Bulletin of Electrical Engineering and Informatics
Vol. 14, No. 1, February 2025, pp. 207~215
ISSN: 2302-9285, DOI: 10.11591/eei.v14i1.8798

X-band and Ku-band PIN diode loaded reflectarray unit cells with adaptive frequency switching

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Article Info

Article history:

Received Jun 10, 2024
Revised Aug 29, 2024
Accepted Sep 28, 2024

Keywords:

Dynamic phase range
Frequency switching
Planar reflector
Progressive phase distribution
Reflectarray antenna

ABSTRACT

The fast advancement of intelligent new applications has led to the creation of high-performance antennas. Reflectarrays (RAs), also known as planar reflectors, are seen as promising antennas for several such modern-day applications. This work presents a comprehensive investigation of frequency switchable RA antennas operating in the X-band and Ku-band frequency ranges. Various strategic configurations of combined slots have been suggested, using integrated P-layer, I-layer, and N-layer (PIN) diodes, with the purpose of creating unit cells in RAs that may switch frequencies and exhibit a gradual change in phase distribution. The frequency variation achieved in X-band for the ON state of PIN diodes is from 8.13 GHz to 11.69 GHz, whereas for the OFF state it is from 8.13 GHz to 11.68 GHz. Similarly, for Ku-band ON and OFF states of PIN diodes provided frequency variations of 13.6 GHz to 17.1 Ghz and 12.8 Ghz to 16.6 GHz respectively. Frequency tunability of 0.85 GHz and 0.72 GHz has been successfully achieved in X-band and Ku-band.

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1. INTRODUCTION

A reflectarray (RA) antenna is a hybrid antenna that incorporates the benefits of both reflector and array antennas. The device comprises a flat surface that reflects waves using a patterned arrangement of parts, allowing for precise control over the phase shift of the reflected wave [1]. The phase shift of each element is determined by its form, size, orientation, or material characteristics. The RA antenna may achieve high gain, low profile, and beam steering capabilities by precisely engineering the phase distribution of its parts [2], [3]. Researchers and professionals are working together to enhance the directional capabilities of millimeter-wave antennas, leading to improved signal strength and consistent functionality [4]-[6]. Various methods for beam-steering may be discovered in the literature. Trade-offs occur due to differences in complexity, performance, cost, and references [7], [8]. Beam-steering is the capability to modify the emission pattern of an antenna in order to optimise amplification in a certain direction [9]. Beam guiding often need an "adjustment". Various methodologies are used to accomplish distinct alterations. RAs and transmitarrays (TAs) are often used in the construction of high-gain antennas. In order to achieve beam scanning, the use of reconfigurable components such as P-layer, I-layer, and N-layer (PIN) diodes [10]-[14] varactors [15] is employed to dynamically alter the phase of reflection or transmission. This allows for the construction of reconfigurable reflectarrays (RRAs) or reconfigurable transmit arrays (RTAs).

The concept of RA antenna was first introduced by Berry in 1963 [16], but, it did not get significant recognition until the 1990s, when other researchers showcased its practicality and prospective uses [1]. RA antennas have undergone extensive research and development for a range of frequency bands and applications, including satellite communication, radar, imaging, and wireless power transfer [17]-[22]. However, the electrically reconfigurable array antennas discussed can only function in one of these modes [23]-[26], and generally exhibit certain limitations due to the implementation of the electronic components [27]-[29].

This study introduces RA unit cells that are loaded with slot and PIN diodes. These unit cells are suitable for designing planar reflectors at various frequency ranges. The desired progressive phase distribution has been accomplished by altering the slot size.

2. DESIGN AND ANALYSIS

One of the most important and fundamental components of planar reflector design is the distribution of progressive phase. Its primary goal is to transform the naturally spherical wave front into a flat wave, which is required for a number of electromagnetic and radiofrequency engineering applications. Through this conversion process, planar reflectors become more efficient at focusing or steering electromagnetic radiation. This makes them particularly useful in applications like wireless communication, radar systems, and antenna construction.

The careful positioning of each component inside the reflector array is essential to attaining a progressive phase distribution. To ensure that the phase of the wave emitted from each element combines in a way that accentuates the chosen focal point, every element's placement, shape, and size must be carefully considered. A homogenous, flat, and precisely aligned reflected wave front is required for long-distance transmission or high-resolution imaging, and constructive interference plays a critical role in attaining this. By incorporating various slot shapes inside the patch components, a progressive phase distribution in planar reflectors is frequently achieved. To produce constructive interference across the array, the slots or apertures in the patch components are purposefully designed to produce phase delays and alter the radiated wave's phase. To ensure that the holes align and form a single, flat wave front, they are carefully positioned and proportioned to accurately control the phase of the radiated waves from each element.

To obtain the appropriate phase distribution, a variety of slot layouts and geometries have been investigated and applied in planar reflector designs. Depending on the specific function and frequency of operation, scientists and professionals have looked at a variety of slot arrangements, including complex, circular, and rectangular designs. Through the use of sophisticated calculations and experimentation, these designs have made it possible to create planar reflectors that are incredibly efficient. These reflectors are essential to satellite technology, radar systems, and wireless communication in the current world, all of which advance the interconnectedness of our planet.

This paper presents a novel method to create a planar reflector that can switch frequencies and has a gradually changing phase distribution. The design included a strategic integration of rectangular and circular holes across the whole width of the patch, as seen in Figure 1. The purpose of implementing these slots was to convert spherical waves into planar waves and allow for frequency change. This makes the reflector flexible and capable of adapting to various operating needs.

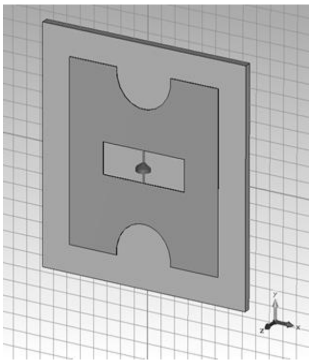


Figure 1. Unit cell of a frequency switchable planar reflector with progressive phase distribution

The rectangular slot that is placed in the middle of the resonating patch is the primary feature of this design. This rectangular aperture serves two purposes: it permits the insertion of a PIN diode and facilitates frequency switching. By carefully connecting the PIN diode to the rectangular slot, the reflector's resonance frequency can be changed. The reflector may be made to operate at different frequencies by adjusting the PIN diode's conductivity, offering flexibility and adaptability for a variety of communication or sensing applications.

In addition to the central rectangular slot, the patch pieces are accentuated by circular slots with different radii placed next to the widths. In order to help achieve the desired progressive phase dispersion, the round holes were purposefully positioned. The coherent combination of the emitted waves is made possible by the employment of circular slots with varying sizes, which cause phase delays across the patch parts. The creation of a flat wave front as a result of the constructive interference is essential to the operation of accurate radar systems and high-gain antennas.

Planar reflector design is made new and efficient by the inclusion of a PIN diode for frequency switching and the usage of rectangular and circular slots. This design has the advantage of being flexible enough to accommodate a wide range of frequencies while also ensuring a progressive phase distribution to enhance wavefront management. There are a lot of possible uses for this frequency switchable planar reflector, such as remote sensing and complex communication systems. It supports the ongoing development of radiofrequency and electromagnetic technology.

2.1. X-band planar reflector design

The design shown in Figure 1 was used in this study, where the radius of the circular slots across the width of the rectangular patch was altered from 2.84 mm to 5.15 mm. This was done to achieve a range of resonant frequencies that covers the X-band frequency range. The resonant patch element was fabricated on a dielectric substrate made of Rogers RT/Duroid 5880. The frequency switching was achieved by including an APD 0805-000 PIN diode with a rectangular slit in the centre, which was employed in both the OFF and ON states. Figures 2(a) and (b) show reflection loss curves for circular slots with varying radii, produced in two distinct switching states of PIN diodes.

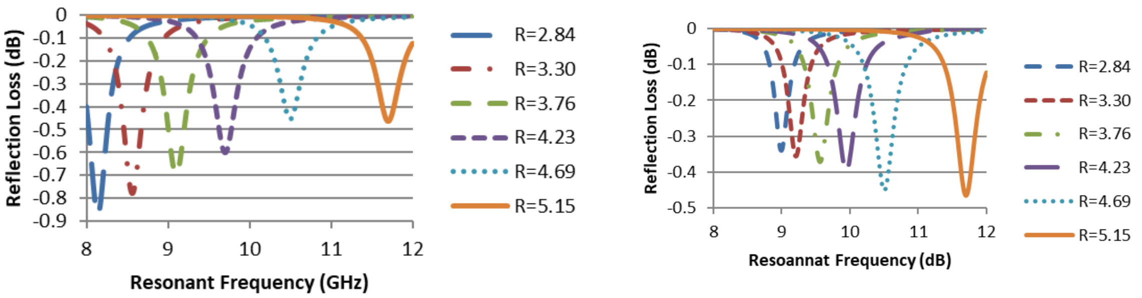


Figure 2. Reflection loss curves for X-band frequency switchable planar reflector; (a) PIN diode OFF and (b) PIN diode ON

Figure 2 illustrates that the reflection loss experiences a sweeping motion over the X-band frequency range in both the OFF and ON switching phases of the PIN diode. Moreover, the reflection losses are amplified while the PIN diode is in the ON state as a result of the supplementary resistance caused by the diode. Table 1 displays a concise overview of the reflection loss data collected for different radii of circular structures used in the fabrication of frequency switchable planar reflectors.

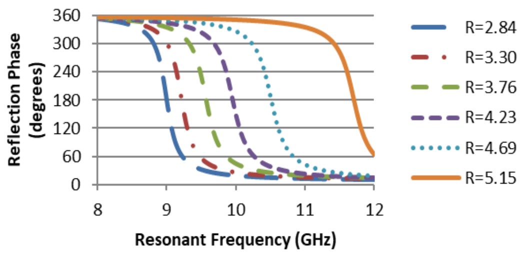
Table 1. Resonant frequency and reflection loss X-band frequency switchable planar reflector

Slot radius (mm)	Resonant frequency (GHz)		Reflection loss (dB)	
	Diode ON	Diode OFF	Diode ON	Diode OFF
2.84	8.13	8.98	-0.86	-0.33
3.30	8.56	9.20	-0.78	-0.35
3.76	9.10	9.56	-0.69	-0.37
4.23	9.69	9.95	-0.59	-0.39
4.69	10.5	10.5	-0.45	-0.45
5.15	11.69	11.68	-0.46	-0.45

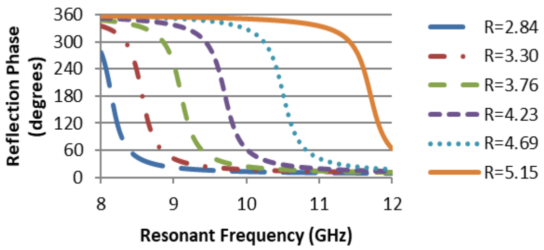
Table 1 demonstrates that increasing the radius of the circular slot from 2.84 mm to 5.15 mm results in an increase in the resonant frequency from 8.13 GHz to 11.69 GHz while in the ON state. In addition, the reflection loss decreases from 0.86 dB to 0.46 dB. On the other hand, when the PIN diode is not conducting, the resonance frequency increases from 8.98 GHz to 11.68 GHz, and the reflection loss goes up from 0.33 dB to 0.45 dB when the circular slot size is changed from 2.84 mm to 5.15 mm. The fluctuations in resonant frequency and reflection loss are a result of changes in the current distribution on the patch surface, which are generated by the changing radius of the circular slot. The variation in the slot radius also affects the associated lumped component values of the resonating patch element. As a consequence, the resonance frequency and reflection loss of the planar reflector design are modified.

Figures 3(a) and (b) show the reflection phase curves for the two switching states of PIN diodes. These curves were generated by varying the circular slot radius throughout the width of the patch element. The analysis of Figures 3(a) and (b) reveals that the slopes of the reflection phase curves are marginally greater when the PIN diode is in the ON state. The reason for this is the heightened reflection loss caused by the additional resistance in the ON state of the PIN diodes, as seen in Figure 2(a).

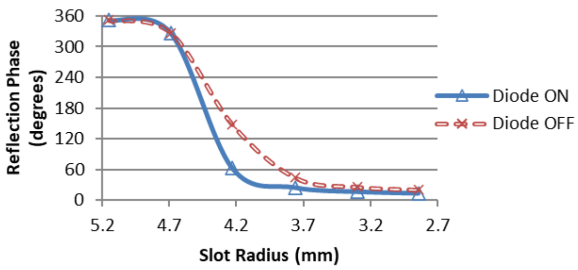
The phase curve of the individual unit cell patch components spans the whole X-band frequency range in both PIN diode switching modes, as shown from Figures 3(a) and (b). Therefore, the phase curves of individual patch components may be used to produce a progressive phase distribution for a planar reflector. Figure 3(c) displays the phase curves for the two switching states of PIN diodes, which were acquired for the suggested planar reflector design at a frequency of 10 GHz. Figure 3(c) shows that the curve of reflection phase against slot radius ranges from 19.75° to 352.16° in the OFF state and from 13.28° to 352.17° in the ON state. This outcome demonstrates the possibility of creating a planar reflector that can switch frequencies and has a progressive phase distribution ranging over more than 332°.



(a)



(b)



(c)

Figure 3. Reflection phase curves for X-band frequency switchable planar reflector; (a) PIN diode OFF, (b) PIN diode ON, and (c) comparison of two states

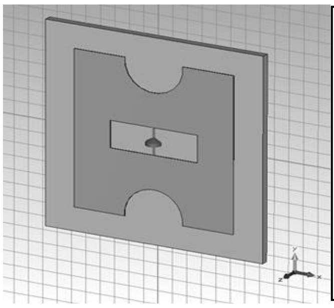
Table 2 presents an overview of the outcomes achieved for the design of a frequency switchable planar reflector with a progressive phase distribution in the X-band frequency range. Table 2 shows that the PIN diode's reflection phase curve has a steeper slope in the ON state. This results in a proven maximum static linear phase range of 198° for a circular slot with a radius of 2.84 mm. Conversely, while the PIN diode is in the OFF state, a circular slot with a radius of 5.15 mm has been able to obtain a larger static linear phase range of 210°. Table 2 also demonstrates that by using a circular slot with a radius of 2.84 mm, it is possible to obtain a maximum frequency tunability (ΔFr) of 0.85 GHz and a maximum dynamic phase range (Δφd) of 297° in the design of a frequency switchable planar reflector.

Table 2. Summary of the results obtained for proposed planar reflector design

Slot radius (mm)	Static linear phase range (°)		Frequency tunability ΔFr (GHz)	Dynamic phase range Δφd (°)
	Diode ON	Diode OFF		
2.84	198	190	0.85	297
3.30	192	201	0.64	270
3.76	182	204	0.46	227
4.23	168	206	0.26	147
4.69	160	209	0.02	3
5.15	156	210	0.01	0.1

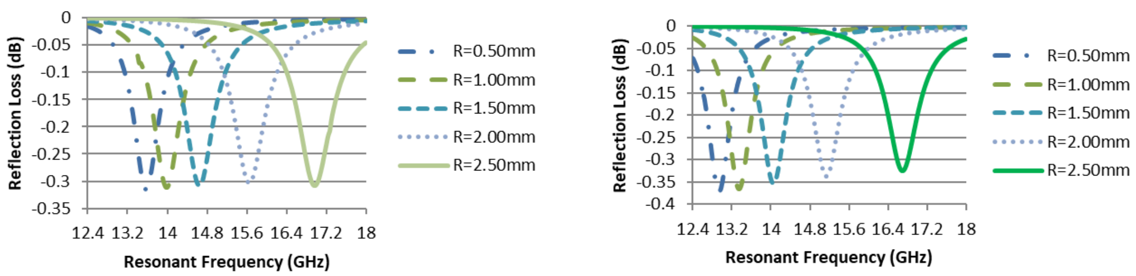
2.2. Ku-band planar reflector design

The design proposal for a planar reflector with the ability to switch frequencies and a progressive phase distribution was also implemented for operating in the Ku-frequency band. Figure 4 displays the suggested design, including the parameters for the Ku-band frequency range. The radii of circular slots throughout the width of the patch element were adjusted, ranging from 0.5 mm to 2.5 mm. In addition, our investigation included varying the thickness of the dielectric substrate from 0.127 mm to 0.787 mm to enhance the performance of the planar reflector in terms of frequency tunability and dynamic phase range. Figures 5(a) and (b) displays the reflection loss curves of a frequency switchable planar reflector operating in the Ku-band. The reflector is based on a 0.381 mm thick Rogers RT/Duroid 5880 substrate and has circular slots of varying radii. It can be observed from the results that the PIN diode exhibits a frequency shift when it is turned ON due to its capacitive and resistive characteristics in various states. In addition, it has been demonstrated that the reflection loss is greater for all unit cells when the PIN diode is in the ON switching state. This is due to the additional impedance introduced by the diode.



- Frequency: Ku-Band
- Dielectric material: Rogers 5880 (ε_r=2.2, tanδ=0.0009)
- Substrate dimensions: Ls x Ws=9.375 mm x 9.375 mm
- Patch dimensions: Lp x Wp=6.34 mm x 7.41 mm
- Rectangular slot dimensions: Lr x Wr=0.8 Lp x 0.5 Wp
- Circular slot radius: 0.5≤R≤2.5

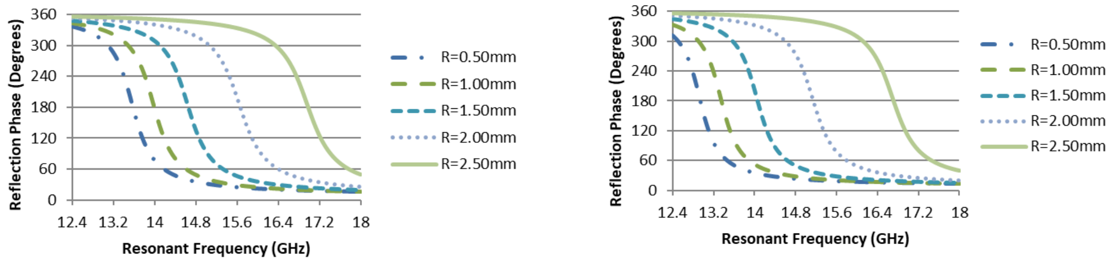
Figure 4. Unit cell for Ku-band frequency with design specifications



(a) (b)

Figure 5. Reflection loss curves for Ku-band frequency switchable planar reflector; (a) PIN diode OFF and (b) PIN diode ON

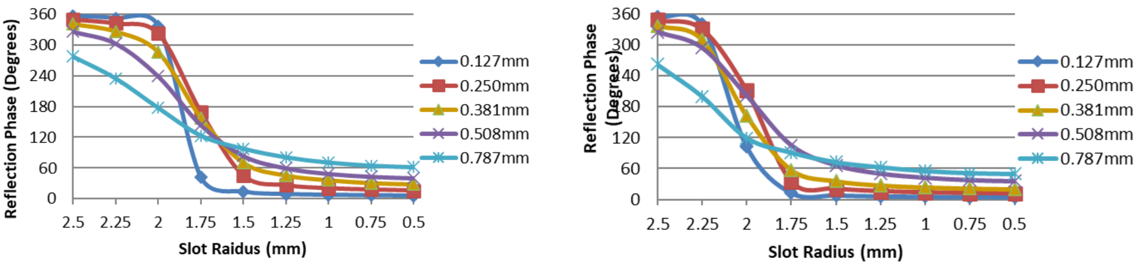
Figures 6(a) and (b) displays the reflection phase curves of the Ku-band frequency switchable planar reflector in the OFF and ON states of the PIN diode respectively. It can be observed from the results that adjusting the radius of the circular slot, which is located across the width of the patch, between 0.5 mm and 2.5 mm, enables the attainment of various frequencies within the Ku-band frequency range. The reason for this is because the variation in the radius of the circular slot impacts the electrical characteristics of the resonant patch component, resulting in a modification in the resonant frequency of the individual cell. Thus, by using unit cells with varying radii of circular slots, it is possible to create a planar reflector in the Ku-band frequency range that may switch frequencies and exhibit progressive phase.



(a) (b)

Figure 6. Reflection phase curves for Ku-band frequency switchable planar reflector; (a) PIN diode OFF and (b) PIN diode ON

To further examine the impact of substrate thickness on the performance of the frequency switchable planar reflector, the relationship between circular slot size and reflection phase for various substrate thicknesses in two switching states of a PIN diode has been plotted. Figures 7(a) and (b) present a comparison between the reflection phase data and the progressive phase distribution in the OFF and ON states of the PIN diode respectively. It can be observed from the results that the slope of the reflection phase curves reduces as the substrate thickness increases. This indicates that a planar reflector constructed with a thicker substrate has a broader bandwidth.



(a) (b)

Figure 7. Slot size vs reflection phase curves for different substrate thicknesses; (a) PIN diode OFF and (b) PIN diode ON

This tendency occurs because increasing the thickness of the substrate has a comparable impact to reducing the permittivity of the dielectric substrate. However, Figure 7 also demonstrates that the reflection phase curves have a greater phase range for thinner substrates compared to larger substrates. Specifically, the design with a substrate thickness of 0.127 mm covers the whole 360° phase range. Consequently, the findings indicate a compromise between the bandwidth and reflection phase range performance.

A brief summary of the results for Ku-band planar reflector unit cells made with different substrate thicknesses is shown in Table 3. The purpose of this comparison is to evaluate the effectiveness of planar reflectors based on their reflection loss, dynamic phase range, and frequency tunability performance. Table 3 shows that the planar reflector unit cells designed with a substrate thickness of 0.127 mm have the highest dynamic phase range of 317° and frequency tunability of 0.72 GHz. In comparison, the unit cells designed on a 0.787 mm thick substrate have the lowest frequency tunability of 74° and frequency tunability of 0.32 GHz. Conversely, the planar reflector unit cells that were constructed with a substrate thickness of 0.127 mm exhibited a maximum reflection loss of 1.7 dB, but the design with a substrate thickness of 0.787 mm showed a reflection loss of 0.13 dB. The underlying cause of this pattern is that in substrates with less thickness, there is a greater occurrence of numerous reflections inside the substrate area compared to thicker substrates. As a result, thinner substrates exhibit higher levels of loss when used for planar reflector design.

Table 3. Performance comparison of frequency switchable planar reflectors designed with different substrate thicknesses

Substrate thickness (mm)	Reflection loss Rl (dB)	Dynamic phase range Max. Δφd (°)	Frequency tunability Max. ΔFr (GHz)
0.127	1.7	317	0.72
0.25	0.63	256	0.73
0.381	0.36	192	0.64
0.508	0.33	77	0.50
0.787	0.13	74	0.32

3. CONCLUSION

The unit cell patch element arrangement described in this paper provides a flexible and promising approach for the advancement of passive and active RA antennas, especially in the X-band and Ku-band frequency ranges. This arrangement is notable for its capacity to produce a gradual dispersion of phase by precisely adjusting the widths of slots. This allows for the optimisation of mutual coupling between neighbouring components while maintaining the constant physical dimensions of the rectangular element. This design innovation not only improves the overall performance of RA antennas but also enables a variety of current antenna applications that need high-gain, planar antenna layouts. This design's versatility and efficiency make it very valuable in the telecommunications, satellite communication, and radar systems industries, as well as in other related fields. With the continuous advancement of technology, this configuration is expected to have a crucial role in addressing the increasing needs of high-performance, frequency-specific antenna systems. It will be a central focus in the future development of antenna engineering.

ACKNOWLEDGEMENTS

The study is funded by the Ministry of Higher Education (MOHE) of Malaysia through the Fundamental Research Grant Scheme (FRGS), No. FRGS/1/2023/TK07/UTEM/02/7. The author would also like to thank the Staff of UTeM for technical support.

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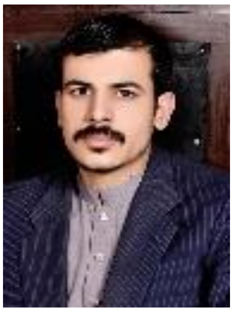

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