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Frequency-Reconfigurable Stacked Patch Microstrip Antenna Using Aperture-Coupled Technique

N. Ramli[1], M. T. Ali[1], A. L. Yusof[1], S. Muhamud – Kayat[1], and A. A. A. Aziz[2]

[1]Antenna Research Group (ARG), Microwave Technology Centre (MTC), Faculty of Electrical Engineering,
Universiti Teknologi MARA, 40450 Shah Alam, Selangor, Malaysia.
[2]Center Of Medical Electronic Technology (CMET), Sultan Salahuddin Abdul Aziz Shah Polytechnic,
Persiaran Usahawan Seksyen U2, 40450 Shah Alam, Selangor, Malaysia.
Tel: +60123263010; E-mail: nurulazlina84@gmail.com[1], mizi732002@yahoo.com, azita968@salam.uitm.edu.my[1],
suzilawati.mkayat@yahoo.com[1], and 9m2agc@gmail.com[2]

***Abstract*—This paper presents a novel structure of a frequency-reconfigurable microstrip antenna fed with an aperture-coupled technique and stacked patch technology. The proposed antenna design has a unique structure; the radiating elements (top and bottom patch) are sorted in stacked substrate layers to indicate the different operating frequencies. One PIN diode switch integrated at the feedline is reconfigured to either ON or OFF mode to control the feedline's length, thus affecting the current distribution along it. Furthermore, a new coupling method in aperture-coupled technique is implemented, whereby the currents flow from the feedline's length will activate selected aperture slots on the ground and the wave will radiate to the selected patch at different substrate layers thus achieving the frequency reconfigurability. When the PIN diode switch is in ON mode, the proposed antenna is capable to operate at 2.6 GHz while in OFF mode, the antenna is able to operate at 3.5 GHz by using the same antenna. Therefore, the effects of an aperture slots characteristic and the PIN diode switch position along the feedline have been studied. The prototype of the proposed antenna is tested/fabricated with the biasing circuit to validate the antenna's performance in terms of return loss and radiation pattern. The results confirm that the antenna has a good agreement between the simulation and measurement results.**

***Index Terms*: aperture-coupled technique, aperture slots, coupling, frequency-reconfigurable antenna, PIN diode and stacked patch**

I. INTRODUCTION

Reconfigurable Microstrip Antennas (RMAs) are a current technology that has been adequately applied in modern wireless systems or radar applications. RMA basically comes from the conventional microstrip antenna. But, the antenna has been upgraded by integrating it with radio-frequency (RF) switches such as PIN diode, microelectromechanical system (MEM) switch, varactor diode, etc. Next, by configuring the RF switches either to ON or OFF mode, the current distribution will be affected. Thus, the antenna has a capability to control or change the frequency, polarization or radiation pattern in real time without changing the whole dimension/structure of the antenna. RMA is cost-effective because it is more convenient to operate certain applications with a single antenna than multiple antennas or known as multi-functional antenna. However, most RMAs have the drawback of narrow bandwidth and low gain.

One of the techniques to improve the bandwidth and gain is by using multilayer structure (stacked patch configuration) [1] or with low dielectric constant, which is between 1.0-1.03, such as air gap filled [2], vacuum, or C-foam [3] material. In [4], parasitic elements are used to provide bandwidth enhancement, while the use of parallel slots offers the antenna a patch size reduction and gain enhancement. By cutting the slots on the radiating elements with different shapes such as U-shaped slot (thus called U-slot), V-shaped slot (thus called V-slot), and a pair of rectangular slots, the dual or triple band microstrip antenna is realized. The switching of a PIN diode switch on U-slot that is incorporated into the square patch results in a dual band microstrip antenna [5]. The combination of nine rectangular patches in the same substrate with eight PIN diodes also produces multiple resonating frequencies with various radiation patterns [6]. In [7], the PIN diode switches are used to switch the parasitic elements of the antenna, thus resulting in a beam-reconfigurable antenna that can switch the radiation pattern to a different direction.

This study focuses on a frequency-reconfigurable antenna that is designed into a multilayer structure (stacked patch) with considerably higher gain. Moreover, a new coupling method is implemented in an aperture-coupled technique to achieve frequency reconfigurability. By using the same antenna, two different operating frequencies at either 2.6 GHz or 3.5 GHz are achieved.

II. ANTENNA DESIGN

The proposed antenna uses the combination of an aperture-coupled technique and stacked patch technology, as shown in Fig. 1 and Fig. 2. The antenna consists of three layers of substrates and all the layers are made of RT-Rogers 5880 materials with the thickness of 0.787 mm each. To improve the gain performance, an air gap (3 mm thickness) filled with low dielectric constant of 1.0 is added between substrate layer 3 and substrate layer 2.

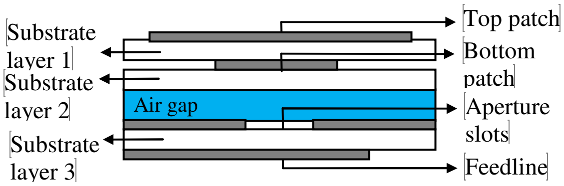


Fig. 1. Side view of the proposed antenna

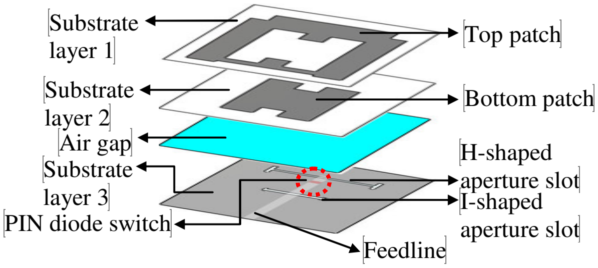


Fig. 2. View of each layer of the proposed antenna

The radiating elements are sorted in stacked patch at different substrate layers. The top patch is etched on top of the substrate 3 and the bottom patch is etched on top of substrate 2. Both patches are designed based on their operating frequency. The larger patch (top patch) is designed based on 2.6 GHz frequency while the smaller patch (bottom patch) is designed based on 3.5 GHz frequency. The basic rectangular shapes and dimensions for both patches are as described in [2] and the geometry of the whole antenna structure in 1-plane view is shown in Fig. 3.

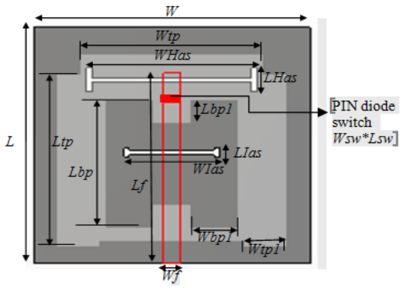


Fig. 3. Geometry of the proposed antenna in 1-plane view

Next, each patch is altered to achieve the desired operating frequency. In this design, the ground plane is located on top of the substrate layer 1 and consists of two different shapes, which are I-shaped and H-shaped aperture slot. The I-shaped aperture slot must be positioned at the centre referring to the bottom patch along C_{bp}, and H-shaped aperture slots must be located at the centre referring to the top patch along C_{tp} (refer to Fig. 6). The I-shaped aperture slot with $WI_{as} \times LI_{as}$ is used to activate the bottom patch while the H-shaped aperture slot with $WH_{as} \times LH_{as}$ is used to activate the top patch. Both aperture slots must be small and located at the centre of patches to produce the maximum coupling [8]. The ratio of slot length to width is typically 1/10. Next, the feedline with dimensions of $W_f \times L_f$ is etched on the bottom of the substrate layer 3 and the line impedance of 50 Ω is matched to this antenna. Moreover, one PIN diode switch with $W_{sw} \times L_{sw}$ is located at the feed line. The function of the PIN diode switch is to control and activate the selected aperture slots on the ground during the

ON and OFF modes. The default dimension of the proposed antenna is presented in Table I.

Table 1: Default dimensions of the proposed antenna

Parameters		Value (mm)
All substrates	Width, *W*	52.0
	Length, *L*	52.0
Top patch	Width of top patch, *Wtp*	34.0
	Length of top patch, *Ltp*	37.5
	Width of top patch 1, *Wtp1*	8.0
Bottom Patch	Width of bottom patch 1, *Wbp1*	9.0
	Length of bottom patch, *Lbp*	28.0
	Length of bottom patch 1, *Lbp1*	5.0
H-shaped aperture slots	Width, *WHas*	32.0
	Length, *LHas*	5.4
I-shaped aperture slots	Width, *WIas*	16.0
	Length, *LIas*	2.0
Feedline	Width of feedline, *Wf*	3.2
	Length of feedline, *Lf*	42.0
PIN diode Switch	Width of PIN diode switch, *Wsw*	3.2
	Length of PIN diode switch, *Lsw*	1.5

Fig. 4 shows the basic design of the equivalent switching circuit that is used to control the PIN diode switch configuration. The circuit is designed using ADS software to ensure the circuit has the same characteristic before it is implemented to the proposed antenna. The circuit consists of one PIN diode switch (Phillipe BAP51-02), two inductors, one capacitor, one resistor with 150 Ω, and the biasing voltage is supplied with 12 V. The capacitor is used for blocking the direct current (DC) from reverse back to the Port 1, which is the Vector Analyser Network (VNA) while the inductors with 22 nH are used to provide a low impedance for direct current (DC) or known as a choke. To limit the current flow to the PIN diode switch, the resistor with 150 Ω is used and connected to the biasing voltage. In ON mode, a biasing voltage of 12 V is supplied while in OFF mode, biasing voltage of 0 V is supplied. The output of the proposed antenna that produces the return loss results of S_{11} and S_{21} is labelled with P2. Fig. 5 (a) shows the calculated return loss when the circuit is supplied with 12 V. At this stage, the circuit has the capability to operate at 2.6 GHz with S_{11} is equal to -14.88 dB while when 0 V is supplied to the circuit, as shown in Fig. 5 (b), the port of S_{21} will be active and the antenna will be operated at 3.5 GHz with -66.58 dB.

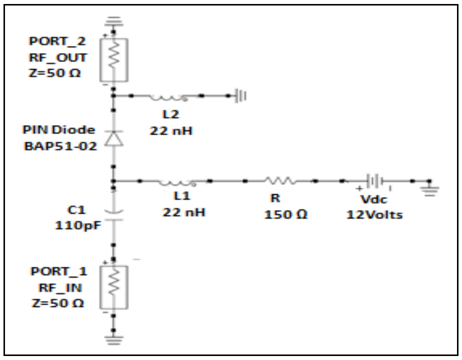
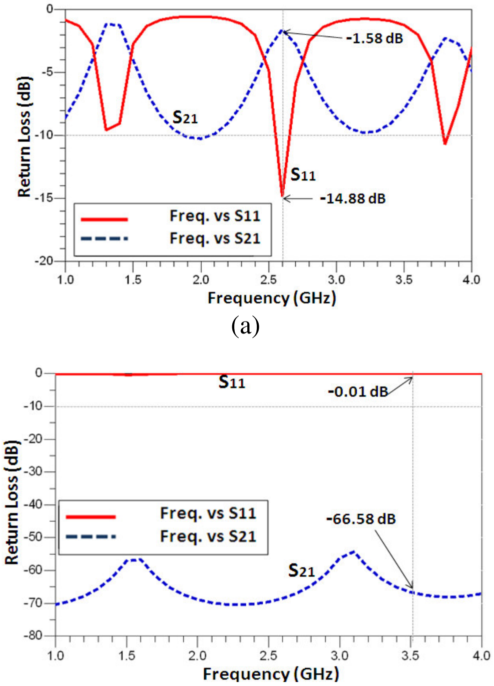


Fig. 4. The basic design of the equivalent switching circuit with the PIN diode switch



(a)

(b)

Fig. 5. Calculation of the return loss (S_{11} and S_{21}) for the equivalent switching circuit in (a) switch ON mode, and (b) switch OFF mode

In this design, a new concept of coupling methods is implemented in aperture-coupled technique to achieve frequency reconfigurability. When the PIN diode switch is in ON mode, both I-shaped and H-shaped aperture slots on the ground will be activated. Therefore, the waves from I-shaped aperture slots will radiate to activate the bottom patch while the waves from H-shaped aperture slots will radiate to activate the top patch. The combination of both radiating patch layers will ensure that the antenna has a capability to operate at 2.6 GHz. When the PIN diode switch is in OFF mode, only I-shaped aperture slots are activated and the waves will radiate to activate the bottom patch. At this time, the top patch acts as a parasitic element to the bottom patch and the antenna can be operated at 3.5 GHz.

III. PARAMETRIC STUDY

At the early stage, the proposed antenna is designed with the PIN diode switch is in ON mode and both aperture slot dimensions are defaulted with maximum aperture slot width, (WH_{as} = 20 mm and WI_{as} = 36 mm). The aperture slots are located at the centre i.e., between the bottom and top patches (C_{tp} and C_{bp}). As shown in Fig. 6, the H-shaped aperture slot and I-shaped aperture slot are located between C_{tp} and C_{bp}. Next, a parametric study has been carried out to achieve the desired target frequencies. Therefore, the aperture slots characteristics in terms of width and the location referring to the centre patch give more resonant frequency effects to achieve the desired frequency, which is 2.6 GHz in ON mode. The Computer Simulation Technology (CST) Microwave Studio is used to simulate the antenna's performance.

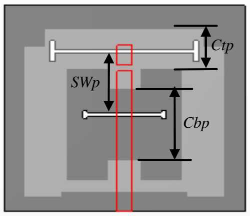
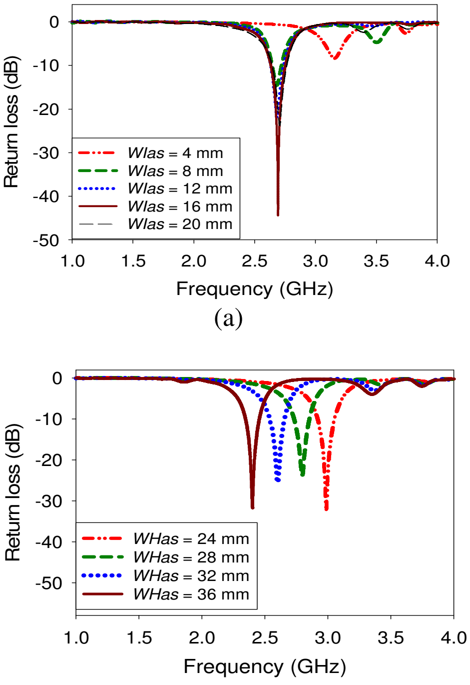


Fig. 6. The position of the PIN diode switch and aperture slots in the proposed antenna

First, the effect of the I-shaped aperture slot width, *WI as* has been analyzed from 4 mm to 20 mm with a fixed width of H-shaped aperture slot. As depicted in Fig. 7 (a), all the variable values are dropped around 2.6 GHz to 2.7 GHz. Therefore, the best value of WI_{as} = 16 mm is chosen because the low magnitude is equal to -4.25 dB. Next, to further improve the antenna's performance to operate at 2.6 GHz, the value of of H-shape aperture slot width, WH_{as} has been analyzed while maintaining the WI_{as} = 16 mm. It is found that the resonant frequencies decreases while the WH_{as} increases. Therefore, the WH_{as} = 32 mm value is chosen because the frequency is resonant at 2.61 GHz with -24.79 dB.

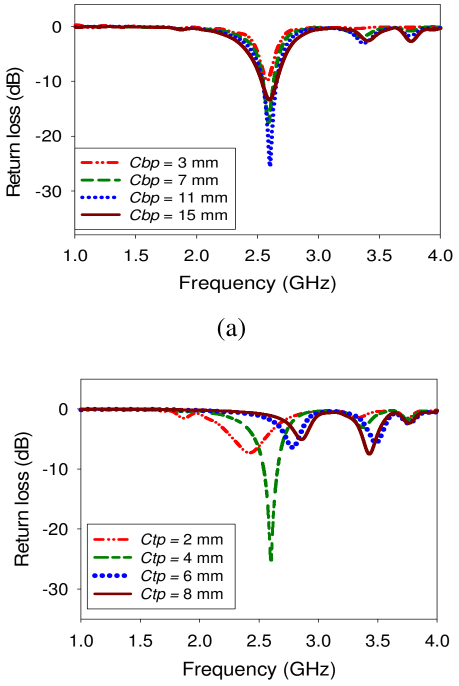


(a)

(b)

Fig. 7. The effect on return loss due to the change of aperture slot width (a) WI_{as}, (b) WH_{as} during ON mode

As the previous result does not achieve the desired frequency of 2.6 GHz, the effect of aperture slots position referring to the aperture-coupled patch has been optimized. Fig. 6 shows that the I-shaped aperture slot is located at aperture-coupled referring to the bottom patch. As for the H-shaped aperture slot, it is located at the aperture-coupled referring to the top patch. The possible location of the I-shaped and H-shaped aperture slot position is labeled as C_{bp} and C_{tp}. Therefore, the effects of the aperture slots position referring to the aperture-coupled patch have been analyzed to achieve the maximum coupling between the ground and the stacked patch radiating elements. Fig. 8 (a) shows the results when the I-shaped aperture slot is varied along C_{bp}, with 3 mm to 15 mm. There are no changes on the resonant frequency. All the optimized values drop at 2.62 GHz. The $C_{bp} = 11$ mm with a -25.8 dB has been chosen due to the lower return loss compared to other C_{bp} results. Next, the position of the H-shaped aperture slot is optimized along the C_{tp} as shown in Fig. 8 (b) while the I-shaped aperture slot position is fixed at $C_{bp} = 11$ mm. The best result is obtained when the $C_{tp} = 4$ mm i.e., when the antenna is resonant exactly at 2.6 GHz with -25.8 dB. From this result, it is proven that aperture slots should be placed at the centre of the radiating elements to increase coupling levels.



(a)

(b)

Fig. 8. The effect on return loss due to the change of aperture slots position referring to the patch centre (a) WI_{as}, (b) WH_{as} during ON mode

Next, the effects of PIN diode switch position along SWp have been analyzed by designing the OFF mode condition. As shown in Fig. 9, when the PIN diode switch is varied along SWp from 3 mm to 12 mm, a significant change in return loss and frequency can be seen. All the frequencies are resonant at higher frequencies, which are more than 2.6 GHz compared to the frequencies in ON mode. From this analysis, the best position of the PIN diode is when $SWp = 12$ mm i.e., when the resonant frequency is exactly resonant at 3.5 GHz with good impedance matching of -48.5 dB. This proves that, once the PIN diode switch is in OFF mode, only the bottom patch radiating element is activated while the top pact acts as the parasitic element and ensures the antenna will be operated at the higher frequency.

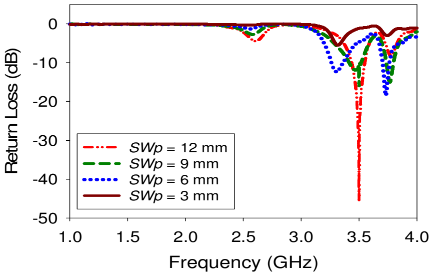
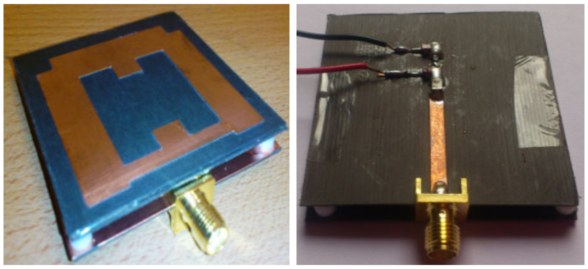


Fig. 9. The effect on return loss due to the change of PIN diode switch position, SW_p in OFF mode

IV. RESULTS AND DISCUSSION

Next, the prototype of the proposed antenna is fabricated to validate the antenna's performance. The prototype is shown in Fig. 10. It is clearly shown that by using stacked patch and air gap filled, the proposed antenna achieves a very high gain compared to other single layer antennas. The antenna's gain is equal to 6.253 dB and 5.429 dB when the PIN diode switch is in the ON or OFF mode, respectively, as depicted in Fig. 11.



(a) (b)

Fig. 10. Prototype of the proposed antenna (a) Top view and, (b) Bottom view with the equivalent switching circuit

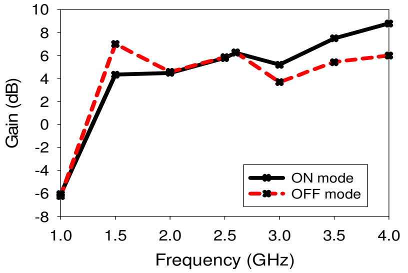
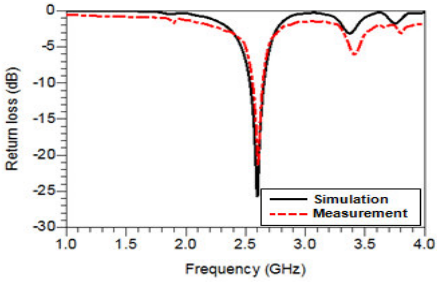
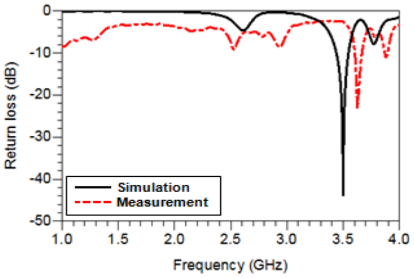


Fig. 11. Comparison of simulated gains in ON and OFF modes in a Cartesian plot

Next, the simulation and measurement results of return loss at both modes, ON and OFF, are shown in Fig. 12. The graph in Fig. 12 (a), indicates a satisfactory agreement at 2.6 GHz with more than -20 dB when the proposed antenna is in ON mode. However, the measurement results in OFF mode seem to have a slight frequency shift and lower value of return loss compared to the simulation results. The measured return loss is resonant at 3.62 GHz with -23.36 dB while during the simulation, the magnitude of return loss is -45.37 dB at 3.5 GHz (Fig. 12 (b)). The discrepancies in the measurement results may due to the improper gluing between the substrate layer 1 and substrate layer 2. Besides that, the passive components from the switching circuit also produce their own electric field and this would give an effect to the feedline. The misalignment problem and the gluing error give significant effect to the resonant frequencies and the radiation pattern characteristics.



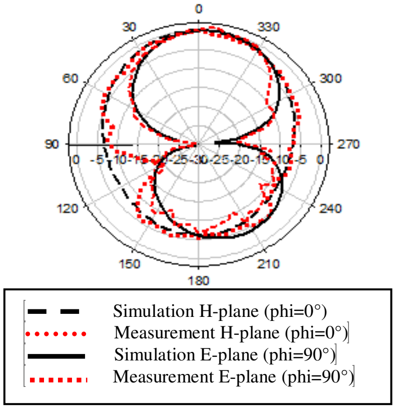
(a)



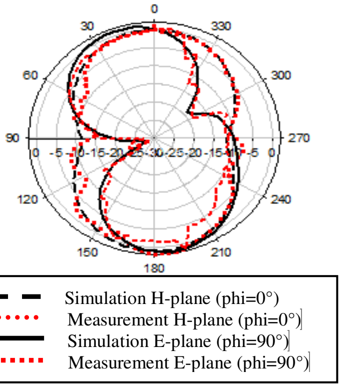
(b)

Fig. 12. Simulation and measurement results of return losses of the proposed antenna in (a) ON mode, (b) OFF mode

Figure 13 shows the simulation and measurement radiation patterns of the proposed antenna based on two different frequency modes i.e., at 2.6 GHz (Fig. 13 (a)) and 3.5 GHz (Fig. 13 (b)). The radiation patterns are cut in both planes either in H-plane (*x*-*z* direction) with phi = 0° and E-plane (*y*-*z* direction) with phi = 90°. As depicted in Fig. 13, a good agreement between the simulation and measurement results is clearly achieved. The main beam is directed to 0° in ON mode and 180° in OFF mode. The simulation radiation pattern characteristics are also summarized in Table 2.



(a)



(b)

Fig. 13. Simulation and measurement radiation pattern in polar-plot in (a) ON mode, (b) OFF mode

Table 2: Simulation radiation pattern characteristics between ON mode and OFF mode

	Switch mode	
	ON	OFF
Resonant Frequency (GHz)	2.6	3.5
VSWR	1.11	1.01
Bandwidth (MHz)	117.2	116.1
Gain (dB)	6.253	5.429
HPBW (°)	94.4	73.8
Side lobe level (dB)	-6.0	-1.1
Efficiency (%)	97.7	88.0

VI. CONCLUSION

A novel frequency-reconfigurable stacked patch microstrip antenna with aperture-coupled technique has been designed and fabricated. The proposed antenna has a novel design with the patches sorted in stacked layer that represents a different operating frequency. Besides that, a new concept of coupling methods has been successfully implemented to configure the PIN diode switch (ON/OFF mode) thus achieving the frequency reconfigurability either at 2.6 GHz (ON mode) or 3.5 GHz (OFF mode) with good impedance matching. The validated results of return loss and radiation pattern between simulation and measurement results prove that the antenna has a good antenna's behavior. Therefore, the antenna has a potential to be applied and tested in a wireless communication system, especially for Long Term Evolution (LTE) and WiMAX applications.

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