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Frequency agile hexagon slot antenna for RADAR applications

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Abstract: This paper presents the design and analysis of a frequency-agile hexagon slot antenna capable of operating across a wideband frequency range from 1 GHz to 12 GHz by toggling diode ON/OFF conditions, making it suitable for radar and high-speed wireless communication applications. The proposed antenna structure is designed with FR-4 epoxy substrate and ground plane is implemented using copper to ensure high conductivity and minimal insertion loss. A microstrip feedline is employed to excite the hexagonal slot, offering efficient coupling and stable impedance matching across the operating bandwidth. The antenna exhibits strong frequency agility through structural optimization and design symmetry, enabling operation across multiple radar bands. The compact form factor and wideband performance of the antenna make it an ideal candidate for integration into modern radar systems.

Keywords: Hexagonal slot, frequency agility, Radar applications, slot antenna, notch, strip

I. INTRODUCTION

Radar systems operating in contested or dynamic electromagnetic environments desperately nee[1] frequency-agile antennas to ensure reliable detection, tracking, and communication. In modern warfare and surveillance scenarios, adversaries often deploy electronic countermeasures such as jamming or spoofing to disrupt radar signals. Without the ability to swiftly change operating frequencies, traditional radar systems become vulnerable to these attacks, leading to degraded performance or complete signal loss. Frequency-agile antennas allow radar systems to hop across multiple frequencies, avoiding interference and evading hostile detection or targeting.

This agility not only improves resilience against electronic threats but also enables better spectrum utilization in crowded bands, making it essential for next-generation radar platforms used in defence, air traffic control, and autonomous navigation systems A slot antenna is a type of antenna that consists of a metal surface with one or more narrow openings or "slots" cut into it, typically backed by a ground plane. [2-3] These antennas operate on the principle that the slot in the conductive surface behaves similarly to a dipole antenna, radiating electromagnetic waves when excited by a transmission line or waveguide.

Slot antennas are often used at microwave and millimetre-wave frequencies due to their compact size, ease of integration into planar structures, and compatibility with printed circuit board (PCB) technologies[4-6]. They offer directional radiation patterns and can be designed for linear or circular polarization. Common applications include radar systems, satellite communication, aircraft and missile systems, and modern wireless networks, where their low profile and ability to conform to surfaces make them especially advantageous. Frequency agility refers to the capability of a communication system, radar, or electronic device to rapidly switch between different frequencies within a designated range.

This ability is critical in environments where interference, jamming, or spectrum congestion is a concern, as it allows the system to maintain reliable performance by hopping to clearer or less-contested frequencies. [8] Frequency-agile systems enhance operational security and robustness, especially in military, wireless communication, and radar applications. By dynamically adapting to changing spectral conditions, these systems can optimize performance, avoid detection, or mitigate the effects of electronic countermeasures. Overall, frequency agility contributes to more resilient and efficient use of the electromagnetic spectrum. Frequency-agile antennas play a vital role in modern radar applications by enabling systems to dynamically switch operating frequencies across a wide band in response to environmental or tactical demands. This capability is crucial in environments where radar systems must contend with interference, signal congestion, or intentional jamming.

By rapidly hopping between frequencies, frequency-agile antennas help radar systems maintain reliable target detection, tracking, and imaging performance even under hostile or unpredictable conditions. [5]They also enhance

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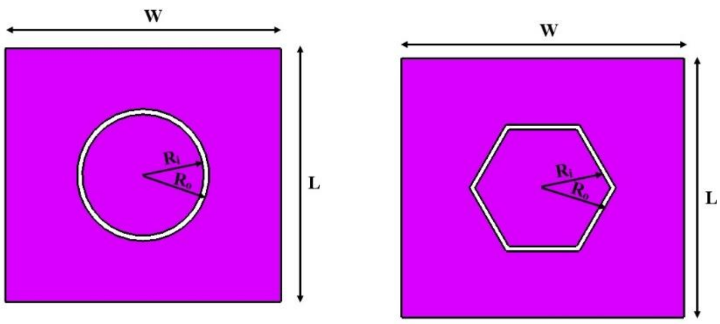
electronic counter-countermeasures (ECCM), making it harder for adversaries to detect, intercept, or disrupt radar signals. Furthermore, frequency agility supports multi-mode radar operations, allowing the same system to perform different functions—such as surveillance, tracking, and weather monitoring—across different frequency bands. As a result, frequency-agile antennas are indispensable in both military and civilian radar platforms, providing flexibility, survivability, and adaptability in increasingly complex electromagnetic environments.

II. DESIGN METHODOLOGY

The proposed frequency agile hexagonal slot antenna with frequency agility and electronic beam steering for cognitive radar applications is developed in 4 stages. The structure uniquely integrates polygonal to enhance frequency response.

2.1 Development of slot antenna



(a) (b)

Fig.1.Evolution of slots.(a) circular slot, (b) Hexagonal slot

Initially, a circular slot antenna was designed with the aim of achieving frequency agility for radar applications. However, this configuration yielded only two distinct frequency bands, limiting its effectiveness for systems requiring wider operational flexibility. To overcome this limitation, the design was modified by replacing the circular slot with a hexagonal slot geometry. The hexagonal slot significantly improved the antenna's performance by producing four distinct frequency bands within the radar frequency range of 8 GHz to 12 GHz, which includes the critical X-band used extensively in radar and satellite communications. This enhancement is attributed to the increased number of resonant paths and edges introduced by the hexagonal shape, which allows for more complex current distributions and multiple resonances. As a result, the hexagonal slot not only expands the frequency coverage but also supports better adaptability for radar systems operating in dynamic and contested environments. This improved design provides enhanced frequency agility, making it more suitable for modern radar applications that demand high performance, robustness, and resistance to interference or jamming across a broad spectrum.

Table.1.Dimensions

Components	**Materials**
Substrate	FR-4 epoxy
Ground	Copper
Feed	Copper

Table.2. component materials

Parameter	Description	Values (mm)
R_0	Outer radius	13
Ri	Inner radius	12
L	length	12.76

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Table.3. obtained frequencies for slots

Stages	Shapes	Frequency Bands (GHz)
Stage1	Circle	2
Stage2	Hexagon	3

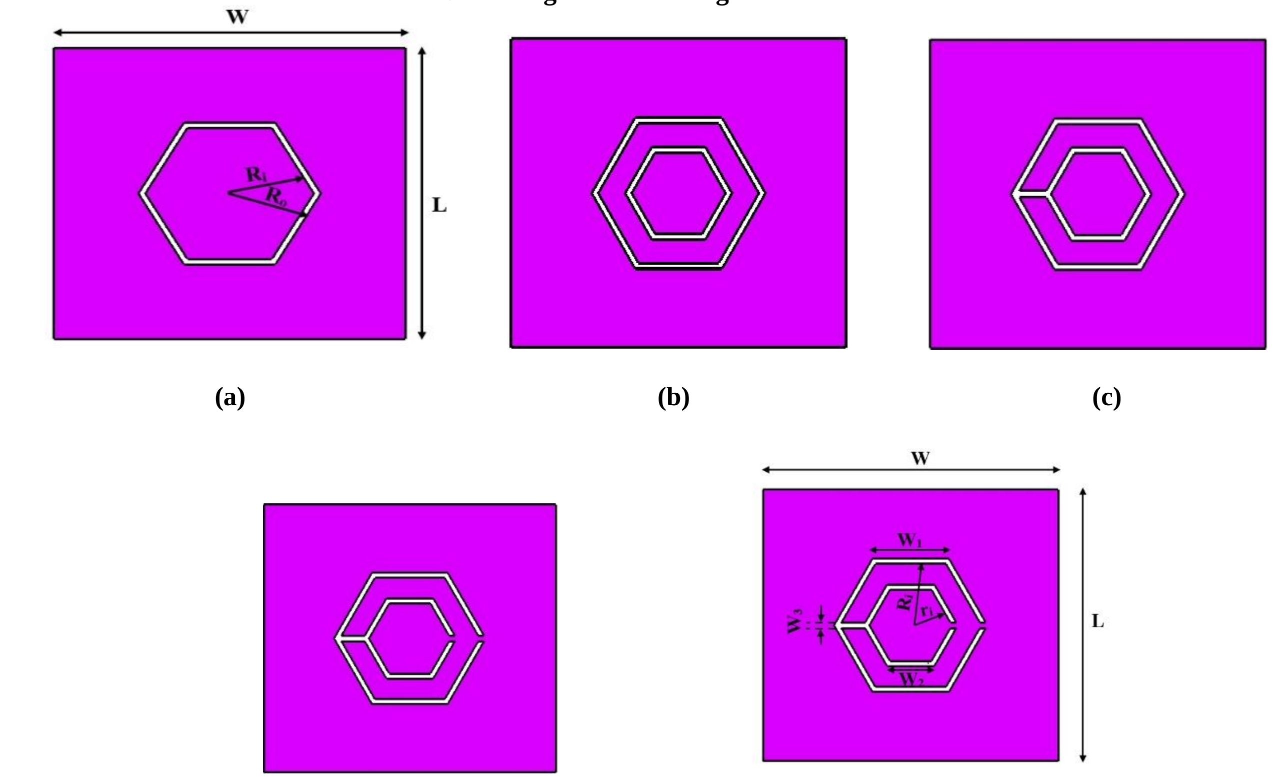
The tables noted earlier showcase are the obtained frequency data, the dimensions applied, and the materials used in the components. It is evident from the frequency data presented above that the hexagon slot antenna exhibits characteristics of multiple frequency bands. Hence hexagon slot is finalised.

2.2 Development of Hexagon slot

The initial stage began with a basic slot antenna, where a single circular slot was etched onto the ground plane, with a microstrip feedline placed on the substrate layer. Hexagon shape was selected for final design as it is obtaining multi resonant frequencies, compared to previous slot.

After selecting the hexagonal slot configuration, a primary hexagonal slot was etched onto the surface. This outer hexagon has an edge length of 12.76 mm, an outer radius of 13 mm, and an inner radius of 12 mm, forming a ring-like hexagonal shape. Within this outer hexagon, a smaller concentric hexagonal slot was etched. The inner hexagon has an edge length of 8 mm, an outer radius of 8 mm, and an inner radius of 7 mm, maintaining a uniform 1 mm thickness around its perimeter. The spacing between the outer edge of the inner hexagon and the inner edge of the outer hexagon is 5 mm, ensuring symmetrical alignment and structural consistency. On the right side of both hexagonal structures, a rectangular notch was introduced. Each notch measures 1 mm in width and 8 mm in length, serving as part of the overall current path design or possibly for impedance matching or field shaping purposes. To facilitate electrical connectivity and current flow between the two hexagons, a conductive strip was integrated on the left side. This strip physically connects both hexagons, creating a continuous conductive pathway. Additionally, three diodes were strategically placed to enable or control switching behavior within the structure. Two diodes were mounted on the top and bottom edges of the outer hexagon, while the third diode was installed directly on the conductive strip connecting the two hexagons on the left side. The placement of these diodes suggests a reconfigurable mechanism, likely intended for switching states or tuning the resonant frequency properties of the structure.

Evolution stages of the Hexagon slot antenna



(d) (f)

Fig.2.(a) Hexagonal slot, (b) Dual Hexagonal Slot, (c) Dual hexagonal slot with left-Side interconnect strip, (d) with dual notch cut on right side, (e) Final hexagonal slot with labelled dimensions

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The above described stages represent the evolutionary development of a novel electromagnetic structure, referred to as the Dual Hexagonal Slot with Left-Side Interconnect Strip and Dual Notch Cut. This structure has been meticulously engineered to achieve frequency agility, a critical requirement in modern radar applications where dynamic tuning across multiple frequencies is essential.

Table.4. Parameters of Dual Hexagonal Slot with Left-Side Interconnect Strip and Dual Notch

Parameters	Values(mm)
W1	12.76
W2	8
W3	1
Ro	13
Ri	12
ro	8
ri	7

III DESIGN OF FEED

Above the ground plane lies the dielectric substrate, which houses the microstrip feedline. The feedline is carefully designed and positioned to excite the slots from above, ensuring efficient energy coupling into the slot structure. Fig 3 shows the microstrip feedline placed on substrate, which is used to excite the slots. The feedline is step feed design it transitions from a wider width to a narrower width for impedance matching. It consists tuning Flexibility to obtain results at desired frequencies. The feedline consists of two sections with different widths:

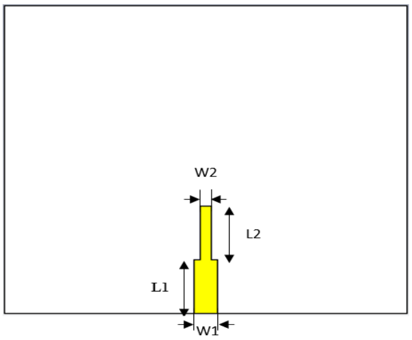

Fig.3. Feed line

1.Width W1, Length L1: the lower (wider) section.
2.Width W2, Length L2: the upper (narrower) section.

Table.5. Dimensions of feedline

Parameters		Existing Values(mm)	Proposed Values(mm)
Width	W1	2	2.92
	W2	1	1.46
Length	L1	7.5	8
	L2	8	8

Integration of PIN Diodes

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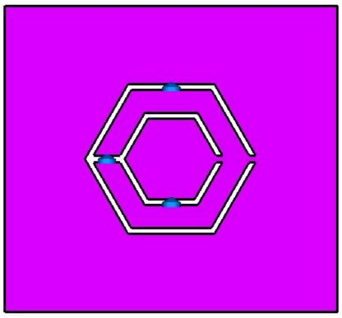

Fig.4. with integration of diodes

An essential characteristic of this antenna is its frequency agility and capability for beam steering, which is realized through the strategic incorporation of three PIN diodes that are symmetrically positioned around the slot architecture. These diodes are strategically integrated within designated segments of the slot. This modification facilitates dynamic variation of the resonant frequency of the antenna. Within the framework of our antenna design, we have incorporated three SMP1320-07LF PIN diodes, which are conspicuously arranged symmetrically, linking the external and internal hexagonal slots. By toggling the diodes ON or OFF (in forward or reverse bias configurations), one can effectively manipulate the flow of surface current.

Table.6. Specifications of diode

Parameter	**Values**
Forword resistance	0.75 ohm
Series inductance	0.7nH
Capacitance	0.23pF
Diode type	PIN diode
Switching speed	Fast
Typical application	RF switching, antenna reconfiguration

IV RESULTS

A Dual Hexagonal Slot with Left-Side Interconnect Strip and Dual Notch Cut slot antenna was designed and simulated using CST software. By toggling the ON-OFF states of the diode, the antenna achieved tunable frequency responses within the 3 GHz to 4 GHz range, suitable for RADAR applications. The below figure shows the circuit of the diode. The s parameters are obtained at different diode conditions.

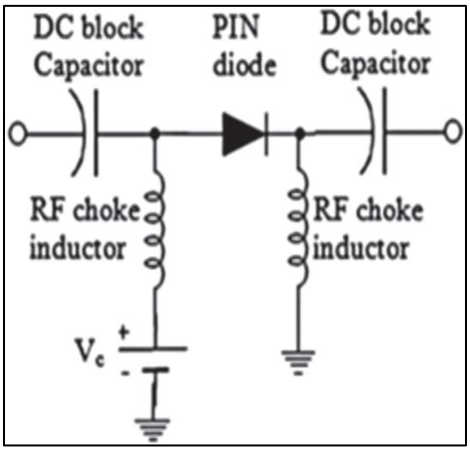

Fig.5. PIN diode circuit

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S parameters

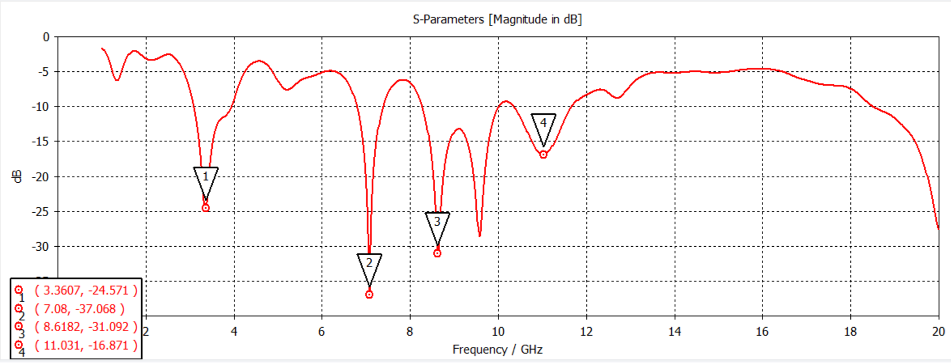

Fig.6. S parameter for diode condition 1 (000)

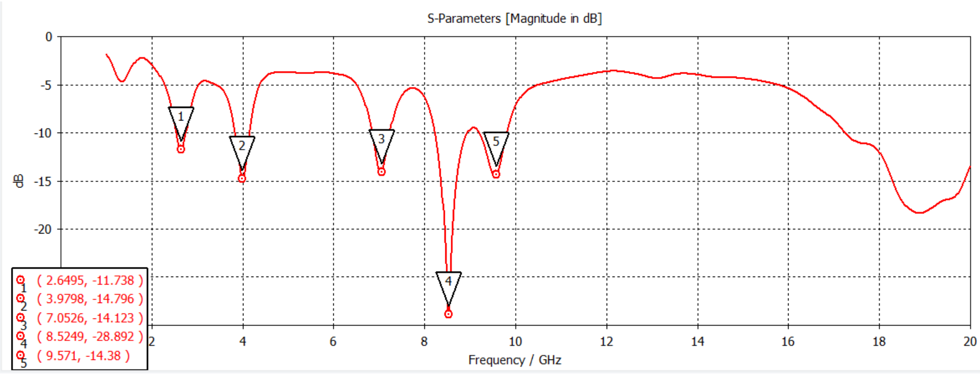

Fig.7. S parameter for diode condition 2 (011)

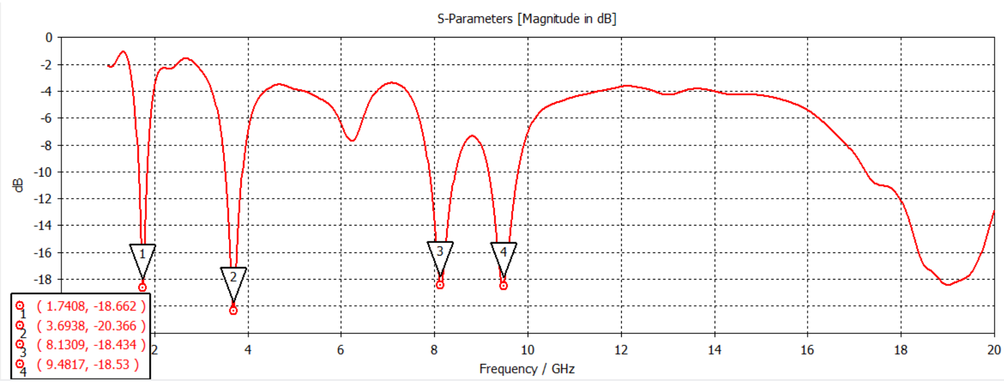

Fig.8. S parameter for diode condition 3 (100)

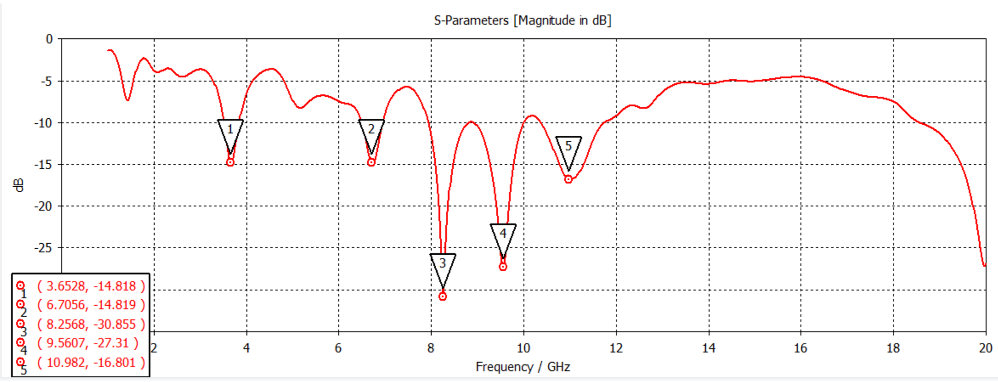

Fig.9. S parameter for diode condition 4 (111)

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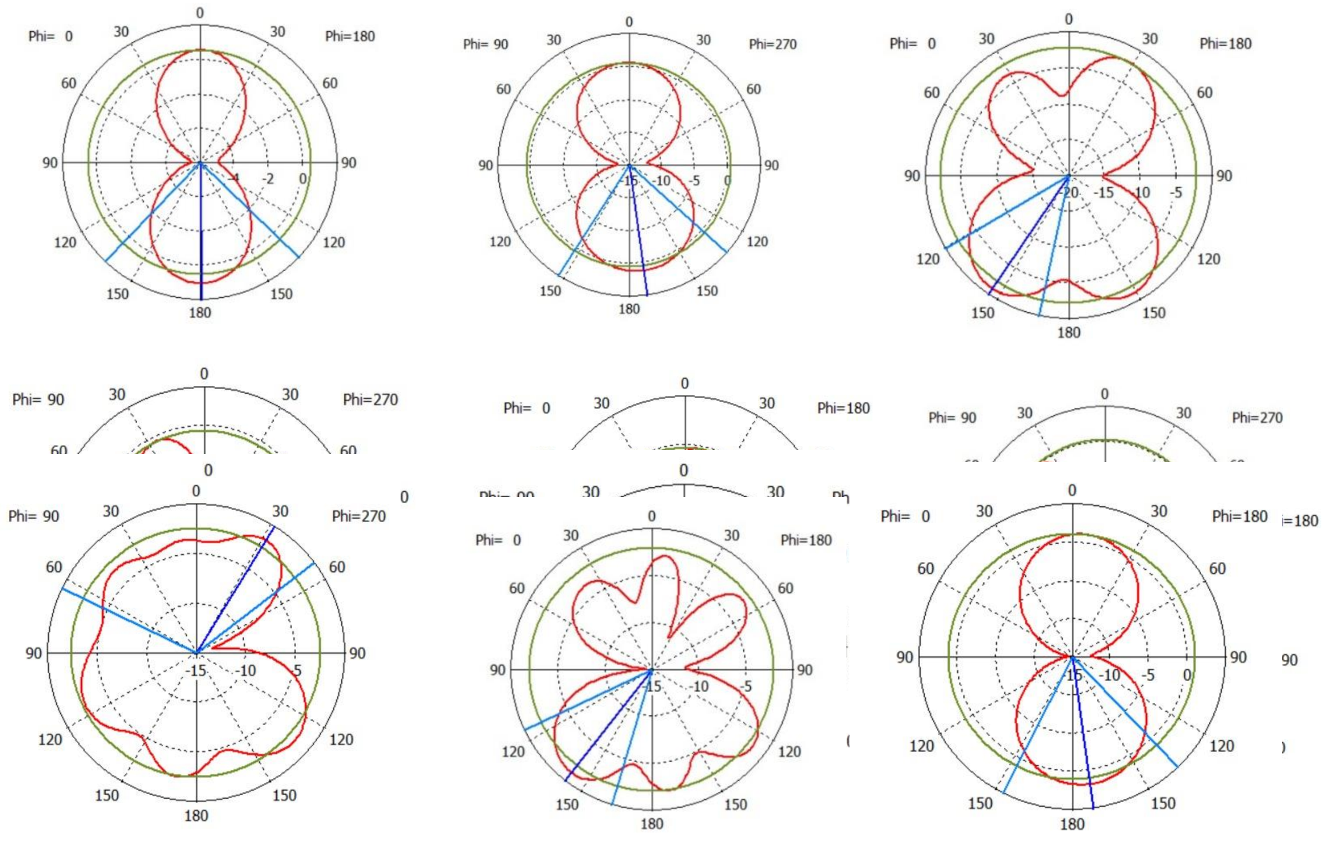
Based on the graphs obtained presented in the above figures, the designed dual hexagonal slot structure with left-side interconnect strip and dual right-side notches exhibits resonant frequencies spanning from approximately 1.74 GHz to 12GHz across different diode biasing conditions (000, 011, 100, 111). This wide operational frequency range effectively covers multiple bands within the 1–12 GHz spectrum, which is of significant interest in modern radar systems.

Table.7. ON/OFF conditions of diode

Conditions	Frequency (GHz)	Return Loss (dB)	E-Plane (°)	H-Plane (°)
000	3.3607	-24.571	172	179
	7.08	-37.068	-148	-146
	8.6182	-31.092	-128	167
	11.031	-16.871	-136	-37
011	2.6495	-11.738	174	178
	3.9798	-14.796	-173	172
	7.0526	-14.123	-147	-149
100	3.6528	-14.818	-178	171
	6.7056	-14.189	-154	-144
	8.2568	-30.855	-135	-119
111	1.7408	-18.662	176	-178
	8.1309	-18.434	-133	1
	9.4817	-18.53	-123	-143

Radiation pattern in both H-plane and E- plane



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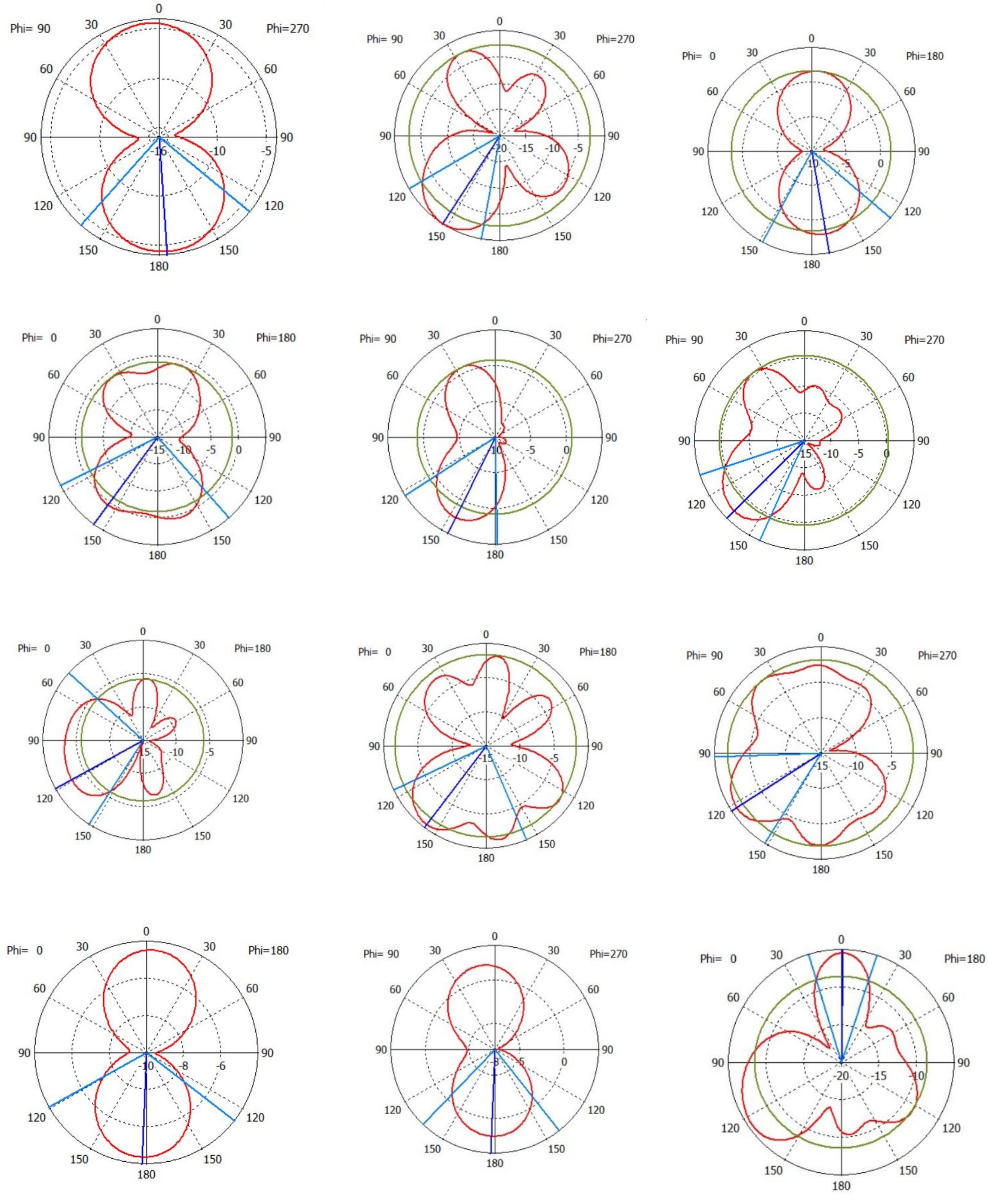

Fig.5. Radiation pattern of diode conditions in both H plane and E plane

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V CONCLUSION

The proposed antenna is specifically engineered for frequency agility within the radar frequency spectrum, enabling dynamic tuning across a wide operational bandwidth. The antenna successfully covers frequencies ranging from 1 GHz to 12 GHz, which encompasses multiple radar bands including X band. This wideband capability is particularly advantageous for modern radar systems that require multi-band operation, electronic counter-countermeasures (ECCM), or adaptable frequency-hopping to mitigate interference and improve detection accuracy. The frequency agility is achieved through [tunable elements, reconfigurable structures], allowing the antenna to adapt to varying operational requirements in real-time.

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