A Hafnium Zirconium Oxide-Based Reconfigurable Reflectarray for THz Communications

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***Abstract*—This study presents the design and simulation of a reconfigurable reflectarray (RRA) utilizing a Hafnium Zirconium Oxide (HZO)-based varactor for terahertz (THz) communication systems. A unit cell analysis investigates the influence of varactor capacitance on reflection magnitude and phase variation, while full-wave simulations of a 10×10 reflectarray array validate its beam-scanning capabilities. The findings indicate that despite a limited phase tuning range and row-wise element control, the design achieves competitive gain performance due to its high aperture efficiency. This work establishes a foundation for advancing THz wireless communication systems using CMOS-compatible ferroelectric materials.**

I. Introduction

The forthcoming sixth-generation (6G) wireless network aims to provide ultra-fast and highly reliable connectivity. The terahertz (THz) spectrum (0.1–10 THz) offers extensive bandwidth potential; however, it faces significant challenges, including high propagation losses and line-of-sight (LoS) dependence, making it vulnerable to blockages. To address these limitations, reconfigurable reflectarrays (RRAs) have emerged as a promising solution, enhancing both reliability and scalability in 6G communication systems.

RRAs integrate active elements into periodic passive antenna arrays, enabling electromagnetic wave control through bias-tunable reflection. However, developing optimal active elements for THz frequencies remains challenging, as traditional low-frequency solutions face cutoff limitations and high losses. Various tuning elements, including MEMS, CMOS transistors, and graphene, have been explored, but each has inherent constraints [1]. To address such limitations, ferroelectric materials such as Barium Strontium Titanate (BST) have been shown to provide analog tunability for programmable antennas [2]. However, their general incompatibility with CMOS fabrication protocols hinders their large-scale integration.

Hafnium Zirconium Oxide (HZO), a ferroelectric material already used in CMOS-foundry processes, offers a promising option for RRAs due to its potential for monolithic integration and non-volatile memory [3]. This study proposes and simulates an RRA design with an HZO-based varactor in its unit cell. Embedding a metal-ferroelectric-metal (MFM) HZO structure within each resonator ensures compatibility with CMOS technology while enabling tunability, paving the way for advancements in THz communication systems.

II. Unit Cell Analysis

This section presents the analysis and design of an HZO-based tunable unit cell. The design consists of two rectangular patches coupled with an HZO varactor (Fig. 1). The application of a variable DC voltage modifies the permittivity of HZO due to its ferroelectric behavior, enabling varactor functionality. Prior experimental data indicate a tunable relative permittivity range between 34 and 46 [3]. To enhance phase tunability, a cascaded scheme as in [4] can be employed.

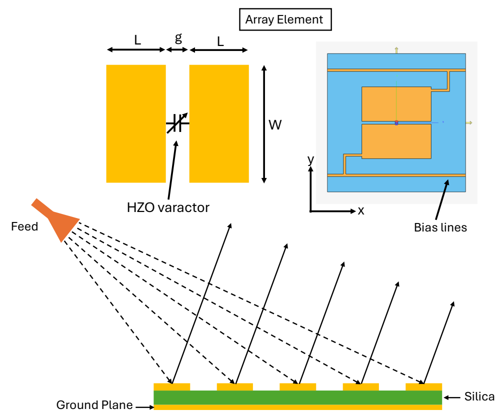

Fig. 1. Schematic of a reflectarray consisting of the proposed HZO-based patch elements with a biasing scheme.

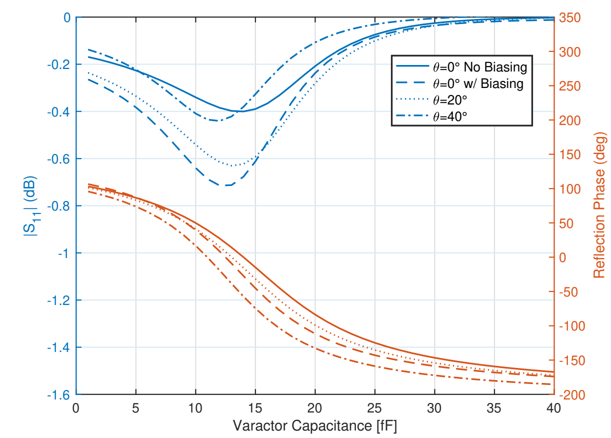

Fig. 2. S-curves illustrating reflection magnitude and phase as functions of varactor capacitance at 130 GHz for different incident angles. The plot also compares the unbiased and biased schemes at normal incidence.

Simulations of the reflection characteristics of the unit cell are conducted in Altair Feko using periodic boundary conditions. Normal incidence and E-plane angles of 20° and 40° are analyzed, comparing biased and unbiased models. The simulations are performed at an operational frequency of 130 GHz, with an inter-element spacing of 1.15 mm in both dimensions and a substrate thickness of 154 μm. The chosen

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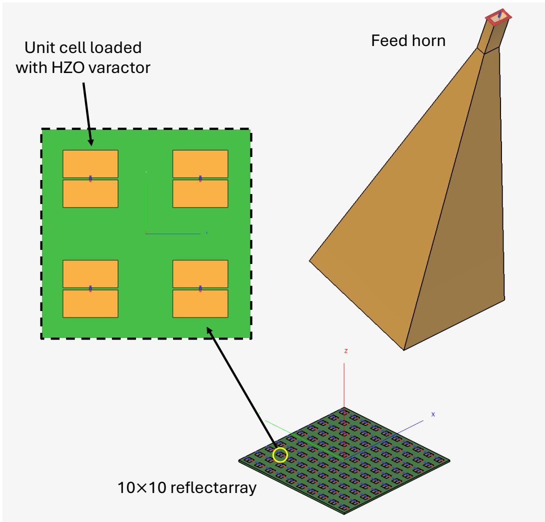

Fig. 3. Schematic of the 10×10 reflectarray and the feed horn antenna.

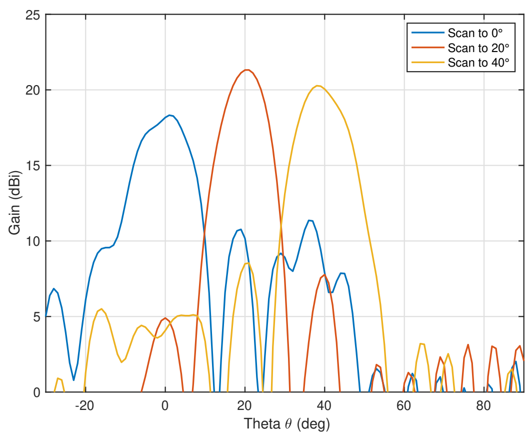

Fig. 4. Simulated radiation patterns on the E-plane for different scan angles, achieved through row-based phase assignment in full-wave simulations.

substrate material is silica (SiO2) with a permittivity of 3.9. The patch antenna dimensions are 288 μm in length (L) and 577 μm in width (W), with a gap size (g) of 23 μm. The varactor capacitance is varied from 1 to 40 fF.

Fig. 2 presents the S-curves for reflection magnitude and phase as a function of capacitance. The resonance occurs at approximately 14 fF, with a maximum reflection loss of 0.7 dB and a phase variation of $\sim$260°. It is observed that variations in the incident angle have negligible effects on performance unless significantly large. Furthermore, biasing lines introduce only slight deviations in results. In subsequent analyses, a varactor capacitance range of 5–30 fF is assumed, achieving a phase variation of approximately 230°.

III. Array Design and Simulations

This section explores the design and simulation of an RRA prototype, employing full-wave simulations with row-wise biasing for phase assignment. A 10×10 element array is designed with an offset feed at $\theta_f = 20°$ along the E-plane. The feed is placed at a relatively short focal distance ($f/D = 2.47$). While individual element control is ideal, scaling challenges require row-wise biasing (Fig. 1). Despite this, our study shows that the high aperture efficiency at close feed distances compensates for spatial phase mismatches.

Using array theory, the required phase shifts for elements at (x_i, y_i) to achieve a scan angle (θ_0, ψ_0) are given by

$$\phi_{RA} = k_0(R_i - \sin(\theta_0(x_i \cos\psi_0 + y_i \sin\psi_0)) + \phi_0, \quad (1)$$

where k_0 is the wavenumber at the center frequency, R_i is the distance from the feed phase center to the i^{th} element, and ϕ_0 is a phase constant. With row-wise biasing, R_i corresponds to the distance between the feed center and the row's y-position.

Fig. 3 illustrates the reflectarray model, which is simulated using the multilevel fast multipole method (MLFMM) due to its efficiency in handling electrically large structures. Fig. 4 presents the achieved gain values for E-plane scanning at varying angles, demonstrating a steerability range of 40° (−20° to 20°), with maximum gains between 18 and 21 dBi. Despite the limited phase range and the absence of individual element phase control, the gains remain comparable to the 21 dBi gain of the feed horn antenna. Overall, full-wave simulations validate the array's beam-scanning capability and its high efficiency at close feed distances.

IV. Conclusion

This study demonstrates the feasibility of HZO-based varactors for RRAs operating in the D-band. The proposed design achieves phase tunability due to the ferroelectric properties of HZO. Full-wave simulations confirm efficient and robust beam-scanning performance, despite potential phase control limitations. Integrating CMOS-compatible ferroelectric materials such as HZO paves the way for scalable, high-performance THz RRAs. Future work will focus on experimental validation and further optimization for practical deployment in 6G applications.

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