Design of a Polarization Reconfigurable and Frequency Tunable Patch Antenna System on a Magnetic Substrate

by

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Abstract

Modern radio frequency (RF) and microwave components are continuously evolving to meet the demands of new wireless technologies. One such demand is the ability of these components to be agile and smart. Thus, the rationale for plethora of research in the field of reconfigurable RF components. In this work, a patch antenna system that can be tuned for its center frequency and reconfigured for its radiation characteristics is studied on a magnetic substrate namely yttrium-iron-garnet (YIG). By integrating PIN diodes along the feed lines of the two antenna elements, one can achieve the above stated control of polarization reconfigurability in tandem with the use of YIG substrate for frequency tuning. The antenna elements are arranged in a manner that provides cross-polarization between them that helps to generate two different linear polarization (one for each antenna). At the same time, the feed line is designed to provide a $90°$ of phase difference between the antenna elements, thus resulting in a circular polarization when both the antennas are activated. The simulated results of the antenna show $-14.15\ dB$ matching at 7.3 GHz with stable radiation performance for three different polarizations that is circular polarization, Linear polarization along x-axis and Linear polarization along y-axis. This is accomplished by toggling the PIN diodes as needed. Furthermore, the antenna system is magnetized in simulations to study its impedance and radiation response for all three polarizations. A tunability of 1 GHz is achieved using full-wave simulations which demonstrate a range of ~14%. These initial results demonstrate the feasibility of using the proposed design concept in current and future wireless communication systems.

ACKNOWLEDGEMENTS

In the name of Allah, Most Gracious, Most Merciful.

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Acronym

Radio frequency (RF)

impedance bandwidth (IBW)

milli tesla (mT)

tesla (T)

Gauss (G)

oersted (Oe)

Magnetization (M)

Saturated Magnetization (M_s)

Circular Polarization (CP)

Linear Polarization (LP)

Positive- Intrinsic-Negative (PIN)

High Frequency Structure Simulator (HFSS)

Chapter 1
Introduction

In modern radio frequency (RF) systems, reconfigurability is the need of the hour. With the introduction of new standards such as internet of things (IoT) and 5G, the applications of today are greatly reliant on RF components that can be tuned for their performance [1]. The same is true for antenna front ends where agility in terms of their impedance, radiation and polarization are the targets for RF engineers. These antennas can be employed in a variety of applications that include but are not limited to military radars, autonomous vehicles, satellite and space communication and biomedical systems as shown in Fig. 1.1.

(a) (b)

Fig. 1.1: Applications of Reconfigurable Antennas (a) Satellite and Space Communication (b) Surveillance Radar [2]

One can define the reconfigurable antennas in terms of their frequency, bandwidth, polarization or beam steering capabilities. The first two among these relate to the impedance characteristics of the antenna while the latter ones deal with the radiation characteristics. The concept of frequency tuning of antennas or for that matter any other RF component is not new in the domain of wireless components. With the advent of new standards, the wave spectrum is seen to become more and more congested. This means that a frequency tunable antenna can be altered for its center frequency or bandwidth to cater for different wireless standards all at one time [2][3][4]. This allows one antenna to cater for a variety of applications such as WiFi, GSM, GPS etc. A pictorial representation of this is shown in Fig. 1.2. By doing so, the use of multiple antennas can be avoided to reduce the system size and its cost. Both these metrics are significant in evolution of today's wireless systems.

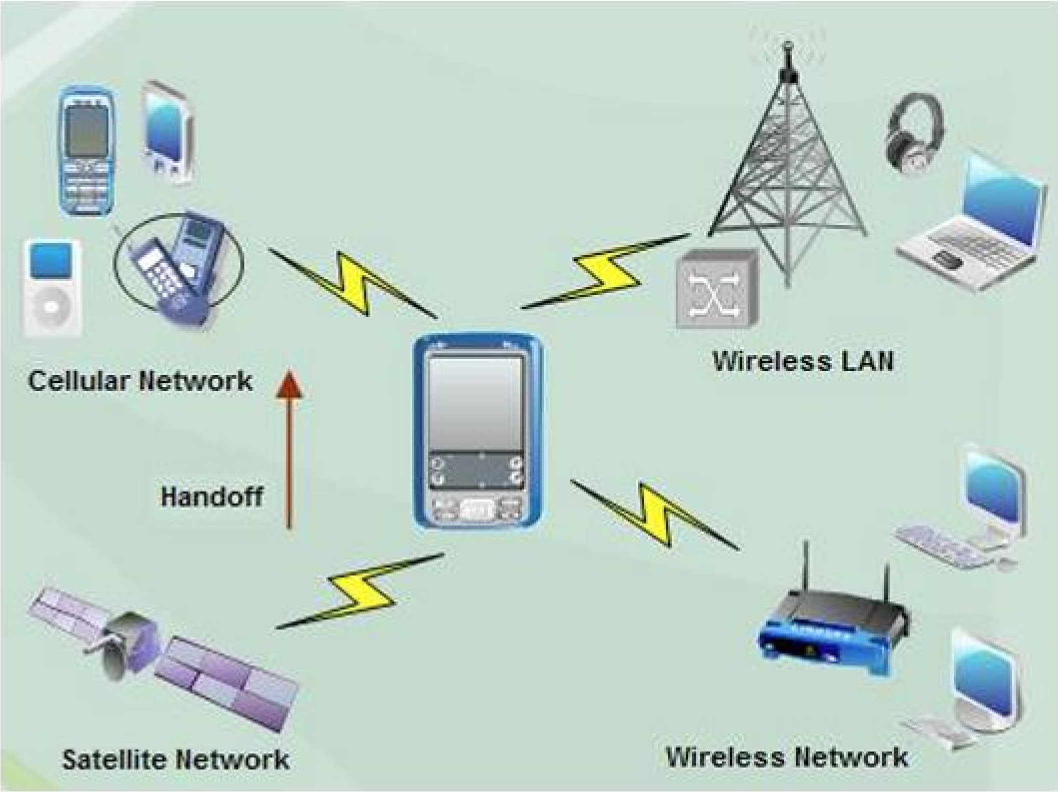


Fig. 1.2: Modern Application. Mobile need to communicate with multiple devices at one time [6].

In terms of radiation pattern, the designers use polarization of the antenna as a key property to provide uniqueness. However, generally one antenna solution can provide a single polarization of radiation [4][5].

These can be horizontal (H), vertical (V) or circular polarization. The first two being linear and their transformation to circular or vice versa. If an antenna design is smart enough to toggle its polarization at a single frequency or even multiple frequency points, this could be of great benefit in applications where secure communication is desired such as military satellites, remote sensing etc as shown in Fig. 1.2. The third scenario of antenna reconfigurability is related to steering the maximum radiation of antenna along its elevation or azimuth plane. For this purpose, phase shifters are used as the active components that are integrated into the feed of array systems [3][4]. By controlling the phase shift between consecutive antenna elements, the main beam of the array can be steered along one of the planes or even both (Fig.1.3). Thus, one can say that there are 3 different commonly known characteristics which are the center of attention under the topic of tunable and reconfigurable antenna systems. In this thesis, the focus will be on the first two since they pertain more to the antenna element design rather than the phase shifting component.

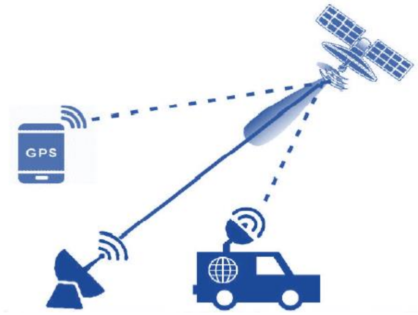


Fig. 1.3: Beam Steering application [6]

The focus of this thesis will be to control the frequency and the polarization of an antenna system. This is to be achieved by integrating PIN diodes on the antenna design while allowing magnetic tuning by exploiting the characteristics of the substrate. The antenna would be studied for three different polarization of radiation while being tuned in each case for its frequency. A close eye will be kept on the impedance as well as radiation of the antenna while tuning the PIN diodes and applying the magnetic field across the substrate. The final antenna results provide a proof-of-concept for such a versatile antenna system.

1.1 Thesis Objective

- To study a patch antenna system on a magnetic substrate (YIG) that can provide the required frequency and polarization reconfigurability.
- Using PIN diodes, the proposed solution is to be studied for polarization agility. It is anticipated that three different antenna radiations, in terms of polarization, would be achieved with the help of the PIN diodes.
- By applying magnetic bias across the antenna substrate, the relative permeability of the substrate would be studied. This study will focus on the center frequency tuning of the antenna.
- The design is to be studied around 7 GHz to avoid the magnetization frequency (f_m = 5.04 GHz) of the YIG substrate. Higher frequency bands can be used for the design, however, for this work staying close to 'f_m' is appropriate for better tuning and gain performance.

1.2 Thesis Contribution

From the proposed thesis research, the following contributions can be outlined.

- Polarization reconfigurability is achieved by using PIN Diode. Three different types of polarizations achieved by controlling the states of the PIN Diodes that is polarization along x-axis, polarization along y-axis and circular polarization.
- Frequency Tuning is achieved by using the magnetic substrate and by applying external magnetic field on antenna design.
- Both polarization reconfigurability and frequency tuning are achieved at the same time using full wave simulations in Ansys High Frequency Structure Simulator (HFSS).. By controlling the states of PIN didoes in tandem with external magnetic field, polarization and frequency reconfigurability achieved over a band of frequencies.

1.3 Thesis Organization

In the first chapter survey of the reconfigurable antenna and their most prevalent from presented. Fig 1.2 explain the requirement for reconfigurable antenna in contemporary applications. The motivation for this thesis is then clearly articulated.

In the second chapter, a brief introduction of the Wilkinson Divider and Microstrip technology is presented that extends into the integration into PIN Diode into the structure. Few articles that used this type of antenna are covered along with the merit of the design and the novelty introduced by the researches.

Chapter 3, begins with the introduction of the how to how to get polarization reconfigurability using two microstrip antenna and then toggle between circular and linear polarization using PIN Diode. It also explain the polarization reconfigurability that is three different types of polarization. Circular polarization, Linear polarization along x-axis and linear polarization along y-axis and discuss the results. In the end conclusion is present.

In chapter 4, a novel reconfigurable method is explained how to obtain frequency tuning using PIN Didoes. These PIN Diodes then integrate it to antenna design to toggle between the polarizations. Using external Magnetic field along with the state of the PIN Diode to obtain the antenna reconfigurability. When both of the PIN Diodes are ON, then the antenna is circularly polarized and when one of the PIN Diode is OFF then antenna is linearly polarized. A complete parametric study is performed on various design parameters to obtain the antenna's best possible impedance and radiation performance.

Chapter 5, finally, the thesis concludes by listing the contributions of this work and highlighting some of the future steps that are currently undertaken to validate the proposed design in measurements. Furthermore, other research directions on the antenna design using polarization and frequency tunability are also explained briefly to hint at possible future initiatives.

Chapter 2

Background and Literature Review

The latest trends in the field of antenna design have shown that printed antennas are becoming more and more popular in a variety of wireless communications systems. Their merits such as low cost, easy fabrication, light weight and low profile could be regarded as the reasons for their repute among antenna engineers. More often than not printed antennas rely on microstrip based design methodology. After their introduction in 1950s, a lot of progress has been made in the design of microstrip based printed antennas [7][8][9]. Due to their simplicity and established knowledge this class of antenna is selected for this thesis.

The reconfigurability of antennas can be achieved by altering their impedance or radiation characteristics. This is done to allow a single antenna to work in multiple bands of frequencies [10] [11] [12] [13]. Or one can modify the antenna structure dynamically to control its radiation characteristics such as direction of main beam, gain of the antenna, polarization of radiation [14] [15] [16] etc.

This reconfigurability is accomplished by using various techniques. The underlying principle of these techniques is to control the dimension of the antenna or to modify the current pattern on the antenna structure. Another method used commonly is to change the material properties of the substrate that can effectively change the antenna dimensions as seen by the incoming radio frequency (RF) wave. Although there can be a number of properties that can be controlled to cater for the needs of an antenna application, for the purpose of compactness, the focus of this work will be on two of these:

1. Frequency Tuning

2. Polarization Reconfigurability

With this being the foundation of the work to follow, some examples from the literature are discussed in this chapter for the benefit of the readers.

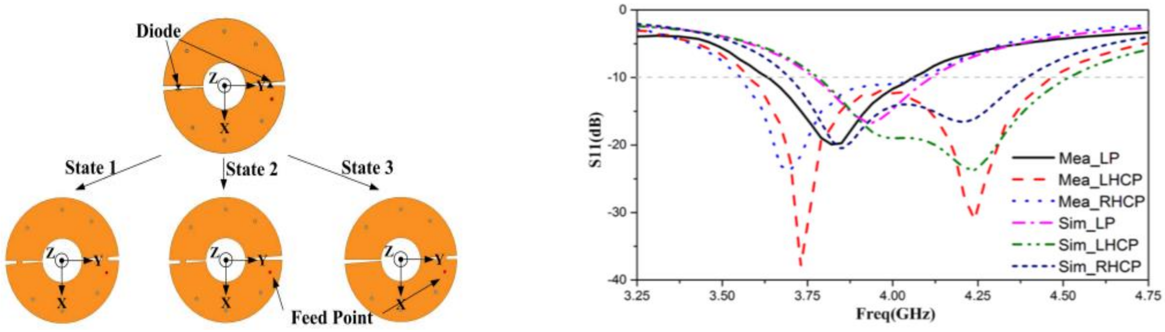
2.1 Polarization Reconfigurability

The polarization of a wave or an antenna qualifies the directions of the electric and magnetic field vector with respect to the direction of propagation of wave. For the case of a radiated wave, the mode of propagation is always transverse electromagnetic, generally known as TEM. In this case of wave propagation, the electric and magnetic field vector are normal to each other and to the direction of propagation. Fundamentally, three different type of wave polarizations can be defined:

1. Linear Polarization
2. Circular Polarization
3. Elliptical Polarization

Since the concept of these three types of polarizations are well-known to the antenna community, their definitions are not really discussed here. However, it is important to introduce these at this point in the chapter to lay down a foundation for the literature review on ‘Polarization Reconfigurability’. More often than not antennas are designed to operate with one type of wave polarization. This puts a constraint on the communication channel by making sure that both the antennas are polarization matched. Antennas can only receive a signal when the incoming wave has the same polarization as their own. Conversely, no information would be captured by a receiving antenna if the incoming wave is cross-polarized to the antenna. However, if the designer can integrate reconfigurability of polarization into the design, then the antenna can configure its characteristics to capture different types of waves. Therefore, polarization reconfigurable antennas might be a good option if you want to create a dependable, high-quality link with little interference from nearby signals in the spectrum [17]. Moreover, having reconfigurability of antenna polarization can help in secure transmission of information which could be handy in several applications especially military ones [18]. It is possible to achieve the polarization reconfigurability between linear (horizontal/vertical) to circular (right-handed/left-handed), within circular from left-hand to right-hand and circular to linear polarizations. To accomplish polarization reconfiguration, structural modifications as well as the employment of switches for various feeding processes have been generally examined by different research groups. Some of these are discussed herewith.

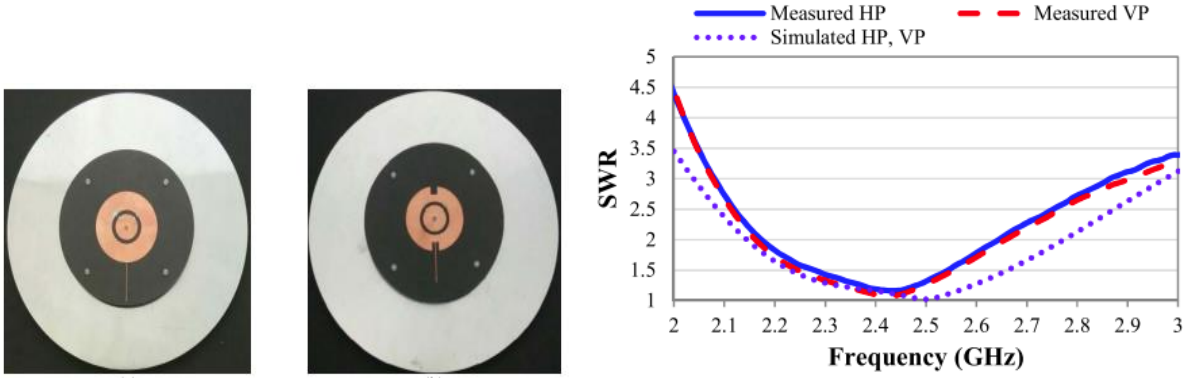
Chen et. al. [19] presented a polarization reconfigurable annular ring microstrip antenna shown in Fig. 2.1. Polarization reconfigurability is achieved by using two PIN diodes placed opposite to each other on the antenna edge. By controlling the states of the diodes, antenna toggles between polarization. When both of the diodes are in the ON state, then the antenna is linearly polarized (LP). On the flip side, by switching off the diodes one by one can provide two different sense of circularly polarized (CP). The design achieves linear polarization (LP), left hand circular polarization (LHCP) and right-hand circular polarization (RHCP). The antenna impedance bandwidth is around 3% for all the three states with an operating frequency from 3.86 to 3.98 GHz, Fig. 2.1 (b). This nature of performance conforms well with the conventional patch antennas.



(a) (b)

Fig. 2.1: (a)Step to realize the proposed antenna (b) S_{11} of four antennas [19]

Similar to [19] another antenna showing polarization reconfigurability using PIN diodes is published by Ming et. al. [20]. This work presents two different antennas each with its own reconfigurability. One is for LP and can switch between two states of linear polarization i.e. horizontal and vertical polarizations while the second one is for CP radiation and can toggle between RHCP and LHCP. This switching between polarizations in the two antennas is accomplished by switching between the ON and OFF states of the PIN diodes. Fig. 2.2 (c) and Fig. 2.3 show the measured impedance and radiation characteristics of the antennas, respectively.



(a) (b) (c)

Fig. 2.2: (a). (b). Polarization Reconfigurable Circular Patch Antenna With a C-Shape.
(c). Simulated and measured SWRs of the proposed linearly polarized antenna. [20]

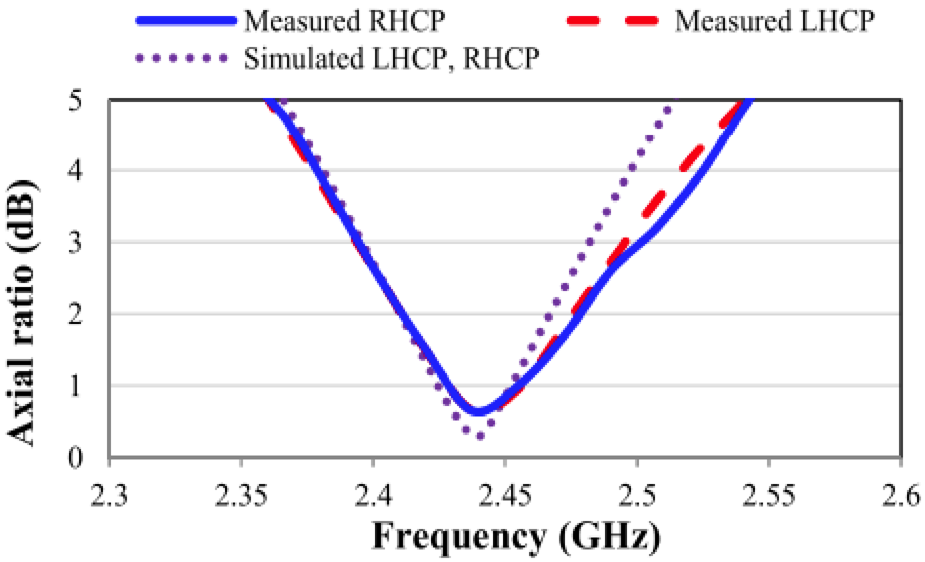
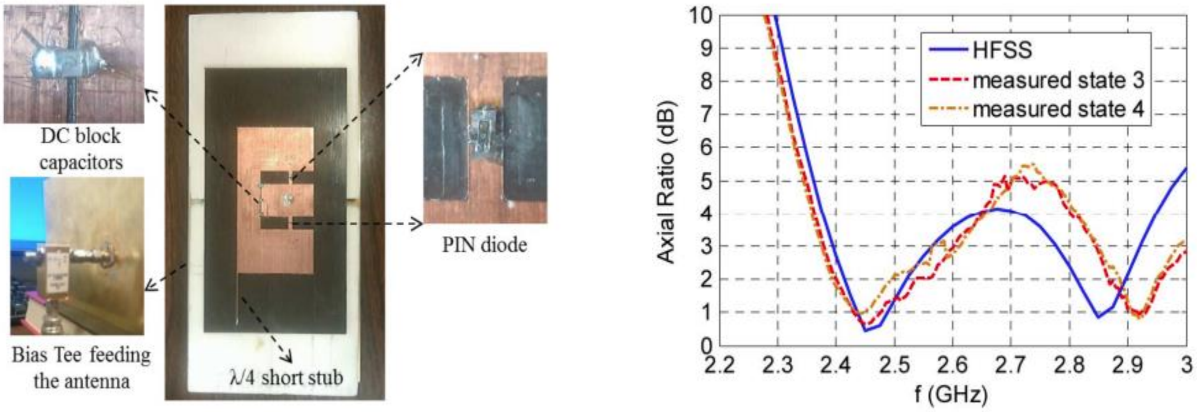


Fig. 2.3: Simulated and measured axial ratio across frequency [20]

The previous two papers focused on using a circular shape for their antennas to demonstrate the results of polarization agility. However, there is no particular constraint on the antenna shape for achieving such a reconfiguration as is shown in [21]. E shaped polarization reconfigurable antenna is present by Ahmed et. al. in this publication. Antenna is resonating at WLAN frequency band (2.4-2.5 GHz) and shows polarization reconfigurability with the help of PIN diodes, Fig. 2.4. When both the diodes are OFF or ON, then the antenna is linearly polarized. When diode 1(switch 1) is ON and second (switch 2) is OFF, then antenna is LHCP. Similarly, when diode 1(switch 1) is OFF and second (switch 2) is ON, then antenna is RHCP.

In [22] Song el. al. proposed a single feed reconfigurable multilayer microstrip antenna working around 3 GHz. Antenna design consists of a ring slot and cross slot, Fig. 2.5 and Fig 2.6. Four PIN diodes are used to determine the state of the antenna polarization.

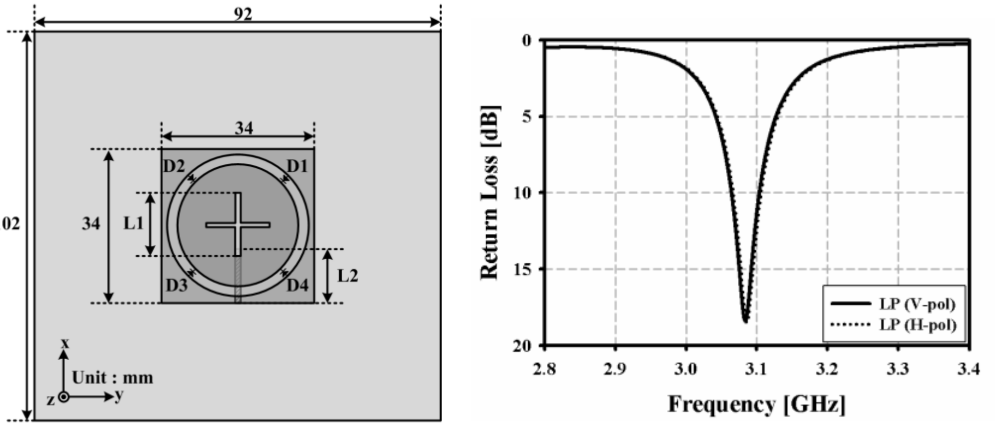


(a) (b)

Fig. 2.4: a). Polarization reconfigurable E-shaped patch antenna with associated switching and biasing assemblies. b) axial ratio of the proposed antenna [21]

Rogers 5880 is used as the antenna substrate and the results demonstrate four different types of polarization. When only PIN diode 3 is ON and all other PIN diodes are OFF, the antenna is RHCP and when only PIN diode 4 is ON and all other PIN diodes are OFF, then antenna is LHCP. To get the vertical polarization (LP) PIN diodes 1 and 3 are ON state, while PIN diodes 2 and 4 are OFF state. For horizontal polarization (HP), PIN diodes 1 and 3 are OFF state, while PIN diodes 2 and 4 are ON state. The reflection coefficient of the antenna for different configurations show good impedance match at the antenna frequency which is a requirement for such smart antenna implementation.

In this section, a brief literature review of polarization reconfigurable antennas is presented herewith. A summary of this study is added in Table 2-1. Characteristics such as bandwidth, number of switches and polarization are added to provide a decent comparison among these publications. The purpose being the validation of the use of PIN diodes to toggle antenna polarization. This theme will be used in the design that will be studied in this thesis.



a) b)

Fig. 2.5: a) Antenna design. b) Simulated return loss, Linear polarizations (HP and VP) [22]

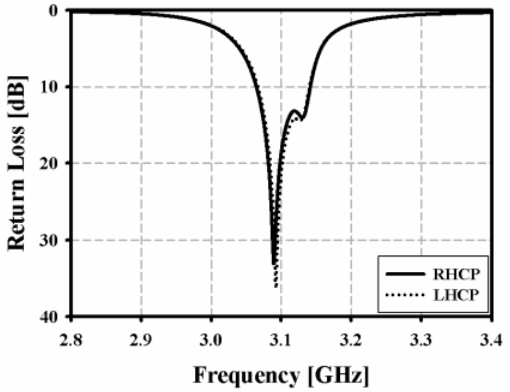


Fig. 2.6: Simulated return loss, Circularly polarizations (LHCP and RHCP) [22]

2.2 Frequency Tuning

Frequency tunability deals with the control of the antenna center frequency and sometime its impedance bandwidth. In some cases, these two are achieved in tandem but for the most part one would like to focus on one of them at a time. Now, the literature on the antenna design show that there is no dearth of frequency tunable designs even if one focuses on printed antennas alone.

Table-2-1
Comparison of Polarization Reconfigurable Antennas

Ref	No. Of switch	Polarization	IBW[%]
[19]	2	LHCP RHCP LP	18.2% (LHCP) 16.7% (RHCP) 8.7% (LP)
[20]	2 2	LHCP RHCP LP (HP and VP)	20% (LHCP) 20% (RHCP) 20% (HP and VP)
[21]	2	LHCP RHCP	8.4% (LHCP) 8.4% (RHCP)
[22]	2	LHCP RHCP	7% (LHCP) 7% (RHCP)
[23]	2	LHCP RHCP LP	5.5 (LHCP) 5.5 (RHCP) 2.9 (LP)
[24]	4	LHCP RHCP	31% (LHCP) 31% (RHCP)

Therefore, this sub-section only focuses on antennas that are tunable because of their substrate being magnetic in nature. The rationale for choosing this group of antennas is the solution presented herewith relies on magnetic substrate to demonstrate its frequency control. Thus, for the purpose of being concise, the focus of this section of literature review will be on printed frequency tunable antennas.

It is well known that an antenna implemented on a magnetic substrate can be tuned for its center frequency by applying external magnetic field [25] [26]. Antennas' center frequency depends on the dielectric and magnetic properties of their substrate. In the case of a magnetic substrate, one can vary the permeability of the material by applying magnetic field across it. Thus, RF waves propagating through that medium experience varying permeability of the substrate. Due to the change in the substrate characteristics, the frequency of the antenna changes and provides a useful control to the designer. For this purpose, the most commonly used magnetic materials in the microwave community belong to the class of ferrites [27] [28]. One of the earliest tunable antennas to this effect has been presented by D. Pozar and D. Sanchez in [34]. The paper discusses the design of a rectangular patch antenna on a transverse as well as longitudinally biased magnetic substrate. The paper presented some measurement data of a YIG based antenna when placed under the influence of an applied magnetic field. A maximum tuning range of 39% of the center frequency has been achieved which shows a good starting point for this technology. The authors did not, however, specify the bias intensity needed to get this outcome. Furthermore, no theorical justification is offered to explain the measurable tuning that the design produced. A clear understanding of how the antenna is working in the presence of the biased magnetic field is presented in [35]. Moreover, the strength of the applied magnetic field vs. the frequency of the antenna is also plotted in the paper to show that how the substrate properties are being controlled. These results are demonstrated in Fig 2.7. Interestingly, it is observed that as the antenna is biased, it starts showing circular polarization with opposite sense at two different frequencies. The two frequencies points can be tuned by changing the magnetic field bias. These results are explained with the help of a mathematical model. It explains that the bias fields cause the substrate permeability to provide two different values for the two frequencies. Hence, allowing for different sense of polarization in the two bands. These results are quite interesting and paved the way for more research to be carried out under the domain of magnetic materials.

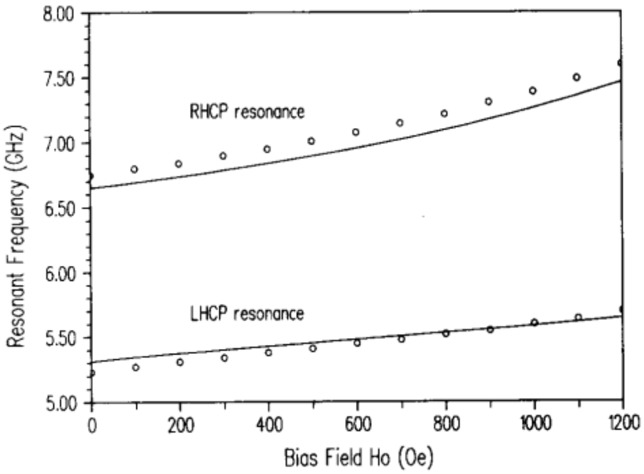
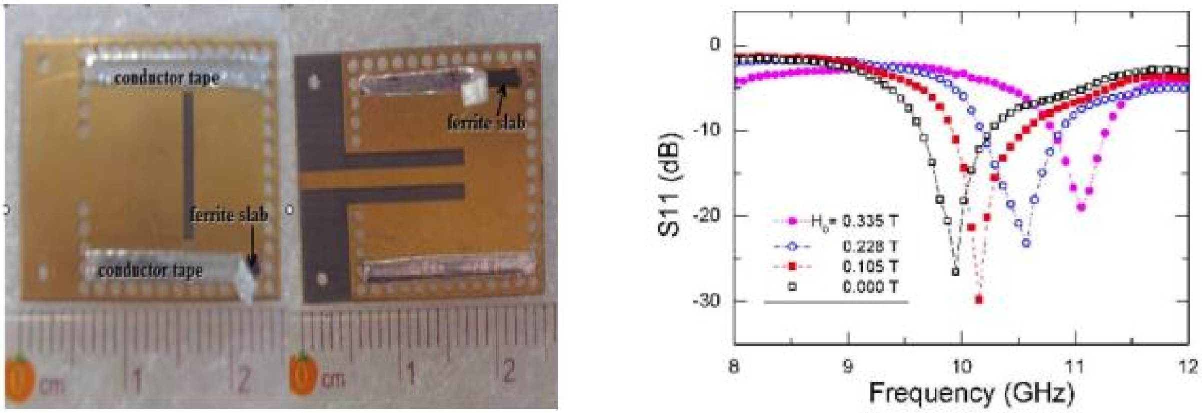


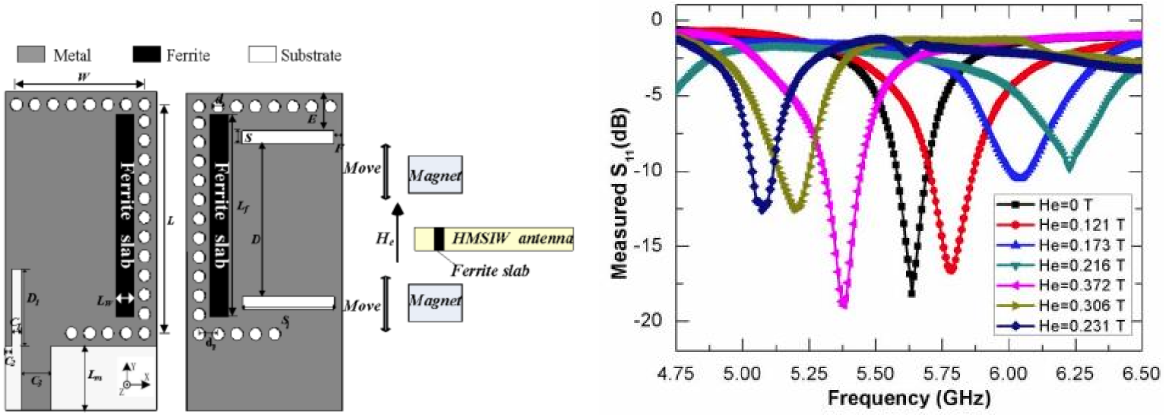
Fig. 2.7: Resonant frequency for RHCP and LHCP for patch antenna [35].

After Pozar's initial work on magnetically tunable antenna, few other designs have also been reported [36]-[38]. The research group of L.R.Tan el. al presented a reconfigurable substrate integrated waveguide (SIW) antenna in [29]. Ferrites slabs are introduced along the side walls of SIW. With the advance fabrication techniques available in this era, this type of design is realizable as shown in Fig 2.8 The resonance frequency of the antenna design is determined by many factors such as cavity dimensions, slot length and applied bias magnetic field. The first among these are optimized initially to determine the center frequency of the antenna without any bias. As the applied external magnetic field strength is changed the center frequency of the antenna tunes to a higher value (from 10 GHz to 11.1 GHz. At the same time, the gain of the antenna is seen to provide a consistent trend around 5 dBi. The same group presented another paper in 2016 using a half-mode substrate integrated waveguide (HMSIW) with two slots. Single ferrite slab is inserted in the structure as is shown in Fig. 2.9. When the external magnetic field is applied, the center frequency is shifted from 5.07 GHz to 6.23 GHz. Similar to [29], these results show a tuning range of around 1 GHz but at a much lower frequency which means that the percentage tuning has actually increased (almost doubled).



(a) (b)

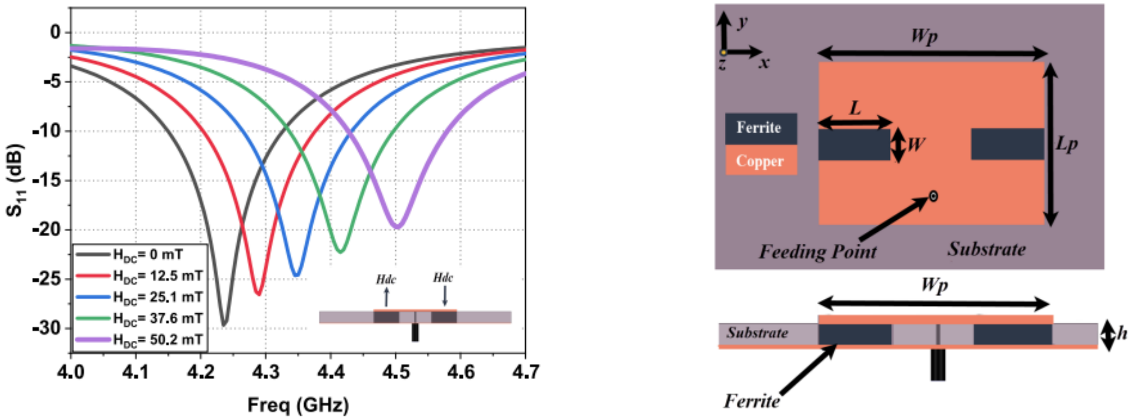
Fig. 2.8: Fabricated antenna design (left: back side; right front side), b) resonance frequency changing with applied magnetics bias [29].



(a) (b) (c) (d)

Fig. 2.9: (a) Front side of our antenna. (b) Back side of our antenna (the bias magnetic field is along -direction). (c) Experimental sketch. D) results of our antenna changing with the external magnetic fields [30]

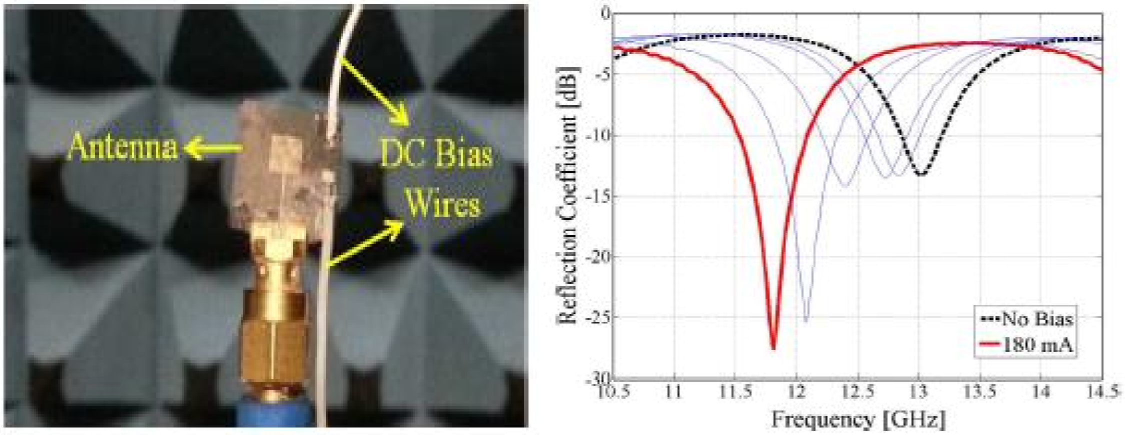
Most recently this phenomenon is presented by M.A. Omari, *et. al.*, where rather than using a full magnetic substrate, the authors preferred using a ferrite disk embedded in a non-magnetic substrate as opposed to the initial work of Pozar in [31] [34] [35]. This allows for the improved antenna performance by increasing the antenna gain and efficiency. The tunability of the design is achieved by applying external magnetic field as in the previous reported designs. Ferrites slabs effect on the center frequency of the antenna. The final results presented in this work show a tuning range of 4.2 GHz to 4.5 GHz which are not as significant as compared to some of the previous reported work. This reduced tuning is at the expense of improving antenna efficiency. The authors have further improved the results by employing other techniques but here the focus will be kept on magnetic tuning and therefore that part will not be covered are placed at the center of the substrate. Length and width of the ferrite slab are also studied to observe their.



(a) (b)

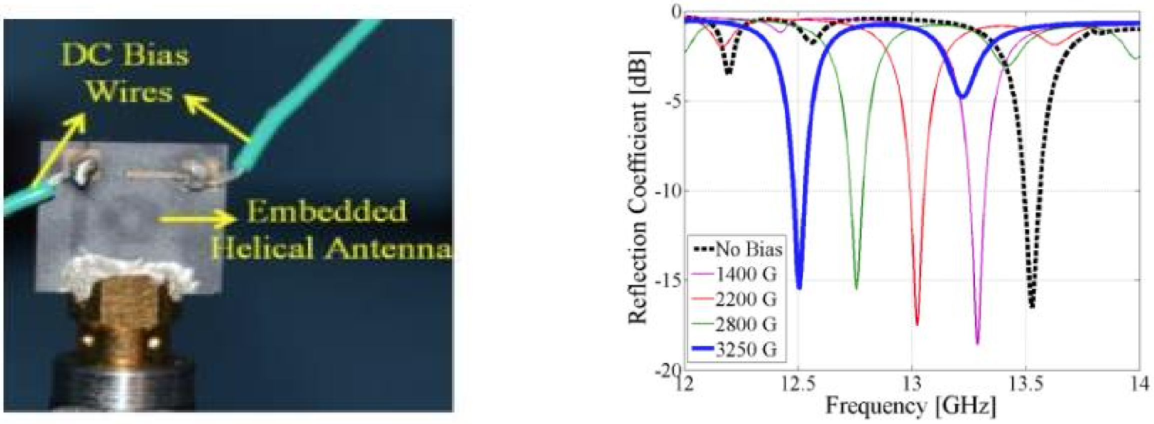
Fig. 2.10: a) Resonance frequency tuning of ferrite-embedded antenna corresponding to the magnetic field. b) Reconfigurable patch antenna printed on a dielectric-ferrite substrate [31].

Up till this point, all the antennas reported in this chapter discuss magnetically tunable antennas on conventional ferrite substrate. A new technology of ferrite based on multilayer fabrication technique of low temperature cofired ceramic (LTCC) has been introduced in 2011 [39]. Farhan et. al. [32] presented a work to predict the frequency tuning of a patch antenna by exploiting the partially magnetized ferrite substrate rather than using the saturated models. This allowed for considerable reduction in the magnetic field strength but then had the challenge of no theory to understand the antenna operation in the partially magnetized state. To cater for this, new models are developed in this work which are validated using simulations and measurements. With the help of embedded bias windings the antenna is shown to provide a tuning range of 1.25 GHz around 13 GHz of center frequency. The same group extended their initial patch antenna work by using the embedded bias windings as a radiator itself [33]. This eliminated the requirement of using two different elements for the antenna and the windings as shown in Fig. 2.12. The concept is quite novel and has never been studied before. The antenna structure and its measured impedance performance for this paper is shown in Fig. 2.11. However, due to the limitation on the helical antenna structure the windings could not be optimized for their best performance. The design used a current of more than 1A as opposed to only 180 mA used in [32]. These two designs show that how external magnets can be replaced by embedded bias windings. However, the challenges of this technology include high cost and heat generation. Ferrite LTCC is a relatively new technology and therefore requires specialized process which is expensive. Furthermore, the designs show that the current in the windings can heat the substrate significantly effecting the antenna performance. This means that the technology needs to be further optimized for cost-effective designs showing adequate RF performance. Although ferrite LTCC is an attractive option to design magnetically tunable antennas but because of its immaturity the focus of this thesis would be on conventional magnetic substrates such as YIG.



(a) (b)

Fig. 2.11: (a) Radiation pattern measurement under biased condition. (b). Measured frequency response [26]



(a) (b)

Fig. 2.12: a) fabricated helical antenna. b) Center frequency changes when a magnetic field is applied [33]

A summary of the papers discussed above is outlined in Table 2-2 below. The table and the literature review presented in this section demonstrate the viability of magnetic substrates to provide frequency tuning from the antenna designs. Therefore, one of the contributions of this thesis will be on the use of a magnetic material to control the impedance of the antenna element.

Table 2-2
Reported Ferrite Based Frequency Tunable Antennas

Reference No.	Frequency Range	Bandwidth	Applied Field
[29]	4.2-4.5 GHz	250 MHz	(0-50.2) mT
[30]	9.95-11.06 GHz	10.5%	(0-0.335) T
[31]	5.07-6.3 GHz	1160 MHz	(0-0.14) T
[32]	13-11.85 GHz	1250 MHz	(0-180) mA
[33]	13.5-12.5 GHz	10%	(0-3250) G
[34]	6.17-5.79 GHz	3.8%	(0-100) Oe

2.3. Conclusion

In this chapter various research papers based on frequency tuning and polarization reconfigurability has been presented. At first frequency tunability is described. When antenna structure is designed on a magnetic substrate and external magnetic field is applied on it, then the center frequency is shown to be controlled/tuned. For polarization reconfigurability, PIN diodes-based designs are discussed to show their viability for such an application. By switching the states of the PIN diodes, different polarizations such as circular polarization (CP) both RHCP and LHCP, linear polarization along different axes are shown to be achieved. The literature review lays the foundation for this work by showing that there is a lack of antenna designs that can achieve frequency tuning alongside polarization reconfigurability in tandem from a single structure. Therefore, this work focusses on such an antenna that can smartly tune its frequency while controlling its polarization. This is to be achieved by using a magnetic substrate for the antenna base with the integration of PIN diodes on the antenna structure. Such a design will prove to be a novel addition to the antenna literature as it stands today.

Chapter #3

Proposed Antenna Front-End

Before delving into the discussion of the components that are to be presented in this work, it is better to discuss the proposed antenna system at a glance. This will help in understanding the reasons for selecting the particular components and their functionality. The antenna concept used in this thesis is shown in Fig. 3.1. It consists of two patch antennas that are placed orthogonally to each other. This is done to ensure that the antennas radiate cross polarization waves with respect to each other. A 3 dB divider is used to feed the two antennas that can be understood with the help of Wilkinson divider. Furthermore, the antenna feed is designed to provide a phase shift of 90° between them and are integrated with two PIN diodes. When both the diodes are in the ON state, one would expect this antenna to radiate circular polarization while if only one antenna is allowed to work then the radiation would be linear. The complete system is to be realized on a magnetic substrate which in this case is yttrium-iron-garnet (YIG), because of it low loss in RF band of frequency. This will allow for frequency control of the proposed antenna front-end.

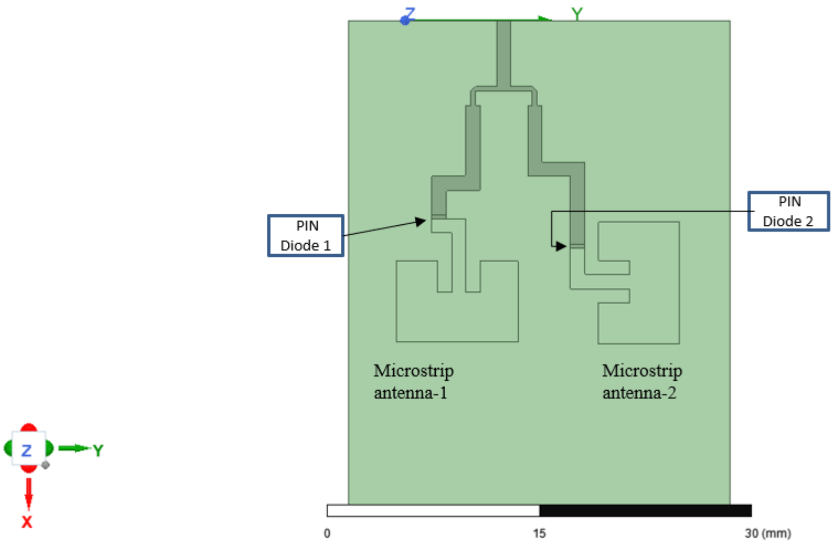


Fig. 3.1: Complete Antenna design.

3.1 Microstrip Patch Antenna

The design starts with a simple rectangular patch antenna to work around 7 GHz. The dimensions of the single feed microstrip patch antenna are shown in Fig. 3.2. The mathematical analysis of the microstrip patch can be found [40] and are very well-known. Therefore, these points are not covered here. Using this reference, it is seen that the length (L) of the antenna combined with the substrate height (h) and its dielectric constant (ε_r) determine the resonant frequency (f_r) of the antenna. From the calculations, shown in [40], one can start with a length of $\frac{\lambda_g}{2}$, where λ_g stands for guided wavelength using these dimensions, the antenna is simulated in Ansys High Frequency Structure Simulator (HFSS). After some modifications, the antenna is optimized to work at 7 GHz. The impedance performance of the antenna is shown in Fig. 3.3 with more than acceptable performance. The reflection coefficient is well below -21 dB with adequate bandwidth response. Similarly, the radiation pattern shows maximum in the bore-sight direction, Fig. 3.4. The maximum gain is observed to be 4.3 dBi which is reasonable considering the high dielectric constant of the YIG substrate ($\varepsilon_r \sim 15$). The simulator also incorporates the losses at RF frequencies for YIG. However, YIG is known to be a very good candidate for antenna designs among magnetic substrate and has low losses. Also, antenna is operating at 7 GHz, which is well above the magnetization frequency. Therefore, the substrate loss is not an issue of concern. With the antenna design ready for the system integration, the next step of the feed network can now be taken up.

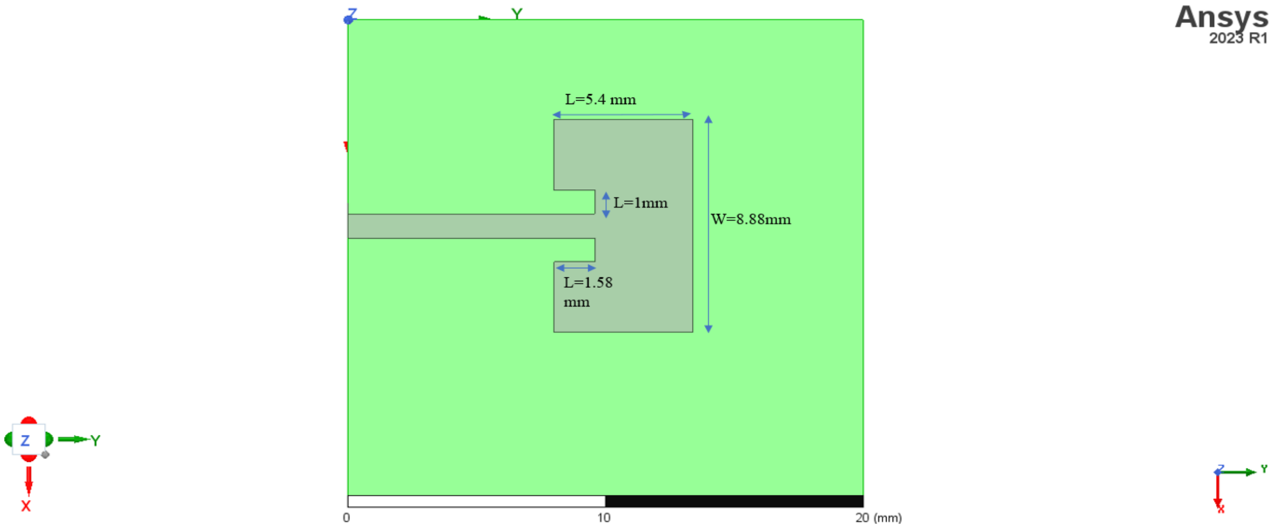


Fig. 3.2: Microstrip Patch Antenna, with inset feed.

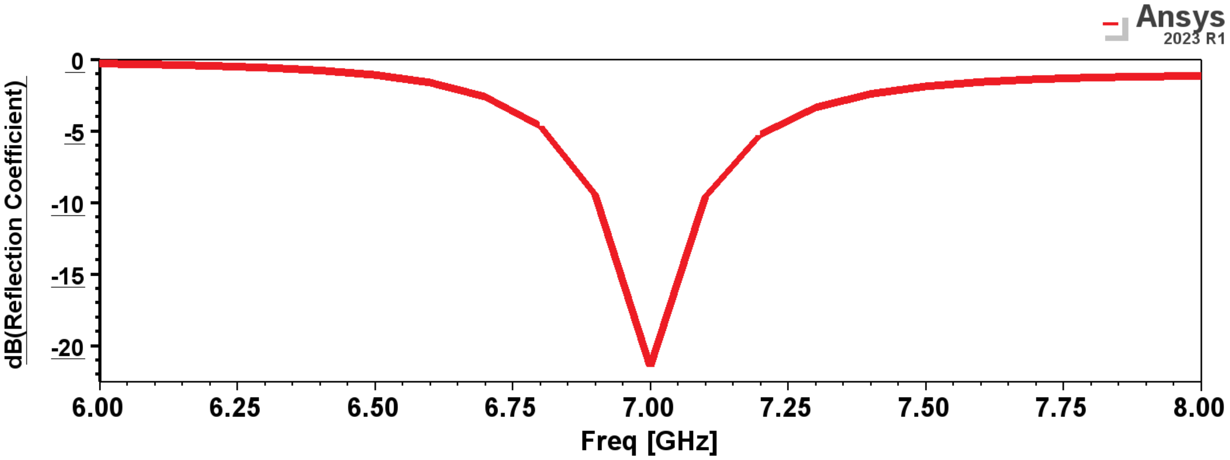


Fig. 3.3: Reflection co-efficient (S11) of Microstrip antenna.

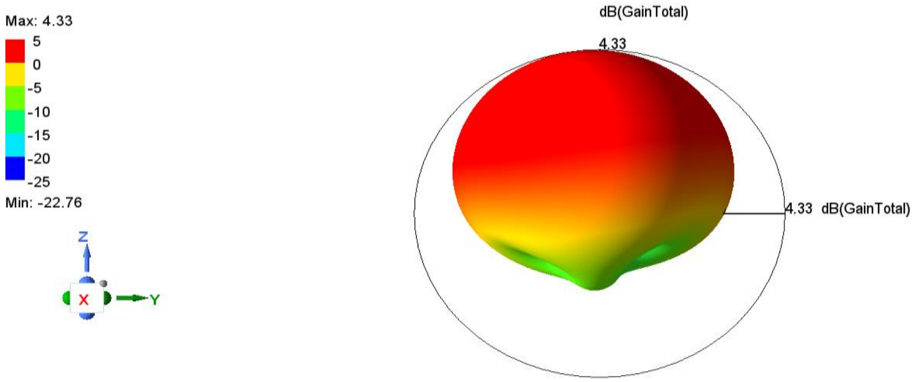


Fig. 3.4: Gain of Microstrip antenna.

3.2 Wilkinson Divider

Considering the antenna system to be employed in this thesis, Wilkinson divider seems to be an appropriate choice for the feed design. Its simplicity and well-known theory will allow for ease in the design process and the modifications required to produce the 90° phase difference between the two output ports can be easily accomplished. The initial structure simulated for the feed structure is shown in Fig. 3.5. It is interesting to see that one of the output ports is provided with an extra length of U-shaped feed line. This is done to accommodate the needed phase shift while providing minimum amplitude imbalance between the two ports. The length of the U-shaped line is calculated using the λ_g value. A 100Ω resistor is used between the two ports to provide the required isolation. The results shown in Fig. 3.6 and 3.7 show acceptable performance in terms of power division and phase response of the divider. The amplitude response shows 3 dB division with 1 dB of insertion loss between the two ports while the phase response provides approximately a 90^0 phase shift. It could be further optimized to improve the isolation, however, this study can be carried out at a later stage. Because the integration of the antenna with the divider would require some steps for the optimization of the antenna system. Therefore, it is better to use this structure with its initial results and optimize the whole system with everything integrated.

3.3 Integration of Microstrip Patch Antenna and Wilkinson Divider

Once the antenna and the divider have been optimized individually, the next logical step is to combine them as a system shown in Fig. 3.1. Initially, it is prudent to avoid the use of PIN diodes in the antenna system and simulate it as is to minimize the number of unknowns. As the two antennas and the divider are integrated together, it is observed that the results are not as expected.

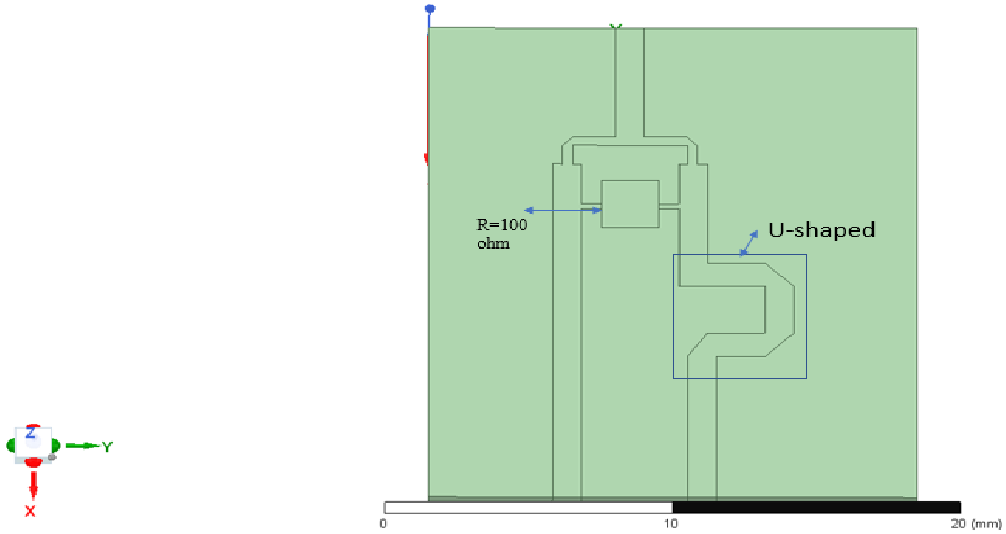


Fig. 3.5: Wilkinson Divider design at 7 GHz.

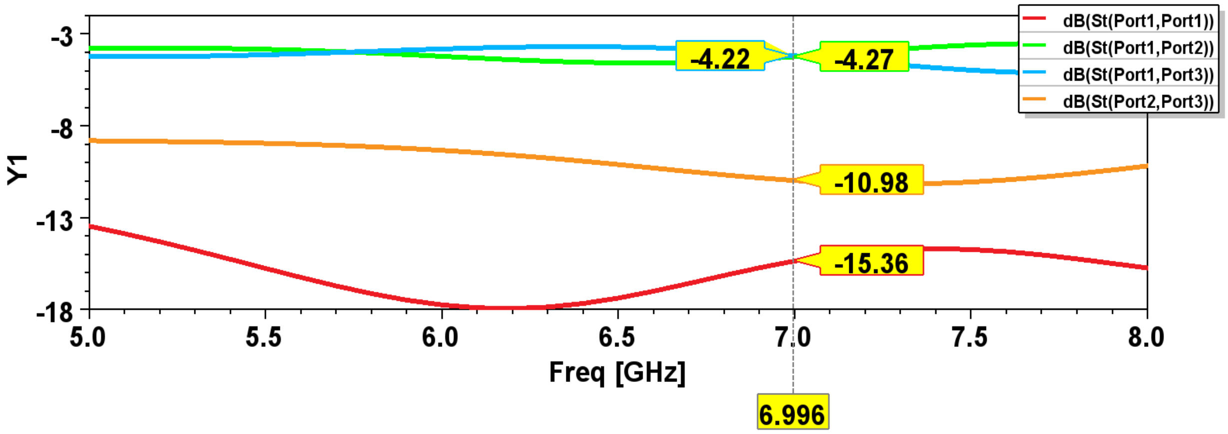


Fig. 3.6: Output, Reflection co-efficient and Isolation of Wilkinson divider at 7 GHz

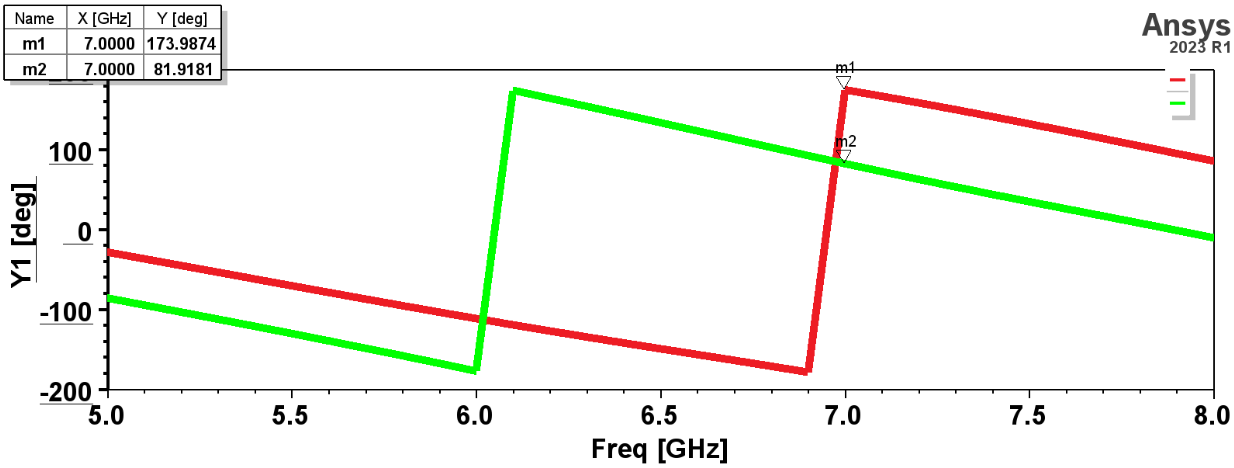
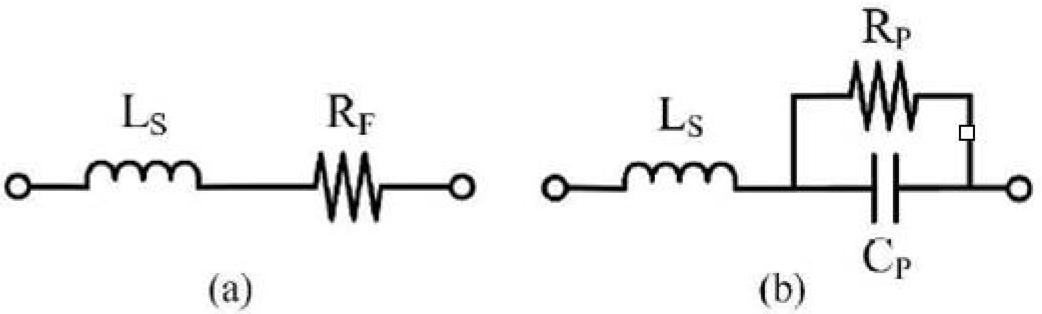


Fig. 3.7: Phase difference at port 2 and port 3 of Wilkinson divider.

The impedance as well as the radiation performance of the antenna is quite off from the standard values. Therefore, a series of steps are employed to modify the antenna structure to achieve the desired results. Due to these changes, the final antenna design looks different from its feed standpoint. However, this is always expected in RF antenna and system designs. The integration of different components together has severe impact on the performance of the components themselves. Therefore, this is something quite anticipated. In order to avoid redundancy, the impedance and radiation results are not shown or discussed here. Rather it would be better to integrated the PIN diodes on the feed lines and then study the results as a whole.

To achieve polarization reconfigurability from the proposed design the thesis proposes to use PIN diodes into the antenna feed. Since there are two microstrip antennas used in Fig. 3.1, so two PIN diodes are to be integrated to control each radiator individually. There are a variety of high speed switching, low resistance diodes that provide low insertion loss and acceptable matching conditions. After a study of the components available in the market, the diode selected for this work is DSG9500-000[41]. A limitation of HFSS is that it cannot solve active components such as diodes and transistors with the passive components. The only way around this deficiency is to use lumped circuit models to realize such active components. Fortunately, the diode under study has been discussed for its circuit model in [41]. The paper reports the model both in the ON and OFF state of the diode with its corresponding element values. The model is shown in Fig. 3.8. This model is quite useful for the integration of PIN diodes in its two states in a full wave simulator like HFSS which is covered in the next section.



Equivalent circuits of the PIN diode. (a) ON state. (b) OFF state. (L_S = 0.5 nH, R_F = 4 Ω, C_P = 0.025 pF, R_P = 10 kΩ)

Fig. 3.8: Lumped equivalent model of PIN Diode [41]

3.4 Antenna Simulations with the PIN Diodes

3.4.1 Circular Polarization

In this section, the system will be studied for three different cases. Let's start with the case when both the diodes are ON and feeding the two antenna elements. It is prudent to mention it here that this integration of diodes using the model shown in the last section required a new step of optimization. When the diodes are first added to the feedlines, it resulted in poor impedance matching at the input. To cater for this, the feedline was optimized using the inset feed of the antenna to achieve acceptable performance in terms of the antenna impedance. The diodes had no to minimal effect on the antenna radiation which was expected as their size is quite small as compared to the radiators themselves. Now, with both of the diodes ON, the antenna feed provides a phase difference of 90^0 between the two antenna elements with minor amplitude imbalance. This case is ideal to generate circular polarization from the antenna. Hence it is seen that the system radiates with a maximum gain of 5 dBi and an axial ratio of 1.4 dB. The impedance matching of the antenna shows that it works well at 7.3 GHz, Fig. 3.9, which compliments the radiation performance shown in Fig. 3.11 and Fig. 3.12. Although the axial ratio value shows in Fig. 3.10, that the antenna to be working as a CP radiator, it does not exhibit the sense of rotation i.e LHCP or RHCP. For this purpose, Fig. 3.12 is plotted to demonstrate that the antenna is RHCP because of dominant strength of radiation for this polarization as compared to the other one. All these results in tandem basically prove the with both the diodes biased to be ON, the antenna provides a good CP radiation. Now, it is possible to switch RHCP radiation to LHCP by using a mirror image of the feed line i.e. to alter the phase shift between the two elements. However, this point is not covered in this thesis as it requires an actual physical change in the antenna structure.

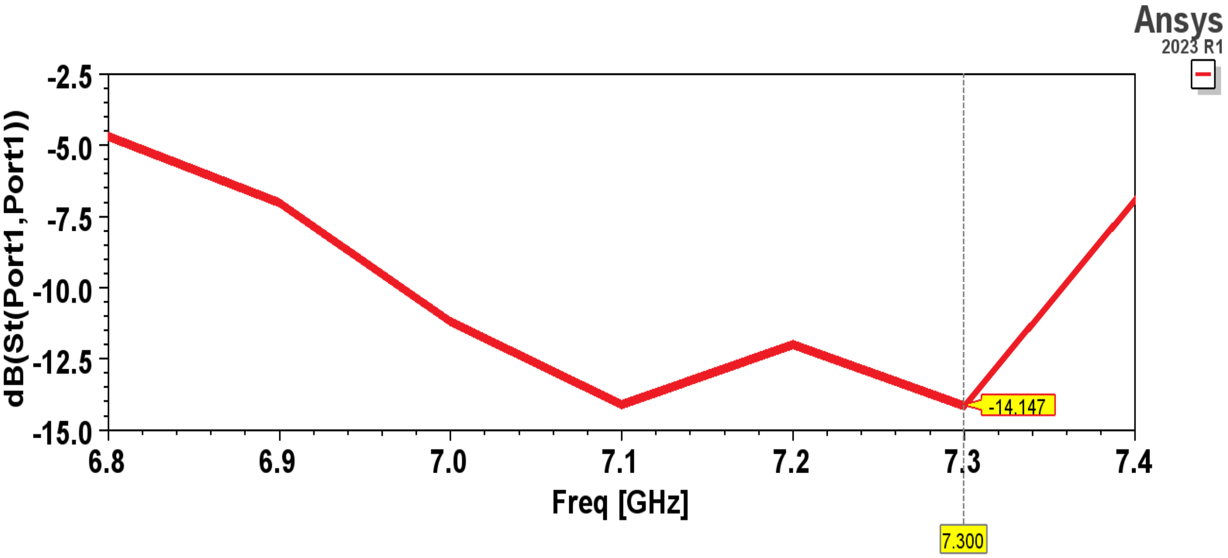


Fig. 3.9: Reflection coefficient when both PIN Diodes are ON.

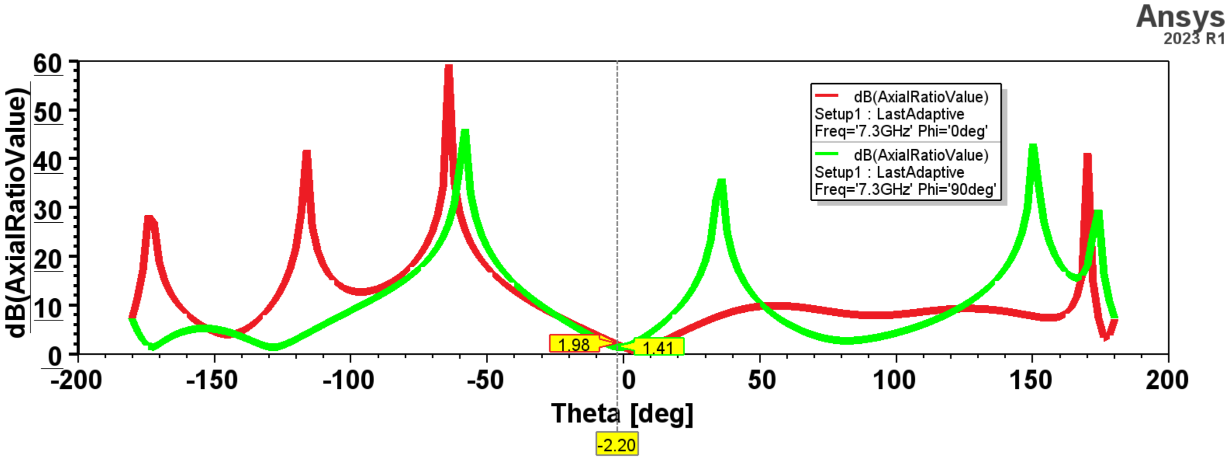


Fig. 3.10: Axial ratio. When both PIN Diodes are turn ON.

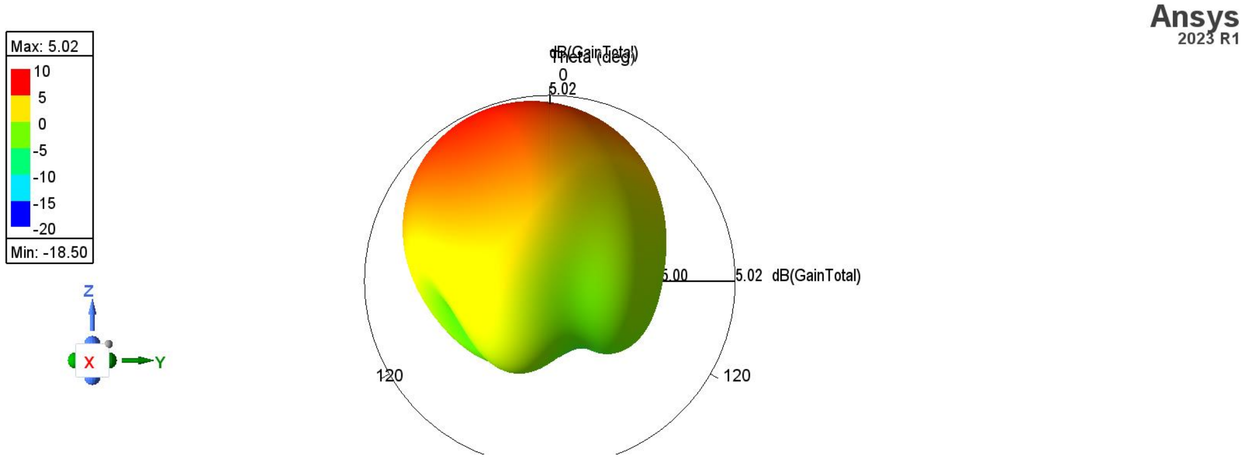


Fig. 3.11: Gain of antenna system, when both PIN Diodes are turn ON.

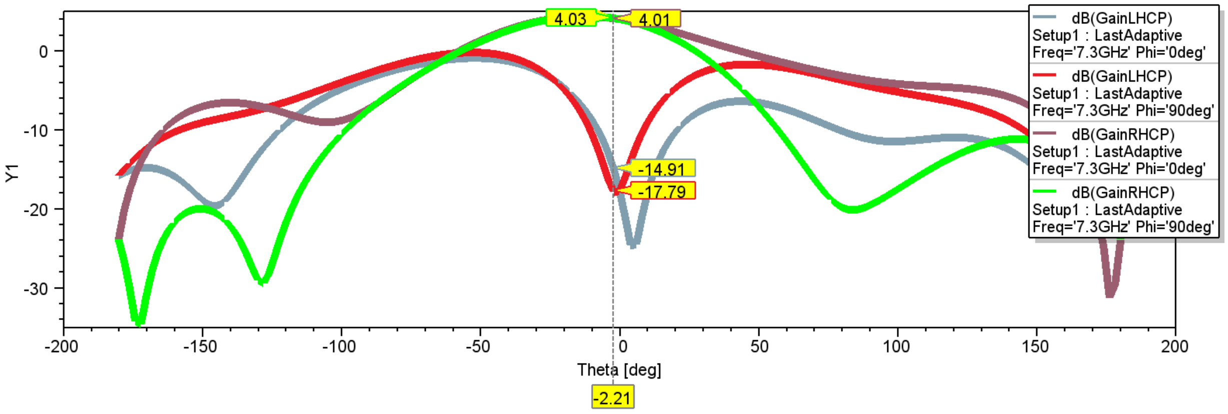


Fig. 3.12: LHCP and RHCP at 0^0 degree and 90^0 degree, when both PIN Diodes are turn ON.

3.4.2 Linear Polarization

After studying the antenna for the case when both the diodes are ON, it is now natural to turn OFF one of the diodes and see the response of the antenna. This is done by first keeping Diode 1 ON and turning off the other diode. This will correspondingly mean that only microstrip antenna 1 is ON and antenna 2 is in a cut off state. With the absence of the other radiator, one can easily fathom that circular polarization can no longer be achieved from this system. In other words, the radiation performance should correspond to linear polarization. The results precisely indicate this as is evident from the axial ratio value of 31 dB. This value is significantly higher than the 3 dB standard used for circular polarization. The antenna radiates with a maximum gain of 6 dBi which is comparable to the case of CP. Now to further investigate the polarization purity of the radiated wave, one should check the LHCP and RHCP gain values. These are depicted in Fig. 3. 15. It can be observed that the two polarizations have almost the same value which again validates the linear polarization of the antenna. Finally, it is also important to determine the polarization direction. For this purpose, Gain_theta and Gain_phi are plotted at Phi = 0 and Phi = 90°. It is seen that for the bore-sight direction of radiation the former is 15 dB more than the later which means that Gain_theta is the co-polarization while the other is cross-polarization. These results again prove the radiation to be linear. The impedance of the antenna remains matched at 7.3 GHz where all the radiation results are presented herewith. It means that the toggling of diodes does not effect the frequency of operation and one is able to achieve both CP and LP radiations at the same center frequency.

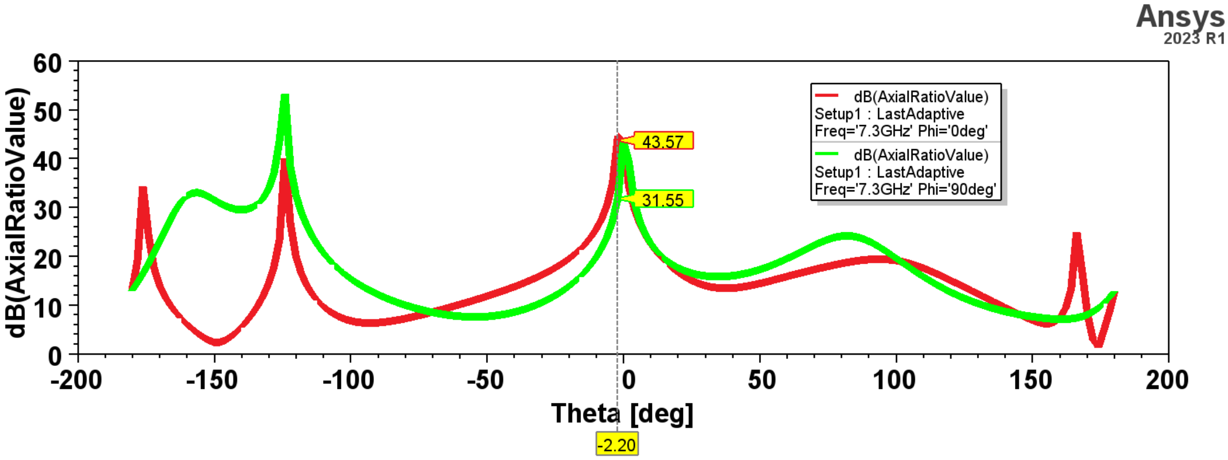


Fig. 3.13: Axial ratio, left side PIN diode Turn ON and Right side PIN Diode Turn OFF.

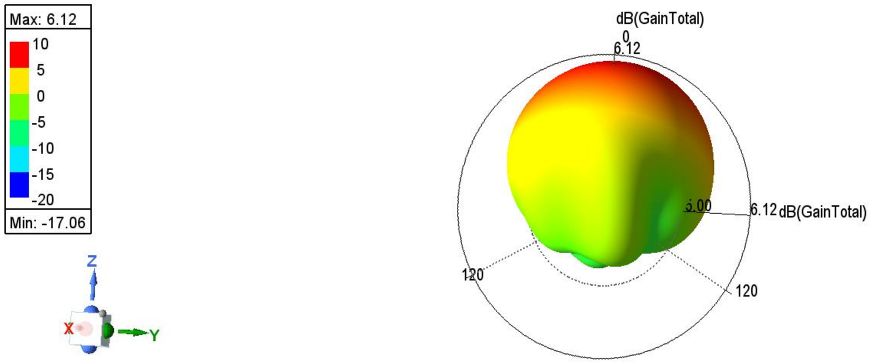


Fig. 3.14: Gain of Patch antenna, Left PIN Diode is turn ON and right PIN Diode Turn OFF.

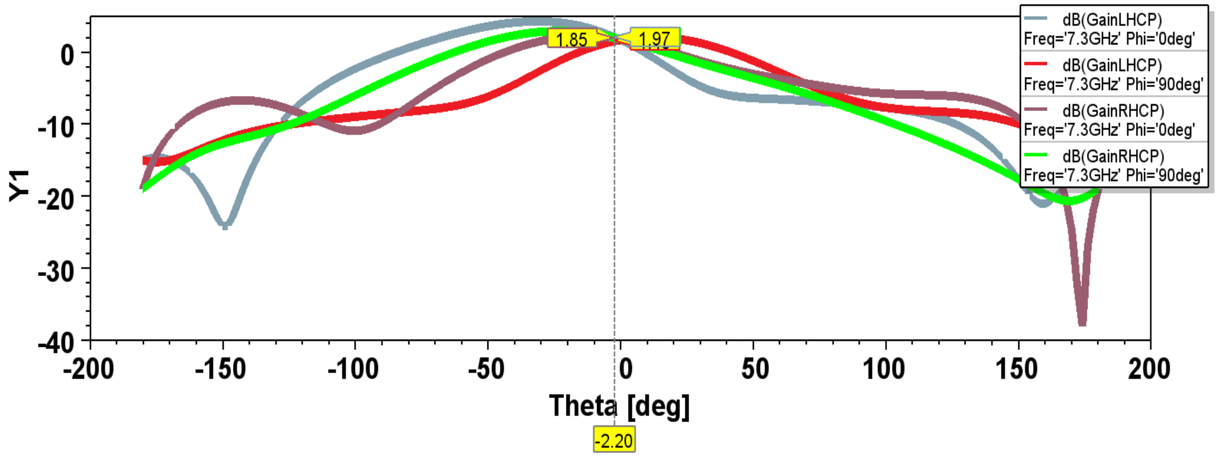


Fig. 3.15: LHCP and RHCP, left side PIN diode Turn ON and Right-Side PIN Diode Turn OFF.

In the last case,left side PIN diode (PIN diode 1) is turned OFF and the right one (PIN diode 2) is kept ON. The anticipation is again to achieve linear polarization with an axial ratio much higher than 3 dB. This is shown in Fig. 3.20 with an AR value of >20 dB. The antenna radiates with a similar gain as the last case however the pattern is little squinted. This can be attributed to the meandered feedline structure that feeds into the antenna element. Similar to the last case, the LHCP and RHCP radiations show almost same values which supports LP radiation. However, to avoid redundancy this plot is shown in this section. Rather, the radiation of Gain_theta and Gain_phi are plotted in Fig. 3.17. Contrary to the last case, in this case Gain_phi is around 15 dB higher than Gain_theta which means that the polarization of radiation in this case is phi. This is something expected from such a design. The impedance of the antenna remains matched at 7.3 GHz which is again desired from such a design. Thus, this case provides a linear polarization that is different from the last case but at the same frequency.

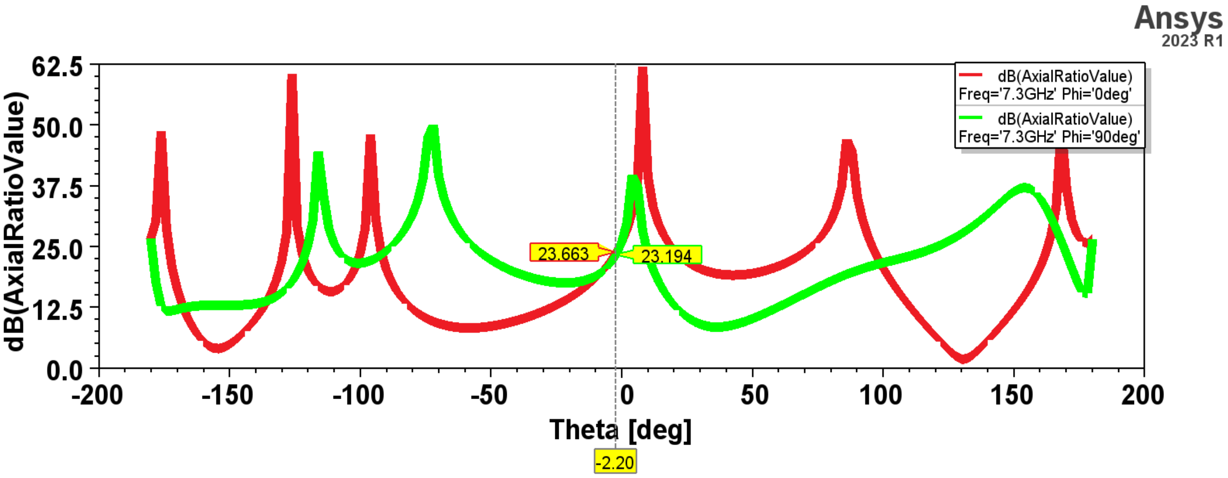


Fig. 3.16: Axial ratio, right side PIN diode Turn ON and left Side PIN Diode Turn OFF.

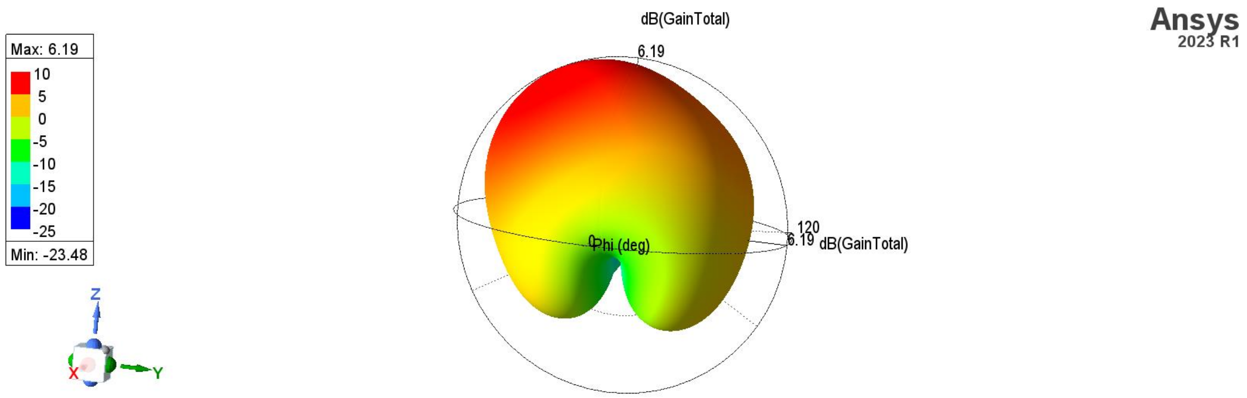


Fig. 3.17: Gain is 6.19, right side PIN diode Turn ON and left Side PIN Diode Turn OFF.

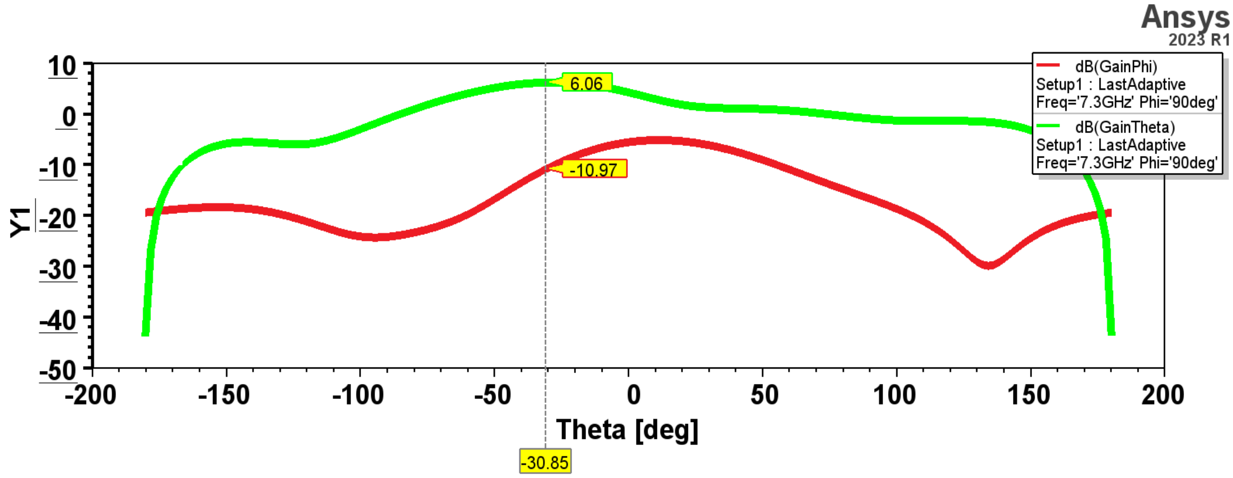


Fig. 3.18: Gain Phi and Gain Theta, when Right side PIN diode Turn ON and left Side PIN diode Turn OFF.

3.7. Conclusion

This chapter introduces the antenna system that is employed in this thesis. Using PIN diodes it is shown that an antenna designed on a magnetic substrate can provide three different polarization of radiations all at 7.3 GHz. PIN diodes play a vital role in achieving these simulation results. This chapter concludes the first part of this thesis where polarization reconfigurability has been achieved from the proposed antenna front-end. In the subsequent chapter, the magnetic substrate would be exploited for its properties to control the frequency of the antenna. It is desired to achieved frequency tuning for all the 3 cases which are discussed in this chapter.

Chapter 4

MAGNETIC TUNING

In the previous chapter, polarization reconfigurability is discussed using the proposed antenna design that is achieved by the use of PIN Diodes. The next part of this work pertains to the frequency control of the antenna by applying magnetic field across the antenna substrate. For this purpose, the antenna is designed on a magnetic substrate i.e. YIG. This chapter is written to focus on the magnetic component of the thesis.

4.1 Theoretical Background of Magnetic Tuning

Ferrites/magnetic substrate-based antenna can be tuned, when exposed to external magnetic field. When biased, they behave as anisotropic medium, which means that their characteristics can be dynamically controlled by varying the strength of the bias. In the presence of an external magnetic field, the ferrite substrates are defined with the help of Polder's tensor and its subsequent equations in [43]. However, the lagging with Polder's theory is the absence of substrate definition in partially magnetized state. In other words, it can also be said that this theory only deals with the substrate in the saturated state. However, here one would like to first study the antenna substrate in the partially magnetized state [32]. For partially magnetized state, when a substrate is biased, the tensor is still defined by Polder's theory given by (4.1). The case under study is when the antenna substrate is biased normally which is to say that the substrate is along xy plane and the magnetic field is applied along z-axis. The elements of the permeability tensor are expressed by Green and Sandy [42] in their modeling of the ferrites in the partially magnetized state as:

$$\mu = \mu'_0 \begin{bmatrix} \mu & -j\kappa & 0 \\ j\kappa & \mu & 0 \\ 0 & jk & \mu_z \end{bmatrix} \tag{4.1}$$

$$\mu_z = {\mu_0}'^{(1-(\frac{M}{M_S})^{\frac{5}{2}})} \tag{4.2}$$

$$\kappa = \frac{\gamma 4\pi \mathrm{M}}{f_{res}} \tag{4.3}$$

$$\mu = {\mu_0}' + (1 - {\mu_0}')\left(\frac{M}{M_S}\right)^{\frac{3}{2}} \tag{4.4}$$

$${\mu_0}' = \frac{2}{3}\left[1 - \left(\frac{\gamma 4\pi \mathrm{M}_S}{f_{res}}\right)^2\right]^{\frac{1}{2}} + \frac{1}{3} \tag{4.5}$$

where μ'_0 is the free space permeability, μ, μ_z and κ are the elements of the tensor, $4\pi M_s$ is the saturation magnetization expressed in Gauss (G), M is the magnetization value in partially magnetized state, γ is gyromagnetic ratio (2.8 MHz/G), and f_{res} is the resonant frequency.

Employing these equations of the magnetized ferrite substrate in the partially magnetized state and solving for patch antenna's cavity model, it has been demonstrated in [32] that the effective permeability experienced by the antenna on a substrate biased normally to its plane comes out to be,

$$\mu_e = \frac{(\mu^2 - \kappa^2)}{\mu} \tag{4.6}$$

where μ_e is the extraordinary permeability of the ferrite substrate and can also be called the effective permeability. Relying on this proposed theory, this work wishes to study two antennas at the same time biased on such a substrate. This theory is not only validated by full wave simulations but also backed by the completed impedance and radiation characterization of the antenna. The antenna substrate, YIG, has a saturation magnetization ($4\pi M_s$) value of 1800 G. This would result in a magnetization frequency ($f_m = \gamma 4\pi M_s$) of around 5 GHz. It is recommended to use a magnetic substrate above this frequency so as to avoid low field losses in the partially magnetized state. Keeping this in view, the antenna frequency is selected to be around 7 GHz in the last chapter of this work. This would allow for tuning in both lower and higher range of frequency band when the substrate is biased with an applied magnetic field. Also, all three polarizations would be studied to see if frequency tuning can be accomplished from them independently. Thus, providing a complete solution for simultaneous polarization and frequency reconfigurability.

4.2 Circular Polarization – Frequency Tuning

At first, the study is started with the case when both of the PIN diodes are in the ON state. It has already been established through simulations that the proposed front-end operates at 7.3 GHz with a decent circularly polarized radiation. One can anticipate the center frequency of the antenna to tune as the magnetic bias is applied across the substrate. To accomplish this, the equations discussed in the last section for the substrate modeling in the partially magnetized state are used in Ansys HFSS. It is worth mentioning here that the simulator can solve the antenna problem on a ferrite substrate both for saturated and unsaturated state. However, the focus is kept on the unsaturated regime for this thesis. By defining the substrate properly for the antenna of Fig. 3.1 on page 31 and varying the magnetization from 0 G to 1800 G, it is observed that the frequency of the antenna moves from 7.3 GHz to 7.9 GHz. This provides a hint of evidence that the antenna is being tuned under the influence of the applied magnetic field, as shown in Fig. 4.1. Having written this, it is equally important to pay attention to the radiation characteristics of the antenna while observing its impedance performance. If the antenna is to be regarded as a tunable CP antenna, its axial ratio and polarization ratio must be maintained during the frequency tuning.

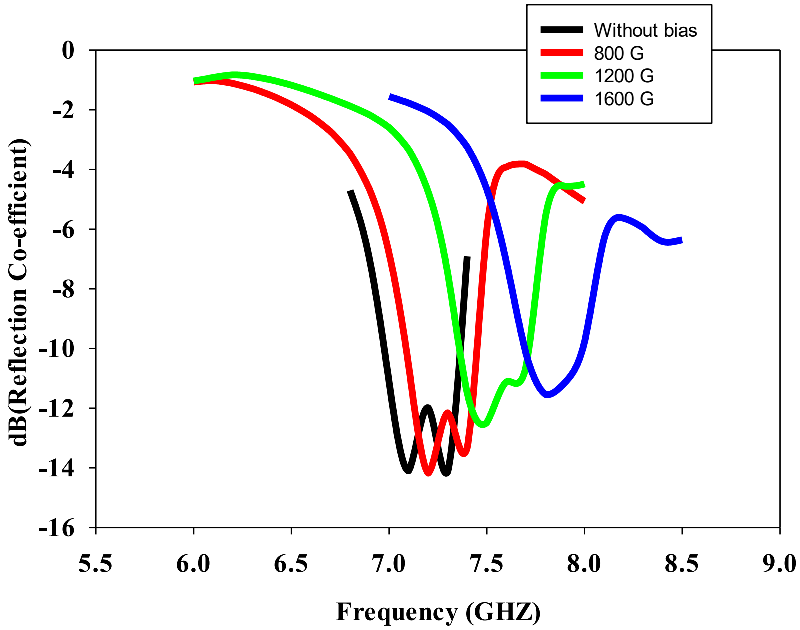


Fig. 4.1: S11 without and with external magnetic field applied.

Thus, these results are plotted and observed for each of the magnetization strength included in Fig. 4.1. To avoid redundancy, only two cases are shown in Fig. 4.2 to Fig. 4.4. The first two among these Figs show the axial ratio and polarization ratio for the case of 1200 G. A value of less than 3 dB can be seen close to the maximum radiation angle while the polarization ratio value strongly suggests a CP radiation with a sense of right hand (RHCP). The same results are observed for 1600 G of magnetization where the polarization ratio is plotted and again shows RHCP radiation. The antenna is originally RHCP without any bias and it is well maintained throughout the range of applied magnetic field strength. This means that a CP antenna under no bias is tuned for its center frequency by applying magnetic bias across the YIG substrate providing a range of ~1GHz and maintaining an acceptable polarization performance. The gain of the antenna stays close to 5 dB with a patch like radiation, Fig. 4.5. To represent this frequency tuning in a simpler fashion, the center frequency of the antenna is plotted vs. the magnetization of the substrate in Fig. 4.6. By increasing the magnetic field strength across the YIG substrate, the center frequency of the antenna is seen to be moving up in the band. This is due to the decrease in the effective permeability of the substrate. Thus, these results are not only anticipated but also in line with the theory of the magnetized ferrite substrate.

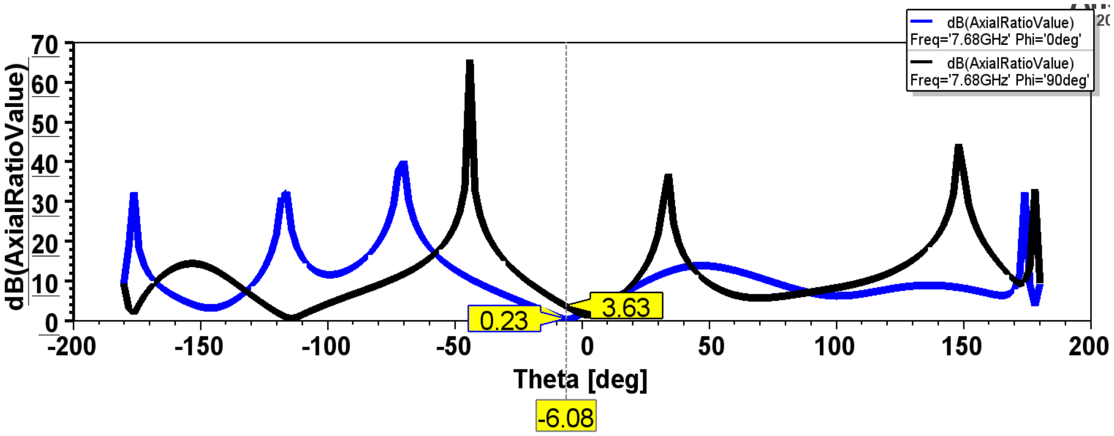


Fig. 4.2: Axial ratio at 1200 G

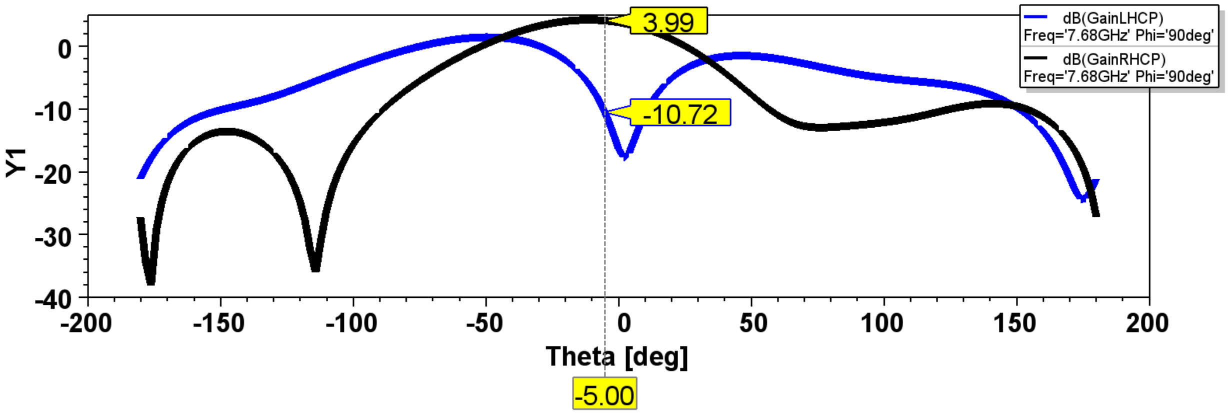


Fig. 4.3: Gain LHCP and Gain RHCP at 1200 G

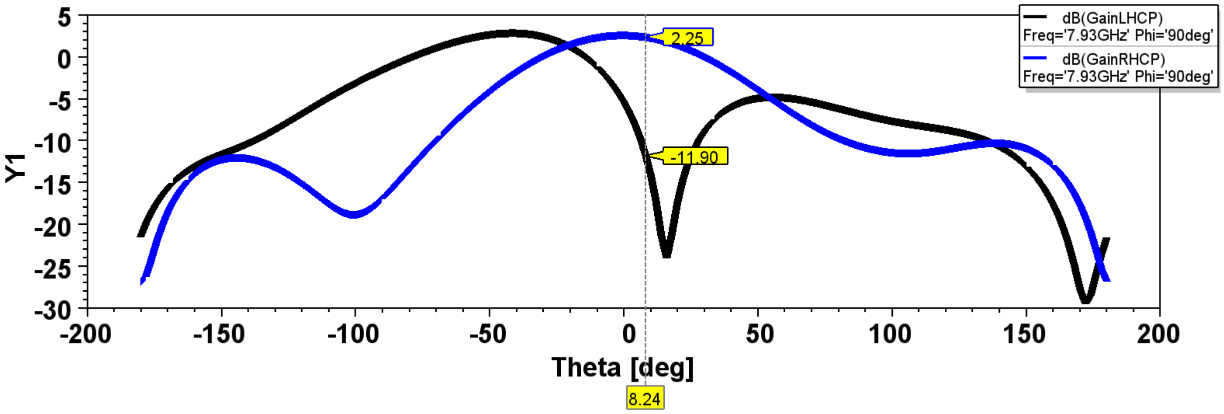


Fig. 4.4: Gain LHCP and Gain RHCP at 1600 G

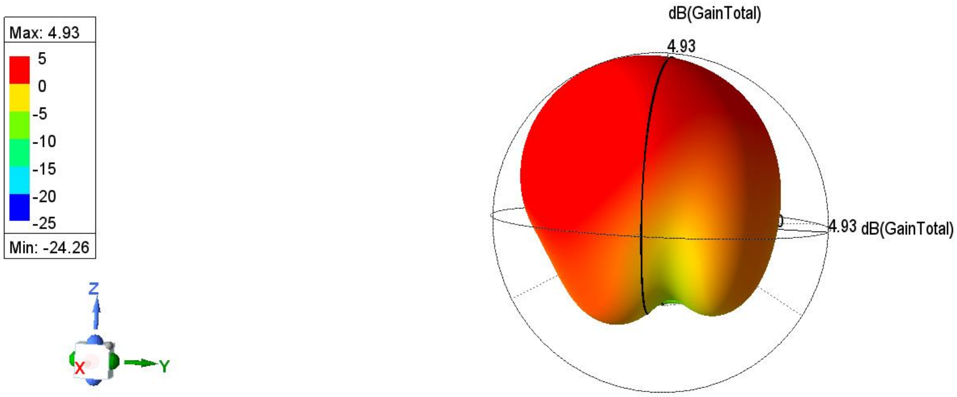


Fig. 4.5: Radiation pattern of the CP case of antenna in the biased state at 1200 G

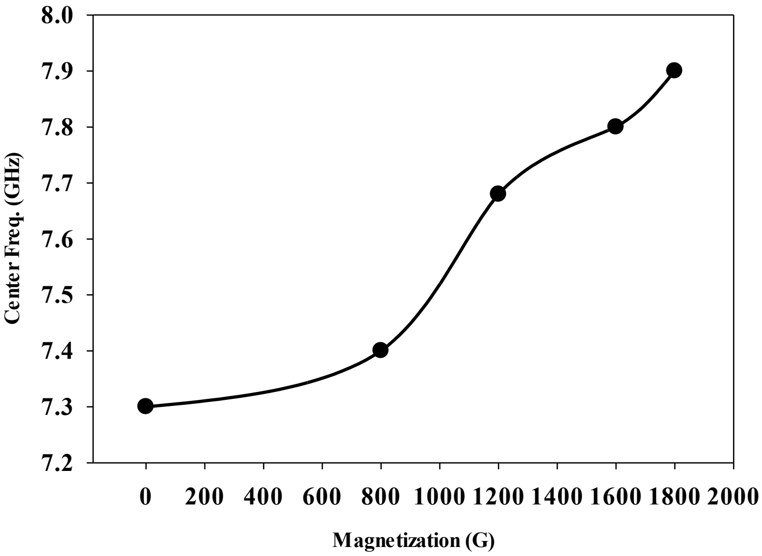


Fig. 4.6: Center frequency of CP case when external magnetic field applied.

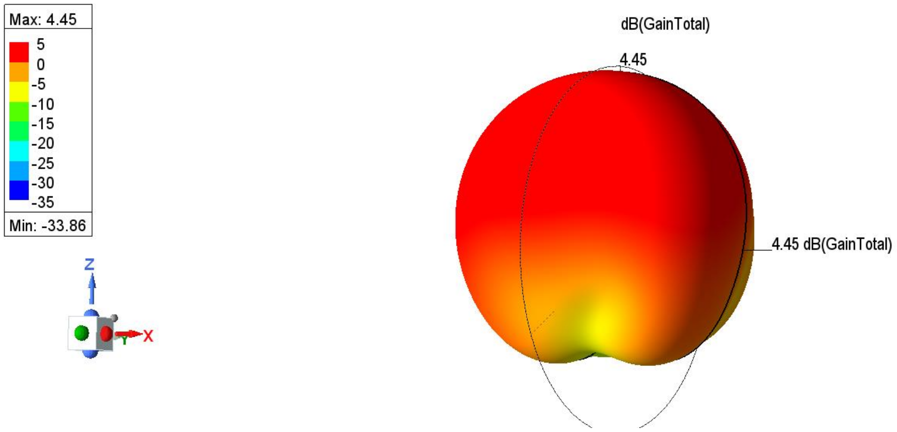


Fig. 4.7: Gain of the antenna at 1600 G

4.3 Linear Polarization – Frequency Tuning (Diode 1 is ON)

Once the antenna has been studied for the case of CP radiation, the natural step is to observe the effect of applied magnetic field on the LP antennas. By turning OFF each of the diodes one by one. This will allow for two different cases of LP radiations from the antenna system. Starting with turning ON the diode 1 of Fig. 3.1, it has already been observed that the antenna would provide a smooth linearly polarized wave at 7.3 GHz. When the magnetic field is applied across the antenna, frequency tuning similar to Fig. 4.6 is observed herein. This is to say that as the magnetization strength is increased all the way upto 1800 G, the center frequency of the antenna system changes from 7.3 GHz to 8.5 GHz. The relationship between the magnetization of the substrate and the resonant frequency of the antenna is shown in Fig. 4.8. These are results resemble the one shown in Fig. 4.6, however, the polarization of the antenna still needs to be verified just as in the last case. As it has been previously explained, that the radiation characteristics can be validated by plotting axial ratio and polarization ratio of the antenna. Thus, in Fig. 4.9, the axial ratio of the antenna is shown for the case of 1200 G with the polarization ratio represented in the

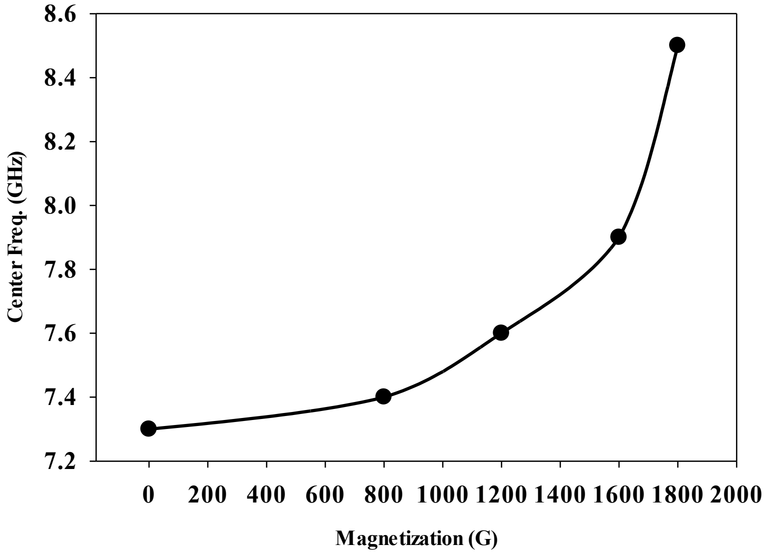


Fig. 4.8: Center frequency of LP case (Diode 1 ON) when external magnetic field applied.

next plot i.e., Fig. 4.9. Both these Figs clearly show that the antenna is operating as a linearly polarized radiator at the new tuned frequency of 7.6 GHz. For 1600 G the plot of polarization ratio is expressed in Fig. 4.11. Same can be concluded for this Fig and the results obtained for this magnetization value. Thus, it can be simply concluded that the antenna is able to maintain its linear polarization with a cross polarization of more than 15 dB as the frequency of the antenna is tuned. Also, the antenna is seen to polarized in the phi direction and maintains this during the process of magnetic field application. The gain of the antenna stays stable between 5 and 5.5 dBi which is acceptable for this class of antenna.

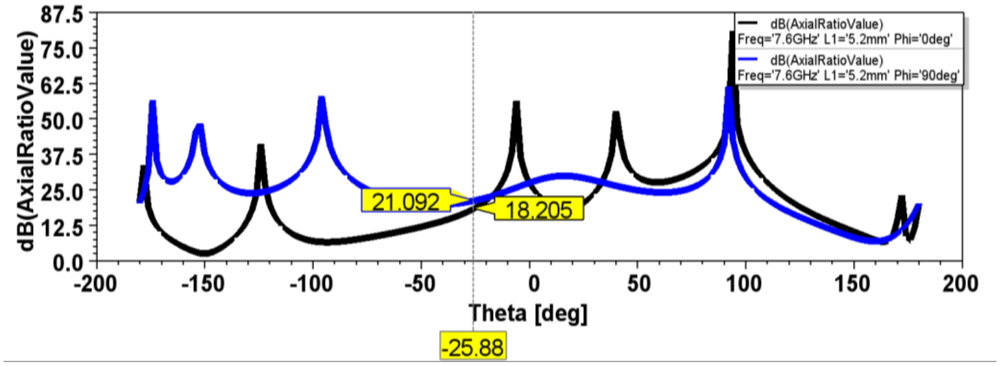


Fig. 4.9: Axial ratio for 1200 G

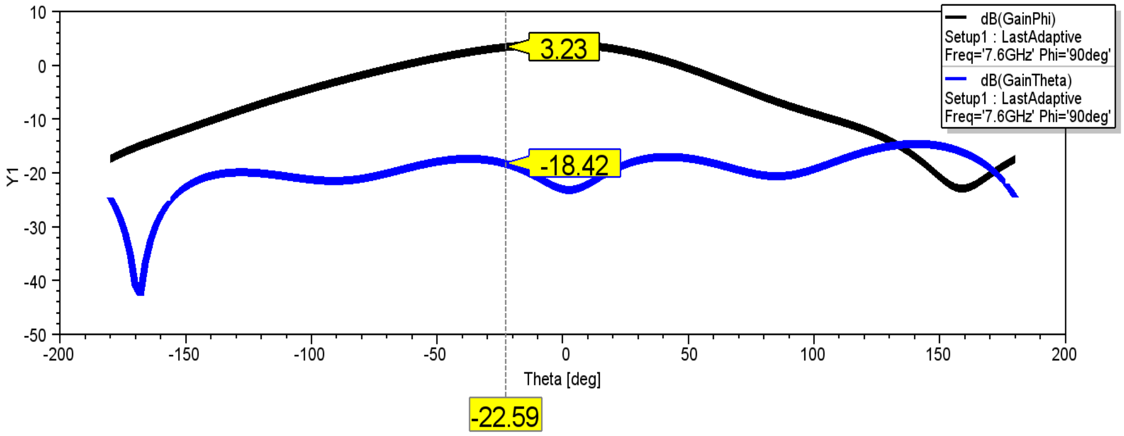


Fig. 4.10: Gain Phi and Gain Theta for 1200 G

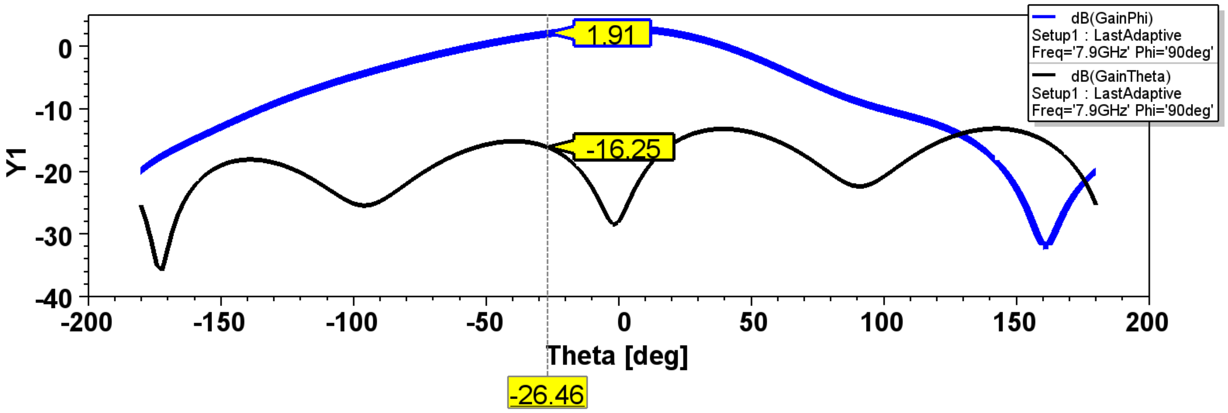


Fig. 4.11: Gain Phi and Gain Theta for 1600 G

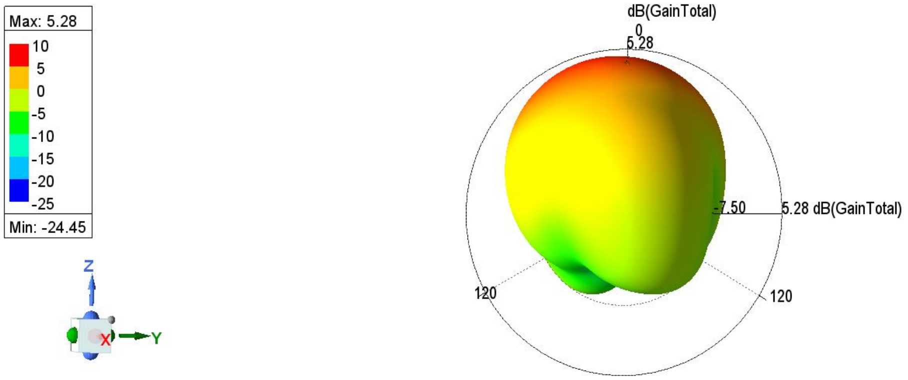


Fig. 4.12: Radiation Pattern for the case of LP when only Diode 1(Left) is ON

4.4 Linear Polarization – Frequency Tuning (Diode 2 is ON)

In the last case of this study, one would like to see what happens to the antenna performance with Diode 2(Right PIN diode) being in the ON state while Diode 1(Left PIN diode) being in the OFF state (of Fig. 3.1). Again, the anticipation is to achieve linear polarization from this case but with frequency tuning due to applied magnetic field. This is illustrated in Fig. 4.13. The same trend can be seen here due to the change in the magnetization of the substrate. The resonant frequency of the antenna tunes in the upward direction with the increase in the applied magnetic field strength. This no different from the case when PIN diode 2 was ON and diode 1 was OFF (last case). The need here is to check the polarization purity of the radiated wave. To avoid repetition, only the polarization ratios for the case of 1200 G and 1600 G are plotted in Fig. 4.14 and Fig. 4.15, respectively. Interestingly, here the antenna is providing linear polarization but it is in theta-polarized rather than phi as was the case in the last section. This is again completely in line with the theory. Since the two antenna elements are placed to generate cross polarization from each other, their individual radiations would be polarized normally. This is validated by the results of Fig. 4.14 and Fig. 4.15, where the cross-polarization levels are for the phi case and they are well below 15 dB of the theta case. Thus, the antenna is being tuned for a 3rd case of polarization using this idea. Finally, the gain is seen to be stable around 6 dBi and the radiation pattern for one case is shown in Fig. 4.16. A slight squint can be observed for this case of radiation which is due to the feeding structure of the system.

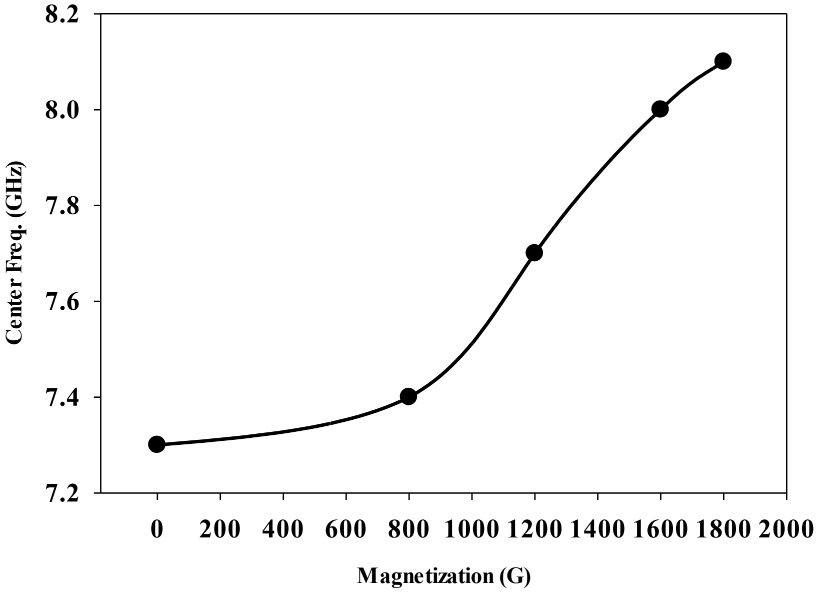


Fig. 4.13: Frequency tuning for PIN Diode 2 being ON vs. applied magnetic field.

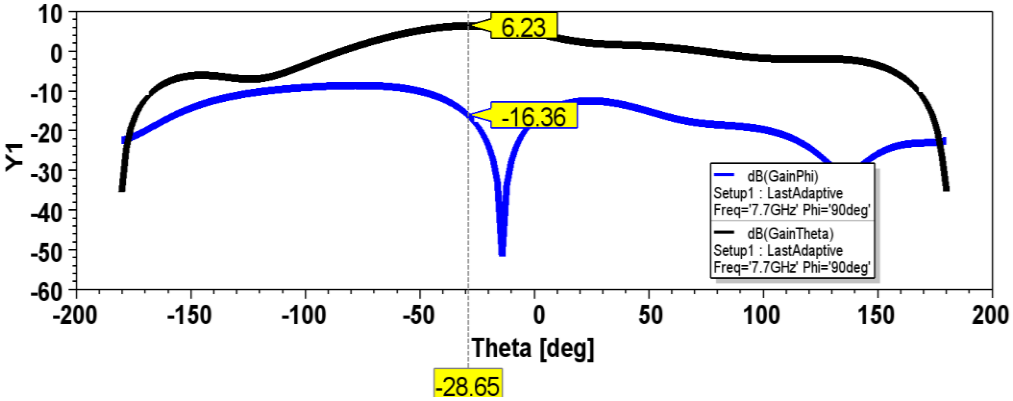


Fig. 4.14: Gain Theta and Gain Phi for 1200 G

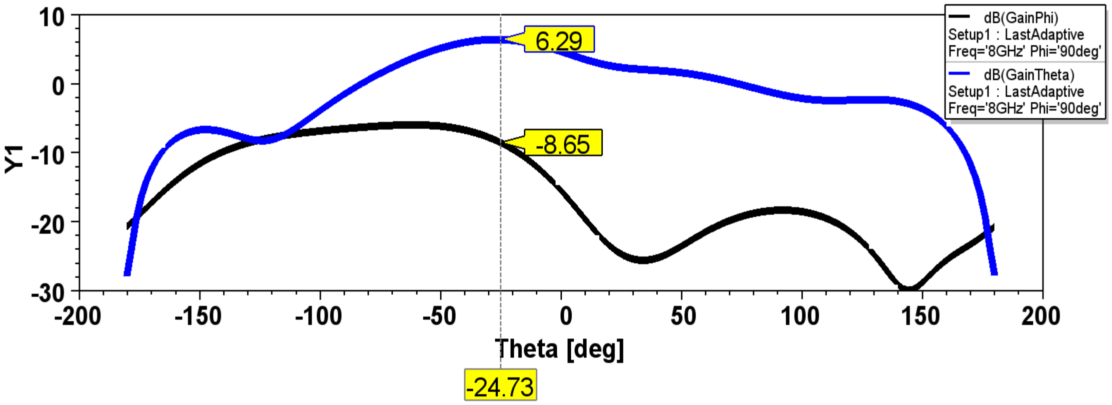


Fig. 4.15: Gain Theta and Gain Phi for 1600 G

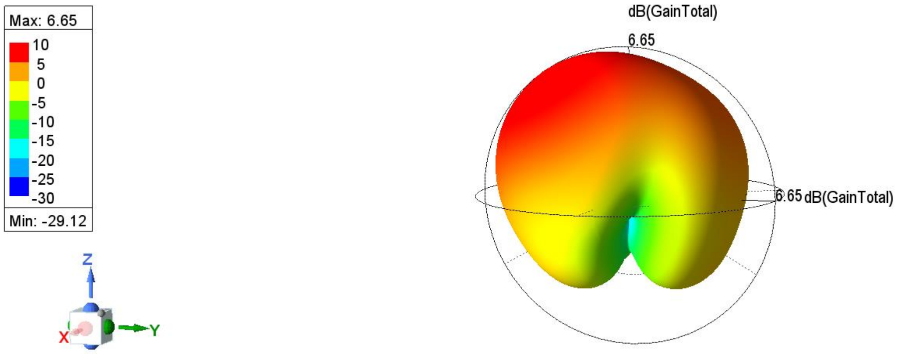


Fig. 4.16: Radiation of the antenna when only Diode 2 is ON

4.5 Validation of Results

The simulation results of the two linear polarizations, that is, polarization along the x-axis (PIN Diode-1 is ON) and polarization along the y-axis (PIN Diode-2 is ON), have been verified by the theory that has been explained in [32]. One can see the similarity between the trend of theory and simulation results. Simulated results show good agreement with the theory. This gives us confidence about our results. Fig. 4.17 shows the results

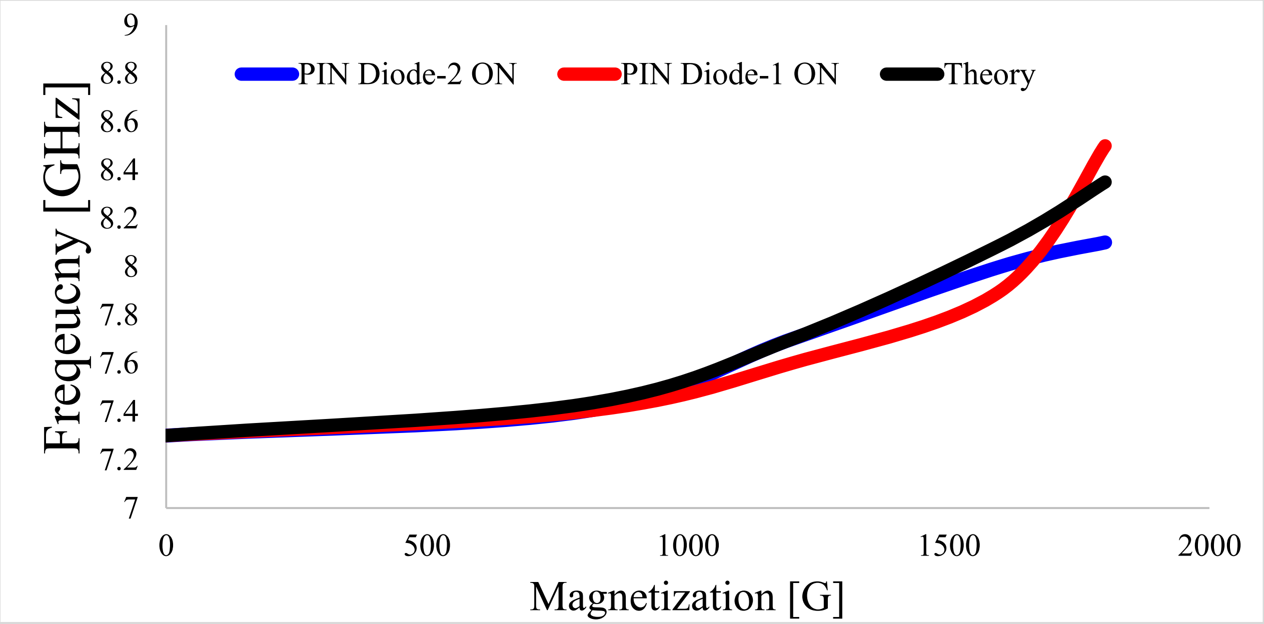


Fig. 4.17: Validation of two Linear Polarizations results [10]

4.6 Conclusion

In this chapter frequency tuning for the three different cases of polarization are discussed using a magnetic stimulus. As the applied magnetic field strength around the substrate is changed, its magnetization changes causing a tuning in the center frequency of the antenna. From this study it is seen that for all three cases, as the magnetization of the substrate increases, the center frequency of the antenna moves in the higher frequency band. Around 1 GHz of tuning has been achieved for each of three cases and the radiation properties of the antenna are well maintained as the frequency is changed. Thus, the antenna system is shown to provide both frequency as well as polarization reconfigurability by combining the use of PIN diodes on a magnetic substrate.

Chapter 5

Conclusion and Future Work

5.1 Conclusion

Incorporating low-cost, small, and agile radio frequency (RF) components is crucial for the development of current wireless applications. This thesis presents one such smart antenna design that can meet the requirements of one such application in the form of radiation pattern reconfigurability. This thesis proposes a unique reconfigurability, that is frequency tunability and polarization reconfigurability on a microstrip patch antenna.

The final optimized antenna design has a patch antenna on magnetic substrate with integrated diodes along the feed of each antenna. Antenna design show circular polarization, linear polarization along x-axis and linear polarization along y-axis. For frequency tuning, around 1 GHz of tuning achieved. Gain of the antenna is also close to $6\ dBi$ or more. Furthermore, axial ratio and radiation pattern is also check in all three cases.

As for next step, the same design is used as an array. Reconfigurable arrays are useful for beamforming as well as for high gain.

5.2 Future Work

The work presented in this thesis can be used to create a wide range of modifications, tests, and experiments. But the first and most obvious step forward is to actually implement the suggested antenna designs and evaluate their radiation as well as impedance characteristics. This will require fabrication of the antenna using YIG substrate. For this purpose, some facilities that can handly such a design with the ability to integrate active components would be contacted. Following the fabrication, one would like to test the proposed design for its impedance and radiation characteristics. It should be kept in mind that the testing of this antenna is more challenging compared to ordinary antenna front ends. This is due to the need of DC biasing for the PIN diodes as well as the magnetic biasing for the substrate. Moreover, the DC biasing needs to be isolated from the RF excitation by proper use of DC block and RF choke circuitry. Therefore, a study would be needed to see their effect on the antenna performance. However, at 7 GHz, this effect could be easily mitigated.

Once this design has been tested for its own performance, new antenna topologies such as leaky wave and other traveling wave antennas can be explored using the same concept. With this class of antennas, the benefit of modulating wave propagation with the PIN diodes can bear even fruitful results. Especially for the avenue of beam steering which has not been explored in this study could be ventured on by employing the combination of PIN diodes and magnetic substrate for a leaky wave antenna. This is one of the examples that can be studied under this domain, however, this filed is quite open for other antennas to be explored under this concept.

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