LETTER

Capacitive probe-compensation-fed wideband patch antenna with U-shaped parasitic elements for 5G/WLAN/WiMAX applications

Huaxiao Lu*, Fang Liu†, Weimin Wang†, Zhaodong Gao†, Xia Bai†, and Yuan'an Liu†

Abstract A novel single layer, single capacitive probe-compensation fed wideband patch antenna is presented and investigated. The antenna consists of a rectangular patch and two identical U-shaped parasitic patches. The two U-shaped patches are incorporated around the radiating edges and non-radiating edges of the rectangular patch. For maintaining a relatively small antenna size, the length and width of this rectangular patch are 1/2λg and 1/4λg, respectively. A novel capacitive compensation technique, that is an annular gap which is concentric with the feed-probe, can introduce an annular gap capacitor to compensate the inductance caused by the feed-probe. By incorporating the U-shaped parasitic patches, an additional resonant frequency is introduced, which incorporates with the original resonant frequency produced by the rectangular patch, thus the wideband performance is achieved. The measured impedance bandwidth with S11 ≤ −10 dB is 40% (1.99 GHz) from 4.03 to 6.02 GHz, which covers 4.8–4.99 GHz band of 5G operation in China, WLAN 5.2 GHz (5.15–5.35 GHz), WLAN 5.8 GHz (5.725–5.825 GHz), and WiMAX 5.5 GHz (5.25–5.85 GHz). The measured peak gain is 9.1 dBi. An equivalent circuit model is established to provide a clear physical insight into the operation of the proposed antenna.

Keywords: wideband, U-shaped parasitic patches, patch antenna, annular gap capacitance, probe-compensation

Classification: Microwave and millimeter-wave devices, circuits, and modules

1. Introduction

Modern high-speed wireless communication systems, such as 5G (the fifth-generation mobile communication), WLAN, and WiMAX wireless applications, require wideband antennas. Microstrip antennas are very attractive in wireless communication systems because they have the advantages of lightweight, low cost, low profile, compactness, and easy integration with active and passive circuits such as filters, amplifiers, oscillators, and mixers. However, the inherent drawback of patch antennas is the narrow bandwidth, which limits their applications in wireless communication systems. Many researchers have devoted to broaden the bandwidth, and some techniques have been proposed. Increasing the thickness of substrate with low permittivity, Cutting slots in a patch, such as E-shaped slot [1], V-slot [2], U-slot [3], a pair of wide slits [4] and so on. Incorporating coplanar [5, 6] or stacked [7, 8] parasitic elements, however, the driven patch and parasitic patches in [5] are all full-size conventional patches, which resultantly suffers from relatively larger antenna size. The usage of stacked structures can generally broaden the bandwidth of patch antennas effectively, however, a stacked structure suffers from difficulty in layer alignment, complex antenna structure, and high fabrication cost. Specific feeding types are widely used to broaden the bandwidth, such as L-shaped probe feed [9], T-shaped probe feed [10], meandering probe feed [11], hook-shaped probe feed [12] and so on. These feeding techniques can provide proximate coupling capacitance to compensate the inductance caused by the feed-probe, and wideband characteristics can be obtained. For instance, a L-shaped probe feed with an impedance bandwidth of 36% is reported in [9]. A meandering probe feed with an impedance bandwidth of 30% is reported in [11]. These antennas maintain single-layer and single-patch. Besides, aperture coupling feed [13] and other feeding types [14, 15] are also used to broaden the bandwidth of patch antennas. For instance, a patch antenna with an aperture-coupled feed and patches of different sizes is reported in [13], which has an impedance bandwidth of 31%. Unfortunately, all these feeding techniques above-mentioned introduce additional complex structures, difficulty in assembling, and high fabrication cost. Furthermore, these antennas do not base on simple theory to help their designs. Therefore, some progress should be made to design wideband antennas with simple structure and theoretical analysis.

In this work, a single layer and a single capacitive probe-compensation fed wideband patch antenna is presented and investigated. The antenna consists of a rectangular patch with a reduced size and two identical U-shaped parasitic patches. The U-shaped parasitic patches are incorporated around both the radiating edges and non-radiating edges of the rectangular patch. A novel capacitive compensation technique, that is an annular gap embedded in the rectangular patch, is used to introduce an annular gap capacitor to compensate the inductance caused by the feed-probe. An additional resonant frequency is introduced by the U-shaped parasitic patches, which incorporates with the original resonant frequency produced by the rectangular patch, thus the wideband performance is achieved. The annular gap is concentric with the feed-probe, and is located on the surface of the rectangular patch. Thus the usage of this annular gap have negligible added design complexity and fabrication cost, and making the antenna a simple single layer and a single feed. Although parasitic patches are incorporated, the size for the whole radiating element of
the proposed antenna is smaller than that of a conventional patch. The proposed antenna has the advantages of wide-band performance, simple structure, small radiating element volume, and high gain. Furthermore, an equivalent circuit model is built to theoretically analyze the proposed antenna and better understand its working mechanism, and also to provide theoretical guidance to help the antenna’s design.

2. Antenna design

2.1 Antenna configuration

The configuration of the proposed antenna is shown in Fig. 1. The antenna consists of a rectangular patch with an annular gap (denoted as the main patch) and two identical U-shaped parasitic elements. The annular gap which is embedded in the rectangular patch, is concentric with the fed-probe, and is located on the surface of the rectangular patch. Generally, the length and width of a conventional patch are close to $1/2\lambda_g$ ($\lambda_g$ is the guided wavelength), respectively. But for the proposed antenna, in order to maintain a small size, the width $W_R$ of the rectangular patch is reduced to $1/4\lambda_g$, and the length $L_R$ of the rectangular patch is about $1/2\lambda_g$. The two U-shaped parasitic patches are placed in proximity of both the radiating edges and non-radiating edges of the rectangular patch. For easy fabrication with PCB technology, the rectangular patch and the two U-shaped patches are both printed on a low cost FR4 substrate with thin thickness of 0.8 mm, relative permittivity of 4.4, and loss tangent $\tan\sigma = 0.02$. Air, with thickness of 5 mm and relative permittivity $\varepsilon_r = 1$, is used as the substrate. A SMA connector whose inner and outer diameters are 1.2 mm and 4.2 mm, respectively, is used to connect the main patch. As can be observed from Fig. 1, the overall antenna is geometrically symmetric along the x-axis, which is useful to maintain low cross-polarization. The final dimensions of the proposed antenna are tabulated in Table I.

![Fig. 1](image)

**Fig. 1.** The configuration of the proposed antenna: (a) top view; (b) side view.

| Parameter | $L_R$ | $W_R$ | $d_p$ | $r$ | $g$ | $G_V$ |
|-----------|-------|-------|-------|-----|-----|-------|
| Values (mm) | 17.2 | 8.5 | 4.5 | 2 | 0.9 | 0.4 |

2.2 Working mechanism and theoretical analysis

As shown in Fig. 1, the rectangular patch loaded with the annular gap is the driven patch, and the two U-shaped patches are the parasitic patches. The annular gap etched in the rectangular patch can introduce an annular gap capacitor in series with the fed-probe, which is used to compensate the inductance caused by the fed-probe. The current distributions at the lower and higher resonant frequencies are shown in Fig. 2(a) and Fig. 2(b), respectively. As shown in Fig. 2(a), the current amplitudes on the two non-radiating edges of the main patch are strong, whereas on the U-shaped patches, are not strong. Therefore, the lower resonant frequency is determined by the main patch. As shown in Fig. 2(b), the current amplitudes around the four vertical gaps ($G_V$) and the two horizontal gaps ($G_H$) are strong. It suggests that the main patch capacitively couples energy to the U-shaped patches through these vertical gaps and horizontal gaps, thus the higher resonant frequency is produced, and can be controlled through adjusting the arm’s length or the base of the U-shaped patches. It should be pointed out that wider variation of $G_V$ or $G_H$ is not suggested, otherwise, making the gain at the higher resonant frequency lower. After properly selecting the dimensions of the proposed antenna, the lower and higher resonant frequencies are merged together to achieve the wideband characteristic.

An equivalent circuit model will gradually be established to theoretically analyze the proposed antenna and also to better understand its working mechanism. The equivalent circuit model of the rectangular patch with the annular gap (the main patch), is shown in Fig. 3.

![Fig. 3](image)

**Fig. 2.** The current distributions at: (a) 4.34 GHz; (b) 5.89 GHz.
can introduce an annular gap capacitor (denoted as probe, is described by its gap width approximated locally by a linear line, and $C_s$ can be calculated by the approximated formulas (2)

$$X_L = \frac{377 f_r h}{\varepsilon_0} \ln \left( \frac{c_0}{\pi f_r d_0 \sqrt{\varepsilon_r}} \right) \quad (1)$$

In (1), $d_0$ is the diameter of the fed-probe, $f_r$ is the operating frequency, $h$ is the thickness of the substrate, and $c_0$ is the velocity of light in free space.

The annular gap which is concentric with the fed-probe, is described by its gap width $g$ and inner radius $r$, can introduce an annular gap capacitor (denoted as $C_s$ in Fig. 3) and a parallel plate radial microstrip line. The effect of this parallel plate radial microstrip line can be modeled by an additional transmission line of length $m$ in the circuit model shown in Fig. 3. Furthermore, the effect of this transmission line can be neglected when the inner radius $r$ is smaller in comparison to the thickness of the substrate [19]. The annular gap capacitor $C_s$ can compensate the inductance caused by the fed-probe, thus $C_s$ plays an important role in the antenna’s impedance matching. $C_s$ can be calculated by the approximated formulas (2)–(4) [20].

$$C_s = 2\pi r \cdot C(g, r, h, \varepsilon_r) \quad (2)$$

$$C(g, r, h, \varepsilon_r) \approx \frac{2\varepsilon_0\varepsilon_{reff}}{\pi} \ln \left( \frac{8r}{g} \right) \quad (3)$$

$$\varepsilon_{reff} \approx 1 + \frac{\varepsilon_r - 1}{2} \left( 1 + \frac{16h}{\pi g} \right) \quad (4)$$

It can be observed from (2)–(4) that $C_s$ is determined by the inner radius $r$ and the gap width $g$ when the substrate has been selected. Furthermore, from (2)–(4), $C_s$ increases when the combination of $r \ln(r)$ increases, which can be approximated locally by a linear line, and $C_s$ decreases when the gap width $g$ increases as expected. However, the dependence of $C_s$ on $g$ is only on its logarithm. Thus, the inner radius $r$ plays a crucial role in controlling $C_s$, while the gap width $g$ has moderate changes on $C_s$. These theoretical analysis on the capacitor $C_s$ can provide guidance to design the antenna, and one can adjust the inner radius $r$, the gap width $g$, and the feed position to achieve an appropriate $C_s$ to compensate the inductance caused by the fed-probe.

When incorporating the two U-shaped patches around both the radiating and non-radiating edges of the main patch, there is electromagnetic coupling between the main patch and the two U-shaped parasitic patches. This electromagnetic coupling is realized through the four vertical gaps ($G_{vi}$) and the two horizontal gaps ($G_{hi}$). Thus there is coupling capacitance (denoted as $C_s$ in Fig. 4) between the main patch and the two U-shaped parasitic patches, which includes two parts. One is the coupling capacitance due to the four vertical gaps, which is mainly governed by the width ($G_{vi}$) and the length (($L_R - G_{li}$)/2) of the four vertical gaps as shown in Fig. 1, and increases with the decrease of the width ($G_{vi}$) (or with the increase of the length (($L_R - G_{li}$)/2). The other is the coupling capacitance due to the two horizontal gaps, which is mainly governed by the width ($G_{hi}$) and the length ($W_R$) of the two horizontal gaps as shown in Fig. 1, and increases with the decrease of the width ($G_{hi}$) (or

$$C_s = \frac{\varepsilon_r \varepsilon_0}{2} \cdot \left[ 2 \cdot \frac{1}{2} \frac{L_R - \frac{1}{2} G_{li} + G_H + L_{UB}}{L_R} \right] \cdot W_{UA} \quad (5)$$

$$\varepsilon_{reff} = \frac{\varepsilon_r + 1}{2} + \frac{\varepsilon_r - 1}{2} \left( 1 + \frac{12h}{W_R} \right)^{-\frac{1}{2}} \quad (6)$$

with the increase of the length $W_R$). The two U-shaped patches can be modeled as the parallel combination of $R_2L_2C_2$ as shown in Fig. 4, wherein $R_2$, $L_2$, and $C_2$ present the equivalent resistor, the equivalent inductance, and the parallel plate capacitance of the U-shaped patches, respectively. Indeed, $C_2$ can be calculated by the formulas (5)–(6). $L_2$ corresponds to the surface current path length $l$ of the U-shaped patches as shown in Fig. 2(b) ($l$ is mainly determined by its part where the current distribution on the U-shaped patch is strong, that is the arm’s length of the U-shape patch), and is increased with the increment of $l$, and vice versa. $R_2$ is increased as the thickness $h$ of the substrate is increased (or as the quality factor $Q$ of the proposed antenna is increased). So far, the complete equivalent circuit model of the proposed antenna has been established in Fig. 4.

### 2.3 Parametric studies

Parametric studies on parameters $L_R$ and $W_{UA}$ are carried out to study how they affect the antenna’s performance.

Fig. 5 shows the simulated reflection coefficients ($S_{11}$) of the proposed antenna with the variation of $L_R$. Observe that with the increase of $L_R$, the lower and higher resonant frequencies both shift to lower frequency considerably. This is because that the lower resonant frequency is determined by the main patch, thus with the increase of $L_R$, the downward frequency shifts for the lower resonant frequency is observed. Meanwhile, with the increase of $L_R$,
accordingly, the arm’s length of the U-shaped patches is lengthened. Thus the surface current path length \( l \) of the U-shaped patches is lengthened, resultantly, the downward frequency shifts for the higher frequency is also observed.

\[
\frac{S_{11}}{\text{Frequency (GHz)}}
\]

**Fig. 6.** The simulated reflection coefficients \( (S_{11}) \) with the variation of \( W_{UA} \).

Fig. 6 shows the simulated reflection coefficients \( (S_{11}) \) of the proposed antenna with the variation of \( W_{UA} \). It can be observed that with the increase of \( W_{UA} \), the lower resonant frequency is almost kept unchanged, whereas the higher resonant frequency shifts to lower frequency moderately. This is because that with the increase of \( W_{UA} \), the resonant length \( L_R \) of the main patch is kept unchanged, thus the lower resonant frequency is almost kept unchanged. However, with the increase of \( W_{UA} \), the surface current path length \( l \) is lengthened, thus the downward frequency shifts for the higher resonant frequency is observed.

3. Results and discussions

The prototype of the proposed antenna is shown in Fig. 7. The measured and simulated reflection coefficients \( (S_{11}) \) of the antenna are shown in Fig. 8, observe that they are in good agreement. The measured impedance bandwidth with \( S_{11} \leq -10 \text{ dB} \) is 40% (1.99 GHz) from 4.03 to 6.02 GHz, which covers 4.8–4.99 GHz band of 5G operation in China, WLAN 5.2 GHz (5.15–5.35 GHz), WLAN 5.8 GHz (5.725–5.825 GHz), and WiMAX 5.5 GHz (5.25–5.85 GHz) bands. The simulated impedance bandwidth with \( S_{11} \leq -10 \text{ dB} \) is 40% (2.05 GHz) from 4.11 to 6.16 GHz. The two measured resonant frequencies are 4.45 GHz and 5.88 GHz, respectively, and those simulated ones are 4.34 GHz and 5.89 GHz, respectively. The discrepancy between the measured and simulated reflection coefficients \( (S_{11}) \) of the antenna is due to the fabrication tolerance and assemble error. The influence of the annular gap on the \( Z \)-parameter is simulated and shown in Fig. 9, by etching the annular gap, more gentle impedance curves are achieved.

**Fig. 7.** Photograph of the proposed antenna.

**Fig. 8.** The measured and simulated reflection coefficients \( (S_{11}) \), the measured gain of the proposed antenna.

**Fig. 9.** The simulated \( Z \)-parameter of the proposed antenna with and without the annular gap
A novel single layer and single capacitive probe-fed wideband patch antenna with two U-shaped parasitic patches is presented and investigated. An annular gap is etched in the rectangular patch, which can introduce an annular gap capacitance to compensate the inductance caused by the fed-probe. The usage of this annular gap has negligible added design complexity and fabrication cost, and resulting in a simple single layer and a single feed. The measured impedance bandwidth is 40% (1.99 GHz) from 4.03 to 6.02 GHz, which covers 4.8–4.99 GHz band of 5G operation in China, WLAN 5.2 GHz (5.15–5.35 GHz), WLAN 5.8 GHz (5.725–5.825 GHz), and WiMAX 5.5 GHz (5.25–5.85 GHz) bands. An equivalent circuit model is established to theoretically analyze the antenna. The proposed antenna has the advantages of wideband performance, simple structure, small size, and high gain, which can be a good candidate for 5G, WLAN, and WiMAX applications.

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