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Design and Experimental Validation of a Polarization-agile Microstrip Antennas with truncated corners for RF Glucose Monitoring Applications

Sneha Shrikant Salvekar[1*], Rajesh Ghongade[2]

[1*]Department of Electronics, Bharati Vidyapeeth College of Engineering (BVPDU), Pune, India, E-mail: sneha.salvekar88@gmail.com
[2]Department of Electronics, Bharati Vidyapeeth College of Engineering (BVPDU), Pune, India

ABSTRACT
Polarization-agile reconfigurable antenna: can dynamically adjust its polarization state to fit application needs. In the proposed research, this concept is applied to a 5.8 GHz microstrip patch antenna intended for non-invasive RF-based blood glucose monitoring. Using carefully positioned copper strip perturbations, the antenna is intended to alternate between linear polarization (vertical and horizontal) and circular polarization (left-hand circular polarization (LHCP) and right-hand circular polarization (RHCP)). This reconfigurability enables improved interaction with human tissue, enhancing sensitivity to dielectric variations caused by changes in blood glucose levels. Existing Polarization-agile antenna structures were analysed, and a prototype microstrip patch antenna capable of quad-polarization states was designed and simulated at 5.8 GHz. The antenna's performance was verified in terms of return loss (S11), polarization agility, and axial ratio. Various design methodologies for achieving polarization reconfigurability including slot perturbation, truncated corners, and switchable strip loading were studied and implemented to optimize impedance matching and polarization purity. Two antenna structures, operating on the same reconfiguration principle as the prototype, were designed to enhance sensing performance. The modifications primarily focused on improving return loss and axial ratio stability within the ISM 5.8 GHz band. Fabricated antennas were experimentally tested with a Vector Network Analyzer (VNA) and the experimental result were in good agreement with the simulated result. Antenna Structure-2 among the tested showed utmost good impedance matching with return loss of −28 dB at 5.8 GHz, which enhanced the sensitivity for biomedical sensing applications.

Keywords: Polarization-agile antenna; Reconfigurable microstrip patch; Circular and linear polarization; RF biomedical sensing; Non-invasive blood glucose monitoring.

Introduction

One of the most crucial elements of contemporary wireless communication systems is polarization-agile reconfigurable antennas. These antennas are such that many problems which are arisen due to rapidly increasing users that has resulted in over occupancy of the spectrum and increasing interference. The operating polarization states can be alternated using these Polarization-agile reconfigurable antennas by switching their polarization sense between the four polarization states namely- Left-hand circular (LHCP), right-hand circular (RHCP), linear vertical, and linear horizontal polarizations [1]. A novel reconfigurable microstrip patch antenna was recorded in [2] in 2012, that can switch polarization states within all four operating polarization states. The design consists of a square patch antenna whose corners are truncated such that slots are created on two diagonally opposite corners. Two orthogonal ports are used to feed this antenna. Every slot is equipped with a diode, and the polarization switching between all four states is accomplished by manipulating PIN diodes and utilizing various feed ports.

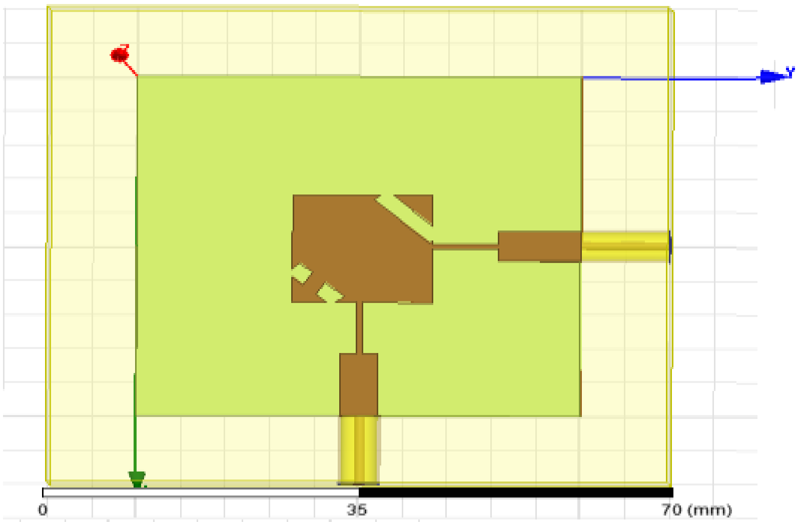
A method of reconfiguring antenna characteristics using PIN diodes was recorded in [5]. It proposed that cognitive radios seem to provide a solution to the problem produced due to the rapidly increasing wireless applications that result in over occupancy of the spectrum and congestion of the spectrum and increase of interference. Cognitive radios need agile components and so it is necessary to make antennas agile and reconfigurable. Such three antennas are suggested in [same as above], which consist of PIN diodes for achieving reconfigurability in frequency, radiation pattern and polarization states.

Another polarization states switchable antenna was proposed in [3] in 2012. It is possible to switch between LHCP and RHCP, as well as vertical and horizontal in linear polarization. Two perturbation elements of the ground plane loop slots ignited the circular polarization waves. Each slot had a PIN diode installed to change the direction of the current, which would subsequently reveal the polarization state.

Antenna Design and Simulation

The proposed Polarization-agile reconfigurable antennas discussed in this paper are a modification of the antenna proposed in [2] to obtain improvement in return loss and axial ratio. The operation mechanism of the above proposed antennas is same as that of the prototype antenna in [2] which is a reconfigurable microstrip antenna with two orthogonal modes (TM01 mode for vertical polarization wave and TM10 mode for horizontal polarization wave) and four quadric-polarization states. These waves will be created when the patch antenna is fed at the center of two neighboring sides of the patch. If the patch is fed from the horizontal and the vertical, then right-hand circular polarized (RHCP) and left-hand circular polarized (LHCP) waves are produced, respectively. The PIN diode switches are integrated on the slots between the chopped corners and with the help of the diodes 4 polarization states can be achieved. The corners can be cut off and will form isolated regions, so capacitors can be avoided. In order to minimize the effects of direct currents on microwave signals, a quarter waveguide length shorting line has been used at each of the four corners that has been cut. The prototype antenna was such that the return loss coefficient of the antenna for both the polarizations were -23 dB and -26 dB corresponding to their resonant frequencies of 5.795GHz and 5.785 GHz respectively. The measured -10 dB S11 bandwidth for the linearly polarization state was about 150 MHz and the measured gain was 7 dB. The operating principle of the proposed antennas is the same as that of the prototype antenna, however, to utilize the available substrate for fabrication, and to enhance its return loss and axial ratio, the antenna design parameters are and the dimensions for ease of feeding are .

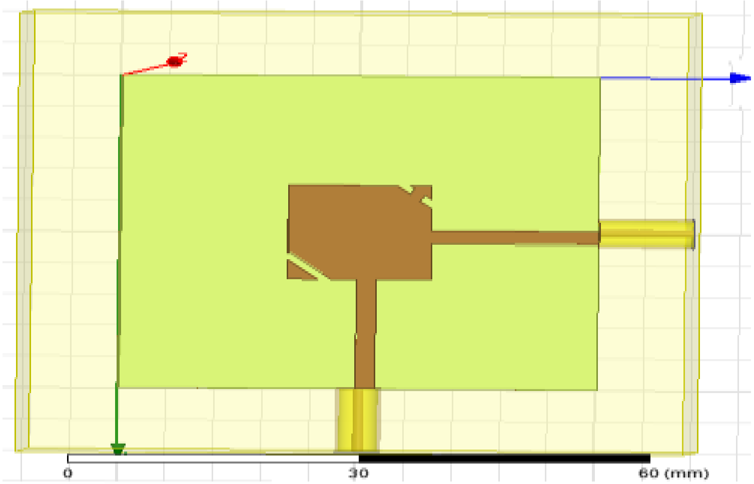
Polarization-agile reconfigurable antenna structure-1 when both strips are present simulated in Ansoft's HFSS 13.



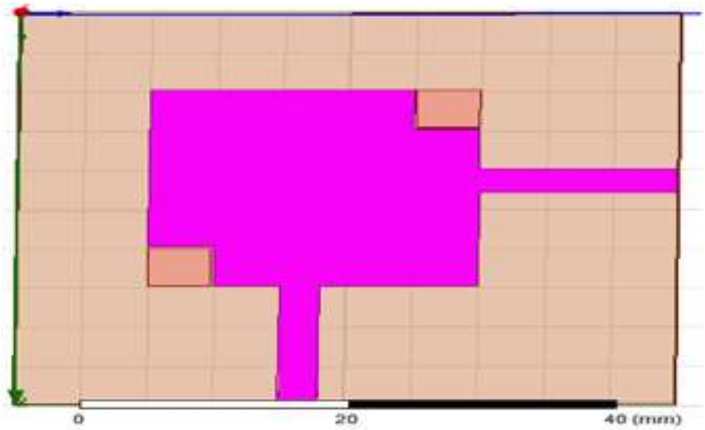
Polarization-agile reconfigurable antenna structure-1 with left strip is present simulated in Ansoft's HFSS 13.

The Polarization-agile reconfigurable antenna structure-1's geometric structure is depicted in Figure 1. Ansoft HFSS 13 simulates the antenna.As shown in the figure 1, instead of diodes, copper strips are used and to show the three states of diodes three different patches are simulated and fabricated. The antenna in figures 1 illustrates a state when both the strips are present. Linear vertical polarization results from feeding the antenna through a vertical port, while linear horizontal polarization results from feeding the antenna through a horizontal port.

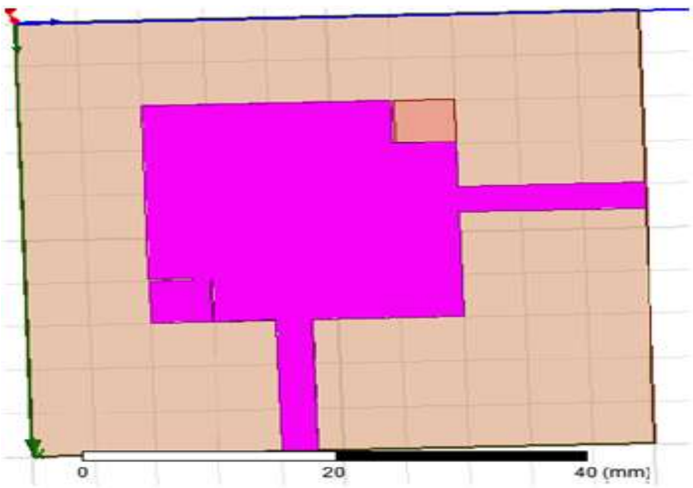
As shown in figure 3 the strip adjacent to the vertical port is not connected and the strip adjacent to horizontal port is connected, in such a case, LHCP is obtained. It is also observed that if both the diodes are OFF and if the antenna is fed through horizontal port even then LHCP is obtained. Figure 4 shows the structure-2 where, instead of cutting the corners two equal square corners are sliced and using similar concept as structure-1, they are attached and detached to obtain circular and linear polarization states[6][7]. Figure 5 shows a condition when left corner is attached to the main patch. At this instant the antenna when fed in vertical direction it will observe circular polarization i.e. LHCP.



Polarization-agile reconfigurable antenna structure-1 when right strip is present simulated in Ansoft's HFSS 13.for structure-2

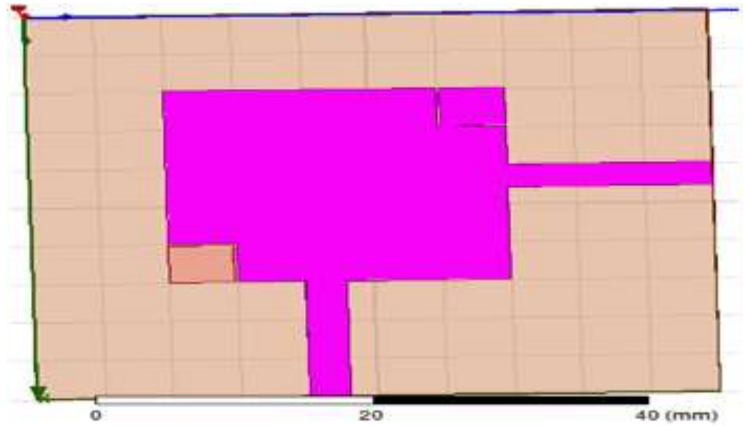


Polarization-agile reconfigurable antenna structure-2 when corners are sliced and detached, simulated in Ansoft's HFSS 13.

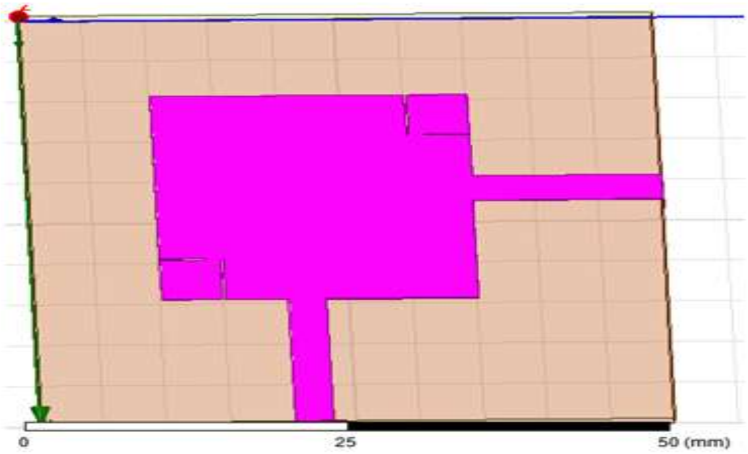


Polarization-agile reconfigurable antenna structure-2 when left strip is connected, simulated in Ansoft's HFSS 13.

Figure 6 shows the condition when right strip is associated to the main patch. At this instant the antenna gives RHCP when fed horizontally. Moreover, in figure 7 it is shown that both the sliced corners are attached to the main patch with copper strip, at these instant linear polarizations are observed namely as; vertical polarization when antenna is fed vertically and horizontal when antenna is fed horizontally. The design specifications and relative mathematical equations are discussed in next subsection. Moreover, in figure 7 it is shown that both the sliced corners are attached to the main patch with copper strip, at these instant linear polarizations are observed namely as; vertical polarization when antenna is fed vertically and horizontal when antenna is fed horizontally.



Polarization-agile reconfigurable antenna structure-2 when right strip is connected, simulated in Ansoft's HFSS 13.



Polarization-agile reconfigurable antenna structure-2 when both strips are connected, simulated in Ansoft's HFSS 13.

The design specifications and relative mathematical equations are discussed in next subsection.

Design Specifications and Calculations

The polarization agile antenna structure-1 has specifications as; Centre frequency f is 5.87GHz, substrate length and width is 51mm respectively, height h is 1.56mm, patch length L and width W is15.785mm respectively, feed strip width is 2mm, feed strip length is 17.6mm, truncated corners, width is 1 mm, Diode strip width is 1.5mm Diode strip length l is 2mm, dielectric constant εr is 4.4. The FR4 epoxy is selected as the substrate due to its local availability. The formulae used for calculating the above parameters are taken from [4] and are given bellow. For calculating effective dielectric constant (εeff) equation 1 is used:

$$\varepsilon_{\text{eff}} = \frac{\varepsilon_r + 1}{2} + \frac{\varepsilon_r - 1}{2}\left[1 + \frac{12h}{W}\right]^{-\frac{1}{2}} \qquad (1)$$

Where, La is actual length of the patch and ΔL is extension in length but the antenna being a square patch antenna length and width are taken same. The specifications of Polarization-agile reconfigurable antenna 2 are:

Centre frequency (fr) is 5.8 GHz, substrate length is 24.269 mm and width is 25.73 mm, height (h) is 1.6 mm, patch length (L) and width (w) is 15.73 mm respectively, feed strip width is 2.95 mm, feed strip length is 5mm, truncated corners squares are 4.8 mm X 4.8 mm, gap is 0.2 mm and dielectric constant (εr) is 4.4. The FR4 epoxy is selected as the substrate due to its local availability. These values are also calculated using equations 1, 2, 3 and 4. Simulation results are discussed in the next subsection.

For calculating width equation 2 is used:

$$W = \frac{1}{2 f_r \sqrt{\mu_0 \varepsilon_0}} \qquad (2)$$

For calculating length equation 3 and 4 is used:

$$L = L_a + 2\Delta L \qquad (3)$$

$$\Delta L = \frac{(\varepsilon_{eff} + 0.3)(\frac{W}{h} + 0.264)}{(\varepsilon_{eff} - 0.258)(\frac{W}{h} + 0.8)} \qquad (4)$$

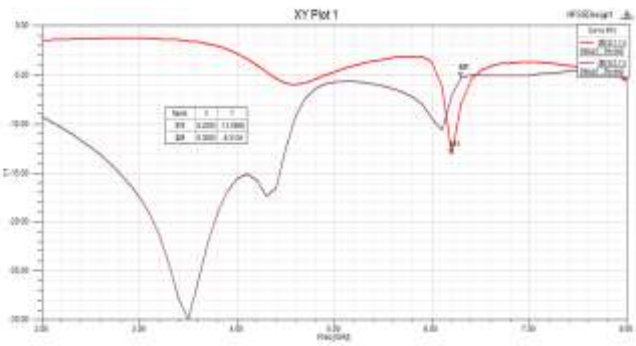
Where, La is actual length of the patch and ΔL is extension in length but the antenna being a square patch antenna length and width are taken same. Designed antenna is simulated in Ansoft's HFSS (v13). The following subsection discusses the simulation findings for both structures.

Simulated and Measured Results of Antennas

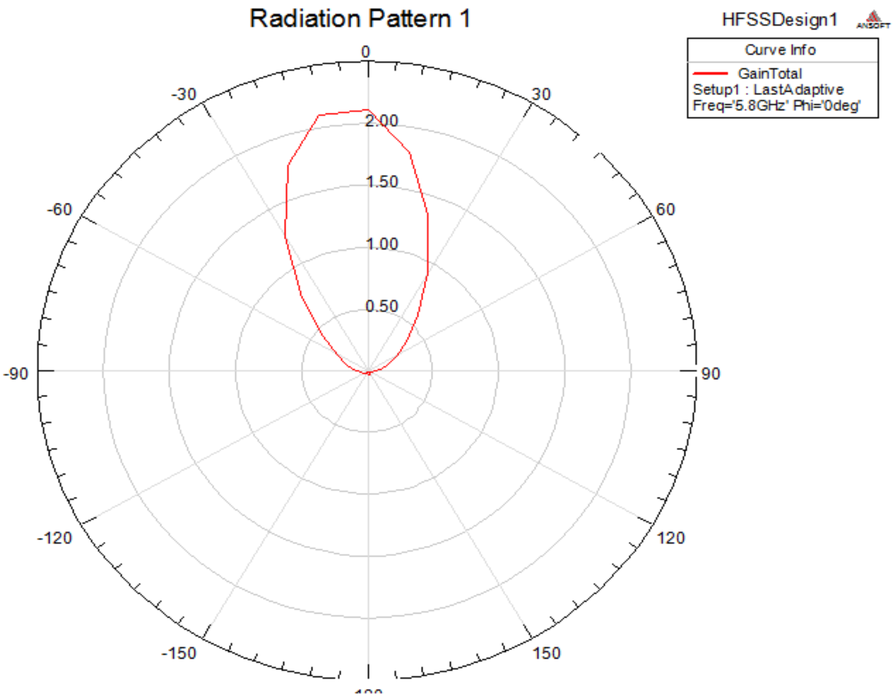
COMPARISON OF SIMULATED AND MEASURED RESULTS

Structure	Left Strip	Right Strip	Simulated	Measured
			S11 (dB)	S11 (dB)
Antenna 1 Frequency 5.8GHz	Off	Off	-13.82	-23.75
	Off	On	-13.065	-16.15
	On	Off	-18.00	-24.75
	On	On	-18.23	-21.23
Antenna 2 Frequency 5.8 GHz	Off	Off	-28.02	-13.27
	Off	On	-14.9	-18.46
	On	Off	-24.11	-16.69
	On	On	-10.81	-18.87

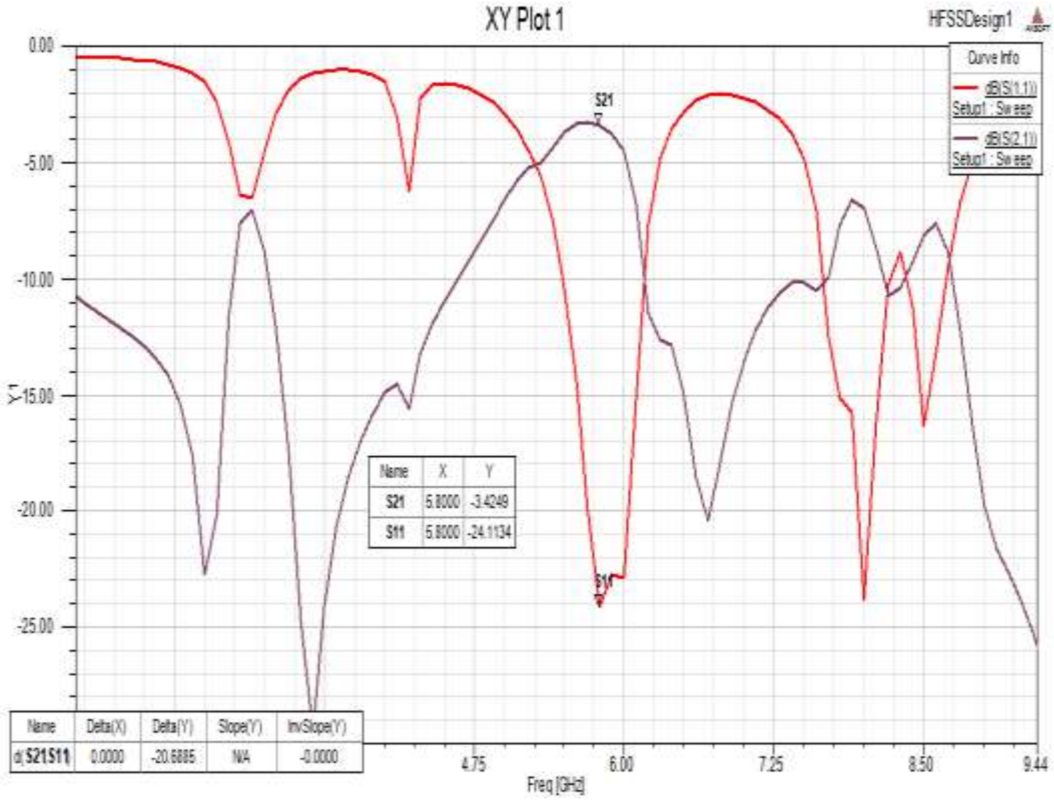
This section presents the Polarization-agile reconfigurable antennas simulation and results. The simulated and measured results of the polarisation-agile reconfigurable antennas are compared in Table 1. The computed and measured findings at 5.8 GHz are found to be in good agreement for both structures 1 and 2.



S11 and S21 parameters of Polarization-agile reconfigurable antenna simulated in Ansoft HFSS 13 for structure 1.



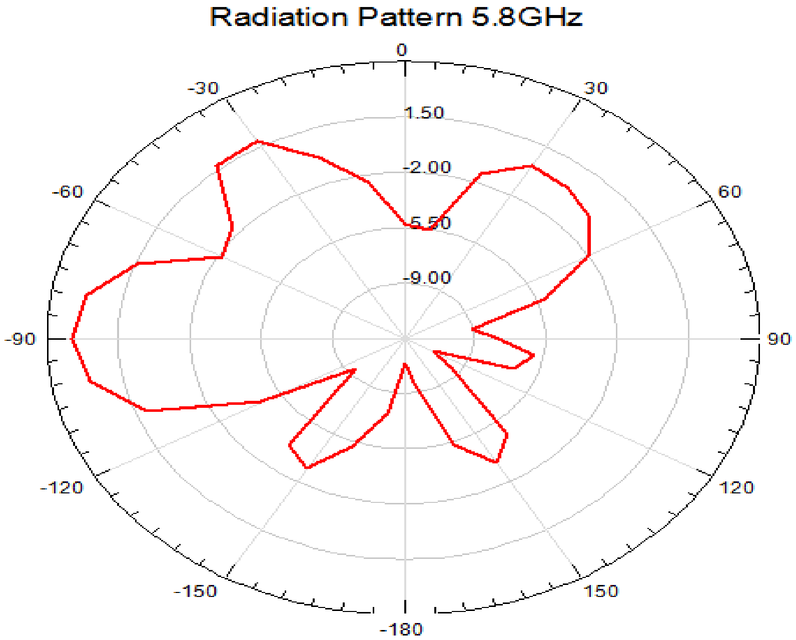
Radiation pattern of Polarization-agile reconfigurable antenna simulated in Ansoft HFSS 13 for structure 1.



S11 and S21 parameters of Polarization-agile reconfigurable antenna structure-2 simulated in Ansoft HFSS 13 for structure 2.

When both the strips are connected linear polarization is observed, it is seen that S11 is less than other two cases. The axial ratio is in tolerable range for all three cases since it should be 3 to 6 dB according to literature [2].

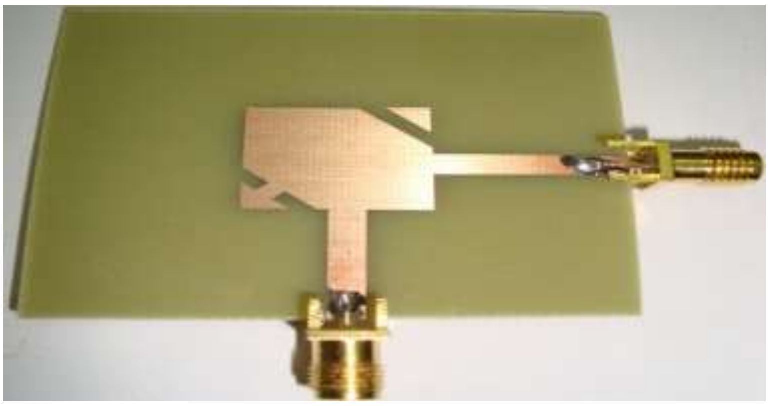
The simulated results of S11 and S21 parameters for structure-1 and structure-2 are revealed in figure 8 and 10 respectively and the radiation pattern obtained is shown in figure 9 and 11, respectively. Also, the structure-2 has better return loss than structure-1. In the next section the fabricated antennas are discussed along with their photographs.



Radiation pattern of Polarization-agile reconfigurable antenna simulated in Ansoft HFSS 13 structure 2.

Fabricated Antennas

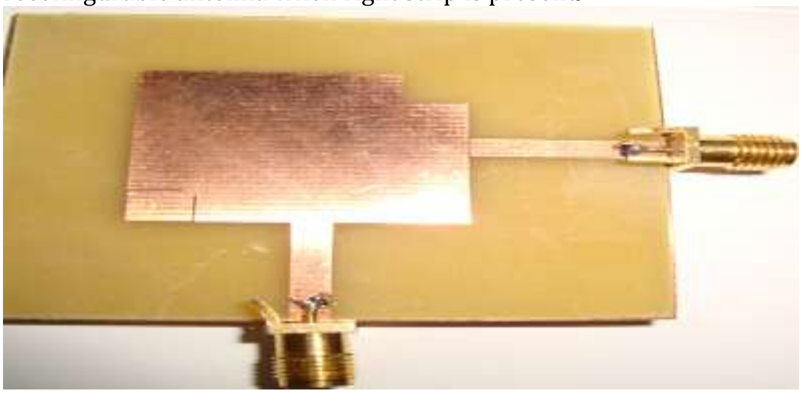
The antennas are fabricated from, by using copper itched technique. The Ansoft HFSS (v13) file is mapped into CorelDraw file. Photographs of fabricated antenna structure-1 and 2 with all the cases are shown in figures 12, 13 and 14(Structure-1), 15, and 16 (Structure-2) respectively. This file is then directly printed on a transparency and



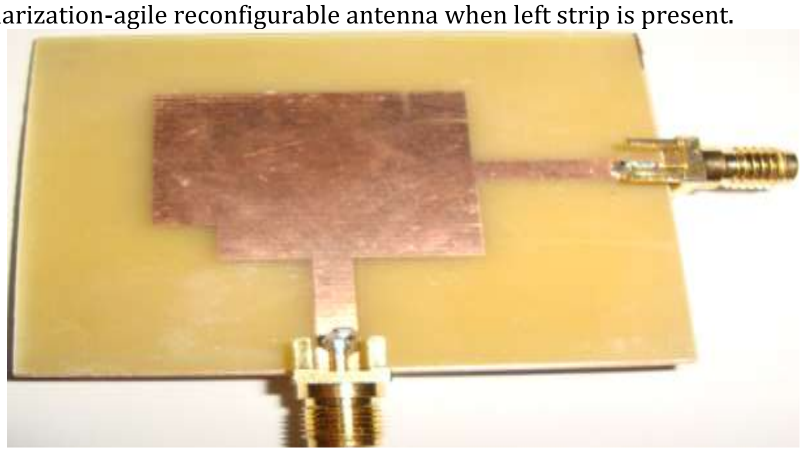
inserted in the copper itching machine. Then SMA ports of desired dimensions are then soldered to the fabricated antennas. These antennas can be reconfigured for getting best possible penetration for measurement of blood glucose levels. If one port is fed using a VNA with 10 dBm power and other is closed with matched load then the same can be used for linear polarization as well. These structures can be efficiently used for monitoring of blood glucose levels non-invasively

Photograph of Polarization-agile reconfigurable antenna when both strips are present.

Photograph of Polarization-agile reconfigurable antenna when right strip is present. Photograph of Polarization-agile reconfigurable antenna when right strip is present.



Photograph of Polarization-agile reconfigurable antenna when left strip is present.



Photograph of Polarization-agile reconfigurable antenna when right strip is present.

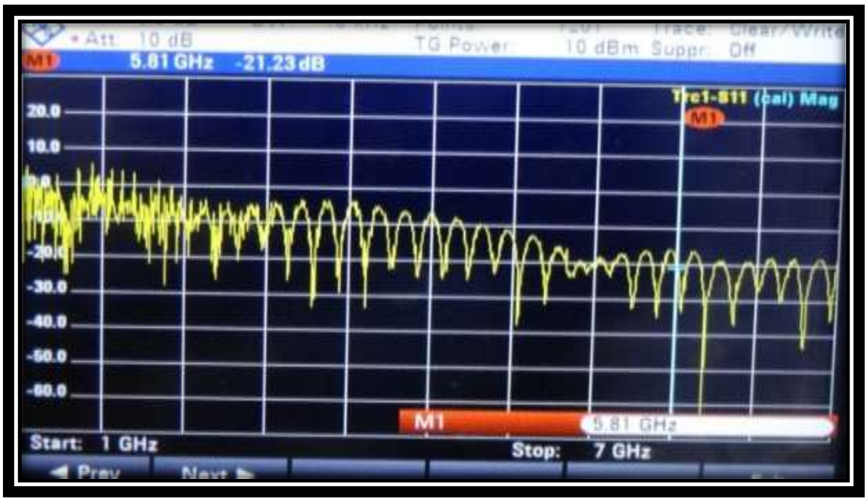
Figures 13–16 present different structural configurations of polarization-agile reconfigurable antennas, highlighting the role of geometric modification in achieving polarization diversity. In all these antenna designs, the corners of the radiating patch are intentionally truncated. This truncation is a commonly adopted approach to modify the surface current distribution on the patch, exciting two orthogonal resonant modes. Nearly equal amplitude and a phase alteration of about 90° between these modes, creates circular polarization. By judiciously choosing the size of the truncation, the antenna can be designed to be LHCP or RHCP.

In addition, the antenna corners have been cut off, which can further improve its polarization agility when used with polarization reconfigurable components like PIN diodes, RF switches, or varactor diodes. These switching components can change the effective current path and electrical length of the antenna which can dynamically change the polarization state. In this way, the antenna can be switched from linear polarization to circular polarization or from LHCP to RHCP (vice versa). This flexibility enhances the signal reliability in wireless communication systems and also minimizes polarization mismatch losses.

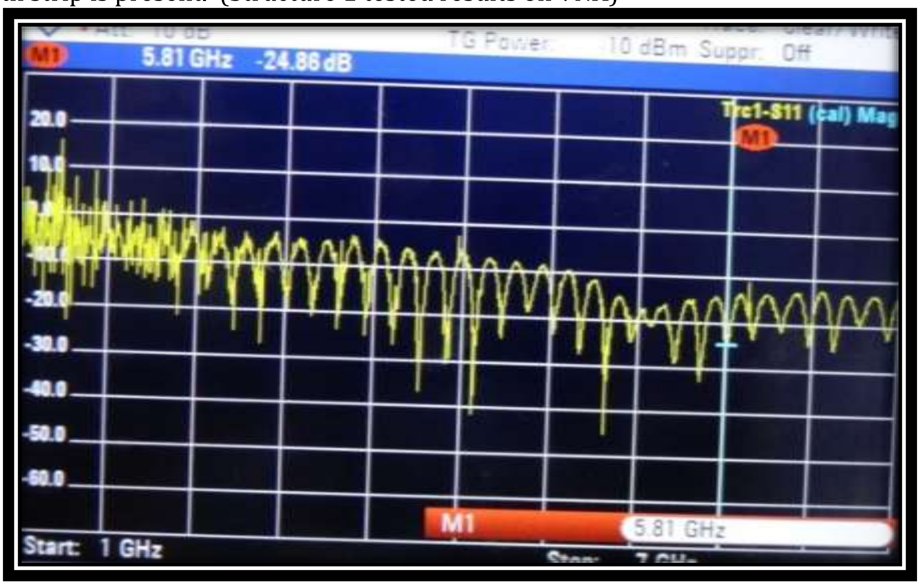
Besides, it is beneficial to corner truncation for steady radiation properties and good impedance matching without compromising compactness. The different truncation patterns and switching arrangements depicted in Figures 13–16 illustrate the different ways in which these structures can be varied to obtain an efficient polarization reconfiguration. The designs are especially convenient for modern wireless and biomedical sensing applications where adaptive polarization can increase the capability of the signal to penetrate the medium, reduce multipath fading, and enhance system performance. With the capability of dynamically controlling the polarization, such antennas are highly suitable for advanced communication systems, satellite links, and biomedical monitoring systems using microwaves.

Testing & Analysis

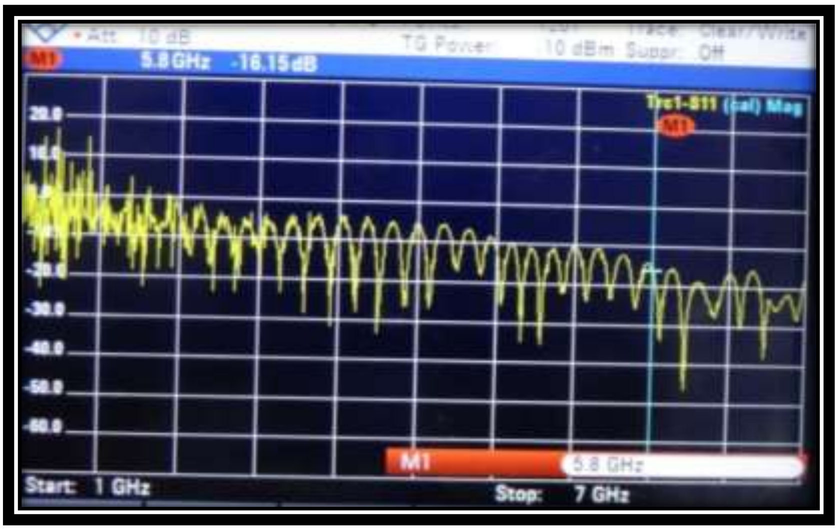
The fabricated reconfigurable antenna has been experimentally verified in order to assess the antenna performance for biomedical sensing applications. The antenna attributes were first measured in free space conditions such as radiation pattern by the calibrated VNA, impedance bandwidth, gain, and reflection coefficient (S11).The design of the antenna was optimized to be around 5.8 GHz, and the reconfigurable states were verified by switching the embedded PIN diode network. For each switching state, the frequency shift, polarization (if any) and stability of resonance were verified. On-body measurements were performed near the human wrist region keeping the separation distance between the human body and the antenna constant for biomedical evaluation. S11 changes, for various test conditions, were measured and several measurements were averaged to minimize random variations. Human tissue was found to shift the resonances and change the amplitude and this was observed, thus confirming the sensitivity to changes in permittivity due to the "dielectric loading effect". Transmitted power levels were limited within the normal ISM band limits and exposure duration was controlled to ensure safety compliance. The repeatability and stability of the signals were evaluated by conducting repeated trials with the same positioning. For the measurement consistency, statistical analysis was done and the mean deviation and standard deviation of resonance frequency shift were calculated.



S11 when both strip is present. (Structure 1 tested results on VNA)

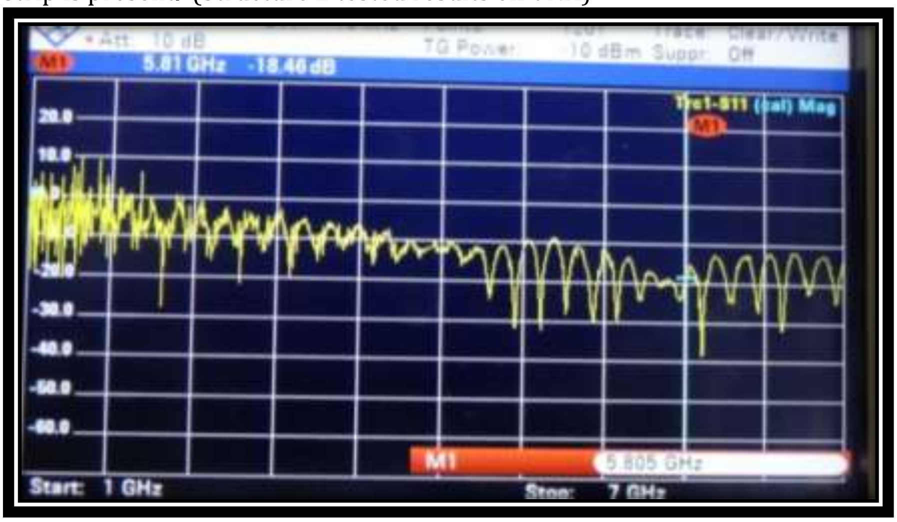


S11 when left strip is present. (Structure 1 tested results on VNA)



S11 when right strip is present. (Structure 1 tested results on VNA)

S11 when left strip is present. (Structure 2 tested results on VNA)



S11 when right strip is present. (Structure 2 tested results on VNA)

In addition, comparative analysis between free-space and on-body states demonstrated the antenna's capability to detect dielectric variations caused by biological tissue. These results validate the feasibility of the proposed reconfigurable antenna for non-invasive biomedical sensing applications.

Conclusion and future scope

The truncated corners are playing an important role about obtaining the circular polarization and retaining linear polarization, when these corners are not connected to the main patch we can have circular polarization and when these corners are attached with the help of copper strips we can have linear polarizations also. Thus with the help of these strips we can switch the polarization states of the antenna into all four polarization states is validated. The antenna thus remains agile but can be made reconfigurable also. Reconfigurability being very necessary criteria this antenna can be used to achieve the need for polarization diversity. It is discovered that the simulated and measured findings agree well, and the antenna structure-2 shows improvement in return loss as compared to the antenna structure-1, i.e. the return loss is reduced to -28dB at 5.8GHz for structure-2In further contributions if PIN diode is used in place of strips a single antenna can be incredibly effective in contemporary wireless communication systems. Additionally, such reconfigurable antennas with polarization agility if formed into an array a very versatile system can be obtained which can help make the modern wireless communication systems more efficient.

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