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Reconfigurable Microstrip Stacked Array Antenna with Frequency and Pattern Characteristics

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Abstract—This paper presents a frequency and pattern reconfigurable stacked patch microstrip array antenna fed by aperture-coupled technique. The antenna consists of three substrate layers with radiating elements sorted at substrate layer 1 (top patches) and substrate layer 2 (bottom patches). The layers have different sizes to indicate different operating frequencies. On the ground plane, the four sets of two different aperture slot shapes (I-shaped and H-shaped) are used to transfer the wave and signal to particular radiating elements during the PIN diode switches configurations. The I-shaped slots are used to activate the bottom patches while the H-shaped slots are used to activate the top patches. Four PIN diode switches are placed at the feed line, positioned between the I- and H-shaped slots. Next, by changing the PIN diode switches configuration to ten cases, the proposed antenna has capabilities to change the operating frequencies and the pattern characteristics itself. The measured results of return loss, gain and radiation patterns have slightly shifted compared to the simulated results.

1. INTRODUCTION

Microstrip Antennas (MAs) technology began its rapid development and became very popular in 1970s for space-borne application. By the early 1980s, the basic MAs had been well known due to their well-established design and applicability in many applications [1]. It is well known that planar antennas such as MAs have significant number of advantages over conventional antennas, such as low profile, lightweight, conformability, low production cost, and easy fabrication [1–3]. These conventional MAs can only operate at a fixed frequency, radiation pattern, and polarization in one time for each antenna. The increasing demand for modern mobile, satellite, radar applications, and wireless communication systems in the world has attracted many researchers to work hard in order to improve the performances and to enhance the application of the MAs.

Consequently, the development of Reconfigurable Microstrip Antennas (RMAs) has received great attention in the modern wireless communication system and radar applications. These RMAs are cost effective because they are more convenient for a certain design to operate with a single antenna than multiple antennas. By using a single antenna, reconfigurable antennas are capable for use in multiple frequencies [4], radiation pattern [5], and polarization [6] by changing its physical structure, length, or size dynamically without changing the whole antenna structure. The RMAs are controlled by configuring the status of Radio frequency (RF) either to ON or OFF mode, thus affecting the current distributions on the antenna and reconfigurability is achieved. In [7, 8], the PIN diode switches are used because they have low insertion loss, fast response, low control voltage, and are reliable. However, some researchers use varactor diodes [9], MEMs [10], and optoelectronic switches in their antenna design

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to achieve reconfigurability functions. Stacked patches are consequently proposed in [11–13] to obtain frequency and pattern reconfigurability. The advantage of stacked antenna is that it produces high gain and bandwidth compared to single substrate layer. Moreover, to reduce the spurious radiation pattern between the radiating elements and the feed line, the stacked reconfigurable antenna fed by aperture-coupled feeding technique has been investigated and designed, as presented in [14, 15].

Therefore, the aim of this study is to design a frequency and pattern reconfigurable stacked patch microstrip array antenna fed by aperture-coupled technique. The effect of the current distribution along the four PIN diode switches located at the feed line is studied. Next, by configuring the PIN diode switches (either ON or OFF mode) to the ten cases, the antenna has capabilities to operate at three operating frequencies with various pattern characteristics.

2. ANTENNA CONFIGURATION

Figure 1 presents the geometry (2 by 2) of the proposed antenna in 3D perspective (Fig. 1(a)) and side view (Fig. 1(b)). The proposed antenna is constructed from three substrate layers made of RT-Rogers 5880 materials with a dimension of $120 \times 120\,\text{mm}^2$ and the thickness of 0.787 mm. The aperture-coupled technique is used to combine all the substrate layers to reduce the spurious radiation pattern between the feed line and the radiating elements. Hence, the radiating elements (top patches and bottom patches) are etched on different substrate layers, i.e., on the top of substrate layer 1 and substrate layer 2, respectively, with a unique structure and shape. Both patches are designed based on their operating frequency. The top patches (large) are designed based on 2.6 GHz frequency while the bottom patches (small) are designed based on 3.5 GHz frequency. At the back of substrate layer 3, the feed line is etched with a line impedance of $50\,\Omega$ to match with this antenna. Besides, four PIN diode switches labeled as $sw1$, $sw2$, $sw3$, and $sw4$ are integrated at the feed line and located between the two aperture slots if referring to the ground. In this design, the ground plane, which consists of two different aperture slot shapes, I-shape and H-shape, is located on top of substrate layer 3. The I-shaped aperture slot must

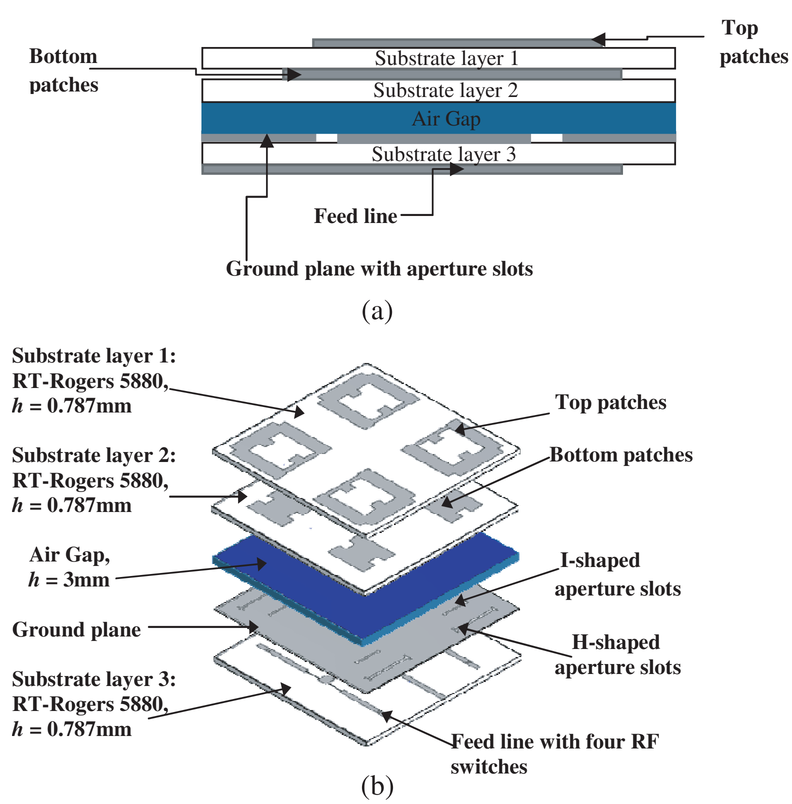


Figure 1. The geometry of the proposed antenna. (a) 3D view, and (b) side view.

be positioned at the centre referring to the bottom patches and the H-shaped aperture slots located at the centre referring to the top patches. The function of the PIN diodes (3.2 × 1.5 mm) switches is to control and activate the selected aperture slots on the ground during the ON and OFF modes to achieve frequency and pattern reconfigurability.

Moreover, to improve the gain and bandwidth of the antenna, an air gap of 3 mm thickness and a low dielectric constant of 1.03 are added between substrate layers 2 and 3. Four stands made of Teflon polytetrafluoroethylene (PTFE) material, each with 3 mm thickness, are used to represent the air gap layer in the antenna structure. In order to combine the substrate layers 1 and 2, the glue type of 'Selleys Pro Spec Epoxy Fast' is used. The key characteristics of these glues are exhibiting good surface finish, high electrical strength, good thermal conductivity, low exotherm and low cure shrinkage. In the simulation process, since the thickness of the glue layer is non-zero, the electrical properties of the glue have an influence on the antenna performance. Therefore, during the simulation of the CST software, a thin layer with 1 mm thickness, which has dielectric constant $\varepsilon_r = 4.8$ and the tangent loss $\delta = 0.060$, is added between the substrate layers to represent the glue. Manual alignment based on visual inspection is used to ensure the substrate layers 1 and 2 glued in a good alignment by using the naked eye, where each of the edges and corners will be ensured to be placed parallel. However, there is still room for the misalignment, but based on the measurement that has been done, the result is almost close to the simulation. Therefore, a small misalignment for the whole structure can be neglected as long as the antenna performance is not affected.

The detailed dimension of every layer of the proposed antenna is shown in Fig. 2. Basically, the design and structure of the proposed antenna have been published in [16], but it only focuses on frequency reconfigurability. Therefore, by applying the structure and concept from the single stacked patch microstrip antenna in [16], the 2 by 2 stacked patch microstrip array structure has been proposed

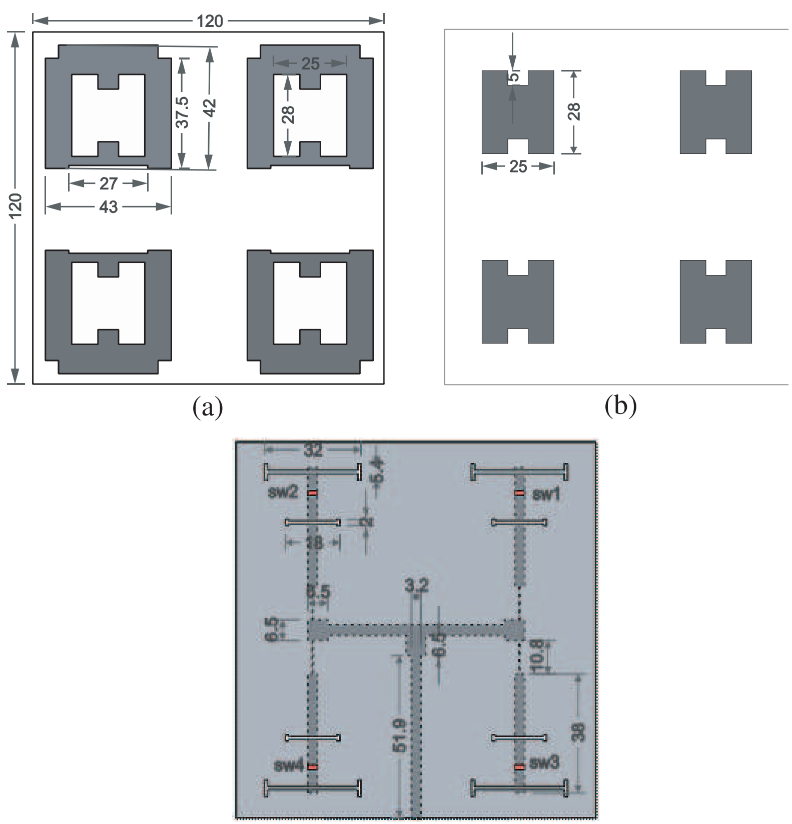
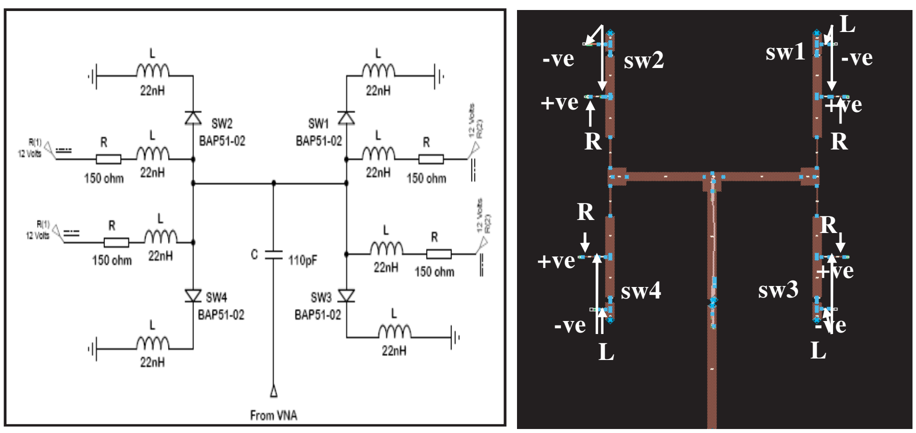


Figure 2. Geometry and dimensions of the proposed antenna. (a) First layer (front view), (b) second layer (front view). (c) Third layer (front and back view).

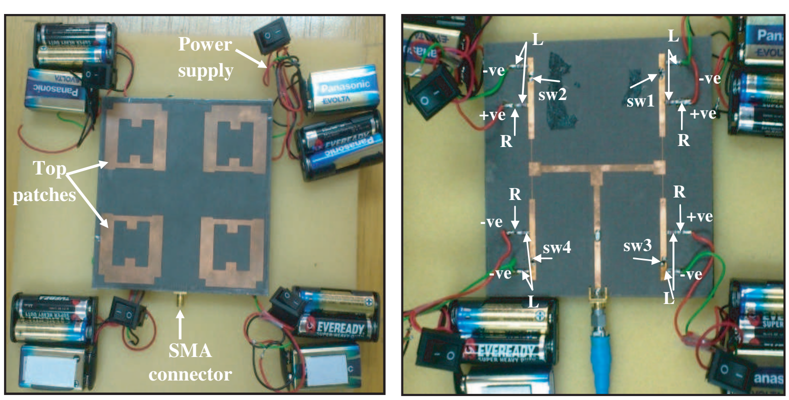
in this paper. With some modification, adjustment of the PIN diodes switches positioned along the feed line, and different numbers of configurations, more frequency and pattern reconfigurability have been achieved. The details about the novelty or a new concept of coupling methods implemented in aperture-coupled technique to achieve the frequency reconfigurability have been explained in [16].

Before the proposed antenna is fabricated and the capability to operate tested, the real switching circuit that represents the PIN diode switches must be implemented at the feed line. Therefore, the basic of PIN diode switching circuit in [8] has been referred and duplicated to four since the proposed antenna has four PIN diode switches. The BAP51-02 (Phillip) PIN diode has been used in this design as it has fast response [8] and is more reliable than other radio frequency switches such as MEMs and varactor. Therefore, the Advanced Design System (ADS) software is used to design, simulate, and validate the PIN diode switching circuit to be suited for the antenna design. Fig. 3(a) shows the equivalent switching circuit to represent the four PIN diode switches for the proposed antenna. The circuit consists of passive components built from Surface Mounted Devices (SMD) used for the Radio Frequency (RF) applications. The circuit includes eight inductors (22 nH), one capacitor (110 pF), and four resistors (150 Ω). The capacitor is used to prevent the Vector Network Analyser (VNA) from DC signal, where the DC signal comes from the biasing equivalent circuit. The DC signal is used to activate the PIN diode switches. The function of the capacitor is to allow the RF current to pass through in one direction and towards the feed line network, while the eight inductors are used as RF chokes to provide



(a) (b)

Figure 3. PIN diodes equivalent switching circuit at the feed network in (a) schematic diagram and (b) the layout by using ADS software.



(a) (b)

Figure 4. Fabrication of the proposed antenna. (a) Front view, (b) back view.

a low impedance for DC. In this circuit, the biasing voltage of 12 V is supplied to activate the whole equivalent switching circuit, but only 1.1 V will be used to activate the PIN diode switches. Besides, a 150 Ω resistor is connected from the supply to limit the current flow to each PIN diode switch. After the position of all the SMD components has been defined and matched to the antenna, the ADS software is used to generate the feed line's layout, as shown in Fig. 3(b). Next, the proposed antenna has been fabricated as shown in Fig. 4(a) and Fig. 4(b). The figures show that the SMD components are located or soldered at the same position as designed in the ADS.

3. SIMULATED AND MEASURED RESULTS

Next, the prototype of the proposed antenna is fabricated to validate the antenna's performance. To control the frequency and pattern characteristics, the four PIN diode switches at the feed line are configured to ten cases. Actually, from the four PIN diode switches, $2^4 = 16$ possibilities of the PIN diode switches configuration will be produced. However, only certain cases as shown in Table 1 are considered as they give more exciting current distributions on the feed line and produce a few groups of pattern and frequencies. Therefore, these ten cases are grouped into A, B, C, and D. As shown in Table 1, the ON mode configuration means that the PIN diode is supplied with 12 V, while during the OFF mode, the 0 V is supplied. The setup of the radiation pattern measurement in an achenoic chamber is shown in Fig. 5.

Table 1. Switches mode configuration.

Group	Case	Description	Switches Mode Configuration			
			SW1	SW2	SW3	SW4
A	Case 1	Only SW1 is ON	✔	✘	✘	✘
	Case 2	Only SW2 is ON	✘	✔	✘	✘
	Case 3	Only SW3 is ON	✘	✘	✔	✘
	Case 4	Only SW4 is ON	✘	✘	✘	✔
B	Case 5	Only 2 up switches are ON (SW1 and SW2)	✔	✔	✘	✘
	Case 6	Only 2 down switches are ON (SW3 and SW4)	✘	✘	✔	✔
C	Case 7	Only 2 left switches are ON	✔	✘	✔	✘
	Case 8	Only 2 right switches are ON	✘	✔	✘	✔
	Case 9	All switches are ON	✔	✔	✔	✔
D	Case 10	All switches are OFF	✘	✘	✘	✘

✔: ON mode, ✘: OFF mode.

Figures 6(a) to 6(j) show the current distributions at the substrate 3 (ground layer), to represent all PIN diodes switches configuration either in ON or OFF modes. The PIN diodes are located in between I-shaped aperture slot and H-shaped aperture slot. It is clearly shown that the PIN diode switches are used to control the activation of the aperture slots located between them. The red color shows the current exciting/distributing along the feed line and the aperture slots. When the PIN diode switch is in ON mode, both aperture slots (I-shaped and H-shaped) will be activated. Therefore, the wave from I-shaped aperture slots will radiate to activate the bottom patch while the wave from H-shaped aperture slots will radiate to activate the top patch. While during the PIN diode switch is in OFF mode, only I-shaped aperture slots are activated, and the wave will radiate to activate the bottom patch. The wave or signal from the activation of the particular aperture slots will be transmitted and radiated to the selected radiating elements either at substrate layer 1 or substrate layer 2, thus resulting in the frequency and pattern reconfigurability.

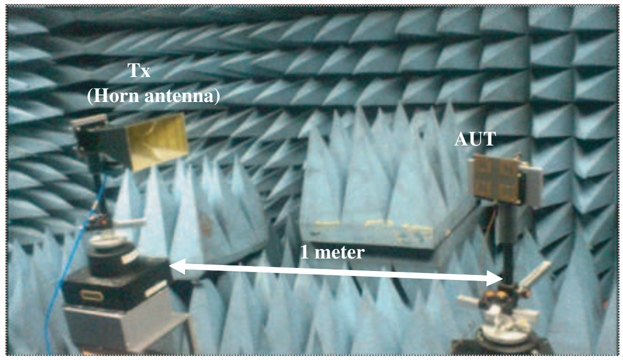


Figure 5. Measurement of radiation patterns set up in an achenoic chamber.

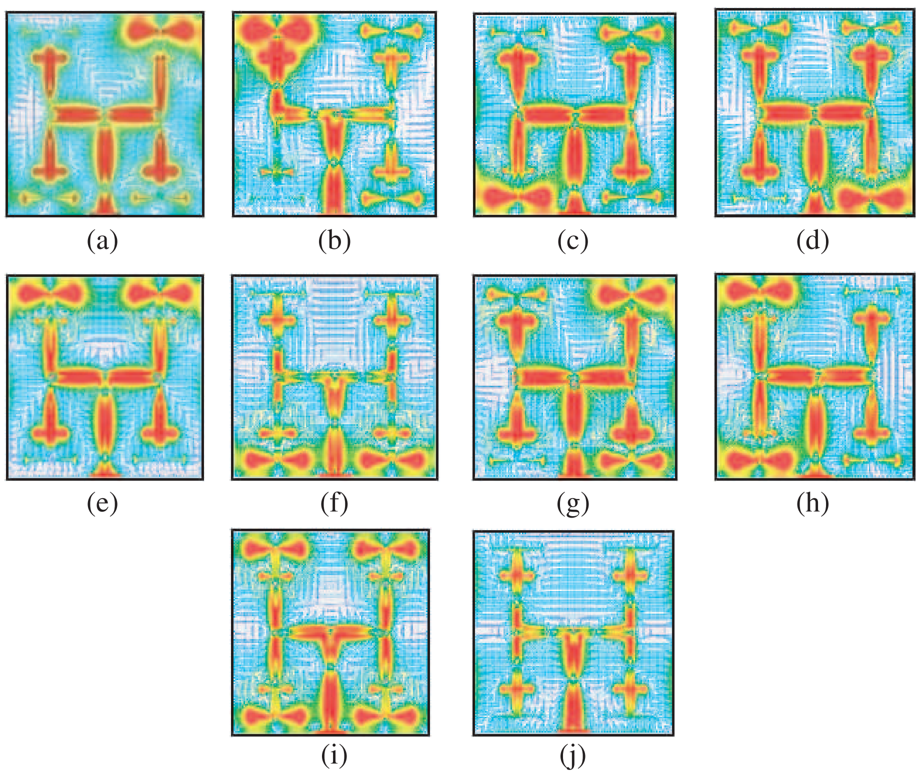
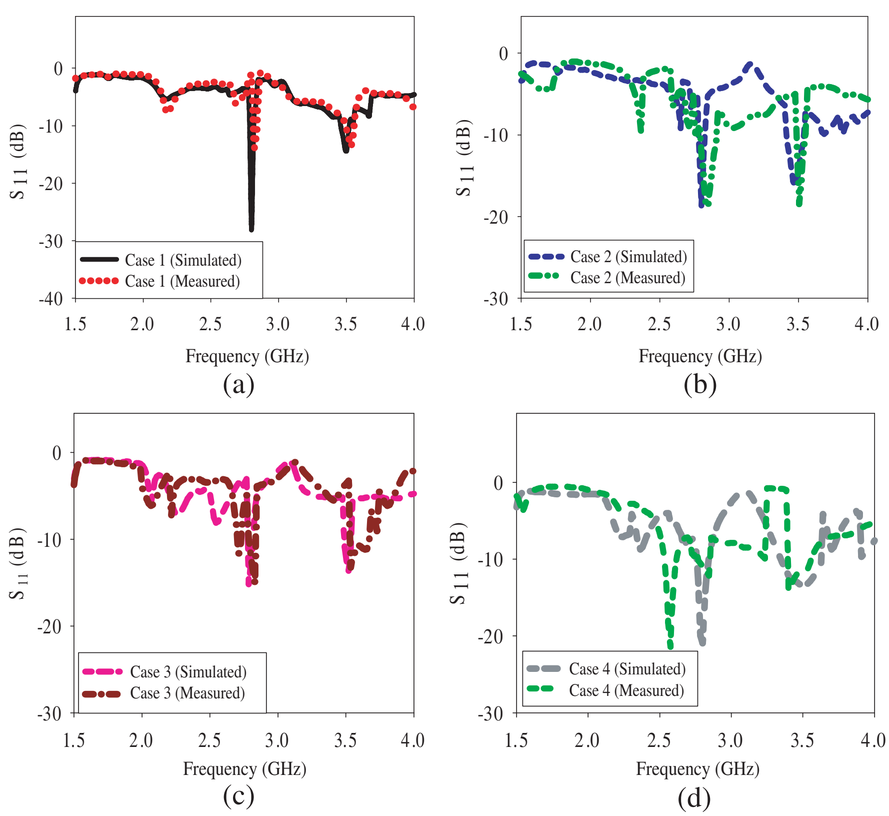


Figure 6. Simulated current distributions at the substrate layer 3 (between feedline and the aperture slots) for all PIN diodes switches configurations. (a) Case 1, (b) Case 2, (c) Case 3, (d) Case 4, (e) Case 5, (f) Case 6, (g) Case 7, (h) Case 8, (i) Case 9, and (j) Case 10.

The simulated resonant frequency and pattern characteristics of the proposed antenna are shown in Table 2. The results clearly show that the PIN diode switches configuration can be divided into 4 groups, A, B, C, and D. The group is determined by sorting the cases into categories based on resonant frequencies achieved during the simulation. Each group has a few operating frequencies and a main lobe direction for the radiation patterns based on the PIN diode switches configuration. Group A (case 1 to case 4) results in the operating frequencies of 2.8 GHz and 3.5 GHz when only one PIN diode switch is in ON mode while the three others are in OFF mode. In group B (case 5 to case 6), two PIN diode switches are in ON mode, and the other two PIN diode switches are in OFF mode. The antenna has possibility to operate at 2.6 GHz and 2.8 GHz. Case 7 to case 9 are categorized under group C, where only two PIN diode switches located at right are in ON mode and the other 2 located at left are in OFF

Table 2. The simulated resonant frequency (GHz) and radiation pattern characteristics.

Group	Cases	Resonant Frequency (GHz)	Main Lobe Direction (°)	Simulated Gain (dBi)	Measured Gain (dBi)	Beam-widths (°)
A	1	2.8	0	7.86	7.8	65.6
		3.5	−17	10.42	10.38	112.2
	2	2.8	0	7.86	7.6	74.8
		3.5	+17	10.42	10.3	80.4
	3	2.8	0	7.37	7.22	58.2
		3.5	−15	10.79	10.6	33.4
	4	2.8	0	7.37	7.35	6.0
		3.5	+15	10.79	10.7	11.0
B	5	2.6	0	11.24	11.2	44.9
		2.8	0	10.45	10.4	39.5
	6	2.6	0	11.27	11.2	45.8
		2.8	0	10.17	10.1	38.5
	7	2.6	−30	8.79	8.7	39.8
C	8	2.6	+30	8.79	8.58	39.8
	9	2.6	+32	9.42	9.1	49.2
D	10	3.5	+160	10.49	10.4	22.2



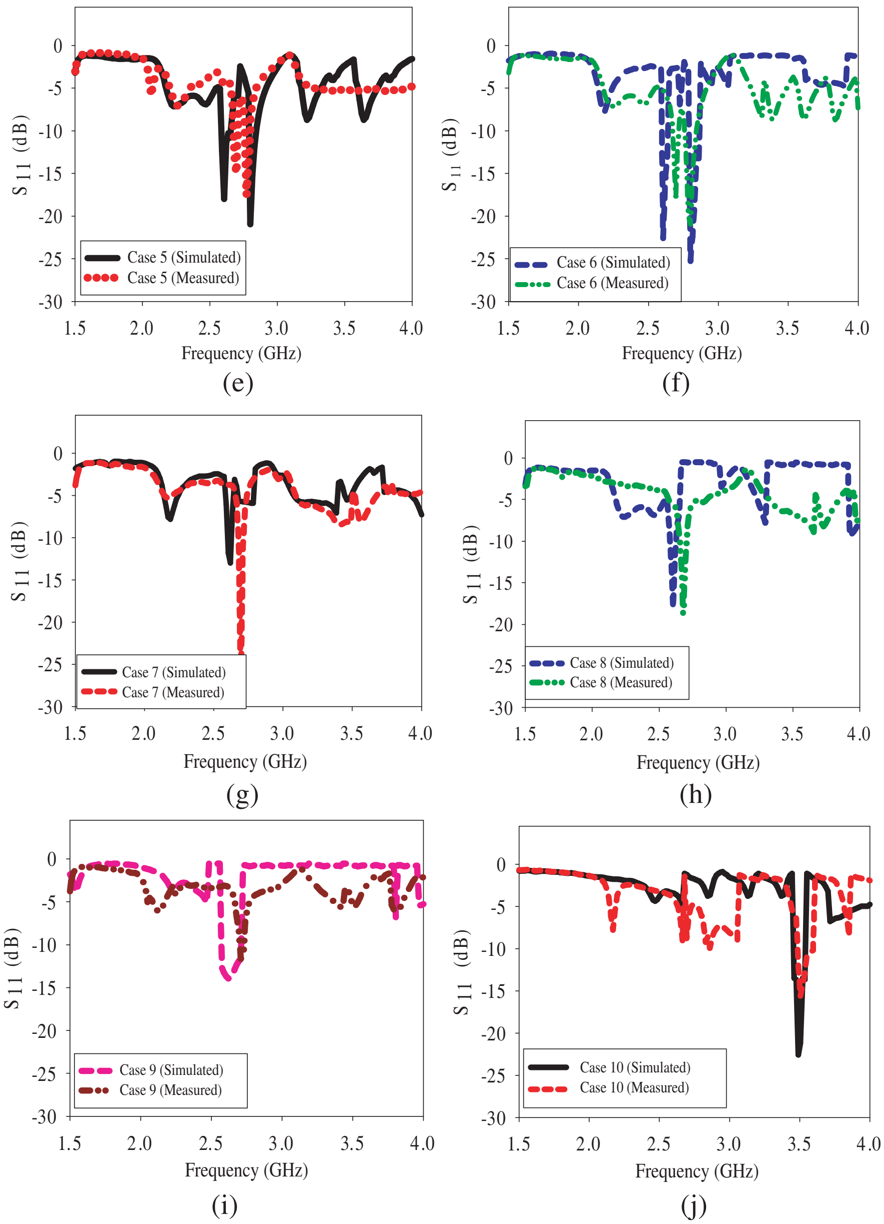


Figure 7. Simulated and measured reflection coefficient, S_{11} for all cases. (a) Case 1, (b) Case 2, (c) Case 3, (d) Case 4, (e) Case 5, (f) Case 6, (g) Case 7, (h) Case 8, (i) Case 9, and (j) Case 10.

mode, or vice versa. The antenna will operate at 2.6 GHz. Last but not least, when all the PIN diode switches are in OFF mode (case 10), only I-shaped aperture slots are activated, then has the possibility to operate at 3.5 GHz frequency.

The average antenna gain is considerably high, which is between 7.37 dBi to 11.24 dBi, due to the use of stacked patch and air gap in the antenna design. Next, to validate and confirm the operation of the proposed antenna, the measurement of the reflection coefficient, S_{11}, has been conducted and illustrated in Fig. 7. From the measured results, we can see that all cases seem to have a slight frequency shift compared to the simulation results. This is due to the effect of the passive components at the feed network where the switching circuit also produces its own electric field, which will give an effect on the antenna's operating frequencies. The misalignment error and improper gluing between the substrate layers 1 and 2 also contribute to the low antenna performance.

Figures 8–11 show the simulated and measured radiation patterns in polar plots of the proposed

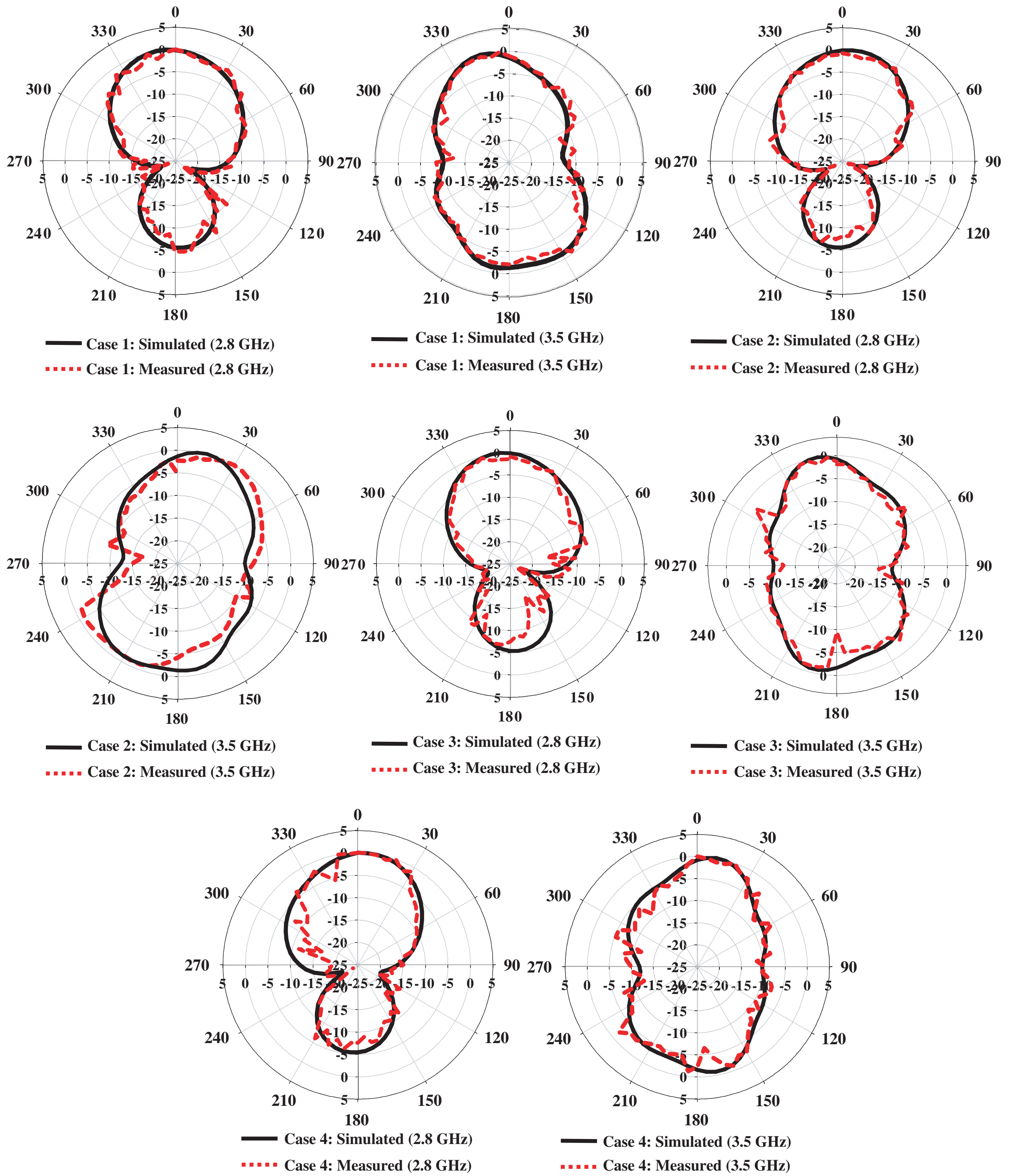


Figure 8. Simulated and measured radiation patterns in a polar plot for Group A: Case 1, Case 2, Case 3, Case 4.

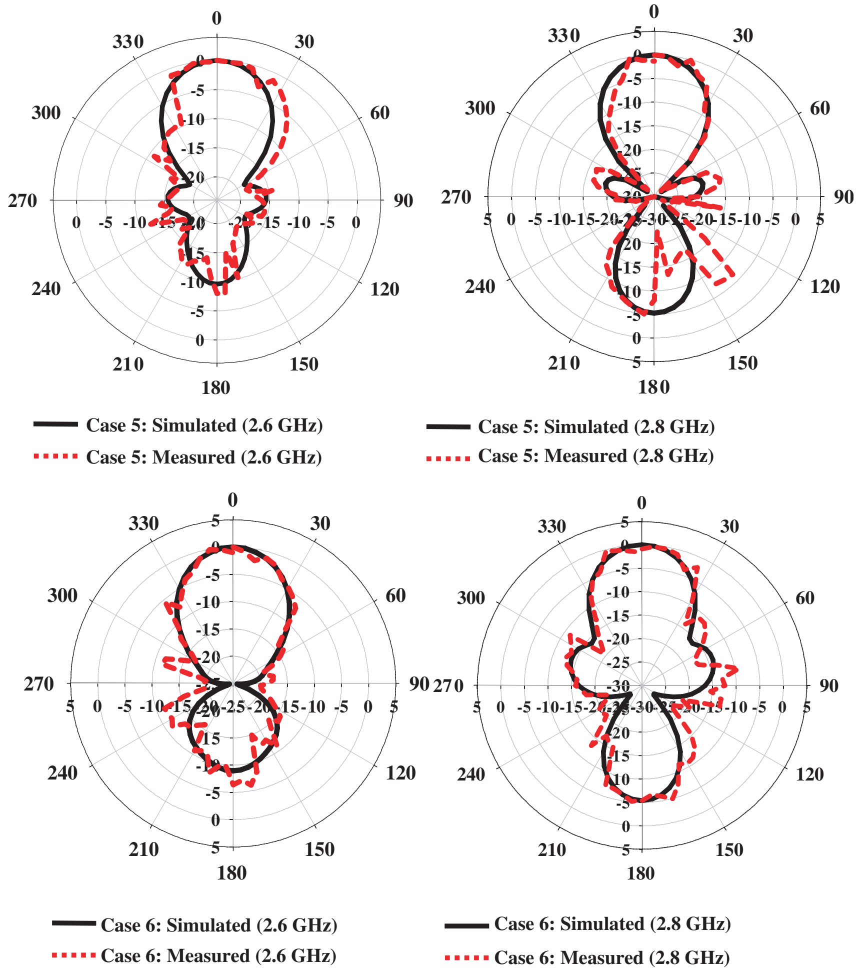


Figure 9. Simulated and measured radiation patterns in a polar plot for Group B: Case 5, Case 6.

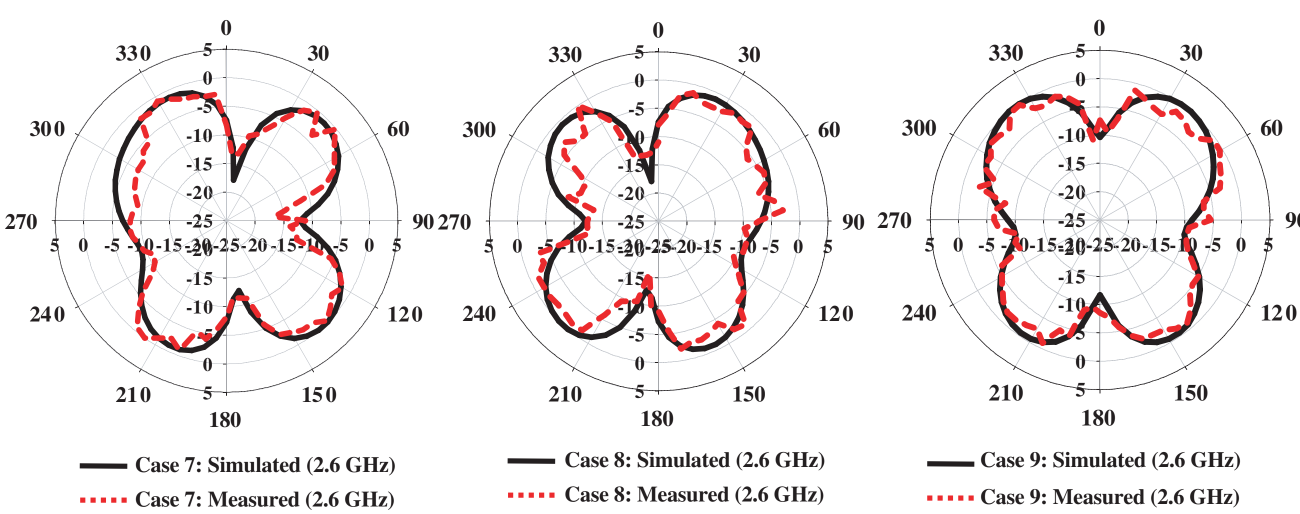


Figure 10. Simulated and measured radiation patterns in a polar plot for Group C: Case 7, Case 8, Case 9.

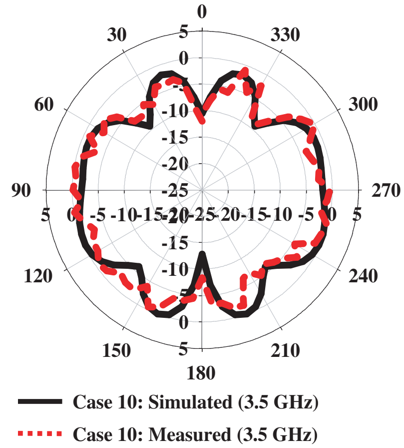


Figure 11. Simulated and measured radiation patterns in a polar plot for Group D: Case 10.

antenna, sorted by groups. The radiation patterns are cut in E-plane (y-z direction) with phi $= 90°$. A good agreement with the minor discrepancies between the simulation and measurement results is clearly achieved. The main beamer is directed to $+0°$, $-30°$, $+30°$, and $+32°$ at the resonant frequency of 2.6 GHz; $0°$ at 2.8 GHz; and $-17°$, $+17°$, $-15°$, $+15°$, and $+160°$ at 3.5 GHz.

4. CONCLUSION

In summary, the unique structure of the proposed antenna with a combination of aperture-coupled technique and stacked patch technology has been presented. The antenna has possibilities to operate at three operating frequencies with various patterns/directed beam by changing the length of the feed network, depending on the PIN diode switches configurations. From the simulated and measured results, it has been confirmed that the antenna is working, but the reflection coefficients (S_{11}) are slightly shifted for certain cases. The misalignment problem and gluing error give significant effect on the resonant frequencies, gains and the radiation patterns characteristics. In conclusion, the proposed antenna can operate at 2.6 GHz with the beam directed to $+0°$, $-30°$, $+30°$, and $+32°$, at 2.8 GHz with the beam directed to $+0°$, and at the 3.5 GHz frequencies with the beam directed to $-17°$, $+17°$, $-15°$, $+15°$ and $+160°$. The results from this research show that the antenna has a great potential to be implemented in wireless communications, especially for WiMAX, WiFi, and Long-Term Evolution (LTE/band 7) in Malaysia.

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