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RESEARCH ARTICLE

Multi-Mode Yagi Uda Patch Array Antenna With Non-Linear Inter-Parasitic Element Spacing

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ABSTRACT A low-profile and broad steerable patch array antenna is presented. The improvement of the multi-directional functions from the broadside is very limited for the patch array antenna. In this work, the number of directional beams is enhanced by 40% using a novel approach, inter-parasitic element expansion technique and adopted only four PIN diode switches. Results in simulation and measurement have verified that the patch parasitic array antenna is capable -of generating seven beam patterns directed towards -52°, -30°, -10°, 0°, +10°, +30°, and +52° at the *xz*-plane. Applying the inter-parasitic element spacing's optimization and minimizing the switching circuitry using four RF PIN diodes on the parasitic elements have contributed to the gain achievement of more than 7 dBi.

INDEX TERMS Antenna and propagation, multi-directional antenna, reconfigurable antenna.

I. INTRODUCTION

Pattern reconfigurable patch antenna is able to enhance the system performance by mitigating interference and improving signal quality by channelling the antenna's radiation towards the desired direction. Patch type antenna offers a good solution with its characteristics such as low profile, compact size, and ease of integrating with the circuit. Antenna with beam steering ability can be obtained using numerous techniques such as switched beam [1], travelling-wave [2], metamaterial () [3], parasitic element [4], and pixels antenna [5].

The main challenge of a multi-mode beam pattern reconfigurable antenna using patch type is achieving adequate steering angle on the broadside. Several reported studies [6], [7], [8], [9] have endeavored to improve the beam steering ability. As listed in Table 1, a study in [10] proposed a pixel patch antenna steered to nine beam directions in a hemisphere space but only managed to steer the beam in three directions with maximum beam tilt angles of ±30°. This antenna also introduces complexity by adapting nine square-shaped metallic pixels with 12 PIN diodes as reconfiguration switches. A similar approach has been adopted in [11] and [12] to achieve three directive beams with optimum tilt angles of ±40° using more than 20 switches.

The study in [13] has a pixel-parasitic patch element to achieve only three directional beam tilt angles on the broadside. Only in [14] and [15] have successfully achieved the highest number of five directive scanning beams in its steering mode on *xz*-plane. Work [14] has adopted a truncated antenna ground plane which only performed the five directional steerable beams within the range of ±50° but contributed to the complexity of DC biasing via modifying the switching circuitry. However, the proposed antenna in this

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work obtained an improved scanning angle of −52° to +52° from the broadside with the seven directional steerable beam patterns by using a non-linear inter-parasitic element spacing approach and minimizing the DC biasing circuit to reduce the effect on dc circuitry and the ohmic losses. Apart from this, the proposed antenna has a better gain of 7.5 dBi compared with work [14]. On the other hand, work [15] has introduced multiple-sized pixels and faces abundantly DC biasing lines for 12 PIN diodes. To the best of our knowledge, none of the earlier works can achieve the following properties in a single design; first, beam steering capability with more than five directions from the broadside; second, the stability of reflection coefficient (S_{11}) and impedance bandwidth for all switching modes.

By adopting the Yagi–Uda concept [16], [17], the proposed antenna achieves stable S_{11} multi-mode beam steering with a high tilted beam angle by introducing non-linear inter-parasitic element spacing. This antenna has attributed a lower design complexity compared to the prior antennas [10], [11], [12], [13], [14], [15], [18]. Besides that, the four PIN diode switches are located at the parasitic patches layer. This has contributed to the stability of the antenna's reflection coefficient since the λ of the driven element is not directly affected. It maintains its linear polarization in all configurations with greater than 70% efficiency.

TABLE 1. State of the art of beam pattern reconfigurable antennas.

Ref.(s)	No. of Switches	Beam Performances	Gain (dB)	BW (MHz)	SLL (dB)
[10]	12	Max tilt angle = ±30°; 3 directions at phi= 0°	6.5	100	Not reported
[11]	52	Max tilt angle = ±40°; 3 directions at phi= 0°	9	200	Not reported
[12]	20	Max tilt angle = ±40°; 3 directions at phi= 0°	9.5	Not reported	Not reported
[13]	6	Max tilt angle = 40°; 3 directions at phi= 0°	8	200	Not reported
[14]	6	Max tilt angle= ±50°; 5 directions at phi= 0°	6.5	245	-4.0
[18]	22	Max tilt angle = ±45°; 3 directions at phi= 0°	7	290	Not reported
This Work	**4**	**Max tilt angle = 52°; 7 directions at phi= 0°**	**7.5**	**79**	**-5.0**

II. ANTENNA DESIGN

Figure 1 shows a circular patch as a driven element placed in the middle of four parasitic patch elements. The radius of the driven element is calculated based on the fundamental microstrip circular patch equation. These patches are located on top of the dielectric substrate Rogers RT/duroid 5880, with a thickness of 1.575 mm, dielectric constant (εr) of 2.2, and tan (δ) of 0.009. The driven patch radius a, is 16.21 mm. The antenna size is $W_A = 185$ mm and $L_A = 74$ mm. The size of parasitic elements (PEs) is denoted by radius a' (1st tier is PE2 and PE3) and radius a'' (2nd tier is PE1 and PE4). Adopting Yagi-Uda concept, the PEs are 5 % smaller than the driven element. This proposed antenna uses an aperture coupled technique for feeding the driven element via the stripline by using of subminiature probe (SMA) at the back of the antenna. The size of the aperture slot and stripline, Ws, Ls, W_{strip}, and L_{strip} are optimized to sizes 5 mm, 14 mm, 4.85 mm, and 40 mm to obtain the required input impedance and coupling effects. In the simulation, the analysis of the parameters achieved the parasitic elements' optimized physical dimensions, with radius $a' = 0.99$ mm and $a'' = 0.97$ mm. The circular parasitic elements are placed with four RF PIN diodes (*D1*, *D2*, *D3*, and *D4*), which are linked to the ground plane's center layer via shorting pins, as portrayed in Figure 1 (a) and (d). The shorting pin's location is critical to look for the optimum tilt beam angle and lower side-lobe level (SLL) besides permitting the optimum currents of parasitic patches flowing to the ground. The initial locations of the PIN diodes should be approximately parallel to the feeding location. Then, the x coordinate of the locations is optimized through parametric studies to identify the optimum beam tilt angle. Parameter sweep as suggested by [19] was carried out to obtain the optimum locations.

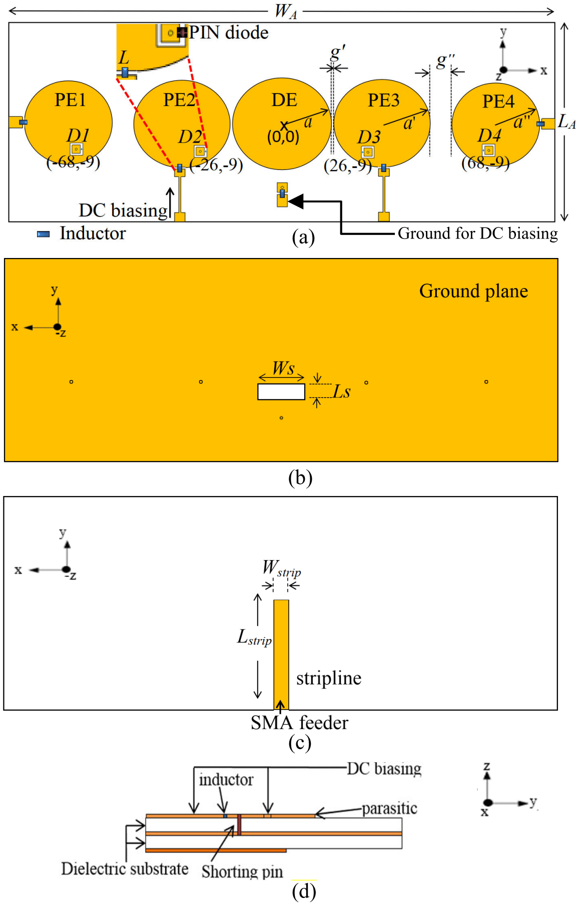
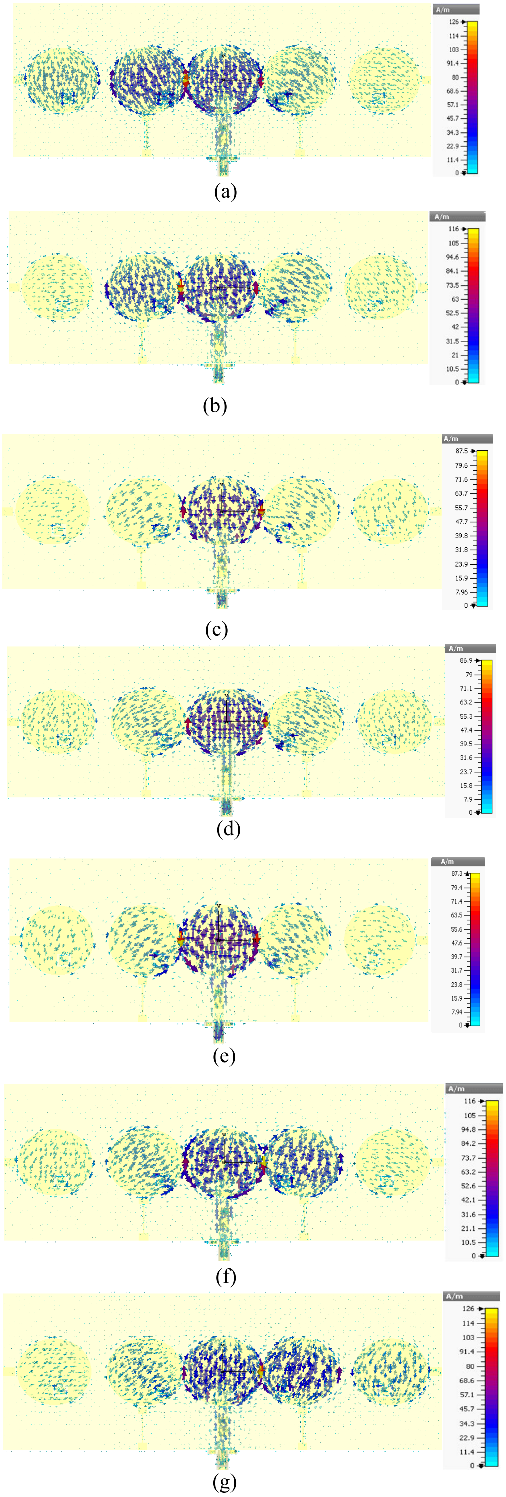


FIGURE 1. Geometrical of the proposed antenna. (a) Top view. (b) Center layer view. (c) Back view. (d) Side view.

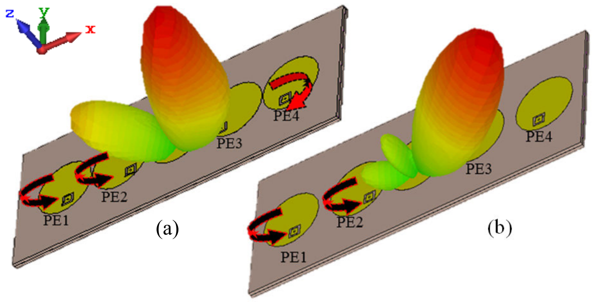
The antenna reconfiguration is achieved using four BAR 50-02V RF PIN diodes that consume 100 mW of power.



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

FIGURE 2. Current distributions for switching modes. (a) B1 (D1&D2- OFF, D3&D4- ON). (b) B2 (D1&D3- ON, D2&D4- OFF), (c) B3 (D1,D2,D3- OFF, D4-ON). (d) B4 (D1&D4-OFF, D2&D3-ON). (e) B5 (D1-OFF, D2&D3&D4-ON). (f) B6 (D1&D3-OFF, D2&D4-ON). (g) B7 (D1&D2-ON, D3&D4-OFF).

This low-cost diode has a high reliability and is easy to install. In the simulation, the ON and OFF conditions of the BAR50-02V PIN diodes are represented by the Touchstone Block (TSB).



(a)
(b)

FIGURE 3. Comparison approaches. (a) Beam tilt with uniform inter-parasitic elements. (b) Beam tilt with inter-parasitic element expansion.

TABLE 2. Parametric simulation result of inter-parasitic element expansion.

Pattern	θ at g''			
	0.5 mm	1.5 mm	3.5 mm	6.5 mm
B1	-31°	-38°	-51°	-53°
B2	-27°	-26°	-27°	-30°
B3	-15°	-11°	-10°	-9°
B4	0°	0°	0°	0°
B5	+15°	+11°	+10°	+9°
B6	+27°	+26°	+27°	+30°
B7	+31°	+38°	+51°	+53°

TABLE 3. Simulated switches configuration and beam directions.

Pattern	Switch				Angle	SLL
	D1	D2	D3	D4	θ	(dB)
B1	OFF	OFF	ON	ON	-53°	-5
B2	ON	OFF	ON	OFF	-30°	-4.9
B3	ON	ON	ON	OFF	-9°	-16.1
B4	OFF	ON	ON	OFF	0°	-16.8
B5	OFF	ON	ON	ON	+9°	-16.1
B6	OFF	ON	OFF	ON	+30°	-4.9
B7	ON	ON	OFF	OFF	+53°	-5

The TSB consists of s-parameter (s2p) information of the diode for ON and OFF conditions. To warrant the OFF capacitance is low to 0.15 pF, the PIN diodes give reverse bias voltage at 0 V during measurements. The inductors (L) with a value of 27 nH permit the DC current to flow through the PEs to the PIN diode but prevent the AC current from flowing out of the PEs to the dc lines.

In a parasitic array antenna, the mutual coupling effect between the excited element and the adjacent parasitic elements is utilized to direct the beam towards the desired direction. A simple rule related to the strengthening of reflection between the elements and the change of electric current distribution on the radiating elements is that the coupling effect is reduced when surface current flow on adjacent elements is reduced [20]. The current distributions at different switching modes are depicted in Figure 2. When the parasitic element is connected to the ground plane, it reacts as a reflector and pushes the beam in the opposite direction; in contrast, it reacts

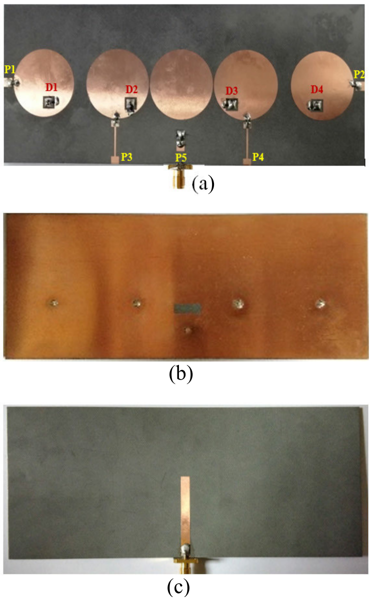


FIGURE 4. Fabricated antenna. (a) Top view. (b) Center layer view. (c) Back view.

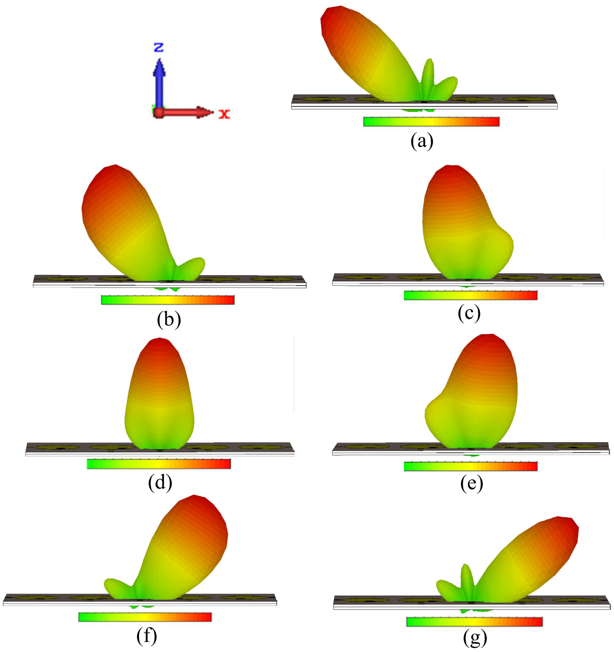


FIGURE 5. Simulated 3-D beam directions on the broadside. (a) B1. (b) B2. (c) B3. (d) B4. (e) B5. (f) B6. (g) B7.

as a director if the parasitic element is disconnected from the ground plane.

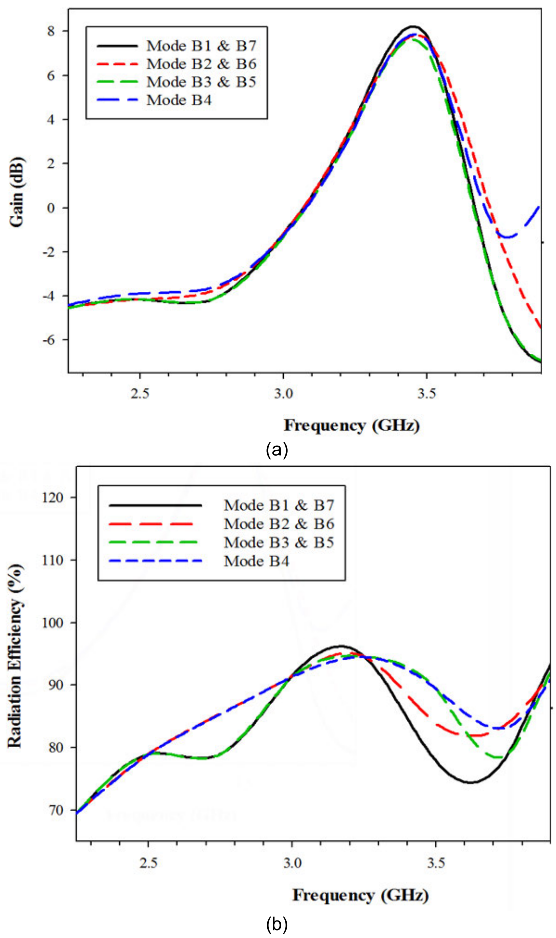


FIGURE 6. (a) Gain vs frequency. (b) Radiation efficiency vs frequency.

The working principle of the antenna to effectively tilt the beam using the inter-element mutual coupling is illustrated in Figure 3. Figure 3 (a) shows the two parasitic elements on the left are connected to the ground, while the remaining elements act as directors. The black arrows refer to the parasitic reflectors' ability to direct the beam in the desired direction; however, strong reflection (red arrows) is caused by the near and uniform spacing between elements ($g' = g'' = 0.5$ mm) impedes the collaborative effort between elements. However, once the spacing between parasitic elements increased, as depicted in Figure 3 (b), the strong reflection in inter-parasitic elements could well be reduced, which resulted in the higher tilted beam of 53° is achieved. The inter-parasitic elements gap expansion g'' is optimized after some parametric routines, and the effect of the g'' towards beam tilt angle is presented in Table 2. It depicts the effect of inter-parasitic element spacing toward the seven mode configuration known as B1 to B7. The spacing's extension in between the parasitic elements at the 2nd tier allows the best agreement for seven beam patterns with acceptable low SLL. Lastly, Table 3 depicts the final optimized effect of inter-parasitic element spacing towards the seven directional beams. The selected g'' is 6.5 mm since it gives the best directions with high beam performance.

III. RESULT AND DISCUSSION

The fabricated antenna prototype is illustrated in Figure 4. the three layers show the antenna's structure after the soldering of the RF components. Figure 5 presents the simulated 3D radiation patterns of the proposed antenna that is able to

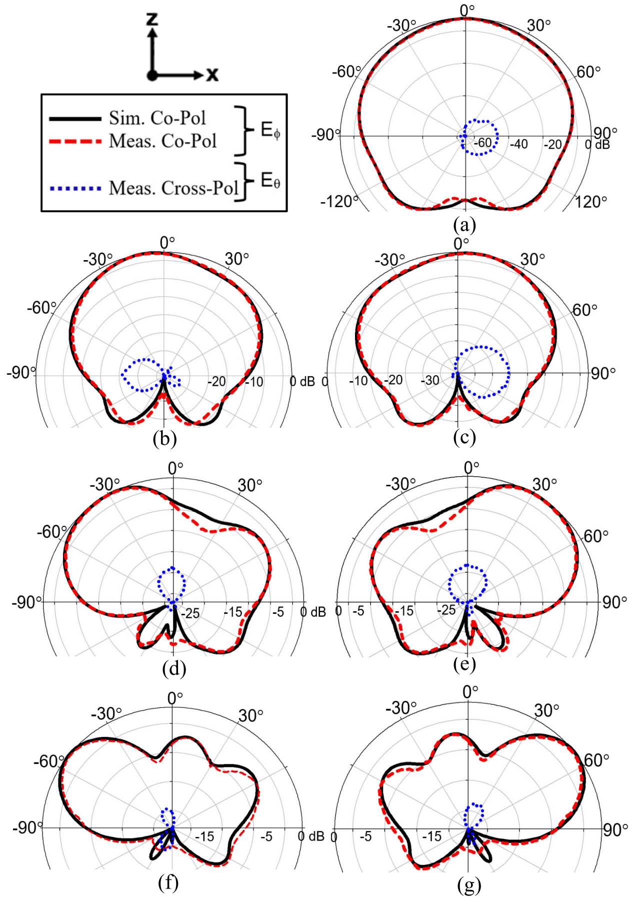


FIGURE 7. Simulated and measured radiation patterns at 3.5 GHz. (a) B4. (b) B3. (c) B5. (d) B2. (e) B6. (f) B1. (g) B7.

TABLE 4. Radiation pattern characteristics.

Criteria	Operation modes						
	B1	B2	B3	B4	B5	B6	B7
Tilt Angle (°)	-52°	-30°	-10°	0°	+10°	+30°	+52°
Gain (dBi)	7.6	7.51	7.27	7.6	7.27	7.51	7.6
HPBW (°)	42	58	85	61	85	58	42
Efficiency (%)	72	80	90	90	90	80	72

steer the beam in seven directions. These results illustrate the capability of the antenna to tilt the main beam in seven different directions with high gain and directivity. The beam steering is carried out in the xz plane. Figure 6 shows the plot of Gain and Radiation Efficiency versus Frequency. An average gain of 7.6 dBi is achieved by this antenna for all steered direction simulations at focus frequency of 3.5GHz.

The beam tilt angle achieved by the antenna is shown in Figure 7. Both simulation and measurement show a good agreement with the maximum tilt angle of the antenna in B2, B4, and B6. While for B3 and B5 obtained the measurement to ±10° compared to ±9° in simulation. The measured maximum tilt angle obtained by this antenna is 52° either in $+x$ or $-x$ directions while achieving 53° in simulation.

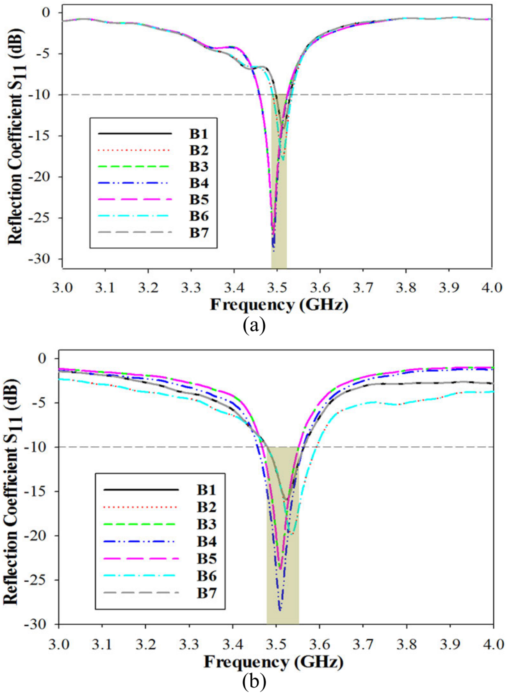


FIGURE 8. Reflection coefficient for antenna modes. (a) Simulation. (b) Measurement.

This proposed antenna has linear vertical polarization, and the measurement revealed at least 15 dB of the cross-polarized level relative to co-polarized for all seven beam patterns. The reconfigurable states do not affect cross-polarization because of the RF signal dissipation. Overall this antenna can steer the beam with -3 dB coverage of -83° to 83°. The measured gain dropped an average of 0.9 dB in all seven modes and achieved an average gain as high as 7.5 dBi.

Figure 8 shows that the simulated common operational bandwidth of the antenna for all modes is from 3.490 GHz to 3.530, which indicates 40 MHz of S_{11} impedance bandwidth. Meanwhile, the result is shifted in measurement from 3.47 GHz to 3.55 GHz with 79 MHz. The DC biasing circuitry that involves the soldering of the PIN diode at the parasitic elements could lead to the overall resistance of the antenna. Apart from this, the resistance of the PIN diodes at the ON state could also have contributed to the slight mismatch of the measured bandwidth at states B1, B2, B6 and B7. This leads to the common operational bandwidth of the antenna at all switching conditions being slightly higher than the measured bandwidth. The overall beam pattern characteristics of the proposed antenna are summarized in Table 4. Regardless of the switching state, the multi-mode patch antenna can maintain more than 70 % efficiency.

IV. CONCLUSION

A multi-mode patch parasitic array antenna using a novel non-linear inter-parasitic element spacing approach is proposed and described. Exploiting four parasitic elements, spacing extended between parasitic elements technique and only employed of four RF PIN diodes, the antenna is capable of tilt angles at seven directions, i.e.−52°, −30°, −9°, 0°, +9°, +30°, and +52° with an average gain are measured of 7.5 dBi. It has stability in S_{11} bandwidth at 3.5 GHz. With these features, the proposed antenna is suited to be installed into portable wireless besides applications such as indoor localization and tracking. Future work may consider on improving the common bandwidth for the switching conditions which is crucial for reconfigurable patch array antenna using parasitic technique.

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