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Design and optimize microstrip patch antenna array using the active element pattern technique

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ABSTRACT

Microstrip patch antennas are widely used in modern day communication devices due to their light weight, low cost and ease of fabrication. In this paper, we have designed and fabricated two Microstrip Patch Antennas (slotted-ring and truncated-slotted ring) and array at 2.4 GHz for Wireless Local Area Network (WLAN) applications using Computer Simulation Technology, CST. The antenna design consists of rectangular radiating patch on Rogers RT5880 substrate and is excited by using coaxial probe feeding technique. The truncated-slotted ring has been designed on top of the radiating patch to improve bandwidth. The simulation and measurement results of the both antennas are in close agreement with each other. Due to the good agreement of simulation and measurement results of truncated-slotted ring antenna in comparison with slotted-ring antenna, it has been selected for antenna array design. The simulated and measured S_{11} of truncated-slotted ring antenna shows -21dB and -15.6 dB at 2.4 GHz respectively. Then, the antenna has been formed into 1x4 array in order to observe its beamforming capability. The proposed antenna array is suitable for 802.11b/g/n Wi-Fi standard which is proposed to be used for IoT.

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1. INTRODUCTION

Antennas play a major role in communicating wirelessly from one source to another destination. It is expected that WiFi will become an eminent choice for IoT due to its popularity especially within indoor environment. Especially at 2.4 GHz, the frequency is a free licensed band which lowering the cost of the network. IoT, or the Internet of Things, can be loosely defined as a network of small, low-cost, low-power, ubiquitous electronic devices where sensing data and communicating information occur without direct human intervention. Each device functions as a “smart node” in the network by sensing information and performing low-level signal processing to filter signals from noise and to reduce the bandwidth needed for node-to-node communications. The booming industry of IoT depends upon wireless connectivity with many available options of wireless interface. There are not limited to Bluetooth, ZigBee, Z-Wave, WiFi and RFID with their own advantages in terms of power, range, data rates, mesh networking, interference immunity and ease of use. However, a few of these interfaces are not IP addressable, which is a requisite feature of IoT. Thus, WiFi which is based on 802.11 standards has IP addressability, is ubiquitous, and provides a good connectivity in preparing itself with IoT technology. Data transfer requirements for IoT differ from small payloads like utility meters to high data rate continuously such as real-time video surveillance. Thus, conventional WiFi which employed single antenna unable to meet the demand of high data rate. The challenge can be overcome by using beam steering capability. The terms 'beam steering' refers to the change of direction of the main lobe of the antenna pattern in comparison by transmitting equally in all directions. It can be accomplished by switching the antenna elements or by changing the relative phases of the RF signals (or existing currents) driving the elements. Moreover, with the capability of beam steering techniques as in 802.11ac is able to increase data rates up to 2.5Gbps. Currently, many 802.11n products have adopted the MIMO technology [1-3] in order to increase data throughput, signal quality and reliability. It is expected that WiFi will serve the purpose of wireless connectivity for IoT due to its popular demand. Plenty of research works have been conducted on WLAN antennas at 2.4 and 5 GHz band [4]. Many types of antennas are proposed to cover these frequency bands, such as dipole, monopole, dielectric resonator antenna (DRA), patch and inverted-F antenna [1, 5-7].

The continuous boom and boost of wireless communication have been leading to more and more demands for small size light-weight and high gain antennas. A microstrip antenna is one of the types of antenna that is chosen by researchers to be used in wireless applications due to the characteristics that distinguish these antennas in terms of small size, low profile, good integration and low cost. The microstrip patch antennas which function via multiple frequency bands are necessary to use with some wireless applications simultaneously like mobile phones. Over the recent past years, great effort has been focusing on the designs of microstrip antennas and enhancing their characteristic. This type of antenna is better used in the applications that require very narrow band properties, like security applications. The principle drawback of the microstrip patch antenna is the restricted bandwidth which is an important parameter in the antenna design. Patch antennas are widely used in modern wireless communication systems because of light weight, high gain, low profile, low cost and ease of fabrication [8-9]. There are number of substrates that can be used for the design of microstrip antenna for e.g. Alumina, FR4, RT-Duroid etc whose dielectric constants vary in the range of 2.2 to 12. For good antenna performance, a substrate with low dielectric constant is needed in order to provide better efficiency [10]. The coaxial probe feeding method is used for feeding the patch antenna because of its impedance matching capability [11] and has low spurious radiation.

This paper aims to design two patch antennas at 2.4 GHz for 802.11b/g/n applications. Both patch antennas are designed using CST software and fabricated on Rogers substrate. Since Wi-Fi is one of the wireless connectivity for IoT, it has been formed in linear array for beamforming techniques. Section 2 discusses details on the antenna and array design, Section 3 represents the simulation and measurement results, while Section 4 concludes the findings of this paper.

2. RESEARCH METHOD

2.1. Design of single patch antenna

Two design of patch antennas have been simulated and fabricated in order to compare their performance. The proposed antenna resonant frequency 2.4GHz, Rogers RT588 material with dielectric constant 2.2 and substrate height 1.6mm are being selected. Steps for proposed antenna are as follows [12-14]. There are two designs of patch antennas for this purpose 1) slotted ring patch antenna, and 2) truncated slotted ring patch antenna is designed based on work by [15]. A rectangular patch whose dimensions are calculated to (1)-(5) are describe as follows:

$$W = \frac{\lambda_0}{2\sqrt{0.5(\varepsilon_r + 1)}} \tag{1}$$

$$\varepsilon_{eff} = \frac{\varepsilon_r + 1}{2} + \frac{\varepsilon_r - 1}{2}\left(\frac{1}{\sqrt{1 + 12h/w}}\right) \tag{2}$$

$$L = \frac{c_0}{2 f_r \sqrt{\varepsilon_{eff}}} \tag{3}$$

$$\Delta L = 0.412h \frac{(\varepsilon_{eff} + 0.300)\left(\frac{W}{h} + 0.264\right)}{\varepsilon_{eff} - 0.258 \left(\frac{W}{h} + 0.813\right)} \tag{4}$$

$$L_{eff} = L - 2\Delta L \tag{5}$$

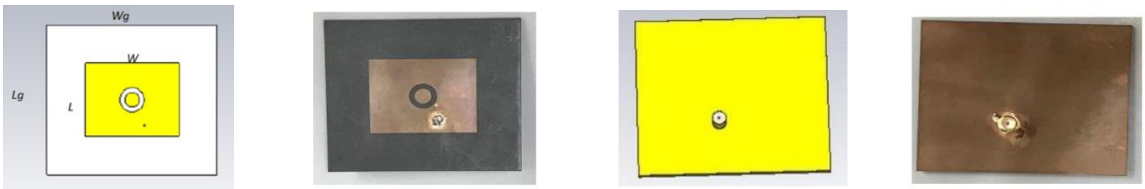
where W and Leff are width and length of the patch respectively.

The main objective is to design patch antenna for WiFi applications. The antenna design is fabricated on Rogers RT5880 (Ɛr=2.2) dielectric material due to its low loss material. The height of the dielectric material is to be 1.6mm which is the default thickness for Rogers RT5880 material. The width of the conducting patch element is 49.38mm and length is 41.32mm for the frequency of 2.4 GHz. The size and dimension for both antennas (slotted ring and truncated slotted ring) are shown in Table 1.

Table 1. Patch antennas parameters

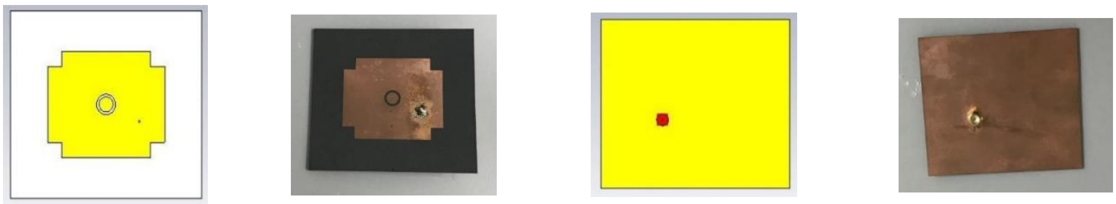
Slotted Ring		Truncated Slotted Ring	
Parameter	Value	Parameter	Value
Substrate material	Rogers RT5880	Substrate material	Rogers RT5880
Substrate thickness (*h*)	1.6mm	Substrate thickness (h)	1.6mm
Operating frequency (f_r)	2.4GHz	Operating frequency (f_r)	2.4GHz
Dielectric constant (ε_r)	2.2	Dielectric constant (ε_r)	2.2
Length of patch (L_{eff})	29.76mm	Length of patch (L_{eff})	41.32mm
Width of patch (*W*)	38.37mm	Width of patch (W)	49.38mm
Slot inner radius (*r*)	3mm	Slot inner radius (r)	3mm
Slot outer radius (*R*)	5mm	Slot outer radius (R)	4mm
Length of ground (*Lg*)	61.01mm	Length of ground (Lg)	72.57mm
Width of ground (*Wg*)	69.62mm	Width of ground (Wg)	80.63mm
Coaxial feed (point)	*X*=39.81, *Y*=4.5	Coaxial feed (point)	X=54.32, Y=14

The most important element to reduce the spurious radiation is the feeding part. Therefore, the coaxial probe is used as the feeding technique for these designs. Figure 1 and Figure 2 show the physical design of the simulated and fabricated antennas using coaxial probe feeding technique for sloted ring patch antenna and truncated slotted ring patch antenna, respectively [16].



(a) (b) (c) (d)

Figure 1. Design of a slotted ring patch antenna, (a) simulation (top view), (b) fabrication (top view), (c) simulation (bottom view), (d) fabrication (bottom view)



(a) (b) (c) (d)

Figure 2. Design of a truncated slotted ring patch antenna, (a) imulation (top view), (b) fabrication (top view), (c) simulation (bottom view), (d) fabrication (bottom view) [16]

2.2. Truncated slotted ring patch antenna array

In Section 3, the comparison performance between the slotted ring patch antenna and the truncated slotted ring patch antenna were discussed and analyzed. It is observed that by comparing the performance of both antennas, the truncated slotted ring patch antenna has a good agreement between simulation and measurement results than slotted ring patch antenna. Therefore, the truncated slotted ring patch antenna is chosen to be formed into a linear array antenna of 1×4 as shown in Figure 3. The spacing between the inter-elements is 0.25λ.

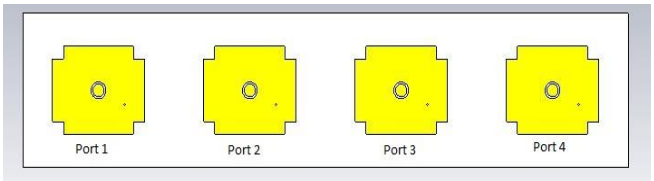


Figure 3. Simulation of a truncated slotted ring patch antenna array (1×4) [16]

2.3. Antenna array optimization using active element pattern and Genetic Algorithm (GA) techniques

This section describes beamforming technique of a linear array using a combination of the active element pattern (AEP taken from CST) with a Genetic Algorithm (GA). A GA was chosen, because it is robust, not easily trapped in local maxima (or minima) and is suitable for complex problems (with a large number of variables), especially those involving mutual coupling. It has been used in many applications especially in wireless communication such in in cognitive radio networks [17].

The fitness function, *f(x)* of GA based on (7) in this optimization is the difference between the desired radiation pattern, $E_{desired}$ and total active element pattern, E_{total} the antenna array. The desired radiation pattern, $E_{desired}$ is a cosine function which is determined by user as shown in Figure 4. Meanwhile the total active element pattern, E_{total} method is calculated based on (6). The active element pattern is defined as the radiation pattern of the array when one radiating element is driven and all others are terminated with matched loads.

$$\boldsymbol{E}_{total} = \sum_{n=1}^{N} \boldsymbol{I}_n \boldsymbol{G}_a^n(\theta,\varphi) e^{jk\hat{r}.\boldsymbol{r}_n} \quad (6)$$

where $\boldsymbol{I}_n$ is the complex valued feed current applied to the nth element, $\boldsymbol{G}_a^n(\theta,\varphi)$ is the active element pattern of the nth element, $e^{jk\hat{r}.\boldsymbol{r}_n}$ is the spatial phase term, $\hat{r}$ is the unit radial vector from the coordinate origin in the observation direction (θ,φ), and r_n is a position vector from the origin to the center of the nth element; boldface type indicates a vector quantity. The AEP for truncated-slotted ring patch antenna array has been obtained from CST by activating one of the element and termination of others as described in [18]. The $\boldsymbol{I}_n$ parameters in (6) will be optimized using Genetic Algorithm so that the total Active Element Pattern, $\boldsymbol{E}_{total}$ will be matched with the desired pattern (for example at theta=30º as in Figure 4). The flow chart for the optimization process is displayed in Figure 5. It explains about the guidelines and flow of the optimization procedure using hybrid methods of AEP and GA in order to steer the beam to the desired direction.

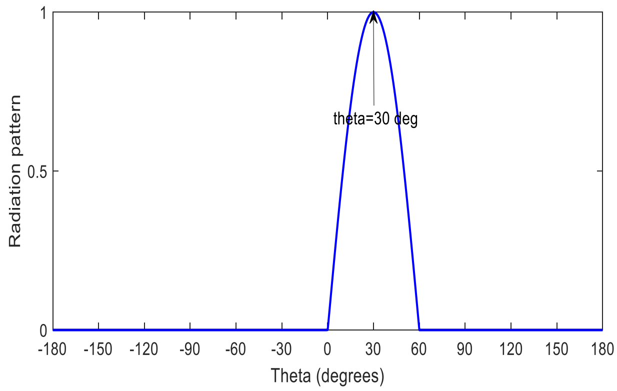


Figure 4. Desired radiation pattern with beam steering at theta=30º [16]

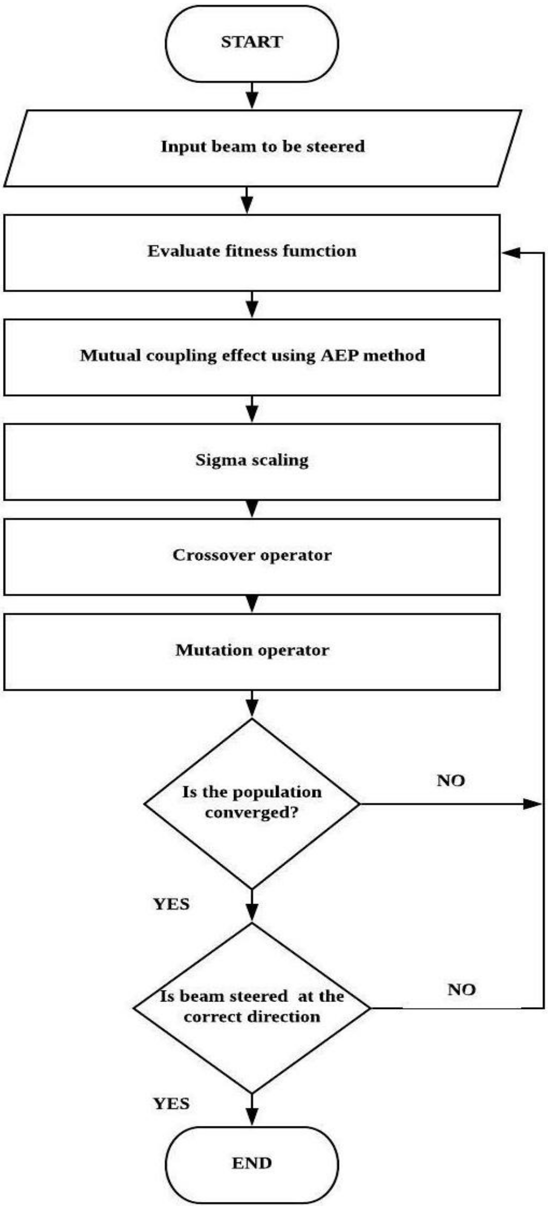


Figure 5. Flowchart of GA and AEP [16]

Based on (7), when *f(x)*=1 refers that the total array pattern calculated from AEP and GA (6) has been fully matched with the desired radiation pattern. In this case, the aim of beam steering of antenna array has been achieved. On the other hand, if *f(x)*=0 refers that the total array pattern is mismatched with the desired radiation pattern. It means that the method is unable to steer (or optimize) the beam to the desired directions.

$$f(x) = \frac{1}{1+0.05|E_{desired}-E_{total}|} \tag{7}$$

3. RESULTS AND ANALYSIS

3.1. Simulated and measured results for a single element of slotted ring and truncated slotted ring antenna

Figures 1 and 2 present the antenna designs using CST Microwave Studio Suite. The response curve for the reflection coefficient, S_{11} parameters between simulated and measured results for both antennas (slotted ring and truncated slotted ring) are depicted in Figure 6 and 7. The simulated results (denoted in red curve) show that both antennas resonate at the expected frequency of 2.4 GHz. Meanwhile, the measurement results (denoted in green curve) show the S_{11} at the resonance frequency of 35dB and 15.57dB respectively. However, the fractional bandwidths are 1% and 2% respectively. Figure 8 shows the radiation pattern and directivity of the slotted ring and truncated-slotted ring patch antenna at 2.4 GHz. It is observed that the radiation patterns are directional with the directivity of 7.1 dBi and 7.8 dBi respectively. Table 2 provides the comparison between slotted ring and truncated-slotted ring patch antennas and it is observed that the truncated-slotted ring patch antenna performs better in comparison with slotted ring at the resonance frequency. Thus, the truncated-slotted ring patch antenna has been selected for antenna array optimization using Active Element Pattern (AEP) and Genetic Algorithm (GA) techniques.

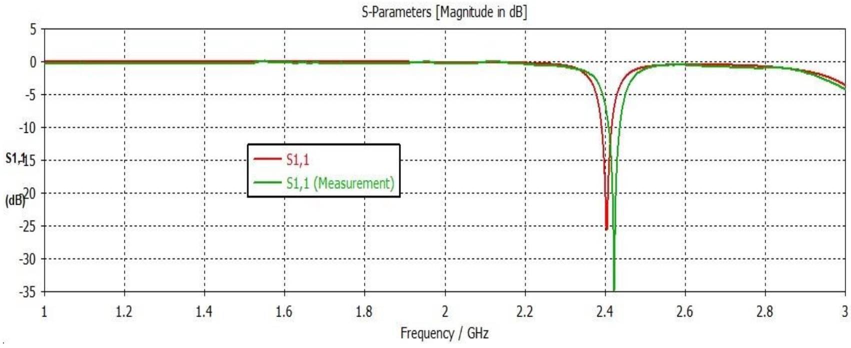


Figure 6. Simulated S_{11} (red curve) and measured S_{11} (green curve) of a slotted ring patch antenna

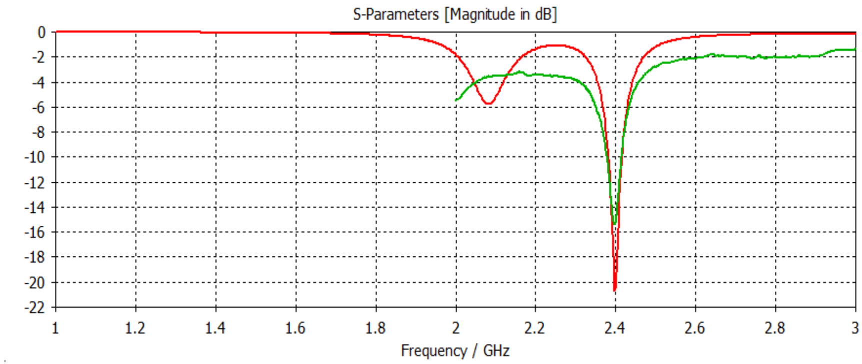


Figure 7. Simulated S_{11} (red curve) and measured S_{11} (green curve)
of a truncated slotted ring patch antenna [16]

(a) (b)

Figure 8. Radiation pattern of a (a) slotted ring, (b) truncated slotted ring patch antenna[16]

Table 2. Comparative results between slotted ring patch and truncated slotted ring patch antennas

Parameters	Slotted Ring Patch Antenna	Truncated Slotted Ring Patch Antenna
Simulated S1,1	-25.68 dB at 2.404 GHz	-20.72 dB at 2.398 GHz
Measured S1,1	-35 dB at 2.42 GHz	-15.58 dB at 2.4 GHz
Bandwidth, BW	1%	2%
Impedance, Z	48.9 Ω	47.5 Ω
Directivity	7.1 dBi	7.78 dBi

3.2. Simulated result of the 1×4 patch array

In this case, 4 elements of truncated-slotted ring patch antenna have been formed into a linear array (1× 4) as shown in Figure 3. Figure 9 shows the S-parameter as a function of frequency. The antenna resonates at 2.4 GHz with S_{11} value of 28.7dB. The high value of the S_{11} indicates good matching which leads to higher value of the directivity and gain for the antenna designed. On the other hand, S_{12}, S_{13} and S_{14} indicate low coupling coefficients between elements of #1 to #2, #1 to #3 and #1 to #4 which are less than -20dB. The coupling coefficients are in close agreement with each other. The directivity obtained in 1×4 patch array is of 21.4 dBi (as shown in Figure 10 which is better when compared to the single element patch (Figure 8(b)). It is expected that as number of elements increase, the gain increases and the beamwidth narrower.

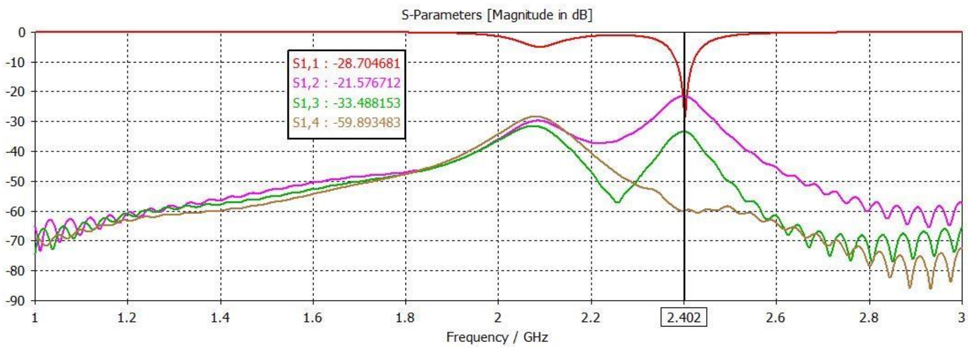


Figure 9. S-parameters of a truncated slotted ring patch antenna [16]

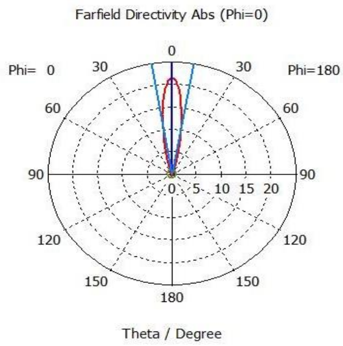
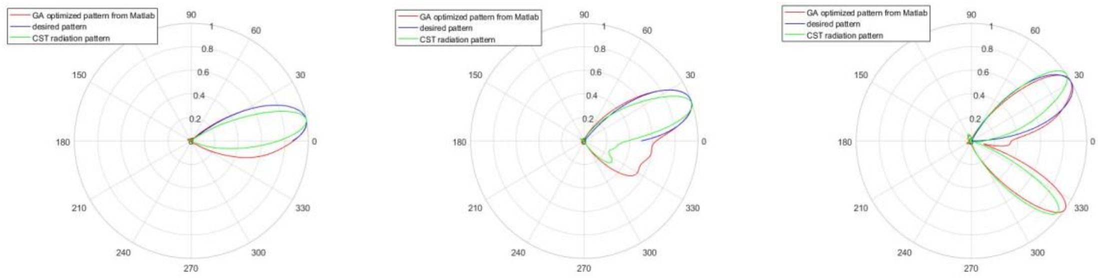


Figure 10. Radiation pattern of 1 by 4 truncated-slotted ring antenna array [16]

3.3. Beamsteering at theta=10º, 20º and 30º

The optimization techniques using AEP and GA has been tested for the desired pattern steered towards 10º, 20º and 30º as shown in Figure 10(a), (b) and (c) respectively. The results show that the radiation pattern of 1×4 antenna array has been successfully steered towards desired direction. However, the limitation of 1× 4 linear patch arrays make it unable to steer the beam higher than 40º using AEP and GA. Table 3 shows the excitation values (amplitude and phase) for each of the antenna element that have been optimized using AEP and GA which are I_1, I_2, I_3 and I_4.



(a) (b) (c)

Figure 11. Beam steering technique of the radiation pattern of 1× 4 truncated-slotted ring antenna array using AEP and GA towards (a) 10º, (b) 20º and (c) 30º [16]

Table 3. Beamsteering vs current values (amplitude and phase) for each of the element in antenna array [16]

Beam steering	I_1		I_2		I_3		I_4	
	Amplitude	Phase	Amplitude	Phase	Amplitude	Phase	Amplitude	Phase
10º	0.06	96.7°	0.28	-21.9°	0.57	-67.1°	0.35	-82.6°
20º	0.18	116.5°	0.13	-140.5°	0.88	-19.1°	0.53	-99.5°
30º	0.55	-14.8°	0.75	-158.8°	0.31	6.4°	0.06	124.9°

4. CONCLUSION

In this paper, two designs of single patch antenna; slotted ring and truncated-slotted ring microstrip patch antenna that resonate at 2.4 GHz have been designed using CST software for WiFi applications. Simulation and measurement results have been observed at the resonance frequency for both antennas. It has been observed that the truncated-slotted ring patch antenna performs better in compared to slotted ring patch antenna at the 2.4 GHz. Due to that observation, a linear of 1× 4 array of truncated-slotted ring patch antenna has been designed and optimize using AEP and GA. It is observed the directivity of 7.8dBi and 28.7dB for single patch and array respectively. A good agreement between simulation and measurement results of truncated-slotted ring patch antenna at 2.4GHz show that the antenna is suitable for WiFi applications. Later, a 1× 4 antenna array has been designed for beamforming capability. The techniques of AEP and GA optimize the excitation amplitude and phase in order to steer the beam from theta=10º, 20º and 30º. The beam has been successfully steered towards 10º, 20º and 30º.

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