

Advanced Inter-Band Frequency Reconfiguration Mechanism for Antenna for Enhanced Automotive Radar in Electric Vehicles

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Research Article

Keywords: Automotive Radar Sensors, Electric Vehicles, Frequency Reconfigurable Antennas, Varactor Diodes

Posted Date: May 22nd, 2026

DOI: <https://doi.org/10.21203/rs.3.rs-9676700/v1>

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Additional Declarations: No competing interests reported.

Advanced Inter-Band Frequency Reconfiguration Mechanism for Antenna for Enhanced Automotive Radar in Electric Vehicles

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Abstract—This paper presents the design of a compact frequency-reconfigurable mechanism for custom wireless sensor applications in electric vehicles (EVs), operating at 24 GHz and 77 GHz. Unlike conventional antennas that operate at fixed resonance frequencies, the proposed design enables selective and electronically switchable operation between automotive radar bands through a simple switching network that uses two PIN diodes as RF switches. When switch S_1 is in the ON state, the proposed design operates at its 24 GHz resonant frequency, and when switch S_2 is in the ON state, it operates at its 77 GHz resonant frequency. The theoretical analysis is conducted to explain the reconfiguration mechanism and design methodology. A prototype is designed and fabricated on a Rogers RT/duroid 5880 substrate with a thickness of 5 mils and excited via an inset feed. All the simulations and measurements align well with each other to validate the design concepts.

Index Terms—Automotive Radar Sensors, Electric Vehicles, Frequency Reconfigurable Antennas, Varactor Diodes, Automotive Radar Sensors.

I. INTRODUCTION

WITH the rapid advancement of technology, one major trend that has captured global attention is the increasing importance of electric vehicles (EVs). With the rise of electric vehicles, significant emphasis has been placed on technological innovations that enhance both performance and safety. Microwaves and millimeter waves play a crucial role in this development, as electric vehicles integrate various sensors operating at different frequency bands. Each frequency band requires a dedicated antenna. Two key antennas used for automotive radars include one operating at 24 GHz, widely used for short-range radar (SRR) applications due to its relatively lower cost and simpler system implementation. In contrast, the 77 GHz

been reported for 24 GHz short-range radar [1], and a large amount of work also exists for 77 GHz long-range radar [2]. Other frequency allocations such as 76-77 GHz and 77-81 GHz are also utilized depending on regulatory and application requirements. Typically, these antennas have been designed independently of each other. However, recent trends indicate a growing demand for devices that can operate in multiple frequency bands. Smart antenna systems (SAS) for MIMO applications are widely used due to their better performance compared to conventional omnidirectional antennas, particularly in terms of spatial selectivity and link reliability. However, the requirement for multiple RF chains and additional digital signal processing (DSP) makes them less cost effective [3]. Array based beam-steering techniques, such as true time delay networks [10] and Butler matrices [4], are used to achieve directional control. However, these approaches require multiple antenna elements and additional RF hardware. To address these issues, reconfigurable mechanisms for antennas are used that present an economical and energy-efficient alternative.

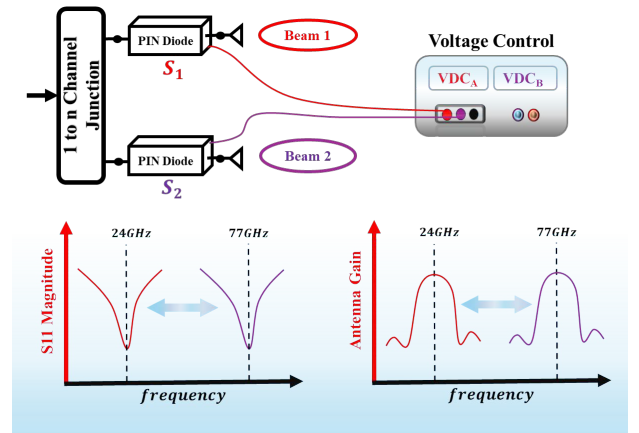


Fig. 1. Proposed frequency reconfigurable antenna system for automotive radar in EVs.

By appropriately biasing the switches, a single antenna can be reconfigured to operate over different frequency bands. Although NMOS-based reconfigurable antennas have also been demonstrated [5], [6], PIN diodes remain a more practical and economical choice due to their passive operation, low insertion loss, and high power-handling capability. Furthermore, PIN diodes enable both frequency and radiation-pattern reconfigurability within compact antenna structures [7]. This research paper presents the design of a single-feed

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spectrum, is commonly used for modern radar systems due to its larger available bandwidth, enabling higher resolution and improved target detection. Numerous antenna designs have

frequency-reconfigurable mechanism for an antenna, utilizing two PIN diodes as switches, as shown in Fig. 1. Unlike conventional single-band automotive radar antennas and recently reported dual-band designs that focus on integrated array configurations, the proposed work introduces a compact single-feed inter-band frequency-reconfigurable antenna mechanism using only two PIN diodes and a simple biasing network. The novelty lies in enabling selective excitation of two widely separated radar bands (24 GHz and 77 GHz) within a single compact structure, without requiring multiple RF chains or complex switching circuitry. This innovative antenna architecture enables operation at two distinct frequencies, specifically 24 GHz and 77 GHz. When S_1 is activated, the antenna resonates at 24 GHz, and when S_2 is activated, the antenna operates at a 77 GHz frequency. RLC circuits are used as PIN Diodes for EM simulations

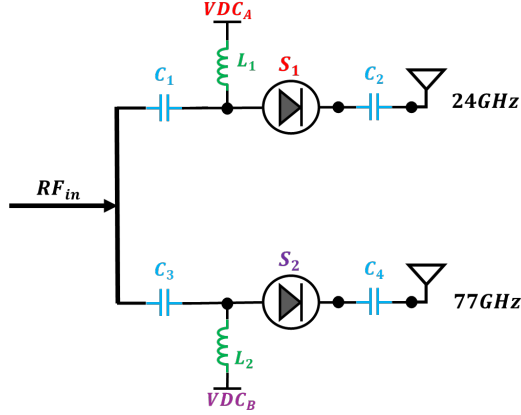


Fig. 2. Schematic of frequency reconfigurable antenna system

II THEORETICAL ANALYSIS

As shown in Fig. 2, our proposed frequency reconfigurable design consists of PIN diodes, two antennas, a biasing network, and a T-junction. The biasing network is designed for biasing the PIN diodes for operation as a switch. Two patch antennas operating at 24 GHz and 77 GHz are designed with inset feed matching.

A. Structure of RLC PIN Diode as a Switch

Fig. 3 shows the equivalent circuits of a PIN diode under forward-bias and reverse-bias (ON/OFF) conditions. When the diode is forward biased (ON state), charge carriers (electrons and holes) are injected into the intrinsic (I) region. These carriers do not recombine instantaneously; instead, they have a finite lifetime (τ) within the intrinsic layer. When the PIN diode is reverse biased (OFF state), no stored charge exists in the I region, and the device behaves as a junction capacitance (C_j) shunted by a high parallel resistance (R_p).

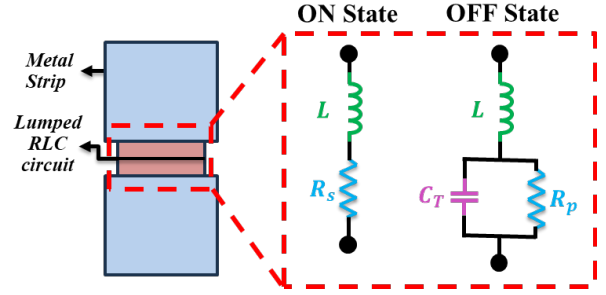


Fig. 3. PIN diode equivalent circuit in ON/OFF states

In the ON state, the PIN diode exhibits the behavior of a series RL network, as shown in Fig. 2(a). Under forward bias, the PIN diode acts as a current-controlled resistor (R_s), which is given by:

$$R_s = \frac{W^2}{(\mu_n + \mu_p)Q} \quad (1)$$

Where W is the width of the I-region, μ_n is the electron mobility, μ_p is the hole mobility, and Q is the quality of the stored charges described by the finite lifetime (τ) and forward biased current (I_f).

$$Q = \tau I_f \quad (2)$$

Combining (1) and (2) gives the inverse relation of the resistance R_s and forward biased current I_f :

$$R_s = \frac{W^2}{(\mu_n + \mu_p)\tau I_f} \quad (3)$$

This equation is valid for frequencies higher than the transit time of the I-region. Hence, for the ON-state, the effective switch parameter of the k th PIN diode D_{s_k} is given,

$$D_{s_k}(On) = R_{s_k} = \frac{W_k^2}{(\mu_{n_k} + \mu_{p_k})\tau_k I_{f_k}} \quad (4)$$

Where $k=1 \rightarrow Nth$

When the PIN diode is in the off state, it behaves as an RLC circuit, as shown in Fig. 3(a). The reverse bias equivalent circuit consists of the PIN diode capacitance ($C_T = \epsilon AW$), a shunt loss element (R_p), and the parasitic inductance (L). Where ϵ is the dielectric constant of silicon, A is the diode junction area, and W is the width of the I-region. The relation

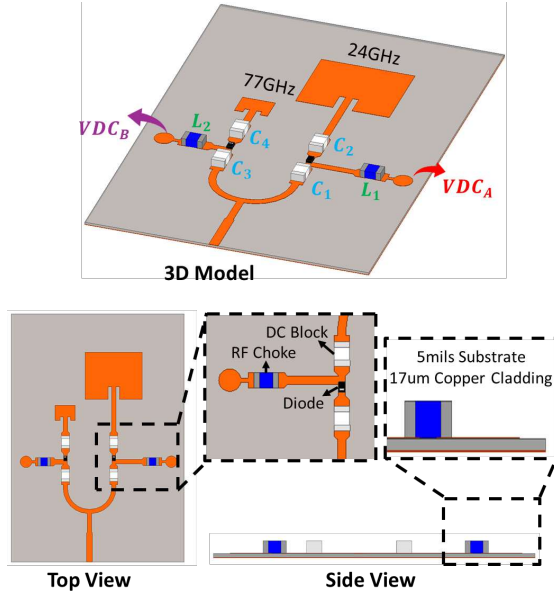


Fig. 4. Layout of the proposed 3D printed time delay block.

is valid for the frequencies above the dielectric relaxation frequency of the I-region and OFF-state relation, i.e.:

$$f > \frac{1}{2\pi\rho\epsilon}, \quad D_{sk}(OFF) = C_{T_k} = \frac{\epsilon_k A_k}{W_k} \quad (5)$$

Where ρ is the resistivity of silicon and $k=1 \rightarrow N$ th.

B. Biasing Components

As shown in Fig. 2, the biasing components ($C1-C4$, $L1$, and $L2$) are carefully selected to ensure that the RF signal at 24 GHz and 77 GHz encounters a high impedance toward the DC bias path while presenting a low impedance toward the PIN diode.

$$X_C = \frac{1}{j\omega C} = \frac{1}{j2\pi f C}, \quad X_L = j\omega L = j2\pi f L \quad (6)$$

Where L is the inductance, C is the capacitance, X_C is the impedance of a capacitor, and X_L is the impedance of the inductors.

C. Proposed Reconfigurable Antenna Design

The three-dimensional and layout views in Fig. 4 illustrate the physical implementation of the biasing circuitry, including the placement of the DC blocks, RF chokes, and PIN diodes along the feed lines. The antenna is fabricated on a Rogers RT/duroid 5880 substrate with a dielectric constant of 2.2 and a thickness of 5 mils, using 17- μ m copper cladding. The overall antenna dimensions are $30 \times 30 \times 1.6 \text{ mm}^3$, and the structure is matched to a 50- Ω transmission line using a quarter-wavelength transformer.

Standard microstrip patch antenna design equations, given in (7)-(11), are used to compute the patch width (W_p), effective permittivity (ϵ_{eff}), effective length (L_{eff}), physical patch length (L_p), and length extension (ΔL). These calculations are initially carried out for the 24-GHz operating mode and subsequently adapted for the 77 GHz configuration through the reconfigurable switching network.

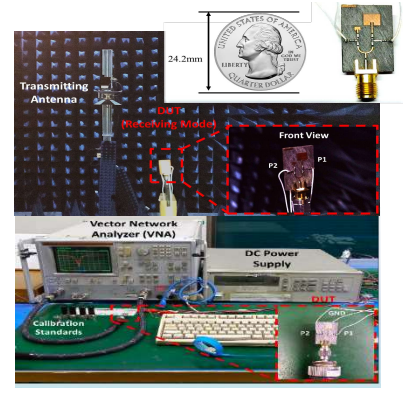


Fig. 5. Experimental validation of proposed RF signal processing TDB

$$W = \frac{c}{2f_r} \sqrt{\frac{2}{\epsilon_r + 1}} = \frac{3 \times 10^8}{2(24 \times 10^9)} \sqrt{\frac{2}{2.2 + 1}} = 4.94 \text{ mm} \quad (7)$$

Where ϵ_{eff} is the effective dielectric constant, and f_r is the resonant frequency. To calculate the patch width (W_{p24}), we have plugged in the values of the knowns:

$$\epsilon_{eff} = \frac{\epsilon_r + 1}{2} + \frac{\epsilon_r - 1}{2} \left(1 + 12 \frac{h}{W}\right)^{-\frac{1}{2}} \quad (8)$$

Where ϵ_r is the dielectric constant of the substrate, and h is the separation of the trace from the ground (thickness).

Similarly, L_{eff} is given by: $L_{eff} = \frac{c}{2f_r \sqrt{\epsilon_r}}$ (9)

And the additional length normalized by the thickness:

$$\frac{\Delta L}{h} = 0.412 \frac{(\epsilon_r + 0.3) \left(\frac{W}{h} + 0.264\right)}{(\epsilon_r - 0.258) \left(\frac{W}{h} + 0.8\right)}, \quad L = L_{eff} - 2\Delta L \quad (10)$$

Designing a frequency-reconfigurable antenna operating at widely separated frequencies (24 GHz and 77 GHz) presents several challenges. To address the challenge of impedance matching, each radiator is individually designed and optimized at its respective frequency using inset feed configurations, and both are integrated through a carefully designed T-junction. Radiation pattern stability is ensured by activating only one radiator at a time using the PIN diode switching mechanism, which minimizes unwanted coupling between the branches. To maintain radiation efficiency at 77 GHz, a low-loss substrate is employed and the layout is kept compact to reduce parasitic effects. Furthermore, isolation between the two antenna branches is achieved by ensuring that the inactive branch presents a high-impedance path, thereby preventing it from degrading the performance of the active radiator.

The forward and reverse-biased characteristics of PIN diodes were utilized as a switch to transition between the 24/77GHz antennas [9]. Table I shows the ON and OFF states of both switches S1 and S2 for both cases. The operation of the proposed antenna is governed by selective current routing enabled by the PIN diode switching network. When switch S1 is in the ON state, and S2 is OFF, the RF current is directed toward the 24 GHz radiator, while the 77 GHz branch presents a high impedance path and remains effectively isolated. Conversely, when S2 is ON and S1 is OFF, the current is redirected toward the 77 GHz radiator, while the 24 GHz branch is suppressed. This mechanism allows the antenna to operate independently at two widely separated frequency

bands within a single compact structure. The switching network thus controls the effective electrical length and current distribution, enabling inter-band frequency reconfiguration.

III IMPLEMENTATION OF THE PROPOSED CIRCUIT

The prototype is shown in Fig. 5(a), and the size of the fabricated circuit is 22×15 mm. The PIN diodes SMSA7621-060 are used to switch between the antennas. The experimental setup is shown in Fig. 5(b). The performance is evaluated for the ON and OFF states of switches S_1 and S_2 , defining the two operating cases summarized in Table I. Fig. 6(a) presents the reflection coefficient of the antenna in case 1, with less than -10 dB at 24 GHz, Fig. 6(b) presents the VSWR, and Fig. 6(c) presents the gain with respect to the frequency, with gain of approximately 8.2 dB at 24 GHz. Fig. 7(a) presents the reflection coefficient of the antenna in case 2, with less than -10dB at 77 GHz, Fig. 7(b) presents the VSWR, and Fig. 7(c) presents the gain with respect to the frequency, with the antenna gain of approximately 7.8 dB at 77 GHz. Fig. 7 presents the results at 77 GHz. The measured reflection coefficient (S_{11}) and VSWR at 77 GHz are not presented due to the unavailability of a calibrated port-based measurement

TABLE I

DIFFERENT CASES OF PIN DIODES (SWITCHES)

Case	State for S_1	State for S_2	Tuned Frequency (GHz)
Case 1	ON	OFF	24
Case 2	OFF	ON	77

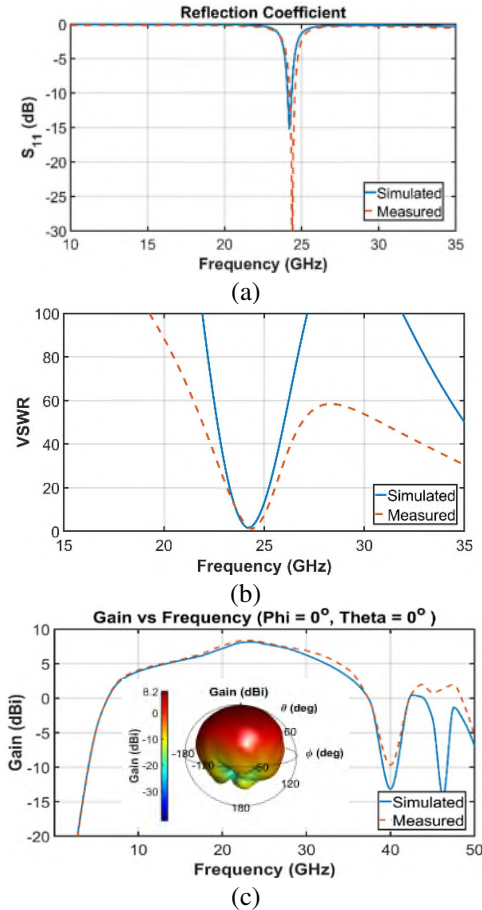


Fig. 6. Simulated and measured results at 24GHz: (a) Return Loss, (b) VSWR, (c) Gain across frequency.

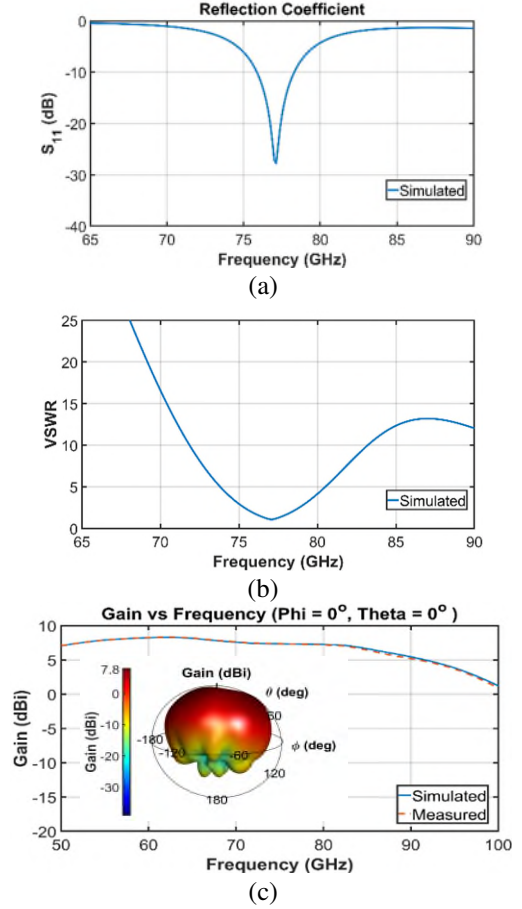


Fig. 7. Simulated and measured results at 77GHz: (a) Return Loss, (b) VSWR, (c) Gain across frequency.

setup at this frequency. However, the antenna gain and radiation characteristics at 77 GHz were obtained through radiated measurements in an anechoic chamber. Small variations in substrate thickness, conductor dimensions, and diode placement can lead to noticeable shifts in resonance and impedance matching, particularly at 77 GHz. In addition, measurement accuracy at higher frequencies is influenced by connector alignment, calibration quality, and setup stability. In this work, careful fabrication and controlled measurement conditions were maintained to minimize these effects. The use of a low-loss substrate and compact layout further reduces parasitic influences, resulting in stable and smooth measured responses. The overall in-band S_{11} is below -10 dB, indicating good impedance matching across the operating bands. A comparison with recent related works is provided in Table II, highlighting the performance and key distinctions of the proposed design.

TABLE II

SWITCHES FOR RECONFIGURATION

Ref	Band (GHz)	Actuator	Gain (dBi)	Key distinction
[14]	24/77	No / Nil	11.78 / 11.03	Compact dual-band MIMO array; true 24/77 baseline, but not switchable.

[15]	75-81	Yes / Switch states	6.18	Pattern-reconfigurable at 77-GHz band only; no 24-GHz operation.
[16]	77	No / Nil	14.2	In-package transmit-array solution with packaging relevance; not dual-band or single-feed switchable.
[17]	24/77	No / Nil	15.23 /13.46	Closest recent 24/77 reference; integrated multi-array solution, not single-feed inter-band switching.
This Work	24/77	Yes / 2 PIN diodes	8.2 / 7.8	Single-feed selective switching between widely separated 24 and 77 GHz radar bands with low circuit complexity.

In EV environments, the antenna may be enclosed within a radome or integrated near metallic structures, which can introduce detuning and affect radiation characteristics. Additionally, temperature variations can influence the electrical properties of the substrate and the behavior of the switching components. While the proposed design is validated under controlled measurement conditions, further investigation of packaging effects and temperature robustness is required for real-world deployment and will be considered in future work.

IV. CONCLUSION

In this design, an electronically frequency-reconfigurable antenna operating at 24 GHz and 77 GHz is presented. The operating frequency is switched using a PIN diode, ensuring stable performance across both bands without introducing impedance mismatch. To validate the concept, a prototype was fabricated and tested using a VNA for reflection-coefficient measurements and an anechoic chamber for radiation-pattern characterization. The design achieves a return loss better than -15 dB and realized gains of 8.2 dBi and 7.8 dBi at 24 GHz and 77 GHz, respectively, demonstrating suitability for EV radar applications, including object detection and velocity estimation in Advanced Driver Assistance Systems (ADAS).

Acknowledgement:

The authors declare that no financial support or funding was received for the research, authorship, and/or publication of this article.

Ethics Approval Statement:

The authors declare that this research did not involve human subjects, animal experiments, or any personal/confidential data. Therefore, ethical approval and informed consent were not applicable

Data availability

No data was associated with this manuscript.

Conflict of interest

The authors have no conflict of interest in this work.

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