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SLOT-FED SWITCHED PATCH ANTENNA FOR MULTIPLE FREQUENCY OPERATION

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Abstract—A switchable microstrip patch antenna for multi-frequency operation is presented. The antenna is fed by a coplanar waveguide via capacitive coupling slot. The antenna allows easy reconfigurability of the frequency band of operation by incorporating switches in the coupling slot. The resonant frequency of the antenna can be adjusted by setting the switches on or off. Two prototypes are presented. The first incorporates two PIN diodes and capable of switching between four frequency bands, over a frequency range of 1.23 : 1. The second prototype incorporates four PIN diodes and is capable of switching between eight frequency bands, over a frequency range of 1.5 : 1. The structure has a compact and simple biasing circuit. Simulation and measurement indicate that the proposed antennas demonstrate very good impedance matching, stable radiation patterns and good gain at all frequency bands.

1. INTRODUCTION

New technologies in communications are emerging, such as software-defined radio (SDR), which add new challenges and opportunities to antenna design. One significant challenge is how to cover several frequency bands with a single antenna having good efficiency and wide bandwidth. Using a reconfigurable antenna that tunes to different frequency bands is one possible solution to the problem. Such an antenna would not cover all bands simultaneously, but would provide

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narrow instantaneous bandwidths that are dynamically selectable and would have higher efficiency than a conventional multi band antenna.

Reconfigurable patches are good candidates for wireless communications because they improve the system's capacity by adjusting the resonant frequency, radiation pattern and polarization modification [1]. To achieve reconfigurability in an antenna, RF switching devices such as PIN diodes, photo conductive switches, micro-electromechanical system (MEMS) switches or FETs can be used. The PIN diode switch is very popular in microwave circuit applications due to its fast switching speeds, reasonably high current handling capabilities, reliability and ease of modelling. Numerous designs for switchable patch antennas are available in the literature. Switchable patch antennas with PIN diode switches loaded in the radiating element were reported in [2–8]. This is normally done by placing slots at the appropriate positions in the radiating patch. In order to achieve different resonances, the length of the slot is adjusted by inserting switches. In case of electromagnetic coupling, switchable patch antennas have been realized by placing the PIN diode switches in the feeding network or the coupling slot [9–14].

This paper presents a multiband switchable patch antenna. The antenna is fed by coplanar waveguide based on capacitive coupling slot. The frequency switching is achieved by altering the length of the coupling slot by using PIN diodes. The PIN diodes are inserted in the coupling slot at certain distances. This allows selection of wide range of frequencies. Each frequency band corresponds to a certain state of the PIN diodes. Many of the switchable patches reported in the literature suffer from limitations such as the ability to switch between limited number of frequency bands and (or) exhibiting wideband resonances for some frequency ranges. An intrinsically narrowband antenna with dynamically controlled frequency response easily achieves the frequency agility. In addition, the narrow instantaneous frequency response reduces the filtering requirement in the RF front end due to the superior out of band rejection that it provides over multi-resonance or wideband antennas. Two switchable patches are presented. They are capable of switching between four and eight frequencies respectively. Good impedance matching, stable radiation pattern, and reasonable gain are obtained in different frequency ranges.

2. STRUCTURE OF THE ANTENNA

2.1. Capacitively Coupled Patch

The antenna shown in Figure 1 consists of a rectangular patch placed on the top of the substrate and a slot arranged opposite to the patch in the ground plane. The slot is capacitively fed by a coplanar

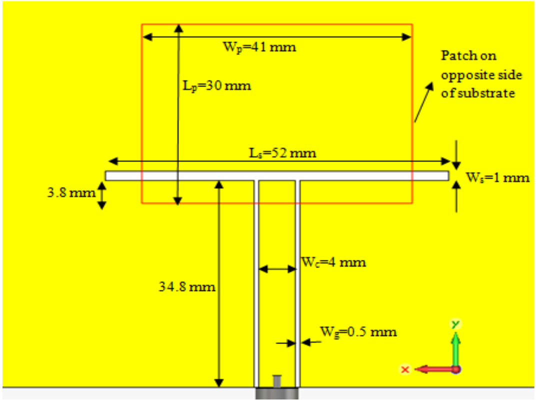


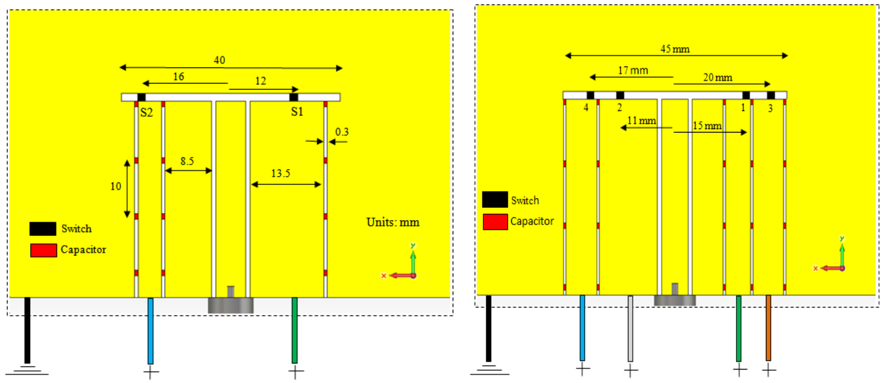
Figure 1. The structure of capacitively coupled patch.

waveguide. The radiating patch was designed using transmission line calculations [15, 16] to operate at 2.4 GHz. The antenna is printed on Taconic (TLC32) substrate of thickness $h = 1.6\,\mathrm{mm}$ and dielectric constant $\varepsilon_r = 3.2$. The patch width is $W_p = 41\,\mathrm{mm}$ and length $L_p = 30\,\mathrm{mm}$, whilst the ground plane and the substrate have a width of $W_g = 100\,\mathrm{mm}$ and a length $L_g = 100\,\mathrm{mm}$. The coplanar waveguide is designed to have $50\,\Omega$ characteristic impedance. The width of the conducting strip is 4 mm and the gap between the conducting strip and the ground plane is 0.5 mm.

The length of the slot affects the resonance frequency but has only a small effect on the return loss. As the slot length increases, the resonant frequency decreases as reported in [17, 18]. Therefore, altering the length of the coupling slot will shift the resonant frequency. The proposed prototypes have different slot lengths (L_s) and the same slot width (W_s) of 1 mm. PIN diodes are inserted across the slot to effectively change its length. Bias isolation is produced by narrow slots in the ground plane as discussed in Section 2.2.

2.2. Switched Antennas

Two prototypes are presented in this paper. The first is shown in Figure 2(a). It uses two PIN diodes that are asymmetrically located in 40 mm length slot and are 28 mm apart. Diode biasing is obtained by etching 0.3 mm width slots in the ground plane parallel to the CPW line. The ground plane is thus divided into DC areas resulting in two wide conducting strips parallel to the CPW. The strips provide a path for the DC current. The area above the slot is the DC earth.



(a) (b)

Figure 2. Bias and switch details of the switched patches: (a) prototype 1; (b) prototype 2.

Metal wires are soldered to the bottom of the conducting strips. The other end of the wires is connected to a DC power supply. Four DC isolation capacitors are soldered across the bias slots 10 mm apart. The capacitors are chosen to isolate the RF components from the DC ones. They provide low capacitive reactance such that the RF signal will pass through the capacitor with little loss or reflection. Thus, the higher capacitance value is the better RF continuity. In practice, however, the choice of the capacitance value is restricted by the self resonant frequency (SRF) of the lumped capacitors used. It is well-known that chip capacitor or inductor will behave ideally at the frequencies below its SRF. Also, it is well-known that the highest capacitance value is the lowest self resonant frequency. Therefore, the choice of the capacitance value presents a trade-off between the value and the SRF. From simulations, which included the S_{2p} file of the capacitors, it was found that a capacitance of 27 pF results in good RF continuity. Therefore, it was used in the antenna design. The prototype 1 is capable of switching between four frequency bands. Since two PIN diodes are utilized and each diode can be either on or off, there are four (2^2) possible states. Each state corresponds to operation in a specific frequency band of operation. The second prototype is shown in Figure 2(b).

2.3. PIN Diodes

To achieve the reconfigurable frequency capability, switching components can be used. PIN diodes are the most commonly used switching devices for RF and microwave front-end application systems. They have several attractive properties such as, low insertion loss, good isolation, low power handling and low cost. BAR50-02V silicon PIN diodes from Infenion® were used in the proposed antennas. Their operating frequency range extends from 10 MHz to 6 GHz. It has low forward resistance and low capacitance at zero volt reverse bias. The PIN diode has current controlled RF resistor, which decreases as the forward current increases. A 100 mA current (maximum current rating) is applied to the diodes for the forward biased which ensures that the parasitic resistance of the PIN diode is minimized. The reverse biased voltage applied to the PIN diodes is 0 V. Current limiting resistors are used to avoid damaging the diodes and/or the DC voltage source. Real components that include parasitics will alter the performance of the antenna. They will also add to the loss, thus causing a reduction in the total efficiency. An S_{2p} file for the "on and off state" of the diode was extracted from the manufacturer's website. The S_{2p} file for the DC blocking capacitors was extracted from the predefined vendor's library in Microwave Office software package®. These S_{2p} files were imported into CST Microwave studio where the simulations were performed.

3. SIMULATION AND MEASUREMENT RESULTS

3.1. Resonance Properties

Simulations of the antenna structures were performed using the transient solver in CST Microwave Studio®. The proposed prototypes have been manufactured and measured using an HP8722D network analyzer. Figure 3 shows the reflection coefficient simulation for different slot lengths (L_S) for the capacitively coupled patch shown

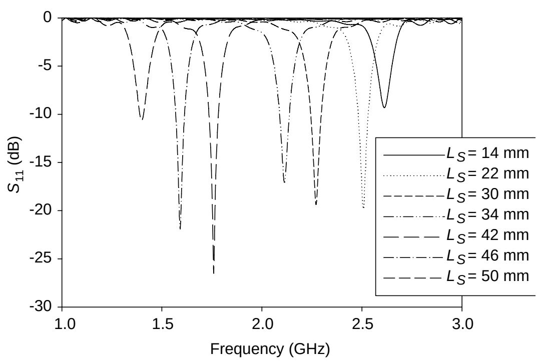


Figure 3. Simulated S_{11} for different slot lengths.

Table 1. Different states of the PIN diodes and corresponding frequency bands of prototype 1.

Switches		Frequency (GHz)		BW %
1	2	measured	simulated	Measured
OFF	OFF	1.83	1.80	2.46
OFF	ON	1.96	1.92	2.54
ON	OFF	2.07	2.04	1.7
ON	ON	2.25	2.16	2.22

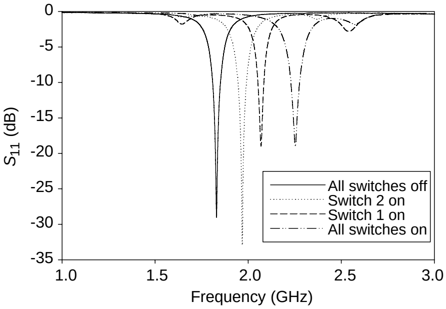


Figure 4. Measured reflection coefficient for different switch states for the prototype 1.

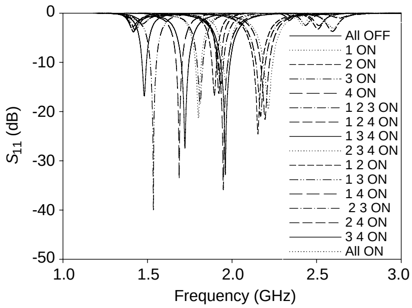


Figure 5. Measured reflection coefficient for different switch states for the prototype 2.

in Figure 1. The slot length has been varied from 14 mm to 50 mm while the slot width is kept fixed at 1 mm. The resonance frequency for a slot length of 14 mm is 2.6 GHz and decreases to 1.4 GHz for a slot length of 52 mm. This result gives an indication of the possible switching bandwidth. As can be seen in Figure 3, excellent matching can be obtained for a wide range of slot lengths. Therefore, the antenna is capable of switching between many frequency bands by inserting switches in the coupling slot to alter its length.

The measured reflection coefficient for the prototype 1 is shown in Figure 4. The measured result for the switches on exhibits a resonance of -20 dB depth at 2.25 GHz. The -10 dB return loss bandwidth is about 2.22%. A small shift was observed in the simulated result towards 2.16 GHz. The lower band is obtained when both switches are off. The measured result for this case exhibits a resonance at 1.83 GHz. The -10 dB return loss bandwidth is about 2.46%. The simulated result shows a narrow band resonance at 1.8 GHz. The results are summarized in Table 1.

Table 2. Different states of the PIN diodes and corresponding frequency bands of the prototype 2.

Switch / Band	1	2	3	4	Frequency (GHz)		BW %	
					meas	sim	meas	sim
1	OFF	OFF	OFF	OFF	1.48	1.5	2.03	2.75
2	OFF	OFF	OFF	ON	1.69	1.66	2.37	2.58
3	OFF	OFF	ON	OFF	1.54	1.56	2.61	2.62
4	OFF	OFF	ON	ON	1.72	1.72	2.76	2.89
5	OFF	ON	OFF	OFF	1.9	1.86	1.58	1.78
6	OFF	ON	OFF	ON	1.92	1.9	1.56	1.72
7	OFF	ON	ON	OFF	1.93	1.9	1.81	2.11
8	OFF	ON	ON	ON	1.96	1.94	1.68	2.05
9	ON	OFF	OFF	OFF	1.8	1.72	2.22	2.43
10	ON	OFF	OFF	ON	1.95	1.86	3.08	3.3
11	ON	OFF	ON	OFF	1.81	1.74	2.07	2.53
12	ON	OFF	ON	ON	1.96	1.88	3.06	3.32
13	ON	ON	OFF	OFF	2.15	2.02	2.79	2.94
14	ON	ON	OFF	ON	2.2	2.08	2.73	2.89
15	ON	ON	ON	OFF	2.17	2.04	2.76	3.03
16	ON	ON	ON	ON	2.22	2.1	2.7	3.02

The second prototype shown in Figure 2(b) utilizes four PIN diodes. The measured reflection coefficient is shown in Figure 5. The measured result shows that it is capable of switching between sixteen matched-impedance frequency ranges. It is noticeable that some combinations result in resonances at the same frequency and that is mainly because they produce almost the same slot length. For instance, activating switches 1 and 4 results in a resonance at the same frequency obtained by activating switches 2, 3, and 4 which is about 1.95 GHz. Thus, the number of distinct frequency bands is reduced from 16 to 8. The positive feature of this prototype is the excellent matching for all possible combination of diode biasing. The frequency bands and corresponding states of the PIN diodes are summarized in Table 2. The number of distinct of frequencies can be increased by re-locating the PIN diodes.

Many factors can contribute to the discrepancy between the simulated and measured results. The main factor is the position of the PIN diodes. A difficulty in placing the diodes in the right positions was experienced while fabricating the antennas. A small shift in the PIN diode position will shift the resonant frequency. Other factors cause the difference between the measured and simulated results are the etching accuracy, the chemicals used, surface finish and the metallization thickness. In addition, the wires soldered to the ground plane have a small effect on the measured result.

3.2. Radiation Properties

The radiation patterns of the proposed antennas have been simulated and measured in different frequency bands. The proposed antennas produce a directional pattern with maximum directivity orthogonal to the patch. The angular beamwidths in $H\,(xz)$ and $E\,(yz)$ planes are typically 80° and 70° respectively. The antenna is linearly polarized. The radiation patterns in H (xz) and E (yz) planes for the antenna prototype 1 are shown in Figure 6.

The operating bands resulting from asymmetric slots (activating one switch) show an increment in the cross polarized waves. Nonetheless, its level remains below $-10\,\text{dB}$. As can be seen in the radiation pattern of prototype 1 shown in Figure 6, the frequency bands 2 and 3 have higher cross polarization levels. This is mainly due to the asymmetry in the structure since it is obtained by activating

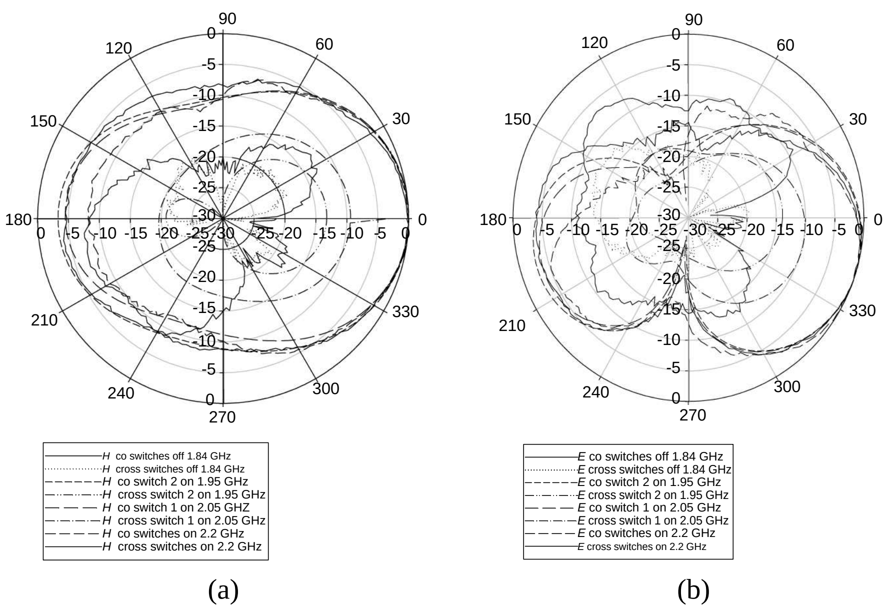


Figure 6. The measured radiation pattern prototype 1: (a) H plane; (b) E plane.

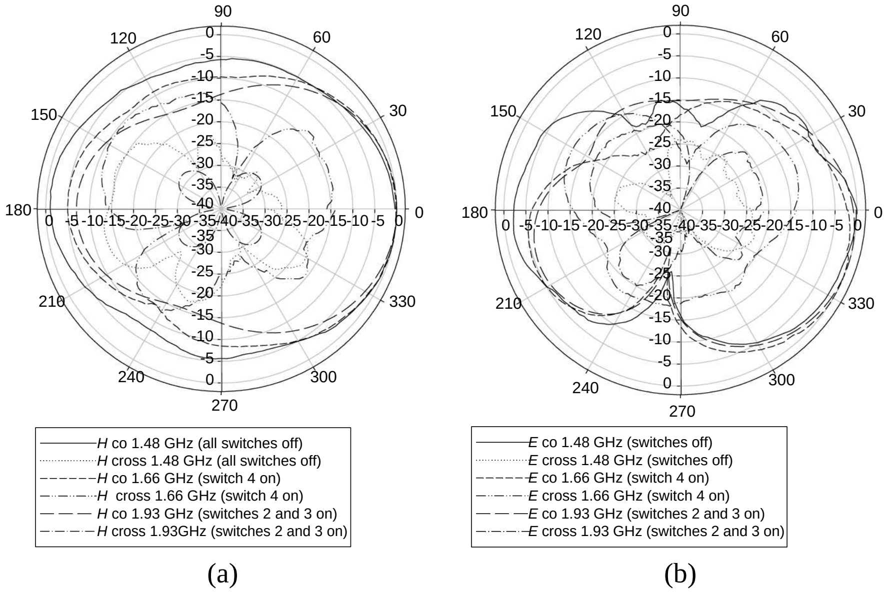


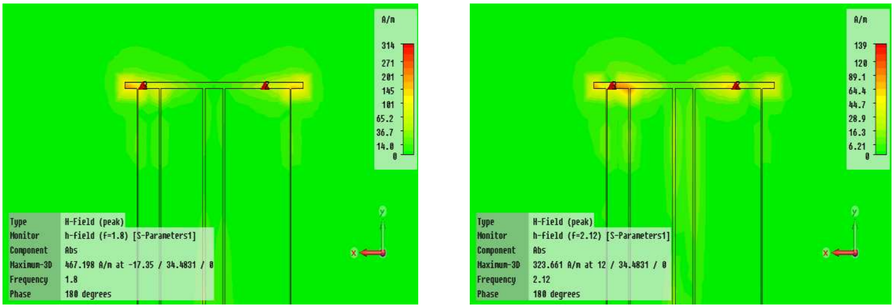
Figure 7. The measured radiation pattern prototype 2: (a) H plane; (b) E plane.

one switch (either 1 or 2) and therefore asymmetrical slot length. The prototype 2 shows very similar patterns as can be seen in Figure 7. The measured radiation patterns show that the proposed antennas have stable radiation properties over the operating bands. That is due to the fact that the biasing circuitry and switching diodes are arranged in the feeding structure rather than the radiating structure (the patch). Therefore, frequency reconfigurability is achieved without degrading the radiation properties.

The directivity of the antenna decreases as the operating frequency decreases. From Figure 6, it can be seen that the lowest operating band (1.83 GHz) has the lowest directivity with considerable back lobe, while the highest band (2.25 GHz) has a smaller back lobe. It was reported in [18] that any reduction in the antenna resonant frequency by slot lengthening results in increased radiation behind the ground plane. Therefore, the front-to-back (F/B) radiated power ratio decreases.

3.3. Surface Current Analysis

The surface currents are calculated directly from the magnetic fields in CST Microwave Studio®. Figure 8(a) shows the surface current



(a) (b)

Figure 8. The surface current plot for the antenna prototype 1: (a) switches off; (b) switches on.

Table 3. The simulated directivity, radiation efficiency and the measured realized gain of the prototype 1.

Operating band	Directivity (dBi)	Realized Gain (dB)		Radiation Efficiency %
		simulated	measured	
1	6.05	4.26	3.8	66.6
2	6.35	4.08	3.4	60.46
3	6.84	4.27	3.6	56.6
4	6.96	4.3	3.9	54.88

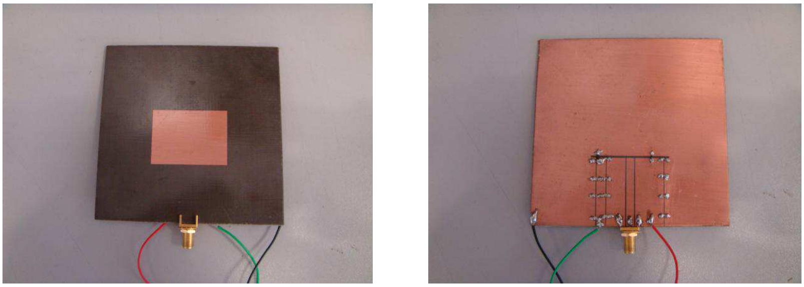
plot for the antenna prototype 1 at 1.8 GHz (switches off). The figure shows strong current is flowing along the edges of the coupling slot. The surface current plot at 2.12 GHz (switches on) is shown in Figure 8(b). It can be seen that some of the current is flowing through the switch. When the switch is in the off mode, the electrical currents on the ground have to flow around the slot, resulting in a relatively long length of the current path as shown in Figure 8(a). Therefore, the antenna resonates at a low frequency. In contrast, when the switch is in the on mode, some of the electric currents can go directly through the switch as shown in Figure 8(b). In this case, the average length of the current path is shorter so that the antenna has a higher resonance frequency.

3.4. Realizable Gain and Radiation Efficiency

The gain has been measured in different frequency bands for the proposed antennas. The prototype 1 has the highest gain levels. The

Table 4. The simulated directivity, radiation efficiency and the measured realized gain of the prototype 2.

Operating band	Directivity (dBi)	Realized Gain (dB)		Radiation Efficiency %
		simulated	measured	
1	4.94	1.53	1.1	48.23
2	5.34	1.96	1.35	49.52
3	5.1	1.97	1.5	50.96
4	5.81	2.06	1.75	43.28
5	6.31	2.72	2.1	47.38
6	6.58	3.2	2.85	49.25
7	6.57	2.81	2	43.69
8	6.77	3.24	2.9	45.51
9	5.46	2.35	1.8	52.67
10	6.46	2.42	1.8	40
11	5.57	2.63	2.1	54.21
12	6.54	2.6	2	40.76
13	7.04	2.99	2.58	40.4
14	7.16	3.32	2.7	41.96
15	7.09	3.15	2.8	41.25
16	7.21	3.54	3	43.23



(a) (b)

Figure 9. Antenna prototype 1: (a) bottom view; (b) top view.

gain of the lower operating band is 4.26 dB measured at 1.83 GHz. While the gain for the higher operating band is 4.3 dB measured at 2.25 GHz. The results are summarized in Table 3. The realized gain and the radiation efficiency for the prototype 2 are summarized in Table 4.

The proposed antennas exhibit stable radiation properties within the operating bandwidth. Inserting PIN diodes and DC isolation capacitors in the antenna will cause degradation in the radiation efficiency and the gain of the antenna. That is mainly due to the parasitic resistance of these components which causes the power loss. As can be seen from Table 3, the prototype 1 exhibits radiation efficiency above 55%. The prototype 2 exhibits radiation efficiency above 40%. This antenna has less efficiency because more switches and capacitors are used. Thus, increasing the number of the PIN diodes to 6 or 8 in order to achieve more frequency bands will further decrease the efficiency of the antenna. It can be seen that the entire proposed antennas achieve reasonable gain. Figure 9 shows a fabricated prototype 1.

4. CONCLUSION

A switchable multi-band reconfigurable patch antenna is proposed. The operating frequency can be switched between different frequency bands by activating PIN diodes loaded in the coupling slot. Two prototypes were designed, simulated, fabricated and measured. They are capable of switching between four and eight frequency bands. The achievable frequency ratios are 1.23 : 1 and 1.50 : 1 respectively. The proposed antennas show very good impedance matching, well-shaped radiation patterns and good gain over all operating bands. The ability of the proposed antennas to easily select of wide range of discrete frequencies makes them of interest when multiple standards to be processed by the same receiver. Single passive antenna with multi-resonance or wideband characteristics is a solution. However, this solution suffers from a drawback since the antenna receives other non desired frequencies and some filtering network is required to cancel the undesirable frequencies.

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