A compact multiband planar antenna using modified L-shape resonator slots

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ABSTRACT

A multiband planar antenna designed and proposed with resonator slots is presented. The proposed antenna consists of a planar hexagonal patch composed of two pairs of resonator slots. The antenna is designed using Isola FR408 substrate ($\varepsilon_r = 3.68$ and $\tan\delta = 0.0092$) with a compact dimension of $21 \times 28 \times 1.6$ mm$^3$. The designed antenna has good impedance matching and radiation characteristics for the desired multiband frequencies. Multibands are obtained by etching two pairs of modified mirror-imaged L-shaped resonator slots on the hexagonal planar patch. Simulated and measured results of the antennas' reflection coefficient are provided and there is good agreement between the simulation and measurement results. The antennas' measured peak gains are between 2 dB and 5 dB and measured efficiencies are between 40% and 80%. The proposed antenna, when compared to other antennas, exhibits multiband characteristic by using a single-feed structure and generates different combinations of isolated lower frequency bands in miniature size. The antenna has stable directional radiation patterns and has the potential to meet the requirements of wireless communications applications.

1. Introduction

Modern wireless communication systems have undergone extraordinary transformations. To facilitate global communication standards and services for personal wireless communications systems, the need to design low-cost, compact size and lightweight antennas that possess multiband functionality has become imperative [1]. Although ordinary half-wavelength patch antennas are promising candidates to be employed in various wireless communications applications, these are voluminous for devices requiring miniature size. Patch antennas designed for portable handheld devices must utilize maximum possible frequency bands to serve multiple wireless communication applications. Several techniques for antenna size reductions have been investigated, such as using metamaterial structures [2, 3, 4, 5] and capacitors and inductors based loaded structures [6, 7, 8].

The ultra-wideband (UWB) antennas experience electromagnetic interference (EMI) from other wireless communication systems since the short pulses occupy extremely wide spectrum of frequencies [9, 10, 11]. The multiband antennas provide customized and selective operations at desired wireless frequency bands with no interference from the other application bands [12]. Considerable interest on multiband antennas got spurred as the demand for mobile devices that can operate over several communication standards has increased [13]. Adaptability to different scenarios in wireless communication systems antennas with multiple operating frequencies is necessary. To achieve multiband operations for compact antennas, different techniques using planar technology have been investigated. Many methodologies were employed including different slot shapes [14, 15, 16], fractal ground [17, 18, 19, 20], split ring resonators [21, 22, 23, 24], shorting walls, and exploiting the fundamental and higher modes of the antenna [25]. A challenging issue for the wireless communications applications is the design and development of miniaturized multiband antennas [26].

Studies on hexagonal patch antennas are becoming more significant for multiband applications [27, 28, 29, 30]. The most effective method for creating multiple operating frequencies is by etching slots on radiating element [19]. This can shift the operating frequency of the antenna by altering the current path, thereby shifting the frequency to higher or lower band. Rectangular slots, G-shaped slots, and fractal grounds can be used to achieve multiple frequency bands in printed planar antennas with average quality of radiation characteristics [31].

The proposed antenna is a compact multiband microstrip patch antennas with two pairs of resonator slots that covers frequency bands for different wireless communication applications. The design combines the hexagonal patch structure with two pairs of modified L-shaped slots and has an overall size of $21 \times 28$ mm$^2$. In the proposed antenna, the resonator slot pairs are mirror imaged replicas, located in very close
proximity. The coupling between the resonators also generates new lower frequency bands, making the size of the antenna markedly reduced.

2. Antenna design and analysis

2.1. Hexagonal patch antenna design

A hexagonal metallic patch placed over a single layer of Isola FR408 substrate with full ground is used for the proposed antenna design. The substrate has a thickness of 1.6 mm and a size of $21 \times 28$ mm$^2$. The relative permittivity of the substrate is 3.68 with a loss tangent ($\tan\delta$) of 0.0092. The proposed hexagonal patch antenna without slots is shown in Figure 1. Commercial electromagnetic simulation software Ansys HFSS is used to perform the simulations.

In this proposed antenna, the hexagonal patch is designed for a frequency of 5.2 GHz. The resonant frequency of the hexagonal patch is obtained using the circular patch equations. The relation between the parameters and dimensions is given in Table 1. The equivalent circuit of modified L-shaped slot loaded hexagonal patch is shown in Figure 2. The fabricated (a) hexagonal patch antenna and (b) proposed antenna are shown in Figure 4.

![Figure 1. The hexagonal patch antenna.](image1)

![Figure 2. Equivalent circuit of modified L-shaped slot loaded hexagonal patch.](image2)

![Figure 3. Antenna geometry and dimension.](image3)

![Figure 4. Fabricated (a) hexagonal patch antenna and (b) proposed antenna.](image4)

| Parameters | $L$ (mm) | $W$ (mm) | $f_x$ (GHz) | $f_y$ (GHz) | $q_f$ |
|------------|--------|--------|----------|----------|------|
| Dimensions | 28     | 21     | 1.7      | 3        | 0.3  |
| Parameters | $q_fy$ | $P_x$  | $V$      | $Q$      | $K$  |
| Dimensions | 7      | 9      | 0.4      | 0.6      | 3.8  |
| Parameters | $L_1$  | $W_1$  | $L_2$    | $W_2$    | $L_3$ |
| Dimensions | 9.7    | 0.6    | 3.8      | 0.3      | 4.4  |
| Parameters | $W_3$  | $L_4$  | $W_4$    | $L_5$    | $W_5$ |
| Dimensions | 10.2   | 4.7    | 0.3      | 3.9      | 0.3  |
| Parameters | $L_6$  | $L_7$  | $W_6$    | $W_7$    |      |
| Dimensions | 2      | 1.8    | 2.6      | 2.7      |      |
areas of hexagonal patch and circular patch is used to obtain the side length of the hexagonal patch [14].

\[
fr = \frac{X_{\text{iso}}}{2 \pi a \sqrt{\varepsilon_r}}
\]  

(1)

\[
a_e = a \left\{ 1 - \frac{2h}{\pi a} \left( \frac{\pi a}{2h} 1.7726 \right) \right\}^{0.5}
\]  

(2)

\[
\pi a_e^2 = \frac{3 \sqrt{3}}{2} P_x^2
\]  

(3)

Where \(fr\) is the resonant frequency of the circular patch antenna with \(X_{\text{iso}} = 1.8411\) for the dominant TM\(_{11}\) mode, \(a\) is the radius of the circular patch. In Equation (2), \(a_e\) is the effective radius of circular patch. Equation (3) gives the relation between the area of the circular patch and the hexagonal patch, with \(P_x\) is the side length of the hexagonal patch. The main advantage of hexagonal patch over circular patch is good impedance matching that improves the sensitivity for the desired frequency [32]. The proposed antenna geometry and dimensions are presented in Figure 3 and Table 1 respectively.

At resonance, the input impedance of a hexagonal patch is real. As in the case of a circular patch, along the perimeter, the input power is independent of the position of the feed. At any radial distance \(\rho\) from the center of the patch, the input resistance \(R_{in}\) can be written as [33].

\[
R_{in}(\rho = \rho_0) = \frac{J_1(k\rho_0)}{G_t J_1(ka_e)}
\]  

(4)

\[
R_{in}(\rho = a_e) = \frac{1}{G_t}
\]  

(5)

Where \(G_t\) is the total conductance due to radiation, conduction, and dielectric losses. Thus the total conductance can be written as

### Table 2. Slot width, W1 variations.

| Slot width, W1 | Frequency bands (GHz) |
|----------------|-----------------------|
| 0.2 mm         | 3.77–3.86, 4.14–4.26, 5.004–5.15, 7.06–7.18, 9.36–9.53 |
| 0.6 mm         | 5.004–5.15, 6.96–7.14, 9.36–9.56 |
| 0.8 mm         | 4.14–4.26, 5.004–5.15, 6.84–6.94, 9.36–9.56 |

### Table 3. Center width, Q variations.

| Center-width, Q | Frequency bands (GHz) |
|-----------------|-----------------------|
| 0.6 mm          | 3.816–3.96, 4.14–4.26, 5.04–5.15, 7.06–7.18, 9.36–9.53 |
| 0.8 mm          | 3.812–3.95, 4.23–4.30, 5.05–5.16, 7.06–7.17, 9.36–9.51 |
| 1 mm            | 3.82–3.966, 4.29–4.35, 5.09–5.2, 7.04–7.16, 9.37–9.51 |
\( G_i = G_{rad} + G_c + G_d \)

Where \( G_{rad} \) is the conductance across the gap between the patch and the ground plane, \( G_c \) and \( G_d \) are the conduction and dielectric losses, these can be written as

\[
G_{rad} = \frac{(k_{0a})^2}{480} \int_0^{\pi/2} \left[ f_{\text{inc}}^2 + \cos^2 \theta f_{\text{inc}}^2 \right] \sin \theta d\theta
\]

\[
G_c = \frac{\varepsilon_0 \varepsilon \pi r_f}{4h^2 \sqrt{\varepsilon}} \left[ (k_{0c})^2 - m^2 \right]
\]

\[
G_d = \frac{\varepsilon_0 \tan \delta}{4\mu_0 \beta r_f} \left[ (k_{0d})^2 - m^2 \right]
\]

2.2. Slot design

The two pairs modified L-shaped slots on the patch surface are considered as parallel combination of two slots impedances \( Z_{s1} \) and \( Z_{s2} \) as shown in Eq. (10). The equivalent circuit of the hexagonal patch antenna including the slots is shown in Figure 2. The equivalent impedance \( Z_{TS} \) of the slots \([34, 35]\) is calculated using Eqs. (11), (12), (13), (14), and (15).

\[
Z_{TS} = \frac{1}{Z_c + Z_e}
\]

\[
Z_{TS} = R_e + jX_e
\]

\[
R_e = 60 \left[ C + \ln(k_{0e}) + \frac{1}{2} \sin(k_{0e}) \left\{ S(k_{0e}) - 2S(k_{0e}) \right\} \right] \cos \phi
\]

\[
X_e = 30 \left\{ 2S(k_{0e}) + \cos(k_{0e}) \left\{ S(k_{0e}) - 2S(k_{0e}) \right\} \right\} - \sin(k_{0e}) \left\{ 2C(k_{0e}) - C \left( \frac{2W}{l} \right)^2 \right\}
\]

Where \( R_e \) is the radiation resistance, \( X_e \) is the reactive component, \( C \) is Euler’s constant, \( k \) is propagation constant in free space, \( W \) is width of slots, \( L \) is length of slots, \( \phi \) is the inclination of slot from the radiating edge, and functions \( S(x) \) and \( C(x) \) are the sine and cosine integrals defined as,

\[
S(x) = \int_0^x \sin \frac{x}{x} dx
\]

\[
C(x) = -\int_0^x \cos \frac{x}{x} dx
\]

The slot loaded patch antenna can be considered as the parallel combination of the patch and slots impedances. Therefore, the total input impedance of the resonator slot loaded patch antenna can be derived as in Eq. (16). Once the antenna input impedance is obtained, one can easily calculate the reflection coefficients and VSWR of the antenna.

\[ Z_{in} = \frac{Z_0 Z_{TS}}{Z_0 + Z_{TS}} \]
centerline to generate the total phase difference of 360° between slots. The presence of the mirror imaged slots affect the path of the current through the bends and correspondingly producing the desired multi-band frequencies.

2.3. Full antenna design

The proposed antenna geometry which comprises of a hexagonal patch with two pairs of mirror-imaged modified L-shaped resonator slots is shown in Figure 3. The antenna design parameters and dimensions are displayed in Table 1. These parameter values were obtained using parametric study in order to tune the antenna for best performance.

3. Results and discussions

The final antenna structure is designed using the commercial finite element method solver for electromagnetic structures field simulation tool, Ansys HFSS. A microstrip feedline is used to match the 50Ω line
impedance. First a parametric study was performed to obtain best geometric values to get best antenna performance, given in Table 1. Then, full wave simulations were performed to investigate the performance of the proposed antenna. Return Loss and gain patterns are analysed. The original antenna (without slots) and the proposed multiband antennas were fabricated and the return loss for both antennas is measured. The photographs of the fabricated antennas are shown in Figure 4.

3.1. Parametric studies

Several parameters are studied and their effects are observed in order to tune the antenna resonant frequencies to the desired configuration. The effects of certain width and gap length of the mirror-imaged modified L-shaped slots on the performance on the multiband of the proposed antenna are investigated.

The resonant modes of any patch can be strongly modified using slot loading. The addition of slot perturbations on the horizontal radiating patch change the surface current path lengths, correspondingly decreasing or increasing the resonant frequencies. It has the advantage of low cross polarization over the antenna with no slots. The main limitation is that the radiating patch area reduces which lowers both the bandwidth and gain of the antenna. As a general explanation for the equivalent circuit corresponding to the slots, each slot can be considered as a slotline terminated with short circuits at both the ends. The radiation conductance mostly determines the power radiated from the slots [1]. The radiation conductance in a microstrip patch antenna is given in Eq. (17).

\[
G_c = \frac{P_{rad} + P_n + P_{nr}}{V_{ref}^2}
\]  
(17)

Where \(P_{rad}\) and \(P_n\) are the radiated power from the slots into the substrate and air. \(P_{nr}\) is neglected as the power carried by surface waves are negligible. \(V_{ref}\) is the reference voltage in the slot which depends on the slot voltage (\(V_s\)), the effective length of the slot (\(L_s\)), phase constant (\(j\beta\)) and offset distance (\(d\)), as given in Eq. (18).

\[
V_{ref} = \frac{V_r}{\sin \beta (L_s/d)}
\]  
(18)

One of the most significant changes observed is with the variation of the slot width, W1. It can be clearly identified from Figure 5 that controlled variations of W1 can ensure better impedance matching at the desired resonant frequencies.

As shown in Table 2 it can be seen that as W1 is increased from 0.2 mm to 0.8 mm, the lower bands experience a frequency shift towards left. With a width of 0.2 mm, the resonant frequencies are achieved successfully and the return loss is less than −10 dB for all the bands.

Another parameter investigated is the effect of metal width between the middle slots, Q, as shown in Figure 6. By changing Q, the resonant frequency near 3.8 GHz can be tuned easily. As Q is varied from 0.6 mm to 1 mm, the sensitivity of frequency band at 3.8 GHz improves while the performance of the frequency band at 5.1 GHz decreases. For the band at 4.21 GHz, the frequency shifts slightly to the left with improved return loss as Q is increased. The other sub-resonators simply help improve the matching as shown in Table 3.

The slot length, L7 also can influence the frequency bands. The simulated return loss of the frequency band near 3.8 GHz of the multiband antenna shifts to lower frequency as L7 is decreased from 1.8 mm to 0.6 mm. On the other hand, there is a frequency shift from 4.21 GHz to 4.58 GHz, while the remaining frequency bands positions remain the same. The return loss of the middle frequency band at 5.1 GHz also improved with the increasing the slot width. So L7 can be used mainly to tune this frequency band as shown in Table 4 and Figure 7. The dimensions of the proposed antenna are fixed based on the performance from this parametric study and thus the frequency bands at 3.71 GHz, 4.21 GHz, 5.16 GHz, 6.98 GHz, and 9.44 GHz are obtained.

The variation of each frequency band with the change in the total length of the modified L-shaped slot is shown in Figure 8 (the selected proposed antenna frequencies are named as Band1, Band2, Band3, Band4 and Band5 respectively in this figure). This provide an insight into the relation of antenna’s behavior with the total slot length variations. The frequency of all the bands are reduced with increased total slot length and is in accordance with the analytical model of the slots discussed before.

3.2. Current patterns

Surface current for all frequencies of the proposed structure with single slot and dual slots are simulated, as shown in Figure 9. The surface currents distribution gives clear view regarding the sections of the slots that contribute to maximum radiation for a particular resonant frequency. Thus, this implies the importance of the slot length effect. For frequency bands of 3.71 GHz and 4.21 GHz, the effective slot length is given by ‘L1+L2:L3+W7’, while for 5.16 GHz band the slot lengths sum corresponds to ‘L6+L7+W6+W7’. Finally the slot lengths sum ‘L1+L2’ affects the frequency bands at 6.98 GHz and 9.44 GHz.

3.3. Return loss

The return loss coefficients of the fabricated antennas are measured with an R&S® ZVL vector network analyzer with
frequency range from 9 kHz to 13.6 GHz. The simulated return loss responses of the antenna with slots and without slots are in Figure 10. The measured return loss of the proposed antenna with slots is compared with the corresponding simulated result in Figure 11, and they are in good agreement. The proposed antenna resonates at six resonant frequencies at 3.71 GHz with a bandwidth of 40 MHz, 4.21 GHz with a bandwidth of 50 MHz, 5.16 GHz with a bandwidth of 110 MHz, 6.98 GHz with a bandwidth of 80 MHz, and 9.44 GHz with a bandwidth of 70 MHz.

3.4. Gain patterns

The simulated and measured gain total patterns in dB at the resonant frequencies of 3.71 GHz, 4.21 GHz, 5.16 GHz, 6.98 GHz, and 9.44 GHz are shown in Figure 12. For the upper band, the
maximum gain observed is 4.89 dB. For the lower band, the maximum gain of about 2.3 dB is observed. The gain total in dB variations with respect to frequency variations are shown in Figure 13. Simulation and measured results show that the radiation efficiency of the proposed design is between 42-75% for all the desired bands (Figure 14).

Comparison of the proposed antenna with the other relevant multiband patch antennas in Table 5 shows that the proposed antenna offers relatively smaller size and supports more bands with robust performance.

4. Conclusion

A single layered, compact multiband antenna based on hexagonal patch and two pairs of mirror-imaged modified L-shaped resonator slots has been designed and the results are analysed. The antenna resonates at frequencies of 3.71 GHz, 4.21 GHz, 5.16 GHz, 6.98 GHz, and 9.44 GHz with desired return loss and gain. Parametric studies are carried out to analyse the performance of the multibands with the variations in parameters of the mirror-imaged modified L-shaped slots. The proposed antenna has a compact size and can be used for various wireless communication applications.

Declarations

Author contribution statement

Indu Jiji Rajmohan: Conceived and designed the experiments; Performed the experiments; Analyzed and interpreted the data; Wrote the paper.

Mousa I. Hussein: Conceived and designed the experiments; Analyzed and interpreted the data; Contributed reagents, materials, analysis tools or data; Wrote the paper.

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Competing interest statement

The authors declare no conflict of interest.

Additional information

No additional information is available for this paper.

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