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Dual-Band Resonant Cavity Antenna for Integrated Sensing and Communication Applications

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Abstract

This paper introduces a single-layer Phase Transformation Surface (PTS) integrated with a Resonant Cavity Antenna (RCA) to achieve dual-band operation and enhance radiation performance. The PTS is located in the near-field of the RCA, allowing it to effectively modify the phase at two operating frequencies: 10.6 GHz and 11.4 GHz. This results in improved far-field directivity of 18.2 dBi and 18.4 dBi, respectively. These enhancements demonstrate the potential of PTS-integrated RCAs for high-directivity and frequency-selective applications in advanced wireless communication and sensing systems.

1. Introduction

Integrated sensing and communication (ISAC) have recently gained significant attention in the research community because they present a promising way to combine data transmission and sensing capabilities within a single system. Traditionally, antennas have been designed for either communication or radar sensing [1,2]. However, the growing demand for dual functionality in modern communication systems has led to the development of antennas operating across two distinct frequency ranges [3]. This dual-band capability allows for the simultaneous execution of communication and sensing tasks, optimizing system efficiency and reducing costs. Dual-band antennas are particularly well-suited for applications on the Internet of Things (IoT), wireless sensor networks, and intelligent systems, where real-time monitoring and communication are essential. By integrating these functions into a single antenna design, dual-band antennas are positioned at the forefront of next-generation wireless technologies [4], providing enhanced performance in a compact and integrated form.

The manipulation of near-field electromagnetic waves has been widely studied to develop low-profile antennas, with various single-band and dual-band configurations proposed using multi-layer structures [5,6]. While these multi-layer designs improve antenna functionality, they also introduce additional costs, losses, and manufacturing complexities. Recently, single-layer phase transformation techniques have been suggested to mitigate these issues [7,8]; however, they are often limited to single-band operation, which restricts their use in communication or sensing applications.

Therefore, we propose a single-layer phase transformation design that supports dual-band functionality for a resonant cavity antenna (RCA) to address these limitations. This innovative approach tackles the misalignment of phase distributions at two distinct frequencies (10.6 GHz and 11.4 GHz) while also enhancing the far-field radiation performance at these frequencies, achieving directivities of 18.2 dBi and 18.4 dBi, respectively. This dual-band RCA design offers a practical solution for the ISAC, optimizing performance and system efficiency.

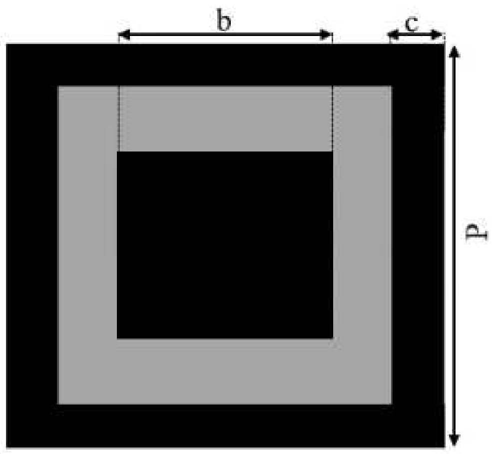


Figure 1. Proposed unit cells: square patch with a ring, p ($\lambda_L/3$) and tunable parameters (b, c).

2. System Configuration

In this work, a Resonant Cavity Antenna (RCA) is employed, incorporating a partially reflective surface (PRS) and a fully reflective surface (FRS) separated by $\lambda_L/2$, where λ_L is lower frequency band of 10.6 GHz is selected to establish constructive interference within the cavity, thereby enhancing radiation performance. The PRS is made of TMM4 substrate (ε_r = 4.7) with a thickness of 3.17 mm, ensuring stable electromagnetic performance. The lateral dimensions of the PRS and FRS are set to $3\lambda_L \times 3\lambda_L$ and $4\lambda_L \times 4\lambda_L$, respectively, to provide sufficient aperture size for effective wave manipulation.

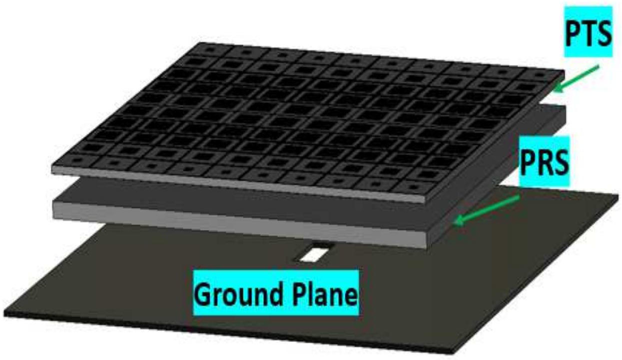
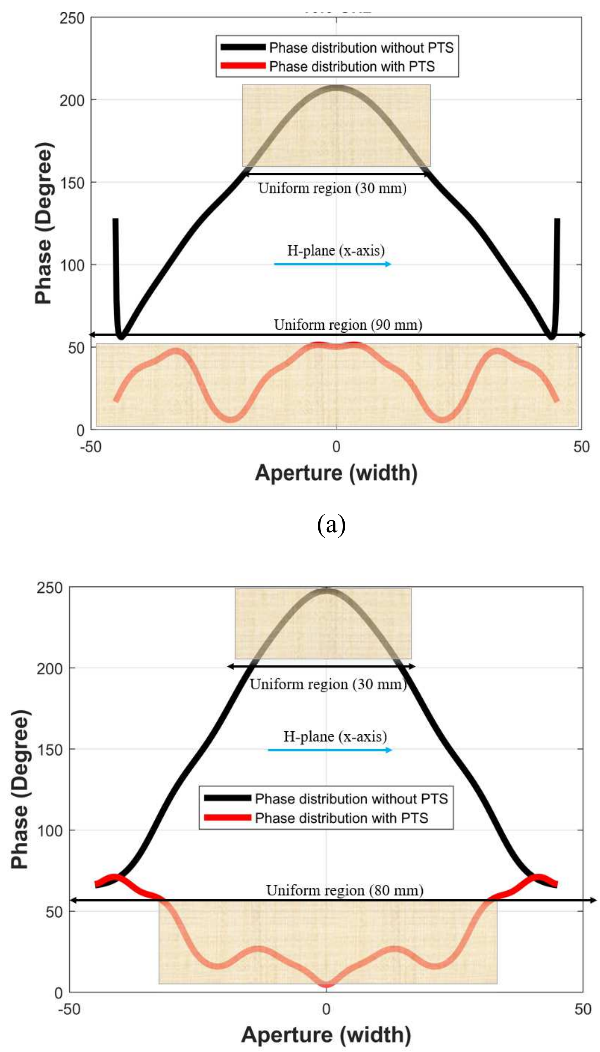


Figure 2. Perspective view of the RCA with PTS.

To achieve independent phase control at 10.6 GHz and 11.4 GHz, a dual-band unit cell is designed, as illustrated in Figure 1. The unit cell consists of a symmetric metallic patch and an edge ring structure patterned on both sides of the TMM4 substrate (ε_r = 4.7). The periodicity of the unit cell is set to ~$\lambda_L/3$, ensuring sub-wavelength operation and mitigating unwanted grating lobes. The phase control mechanism relies on two key geometric parameters (b, c), which govern the transmission phase response across the two frequency bands. Systematically adjusting these parameters achieves the required phase shifts at both frequencies, ensuring optimal wavefront correction and radiation enhancement.

To precisely control the radiated wavefront, the dominant electric field phase distribution (E_γ) along the x-axis is analyzed at a height of $\lambda_L/6$ above the PRS. Near-field phase distributions are recorded at five equally spaced points along the aperture of RCA with a period ($\lambda_L/3$) to evaluate the phase variations at 10.6 GHz and 11.4 GHz. Any deviations from the desired phase distribution are quantified by computing phase errors relative to a predefined reference plane. Strategically designed unit cells with distinct phase shifts are positioned at the identified locations to correct these phase errors. These unit cells are then uniformly distributed along the y-axis, forming a Phase Transformation Surface (PTS), as depicted in Figure 2. The PTS modifies the near-field phase distribution independently at both frequency bands, ensuring an optimized far-field radiation pattern with enhanced directivity and beam symmetry. This approach enables efficient dual-band operation while maintaining a low-profile and cost-effective design. It is well suited for integrated sensing and communication (ISAC) applications in next-generation wireless systems.



(b)

Figure 3. Phase distribution results with PTS at both frequency band: (a) 10.6 GHz and (b) 11.4 GHz.

3. RESULTS and DISCUSSION

Figure 3 illustrates the near-field phase distribution before and after implementing the Phase Transformation Surface (PTS), demonstrating a significant enhancement in phase uniformity. The uniformity criterion is established within a 45-degree phase range from the center of the distribution. The results indicate that phase uniformity is significantly enhanced after applying the PTS, leading to a substantial improvement in antenna performance, particularly in directivity, which exhibits an increase exceeding 6.5 dBi at both frequency bands. This enhancement is critical for high-gain beamforming applications in dual-band integrated sensing and communication (ISAC) systems. The near-field phase distribution exhibits high uniformity at 11.6 GHz and 11.4 GHz. Notably, at 10.6 GHz, the phase distribution is fully transformed into a uniform region within a 90 mm range, compared to the 30 mm range before applying the Phase Transformation Surface (PTS), as depicted in Figure .3(a). At 11.4 GHz, the uniform phase region extends beyond its original range, reaching 80 mm after positioning the PTS above the Partially Reflecting Surface (PRS), whereas it was only 30 mm prior to the application of PTS, as illustrated in Figure. 3(b). This transformation highlights the efficacy of the PTS in enhancing phase uniformity, which directly impacts far-field characteristics, ensuring precise wavefront manipulation essential for multi-band ISAC frameworks.

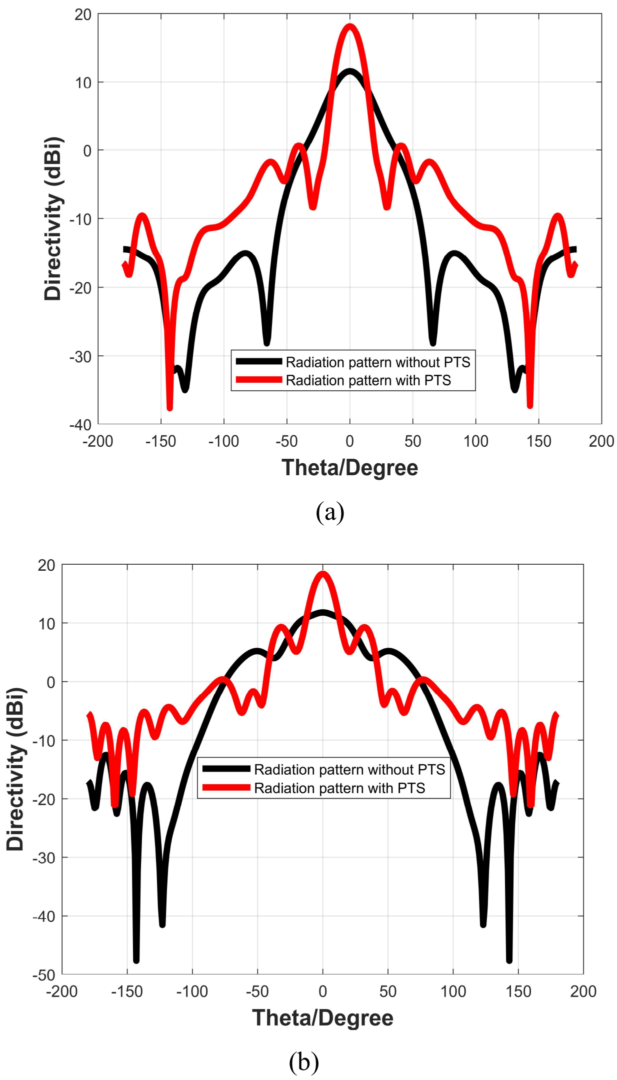


Figure 4. Radiation pattern performance; (a) 10.6 GHz, (b)11.4 GHz.

The influence of near-field phase uniformity is evident in the far-field radiation performance at both frequency bands. At 10.6 GHz, the directivity is enhanced from 11.6 dBi to 18.2 dBi after incorporating the PTS, with the corresponding beamwidth reduced from 29.3 degrees to 16.7 degrees, as presented in Figure. 4(a). Similarly, at 11.4 GHz, the directivity increases from 11.8 dBi to 18.4 dBi, while the beamwidth narrows from 44.5 degrees to 14 degrees, as demonstrated in Figure. 4(b). These results confirm the significant role of the PTS in improving the antenna's radiation performance by optimizing phase distribution and enhancing directivity, which is crucial for high-resolution radar sensing and high-data-rate communication in ISAC-enabled networks.

Furthermore, the 3 dB bandwidth is measured to be approximately 6% for the lower frequency band and 4% for the higher band, as shown in Figure 5 (a). The impedance matching across the entire operational bandwidth (10–12 GHz) is well-maintained, as demonstrated in Figure 5(b), indicating the robustness of the proposed antenna system in terms of impedance stability. This broad impedance bandwidth is particularly advantageous for dual-band ISAC applications, where simultaneous transmission and sensing require low insertion loss and stable impedance characteristics.

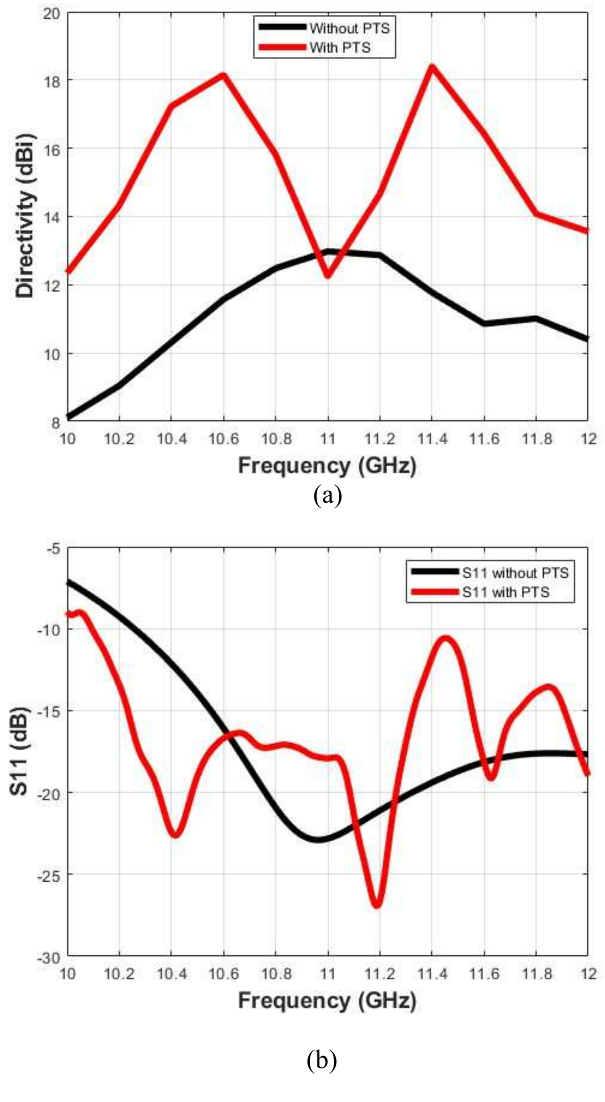


Figure 5. (a) directivity as a function of frequency, and (b) reflection coefficient (S11) results.

5. Conclusion

In this study, we paper presented a single-layer Phase Transformation Surface (PTS) integrated with a Resonant Cavity Antenna (RCA) for dual-band operation, enhancing radiation performance at 10.6 GHz and 11.4 GHz with directivities of 18.2 dBi and 18.4 dBi, respectively. The design addresses the challenges of multi-band operation while avoiding the complexities and losses of multi-layer structures. This dual-band RCA is well-suited for integrated sensing and communication (ISAC) applications, offering improved efficiency and compact performance for next-generation wireless systems. Future studies will explore extending this approach to multi-beam configurations, enhancing system versatility and performance in diverse communication and sensing scenarios.

References

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