X-Band and Ku-Band Frequency Switching Planar Reflecting Surface Unit Cells

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***Abstract*— This work provides an investigation for the design and analysis of frequency-switching planar reflecting surface unit cells designed in X-band and Ku-band frequency ranges. Slot and gap-embedded configurations have been proposed to obtain optimum reflection phase performance from the unit cells. The proposed design also helps to minimize the mutual coupling in the array environment. A PIN diode has been attached to the patch surface of each unit cell for frequency switching. Various design parameters have been investigated in order to study their effect on the performance of proposed unit cell designs. Based on the frequency variation using PIN diodes frequency tunability of 0.43 GHz and 0.35 GHz have been demonstrated for X-band and Ku-band frequency ranges.**

Keywords—Planar Reflecting Surface, Reflectarray Unit Cells, PIN Diodes, Frequency Switching

I. Introduction

The concept of reflectarrays or also known as planar reflecting surfaces was first introduced to overcome the drawback which are generally associated with the parabolic reflectors: its large size and mechanical pointing system. Reflectarrays are more compact designs and offer control flexibility that is ideal when it comes to design applications that have low profiles these include space applications like satellite communication, aerospace etc [1]. The geometry of reflectarray antennas include a planar array of radiating elements all of which are made in such a way that they reflect incident waves by a predetermined phase shift. Through precise regulation and determination of the phase state of each element, it is possible to manage the direction of the reflected wave, which results in high directivity and great gain and provides for the use of a flat and lightweight structure.

Regarding the numerous improvements made in the field of reflectarray technology, one has to mention the usage of microstrip patches with various design configuration as the radiating elements. The reason why microstrip patches are more favoured, is because it is cheap, simple in fabrication and it can be fabricated using PCB techniques. These patches can probably be dimensioned in such a way that they offer the needed phase shift or that further tuning elements can be integrated in these patches [2]-[5].

Some developments are done in increasing the bandwidth and performances of the reflectarray antennas. Methods like rotation of elements, use of different substrates and multi resonant designs have been used to achieve low frequency extension of bandwidth. Secondly, the use of tunable components/materials including PIN diodes [6], varactors [7], liquid crystals [8], [9], graphene [10], [11] etc. has made the beam steering or the real time traced possible, taking the applications of reflectarrays to the next level.

In the context of 5G communications, the reflectarray antennas are steadily finding the place in the market owing to the features like high gain and narrow beam which is the basic requirement for high frequency bands used in 5G. Because of their planar shape they can be incorporated into building façade, vehicles and other construction hence being a preferred solution in urban environment to expand the network size and density [12]-[14].

The research is still going on in this area and the studies that are being conducted in this regard are further enhancing the capabilities of reflectarrays in the future and focus on providing higher efficiency, broad bandwidth and even compact structures. Reflectarray antennas are expected to become indispensable as the application of communication methods with higher capability demands continuously expands.

From the design perspective, reflectarray consists of two phases; first, the design and detailed analysis of the unit cells, to finalize the selection of specific unit cells according to the requirement of the applications and second, the design of periodic reflectarray based on the phase distribution of the unit cells. This work focuses on the design and analysis of reflectarray unit cells with frequency switching using PIN diodes in the X-band and Ku-Band frequency ranges for radar and satellite communication applications.

II. Slot and Gap Embedded Active Patch Elements

The feasibility of using different slot configurations for frequency switchable planar reflector design with improved performance has been demonstrated earlier. In this work, a gap was introduced in the resonant slot embedded within the patch element to facilitate the practical implementation of PIN diodes. This gap allows for the connection of the diode in such a manner that it can have different potentials at its two connecting ends. The investigations were carried out for both

X-band and Ku-band designs using Rogers RT/duroid 5880 dielectric material. The detailed analysis for each of the configuration is provided in this section.

A. X-Bband Unit Cell Design

For the verification of the proposed design configuration, rectangular patch with circular slot and rectangular patch with rectangular slot were selected. A vertical gap was inserted throughout the patch element in order to separate the two sides. Fig. 1 shows the configuration of circular slot embedded patch element with gap. The patch had dimensions of L x W = 9.4mm x 10 mm and was printed on 0.508mm Rogers RT/Duroid 5880 dielectric material. The slot radius was kept 2.5mm and gap is 0.5mm wide. The APD 0805-000 PIN diode had to be placed a little bit slanted in order to connect the two sides of the patch element.

In order to observe the effects of introducing gap on the design, surface current distribution was observed. Fig. 2 shows the surface current distribution for the slot embedded patch element with and without gap. It can be observed from Fig. 2 that the surface current distribution is not modified significantly by the introduction of gap. The maximum surface current density varied only by 5.1% by the introduction of 0.5mm gap. The variation in the surface current distribution is minimal because of the fact that the surface currents are maximum on the left and right side of the patch element centre.

Fig. 3 illustrates the reflection loss and reflection phase curves of the slot and gap embedded planar reflector designed for the X-band frequency range. As shown in Fig. 3, changing the state of the PIN diode from OFF to ON shifts the resonant frequency from 9.30 GHz to 8.88 GHz and increases the reflection loss from 1.06 dB to 1.57 dB. The variation in resonant frequency and reflection loss is because of the characteristics of PIN diodes in different operating states. The frequency variation of 0.42GHz also provides a dynamic phase range of 224° at 9.09GHz as can be observed by the reflection phase curves of Fig. 3.

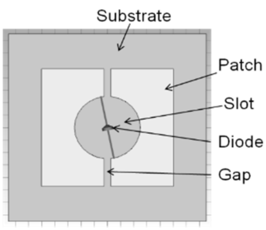

Fig. 1. Circular slot in the centre of patch element with gap

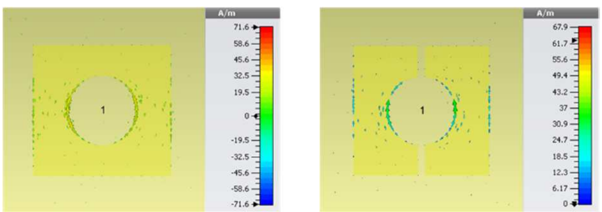

Fig. 2. Surface current distribution for circular slot with gap

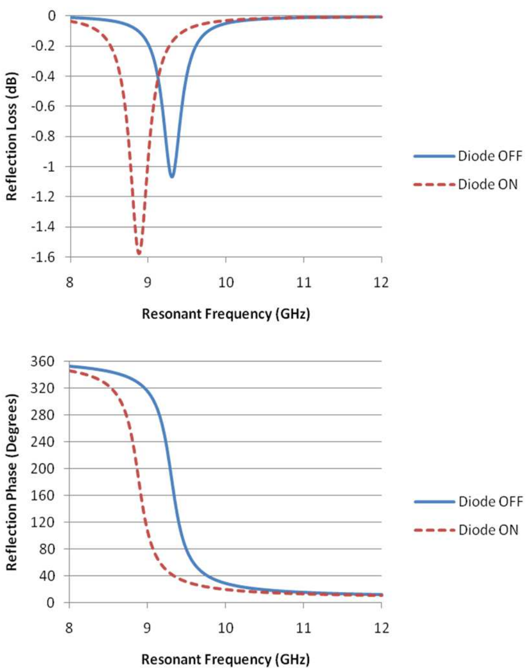

Fig. 3. Reflection loss and reflection phase curves for the circular slot and gap

A similar analysis was carried out for the rectangular slot embedded resonant patch configurations. Same dielectric material and dimensions of the substrate and patch were used while the width of the rectangular slot was chosen to be 0.5W (W is the patch width). Fig. 4 shows the surface current distribution of the rectangular slot embedded patch with and without gap. It can be observed from Fig. 4 that a very slight change in maximum surface current density of 2.7% occurs by the introduction of gap in the patch element.

Fig. 5 shows the reflection loss and reflection phase curves of the planar reflector designed with rectangular slot and gap embedded patch element configuration. It has been demonstrated from Fig. 5 that in the OFF and ON state of the PIN diode the resonant frequency changes from 9.39GHz to 8.96GHz with a reflection loss of 1.37dB and 1.64dB respectively. Moreover a dynamic phase range of 229° at 9.17GHz has also been demonstrated using the proposed design.

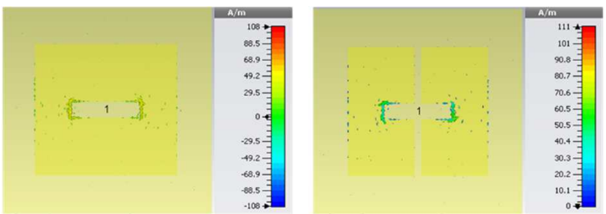

Fig. 4. Surface current distribution for rectangular slot with gap

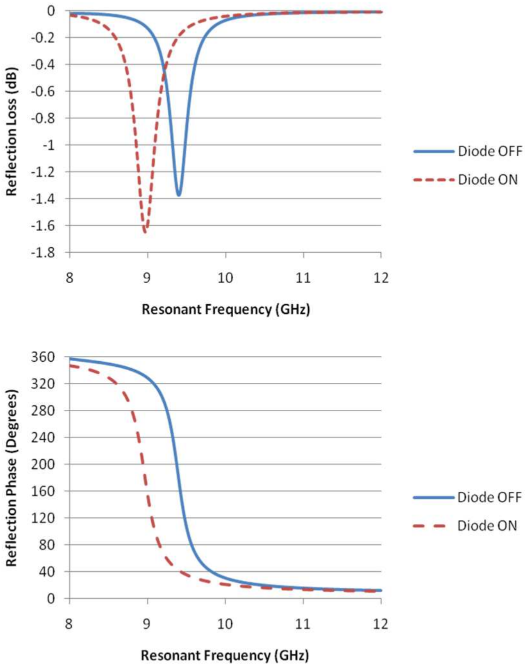

Fig. 5. Reflection loss and reflection phase curves for the rectangular slot and gap

B. *Progressive phase distribution*

The design of a complete planar reflector necessitates a progressive phase distribution. To achieve this, configurations of slot and gap embedded patch elements were also demonstrated for the planar reflector design with a progressive phase distribution.The design configuration with circular slot in the centre and two circular slots along width was utilized as shown in Fig. 6.

Two circular slots along the width of the patch element provided the ability of sweeping the frequency through the X-band frequency range which is required for progressive phase distribution. In this design, the width slot radius (WSR) was varied from 0.5mm to 2.5mm for frequency variation in both OFF and ON states of the PIN diodes. Fig. 7 and Fig. 8 show the reflection loss and reflection phase curves respectively for different radius of the width slots.

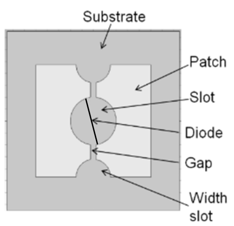

Fig. 6. Slot and gap embedded configuration for progressive phase distribution

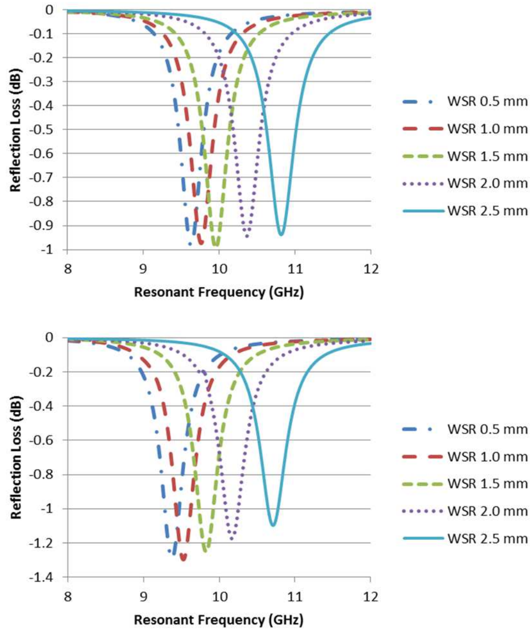

Fig. 7. Reflection loss curves for different radius of width slots in OFF and ON states

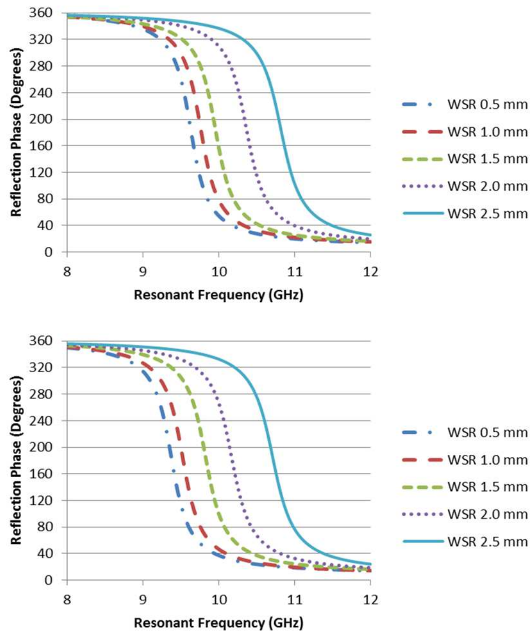

Fig. 8. Reflection phase curves for different radius of width slots in OFF and ON states

It can be observed from Fig. 7 and Fig. 8 that in OFF state, the resonant frequency changes from 9.60GHz to 10.78GHz while in the OFF state the resonant frequency change from 9.34GHz to 10.67GHz as the WSR is varied from 0.5mm to 2.5mm. This variation in frequency in both the states of PIN diode can be used for planar reflector design with progressive phase distribution. Moreover, it can also be observed that the reflection loss in the ON state of PIN diode is higher in all cases due to added PIN diode resistance which makes the reflection phase slightly steeper.

C. Ku-Band Unit Cell Design

For the verification of the proposed designs, investigations were also carried out for slot and gap embedded resonant patch element configurations in Ku-band frequency range. Same dielectric substrate of Rogers 5880 RT/duroid was used with dimensions of 9.37mm x 9.37mm. The dimensions of rectangular patch for Ku-band designs were kept at L x W = 6.34mm x 7.41mm while the gap width (wg) for initial investigation was 0.5mm. In the case of circular slots, the slot radius used was 1.2mm and for rectangular slot, the slot dimensions were chosen to be 0.15L x 0.5W (L and W are length and width of patch element respectively). The change in surface current distribution was also studied in Ku-band design and only a change of 1.16% was observed in maximum surface current density by the introduction of gap in the rectangular slotted patch element as shown in Fig. 9.

Fig. 10 shows the reflection loss and reflection phase curves for the switchable planar reflector patch element with circular slot and gap designed in Ku-band frequency range. It can be observed from Fig. 10 that when the PIN diode is switched from OFF to ON state, the resonant frequency changes from 14.74 GHz to 14.60 GHz with reflection loss of 0.45 dB and 0.54 dB respectively. This shows a frequency tunability of 0.14 GHz and dynamic phase range of 28° as can be observed from reflection phase curve.

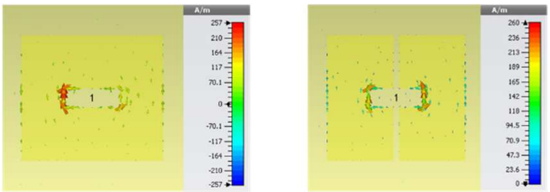

Fig. 9. Surface current distribution with and without gap for Ku-Band design

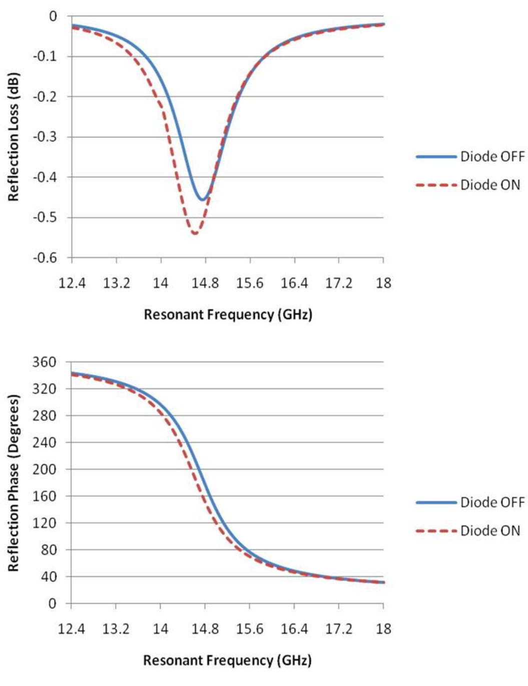

Fig. 10. Figure 5. 45: Reflection loss and reflection phase curves for Ku-band circular slot switchable planar reflectors

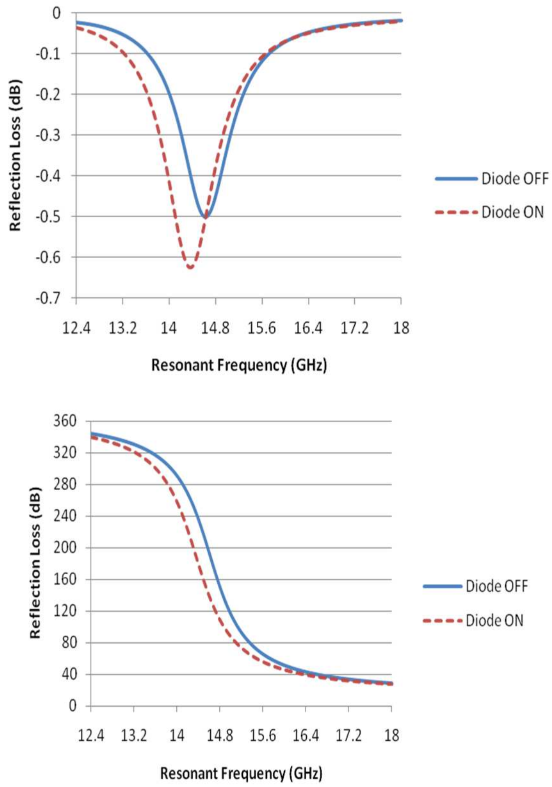

Fig. 11. Reflection loss and reflection phase curves for Ku-band rectangular slot switchable planar reflectors

In the case of rectangular slot and gap design for Ku-band frequency switchable planar reflectors, the frequency tunability and dynamic phase range are relatively higher as shown on Fig. 11. It is depicted in Fig. 11 that in the OFF state of PIN diode, the resonance frequency is 14.36GHz with a reflection loss of 0.50dB while in the ON state, the resonance frequency changes to 14.62GHz with a reflection loss of 0.62dB. Hence a frequency tunability of 0.26GHz and a dynamic phase range of 58° have been achieved. Therefore the analysis demonstrated that introducing a vertical gap in the centre of the patch does not affect the surface currents significantly and provides the feasibility of using the modified slot and gap embedded patch configuration for frequency switchable planar reflector designs. However as in the case of configuration without gap, the gap and slot embedded patch element also provides lower frequency tunability and dynamic phase range when designed for Ku-band frequency range as shown in Table I. Further investigations were carried out for the enhancement of frequency tunability and dynamic phase range of Ku-band design. The details are provided in the next section.

TABLE I. SUMMARY OF GAP AND SLOT EMBEDDED DESIGN RESULTS

Frequency Range	Design Configuration	Frequency Tunability ΔFr (GHz)	Dynamic Phase Range Δφd (°)
X-Band Frequency	***Rectangular Slots***	0.43	229
	Circular Slots	0.42	224
Ku-Band Frequency	***Rectangular Slots***	0.26	58
	Circular Slots	0.14	28

D. Dynamic phase range enhancement of Ku-band designs

It was observed from the above analysis that the Ku-band frequency switchable planar reflectors provide lower dynamic phase range and frequency tunability as compared to X-band design. In order to investigate possible reasons for this limitation and to improve the Ku-band design performance, a number of investigations were carried out. Rectangular slot and gap embedded patch element of planar reflector was chosen for this purpose. Initially the gap width (wg), as shown in Fig. 9 was varied from 0.3mm to 0.7mm in order to analyse the effect of gap width on frequency tunability and dynamic phase range. Table II summarizes the results obtained by using different gap widths in Ku-band frequency switchable planar reflector design. It can be observed from Table II that by reducing the gap width from 0.7mm to 0.3mm, the dynamic phase range increases from 49° to 78° whereas frequency tunability increases from 0.22GHz to 0.35GHz. The total increase in dynamic phase range is only 29° which is not very significant. Moreover reducing the gap width can also cause problem when fabrication is done by using conventional PCB etching machines which have a minimum etching resolution of 0.5 mm. Therefore it can be concluded that decreasing gap width is not the best possible solution for increasing the dynamic phase range and frequency tunability of switchable planar reflectors.

In order to further investigate the possibility of performance enhancement of frequency tunability and dynamic phase range, effects of substrate thickness was observed. Various thicknesses of Rogers RT/duroid 5880 substrate ranging from 0.237mm to 0.787mm were used in this design. Fig. 12 shows the reflection phase curves in both states of PIN diodes obtained for different substrate thicknesses. It can be observed from Fig. 12 that, as the substrate thickness is decreased from 0.787mm to 0.237mm, the slope of the reflection curve increases from 0.036˚/MHz to 0.16˚/MHz for the ON state of PIN diodes. This is because in thinner substrates a higher number of multiple bounces occur which increases the loss in the substrate region of planar reflector. The increased loss causes a sharp change in reflection phase around the resonance frequency and hence increases the slope of the reflection phase curve. Moreover it can also be observed from Fig. 12 that the increased slope causes an enhanced phase range in reflection phase curve. Therefore 0.237mm substrate provides a phase range closer to 360° in both OFF and ON states as compared to the 0.787mm substrate. This increased phase range reduces the phase errors and enhances the dynamic phase range of switchable planar reflector design but at a cost of limited bandwidth.

TABLE II. EFFECT OF GAP VARIATION ON KU-BAND FREQUENCY SWITCHABLE PLANAR REFLECTOR DESIGN

Gap Width (mm)	Diode ON		Diode OFF		Frequency Tunability ΔFr (GHz)	Dynamic Phase Range Δφd (˚)
	Fr (GHz)	*Rl (dB)*	*Fr (GHz)*	*Rl (dB)*		
0.3	14.32	0.65	14.67	0.52	0.35	78
0.4	14.34	0.64	14.59	0.50	0.26	58
0.5	14.36	0.62	14.62	0.50	0.25	53
0.6	14.42	0.61	14.65	0.49	0.23	50
0.7	14.45	0.60	14.67	0.49	0.22	49

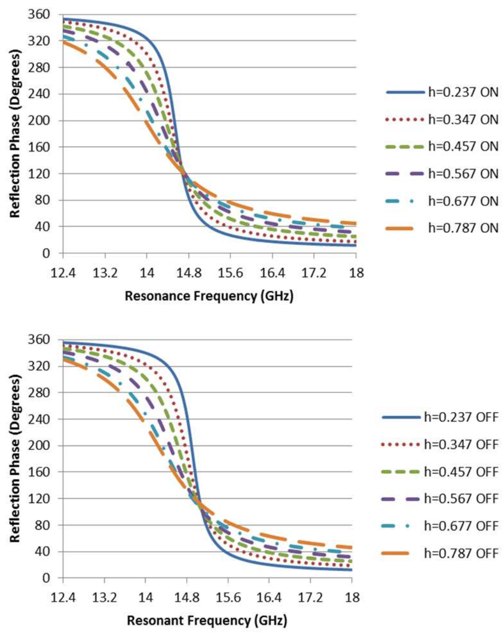

Fig. 12. Effect of substrate thickness on reflection phase of frequency switchable planar reflectors

In order to propose an optimum design, X-band and Ku-band results were compared. Fig. 13 shows the comparative results of both the designs in terms of frequency tunability and dynamic phase range. It can be observed from Fig. 13 that the thinnest substrate (0.237mm) provides a maximum frequency tunability and dynamic phase range of 0.55GHz and 321° for X-band design and 0.37 GHz and 168° for Ku-band respectively. On the other hand, for the thickest substrate (0.787 mm) the frequency tunability and dynamic phase range are minimum at 0.32GHz and 122° for X-band and 0.25GHz and 35° for Ku-band design respectively. It can also be observed that on all the thicknesses the frequency tunability and dynamic phase range are higher for X-band design as compared to Ku-band design. This is because at higher frequencies (Ku-band), the capacitance of the unit cell is lower as compared to X-band design. Therefore by introducing a PIN diode and using it in OFF state, the relative change in capacitance is lower in the case of X-band design which provides higher frequency tunability and enhanced dynamic phase range.

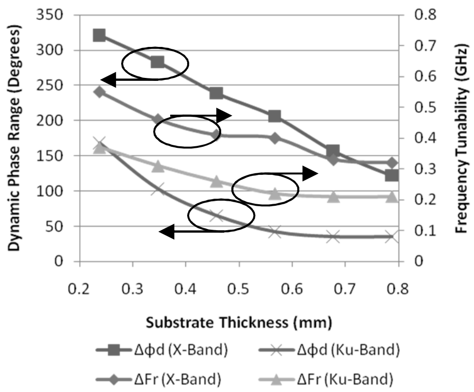

Fig. 13. Comparison of X-band and Ku-band results for different substrate thicknesses

III. CONCLUSION

In this investigation, the approach of utilizing PIN diodes to obtain switched reflectarray antennas for frequency reconfigurable applications was explored and confirmed to be possible and efficient. The implications of this work are significant for the advancement of multi-band reflectarray technologies. The ability to switch frequencies seamlessly paves the way for more versatile and efficient antenna systems, particularly in applications requiring dynamic frequency agility. Future research could explore further optimization of the unit cell design to enhance bandwidth and efficiency, as well as the integration of more advanced reconfigurable elements to expand the functionality of frequency switchable reflectarrays or planar reflecting surfaces.

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