An Inset-Feed On-Chip Frequency Reconfigurable Patch Antenna Design with High Tuning Efficiency and Compatible Radome Structure for Broadband Wireless Applications

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ABSTRACT- A novel, dual edge-shaped frequency reconfigurable antenna with a highly compact size is proposed, using microstrip line-based inset-feed mechanism. Proposed antenna uses cost-effective ROGER substrate of 0.787 mm thickness. The tuning reconfigurability has been achieved using two PIN diode switches, placed on the patch surface. The On-Off switching combinations of the PIN diodes provide variations in the current distribution and thereby altering the resonant frequencies. The proposed antenna offers the resonating spectrum in the range of 3 GHz to 9 GHz approximately, with maximum tuning efficiency of 43% at 6.5 GHz, covering majority of modern RF standards. The proposed patch antenna design radiates with a reasonably high gain of 2.3 dBi at 5.04 GHz, with effective bandwidth of 2800 MHz (maximum at 6.5 GHz). The proposed multiband antenna with radome structure (ABS material) has been investigated under high-frequency simulation environment of HPEEsof (ADS- Keysight Technologies) and 3d radiation pattern (far-field gain, directivity and power calculations) have been obtained using momentum and EMDS. The final implementation size (without radome structure) comes as 23 mm x 26 mm large (595 mm²). The proposed design paves the way for wireless applications including WLAN and WiMAX communication with its uniform far-field radiation pattern.

Keywords- Microstrip, PIN diodes, patch, radiation pattern, Reconfigurable, Bandwidth

1. INTRODUCTION

With the rapid increase in modern RF Integrated Circuits in the recent wireless systems, a compatible and reconfigurable wideband antenna solutions are being sought very frequently. A key design challenge is to choose the right antenna according to the specific applications. Power efficiency and Impedance bandwidth are the most important parameters, which an RF engineer would like to work upon. The exponential increase in the demand of internet of things and brilliant modern applications impose the numerous scientific and engineering challenges that require smart research efforts from both academia and industry to improve efficiency, cost-effective, scalable and reliable IoT antenna systems. Antenna systems are used to essentially improve the field of IoT and in numerous applications corresponding remote sensing, satellite communication, navigation systems, GPS etc. In most of the modern wireless systems, the conventional practice of usage of multi-antenna patches for wider and multi-band coverage has been avoided. Instead, the radiation spectrum reconfigurability has been envisaged and adopted by multi-band reconfigurable antenna design, which is able to resonate at multiple desired frequencies. In addition to the compactness in die-size, this also helps in reducing the overall cost of the RF-front end system on a chip or SoC. The major design effort in enhanced bandwidth (broader spectrum) and multi-
band reconfigurability of the patch antenna has also been considered in this work. The conceptual idea of a patch antenna based on microstrip-line concept, has been shown in Figure 1. The wider spectrum coverage has become an essential feature of the modern communication systems due to the high data rates and other emerging trends in wireless standards. These modern wireless standards demand for the reconfigurability of the antenna for their diverse applications and coverage range. This is in addition to the reduction in simultaneous demand of bandwidth coverage in cellular application with the extensive inception of spread-spectrum signals and bandwidth efficient modulation techniques. The recent trends and techniques of wireless tuning to the cellular bands therefore is to avoid the simultaneous application coverage. One side where it necessitates the frequency reconfigurability, the functionality of patch antenna is improved by keeping the size small and less complicated (important geometries shown in Figure 1). Frequency reconfigurable patch antennas therefore hold certain other necessary constraints to characterize itself as compact size, compatibility to the analog-RF front end systems and quick hopping between resonating bands. These features let them to serve efficiently in maximum modern wireless communication systems.

Different modern techniques for reconfiguration have been illustrated by Shakhirul et al. [1]. A comprehensive and detailed review regarding microstrip reconfigurable antennas has been provided, with a subjective discussion of the pros and cons of their wideband applications have also been discussed. The work offered by Shakhirul also entails the switching behavior of the RF switches and incorporates the efforts to enhance their switching characteristic at different frequency bands. The frequency reconfigurability using the change of operative length of the patch antenna is covered by most of the researchers and in their corresponding articles. Several researchers have attained frequency reconfiguration by changing the operative length of the antenna by removing or adding part of its length by using various approaches, such as varactors or variable capacitors. A work by Rahman M. et al. [2] reports the incorporation of a varactor in the patch design and thereby enhancing the bandwidth to a greater extent. The surface currents are redirected by varactor diodes, which ultimately brings in the frequency modulation with capacitive variation. A similar approach has been reported in the work by Li. T., Zhai H., Li, L. Liang [3]. In some other similar works, a high degree of impedance matching has been achieved in the spectrum of 890 MHz to 1500 MHz. Several other articles show that the designed antenna proves its compromising abilities to incorporate the 50 Ω impedance [4, 5]. Antenna shows a promising performance as the multiple smaller patches are connected using varactors which offers ease of switching between multiple polarization offered by the work, frequency tuning, and phase shifting also. Korosec et al. [5] also, presented a different multi-sub patch microstrip antenna loaded with varactors for solving the reconfiguration problem. In addition to the frequent usage of PIN and varactor devices, RF MEMS offer a domain for high Q tuning performance along with low losses in the wideband applications [6]. Amongst these switching techniques, the performance of PIN diodes is very consistent and compact as they tend to increase switching speeds and decrease resistive capacitance in both states, i.e., ON and OFF. The slot lengths are also switched particularly in the CPW fed antenna and folded slot antenna to change the resonant frequency as a reconfigurable phenomenon. One such approach has been presented by N. Trong et al. [7]. Considering the conventional integration of heterogeneous front-end wireless systems, multichip module and system in- package (SiP) solutions can suffer from large antenna size [8]. Furthermore, an in-
package antenna flip-chipped on the transceiver module substantially increases its packaging cost [9, 10]. Also, package integration becomes more challenging due to the increasingly lossy interconnects, such as wire-bonds and solder bumps [8]. As an alternative to SiP, a system-on-chip (SoC) approach integrates the complete RF front-end and an on-chip antenna directly on the same silicon die in a so-called antenna-on-chip (AoC), thereby avoiding lossy interconnections. Besides, compared to AiP, AoC reduces the reliability dependence on manufacturing precision [11]. The SoC advancement and applications in modern VLSI solutions have invited more and more antenna applications to higher spectrum and Q-band on-chip antennas with high gain and wideband have resulted due to these efforts. The substrate of high resistivity and low dielectric constant reduces the losses by minimizing the radiation and current leakage to the other on-chip components for a patch antenna implementation. In a work [12], a major effort has been kept to improve the antenna gain (achieving around -1.8 dBi), by employing a high resistivity silicon substrate in association with CMOS-SOI (silicon on insulator) technology. Another effort [13] has been placed to associate an off-chip dielectric resonator with a high permittivity, by placing it on the top of the chip. An H-slot has been designed and implemented to excite that dielectric resonator, which finally resulted in the antenna gain of 1 dBi (closed to what expected in simulation). On the other side, a triangular patch antenna has been designed and implemented [14], to serve to the Q-LINKPAN standards. Its implementation in the standard CMOS process and approximate gain of 1.5 dBi (at central frequency of 45 GHz, in simulations) makes it quite reasonable and market ready for the spectrum range of 40-50 GHz applications. In a very recent attempt [15], a monolithic on-chip antenna is designed and optimized with back-end-of-the-line (BEoL) challenges of the nanoscale technology for 5G applications, using mm-wave. The high radiation efficiency of 37.3 % and power gain of 9.8 dB has been achieved with the use of ground metallization on a PCB board which served as a reflector.

The compatibility of a microstrip based design line with the conventional CMOS technology implementation has been a major bottleneck since long. This perhaps been a strong reason due to which the developments of RF integrated circuits and especially the patch antenna designs have followed their own design routines using microstrip and high-k substrate based off-chip implementation [16]. Wherever possible, the CMOS integrity demands a greater effort towards combating the noise and signal attenuation, as has been explained in [16, 17], with the conventional design style of CMOS based low noise LNA circuit. The LNA design targets the application in the same spectrum range as that of the proposed patch antenna design in this presented work. A compact front end solution, demanded by 5G communication, adds on to this constraint of on-chip CMOS implementation of patch antenna. A recently published article [17] emphasizes this issue and offers a solution in nanoscale 28 nm-CMOS technology for millimeter-wave (mm-wave) applications. Due to its high mobility ratio and fast turn ON characteristic, PIN diode has been the most favorable RF switch for the frequency reconfigurable antennas sought today in modern wireless systems. Demonstration of the PIN diode based switchable microstrip patch antenna is presented in some recently published works [18, 19], for WLAN/WiMAX applications. The miniaturized dual band microstrip patch antenna array in [18] resonates at 2.2 GHz and 3.8 GHz, whereas a frequency-reconfigurability is obtained in [19] using six PIN diodes positioned symmetrically along the non-radiating edges. Both the works offer a highly compact solution, with stable and directional patterns obtained on a
single layer substrate. Another frequency reconfigurable work based on 0.18-μm CMOS SOI process [20], also presents an on-chip antenna solution for broadband characteristic. A bandwidth of -10 dB was obtained for Q-band operation (29.5 GHz to 51.0 GHz), by toggling the state of the on-chip switches.

A typical inset feed mechanism for better impedance matching is presented in the proposed work of this article. Two similar rectangular patches have been designed and are selectively shorted using PIN diode-based switches, to enhance the bandwidth of the proposed patch antenna design. The effective length of the radiating patch is moderated by changing the states of the two on-chip RF diode-based switches. The resonating spectrum of this whole patch antenna (along with the switches) shifts according to the effective length (i.e., according to the diodes’ states), and thereby the whole bandwidth of the proposed antenna changes. The selection of a reasonable gate width is also a considerable task as the resonating bandwidth and antenna gain depends upon the switches’ gate width. Design simulations have been performed to arrive on to optimum value of the gate widths. Section II describes the basic development and theoretical support behind the design one by one, starting from inset feed topology to on-chip PIN diode incorporation. The quantitative developments and calculations behind the integrated patch have been presented later in this section. Section III then briefly presents the reasoning behind selected radome structure and argues about the impact of its inclusion. Finally, section IV presents the actual design implementation along with high-frequency simulation setup and measurement results. It is shown that the proposed antenna has a favorable -10 dB impedance bandwidth from 3 to 9 GHz approximately in multiple-band segments. The tuning in those bands has been achieved by reconfigurability of the proposed design. A promising measured gain of -2.3 dBi at 5.12 GHz has been obtained in one of the tuned bandwidths. In addition to the above-mentioned features, a highly compact die size 595 mm² has been achieved.

2. INTEGRATED ON-CHIP ANTENNA DESIGN

The section demonstrates the complete patch antenna design with the proposed inset feed line. Both the structures are compatible with microstrip topology and implemented with a metal line of chosen specifications.

A. Inset feed design calculations

The feeding of antenna is as important as that of the patch design for that antenna, as feed design and insertion provision affects the overall performance characteristics of the antenna design, including the radiation pattern. Two conventionally used feeding mechanisms for the microstrip patch antenna are coaxial probing and inset microstrip line. Coaxial probe feeding is sometimes advantageous for applications like active antennas, while microstrip line feeding is suitable for developing high gain microstrip array antennas [15]. In both cases, the probe position or the inset length determines the input impedance. By using a straightforward transmission-line model, it is possible to accurately model and analyzes microstrip-line inset-fed patch antenna designs [15, 21]. For a 50-Ω input impedance, the calculations could be carried out to get exact inset length and location of feed joint at the patch, using the curve-fitting approach.
For a patch to work on the targeted range of spectrum chosen for the work (mm-wave applications of S and C bands), the design geometry of feed line has been calculated for a Roger substrate (ROGER 5880) of height $H$ (or $h$) = 0.787 mm and loss tangent ($\tan D$) of 0.0009. The copper has remained the choice of metal with a thickness of $T = 35 \mu m$. The Inset feed length is given as equation (1) for the conventional range of dielectric strength ($2 \leq \varepsilon_r \leq 10$):

$$y_o = 10^{-4} \left\{0.001699\varepsilon_r^7 + 0.1376\varepsilon_r^6 - 6.1783\varepsilon_r^5 + 93.187\varepsilon_r^4 - 682.69\varepsilon_r^3 + 2561.9\varepsilon_r^2 - 4043\varepsilon_r + 6697\right\}$$

(1)

The fringing effects, substrate imperfections and feeding leakages modify the understanding of the $\varepsilon_r$ presented in the equation (1), and hence the following equation presents a more practical value of effective dielectric strength ($\varepsilon_{eff}$) for the width of the proposed patch ($W$) higher than substrate height ($H$ or $h$):

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

(2)

Through an iterative manual calculation could lead to a feasible geometry solution for inset feed length and width, the line-calc (ADS) has been used for the geometry calculations, which inherently makes use of above equations. A roughly approximated patch line and width as 24 mm and 20 mm are envisaged to make the use of above equations in the calculator. This gives the effective dielectric strength ($\varepsilon_{eff}$) of value 2.095. The lowered value of $\varepsilon_{eff}$ below $\varepsilon_r$ accounts for the leakage through fringing and feeding imperfections and substrate anomalies. The exact calculations of $W$ and $L$ will be re-encapsulated in the upcoming subsections.

Using the above initial guesses for patch line and width along with modified dielectric strength in the line-calculator, the inset feed line length ($y_o$) and width ($W_f$) comes out to be 10.934 mm and 2.375 mm respectively (Figure 2, the prototyped model). The obtained dimensions are completely in the agreement of the compact nature of the complete design target. Now the actual feed point connections to the patch will be handled after the finalization of the patch dimensions. A conventional topology of central contact will be adopted here to minimize the leakage and maximize the gain of the antenna. This again elucidates the utility of the microstrip line based inset feed.

**B. PIN diode model and inception**

The PIN diode has been the primary choice for RF circuit designers for several decades as a unique high frequency capable of handling high EM power. Whereas, it uses only a very small amount of current to bring in the control mechanism this huge radiated power, which makes it suitable for low power RF and microwave circuit implementation. The segment sandwiched between the two sides of doped semiconductor in the PIN diode construction is called the intrinsic region, which shows a smaller and
linear junction capacitance, even at very high frequencies (modern RF spectrum). This makes the PIN diode is suitable for the implementation of RF/microwave attenuators. An important limitation in the modeling of PIN diode behavior is to find a consistent model ubiquitously. This constraint of complicated switching behavior of the PIN diode makes it quite difficult for most of the circuit simulator to precisely model the transition characteristics. Varieties of RF applications and circuit behavior brings in the variation in the construction and exact implementation of PIN diodes. As in most of the RF applications, the switching behavior of PIN diode is utilized, the thin intrinsic region of the diode is the major focus in its construction. By controlling the forward current, a range of attenuation values can be achieved [22, 23]. The excellent characteristics of PIN diodes in terms of wider bandwidth, high-power handling capability and compactness in design make them the first choice as RF switches. Figure 3 and 4 show the PIN diode construction and its equivalent forward and reverse bias equivalent circuits [23, 24].

*Figure 3(a)* demonstrates the terminal equivalence of the PIN diode switch modelled in the layout geometry. In this, the distributed impact of PIN geometry has been equated to the lumped passive characterization (*Figure 3(b)*). The opted PIN diode at low frequencies (below the transit time-frequency of the I-region) behaves like a conventional silicon PN junction diode. Out of certain important parameters, the forward voltage drop of PIN diodes are mostly the important consideration. The switching behavior of the PIN diode current is utilized to remove off the stored charge $Q$, which gets accumulated there in the forward biased condition. For this to happen, the incremental stored charge must definitely be lower than the junction stored charge $Q$, and hence is easily wiped out by the RF current [25]. Another important parameter is defined as the maximum reverse bias rating, $V_R$ as a permissible limit. Apart of regular forward and reverse bias ratings, the breakdown mechanism also offers the noticeable parameter of the PIN diode as breakdown voltage, $V_B$, corresponding to avalanche effect. Therefore, in a typical application, maximum negative voltage swing should never exceed $V_B$. An instantaneous excursion of the RF signal into the positive bias direction generally does not cause the diode to go into conduction because of the slow reverse to forward switching speed, $T_{RF}$, of the PIN diode.

*Figure 4* simplifies the operational model of a PIN switch and presents the most lucid lumped model understanding based on its functionality. The opted BAR6402 PIN diode behaves as a conventional $RL$ series combination in $ON$ mode and $RC$ parallel along with series $L$ in $OFF$ mode (obtained values of passive components are mentioned in *Figure 4*), where a high value of the resistor in $OFF$ mode makes it to offer the cutoff topology from the remaining patch edge as shown in *Figure 5*.

**C. Patch Geometry and Design Integration**

This section discusses the patch design geometry calculations, which so far is the most crucial step and core part of the microstrip patch antenna design. Width and length of the patch are conventionally given by following equations:
\[ W = \frac{1}{2f_T \sqrt{\mu_0 \varepsilon_0}} \sqrt{\frac{2}{\varepsilon_r + 1}} \]  

\[ L = \frac{1}{2f_T \sqrt{\mu_0 \varepsilon_0 \varepsilon_{eff}}} - 2\Delta L \]

The first initial guess for the width has been made using equation (3) with \( \varepsilon_{eff} \) of value 2.095 from equation (2). This gives an approximate antenna width \( (W) \) of 23 mm for the most sought application of 5.4 GHz (for wireless LAN, WiFi) in the targeted band of operation. Where the patch length (equation 4) takes care of fringing leakage and substrate irregularities, whereas only little insignificant effects on patch width are observed. The effect of leakage and other parasitic anomalies have been incorporated in channel length via a length corrective parameter \( \Delta L \) (given in equation (5)).

\[ \frac{\Delta L}{h} = 0.412 \left( \frac{\varepsilon_{eff} + 0.3}{\varepsilon_{eff} - 0.258} \right) \left( \frac{W}{h} + 0.264 \right) \left( \frac{W}{h} + 0.8 \right) \]  

\( \Delta L \) from the above equation (5) is kept in equation (4) as a corrective parameter, which finally provides a patch length of \( L = 26 \text{ mm} \). It can be observed from above practice that obtaining patch width \( (W) \) is a subject of iterative calculations whereas patch length \( (L) \) is rather obtained straightforwardly. Patch width thereby accounts for the antenna gain and directivity in a more significant manner. The idealistic scenario for any patch geometry for microstrip antenna is to maintain \( W \gg h \), where \( W \) is the approximate patch width and ‘\( h \)’ is the substrate height (or thickness). Even though it is impractical to have this idealistic scenario in most of the practical designs, the planar IC practices tend to comply with this condition in close proximity. The final designed patch along with inset feed and on-chip PIN switches is shown in Figure 5, where the geometrical dimensions of the proposed antenna designs could easily be identified. The patch dimensions are listed in Table 1 also.

*ROGER-5880 (RT/Duroid)* materials have been in extensive use as a substrate for RF applications for two decades. The excellent characteristics of low loss and low-cost of *ROGER-5880* substrate has been tried to obtain here also, with loss tangent \( \tan D = 0.0009 \), dielectric constant \( \varepsilon_r = 2.2 \), and thickness of 0.787 mm. The overall dimensions of the antenna finally are 23 mm x 26 mm. The antenna design modelling is carried out in a commercially available FEM (Finite element method)-based simulator, *ADS-HPEEs* and *momentum*. A dual-edge rectangular shape is used for the designed patch to achieve high gain and better impedance matching. Also, the inset feed line is connected at a central feed point of the lower edge of the patch, as shown in Figure 5. The spectrum reconfigurability and wide band coverage has been maintained with the help of the PIN diodes (shown with yellow strips in Figure 5), with a lumped element boundary in a reserved slot of 1 mm.
3. INTEGRATED DESIGN WITH RADOME STRUCTURE

Metamaterial attracted great interest in the field of antenna designing mainly from the year 2000 onwards [26, 27, 28]. They are the class of materials that exhibit unique properties which do not exist for naturally occurring materials. Metamaterial cover can efficiently improve antenna directivities with the correct selection of the working frequency and the cover dimensions. The metamaterial cover termed as radome has a congregating effect on the EM wave’s transmission direction, which is similar to the congregation effect of a convex lens to the radiation of light wave. Under ideal conditions, the larger cover size of the metamaterial and a greater number of layers is better. But under actual conditions, one must use the least space resource to obtain the best functions of the antenna [29, 30], and for this special purpose, Newton’s divided difference method is used.

Radomes are the associated frequency selective structures (FSS) to further improvise the antenna radiation and efficiency by providing band-pass selectivity in the electromagnetic domain. An ideal radome structure is expected to remain electromagnetically transparent to the desired frequency bands of operation, and offering significant attenuation to the out of band radiations. In addition to their support in radiation efficiency, a radome structure is also expected to strengthen the physical strata of the antenna geometry. With this virtue, they help to protect radars against the odds of physical environment. This finally reduces the operational cost of the implemented antenna and provides durability also [31]. Frequency selective radome structures are generally employed in curved shapes with compact size to adhere the compatibility of the physical neighborhood of the antenna. But the close proximity required to maintain the compactness with antenna also brings in the mutual coupling effect between antenna and radome structure, which cannot be neglected in the practical applications. This coupling phenomenon also impacts the radiation performance of the antenna already planned [32]. The wet and humid conditions (like presence of water and/or ice) may further degrade strength of radio signals present in the desired band, due to the susceptibility of the radome structure. Radome FSS significantly deteriorate the radar signals, but the exact performance and amount of attenuation depends upon the operating frequency and physical elements present in the radome implementation [33]. Therefore, it is recommended to meet the specific constraints related to these degradations in the radome FSS based antenna implementations, especially in the mm-wave systems. This further demands the higher directivity from implemented patch antennas to compensate for the aforementioned degradations.

In this paper, a frequency selective structure (FSS) radome is proposed to improve a patch antenna gain and make it more directive without any significant loss of gain, as shown in Figure 6. The proposed FSS radome shown has been used as an addition layer. The radome structure has been purposely placed in the proximity of the near-field region of the patch antenna. In this work, the patch antenna and radome structure are designed as the separate units to keep the dimensional and radiation pattern control intact. A very popular and conventional ABS plastic material has been used for the analysis of radome structure, and simulation.
4. SIMULATION AND MEASUREMENTS RESULTS

The present section presents the performance characteristics of the antenna which have been analyzed with HPEEs of (ADS-momentum). The reflection loss ($S_{11}$) analysis of the high-frequency S-parameters simulations is the most frequent one to analyze the antenna and any other microwave circuital performance. The patch has got fabricated as per the proposed dimensions and shown in Figure 7 below. The fabricated structure (Figure 7) was measured around to be 23 mm wide and 26 mm long (with area approx. 595 mm$^2$) including the probe connector, via an outer periphery. The design area claims its supremacy for a highly compact design.

The simulation results obtained here, are also compared with the measured results of the implemented structure, which prove the coordination of the design analysis with the practical scenario. Far-field results have also been obtained along with 3-dimensional radiation pattern.

(a) Tuning and radiation characteristic of the proposed reconfigurable patch antenna

Obtained results indicate that the variation of $S$-parameter ($S_{11}$ in dB) with frequency has four operating frequency resonances (Figure 8). When the switch is turned ON and OFF, the antenna operates in a dual operating band and desired return loss is obtained. The operating frequency ranges of the antenna are found to be as follows: 3.1 to 3.6 GHz, and 6 to 8.8 GHz in ON state while 3.8 to 5.05 GHz and 7.55 to 9 GHz in OFF state of diodes respectively. Table 2 summarizes all three cases of reconfiguration based on modes of PIN diode switches. Due to the symmetry of patch design as well as the placement of both PIN switches, the ON condition of any one of the diodes results in the same analysis.

The regular distribution of the spectrum including both ON and OFF conditions of the proposed design offers its application to the complete span of S and C band including the most sought WLAN, Wi-Max and Wi-Fi applications. The ON mode of PIN diodes shorten the wider/upper edges of the patch with the lower one, and this expands the overall length ($L$) of the antenna design (Figure 5), which makes it to resonate at a slightly lower frequency. This inherently brings the reconfigurability in the tuning characteristic of the proposed antenna design.

(a) Gain, power and efficiency analysis using far-field radiation pattern in the XZ plane ($\phi = 0^\circ$, with both diodes OFF: 4.2 GHz operation)

The far-field simulations have been performed using momentum and EMDS (Electro-Magnetic Design Simulator) of ADS (from Keysight Technologies) and 3-D radiation pattern in THETA ($\theta$) and PHI ($\phi$) variations are shown in Figure 9, for the PIN switches in ON condition. Whereas Figure 10 depicts the 2-D polar radiation plots for 4.2 and 5.04 GHz which validate both the ON and OFF conditions of the PIN switches. The results also extend their genericity over other resonating spectrums of the proposed design as the feeding and geometrical design on the antenna remain the same. The symmetry of the far-field radiation pattern over the azimuth plane, over THETA ($\theta$), is easily observed from the 3-D simulation
results in Figure 9. This mainly occurs due to the symmetry of the design and symmetry in the feeding mechanism as well (inset feed, discussed in the previous section).

Various fields components have been shown in Figure 10, for both linear and circular polarization pattern in the far-field. The dominance of cross-sectional component in the linear polarization enables the design to offer a higher gain in the radial direction [34, 35]. Inset feed mechanism also brings in a higher gain both in terms of power and in terms of directivity.

Figure 10 (c) and (d) show the simulated 2-D radiation patterns of the proposed patch antenna with inset feed at resonant frequency of 4.2 GHz and 5.04 GHz placed in x-z (φ = 0°) and y-z (φ = 90°) plane. This completely covers the ON and OFF conditions of the PIN diodes. The simulated co-polarization and cross-polarization radiation patterns for the patch antenna are demarcated with different color lines. It is observed that the measured antenna gain varies from -1.9 to 2.3 dBi with peak efficiency of 89%. The maximum gain is 2.3 dBi with efficiency of 89% at 5.04 GHz and lowest gain is -1.9 dBi with efficiency of 48% at frequency of 4.2 GHz. To further support the radiation pattern performance of the proposed antenna design, the power gain, directivity and efficiency of the antenna are also analyzed and plotted at 5.05 GHz from Momentum/EMDS (ADS) and are shown in Figure 11.

Some important parameters of antenna (especially in the far-field patterns) are simulated and analyzed in Figure 11, which demonstrates a higher gain of 2.3 dBi along the azimuthal plane, for the frequency of 5.04 GHz, which gives the best efficiency as mentioned above (Figure 11 (a)). The obtained efficiency for theta direction comes out to be 89%, which proves the novelty of the design again with its compact structure. Uniformity in the radiation pattern along azimuth plane with THETA (θ) variation enables the design usage for multi-band and large coverage mode, especially for the fading environment [36-38], which has been a major concern for the modern RF scenario [39, 40].

(c) Effect of Radome structure and its thickness variation (D₁ ON and D₂ OFF at 5.12 GHz operation)

To study the effect of radome structure on antenna gain and radiation pattern, the EMDS simulation environment has been used under ADS platform. The same proposed patch antenna in this section has been stimulated by the inclusion of the designed radome structure, and reflection coefficient (S₁₁) has been obtained in Figure 12 again along with the smith chart visualization of the complex behavior of the reflection coefficient (Figure 12 (b)). The complete structure is subjected to EMDS simulation to analyze the effect of the radome. The radome structure is placed over the microstrip antenna and its impact on the tuning characterization has been obtained by a sample simulation set of D₁ ON and D₂ OFF condition.

The ABS based radome structure presence brings in the reduction of gain by 4 dB, whereas the radiation pattern and tuning range remains unaffected (Figure 12). This is due to the proper selection of the radome structure material, dimensions and orientation. A little upper shift in the very high-frequency tuning of the patch antenna (around 6 to 9 GHz) has been obtained but with the insignificant change in impedance bandwidth.
The proposed patch design has been contrasted with several other contemporary design work for the similar spectrum applications in recent years. The comparison table is presented (Table 3), which highlights the major distinguished features and achievements of the antenna in terms of multi-band reconfigurable operation along with wide band coverage, low-cost implementation, effective inset-feeding and compact die-size.

5. CONCLUSION

A broadband on-chip frequency reconfigurable antenna with PIN diode switches is presented, for S and C-band applications and the effect of ABS based Radome structure on radiation pattern and power efficiency has also been studied. The frequency reconfigurability feature has been exploited from the switching characteristic of the PIN diodes. With these switches, the proposed antenna obtained an attractive -10 dB impedance bandwidth of 1450 MHz at 8.1 GHz and 2800 MHz at 6.5 GHz, out of 6 bands of operation. The superior performance for 2800 MHz bandwidth corresponds to 43.08 % tuning at the center frequency of 6.5 GHz. This remarkable achievement is a result of the dual-edge shaped patch antenna and centered inset feed implemented in this work. A reasonably high gain (peak gain value) of 2.3 dBi at 5.04 GHz is obtained in simulation and measurement results closely align with the value. This offers the validation of the proposed on-chip patch design and its simulated behavior, along with the inset feed mechanism and particularly the model of the on-chip switches is generally reliable. The proposed antenna is studied and optimized in different reconfigurable scenarios, especially including the effect of radome structure. The designed patch antenna is studied in terms of important antenna parameters, including reflection coefficient, antenna gain, and radiation pattern, through simulation as well as measurements. This antenna with a highly compact size of 595 mm², radiates efficiently at all the desired bands. Design simplicity, compactness, and reconfigurability are the features that make this antenna a good choice for future wireless communication applications.

REFERENCES


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<td>Radiation patterns of the proposed patch antenna (a) Far-field magnitude of linear polarization (at 5.04 GHz), (b) Far-field magnitude in circular polarization (at 5.04 GHz), (c) 2-d pattern in polar co-ordinates at 4.2 GHz (Diodes/Switches OFF) and (d) 2-d pattern in polar co-ordinates at 5.04 GHz (Diodes/Switches ON)</td>
</tr>
<tr>
<td>Figure 11</td>
<td>Simulated Antenna parameters in the far-field pattern at 5.04 GHz (a) power gain (red) and directivity (blue) effective area (c) antenna efficiency in percentage (d) radiated power</td>
</tr>
<tr>
<td>Figure 12</td>
<td>(a) Simulated S11 (dB), with PIN Diode1 ON and diode2 OFF conditions, without radome (Blue) and with radome structure (red), (b) smith chart demonstration for complex reflection S11 for 4.9 GHz to 5.7 GHz</td>
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<table>
<thead>
<tr>
<th>Table No</th>
<th>Table Captions</th>
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<tbody>
<tr>
<td>Table 1</td>
<td>Dimensions of the proposed patch antenna (all values are in mm)</td>
</tr>
<tr>
<td>Table 2</td>
<td>Antenna operational tuning range for PIN diode modes’ configurations</td>
</tr>
<tr>
<td>Table 3</td>
<td>Performance comparison of proposed design with other contemporary and recent designs</td>
</tr>
</tbody>
</table>
Figure 3

Equivalent PIN diode model in HFSS

(a) 

(b) 

Figure 4

\[ C_p = 0.17 \text{pF} \]

\[ L_f = 0.6 \text{nH} \]

\[ R_f = 2.1 \Omega \]

ON state

OFF state

\[ R_p = 3 \text{k}\Omega \]

Direct current path

Alternating current path

Ground 3.3 or 0 volt

Lumped RLC Boundary
Figure 10

(a) 

(b) 

(c) 

(d) 

E_{co} in x-z plane
E_{co} in y-z plane
E_{cros} in x-z plane
E_{cros} in y-z plane
**Table 1**

<table>
<thead>
<tr>
<th>Parameters</th>
<th>L</th>
<th>L₁</th>
<th>L₂</th>
<th>L₃</th>
<th>L₄</th>
<th>Lₓ</th>
<th>y₀</th>
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<tbody>
<tr>
<td>Dimensions(mm)</td>
<td>20</td>
<td>3</td>
<td>6</td>
<td>3</td>
<td>5</td>
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<table>
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<tr>
<th>Parameters</th>
<th>W</th>
<th>W₁</th>
<th>W₂</th>
<th>W₃</th>
<th>W₄</th>
<th>Wₓ</th>
<th>C₁, C₂</th>
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</thead>
<tbody>
<tr>
<td>Dimensions(mm)</td>
<td>22</td>
<td>7</td>
<td>6</td>
<td>4</td>
<td>2</td>
<td>2</td>
<td>PIN switch connections</td>
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**Table 2**

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<tr>
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<th>Simulated (Momentum @ ADS)</th>
<th>measured</th>
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<tr>
<td>Diodes OFF</td>
<td>Centered at 4.2 GHz and 8.1 GHz</td>
<td>Centered at 4.3 GHz and 8.05 GHz</td>
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<tr>
<td></td>
<td>Two bands from 3.8 to 5.05 GHz and 7.55 to 9 GHz</td>
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</tr>
<tr>
<td>Diodes ON</td>
<td>Centered at 3.35 GHz, 5.04 GHz, 5.56 GHz and 6.5 GHz</td>
<td>Centered at 3.05 GHz and 8.05 GHz</td>
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<tr>
<td></td>
<td>Total 4 bands from 3.1 to 3.6 GHz, 4.9 to 5.2 GHz, 5.33 to 5.7 GHz and 6 to 8.8 GHz</td>
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<tr>
<td>D1 ON, D2 OFF</td>
<td>5.12 GHz (with and without Radome structure)</td>
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**Table 3**

<table>
<thead>
<tr>
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<th>[39]</th>
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<th>[43]</th>
<th>This work*</th>
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<tr>
<td>Area (mm²)</td>
<td>3900</td>
<td>675</td>
<td>1852.3</td>
<td>400</td>
<td>1720</td>
<td>1892</td>
<td>337.5</td>
<td>2400</td>
<td>7200</td>
<td>1370</td>
<td>595</td>
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<tr>
<td>Substrate</td>
<td>FR4</td>
<td>RO4350</td>
<td>FR4</td>
<td>RO4350</td>
<td>FR4</td>
<td>PET</td>
<td>FR4</td>
<td>FR4</td>
<td>RO5880</td>
<td>RO5880</td>
<td></td>
</tr>
<tr>
<td>Thickness (mm)</td>
<td>1.55</td>
<td>0.8</td>
<td>1.5</td>
<td>0.8</td>
<td>1.6</td>
<td>0.1</td>
<td>0.8</td>
<td>1.6</td>
<td>1.6</td>
<td>1.57</td>
<td>0.787</td>
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<td>No. of resonances</td>
<td>6</td>
<td>6</td>
<td>4</td>
<td>3</td>
<td>3</td>
<td>3</td>
<td>2</td>
<td>12</td>
<td>2</td>
<td>1</td>
<td>6</td>
</tr>
<tr>
<td>No. of switches</td>
<td>6</td>
<td>3</td>
<td>5</td>
<td>3</td>
<td>4</td>
<td>1</td>
<td>N/A</td>
<td>4</td>
<td>N/A</td>
<td>N/A</td>
<td>2</td>
</tr>
<tr>
<td>BW at different resonance bands (MHz)</td>
<td>1400 to 4600</td>
<td>100; 120; 280; 220; 100; 320</td>
<td>690; 300; 740; 620</td>
<td>210; 400; 580</td>
<td>500; 380; 800</td>
<td>160; 180; 270</td>
<td>1575; 244</td>
<td>1200; 900; 600; 500; 700; 260; 400; 400; 500; 800; 800; 700</td>
<td>1300-2600 (dual band)</td>
<td>1980-4000 (centre: 3 GHz)</td>
<td>1200; 1450; 500; 300; 270; 2800</td>
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<tr>
<td>Tuning efficiency (best case)</td>
<td>57.5 %</td>
<td>33.5 %</td>
<td>39 %</td>
<td>37.8 %</td>
<td>38 %</td>
<td>30.6 %</td>
<td>41.5 %</td>
<td>28.8 %</td>
<td>66%</td>
<td>66%</td>
<td>43.1 % (2800 MHz at 6.5 GHz)</td>
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<tr>
<td>Application</td>
<td>WIFI and Wimax</td>
<td>2G and 3G band</td>
<td>WLAN, WiMAX</td>
<td>3G, 4G spectrum</td>
<td>WLAN, WiMAX, C band &amp; I TU</td>
<td>3G, 4G spectrum</td>
<td>Smartphone Applications</td>
<td>WLAN, WiMAX, X-band satellite</td>
<td>Multi-band MIMO applications</td>
<td>Monopulse radar</td>
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<tr>
<td>Special features</td>
<td>Frequency Tunable Cedar-Shaped</td>
<td>slot antenna, compact design</td>
<td>pattern reconfigurable antenna</td>
<td>miniaturized microstrip antenna</td>
<td>switchable stubbed ground structure, monopole, triple-band</td>
<td>narrowband microstrip slot antenna</td>
<td>Use of common Metal rim</td>
<td>Cedar shaped, ultrawideband, CPW fed</td>
<td>reconfigurable MIMO antenna, 4-slots, 12-dB isolation</td>
<td>reconfigurable radiation patterns, inverted U-slots, peak gain of 9.6dBi</td>
<td></td>
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<tr>
<td></td>
<td>Inset Feed, Wideband and compact design with radome structure</td>
<td></td>
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</tbody>
</table>
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