A dual-band CPW-fed miniature planar antenna for S-, C-, WiMAX, WLAN, UWB, and X-band applications

Md. Mottahir Alam1*, Rezaul Azim2*, Nebras M. Sobahi3, Asif Irshad Khan3 & Mohammad Tariqul Islam4

A miniature planar antenna is a vital component of any portable wireless communication device. The antenna in portable devices should provide wide/multiple operating bands to cover a good number of narrowband services as a multi-band antenna not only reduces the number of antennas but also lessens the system complexity, cost, and device size. To operate over S-, C-, WiMAX, WLAN, UWB, and X-communication bands, in this paper, a dual-band CPW-fed antenna is presented. The anticipated antenna is made up of a vertical bow-tie-shaped patch and two asymmetric ground planes and etched on the same side of the single-sided standard substrate material. To generate two distinct operating bands, an inverted L-shaped parasitic element is inserted within the modified U-shaped coplanar ground plane. The antenna achieved dual operating bands of 3.24–8.29 GHz and 9.12–11.25 GHz in measurement which helps the proposed antenna to cover S-, C-, WiMAX, WLAN, 4G LTE, 5G sub-6 GHz, UWB, and X-communication bands. In the two operating bands, the antenna realized a peak gain of 4.33 dBi, and 4.80 dBi, the maximum radiation efficiency of 86.6%, and 72.6%, and exhibits symmetric radiation patterns. In the operating bands, the antenna also exhibits good time-domain behavior which helps it to transmit the signal with minimum distortion.

As modern wireless communications devices are shifting towards ultra-small sizes, the miniaturization of antennas is indispensable. The design of small wideband/multi-band antennas for handheld communication devices is very tough as it must fulfill broad bandwidth requirements, symmetric radiation pattern, stable gain, compact size, lightweight, and easy fabrication. Recently, there has been increasing attention in searching antennas to cover multiple frequency bands such as S-band (2–4 GHz), WiMAX (3.3–3.8 GHz), 5G mid bands (3.3–3.8 GHz, 4.4–4.9 GHz), C-band (4–8 GHz), WLAN (5.15–5.825 GHz), UWB (3.1–10.6 GHz), X-band (8–12 GHz) due to the numerous operating necessities of communication devices1–5. A narrow band microstrip patch antenna can be switched into a multi-band antenna by adding a slit/slot in the patch/ground plane at suitable positions. The size, shape, and placement of this slit/slot play a significant role in the resonances and stopband. If the slot/slit length is either quarter-wavelength or half-wavelength in size at a proper place in the patch/ground plane, it excites the higher modes near the fundamental mode, which helps to achieve multiple operating bands6.

Several microstrip line and CPW-fed antennas have already been reported for wideband/multi-band applications. To achieve multi-band operation, they either use slot/s in the patch/ground plane or parasitic slit7–27. Unlike microstrip line-fed antennas, CPW-fed antennas occupy nearly all areas surrounding the patch. In a CPW-fed antenna, both the patch and ground plane are designed on one side of the substrate. Due to the existence of the main radiator and the closeness to the ground, CPW feeding is very advantageous for manufacturing antennas. CPW-fed antennas are characteristics with a larger operating band, lower dispersion, and low radiation leakage. Besides, it simplifies construction, allows simple shunt & series surface attachment of additional circuit components, and eliminates the necessity for wraparound and via holes28. For example, in Ref. 9, a CPW-fed tri-band bow-tie-shaped antenna is reported. By implanting three slots in the bow-tie patch, this design achieved...
This article introduces a CPW-fed antenna for multi-band communication applications. The presented antenna is comprised of a CPW-fed radiator and two coplanar asymmetrical ground planes. The coplanar ground plane has introduced an inverted L-shaped parasitic element to provide the necessary dual-band operation. The radiation from the ground planes enables the antenna to operate in dual wideband mode with a very compact size. The effect of different parameters on impedance bandwidth is studied using surface current and analyzed in conjunction with supporting parametric analysis. A prototype with optimized parameters is fabricated, and the measured results show that it can work over the 3.24–8.29 GHz and 9.12–11.25 GHz bands.

**Antenna configuration**

The footprint of the studied antenna is depicted in Fig. 1. The anticipated antenna consists of a vertical patch and two asymmetric grounds. The patch and two asymmetric ground planes are designed on the same side of an inexpensive FR4 material with a dielectric constant \( \varepsilon_r \) of 4.6, thickness \( h \) 1.6 mm, while the other side is without any materialization of copper. A CPW stripline of width \( S \) and length \( H \) is used to feed the antenna. The separation between the patch and ground planes is \( d \).

To achieve the wideband matching, the characteristic impedance of the feedline can be calculated by

\[
Z_0 = \frac{30\pi K(k_0)}{\sqrt{\varepsilon_r} K(k_0)}, \tag{1}
\]

where \( K(k_0) \) is the complete elliptic integral of the first kind. The characteristic impedance of the feedline for WLAN and WiMAX applications is 50 \( \Omega \), and for UWB applications, it is 50 \( \Omega \).
where $\varepsilon_e$ is the effective dielectric constant of the substrate and $K(k_0), K(k_1), K(k'_0), K(k'_1)$ are the modulus of the complete elliptic integrals and can be calculated using\(^{31}\)

\[
\varepsilon_e = 1 + \frac{(\varepsilon_r - 1)}{2} \frac{K(k_1)K(k'_0)}{K(k'_1)K(k_0)},
\]

(2)

\[
k_0 = \frac{S}{S + 2d},
\]

(3)

\[
k'_0 = \sqrt{1 - k_0^2},
\]

(4)

\[
k_1 = \frac{\sinh(\pi S/4h)}{\sinh[\pi(S + 2d)/4h]},
\]

(5)

\[
k'_1 = \sqrt{1 - k_1^2}.
\]

(6)

In the above equations, $\varepsilon$ and $h$ are the relative permittivity and thickness of the substrate. The width $S$ and gap $d$ of the proposed can be calculated using the above formulas.

The width, $W$ of the radiator, which has a slight effect on the resonance, can be obtained using\(^{32}\)

\[
W = \frac{c}{2 f_r} \sqrt{\frac{2}{\varepsilon_e + 1}},
\]

(7)

where $c$ is the speed of light, and $\varepsilon_r$ is the relative permittivity. As the radiator is on top of the substrate, the effective permittivity of the substrate is\(^{32}\)

\[
\varepsilon_e = \frac{(\varepsilon_r + 1)}{2} + \frac{(\varepsilon_r - 1)}{2} \left[ 1 + \frac{10h}{W} \right]^{1/2}.
\]

(8)

The length, $L$ of the radiator, plays a vital role in generating the resonances and can be calculated using\(^{32}\)

\[
L = \frac{c}{2 f_r \sqrt{\varepsilon_e}} - 2 \Delta L,
\]

(9)

where $\Delta L$ is the extension of length due to fringing field and can be calculated using\(^{32}\)}.
The effective length of the radiator is then

\[ L_e = L + \Delta L. \]  

(11)

To attain the desired operating band, an inverted L-shaped ground is positioned on the right side of the patch. The L-shaped ground consists of overlapped horizontal and vertical portions with sizes of \( W_4 \times L_4 \) and \( t_1 \times (L_6 + L_4) \), respectively. The area of the overlapped portion is \( t_1 \times L_4 \). On the left side, one modified inverted U-shaped ground is placed. The modified inverted U-shaped plane comprised of four parts having the area of \( W_3 \times L_3, t_1 \times L_1, W_1 \times t_1, \) and \( t_1 \times L_5 \). Contrary to the antenna reported in Ref. 33, in this design, one inverted L-shaped parasitic element with an area of \( t_2 \times L_2 + W_2 \times t_3 \) is placed inside the inverted U-shaped ground. This parasitic element and lower end of the patch help the antenna to achieve the higher X-band. The main radiating element of the presented antenna is a vertical bow-tie-shaped patch. The entire length of the patch is \( L_{f1} \). The length of the tapered section is \( L_{f2} \), and the length of the upper portion is \( (L_{f1} - L_{f2}) \).

The theoretical and lumped circuit model return loss curves are depicted in Fig. 2b. Despite the slight discrepancy between theoretical and lumped model return losses, it is evident that the designed antenna realized dual operating bands and is suitable for S-, C-, WiMAX, WLAN, UWB, and X-band applications.

### Table 1. Final geometrical parameters of the antenna.

| Parameter | Value (mm) | Parameter | Value (mm) | Parameter | Value (mm) |
|-----------|------------|-----------|------------|-----------|------------|
| \( W_1 \) | 16.5       | \( d \)   | 1          | \( L_9 \) | 15         |
| \( W_2 \) | 1.5        | \( L_1 \) | 20         | \( L_{10} \) | 6.5         |
| \( W_3 \) | 5.5        | \( L_2 \) | 7          | \( L_9 \) | 1.5        |
| \( W_4 \) | 11         | \( L_3 \) | 5          | \( H \) | 6          |
| \( W_5 \) | 5          | \( L_4 \) | 5          | \( t_1 \) | 1.5        |
| \( S \) | 3          | \( L_5 \) | 13         | \( t_2 \) | 0.5        |

The equivalent circuit of the studied antenna is a combination of capacitance, inductance, and resistance, and their values are given by Ref. 34:

\[ C = \frac{\varepsilon_0 \varepsilon_r WL}{2h} \cos^{-2}\left(\frac{\pi S}{2L}\right), \]  

(12)

\[ L = \frac{1}{\omega^2 C}, \]  

(13)

\[ R = \frac{Q}{\omega C}, \]  

(14)

where \( \omega = 2\pi f \), and Q is the quality factor having a value of

\[ Q = \frac{c\sqrt{\varepsilon_r}}{4f_r h}, \]  

(15)

with \( f_r \) as the resonant frequency. The input impedance of the designed antenna is, therefore

\[ Z_{in} = \frac{1}{\frac{1}{Z_0} + \frac{j}{j\omega L} + j\omega C}. \]  

(16)

Therefore, the reflection coefficient and return loss values can be evaluated using

\[ \Gamma = \frac{Z_0 - Z_{in}}{Z_0 + Z_{in}}, \]  

(17)

\[ \text{Returnloss}_{dB} = 20\log|\Gamma| \]  

(18)

After extracting and calculating the parameters from the simulation, a lumped equivalent circuit model of the anticipated antenna is constructed and is portrayed in Fig. 2a. Additionally, this layout is verified by circuit theory analysis using advanced design system (ADS). The theoretical and lumped circuit model return loss curves are depicted in Fig. 2b. Despite the slight discrepancy between theoretical and lumped model return losses, it is evident that the designed antenna realized dual operating bands and is suitable for S-, C-, WiMAX, WLAN, UWB, and X-band applications.
Design investigation and analysis

Design evolution. To know the operating process and effect of different parts, Fig. 3 portrays the development of the expected antenna. Figure 4 illustrates the return losses and input impedances for various phases of evolution. In the development procedure, the initial design Ant#1 includes one L-shaped and one inverted L-shaped ground plane and a CPW-stripline-fed bow-tie-shaped patch. To form Ant#2, a section, PQR consisting of two rectangular bars of area $W_1 \times t_1$ and $t_1 \times L_1$ is incorporated at the upper part of the L-shaped ground plane, which in-turns convert into a modified inverted U-shaped ground. In Ant#3, one inverted L-shaped parasitic element of area $(t_2 \times L_2 + W_2 \times t_2)$ is placed inside the U-shaped ground. Finally, the anticipated antenna is formed by adding two triangular sections to the patch’s left and right lower end, as depicted in Fig. 3.

The return loss curve displayed in Fig. 4a shows that Ant#1 can operate over a 4.94–8.81 GHz frequency band, where the impedance is very much near to 50Ω. The addition of conducting section PQR to the L-shaped ground of Ant#1 increases the inductive effect of the antenna. This enhanced inductive effect due to a more protracted current path introduced three extra resonances at around 3.39 GHz, 3.81 GHz, and 8.37 GHz and helped Ant#2 in exhibiting a working band of 3.24–8.60 GHz. As shown in Fig. 4b, this band’s input impedance is better than Ant#1. When the parasitic element is positioned inside the modified U-shaped ground to form Ant#3 (Fig. 3), a stopband ranging from 7.84 to 8.14 GHz is created, and two separate working bands of 3.24–7.84 GHz and 8.14–8.69 GHz are exhibited as shown in Fig. 4a. This is due to the extra capacitive effect between the parasitic element and inverted U-shaped ground. When two triangular sections are added to the left and right lower end of the patch to look hexagonal, the inductive and the capacitive effects are increased further. The increased inductive and capacitive effects widen the stopband and move the higher resonance near the upper band, as portrayed in Fig. 4a. The final anticipated antenna exhibits two distinct operating bands of 3.248–8.31 GHz and 9.11–11.19 GHz. In the two bands, the impedance matching is much better and nearly equal to 50Ω.

Computation of equate-length of the current path. The surface current distribution on the antenna at four resonance frequencies of 3.375 GHz, 5.90 GHz, 7.98 GHz, and 10.1 GHz are presented in Fig. 5. In the figure, $L_{P1}$, $L_{P2}$, $L_{P3}$, and $L_{P4}$ displayed four current streamlines. In Fig. 5, the arrow signs show the current direction, the red color signifies the peak current density, and the blue color indicates a null. The effective length of the current path is evaluated analytically and produced directly from the CST simulator. To calculate

![Figure 2](image-url)
the current streamline lengths, the numerical values of the geometrical parameters of Table 1 are used. At the fundamental resonant mode of 3.375 GHz, as portrayed in Fig. 5a, the current around the inner edge of the inverted L-shaped ground is significantly larger than other portions of the antenna. The first streamline length $L_{P1}$ corresponding to the first resonance frequency is

$$L_{P1} = AB = L_6 + W_4 = 26 \text{ mm}. \quad (19)$$

This current path length is slightly longer than the corresponding quarter wavelength. As shown in Fig. 5b, at the first excited mode of 5.9 GHz, maximum currents are concerted in section CD of the inverted U-shaped ground. The second streamline length $L_{P2}$ corresponding to this resonance frequency is

$$L_{P2} = CD = \frac{W_1}{2} + \frac{L_2}{2} = 11.75 \text{ mm}, \quad (20)$$

which is also one-quarter of the wavelength. At 7.98 GHz, as in Fig. 5c, the second excited resonance is primarily due to the strongest current flow in the parasitic element. Here the third streamline length $L_{P3}$ is

Figure 3. Design evolution of the proposed antenna.

Figure 4. (a) Return loss curves, and (b) input impedances for the different evolution stages.
which is again a quarter wavelength of the corresponding wavelength. As shown in Fig. 5d, at \( f = 10.1 \) GHz, the fourth resonance is essentially owing to the monopole behavior of the vertical radiator. The streamline length \( L_{p4} \) for this resonance is

\[
L_{p4} = GI = H + \sqrt{L_{f2}^2 + \left( \frac{W_{f3} - S}{2} \right)^2} + \sqrt{(L_{f1} - L_{f2})^2 + \left( \frac{W_{f1}}{2} \right)^2} = 13.95 \text{ mm},
\]

and is a bit shorter than half of the wavelength. From the current distribution, it is clear that three dominant current streamlines have been observed in the first working band of 3.248 to 8.31 GHz, and one dominant streamline of current has been spotted in the second working band, which generates the fourth resonant mode. It is also worthy of revealing that the current streamline is nearly one-quarter/half of the wavelength at corresponding frequencies in the resonances. The small shifting from the quarter/half wavelength is primarily owing to the additional loading effect from the non-resonating parts of the antenna.

**Parametric study.** A parametric study was undertaken to investigate the impact of various parameters on antenna performance, which enables a more detailed optimization process. To inspect the sensitivity of \( W_i \) on antenna performances and resonance frequencies, the change of return loss and resonances are portrayed in Fig. 6a. As predicted, with the increment of \( W_i \), the first resonance moves towards a higher band while the second and third resonances shift downward, and the fourth resonance remains unaltered. The plot shows that the second and third resonances decrease with increasing \( W_i \). This is also justified by the mathematical expression of \( L_{p2} \) mentioned in Eq. (20). Figure 6b portrayed the effect of changing \( L_1 \) on the resonances and antenna performances. It is seen that the length \( L_1 \) has a minimal impact on the first resonance \( (f_1) \) and fourth resonance \( (f_4) \) while it influences the second \( (f_2) \) and third \( (f_3) \) resonances. Both the second and third resonance frequencies tend to decrease as \( L_1 \) is increased from 18.5 to 21.5 mm. This may be a way to generate a stop band at around 8.22 GHz. The equation for the first current path, \( L_{p1} \), leads us to the effect of changing \( L_6 \), which is verified by the parametric study portrayed in Fig. 6c. As the value of \( L_6 \) changes from 13 to 17 mm, the first

\[
L_{p3} = EF = W_2 + L_2 = 8.5 \text{ mm},
\]

\[
L_{p4} = GI = H + \sqrt{L_{f2}^2 + \left( \frac{W_{f3} - S}{2} \right)^2} + \sqrt{(L_{f1} - L_{f2})^2 + \left( \frac{W_{f1}}{2} \right)^2} = 13.95 \text{ mm},
\]
Figure 6. (a) Effect of $W_1$ on return losses and resonance frequencies, (b) effect of $L_1$ on return losses and resonance frequencies, (c) effect of $L_6$ on return losses and resonance frequencies, (d) effect of $L_{11}$ on return losses and resonance frequencies, (e) effect of $H$ on return losses and resonance frequencies, and (f) effect of $d$ on return losses and resonance frequencies.
resonance frequency decreases from 3.66 to 3.14 GHz. The evolution of \( L_6 \) also has some additional effects on the second and third resonances as well as the stopband at around 8.37 GHz. The current streamline length of the fourth resonance, \( L_4 \), demonstrated a strong dependence on \( L_{f1} \) and \( H \) portrayed in Fig. 6d,e, respectively, keeping all other parameters unaltered. The fourth resonance frequency changes from 10.31 to 9.76 GHz when the value of \( L_{f1} \) increases from 5.5 to 7.5 mm. On the other hand, the fourth resonance point decreases from 10.31 to 9.47 GHz as the value of \( H \) changes from 5 to 7 mm. However, the change of \( L_{f1} \) and \( H \) affects other resonances and stopbands. In addition to the above parameters, the coupling gap between the feedline and coplanar ground planes, \( d \), dramatically influences the two operating bands, especially on the third and fourth resonances. The effect of \( d \) on the return loss and resonances is depicted in Fig. 6f. The plot shows that the third and fourth resonance frequencies sharply increased when the value of \( d \) increased from 0.5 to 1.5 mm. The first and second resonance points also slightly rise with \( d \). Moreover, the bandwidth of the stopband at around 8.49 GHz is increased with decreasing coupling gap between the radiator and coplanar ground plane.

**Results and discussion**

**Frequency-domain analysis.** The anticipated antenna has been fabricated for experimental verification, and its performance is measured using the N5227A network analyzer from Keysight Technologies. The fabricated antenna is displayed in Fig. 7a, and its simulated, measured, and circuit model return loss curves are shown in Fig. 7b. A good agreement between the results has been observed. For RL ≥ −10 dB, the measured results portrayed that the anticipated antenna produces dual working bands with a bandwidth of 5.05 GHz (3.24–8.29 GHz, 87.6%) and 2.13 GHz (9.12–11.25 GHz, 20.9%). The slight disagreement may be attributed to the prototyping and measurement limitations.

The radiation characteristics of the antenna have been measured in MVG’s near-field antenna measurement system, StarLab. Figure 8a portrayed the gain of the anticipated antenna. The plot demonstrates that in the first and second bands, the average measured gains are 2.98 dBi and 4.37 dBi, with the maximum values of 4.33 dBi and 4.8 dBi. The studied antenna’s radiation efficiency is displayed in Fig. 8b. A good match between the simulated and measured efficiency has been observed. The plot shows that the antenna attained an average efficiency of 72.4% and 68.4% in the lower and higher band. The maximum efficiency at lower and higher bands is 86.6% and 72.6%, respectively.

The anticipated antenna’s measured \( E(\text{yz}) \) and \( H(\text{xz}) \)-field patterns at four resonance frequencies of 3.375 GHz, 5.90 GHz, 7.98 GHz, and 10.1 GHz are portrayed in Fig. 9. It can be observed that the anticipated antenna demonstrates a nearly omnidirectional radiation pattern. Despite an asymmetrical structure, the antenna exhibits symmetrical radiation patterns over the two bands with no back lobes. The primary benefit of the antenna’s symmetric radiating patterns is that the highest power is focused in the broadside direction that is unaffected by frequency changes. Therefore, the antenna exhibits broad half-power beamwidth in both \( E \)- and \( H \)-planes. At the low frequency of 3.375 GHz, the cross-polarization level of the \( H \)-plane pattern is more significant, which may be owing to the degeneration of the small antennas. Some nulls have also been observed, especially in...
the E-plane, mainly due to the agitation of the higher-order current modes. Despite these nulls, the radiation patterns of the studied antenna are still symmetrical, which is a primary requisite for WiMAX, WLAN, UWB, etc., applications.

**Time-domain analysis.** As a UWB antenna directly transmits narrow pulses, it is essential to inspect its time-domain behavior. The easiest method to test the time-domain behavior is to find the fidelity factor (FF). The FF measures the degrees of similarity between the transmitted and received signals. The FF can be calculated using

\[
\text{FF} = \frac{\left( \int_{-\infty}^{+\infty} |T_x(t)R_x(t + T)|^2 dt \right)^{1/2}}{\left( \int_{-\infty}^{+\infty} |T_x(t)|^2 dt \int_{-\infty}^{+\infty} |R_x(t)|^2 dt \right)^{1/2}},
\]

where \(T_x(t)\) and \(R_x(t)\) are respectively the transmitted and received signals.

A pair of transmitting and receiving antennas are positioned at 240 mm apart to calculate the FF using the CST simulator. A Gaussian pulse is selected for transmission, covering the entire UWB spectral mask. A number of virtual probes are positioned every 10° from 0° to 90°. Figure 10a displayed the normalized transmitted and received pulses. It is revealed that the FF is around 89.6% in face-to-face position, which has a value of 85.5% in side-by-side placement. These higher values of the FF indicate that the designed antenna can receive the input signal without any distortion. The group delay that quantifies the dispersion of the transmitted electromagnetic signal is defined as the negative derivative of the phase to frequency. Contrary to the narrowband counterpart, the group delay of an ultra-wideband antenna may vary significantly. The group delay should be small or flat in the working band for distortion-free transmission. The group delay is measured by exciting two identical antennas kept in the far-field region, maintaining a distance of 240 mm between them. The group delay of the studied antenna at the 3–12 GHz band is depicted in Fig. 10b. It can be seen from the plot that except at the stopband of 8.3–9.11 GHz, the group delay is almost flat over the two operating bands. The average measured group delay in face-to-face alignment is 1.02 ns and 0.92 ns in the first and second bands. The first and second bands’ measured group delays are 1.26 ns and 1.07 ns in a side-by-side alignment. These slight variations ensure
Figure 9. Measured radiation pattern at (a) 3.375 GHz, (b) 5.90 GHz, (c) 7.98 GHz, and (d) 10.1 GHz.
the phase linearity of the transmitted signal. Figure 10c demonstrates the simulated and measured transfer function for a pair of antennas in face-to-face and side-by-side placement. Relatively flat values of the transfer function have been seen in the functional bands with little variations in the stopband. The transfer function's
| References | Dimension (mm\(^2\)) | Operating bands (GHz) | Peak gain (dBi) | Substrate ε\(_r\) | Design complexity |
|------------|------------------------|-----------------------|-----------------|-----------------|-----------------|
| Ref.9      | 100 × 60 = 6000        | 2.17–2.72             | 3.75            | FR4 4.2         | Moderate        |
|            |                        | 3.34–3.66             | 3.56            |                 |                 |
|            |                        | 4.85–5.77             | 3.93            |                 |                 |
| Ref.11     | 30 × 65 = 1950         | 2.375–2.525           | 1.30            | FR4 4.3         | Moderate        |
|            |                        | 3.075–3.80            | 5.20            |                 |                 |
|            |                        | 5.80–6.90             | 3.10            |                 |                 |
| Ref.12     | 40 × 45 = 1800         | 2.02–2.14             | 1.87            | FR4 4.4         | Complex         |
|            |                        | 4.26–4.28             | 2.90            |                 |                 |
|            |                        | 5.45–5.56             | 4.13            |                 |                 |
| Ref.13     | 33 × 50.9 = 1680       | 2.80–3.00             | 2.32            | FR4 4.4         | Moderate        |
|            |                        | 3.30–3.50             | 1.21            |                 |                 |
|            |                        | 3.80–8.00             | – 6.00          |                 |                 |
| Ref.14     | 40 × 40 = 1600         | 2.20–2.50             | NR              | FR4 4.4         | Complex         |
|            |                        | 4.00–4.20             |                 |                 |                 |
|            |                        | 6.70–8.10             |                 |                 |                 |
| Ref.15     | 37 × 40 = 1480         | 2.30–2.75             | 2.50            | FR4 4.4         | Complex         |
|            |                        | 3.19–3.82             | 0.83            |                 |                 |
|            |                        | 5.06–6.15             | 2.02            |                 |                 |
| Ref.16     | 28 × 32 = 896          | 2.29–2.88             | 4.10            | FR4 4.4         | Moderate        |
|            |                        | 3.26–3.88             | 4.33            |                 |                 |
|            |                        | 4.17–6.07             | 2.70            |                 |                 |
| Ref.17     | 23 × 38 = 874          | 2.28–2.56             | 1.72            | FR4 4.4         | Moderate        |
|            |                        | 3.29–4.21             | 2.66            |                 |                 |
|            |                        | 5.05–5.91             | 3.10            |                 |                 |
| Ref.18     | 23 × 36 = 828          | 2.35–2.59             | 2.93            | FR4 4.4         | Simple          |
|            |                        | 3.31–3.93             | 2.25            |                 |                 |
|            |                        | 5.07–6.35             | 3.04            |                 |                 |
| Ref.19     | 26 × 30 = 780          | 2.33–2.55             | 1.24            | NR              | 2.65 Moderate   |
|            |                        | 3.00–3.88             | 2.92            |                 |                 |
|            |                        | 5.15–5.90             | 2.87            |                 |                 |
| Ref.20     | 20 × 38.5 = 770        | 2.10–2.49             | 2.95            | FR4 4.4         | Complex         |
|            |                        | 3.22–4.30             | 3.30            |                 |                 |
|            |                        | 4.89–6.12             | 3.05            |                 |                 |
| Ref.21     | 24 × 30 = 720          | 2.50–2.71             | 1.93            | Rogers 2.2      | Simple          |
|            |                        | 3.37–3.63             | 1.89            |                 |                 |
|            |                        | 5.20–5.85             | 1.94            |                 |                 |
| Ref.22     | 50 × 50 = 2500         | 2.35–3.61             | 2.8–3.5         | FR4 4.4         | Moderate        |
|            |                        | 5.15–6.25             | 3.7–4.3         |                 |                 |
| Ref.23     | 40 × 40 = 1600         | 2.24–2.93             | 2.8–3.3         | Rogers 4.5      | Complex         |
|            |                        | 4.48–5.54             | 3.2–5.7         |                 |                 |
| Ref.25     | 33 × 17 = 561          | 2.47–2.77             | 2–3.8           | FR4 NR          | Moderate        |
|            |                        | 3.30–3.70             |                 |                 |                 |
|            |                        | 5.10–6.62             |                 |                 |                 |
| Ref.29     | 18 × 34.5 = 612        | 2.28–2.57             | ≈ 1.40          | FR4 4.4         | Simple          |
|            |                        | 5.00–6.27             | ≈ 2.70          |                 |                 |
|            |                        | 7.11–7.96             | ≈ 3.35          |                 |                 |
| Ref.30     | 50 × 30 = 1500         | 1.42–2.08             | 2.10            | FR4 4.4         | Moderate        |
|            |                        | 3.49–4.13             | 1.75            |                 |                 |
|            |                        | 5.23–7.53             | 2.50            |                 |                 |
|            |                        | 8.00–9.87             | 5.50            |                 |                 |
|            |                        | 10.7–20.0             | 6.50            |                 |                 |
| Ref.41     | 40 × 49 = 1960         | Centred at 3.54 and 6.72 GHz | 4.78 | FR4 4.2       | Moderate        |
|            |                        | 4.65                  |                 |                 |                 |
| Ref.42     | 24 × 32 = 768          | 3.1–4.5               | 3.80            | RT/Duroid 5880 2.2 | Complex       |
|            |                        | 10.3–11.7             | 3.60            |                 |                 |
|            |                        |                       |                 |                 |                 |

Continued
Table 2. Comparison of the proposed antenna with recently reported multi-band antennas.

| References | Dimension (mm²) | Operating bands (GHz) | Peak gain (dBi) | Substrate εr | Design complexity |
|------------|-----------------|-----------------------|----------------|--------------|------------------|
| Ref. 43    | 58 × 40 = 2320  | 3.00–3.25             | 4.00–4.20      | NR           | FR4 4.4          |
|            | 29 × 30 = 870   | Centred at 2.5 and 4.2 GHz | 3.20 |             |                  |
|            | 96 × 100 = 9600 | 1–30                  | 2.2–11         | Rogers 2.2   | Moderate         |
| Proposed   | 24.5 × 20 = 490 | 3.24–8.29             | 4.33           | FR4 4.6      | Simple           |
|            |                 | 9.12–11.25            | 4.80           |              |                  |

measured and simulated phase distribution for both placements, shown in Fig. 10d, is linear except at the stopband. The smooth simulated result can be attributed to the distortion-free simulation setup.

A comparison of the presented antenna with recently proposed multi-band antennas is summarized in Table 2. As the studied antenna is smaller than existing antennas and can operate in two different frequency bands, it is ideal for use in the S-, C-, WiMAX, WLAN, 4G LTE, 5G sub-6 GHz, UWB, and X-communication bands. Although some antennas’ working bands and bandwidth are higher than those of the proposed antenna, the studied design offers the advantages of a compact footprint, a smaller physical dimension, and ease of commercial production for small-volume multi-band antenna applications.

Conclusions

Currently, many portable communication devices require an antenna that is small, planar, and operable over multiple bands to cover a good number of communication services. This paper proposes a dual-band CPW-fed antenna with two asymmetrical radiating coplanar ground planes. Including an inverted L-shaped parasitic slit helps the designed antenna generate two distinct operating bands. The fabricated antenna shows dual operating bands of 3.24–8.29 GHz (5.05 GHz) and 9.12–11.25 GHz (2.13 GHz). The antenna achieved the highest gain of 4.33 dBi and 4.8 dBi and the highest efficiency of 86.6% and 72.6% in the two working bands. The antenna also exhibits stable radiation patterns and excellent time-domain characteristics in the two operating bands, making it suitable for handheld communication devices. The prime advantage of the studied antenna is that it covers different service bands, including S-, C-, WiMAX, WLAN, UWB, and X-band communication systems, with very compact size (24.5 × 20 mm²) and a uniplanar profile.

Received: 24 June 2021; Accepted: 26 April 2022
Published online: 09 May 2022

References

1. Mohamadzade, B., Simorangkir, R. B. V. B., Hashmi, R. M, Lalbakhsh. A. UWB antenna for application in impulse radio regime. In Proc. IEEE Asia-Pacific Microwave Conference, 682–684 (2020).
2. Alibakhshi-Kenari, M., Naser-Moghadasi, M., Sadeghzadeh, R. A., Virdee, B. S. & Limiti, E. A new planar broadband Mohammad antenna based on meandered line loops for portable wireless communication devices. Radio Sci. 51, 1109–1117 (2016).
3. Alibakhshikenari, M., Limiti, E., Naser-Moghadasi, M., Virdee, B. S. & Sadeghzadeh, R. A. A new wideband planar antenna with band-notch functionality at GPS, bluetooth and WiFi bands for integration in portable wireless systems. Int. J. Electron. Commun. 72, 79–85 (2017).
4. Alibakhshikenari, M., Naser-Moghadasi, M., Sadeghzadeh, R. A. & Virdee, B. S. Metamaterial-based antennas for integration in UWB transceivers and portable microwave handsets. Int. J. RF Microw. Comput. Aided Eng. 26, 88–96 (2016).
5. Alibakhshikenari, M., Naser-Moghadasi, M. & Sadeghzadeh, R. A. Composite right-left-handed-based antennas for integration in UWB transceivers and portable microwave handsets. Int. J. RF Microw. Comput. Aided Eng. 26, 88–96 (2016).
6. Azim, R., Islam, M. T. & Mobashsher, A. T. Design of a dual band-notch UWB slot antenna by means of simple parasitic slits. IEEE Antennas Wirel. Propag. Lett. 12, 1412–1415 (2013).
7. Alibakhshikenari, M., Naser-Moghadasi, M. & Sadeghzadeh, R. The resonating MTM-based miniaturized antennas for wideband RF-microwave systems. Microw. Opt. Technol. Lett. 57, 2339–2344 (2015).
8. Alibakhshikenari, M. & Naser-Moghadasi, M. Novel UWB miniaturized integrated antenna based on CRLH metamaterial transmission lines. Int. J. Electron. Commun. 69, 1143–1149 (2015).
9. Hajiaoui, E. A. New triple band electromagnetic band gap microstrip patch antenna with two shaped parasitic elements. J. Comput. Electron. 17, 452–457 (2018).
10. Wu, M. T. & Chuang, M. L. Multibandwidth slotted bow-tie monopole antenna. IEEE Antennas Wirel. Propag. Lett. 14, 887–890 (2014).
11. Li, J. et al. Tri-band CPW-fed stub loaded slot antenna design for WLAN/WiMAX applications. Frequenz 70, 521–526 (2016).
12. Gupta, A. & Chaudhary, R. K. A compact planar metamaterial tripleband antenna with complementary closed-ring resonator. Wirel. Pers. Commun. 88, 203–210 (2016).
13. Goswami, S. A. & Karia, D. A compact monopole antenna for wireless applications with enhanced bandwidth. Int. J. Electron. Commun. 72, 33–39 (2017).
and requests for materials should be addressed to M.M.A. or R.A.

Additional information
The authors declare no competing interests.

Competing interests
Review. All authors reviewed the manuscript.

Author contributions
Conceptualization, Supervision, & Writing-original draft. N.M.S.: Analysis, Methodology, Writing.

Acknowledgements
The Deanship of Scientific Research (DSR) at King Abdulaziz University, Jeddah, Saudi Arabia, has funded this project under Grant No. (KEP-26-135-42).

Author contributions
M.M.A.: Methodology, Analysis, Writing-editing, Project administration, & Funding acquisition. R.A.: Conceptualization, Methodology, Validation, & Writing-original draft. N.M.S.: Analysis, Methodology, Writing-editing. A.I.K.: Structural analysis, Software & Visualization. M.T.I.: Conceptualization, Methodology, Validation, & Writing.

Competing interests
The authors declare no competing interests.

Additional information
Correspondence and requests for materials should be addressed to M.M.A. or R.A.

Reprints and permissions information is available at www.nature.com/reprints
