Design of Compact Reconfigurable Antenna Array for WLAN Applications

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Abstract ─ In this communication, a compact design of a reconfigurable antenna array operating in the band IEEE 802.11a is presented. The proposed antenna array contains four radiating elements excited by a hybrid parallel-series-feed network. The hybrid feed technique is used to avoid the main beam squint due to frequency changes compared to series and parallel array feed topologies. Each of the four radiating elements consists of straight narrow strip inductor in parallel with an interdigital capacitor. The antenna resonant frequency is electronically controlled by placing PIN diodes switches at the resonant element's inputs. The antenna permits reconfigurable switching frequency bands between 5.25 and 5.82 GHz. The results of the return loss and pattern radiation are shown. The size of the whole antenna structure is about 64 × 18 mm^2 and can potentially be used in wireless systems.

Index Terms ─ Antenna array, hybrid feed, reconfigurable, miniaturized.

I. INTRODUCTION

Recent advancements in wireless technology components have resulted in their increased use in gadgets meant for numerous wireless applications and use cases. Even when is a constant push for miniaturization of gadgets, reducing the sizes of antennas and batteries have been historically difficult, owing to performance constraints [1].

For instance, the principal limitation of the microstrip patch antenna is its narrow impedance bandwidth which is usually a few percent. Various procedures have been proposed to increase this bandwidth [2-3]. The techniques include using a parasitic patch stacked, a substrate of a low dielectric constant, as well as employing matching structures [4-6]. However, these techniques can only achieve limited degrees of bandwidth advancement.

The frequency agile antennas were introduced to overcome the microstrip antenna narrow resonance [7]. These antennas can alter their resonant frequency to function at a specific frequency with the multi-serviced frequency bands [8]. As such, they can be built in lower sizes, and finds multipurpose uses for several wireless equipments. The feature of the antenna's ability to be built in lower sizes, is highly demanded for cognitive radio systems [9-10]. Numerous methods were reported to achieve frequency tunable antennas, and they can be fundamentally categorized into three main types namely mechanical tuning [11,12], using tunable materials [13,14] and electronics switches [15,16]. Mechanical tuning involves a physical displacement, which needs some time suspension. It is difficult to attain consistent performance with mechanical tuning. Using tunable material also have drawbacks such as high bias voltages, temperature sensitivity and dc power consumption. To address these shortcomings, electronic switches are preferred in designing frequency tunable antennas. Additionally, electronic elements provide the benefit of packing efficiency, size reduction, and the ready availability of miniaturized commercial components that easily combined with the antennas.

A few rounded electronically reconfigurable arrays were reported in the literature to operate in the band IEEE 802.11a. Byford et al., (2015) presents a 2 × 2 reconfigurable array consisting of interconnected radiating elements which is controlled by switches. If the switch is ON state, a larger radiating element with lower resonating frequencies than the individual elements is formed [17]. Li et al. (2014) introduced an array that consists of four double-sided bow-tie elements as well as an ultra-wideband feed network. The effective electrical lengths of the elements can be altered, once the state of the PIN diodes loaded on the radiators is controlled. Hence, the array resonant frequency can be electronically switched [18].

The purpose of this paper is threefold. The first is to propose a way for antennas to acquire frequency agile resonance, by using the PIN diodes as ON/OFF switches at each of the four array element inputs. Next, the paper proposes a way to avoid radiation pattern squint due to frequency change by using a hybrid feeding technique. The third is to present a miniaturized array real estate compared with the ones reported in the literature. If the radiating elements are compact, then the array size would be reduced.

The remainder of this paper is structured as follows.

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In Section 2, the single element resonator is explained. Description of the array is presented in Section 3. The PIN diode integration at array feeding arms is investigated in Section 4. Section 5 gives a comparison between the proposed antennas's simulated measured results for the reconfigurable reflection coefficient and radiation pattern. The conclusions are drawn in Section 6.

II. SINGLE ELEMENT ANTENNA GEOMETRY

Quasi lumped resonators (QLR) are widely discussed in literature owing to its attractive feature of reduced size. Its intrinsic circuit components determine the resonance frequency, and its periodic interdigital lumped element geometry enables it to have miniature size, which is its premium advantage. Quasi lumped elements are microwave elements whose physical lengths are very small compared to their respective wavelength. The microstrip lines used in microwave realization with lengths are shorter of quarter wavelength at the operating frequency, are generally denoted by the QLR.

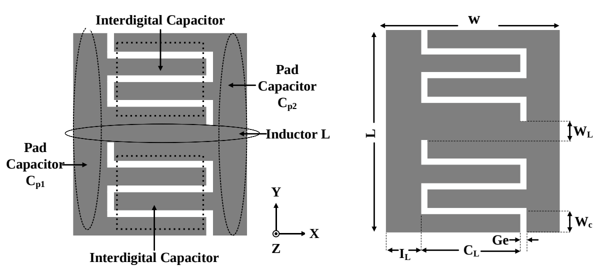


Fig. 1. Quasi-lumped element layout.

For the QLR shown in Fig. 1, the inductance that at the center and can be obtained by solving equation (1):

$$L = 200 \times 10^{-9} I_L \left(ln\left(\frac{2I_L}{W_L + h}\right) + 0.50094 + \frac{W_L}{3I_L} \right), \quad (1)$$

where h is the substrate thickness

In Fig. 1, the periodic multifinger structure represents the interdigital capacitor. The capacitance exists between the slits between the conductors. Naturally, these slits are very long. Hence, for reducing the QLR real estate, they are bent. Equation (2) reported by [19,20] is used to determine the interdigital capacitance:

$$C = \varepsilon_0 \left(\frac{\varepsilon_r + 1}{2}\right)(N - \Delta)C_L \,, \quad (2)$$

where Δ is the correction factor Δ= (w_{eff}-w), w_{eff} is the effective width, w finger is the width:

N is the fingers number.

The pad capacitors C_{p1} and C_{p2} are situated at the QLR sides are used to fine tune the resonant frequency. equation (3) given by [21], is used to calculate the pad capacitors:

$$C_p = \left(\frac{2.85\varepsilon_{eff}}{ln\left(1 + (0.5) \times \left(\frac{8h}{w_{eff}}\right)\right) \times \left(\frac{8h}{w_{eff}} + \sqrt{\left(\frac{8h}{w_{eff}}\right)^2 + \pi^2}\right)} \right) \times \left(\frac{1}{25.4 \times 10^{-3}}\right). \quad (3)$$

The resonant frequency of proposed QLR antenna can be estimated using equation (4) reported by [22,23]. Table 1 shows the dimensions of a single quasi lumped element at a resonant frequency of 5.8 GHz:

$$f = \frac{1}{2\pi \sqrt{L\left(\frac{C_{p1}C_{p2}}{C_{p1} + C_{p2}} + C\right)}} \,. \quad (4)$$

Table 1: The proposed quasi lumped antenna element parameters

Parameter	Dimensions [mm]
W_e	0.35
I_L	3.35
C	3.05
N	8
$I_L^{\backslash}$	1.23
g_e	1.23
W_L	1.2
L	5.4
W	5.8
h	0.813

III. DESCRIPTION OF THE ARRAY

Two kinds of array feeding topologies are frequently used, parallel topology and series topology geometries [24,25]. The series fed structures are mainly classified into resonant and traveling wave feeds [26,27]. The arrays for which the impedances at the junctions of the feeding line and the resonant elements are not matched are called the resonant arrays. In the traveling-wave array topology, the feeding line impedances and the radiating elements are commonly all matched. The advantages of series topology is that it primarily reduces the feed lines' dielectric insertion losses. Furthermore, it decreases the radiation leakage of the feeding network compared to the parallel feed network. Broadly, the series feed arrangements are more compact as they need shorter transmission lengths, lower insertion loss and fewer junctions. However, it mainly produces narrow bandwidth and suffers of inherent phase difference produced by lengths differences of the feed lines [28]. The parallel feed, also called the corporate feed [29], are common and versatile as it enables controlling the feed of each element. However, corporate feeds need a relatively larger size, and it can be complicated to integrate them into an array environment. Also, due to the supplementary line lengths, losses are increased [30].

The hybrid feed is a combination of series and parallel feed lines, and its design can eliminate the disadvantages of each of the parallel and the series feed networks. It provides a wider bandwidth over the series feed and can be more miniaturized than the corporate feed design. For purely series-feed array, the antenna input power is transmitted from one end of the array. The main beam angle will be quite sensitive to frequency variation because of the phase variation of the series-fed elements. A combination of parallel-series feed geometry can be employed to prevent the main beam squint due to frequency variations. For the hybrid feed, the beam phase of the series array will squint away from broadside as frequency varies, but, with parallel integration, the beam of the entire array will sustain pointed in the broadside direction. However, the hybrid array insertion loss is higher than purely series-fed array due to its fractional parallel feed. Nonetheless, the hybrid technique provides the designer with the opportunity to trade-offs between insertion loss and bandwidth [31].

The proposed center-fed series-parallel array is employed to design the array as shown in Fig. 2. The power distribution and phase arrangement are accomplished by means of quarter-wavelength lines in the feeding network. The figure shows the array sub-element dimensions and impedances calculated at 5.8 GHz. The quarter-wavelength segment is employed for several reasons as the shortest length for a transformation, reduced size and overall loss. The use of multi-sections of quarter-wavelength transmission lines to gradually transform an impedance will result in lowering dissipation compared to a single quarter-wavelength transmission line [32].

IV. TUNING TECHNIQUE

Different electronic components, such as PIN diodes, FETs, and MEMS, are used to build an RF switch for frequency reconfigurable antennas [33,34]. The MEMS-based RF switches are useful in cases where low loss and high isolation are required, although they are costlier and require higher operating voltage. The FETs have low power consumption, yet suffer from higher loss and poor linearity. The PIN diode-based RF switches are cheaper and offer low-loss operation. The limitation of a PIN diode switch is that a forward DC current is required to switch the diode in the ON state, leading to poor radiation efficiency.

The Schematic diagram of the diode coupling circuit is depicted in Fig. 5. The appropriate value of the RF choke can be estimated to get a very high impedance (approaching infinity) at the desired frequency. However, it’s important to refer to the inductor’s datasheet and make sure it does not resonate at the designed frequency of the antenna in which it is deployed.

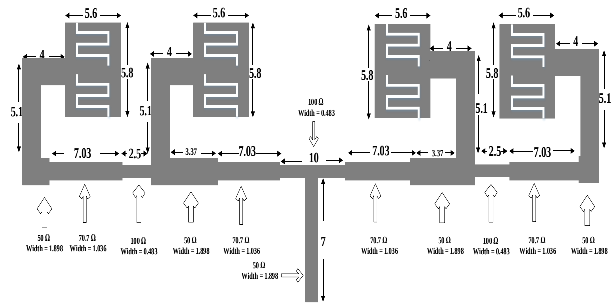


Fig. 2. The proposed hybrid series-parallel array.

The RF PIN diodes is the most prominent in designing reconfigurable antenna among other switches. The PIN diode has several advantages. It requires less complicated biasing components, and its cost makes it a preferable choice for researchers. However, PIN diodes have several weaknesses such as high insertion loss, low efficiency, and requires an additional RF extension. The direct current blocks is mandatory and must be taken into account during the design. The PIN diode equivalent circuit of forward bias and reverse bias is shown in Fig. 3. The allocation of the PIN diodes on the array is depicted in Fig. 4.

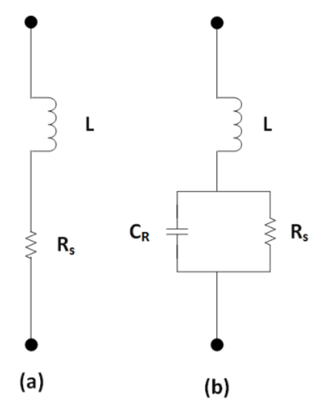


Fig. 3. PIN diode equivalent circuit. (a) Forward bias and (b) reverse bias.

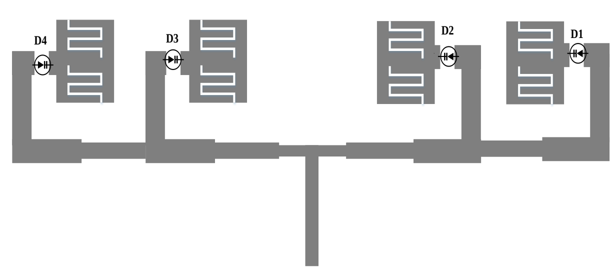


Fig. 4. The proposed array with PIN diodes located at QLR inputs.

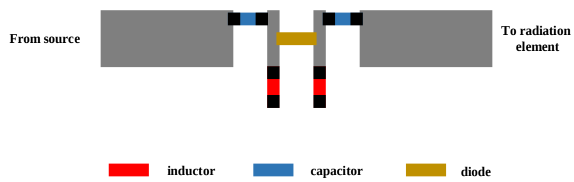


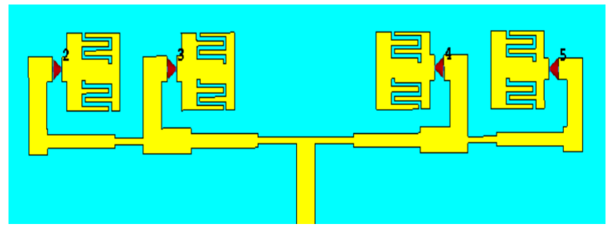
Fig. 5. The schematic coupling circuit of the PIN diode.

V. RESULTS AND DISCUSSIONS

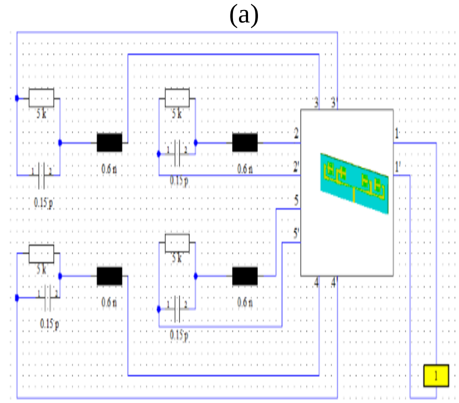
Figure 6 depicts the proposed antenna prototype. The simulation has been executed by 3D Simulation Technology (CST) microwave studio software. The BAR63-02V PIN diode from Infineon Technologies is used as a switch for the reconfigurable antenna design. The diode used provide the advantage of very low capacitance that offers high isolation. Figure 6 (a) shows the discrete ports allocation coupled to resonating elements. The PIN diode equivalent circuit model in the ON and OFF states are shown in Figs. 6 (b) and 6 (c) respectively.

The assembled antenna with the integrated PIN diodes switches is depicted in Fig. 7. Surface mount component (SMC) were integrated to PIN diodes circuits. The circuit consists of one PIN diode, two DC block capacitors and two RF choke inductors. The DC source is applied to the inductor to perform as a short circuit. On the other side, the capacitor only permits the AC current to flow through. For that, the DC run though the other route and ON the PIN diode. A 5 volt DC supply is applied through the red wire. Whilst, the ground is connected to the green wire.

The simulated and measured S_{11} parameters of the proposed antenna are shown in Fig. 8 and Fig. 9, respectively. For the simulated ones, when all diodes are ON, a resonating notch occurs at 5.82 GHz (mode 1). In mode 2, frequency is shifted to between 5.762 to 5.558 GHz by putting one PIN to OFF condition. In mode 3 the resonance is moved between 5.6 to 5.29 GHz when two PIN are OFF. Finally, with three diodes at OFF state, the antenna resonates at 5.107 to 5.298 GHz. From the measured results, at mode 1 if all diodes are ON state the resonating notch occurs at 5.836 GHz. For mode 2 at which three diodes is ON state is observed that the maximum resonance occurs at 5.758 GHz whilst the minimal 5.532 GHz. For mode 3, when two diodes are OFF state, the maximum resonance obtained at 5.586 GHz and the minimal is 5.27 GHz. Lastly, if three diodes are OFF state the resonance occurs in between 5.276 GHz and 5.1 GHz. Different modes for PIN diode modes and corresponding resonance frequencies are given in Table 2.



(a)



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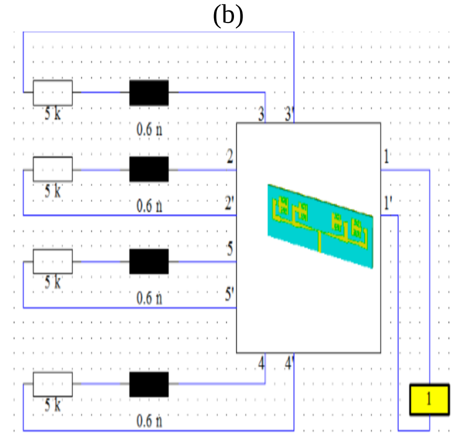


(c)

Fig. 6. The discrete port to connect the main radiation plane to the additional plane. (b) Equivalent circuit model of theBAR63-02V PIN diode in the ON state. (c) Equivalent circuit model of theBAR63-02V PIN diode in the OFF state.

In Fig. 8, the reflection coefficients shifts further to the left if more diodes are in OFF mode state. Generally, the matching impedance is decreased if more PIN Diodes are OFF state. The Simulated S_{11} results are also in good agreement with the measured ones. This is due to the accuracy level of the adjustment of both simulation and measurement.

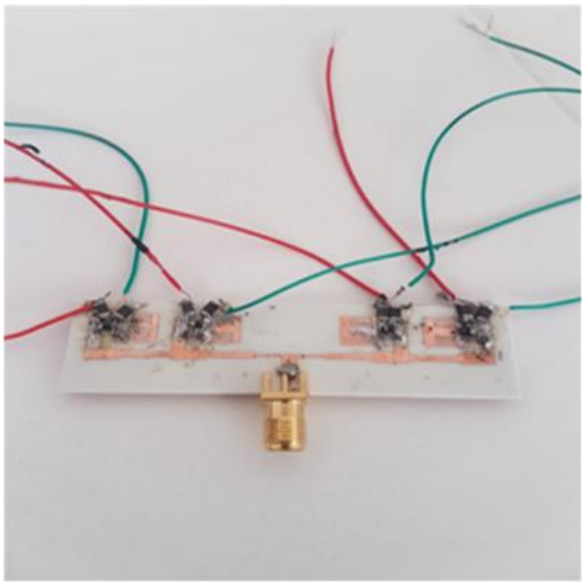
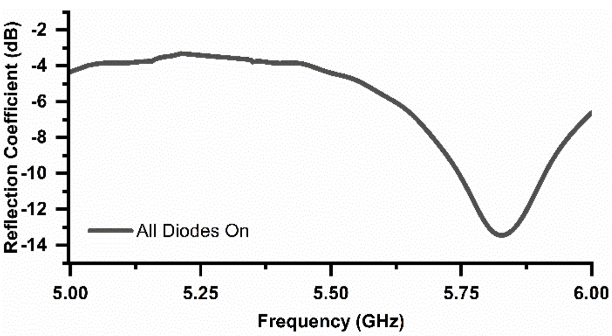
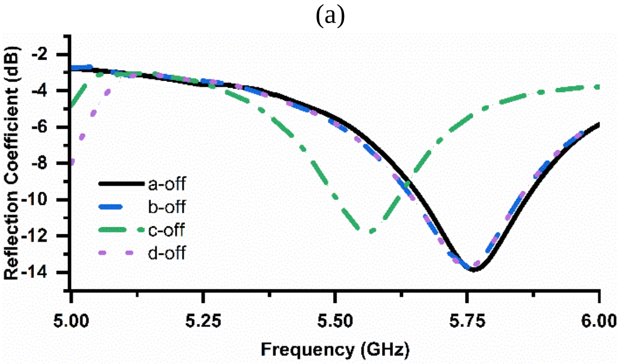


Fig. 7. Geometry of the fabricated antenna structure.



(a)



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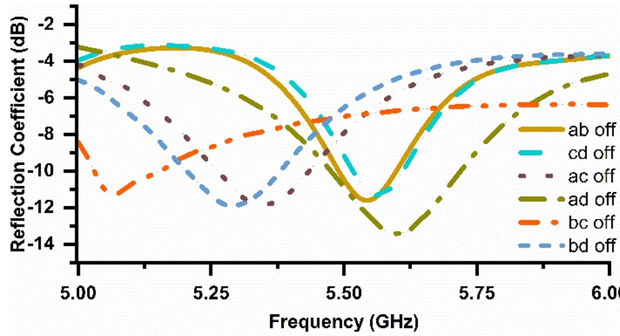

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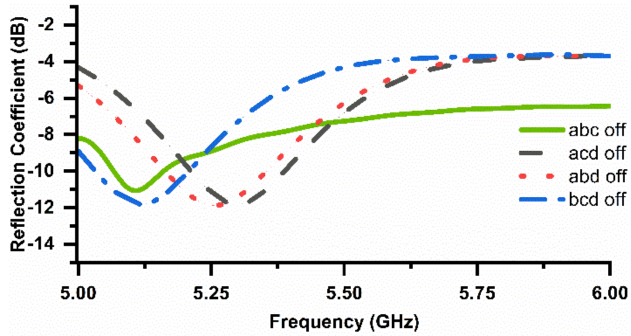
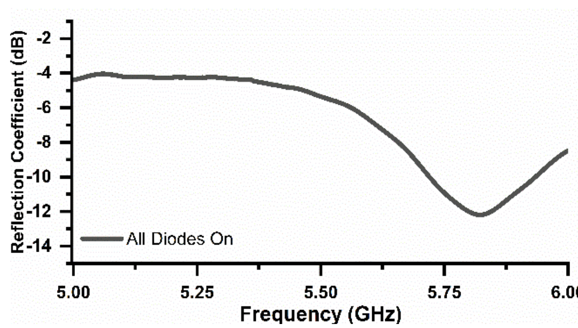
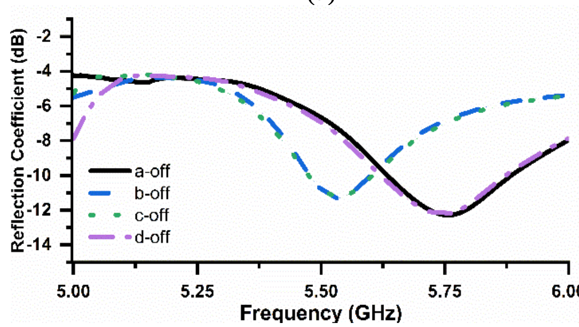


(d)

Fig. 8. Simulated reflection coefficient of the proposed antenna. (a) All Diodes are ON. (b) One diode is OFF. (c) Two Diodes are OFF. (D) Three Diodes are OFF.



(a)



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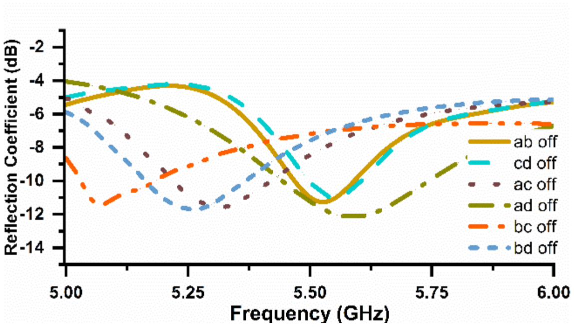

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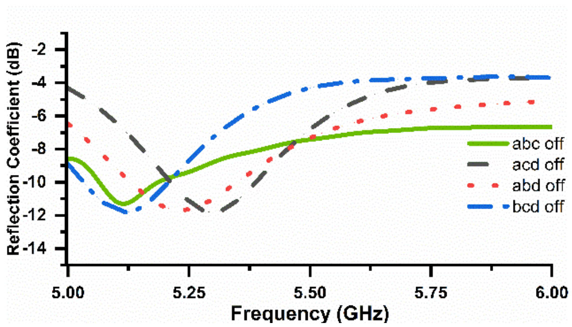
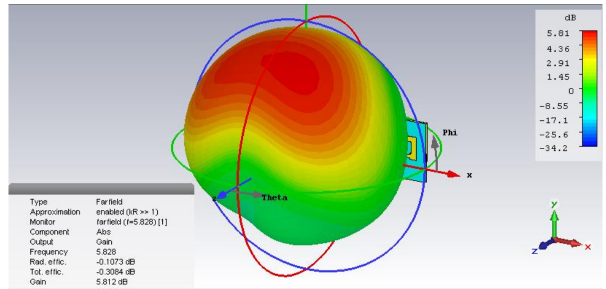


(d)

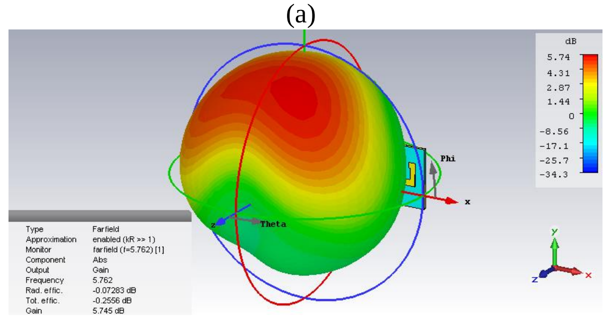
Fig. 9. Measured reflection coefficient of the proposed antenna. (a) All Diodes are ON. (b) One diode is OFF. (c) Two Diodes are OFF. (d) Three diodes are OFF.

Figure 10 depicts the simulated 3D radiation pattern of the PIN diode switches configurations. The figure reveals that the radiation pattern is maintained despite the frequency variation. This result coincides with the assumption that the hybrid feeding topology results in no alteration on the radiation pattern orientation. The figure shows the radiation pattern with all diodes ON state, one diode (a) is ON state, two diodes (a) (b) and (b) are OFF state and three diodes (a) (c) (d) are OFF state. Also, other the diodes states produce the same radiation orientation, i.e., no beam squint due to frequency changes. Figure 11 depicts the polar simulated, and measured radiation pattern of the PIN diode switches configurations for both elevation and azimuth plane. The agreement between the simulated and measured pattern was fairly good.

Figure 12 depicts the simulated and measured realized gains of the proposed antenna. The simulated gain ranges from 5.16 to 5.87 dBi. While the measured gain is maintained between 5.14 and 5.84 dBi. Good correspondence exists between these two results. The simulated total efficiency ranges from 0.75% to 0.82.



(a)



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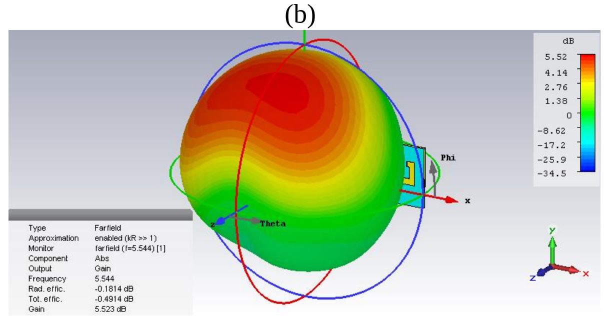

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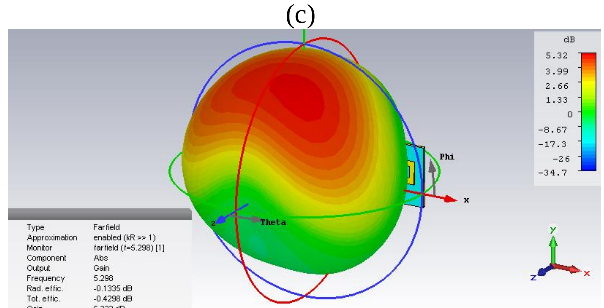

(d)

Fig. 10. 3D simulated radiation pattern of the proposed antenna. (a) All Diodes are ON. (b) One diode is OFF. (c) Two Diodes are OFF. (d) Three Diodes are OFF.

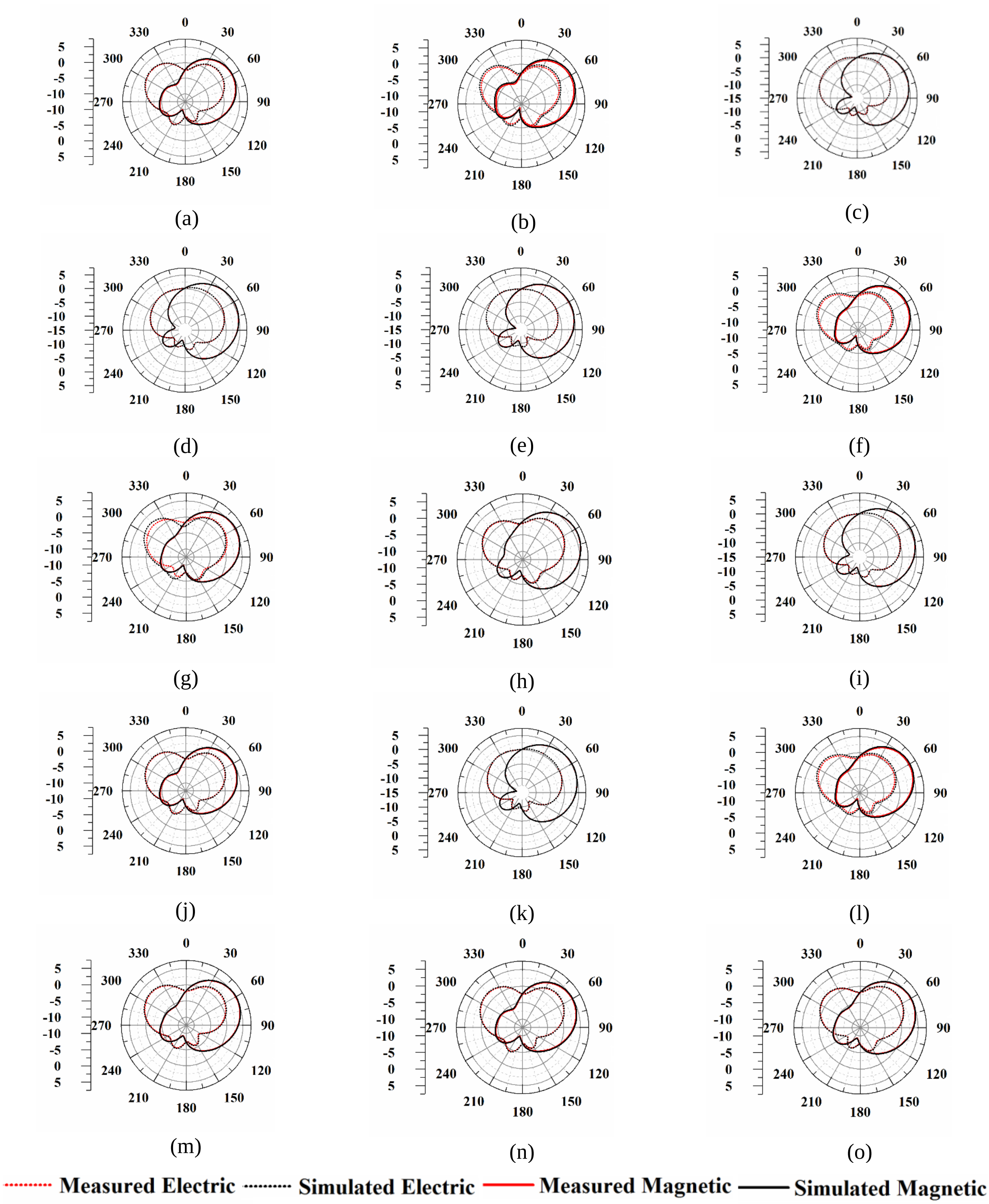

Fig. 11. 2D simulated radiation pattern of the proposed antenna. (a) All Diodes are ON. (b) Diode a is OFF. (c) Diode b is OFF. (d) Diode c is OFF. (e) Diode d is OFF. (f) Diodes ab are OFF. (g) Diodes ac are OFF. (h) Diodes ad are OFF. (i) Diodes bc are OFF. (j) Diodes bd are OFF. (k) Diodes cd are OFF. (l) Diodes abc are OFF. (m) Diodes abd are OFF. (n) Diodes bcd are OFF. (o) Diodes acd are OFF.

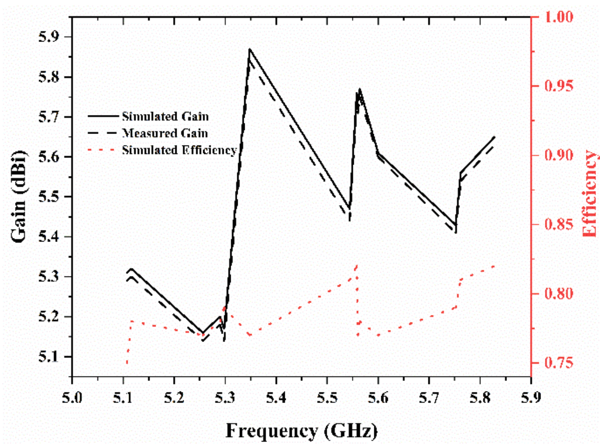

Fig. 12. Simulated and measured realized gain and simulated efficiency.

VI. CONCLUSION

A novel hybrid frequency agile array antenna design with directional and main beam squint immunity operating in the band IEEE 802.11a is proposed. The antenna applies the miniaturized quasi- lumped elements to reduce the array real estate. The array shows the validity of frequency reconfigurability through the range of 5.1 - 5.836 GHz. The proposed antenna with abundant diode modes finds potential use as a portable WiFi application. Moreover, the array has attained a compact physical measurement of by 64×18 mm^2. Table 3 shows the noteworthy size mitigation once compared with other designs reported in literature employed diodes operating in the band IEEE 802.11a.

Table 3: A size comparison between the proposed design and other designs reported in the literature meant for IEEE 802

Reference	Size [mm^2]	Tuning Technique	Number of Elements	Freq [GHz]
17	130x80	PIN diode	4	4.14 – 6
18	68x68	Capacitor switches	4	5.4 - 5.6
Proposed work	64x18	PIN diodes	4	5.1 - 5.836

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Table 2: Summary of PIN diode status and corresponding simulated and measured resonance

Pin Diode Status					Simulated		Measured	
Mode	A	B	C	D	Frequency [GHz]	Reflection Coefficient [dB]	Frequency [GHz]	Reflection Coefficient [dB]
All on	On	On	On	On	5.828	-13.44	5.836	-12.11
One Off	Off	On	On	On	5.762	-13.85	5.758	-12.28
	On	off	On	On	5.558	-11.87	5.532	-11.3
	On	On	Off	On	5.56	-11.78	5.538	-11.2
	On	On	On	Off	5.752	-13.71	5.744	-12.23
Two off	Off	Off	On	On	5.544	-11.61	5.526	-11.26
	On	On	Off	Off	5.564	-11.34	5.54	-10.98
	Off	On	Off	On	5.348	-11.83	5.32	-11.55
	Off	On	On	Off	5.6	-13.43	5.586	-12.16
	On	Off	Off	On	5.29	-11.25	5.27	-11.42
	On	Off	On	Off	5.29	-11.91	5.264	-11.67
	Off	Off	Off	On	5.107	-11.06	5.115	-11.29
Three Off	Off	On	Off	Off	5.298	-11.8	5.276	-11.47
	Off	Off	On	Off	5.256	-11.87	5.232	-11.68
	On	Off	Off	Off	5.116	-11.08	5.1	-11.45

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