

Article

Range Enhancement and Passive Beamforming of a 24-GHz Object Detection Radar Using Partially Reflective Surfaces

Hong Ju Lee ¹ and Jae-Gon Lee ^{2,*} ¹ Department of Electronic and Software Engineering, Kyungnam University, Changwon 51767, Republic of Korea² Department of Electrical Engineering, Kyungnam University, Changwon 51767, Republic of Korea

* Correspondence: jaegonlee@kyungnam.ac.kr

Abstract

This paper presents two partially reflective surface (PRS)-based techniques to enhance the performance of a 24-GHz object detection radar system. The first technique employs a flat PRS superstrate to increase antenna gain and thereby extend the detection range, while the second utilizes an inclined PRS structure to achieve passive beamforming and directional control. The conventional radar module consists of a 1×4 transmit array and two 1×4 receive arrays implemented on the opposite side of the PCB from the RF circuitry. Although increasing the number of antenna elements is an effective way to improve antenna gain and detection range, such an approach inevitably enlarges the antenna area and increases system complexity. In contrast, the proposed PRS-based structures enhance the effective aperture efficiency without expanding the planar dimensions of the antenna. The flat PRS configuration improves the antenna gain by approximately 5.8 dB (4.3 dB in Tx and 1.5 dB in Rx), which corresponds to a theoretical detection range extension of approximately 40% according to the radar range equation. Furthermore, the inclined PRS introduces a spatial phase variation across the aperture, resulting in passive beam steering of approximately -10 degrees while preserving the gain enhancement effect. Prototypes of both configurations were fabricated, and the measured results show good agreement with full-wave simulation data. These techniques provide compact and low-complexity solutions for extending detection range and enabling directional sensing in 24-GHz object detection radar applications.

Keywords: object detection radar; partially reflective surface (PRS); detection range enhancement; passive beamforming



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1. Introduction

Object detection radar operating in the industrial, scientific, and medical (ISM) band has been widely adopted in smart infrastructure, security monitoring, occupancy sensing, and healthcare applications [1–8]. In these systems, reliable target detection at extended distances and flexible control of the sensing direction are essential performance requirements. As radar modules become increasingly compact and integrated, improving detection capability without enlarging hardware dimensions has become a significant design challenge. The maximum detection range of a radar system is fundamentally governed by the radar range equation, which indicates that the detectable distance is proportional to the fourth root of the product of transmit power and antenna gains. In practical mm-wave radar

systems, transmit power is restricted by regulatory limits, making antenna gain enhancement one of the most effective approaches for extending detection range. One of the good solutions is to increase the number of antenna elements in the array. Although this method improves directivity, it inevitably enlarges the effective antenna area, increases feed network complexity, introduces additional losses, and raises fabrication cost. For compact radar modules where the antenna and RF circuitry are integrated on a single printed circuit board (PCB), expanding the antenna aperture is often impractical.

Partially reflective surface (PRS) structures have been extensively studied for gain enhancement in antenna systems [9–14]. By placing a PRS superstrate above a radiating element, a Fabry–Pérot resonant cavity can be formed between the PRS and the ground plane. When the cavity satisfies the resonance condition, constructive interference reinforces radiation in the broadside direction, leading to increased directivity and gain without increasing the planar aperture size. This characteristic makes PRS-based antennas particularly attractive for compact radar applications. However, previous PRS studies have mainly focused on antenna-level gain enhancement. In contrast, this work demonstrates the integration of interchangeable flat and inclined PRS structures into a practical 24-GHz object detection radar system, enabling either detection-range enhancement or passive beam steering using the same radar platform. In addition to detection range, directional control of the sensing region is another important requirement in object detection radar systems. Various antenna and array techniques have been investigated to manipulate radiation patterns and achieve beam steering, including integrated multi-port antenna architectures and compact antenna arrays with enhanced wavefront control capabilities [15,16]. However, many of these approaches still require relatively complex antenna structures or are not specifically intended for low-cost radar beamforming applications. Conventional beam steering is typically achieved using phased-array architectures, which require active phase shifters and complex feeding networks. Such solutions significantly increase system complexity, power consumption, and cost. Therefore, passive beamforming techniques that do not rely on active RF components are highly desirable for compact radar modules.

In this paper, two PRS-based performance enhancement techniques are proposed for a 24-GHz object detection radar system. First, a flat PRS superstrate is introduced to enhance antenna gain and consequently extend the detection range without increasing the effective antenna area. Second, an inclined PRS structure is investigated to realize passive beamforming by introducing a spatial phase gradient across the antenna aperture. The flat PRS configuration focuses on maximizing detection distance through gain enhancement, whereas the inclined PRS configuration enables directional sensing by modifying the radiation pattern while preserving compact size. This work investigates the use of interchangeable passive PRS structures in a practical 24-GHz object detection radar system. By selectively employing planar and inclined PRS configurations, the radar can be configured for either detection-range enhancement or directional target detection without the need for electronically controlled beamforming circuits. Such an approach offers a simple and cost-effective alternative to conventional electronic beamforming while maintaining operational flexibility through structural reconfiguration.

The organization of this paper is as follows. The design approach and simulation analysis of the FPC antennas are presented in Section 2. Section 3 provides the experimental validation and corresponding discussion for the 24-GHz object detection radar system. Finally, the conclusions are presented in Section 4.

2. Design of Fabry–Pérot Resonant Cavity Antenna

The proposed antenna structure is based on a Fabry–Pérot cavity (FPC) configuration employing a partially reflective surface (PRS) superstrate to enhance radiation performance

without increasing the antenna aperture size of the radar module. A PRS layer is placed above the antenna aperture at an optimized cavity height to form a resonant structure between the PRS and the ground plane. Figure 1 shows the Structure of the FPC with an excitation source located between the ground plane and the PRS. The directivity (D) of the FPC antenna is given by [9]

$$D = \frac{1 - \Gamma_{PRS}^2}{1 + \Gamma_{PRS}^2 - 2\Gamma_{PRS}\cos\left(\varphi_{PRS} + \varphi_{GND} - \frac{4\pi}{\lambda}d\right)} f^2 \quad (1)$$

where φ_{GND} and φ_{PRS} are the reflection phases of the ground plane and the PRS, respectively. f is defined as the radiation pattern of the antenna source. Also, Γ_{PRS} is defined as the reflection coefficient of the PRS, and λ represents the wavelength in free space at the operating frequency. From Equation (1), $\varphi_{PRS} + \varphi_{GND} - \frac{4\pi}{\lambda}d$ and Γ_{PRS} should be $2\pi N$ ($N = \text{integer}$) and close to 1, respectively, to maximize the antenna directivity. Then, the height (d) of the FPC antenna is determined from Equation (2) based on the reflection phases of the ground plane and the PRS.

$$d = (\varphi_{PRS} + \varphi_{GND}) \frac{\lambda}{4\pi} + N \frac{\lambda}{2} \quad (2)$$

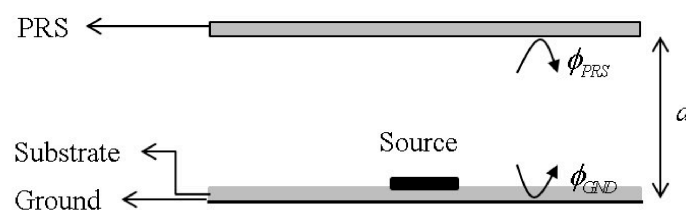


Figure 1. Structure of the Fabry–Perot cavity (FPC) with an excitation source located between the ground plane and the PRS.

The gain enhancement mechanism can be understood through the constructive interference of multiple reflected waves inside the cavity. Electromagnetic waves radiated from the source antenna are repeatedly reflected between the PRS and the ground plane, producing multiple radiating wave components. When the resonance condition given by Equations (1) and (2) is satisfied, these components are added in phase in the broadside direction, resulting in enhanced directivity and gain.

Based on this principle, a flat PRS configuration was first designed to maximize gain and extend the radar detection range. The design procedure was based on forming an FPC using a uniform dielectric superstrate. A dielectric slab having a relative dielectric constant of 6 and a thickness of 3.2 mm was employed as the partially reflective layer. It should be noted that the selected dielectric constant does not represent a universally optimal solution. According to conventional FPC theory, the antenna directivity increases as the reflection magnitude of the PRS approaches unity under the assumption of an infinitely large and lossless structure. However, practical PRS antennas have finite dimensions, and their performance is affected by edge diffraction, cavity leakage, and dielectric losses. Consequently, the optimum reflection magnitude depends on the physical dimensions of the cavity, and a larger reflection coefficient does not necessarily yield the highest gain. Therefore, the dielectric slab employed in this work was selected as a practical design choice satisfying the resonance condition and fabrication constraints of the proposed radar system. The dielectric superstrate inherently provides partial reflection and transmission at the air–dielectric interface, enabling the formation of a resonant cavity with the ground plane. The cavity height was then optimized to satisfy the resonance condition at 24 GHz,

and the optimal air gap between the antenna and the dielectric slab was determined to be 6.25 mm. The optimal cavity height is not determined solely by the reflection phase predicted by the simplified resonance model. In a practical FPC antenna with finite dimensions, the radiation characteristics are additionally influenced by finite-aperture effects, edge diffraction, multiple reflections inside the cavity, and coupling between the source antenna and the PRS. Therefore, the final cavity height was optimized through full-wave electromagnetic simulations. The simulation results showed that the maximum antenna gain was obtained at an air-gap height of 6.25 mm, which was consequently selected for the fabricated prototype. By adjusting this spacing, the overall phase accumulation within the cavity was controlled to achieve constructive interference in the broadside direction and maximize radiation enhancement. The reference antenna consists of a 4×1 transmitter (Tx) array and two 4×1 receiver (Rx) arrays implemented on the same PCB, as shown in Figure 2a. The Tx, Rx1, and Rx2 antennas are implemented as four-element patch arrays fed by microstrip corporate-feed networks. The feeding networks provide equal-amplitude and in-phase excitation to all patch elements within each array. For the S-parameter analysis shown in Figure 2c, port 1 is assigned to the input port of the Tx antenna array, whereas port 2 is assigned to the input port of the Rx antenna array. Therefore, S_{11} and S_{22} denote the input reflection coefficients of the Tx and Rx arrays, respectively, while S_{21} represents the transmission coefficient between the two arrays. Each radiating element is a rectangular microstrip patch designed for operation at 24 GHz. The element dimensions are $3.1 \text{ mm} \times 2.9 \text{ mm}$, and the center-to-center spacing between adjacent elements is $0.4\lambda_0$. The separation between the Tx and Rx arrays is 9.2 mm. The array elements are excited through a corporate microstrip feeding network designed to provide uniform amplitude and phase distribution across the array aperture. The feeding network is integrated on the same PCB as the radar RF circuitry to realize a compact radar module. The Tx and Rx antennas are positioned laterally adjacent to each other to achieve compact integration with the RF circuitry. The simulated S-parameters of the flat PRS configuration of Figure 2b are shown in Figure 2c. All simulations were performed using ANSYS Electronics Desktop (HFSS) 2024 R1. The results indicate that the introduction of the PRS does not significantly degrade impedance matching, and the reflection coefficient remains below -10 dB within the operating band around 24 GHz. This confirms that the PRS primarily influences the radiation characteristics rather than the input impedance. The computed radiation characteristics in the far field of both Tx and Rx patch arrays, with and without the flat PRS, are presented in Figure 3. To implement the antenna together with the RF circuitry on the same PCB, the Tx and Rx antenna prototypes were realized using an FR4 material characterized by a dielectric loss factor of 0.02. The relatively high dielectric loss introduces significant attenuation in the feeding network, resulting in a reduction in the realized gain. Full-wave simulations indicate that the use of the FR4 substrate causes approximately 1.5 dB gain degradation compared with an equivalent low-loss substrate. Furthermore, owing to the limited PCB size, the element spacing of the 4×1 patch array could not be designed at the conventional value of approximately $0.7\lambda_0$, which is typically chosen to maximize array directivity. Instead, a reduced inter-element spacing of $0.4\lambda_0$ was adopted to satisfy the compact layout constraint. As a result, stronger mutual coupling and reduced effective aperture lead to an additional gain reduction. Simulation results show that the reduced element spacing causes about 4.5 dB degradation in array gain compared with an optimally spaced array configuration. Because of both the material loss and the suboptimal element spacing, the overall realized gains of each Tx and Rx array was limited to about 8 dBi at the operating frequency. Compared to the reference antenna without PRS, the proposed configuration achieves a gain enhancement of approximately 4.3 dB in Tx and 1.5 dB in Rx in the broadside direction. The half-power beamwidth is reduced, indicating increased

directivity due to the cavity effect. Since the cavity height is uniform across the entire aperture, the phase distribution remains nearly constant, and the radiation is concentrated in the broadside direction without beam steering. This gain enhancement directly contributes to detection range extension, as the maximum detectable range is proportional to the fourth root of the antenna gain product.

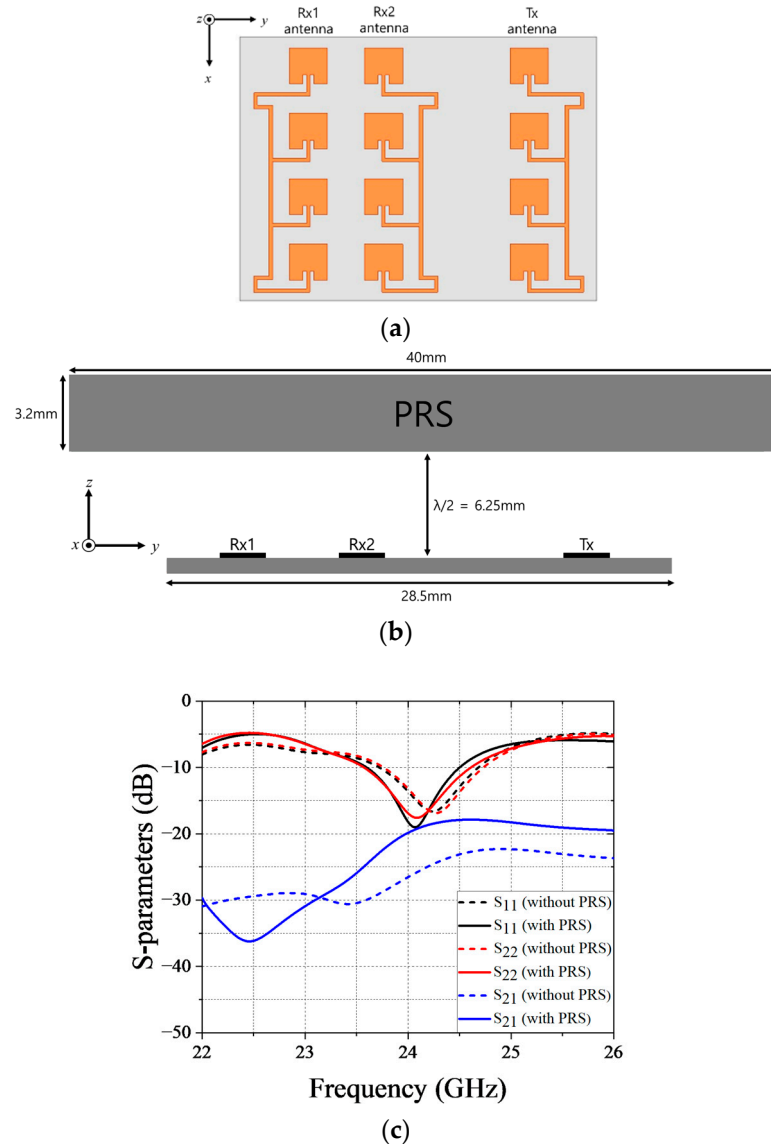


Figure 2. Tx and Rx antennas of 24 GHz object detection radar system. (a) Top view of the antennas (b) Side view of patch arrays with flat PRS. (c) Full-wave simulated S-parameters of the Tx and Rx with and without PRS.

To further enable directional sensing capability, the PRS structure was modified into an inclined configuration, as shown in Figure 4. Instead of maintaining a constant cavity height, the PRS was tilted along one axis to introduce a linearly varying cavity profile. An inclined dielectric PRS introduces a spatially varying electrical thickness across the aperture. Assuming normal incidence, the transmission phase delay at position y can be approximated as $\phi(y) = k_0 \sqrt{\epsilon_r} t(y)$, where $t(y) = t_0 + y \tan \alpha$. k_0 is the free-space wavenumber, ϵ_r is the relative permittivity of the PRS, and $t(y)$ is the local thickness of the inclined PRS. Also, t_0 and α are the initial PRS thickness and the inclined angle of the PRS,

respectively. According to aperture antenna theory, such a linear phase distribution steers the main beam away from the broadside direction.

$$\theta_s \approx \sin^{-1} \left[\frac{1}{k_0} \frac{d\phi(y)}{dy} \right] \quad (3)$$

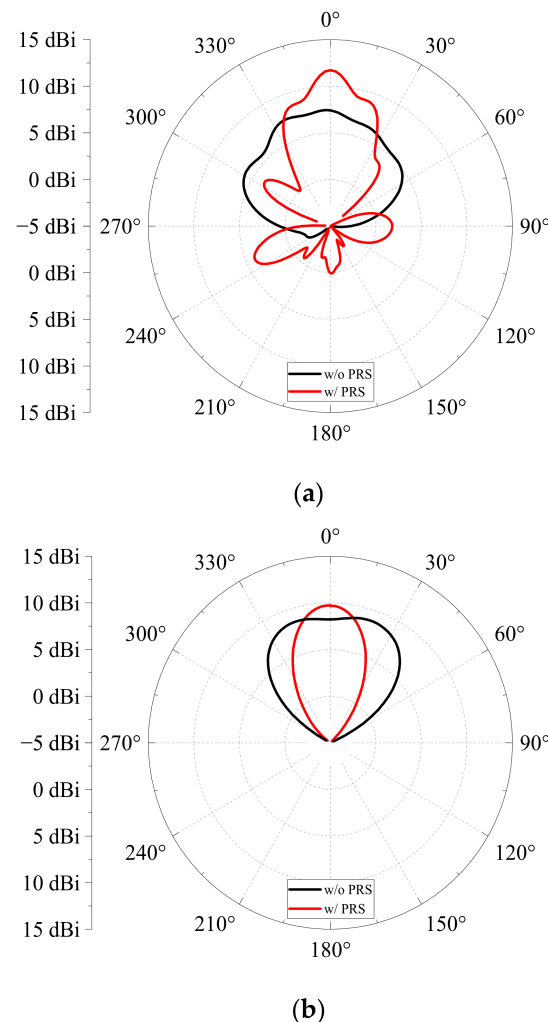


Figure 3. Comparison of full-wave simulated far-field radiation patterns for the Tx and Rx patch arrays with and without a flat PRS (y - z plane). (a) Tx antenna. (b) Rx antenna.

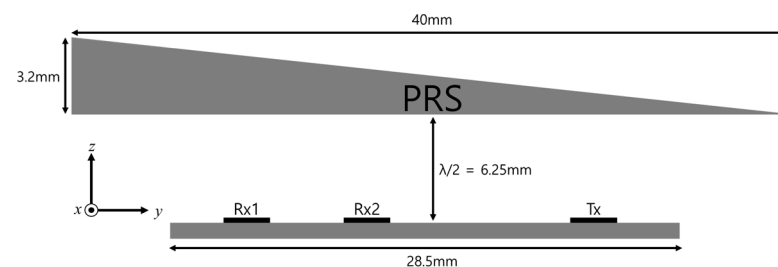


Figure 4. Tx and Rx antennas of 24 GHz object detection radar system with inclined PRS.

The beam steering angle (θ_s) can be approximately related to the spatial phase gradient across the aperture from Equation (3). Equation (3) indicates that a larger phase gradient results in a larger beam steering angle. Since the inclination angle of the PRS determines the spatial phase variation across the aperture, increasing the inclination angle leads to a greater beam deflection. It should be noted that Equation (3) provides only a first-order approximation of the beam-steering mechanism. In the proposed FPC structure, the

actual steering angle is additionally affected by local variations in the PRS reflection and transmission phase responses, multiple reflections within the cavity, finite-size effects, and near-field coupling between the PRS and the antenna array. Therefore, the final beam-steering performance was evaluated using full-wave electromagnetic simulations, which inherently account for these effects. The far-field radiation characteristics predicted by full-wave electromagnetic simulations are presented in Figure 5, demonstrating that the main beam is steered by approximately -10 degrees from the broadside direction while maintaining a gain level comparable to that of the flat PRS configuration. The S-parameters of the Tx and Rx antennas employing the inclined PRS structure were also simulated. The obtained response is found to be very similar to that of the flat PRS configuration, indicating that the beam-steering functionality introduced by the inclined PRS does not significantly alter the impedance matching characteristics of the antenna. The realized gains of the Tx antenna, corresponding to the three antenna configurations (without a PRS, with a flat PRS, and with an inclined PRS), are summarized as follows. The antenna without a PRS exhibits a realized gain of 7.4 dBi. By introducing the flat PRS, the gain increases to 11.7 dBi, corresponding to a gain enhancement of 4.3 dB. For the inclined PRS configuration, the realized gain is 10.8 dBi while simultaneously providing a beam-steering angle of approximately -10° . These results demonstrate that the flat PRS primarily improves the antenna directivity and gain, whereas the inclined PRS enables beam steering with a moderate gain enhancement.

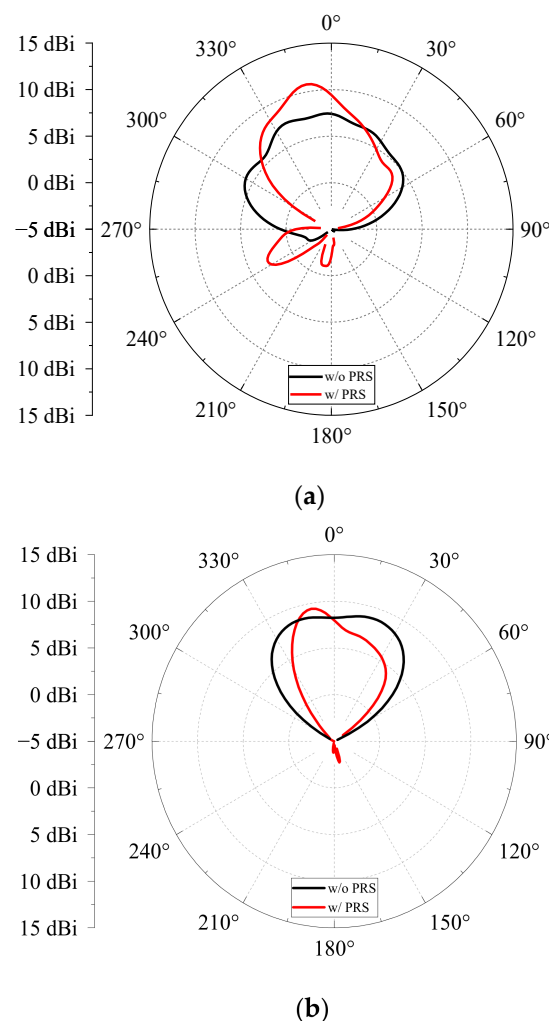


Figure 5. Full-wave simulated far-field radiation patterns of the Tx and Rx patch arrays without and with inclined PRS (y - z plane). (a) Tx antenna. (b) Rx antenna.

The steering angle is controlled by the inclination angle, which determines the magnitude of the spatial phase gradient. Unlike conventional phased-array systems requiring active phase shifters, the proposed inclined PRS achieves beam steering through passive structural modification, thereby maintaining low system complexity and power consumption. Through these design procedures and simulations, both flat and inclined PRS configurations demonstrate improved performance without enlarging the planar dimensions of the antenna module. The flat PRS primarily enhances broadside gain for detection range extension, whereas the inclined PRS provides additional directional control through passive beamforming while preserving gain improvement.

3. Experimental Results and Discussion of 24-GHz Object Detection Radar System

Figure 6 presents a block diagram of a bistatic 24-GHz object detection radar system. It consists of a graphical user interface (GUI), an RF module, and an antenna array. The RF module includes a transceiver, band-pass filters, power limiter, and multiple Rx channels, forming a multi-channel radar front-end. The antenna array comprises one Tx antenna and two receive antennas (Rx1 and Rx2). The Tx antenna radiates a 24-GHz signal toward the observation region, while the reflected signals from a target are received by the Rx channels. After filtering and amplification, the received signals are processed by the transceiver to estimate the target range and angular position. The dual-Rx configuration enables angular estimation by utilizing the spatial separation between the receiver channels. The processed information is displayed on the GUI as a real-time range-angle map, enabling intuitive monitoring of detected targets. This architecture provides a compact and practical platform for evaluating the detection-range enhancement and beam-steering characteristics introduced by the proposed PRS structures. This baseline configuration represents a typical radar sensing structure used for object detection applications. To enhance the detection performance without increasing system complexity, a PRS is introduced into the antenna structure. The antenna is implemented on the PCB, and the PRS is positioned on the opposite side of the PCB relative to the RF circuitry. Based on this concept, three different configurations are fabricated, as shown in Figure 7. The inclined PRS was fabricated by machining a 3.2 mm-thick dielectric slab to obtain the required tapered profile. Since the fabricated PRS cannot be mechanically supported by itself, a custom-designed 3D-printed holder was used to maintain the designed position during the measurements. The white and black structure shown in Figure 7b,c corresponds to this supporting holder and is not part of the PRS. The experimental setup for object detection is illustrated in Figure 8. A human is positioned in front of the radar system at a certain distance and angle, while the radar module is connected to a laptop for real-time signal acquisition and processing. The measurements are performed with a distance interval of 0.5 m and an angular resolution of 5 degrees in an indoor environment under controlled conditions to ensure consistent comparison across different configurations. Figure 9 shows the measured range-angle maps comparing detection performance with and without PRS. With the PRS, the maximum detectable range is extended from 4.5 m to 6.0 m in the boresight direction, corresponding to an improvement of approximately 35%. This measured enhancement is in good agreement with the simulation results discussed in Section 2, where a range increase of about 40% was predicted based on the radar range equation and the total gain improvement of 5.8 dB. The slight discrepancy can be attributed to practical factors such as propagation loss, target reflectivity variation, fabrication tolerances, and environmental conditions. In addition, due to beamforming toward approximately -10 degrees, the detection range in that direction is observed to reach about 5.5 m, demonstrating that the proposed structure not only improves

the overall detection range but also enhances directional sensitivity. These results confirm that the measured performance closely follows the theoretical and simulated expectations.

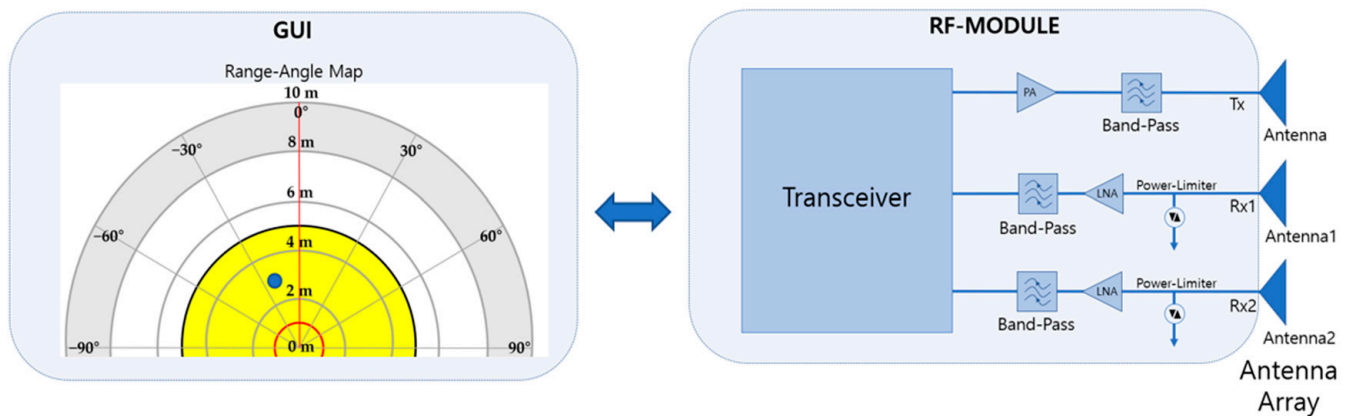


Figure 6. Block diagram of an object detection radar system including GUI, RF module, and antenna array.

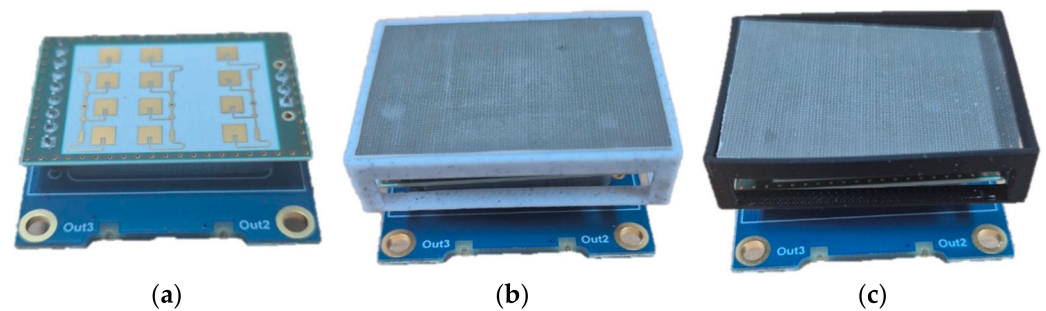


Figure 7. Photograph of the 24-GHz object detection radar module. (a) Tx and Rx antenna configurations without PRS layer. (b) Tx and Rx antenna configurations with flat PRS. (c) Tx and Rx antenna configurations with inclined PRS.

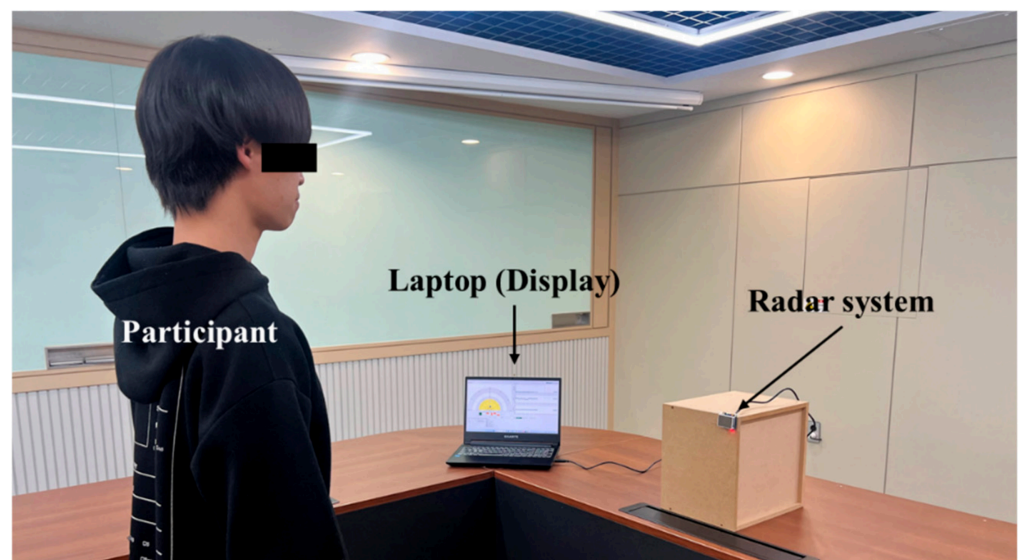


Figure 8. Experimental setup of the 24-GHz object detection radar system.

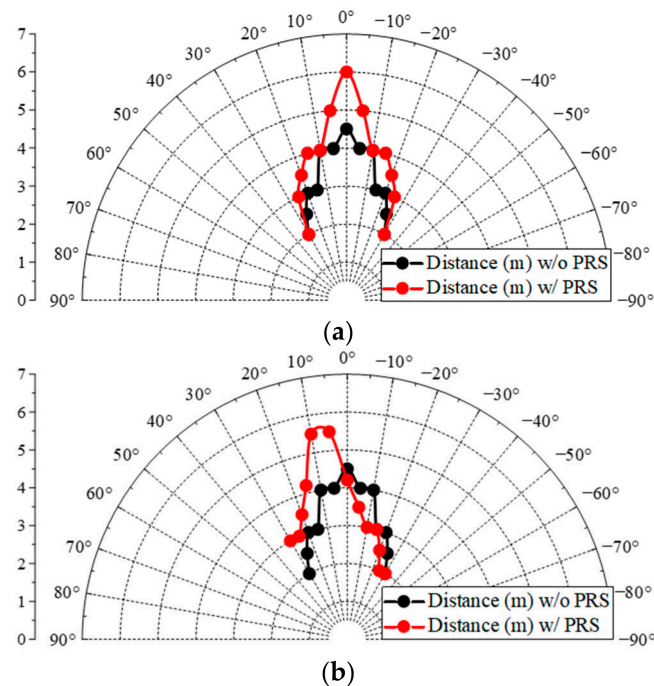


Figure 9. Measured range-angle maps comparing detection performance with and without PRS. (a) Case of flat PRS. (b) Case of inclined PRS.

4. Conclusions

This paper proposes a PRS-integrated radar system for enhanced object detection, where PRS is incorporated on the opposite side of the PCB to improve antenna performance without increasing system complexity. The proposed approach eliminates the need for conventional electronically controlled phase shifters, thereby reducing hardware overhead and implementation cost. A key contribution of this research is the system-level implementation and experimental validation of alternative passive PRS configurations for realizing different sensing functionalities using a common 24-GHz radar platform. Unlike traditional electronic beamforming techniques, the proposed method enables environment-dependent operation through structural reconfiguration. Specifically, different PRS geometries can be selectively applied to realize either broad coverage or directional beam focusing, depending on the sensing requirements. This flexibility provides a practical advantage in real-world applications, where sensing conditions may vary and system simplicity is critical. By employing passive structural modifications rather than active circuit complexity, the proposed system offers an efficient and scalable solution for adaptive radar sensing. Overall, the results demonstrate that PRS-based beam control is a viable alternative to conventional electronic beamforming, with strong potential for low-complexity, cost-effective, and application-specific radar systems.

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Informed Consent Statement: Informed consent was obtained from the participant involved in the study.

Data Availability Statement: The original contributions presented in this study are included in the article. Further inquiries can be directed to the corresponding author.

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