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APERTURE-COUPLED FREQUENCY-RECONFIGURABLE STACKED PATCH MICROSTRIP ANTENNA (FRSPMA) INTEGRATED WITH PIN DIODE SWITCH

Nurulazlina Ramli*, Mohd Tarmizi Ali, Azita Laily Yusof, Suzilawati Muhamud-Kayat, and Hafiza Alias

Antenna Research Group (ARG), Microwave Technology Centre (MTC), Faculty of Electrical Engineering (FKE), UiTM, Shah Alam, Selangor 40450, Malaysia

Abstract—In this paper, a new Frequency-Reconfigurable Stacked Patch Microstrip Antenna (FRSPMA) with a new coupling method applied in an aperture-coupled technique controlled by the switching circuit is presented. This antenna uses a combination of aperture-coupled technique and stacked patch in order for the radiating elements to increase the bandwidth. Two shapes (I-shape and H-shape) and sizes of aperture slots are etched onto the ground with a purpose to couple the energy between feedline and stacked patch. One PIN diode switch is integrated in the feed network to control the length of the feedline. A variation of the feedline length controls the selected aperture slots to be active. The waves from the selected activated aperture slots will radiate to particular radiating patch (top or bottom patch) and achieve the frequency reconfigurability. When the switch is in ON mode, the antenna has a capability to configure its operating frequency at 2.6 GHz and at 3.5 GHz during the OFF mode. Besides that, the air gap is used to improve and avoid any coupling problem between the aperture slots and both of the two patches. Improper alignment between the aperture slots and patches will interfere waves radiating from aperture slots to the particular patch. In addition, the proposed antenna produces a high gain of more than 5 dB during ON or OFF modes, respectively. The simulated results are compared with measured results.

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* Corresponding author: Nurulazlina Ramli (nurulazlina84@gmail.com).

1. INTRODUCTION

Reconfigurable microstrip antenna (RMA), also known as a multi-function antenna, has several advantages and capabilities in the technology market especially in wireless and mobile communication transceivers. It is widely explored since it gives more benefit than the conventional antennas whereby using a single antenna is competent to operate or support multiple operating frequencies [1], radiation patterns [2] and polarization [3]. Moreover, RMA is convenient for a certain design because its manufacturing cost is very economical as the size is small and compact. It is also easy to fabricate. This Frequency-Reconfigurable Stacked Patch Microstrip Antenna (FRSPMA) can be realised by changing its physical structure or size dynamically without changing the whole antenna structure. The basic working principle of this reconfigurable antenna is achieved by switching the status of an RF switch either to ON or OFF mode which then affects the current distribution of the antenna. Switching components such as PIN diodes [2], varactor diodes [4], MEMs switches [5], and optoelectronic switches [6] are normally used to achieve frequency-reconfigurable antenna. Yet, the PIN diode switch is an optimum choice because it has low insertion loss, fast response, low control voltage, and reliable. However, most of the RMAs especially conventional microstrip antennas have drawbacks, i.e., narrow bandwidth and low gain performances. Therefore, this FRSPMA is designed to complete the needs of reconfigurable antenna, which are to have wide bandwidth and high gain performance. Hence, this paper discusses the techniques that have been applied or combined. This paper also discusses a new switching method implemented in this FRSPMA in order to receive unique structures of the reconfigurable antenna.

Most reconfigurable antennas are frequency-reconfigurable antennas due to their high reliability to be applied in multiple applications using a single antenna. There are a few methods that are normally used in order to achieve frequency-reconfigurable antenna. The first method is by controlling the connection or disconnection of the connecting elements (patches) on the same substrate, which results in multiple frequency-reconfigurable antenna [7–9]. The major disadvantage of this technique is that the antenna can be considered big and bulky where all the radiating elements are positioned on the same substrate. The second method is by varying the effective length of the slot with embedded RF switches across slots such as U-slot, V-slot, rectangular slots or other shapes of slots to make the antenna switchable. These slots with RF switches are normally etched on the radiating patch [10, 11] or on the ground plane [1, 12], which results in multiple resonant frequencies. In [18], the frequency-reconfigurable aperture coupled antenna is achieved by controlling the switch at the slot on the ground plane. Four different sub-bands have been accomplished by configuring seven PIN diodes switches into four configurations. By applying this method, the lower resonant frequency will be obtained without increasing the overall structure of the antenna where the size of the antenna is proportional to the operating frequency. Subsequently, for the quasi-Yagi microstrip antenna, the resonant frequency can be tuned by varying the driven element length of the antenna [13]. By using PIN diode switches, it allows the quasi-Yagi microstrip antenna to operate at different frequencies and directions, as shown in the results of [14]. Consequently, by configuring the switches at the feed network to ON or OFF mode, the number of the activated patches can be controlled thus frequency-reconfigurable antenna can be achieved. In [15], the authors use the aperture-coupled technique to achieve the frequency-reconfigurable antenna. In this design, when one of the two switches at the feed network is in ON mode, two of four patch elements are activated (either on the left hand side or on the right hand side). This ensures the antenna to operate at either 5.3 GHz or 5.8 GHz. In this design, all patch elements have the same size due to the usage of the slotted patches. However, the patch elements are divided into two sides (two on the left and two on the right) to represent the different operating frequencies. In [16], a novel reconfigurable microstrip antenna has a capability to operate in single, dual, and triple band applications by electronically varying the value of the diode capacitance. Another method that does not use RF switches to achieve frequency-reconfigurable antenna is reported in [17] where the concept of rotatable patches that have different sizes and shapes in a same radiating layer is used. Every rotation at a different antenna structure is fed to produce a different frequency range. However, reconfigurable antenna with a combination of aperture-coupled stacked patch technology has yet to receive the significant attention due to its complex multilayer design structure. This is particularly when an aperture-coupled technique that involves alignment between the aperture slots on the ground is used. The patch must be central to obtain maximum coupling between aperture slots on the ground and the patches.

Therefore, this paper exemplifies the behaviours of Frequency-Reconfigurable Stacked Patch Microstrip Antenna (FRSPMA) with a combination of aperture-coupled technique with two different shapes of aperture slots placed on the ground and stacked patch with a purpose to radiate elements. This technique reduces the spurious radiation patterns and increases the bandwidth of the antenna. A unique structure with a new approach to switching technique applied in an aperture coupled concept gives the novelty of this design. By configuring the PIN diode switch at the feed network, the activation of particular aperture slots on the ground and the different radiating patch at different substrate layers (top or bottom patch) can be controlled to ensure the functionality of the reconfigurable antenna. The proposed antenna can be constructed for applications in Malaysia, either for WiMAX technology (IEEE 802.16e-2005 standard) at a frequency of 3.5 GHz or for Long Term Evolution (LTE) at 2.6 GHz. A new concept of this coupling method in order to attain frequency reconfigurable antenna will be explained in Section 2.1. In Section 3, the antenna performances in terms of the frequency, return loss and antenna gain, and the characteristic of the radiation pattern between simulated and measured results will be compared. Finally, the conclusions are presented in Section 4.

1.1. Aperture-coupled Technique

The aperture-coupled technique is one of the feeding methods in designing microstrip antenna. It was first introduced by D. M. Pozar in 1985, where it consisted of two substrates separated by a common ground plane in between [19]. In this method, the radiating patch element and the feedline are not in direct connection; the radiating patch is etched on top of the substrate and the feedline is etched on the bottom (back) substrate. A small aperture slot on the ground is oriented to excite the magnetic field between the feedline and patch. Maximum coupling would occur when the patch is at the centre across the aperture slot. However, the shape and the sizes of the aperture slot influence the mechanism for coupling. Conventional methods in aperture-coupled technique allow much stronger coupling, but the H-shaped, dog bone, bowtie, and hourglass-shaped aperture slots yield better coupling [20]. The coupling mechanism and the aperture slot placement for desired coupling are explained in [19, 21]. The advantage of this technique is that it eliminates the spurious signal radiation between feedline and radiating patch. In [22], an air layer (stand-by honeycomb or foam) is added in between the patch and the ground. The purpose is to limit the effect of surface waves from the slot and to enable easy adjustment of the slots to patch. These features give a broad bandwidth and high gain performances.

In [23], aperture-coupled stacked microstrip antenna is presented. The antenna has the capability to operate over a frequency bandwidth excess of 20%. Another rectangular patch is etched on a new substrate located on top of the previous aperture-coupled design and an air gap of 0.1 mm is added between the ground plane and first dielectric layers. Both radiating substrates are thick enough to provide low Q-resonator [23]. The dimension of bottom and top patch must be similar to maximise coupling factor from aperture to each patch [23]. The function of the top patch is like a parasitic element placed over the lower patch. In [24], the authors suggest and highlight that the top patch dimension must be larger than the bottom patch if both patches have dissimilar dimensions. If the bottom patch dimension is larger than the top patch, it produces a low resonant frequency that results in poor coupled energy from bottom patch to upper patch. Hence, the antenna only operates at a low resonant frequency and the top patch acts as a parasitic element. As reported in [25], a novel broadband aperture coupled microstrip patch antenna enhances the bandwidth from 11.22–12.21 GHz to 11.58–13.55 GHz where the apertures slot is offset to 1.5 mm from the patch centre. Therefore, it is possible to allocate the aperture slot not exactly at the patch centre as long as it gives the maximum coupling and resonant at the desired frequency.

2. ANTENNA CONFIGURATION

The geometrical structure and dimensions of the novel FRSPMA are shown in Fig. 2. The basic configuration uses a combination of aperture-coupled technique and stacked patch as a radiating element. This FRSPMA consists of 3 substrate layers that use the RT-Rogers Duroid 5880 substrate layers that have a dielectric constant, $\varepsilon_r = 2.2$, thicknesses, $h_1 = 0.787$ mm, and tangent loss, $\delta = 0.0009$. In order to increase the gain of the antenna, an air gap structure of $h_2 = 3$ mm thickness with dielectric constant, $\varepsilon_r = 1$ is added between the feedline substrate (layer 3) and substrate (2 layers). The advantage of having an air gap is to avoid coupling problems between the aperture slots and the two patches due to improper alignment between them. All substrate dimensions are 52 mm × 52 mm and the total thickness of this FRSPMA is 5.361 mm. The structure's top view and every layer's view of this RSPMAA with fixed dimensions are shown in Fig. 1 and Fig. 2. The geometry of the whole FRSPMA structure in a 1-plane

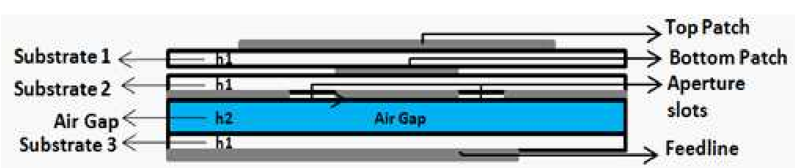
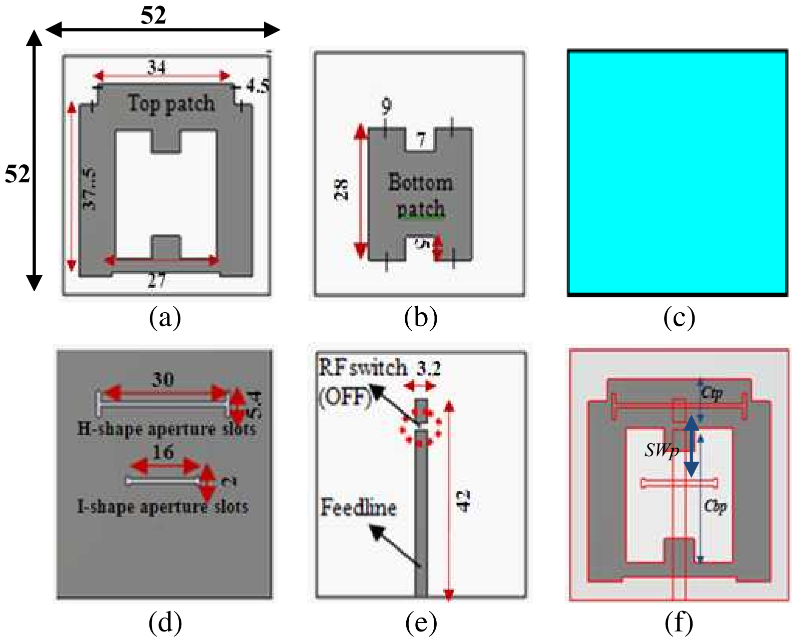


Figure 1. Side view structure of the FRSPMA.



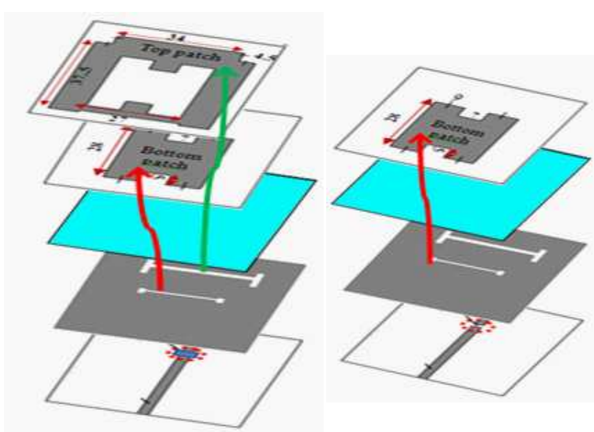
(a) (b) (c)
(d) (e) (f)

Figure 2. Geometry and dimensions (mm) of the FRSPMA. (a) Substrate 1: Top patch, (b) substrate 2: Bottom patch, (c) air-filled gap, (d) ground plane with two aperture slots, (e) substrate 3: Feed network with one RF switch (back view), and (f) geometry of the whole antenna structure in 1-plane view.

view is shown in Fig. 2(f). A rectangle shape with an H-shaped hole at the centre (known as top patch) is etched on top of substrate 1 while H-shaped patch (known as bottom patch) is etched on top of substrate 2. The basic rectangular dimensions for both patches are designed based on 2.6 GHz and 3.5 GHz. However, the structure has been altered and by configuring the switch, frequency-reconfigurable antenna has been achieved. The feedline is etched on the bottom of substrate 3 to maintain a characteristic impedance of 50 Ω. One PIN diode switch is integrated along the feedline to control the feedline's length. The switch dimension of 3.2 mm × 1.5 mm is reconfigured to the ON or OFF mode, and thus controls the electricity flow to the ground where it is located between the feedline substrate and an air-filled substrate. In this design, the aperture coupler technique is used to separate the feedline and the radiating layers on different substrate layer, hence reduces the spurious radiation patterns between them.

Two sets of aperture slots with different sizes and shapes (H-shape and I-shape) are etched onto the ground plane. The H-shaped aperture slot on the ground plane is positioned at the centre with reference to the top patch while the I-shaped aperture slot is positioned at the centre with reference to the bottom patch. The function of an I-shaped aperture slots is to radiate the waves and to activate the bottom patch while the H-shape aperture slot is used to activate the top patch. The ratio of the slot length to width is typically 1 : 10. In a nutshell, all of the aperture slots must be precisely positioned at the feedline and at the centre with reference to the top and bottom patches in order to produce maximum coupling [5]. In simulation, the presence and absence of copper strip line are used to present the PIN diode switch during ON or OFF mode, respectively. Thus, two prototypes of the antenna structures have been evaluated and compared with the simulated results.

In this design, a new concept of coupling methods is implemented in aperture-coupled technique by controlling the length of the feedline when the PIN diode switch is in ON or OFF mode. The increase and decrease of the feedline length will control the electrical flow from the feedline to the selected aperture slots (either H-shape or I-shape) on the ground plane. Then, the waves from the activated aperture slots will radiate to the particular radiating patch at different substrate layers. Fig. 3(a) shows the FRSPMA during ON mode where both aperture slots are activated and the waves radiate to the selected patch thus activating it or turning it to ON mode. The top patch and bottom patch are then combined and connected with each other to become a large patch, which results in a lower resonant frequency of 2.6 GHz.



(a) (b)

Figure 3. Operation of the RSPMAA when all switches are in (a) ON mode and (b) OFF mode at 3.5 GHz.

However, when the PIN diode switch is in OFF mode (Fig. 3(b)), only I-shaped aperture slots on the ground are activated and the waves radiate to activate the bottom patch. In this state, the activation of the bottom patch allows the antenna to operate at a high resonant frequency of 3.5 GHz.

2.1. PIN Diode Switching Circuit

In this work area, an ideal switch (presence and absence of copper strip line) is used in CST simulation based on the basic concept of the PIN diode switch configuration. To prove the simulated concept, a real PIN diode switch is placed on the prototype. The basic switching circuit, as shown in Fig. 4(a), has been analysed and tested first to suit the design. The basic switching circuit consists of one PIN diode, one capacitor, two inductors, and one resistor. The Philips PIN diode, BAP51-02 is selected as the RF switch in this design. The capacitor (C_1) is used for DC blocking, while the inductors (L_1, L_2) are used as RF chokes, thus providing low impedance for DC. During the ON state, the biasing voltage of 12 V is connected to a 150 Ω resistor (R_1) to limit the current flow to the switch, while for the reverse state, 0 V is supplied. Therefore, the Advanced Design System (ADS) software is used to design, simulate, and validate the performance of this switching circuit. Next, from the analysis in ADS software, the layout of the proposed feed network integrated with a few RF components is generated, as

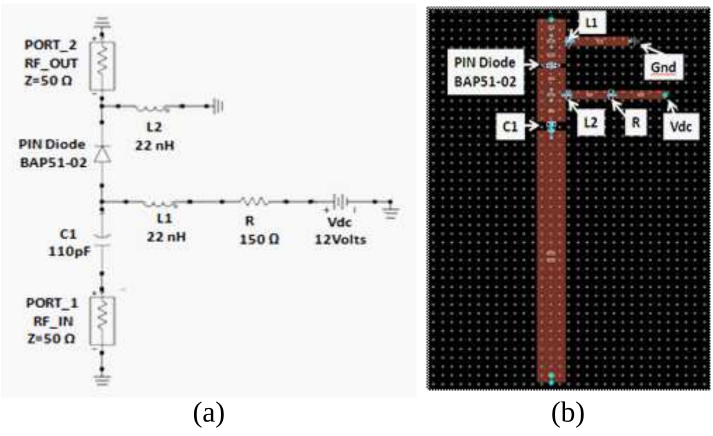


Figure 4. (a) The basic design of the equivalent switching circuit with the PIN diode switch, and (b) the layout of the switching circuit in ADS software.

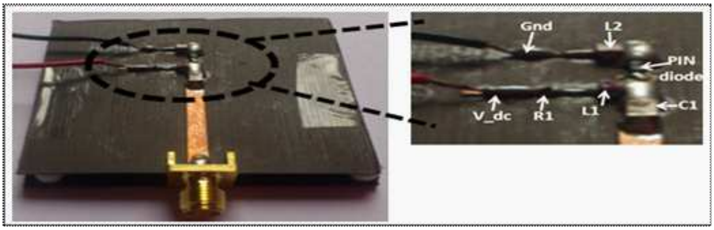
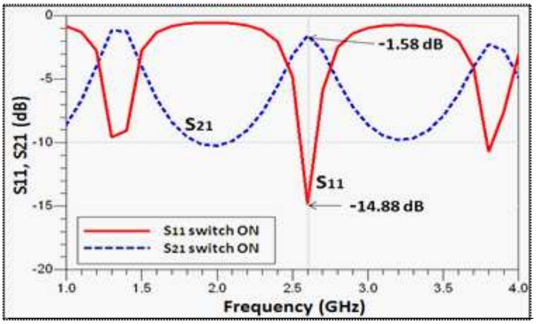
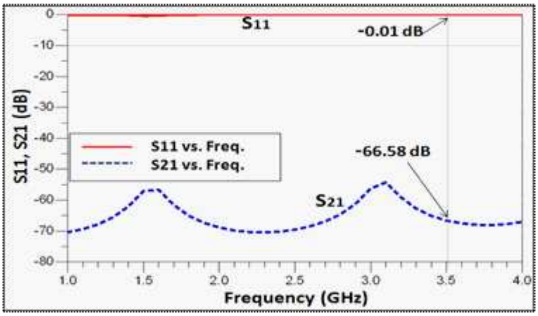


Figure 5. The back view of the FRSPMA with equivalent switching circuit models.



(a)



(b)

Figure 6. Simulated results of S_{11}, S_{21} (dB) vs. Frequency (GHz) for the equivalent switching circuit during (a) switch ON mode and (b) switch OFF mode.

shown in Fig. 4(b). The back view of the FRSPMA integrated with equivalent switching circuit is shown in Fig 5. The simulation using the PIN diode equivalent circuits in the ON and OFF modes is shown in Fig. 6. When the PIN diode switch is in ON mode, Port 1 (S_{11}) is in perfect match conditions and it allows all the signals to pass through to Port 2 (S_{21}). Therefore, the current flows along the feed network and activate the selected aperture slots and patches. Thus, when the switch is in ON mode, the S_{11} is resonant at 2.6 GHz with -14.88 dB while S_{21} is equal to -1.58 dB. However, when the switch is in OFF mode, Port 1 will reflect all the signals and no signals are allowed to pass through to Port 2. In this mode, the S_{11} is equal to -0.01 dB and S_{21} is equal to -66.58 dB at 3.5 GHz. The prototype of the proposed antenna is shown in Fig. 7. Two prototypes of the FRSPMA, without using the real PIN diode switch (absence and presence of copper strip line) as in Fig. 7(b) and FRSPMA with real PIN diode switch shown in Fig. 7(c), have been fabricated.

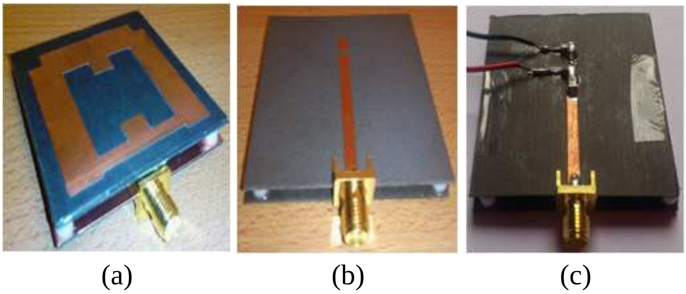


Figure 7. Prototype of FRSPMA. (a) Top view, (b) bottom view without a real PIN diode switch, and (c) bottom view with real PIN diode switch.

3. RESULTS AND DISCUSSION

At the early stage of this design, the FRSPMA is evaluated with the ON mode switch. Copper strip line is used to represent the ON condition of the PIN diode switch. At this stage, the FRSPMA is capable to operate at the frequency of 2.6 GHz. The Computer Simulation Technology (CST) Microwave Studio is used to simulate the proposed antenna. In order to achieve the frequency-reconfigurable antenna, the PIN diode switch is changed to the OFF mode (i.e., the copper strip line is absent). The position of the PIN diode switch is optimised along SWp of 15 mm in length (refer to Fig. 2(f)). As illustrated in Fig. 8, with an increase of 3 mm of the sweep from 3 mm to 12 mm, all of the frequencies are resonated at a high range between 3 GHz to 4 GHz whilst decreasing the impedance matching. In this case, 12 mm is an appropriate choice for the switch position due to

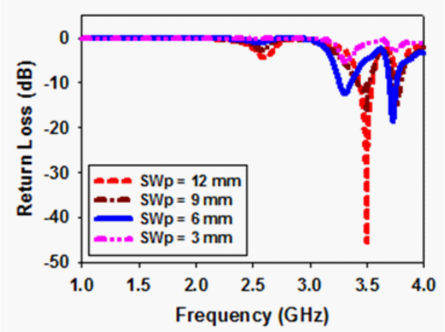


Figure 8. The return loss effects of switch position along SWp during SW OFF.

its resonance at a fixed frequency of 3.5 GHz with good impedance matching of -45.37 dB.

Figure 9 shows the effect of the surface current from the back view of the proposed antenna when the PIN diode switch is in the ON or OFF mode. When the switch is in ON mode, the length of the feed network at the back of the antenna is fully connected and both aperture slots are activated too. Fig. 9(a) shows how the current travels from the SMA connector to both aperture slots (H-shape and I-shape) and each aperture slot will produce waves to activate the top and bottom patches, respectively. On the other hand, when the switch is in OFF mode, only the small aperture slot (I-shape) is activated and thus radiating the waves to activate the bottom patch, as shown in Fig. 9(b). Fig. 10 demonstrates the simulated results when the PIN diode switch is in ON or OFF mode. The antenna is capable to operate at 2.6 GHz with -25.58 dB return loss when it is in ON mode. On the other hand, in OFF mode, the antenna operates at the frequency of 3.5 GHz with -45.37 dB return loss.

The characteristics of the simulated radiation pattern for the FRSPMA are shown in Table 1. The HPBW at 2.6 GHz is 94.4° and

Table 1. Radiation pattern characteristics of FRSPMA during ON and OFF modes.

Switch Mode	Resonant Frequency (GHz)	Gain (dB)	HPBW (°)	Side Lobe Level (dB)	Efficiency (%)
ON	2.6	6.253	94.4	-6.0	97.7
OFF	3.5	5.429	73.8	-1.1	88.0

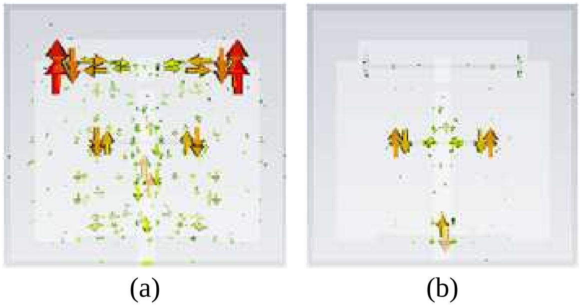


Figure 9. Simulated results of surface current from back view of the FRSPMA during (a) ON mode at 2.6 GHz and (b) OFF mode at 3.5 GHz.

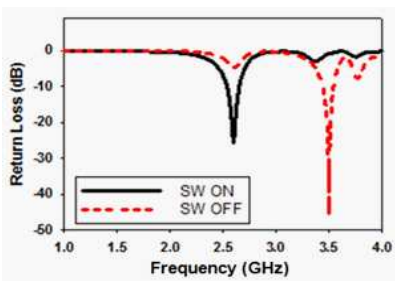


Figure 10. Simulated results of return loss when the switch is in ON and OFF modes.

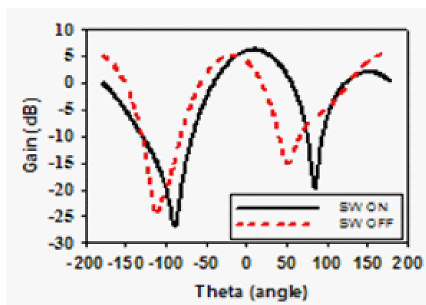
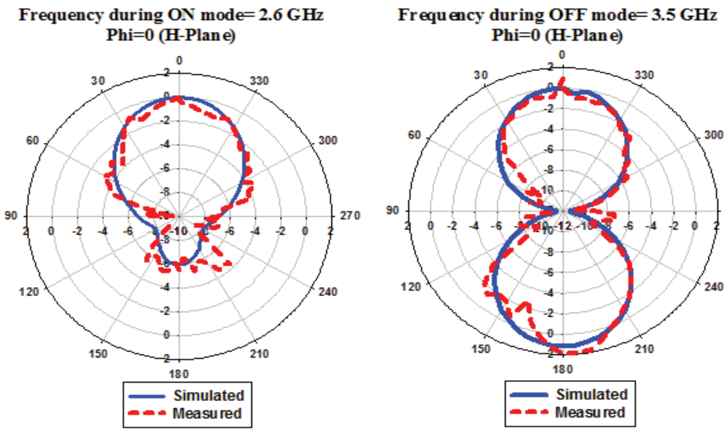
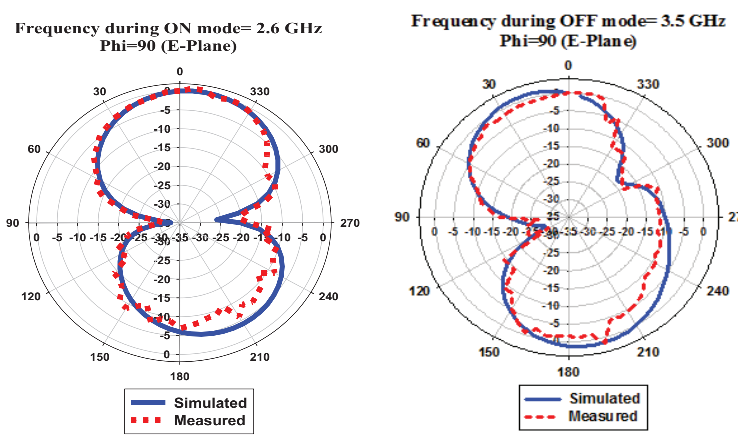


Figure 11. Simulated gains in Cartesian plot during ON mode at 2.6 GHz and OFF mode at 3.5 GHz.

at 3.5 GHz is 73.8°. The antenna can cover large areas but in short distance to transmit and receive the signal. The gain is 6.253 dB and 5.429 dB in ON and OFF mode, respectively. Fig. 11 clearly shows that the proposed FRSPMA has similar gains of more than 5.4 dB when the switch is in ON or OFF mode. By using stacked patch technology, the gain is considerably higher compared to the conventional single layer antenna. Fig. 12 shows the radiation pattern in a polar plot (H-plane and E-plane) during the simulation and measurement process for different PIN diode switch configuration. Fig. 12(a) illustrated the radiation pattern in H-plane view, where when the switch is in ON mode, the main beam direction for 2.6 GHz is directed to 0° and the signal strength is directed towards the radiating patches. On the other hand, when the switch is in OFF mode, the main beam is directed



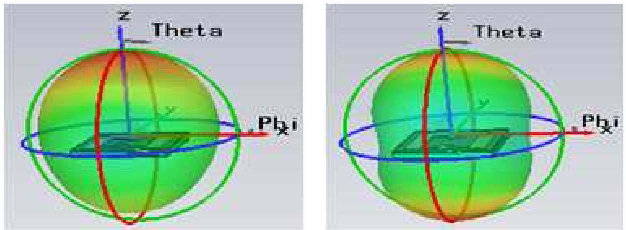
(a)



(b)

Figure 12. Simulated and measured radiation patterns in polar plot during ON mode at 2.6 GHz and OFF mode at 3.5 GHz with (a) Phi = 0 (H-plane) and (b) Phi = 90 (E-plane).

to 180° at the frequency of 3.5 GHz. It is clearly shown that the measured results are similar to the simulated results. However, some discrepancies can be seen in the measured but it can be accepted due to the fact that the radiation pattern measurement is done in an anechoic chamber. The radiation pattern in 3D view (H-plane) in Fig. 13 clearly shows that the signal strength transmission reflects from both sides, either towards the radiating patches or backwards to the feedline. This might be due to the effects of non-activation of H-shaped aperture slot during OFF mode. Even when this aperture slot is not activated, there are still radiations towards the feedline network. Therefore, the beam is directed to 180° during the OFF mode.



(a) (b)

Figure 13. Radiation patterns in 3D plot during (a) ON mode at 2.6 GHz and (b) OFF mode at 3.5 GHz.

In Table 2, the simulated and measured bandwidths for all cases are shown in details. The results show that the FRSPMA provides a bandwidth of around 120 MHz to 250 MHz during the ON mode and a bandwidth of around 115 MHz to 130 MHz during OFF mode switch. The simulated and measured return loss responses are given in Fig. 14. The prototype of the proposed antenna is done in two cases. The first case is FRSPMA without using the real PIN diode switch (copper strip line) and the second case is FRSPMA with real PIN diode switch. A good agreement is plotted between the simulated and measured return loss. Fig. 14(a) shows the experimental results when the PIN diode switch is in ON mode. Both simulated and measured return losses occur across 2.58 GHz to 2.605 GHz with less than −20 dB. The measured result using the real PIN diode switch is shifted about

Table 2. Comparison of the bandwidth (BW) values between simulated and measured resutls in ON and OFF modes.

Antenna Structure	PIN Diode Mode	
	ON mode (2.6 GHz)	OFF mode (3.5 GHz)
Simulated BW	119.8 MHz	129.5 MHz
Measured BW (without real switch/copper strip)	255 MHz	120 MHz
Measured BW (with real switch/PIN diode)	225 MHz	115 MHz

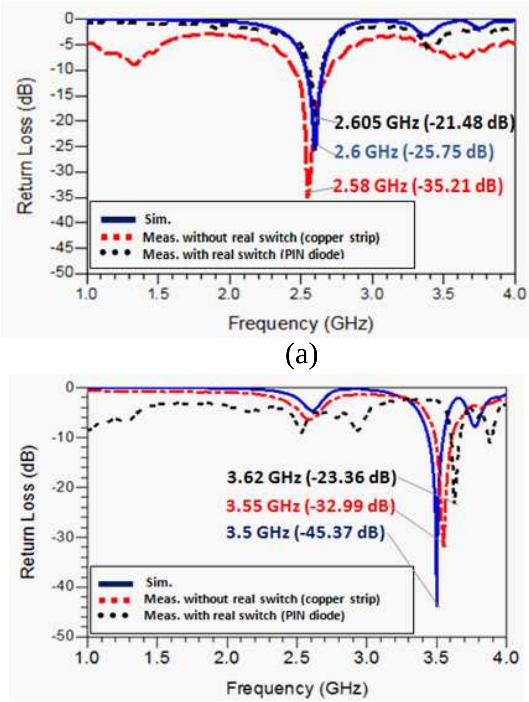


Figure 14. Comparison of S_{11} values between simulated and measured results during (a) ON mode and (b) OFF mode.

0.005 GHz with −21.48 dB while the measured antenna without using the real PIN diode switch is resonated at 2.58 GHz with −35.21 dB as compared to the simulated results. However, the shifted frequency is not too far from the desired frequency and achieved a good return loss with lower than −20.0 dB. The result during the OFF mode is shown in Fig. 14(b). The simulated result drops exactly at 3.5 GHz with −45.37 dB while the measured results, either without or with the real PIN diode switch, are slightly shifted from the 3.5 GHz frequency with a shifting variance of approximately 0.05 GHz and 0.12 GHz, respectively. All these discrepancies are due to the usage of an ideal switch in CST simulations. In addition, during antenna fabrication, there are already some imperfections emerging from the antenna such as improper handling when gluing all of the layers and misalignment of the aperture slot when positioning them onto the ground plane. These situations will definitely affect the antenna's performance in terms of resonant frequency, return loss, antenna gain, and antenna's efficiency.

4. CONCLUSION

In conclusion, both simulated and measured results on the FRSPMA structure demonstrate good results with good impedance matching by applying the concept of the reconfigurable antennas. The FRSPMA has been successfully developed with a unique structure, where the radiating patches are sorted in stacked (multilayer) structure and consist of two shapes of aperture slots positioned on the ground. On top of that, a new approach of the coupling methods has been successfully implemented based on the aperture-coupled technique, where one PIN diode (ON/OFF mode) switch is reconfigured on the feed network with the purpose to control the feedline length and the activation of the aperture slots on the ground plane. Thus, the waves will radiate to the particular radiating patch to excite the resonant frequency at either 2.6 GHz or 3.5 GHz. In this design, the passive components are employed on the feed network to implement the basic switching concept of a PIN diode switch. Furthermore, the gain is considerably higher with more than 5.4 dB during ON and OFF mode, respectively, compared to other single antennas. By using the proposed antenna, a single antenna can be used for multiple systems or applications. The results from this research will contribute towards the use of wireless communication system, especially for Long Term Evolution (LTE) and WiMAX applications.

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