifically, we begin by expressing the reflected field from the RIS as,

$$E_{\text{ref}} = \sum_{m=1}^{N_E} A|\Gamma(m)|e^{j(\beta d(m-1)\sin(\theta) - \phi(m))} \quad (1)$$

where A is the element pattern of each unit cell, β is the free-space wave number, N_E is the number of each elements in the RIS, and d is each unit-cell periodicity, which is set to 0.326λ at 4.45 GHz and 0.44λ at 12 GHz. Also, $\phi(m)$ and $|\Gamma(m)|$ represent the phase and amplitude of the reflection coefficient of the m^{th} unit cell in the RIS, respectively, which can be obtained from Fig. 2.

The cost function of GA for dual-beam generation at 4.45 GHz, F_{cost1} , is then defined as,

$$F_{\text{cost}} = W_A * ((E_{\text{ref}}(\theta) - E_{\text{des}}(\theta_o))^2 + W_B * (\theta - \theta_o)^2 + W_C * \text{SLL} \quad (2)$$

where $E_{\text{des}}(\theta_o)$ represents the desired field values at user-specified locations, denoted as θ_o and SLL denotes a desired side lobe level. Finally, W_A , W_B , and W_C are the weights whose values are set to 0.2, 0.8 and 1.

Similarly, to synthesize a sector pattern at 12 GHz, the cost function is defined as,

$$F_{\text{cost}} = W_A * ((E_{\text{ref}}(\theta) - E_{\text{des}}(\hat{\theta}_o))^2 + W_B * STD[(E_{\text{ref}}(\tilde{\theta}))] + W_C * \text{SLL} \quad (3)$$

where $\tilde{\theta} \in [\hat{\theta}_o - \frac{\Delta\theta_o}{2}, \hat{\theta}_o + \frac{\Delta\theta_o}{2}]$ and $\Delta\theta_o$ is the desired beamwidth. Additionally, $STD[(E_{\text{ref}}(\tilde{\theta}))]$ represents the standard deviation of E_{ref} . Finally, similar to before, W_A , W_B and W_C represent the weights whose values are set to 0.8, 0.4 and 1, respectively.

Based on these cost functions, the required reflection phase profiles (i.e., $\phi(m)$) are derived to achieve the desired radiation patterns at two frequency bands. Specifically, for dual-beam generation, two beams are directed at -25° and 40° at 4.45 GHz, while a sector pattern spanning 20° to 40° is targeted at 12 GHz.

IV. FULL-WAVE VERIFICATION

To verify the proposed RIS and GA-based optimization technique, ANSYS HFSS is employed to simulate the overall structure. In particular, the simulated surface consists of 10 unit cells for the lower band and 21 unit cells for the upper band. As shown in Fig. 3, the beam shaping of the desired pattern has been successfully achieved at each frequency. Furthermore, the proposed structure demonstrates CP operation by maintaining a low axial ratio, confirmed by the values of 3.36 dB and 2.87 dB for dual-beam at -25° and 40° , respectively. The average axial ratio for the sector pattern is measured to be 1.058 dB.

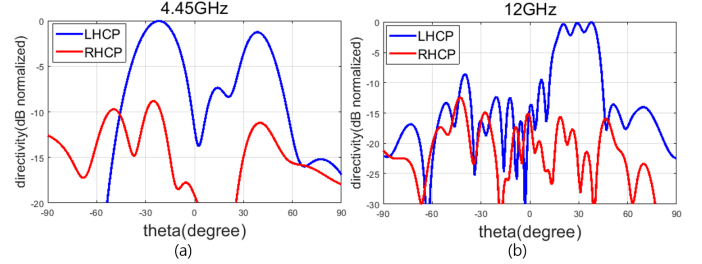


Fig. 3. Radiation patterns of the RIS under RHCP incidence: (a) The radiation pattern of the RIS under RHCP incidence at 4.45 GHz (b) The radiation pattern of the RIS under RHCP incidence at 12 GHz

V. CONCLUSION

This work presents a dual-band, circularly polarized reconfigurable intelligent surface with compact unit cells that enable arbitrary beam shaping. The proposed reconfigurable unit cell incorporates structural symmetry, providing continuous phase tunability for two orthogonal linear polarizations. Furthermore, a genetic algorithm-based optimization technique is developed to achieve beam shaping capabilities beyond simple beam steering, with phase-only control. The versatility of the proposed architecture and beam synthesis method is thoroughly validated through full-wave simulations, demonstrating dual-beam and sector pattern generation at 4.45 GHz and 12 GHz, respectively.

ACKNOWLEDGMENT

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