Compact Multiband Microstrip Printed Slot Antenna Design for Wireless Communication Applications

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Abstract

In this paper, a compact multiband printed antenna is proposed to cover four resonant bands in the range of 1-6 GHz. The antenna structure is inspired from that of the classical multi-cavity magnetron resonator. The antenna comprises a slot annular ring structure in the ground plane of an Isola FR4 substrate having ε_r = 4.4 and thickness h=1.5 mm. The outer circle of the annular ring is loaded with radial arranged small circular slots. On the opposite side of the substrate, the antenna is fed with a 50-Ohm microstrip line. To investigate the effect of different antenna elements on the antenna performance, a parametric study is conducted. The antenna is simulated, fabricated, and measured. The simulated 10 dB input reflection coefficient bandwidths for the four resonant bands are 35% (1.53–2.11GHz), 14% (2.9–3.34GHz), 12% (4.2–4.75GHz), and 9% (4.94–5.39GHz), respectively. Thus, the antenna is a proper candidate for many in use bands of wireless systems (1.65, 3.14, 4.44, 5.24 GHz), including LTE-FDD, GNSS, GSM-450, W-CDMA/HSPA/k, 802.11a, and IEEE 802.11ac WLAN. The results indicate that the designed antenna has quad-band resonant responses with substantial frequency ratios of f_4/f_3, f_3/f_2 and f_2/f_1. Besides, the antenna offers reasonable radiation characteristics with a gain of 2.5, 4.0, 6.2, and 4.2 dB, throughout the four resonant bands.

1. Introduction

Many wireless communication applications are recently becoming available below 6 GHz, and some of which with multiple frequencies are billed for the growth of high-speed mobile telecommunication systems. For this reason, researchers are inspired to design compacted and multiband antennas [1]. Therefore and due to the desirable properties of microstrip antennas, they are considered as good candidates for these purposes [2].

Alternatively, a variety of slot antenna designs are introduced to fabricate compact and multiband antennas. Slot structures are commonly used to achieve bandwidth enhancement in multiband printed antennas. Traditional slot fractal shapes and other structures have been effectively used to design antennas with and multiband for a variety of wireless applications [3–19].

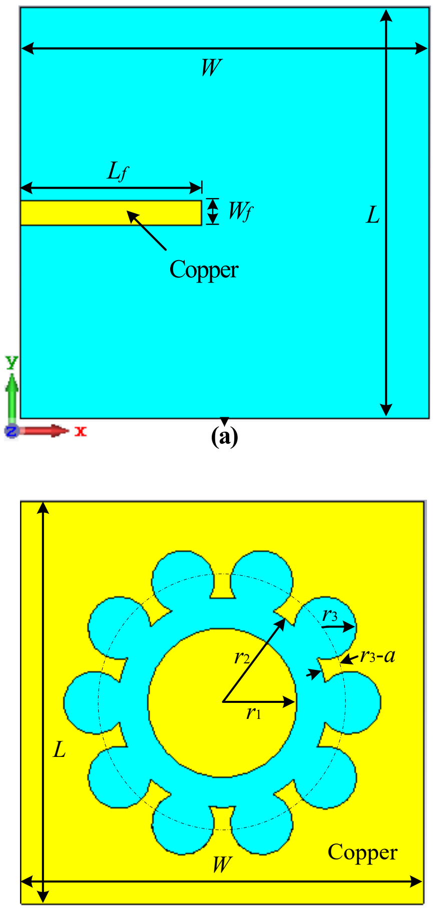
Sze et al. [7] suggested a low profile dual-band Annular Ring Slot Antenna (ARSA) for the use in 2.4/5 GHz (WLANs). The ring slot is embedded with a meandered grounded strip, thereby exciting three resonant modes. Ali et al. [8] presented the design of a new compact dual-band slot antenna in the form of Cantor square fractal geometry for wireless applications. Sedghi et al. [10] investigated a Minkowski slot antenna integrated with a Jerusalem cross (JC) for dual-band operation with compact size to improve the bandwidth. The feed line of the proposed antenna is constructed as a T-shape. Zahid et al. [15] proposed a dual-band radiation antenna with a tunable slot ground. The design comprises a coplanar waveguide feeder with a lumped capacitance element to stimulate both first and second order modes for the ground plane in terms of currents. These bands are controlled by a series combination of a capacitor and an inductor. Hamad et al. [17] suggested a tri-band, as notches, low profile UWB microstrip monopole antenna. The slot structure is obtained by introducing inverted Ω- and L-shaped slots in the partial ground plane, rather than using the conventional microstrip patch antenna as a radiating element. Lv et al. [18] proposed a compact, wideband antenna with dual circular polarization. The antenna consists of a patch with an inverted-L structure and a small slit in the ground plane. The wide bandwidth characteristics are obtained from the use of monofilar stubs in a spiral form with a slitted uneven ground plane. Behera et al. [19] suggested a floating slotted microstrip antenna with U shapes to excite three bands for modern wireless telecommunication applications. The antenna is aimed to serve for WLAN and WiMAX applications. The use of U-slots in the patch improves the gain response and increases the resonant frequencies. To improve the antenna bandwidth, a suitable air gap was sustained, separating the patch layer from the ground plane.

In this paper, a low profile microstrip slot antenna is proposed to be used in multiband wireless communication systems covering a band ranging from one to six GHz. The antenna structure suggested is in the form of ring slot geometry loaded with ten small circular cavities on its outer circumference in the ground plane. The opposite side of the ground plane is a microstrip line fed with a 50 Ω. The proposed antenna offers a quad-band response suitable for many applications available within the 1 - 6 GHz range. A parametric study is conducted on many parameters of the antenna structure to show the flexibility of tuning the antenna within these bands.

2. The Antenna Structure

This section presents a miniature slot antenna design with a microstrip feed line as a top layer and a slotted ground plane at the bottom layer. Figure 1 shows the layout of the proposed slot antenna.

The slot structure is created by adopting two annular rings for the proposed printed antenna with inner radius r_1 and outer radius r_2. Ten circular slots with radius r_3 are loaded on the outer ring.



(a)

(b)

Figure 1: Structure of the proposed slot antenna: (a) upper layer, (b) bottom layer.

3. The Antenna Design

The proposed slot antenna with quad-band characteristics is fed with a microstrip line in the top layer, while the ground plane is composed of slotted annular rings loaded with ten outer circles. The antenna is designed, and its performance response is evaluated within a frequency band of 1–6 GHz. The slot structure of the suggested antenna is engraved using a CNC machine on an Isola FR4 laminate with 1.5 mm thickness (h), relative permittivity $\mathcal{E}_r$ = 4.4, 35µm copper thickness (t) and tanδ of 0.02. Table 1 depicts the proposed slot antenna dimensions of Figure 1 (a) and (b). These dimensions are specified for the lowest frequency.

The proposed antenna is modeled using the Computer Simulation Technology (CST) Microwave Studio [20]. The overall size of the antenna is 53.8×53.8×1.5 mm^3. Figure 2 shows the simulated input reflection coefficient of the proposed slot antenna.

Table 1: Antenna dimensions.

Parameter	L	W	L_f	W_f	a	r_1	r_2	r_3
Dimension in mm	53.8	53.8	26.9	3.2	1.2	10	14	4.2

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4. Parametric Study

The simulation results of the proposed slot antenna design show that there are four factors affecting the ratio of the resonant frequencies relating them. These factors are; the feeder length (L_f), the Aspect Ratio (*AspR)*, the radius of the largest center slot (r_1), and the radius of the outer small cavity circle (r_2). To investigate the specific effects of these four factors, a parametric study is conducted.

4.1. The effect of feeder length (L_f):

The first parameter studied is the feed line length variation, as demonstrated in Fig. 3. The feed line length is varied from 24.9 to 28.9 mm. It is clear from the figure that when increasing the feed line length, the first two lower resonant bands disappear. Furthermore, decreasing the feed line length offers an interesting feature by allowing the capability of fine-tuning to the antenna resonant frequency.

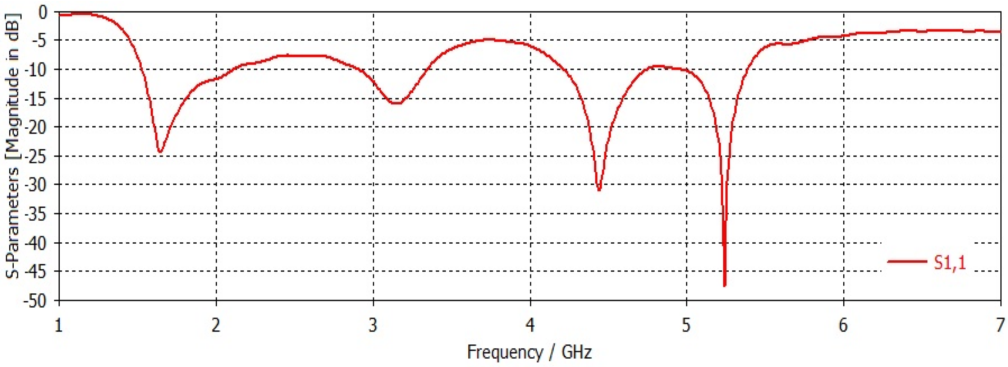


Figure 2. The simulated input reflection coefficient of the antenna.

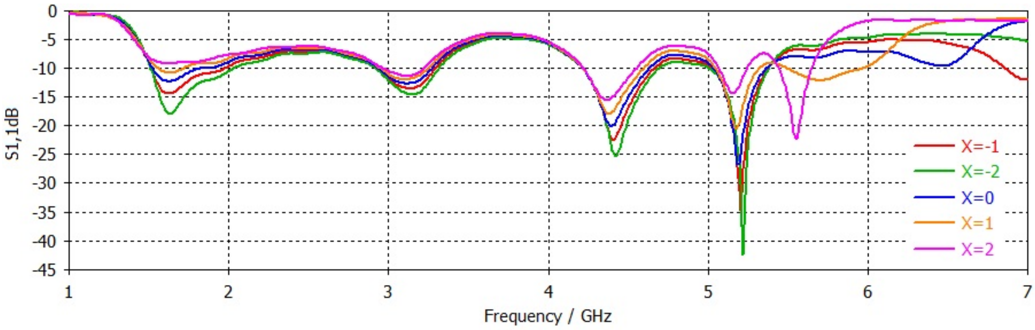


Figure 3. The simulated input reflection coefficient of the antenna with different values of feed line length (L_f+X).

4.2. The effect of varying the antenna Aspect Ratio *(AspR)*:

An attractive attribute of the designed slot structure is obtained on the variation of the Aspect Ratio *(AspR)*. The ratio of *W / L*, identifies the *AspR* of the slot structure. Here, only the width W is varied, keeping the length L unchanged. Accordingly, four responses are obtained with substantial resonant frequency ratios: f_4/f_3, f_3/f_2, and f_2/f_1 within the simulated frequency range. Figure 4 shows the simulated input reflection coefficients of the proposed antenna for various values of the *AspR*, ranging from 0.8-1.2 % in steps of 0.1 %. The responses illustrated in Fig. 4 reveals that there exists a considerable change of the resonant frequencies of the four bands which is suitable for coarse tuning to the desired frequency application.

4.3. The effect of r_1:

Another interesting parametric study is shown in Fig. 5, where the variation of r_1 given in Fig. 1 (b) and Table 1 has a noticeable impact on the antenna response. The second resonant frequency around 3 GHz offers better impedance matching of -22 and -26 dB, especially for values of r_1 equals to 11 and 12 mm. It is clear from Fig. 5 that the variation of r_1 has little effect on the upper-frequency band (5.24 GHz), while there exists a considerable shift on the other three lower bands, thereby allowing for tuning the desired center frequency within these bands.

4.4. The effect of r_2:

The last parameter affecting the antenna response is r_2. Figure 6 shows the simulated S_{11} of the designed slot structure for different values of r_2. On the contrary to the last parameter variation (r_1) depicted in Fig. 4, the first resonant band obviously shows a very small variation in its center frequency, while the other upper three bands exhibit considerable variations.

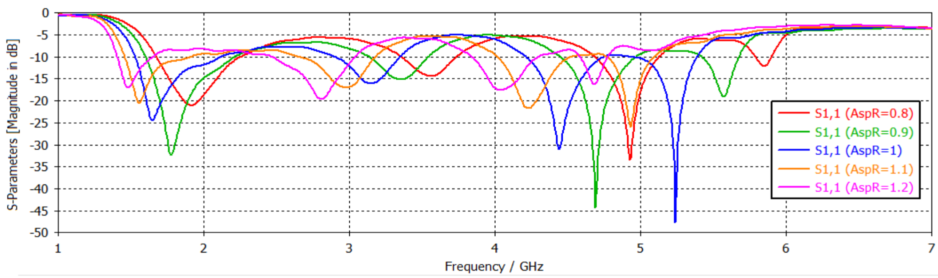


Figure 4. The simulated input reflection coefficient of the antenna for different values of (*AspR)*.

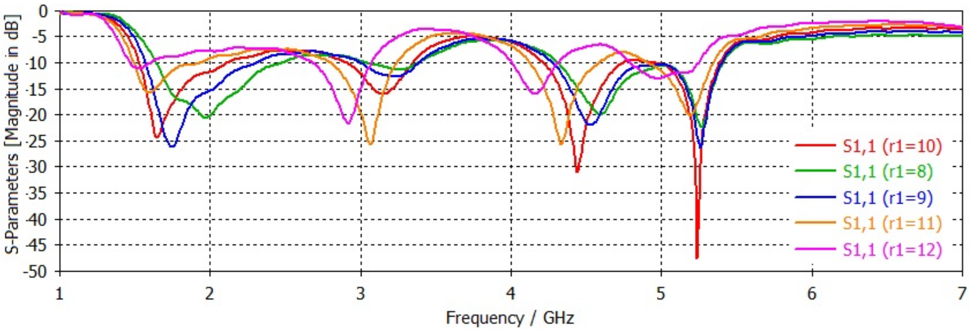


Figure 5. The simulated input reflection coefficient of the antenna for different values of r_1

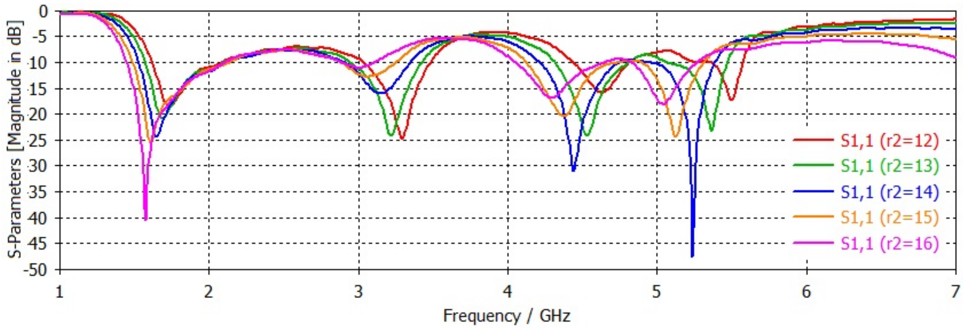


Figure 6. The simulated input reflection coefficient of the antenna for different values of r_2

5. Results and Discussion

Figure 7 shows the simulated and measured results for the designed slot antenna. The configurations of Fig. 1 (a) and (b) have been fabricated as shown in the photograph of Fig. 8, according to the dimensions given in Table 1. It is clear from Fig. 8 that there is some discrepancy between the measured and simulated input reflection coefficient of the proposed slot antenna. The centers of the measured four resonant bands are, to some extent, shifted to the right from the simulated ones, while the simulated bandwidth is somewhat narrower. This might be because of errors that are occurring due to that the FR4 material has frequency variant permittivity. Also, the soldering of the SMA connector may add some measurement errors.

By proper scaling of the antenna parameters, the four resonant bands may be allocated in a frequency range of 1–6 GHz. The suggested antenna is of a square-shaped ground plane of width (side length), L = 52.8 mm, while the circular slot structure is with a diameter, D = 33 mm. The feeding line on the bottom plane of the substrate has a width of 3.25 mm, (W_f) and a length of 26.9 mm (L_f).

However, examining the effect of several parameters studied in section IV, on the antenna performance, it is realized that the most effective parameter on the antenna performance in terms of input reflection coefficient is the outer diameter (D) of the slot structure, which determines the guided wavelength λg as:

$$\lambda_g = \frac{\lambda o}{\sqrt{\varepsilon_{eff}}} , \quad (1)$$

where ε_{eff} is the effective relative permittivity and is given by [21]

$$\varepsilon_{eff} = \frac{\varepsilon_r+1}{2} + \frac{\varepsilon_r-1}{2} + \frac{1}{\sqrt{1+12h/w_f}} , \quad (2)$$

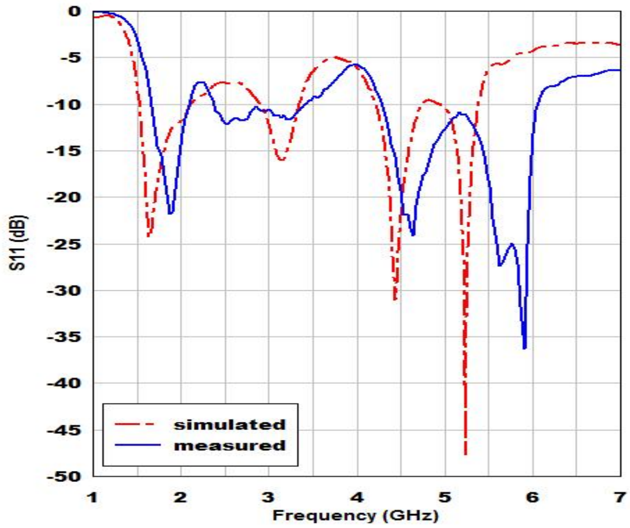


Figure 7: The simulated and measured input reflection coefficient of the designed slot antenna.

In this perspective, a majority of the existing electromagnetic packages support an instant determination of ε_{eff} by using substrate properties at the required frequency. The lowest resonant frequency, f_1, is governed by slot diameter D and the guided wavelength λg:

$$f_1 \approx \frac{c}{2D\sqrt{\varepsilon_{eff}}} \ , \qquad (3)$$

where c is the free space speed of light, and λg is calculated at the lowest resonant frequency.

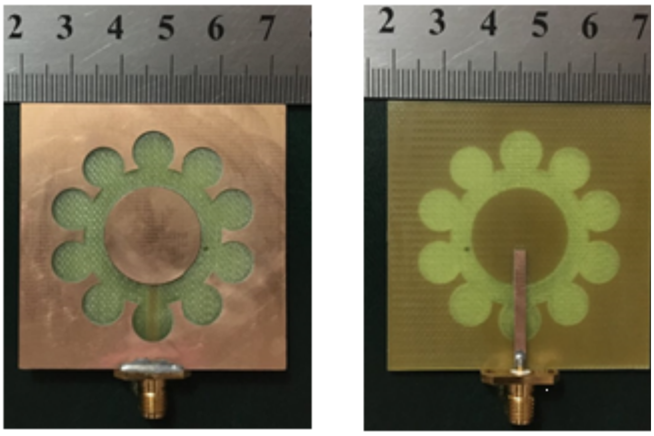
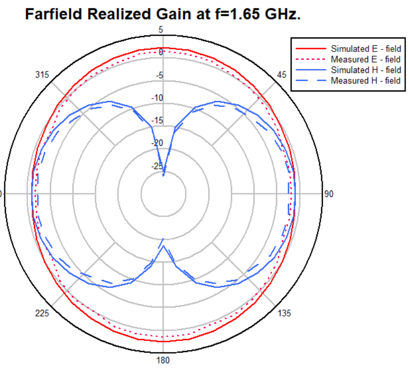
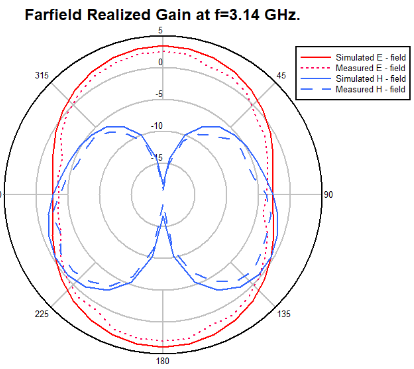


Figure 8: Photograph of the fabricated antenna with SMA.

Figure 9 shows the simulated radiation patterns in its polar form at the four resonant bands, clarifying that they have almost Omni-directional properties.



(a)



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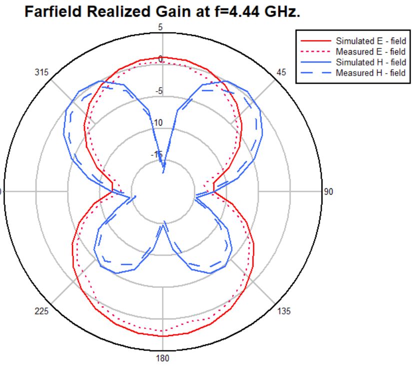
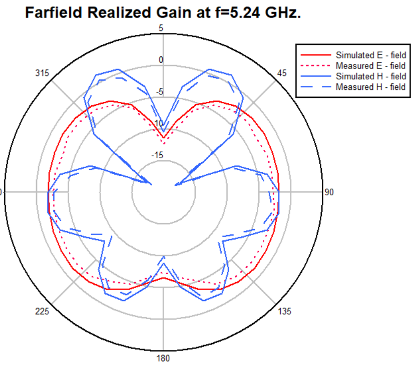


(c)



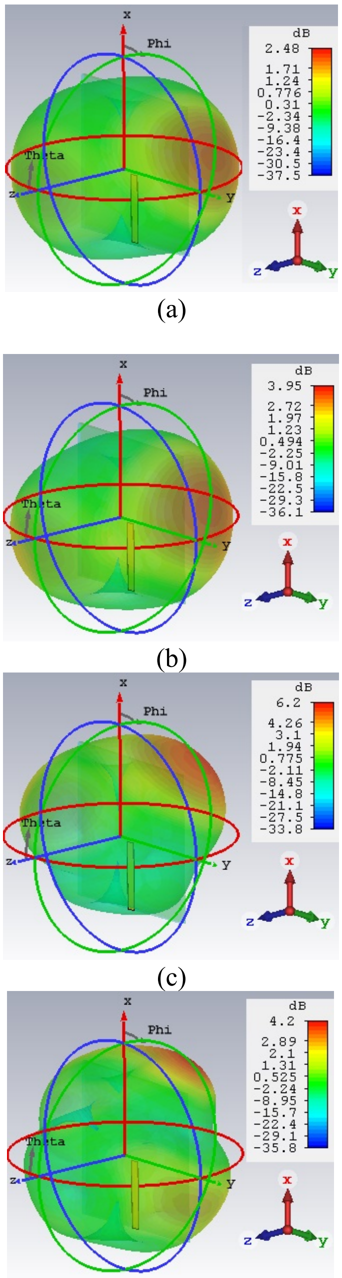
(d)

Figure 9: The simulated and measured radiation patterns in the polar at: (a) 1.65 GHz, (b) 3.14 GHz, (c) 4.44 GHz and (d) 5.24 GHz.

Figure 10 demonstrates the simulated results of the three-dimensional (3D) radiation patterns of the slot antenna at 1.65, 3.14, 4.44, and 5.24 GHz, with a feeder length of 26.9 mm. Table 2 shows the measured and simulated realized gain of this antenna at the aforementioned frequencies. The antenna radiation efficiency at the four resonant frequencies is 66 %, 95 %, 91.5 %, and 78.5 %, respectively. The antenna efficiency is the ratio of the power delivered to the antenna with respect to the power radiated from that antenna. An antenna with high efficiency is the one that has the majority of the power presented at the antenna's input radiated away. The antenna of low efficiency is the one that has most of the power absorbed in the form of losses within the antenna, or reflected away as a result of a mismatch in impedance.

Table 2: Simulated and measured realized gain (dB).

Frequency (GHz)	1.65	3.14	4.44	5.24
Simulated	2.48	3.95	6.20	4.20
Measured	2.33	3.57	5.96	4.01

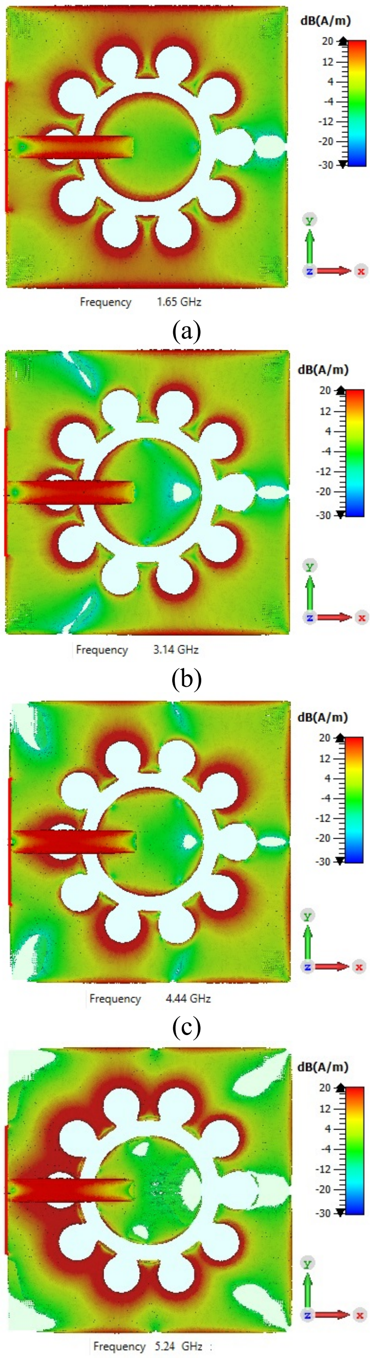


(a) (b) (c) (d)

Figure 10: The far-field simulated 3-D radiation patterns of the proposed slot antenna at: (a) 1.65 GHz, (b) 3.14 GHz, (c) 4.44 GHz, and (d) 5.24 GHz.

To get more insight into the performance of this antenna, the current distribution can be used for this purpose. Figure 11 demonstrates the current distribution on the surface of the antenna at the resonant frequencies. The various current distributions show different densities throughout the slotted structure of the antenna, depending on its impedance matching at each frequency. The highest current density is very clear at the 5.24 GHz frequency band due to the lowest input reflection coefficient. The lowest current density is at the 3.14 GHz frequency band since it shows the minimal impedance matching, as depicted in Figure 2.

Table 3 shows a comparison between previous works and the proposed work.



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

Figure 11: The current distributions on the surface of the proposed slot antenna at: (a) 1.65 GHz, (b) 3.14 GHz, (c) 4.44 GHz and (d) 5.24 GHz.

Table 3: Comparison with previous work.

[Ref]	Antenna Type	Physical size	Electrical size	Number of bands	Center frequency [GHz]	Realized gain, [dB]
[3]	Microstrip-fed Hilbert slot	31.7×31.7	4.3x4.3	2	2.19 3	9.02 4.2
[4]	Printed slot	35.25x17.3	3.5x7.22	2	2.4 5	1.95 4.48
[6]	Fractal printed slot	47.23x47.23	2.64x2.64	2	2.4 5.2	2.11 3.72
[7]	Annular ring slot	30x30	4.16x4.16	2	2.4 5	1 3.6
[8]	Cantor fractal slot	50x50	2.5x2.5	2	2.4 5.8	2.8 4.4
[9]	Printed slot dual notch	23x28	3.72x3.06	2	3.5 5.8	3 4.5
[10]	Fractal slot with Jerusalem crosses	40x40	3x3	2	2.5 5.5	3.14 2.5
The proposed antenna	Printed slot	53.8x53.8	3.38x3.38	4	1.65 3.14	2.48 3.95

6. Conclusion

An annular ring magnetron-like printed slot antenna is introduced for use in multiband wireless communication operating at 1.65, 3.14, 4.44, and 5.24 GHz. Results show that this antenna offers remarkable features making it a proper candidate for most of the communication services within these bands. The antenna shows a quad-band operation with better bandwidths and Omni-directional radiation patterns. The parametric study conducted reveals that the resonant bands can be shifted up or down depending on the required application with fine adjustment capability. The highest resonant frequency is determined by the smallest slot in the antenna's ground plane, while the lowest one is controlled by the overall slot size. Measurements of the fabricated antenna in terms of input reflection coefficient are in good agreement with simulated results. The 10 dB input reflection coefficient bandwidths at the center frequencies of 1.65, 3.14, 4.44 and 5.24 GHz are of about 35% (2.11–1.53 GHz), 14% (3.34–2.9 GHz), 12% (4.75–4.2 GHz), and 9% (5.39–4.94 GHz), respectively. This makes the proposed antenna fit for many in use bands within the wireless communication systems (1.65 GHz - LTE-FDD and GNSS, 3.14 GHz - W-CDMA/HSPA/HSPA+, 4.44 GHz - GSM-450, 5.24 GHz - IEEE 802.11a and IEEE 802.11ac WLAN). Hopefully, the high degree of freedom obtainable by this antenna will make it a desirable option for antenna designers.

Acknowledgements

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