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Low-profile patch antennas with enhanced horizontal omnidirectional gain for DSRC applications

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Abstract: Here, a low-profile microstrip patch antenna with vertical polarisation and over 3 dB enhanced gain in the horizontal plane is proposed for dedicated short-range communications (DSRC) application. It is a centre-fed circular patch antenna coupled by an annular ring and shorted concentrically with a set of shorting vias. For further increasing the gain in the horizontal plane, six groups of microstrip patches with one edge open and three edges shorted, which work as magnetic dipole antennas, are laid around the shorted circular patch-ring antenna (SCPRA). These gain enhancement elements resonate at 5.9 GHz and guide the TM wave along the horizontal surface. In addition, an equivalent circuit model of SCPRA is presented as a tool for easier impedance matching. The number of gain enhancement elements in each group can be adjusted to achieve variable radiation patterns in the horizontal plane. Two antennas achieving omnidirectional and quasi-elliptical radiation patterns are proposed, simulated, and measured. The measured results agree well with the simulated results, and the quasi-elliptical radiation patterns in the horizontal plane of the antenna demonstrate the desirable performance for DSRC applications.

1 Introduction
Dedicated short-range communications (DSRC) technology is an emerging and promising technology enabling cars to communicate with other devices like other vehicles, traffic lights, and road side units [1]. DSRC contributes to reducing road accidents and improving time and energy efficiency, especially for self-driving vehicles. For DSRC systems, the communication mainly takes place in the horizontal plane; therefore, the gain at \( \theta = 90^\circ \) should be as large as possible to ensure reliable communication. Besides, a low-profile antenna is more desired for aesthetic purpose while maintaining smooth radiation in the horizontal plane (≤3 dB).

Widespread vehicle antennas are almost monopole antennas with omnidirectional radiation patterns and vertical polarisation. As one type of the most popular antennas, monopole antenna attracts much attention in its performance improvement. In [2–4], the bandwidth of monopole antenna has been remarkably increased. Periodic structures such as frequency-selective surface (FSS) and metasurface have been widely used to realise gain enhancement in a specific direction [5–7]. Multi-band antennas have also been proposed and studied in [8, 9]. However, due to its resonant radiation property, it is a challenging work to reduce the height of a monopole antenna to a rather low profile while achieve enough horizontal gain.

Circular patch antennas which achieve a very low profile with monopole-like radiation patterns are another more promising candidate for the vehicle antenna. The circular patch antenna was firstly proposed in [10]. In [11–18], patch antennas were studied and they provided monopole-like radiation patterns and vertical polarisation. However, for these antennas, the gain values in the horizontal plane are all below −5 dB.

Many researchers have devoted to improving microstrip patch antenna's gain. The spiral-shaped electromagnetic bandgap structures were applied to enhance the gain of the microstrip antenna [19]. In [20], a novel type of defective ground surface was proposed and the antenna achieves higher gain and multi-resonant frequency with compact size. To reduce design complexity, a ring resonator was applied to achieve gain enhancement with wide bandwidth [21]. However, it is the gain of the broadside radiation pattern that [19–21] aimed to improve. For increasing the gain of the conical radiation pattern, especially in the horizontal plane, circular patch antenna with corrugated ground for guided wave was proposed with a diameter of 3.2\( \lambda_0 \) and a thickness of 0.14\( \lambda_0 \) [22]. The gain in H-plane is 0.55 dB. To maintain the size of the circular patch antenna, an electric bandgap (EBG) structure was applied to increase the gain in horizontal plane to −0.55 dB in [23], which is still relatively low. Besides, the size of the antenna is still large with a diameter of 1.98\( \lambda_0 \).

In this paper, a low-profile antenna with higher gain in the horizontal plane and reduced size compared with the antennas in [22, 23] is proposed for DSRC applications. Shorted circular patch-ring antenna (SCPRA) as shown in Fig. 1a is firstly proposed based on circular patch-ring antenna (CPRA) in [13]. Owing to the low horizontal gain of CPRA, 12 shorting pins are applied in SCPRA to increase the horizontal gain by 0.5 dB. To further increase the gain in the horizontal plane, half-width microstrip lines with two flanks shorted and one edge open were employed, which work as magnetic dipole antennas [24], to guide the wave along the horizontal surface in our proposed antenna. The half-width microstrip line works in EH mode and details of the half-width microstrip line have been analysed by Liu et al. in [25]. The gain enhancement in the horizontal surface (\( \theta = 90^\circ \)) is 3.10 dB (from −2.04 to 1.06 dB) with the aid of the gain enhancement elements. Besides, to better understand the effects of the annular ring and the conductive pins on the matching property, we use the equivalent circuit method to analyse the SCPRA. The proposed antennas are designed using FR4, a low-cost printed circuit board (PCB), with a diameter of 1.65\( \lambda_0 \) (84 mm) and a thickness of 0.033\( \lambda_0 \) (1.6 mm) at 5.9 GHz.

An omnidirectional vertically polarised circular patch antenna is firstly presented and the horizontal gain improves markedly compared with the conventional circular patch antenna without gain enhancement elements. Moreover, in DSRC system, the communication distance between front and back vehicles in the same lane/different lanes is supposed to be much longer than that between vehicles in different lanes when they are side by side. Therefore, elliptical radiation patterns in the horizontal plane are more desirable than omnidirectional radiation patterns in some cases. The number of the gain enhancement elements of two opposite groups on the proposed antenna is reduced to achieve quasi-elliptical radiation patterns for these cases.
2 Antenna design and operating principles

2.1 Antenna’s configuration

As illustrated in Fig. 1, the circular patch antenna is centre-fed by a coaxial probe with a radius of 0.64 mm. An annular ring is concentrically coupled to the circular patch, which improves the antenna’s matching characteristics. Besides, the ring increases the distance between the gain enhancement elements and the centre; therefore, the number of groups of gain enhancement elements can be increased. Twelve shorting pins are applied on the patch and the ring to increase the horizontal gain by 0.5 dB. The theoretical radius of the centric circular patch working in \( TM_{01} \) mode is calculated by \( a = \frac{F}{(1 + (2h/\pi \varepsilon_r F)[\ln(\pi F/2h) + 1.7726])^{1/2}} \) (1)

where

\[ F = \frac{\chi{\prime}_{mn} c}{2\pi f \sqrt{\epsilon_r}} \] (2)

In (2), \( \chi{\prime}_{mn} \) represents the zeros of the derivative of the Bessel function and for \( TM_{01} \), \( \chi{\prime}_{01} = 3.8318 \).

To further increase the gain in the horizontal plane, six groups of gain enhancement elements are added around the ring. The gain enhancement element with three edges shorted and one long edge open behaves like a magnetic element providing vertical polarisation and enhanced gain in the horizontal plane [24]. The three shorted edges are realised by closely spaced shorting pins. It should be noted that during the antenna optimisation, the shorting pins can be replaced by perfect electric conductor (PEC) walls to reduce the simulation time [27]. Through the optimisation of the length and width, the gain enhancement element can resonate at desired frequency to guide the TM wave along the surface and thus increase the gain in the horizontal plane.

The gaps \( S_0, S_1, \) and \( S_2 \) are also critical parameters in the antenna design. \( S_0 \) should be small for avoiding large energy leakage from the gap when the antenna matching property is maintained. \( S_1 \) and \( S_2 \) should not be larger than the thickness of the substrate in order to realise strong coupling between the gain enhancement elements and the ring. The details of the antenna parameters are shown in Table 1.

Table 1 Parameters of the proposed omnidirectional antenna

<table>
<thead>
<tr>
<th>Parameters</th>
<th>Value</th>
<th>Parameters</th>
<th>Value, mm</th>
</tr>
</thead>
<tbody>
<tr>
<td>( R_1 )</td>
<td>13.4 mm</td>
<td>( R_2 )</td>
<td>14.7 mm</td>
</tr>
<tr>
<td>( R_3 )</td>
<td>19.6 mm</td>
<td>( R_g )</td>
<td>42 mm</td>
</tr>
<tr>
<td>( h )</td>
<td>1.6 mm</td>
<td>( S_0 )</td>
<td>0.3 mm</td>
</tr>
<tr>
<td>( R_e )</td>
<td>6.4 mm</td>
<td>( S_1 )</td>
<td>1.5 mm</td>
</tr>
<tr>
<td>( a )</td>
<td>66.4°</td>
<td>( D_1 )</td>
<td>1.8 mm</td>
</tr>
</tbody>
</table>

2.2 Gain enhancement element

In this section, the gain enhancement element is analysed based on both the calculated and the simulated results. Basically, the gain enhancement element can be regarded as a half-width microstrip line in \( EH_1 \) mode with two flanks shorted [25, 28] as shown in Fig. 2. It works as a magnetic dipole, and thus, the length of the half-width microstrip line \( L_1 \) is \( \lambda_1/2 \) in the \( x \) direction (Fig. 2b), where the wavelength \( \lambda_1 \) can be expressed as

\[ \lambda_1 = 2\pi/\beta \] (3)

To reduce the complexity, the straight gain enhancement element (Fig. 2b) is firstly analysed rather than the curved one (Fig. 2a).

The propagation wavenumber for half-width microstrip lines in \( EH_1 \) have been fully analysed in [25]. At the resonant frequency 5.9 GHz, the phase constant calculated by Liu et al. [25] based on the Liu–Oliner’s method [28] is

\[ \beta = 1.06k_0 \] (4)

Therefore, the calculated wavelength at 5.9 GHz is 47.97 mm.

To verify the calculated results above and offer a simple way to obtain the gain enhancement element’s length, a 200 mm half-width microstrip line (much longer than 1 wavelength) is simulated...
in HFSS and the normalised $E_z$ versus varying distance from the source is shown in Fig. 3. The simulated wavelength at 5.9 GHz can be calculated by

$$\lambda_x = \frac{200 \times (0.762 - 0.036)}{3} = 48.4 \text{ mm}$$ (5)

The simulated wavelength $\lambda_x$ is 48.40 mm which is close to the calculated value.

The width $R_e$ can be varied to make the gain enhancement element resonate at desired frequency when the length $L_e$ is fixed at $\lambda_x/2$. We use HFSS with ‘eigenmode’ solution type to calculate the resonant frequency of the gain enhancement element. It is found that when $R_e = 5.7$ mm, the gain enhancement element resonates at 5.9 GHz.

The parameters of the straight gain enhancement element have been solved, while only the curved elements are suitable for our proposed antenna. The propagation wave number of the curved half-width microstrip line approaches that of the straight half-width microstrip line [29]. Therefore, the arc length of the curved element and the length of the straight element have similar values; the angle of curved gain enhancement element $\alpha_1$ can be estimated by

$$\alpha_1 = \frac{360^\circ L_e}{2\pi R_c}$$ (6)

In addition, the width $R_e$ of the curved gain enhancement element after optimisation in the final design is 5.4 mm which is close to that of the straight element (5.7 mm).

2.3 Number of gain enhancement element's groups

There are several considerations to determine the number of gain enhancement elements:

i. Owing to the limited space and fixed size of gain enhancement elements, the number of groups cannot increase without limit. The number of groups should satisfy

$$N \leq \frac{2\pi R_c}{L_e}$$ (7)

where $R_c$ and $L_e$ have been labelled in Fig. 2. Therefore, the value of $N$ cannot be larger than 6. Besides, (7) shows that larger $R_c$ means more groups of gain enhancement elements. That is another reason that we bring in an annular ring.

ii. The number of groups should ideally be as large as possible for increasing the gain in the horizontal plane. As shown in Fig. 4, the horizontal radiation pattern of the antenna with six groups of gain enhancement elements (the largest number of groups allowed in our design) is compared with that of the antenna with four groups. Apparently, the gains of the antenna with six groups (max: 1.1 dB; min: −0.5 dB) are higher than those of the antenna with four groups (max: 0 dB; min: −1.6 dB).

In our design, the number of gain enhancement elements is optimised to be 6.

2.4 Gain enhancement principles

To verify the principles of enhancing the gain in the horizontal plane, we compared the E-field distributions of SCPRA and our proposed circular patch antenna with enhanced gain. As shown in Fig. 5a, the gain enhancement elements of our proposed antenna resonate at the 5.9 GHz and guide the wave along the horizontal plane due to the effects of ground. In this case, more energy can be retained in the horizontal plane of our proposed antenna, while energy of the SCPRA will mostly be reflected upwards. Therefore, the proposed antenna can achieve higher omnidirectional gain in the horizontal plane, compared with that of SCPRA without gain enhancement elements.

3 Equivalent circuit of SCPRA

Our proposed antenna's matching property mainly depends on the parameters of SCPRA, as the gain enhancement elements have little effects due to the relatively weak coupling from the feed. Therefore, we only focus on the influence of shorting pins and the annular ring on the antenna's input reflection coefficients. An equivalent circuit model has been built which gives physical insight to the behaviour of SCPRA. Fig. 6 shows the proposed equivalent circuit model of SCPRA. Both the circular patch and the annular ring are represented by $RLC$ circuit ($R_p\|L_p\|C_p$) and ($R_r\|L_r\|C_r$),
respectively) [30, 31]. \( C_g \) is the coupling capacitance between the circular patch and the shorted annular ring. The shorting pins are represented by an inductance. The resonant frequency can be calculated by [31]:

\[
f_0 = \frac{1}{2\pi\sqrt{LC}}
\]

(8)

Therefore, we can find the varying tendency of the resonant frequency, since based on (8), the resonant frequency is inversely proportional to the value of \( L \) and \( C \).

3.1 Annular ring

The circuit of the annular ring and the gap between the ring and the patch are regarded as entirety and HFSS simulation shows that it is capacitive with a capacitance \( C_{in} \) within the antenna operating frequency. It is observed that the resonant frequency of SCPRA is much lower than that of shorted circular patch antenna (SCPA (Fig. 7b)) in Fig. 8. This is due to the existence of \( C_{in} \) which makes the capacitance of SCPRA increases; hence, the resonant point of SCPRA moves to a lower frequency compared with SCPA.

The gap between the circular patch and the annular ring is a critical parameter in antenna’s impedance property. As illustrated in Fig. 9a, with the increase in the gap, the resonant frequency shifts to a higher value. This is attributed to the fact that the larger gap reduces the value of the capacitance \( C_g \), meaning decrease in \( C_{in} \), which surely increases the resonant frequency. In addition, the width of the annular ring is another important factor affecting the reflection coefficient of SCPRA. Decreasing the width reduces \( C_r \), the capacitive reactance of the ring, meaning the value of the
capacitive loads of SCPRA decreases. Therefore, as shown in Fig. 9b, the resonant frequency of SCPRA increases with the ring width decreasing.

3.2 Shorting pins

The six vias connecting the circular patch and the ground play a critical role in SCPRA's impedance matching. As demonstrated in Fig. 8, the resonant frequency of circular patch shorted-ring antenna (CPSRA (Fig. 7a)) is lower than that of SCPRA. This is due to the fact that the shorting pins are inductive, which reduces the inductance of the equivalent circuit; hence, the shorting pins lead to the higher resonant frequency of SCPRA compared with CPSRA.

As illustrated in Fig. 9c, the reflection coefficients of SCPRA are also very sensitive to the radius of the shorting pins. The increased radius of shorting pins reduces its inductance $L_s$, which decreases the inductance of the equivalent circuits. Therefore, the resonant frequency increases when the radius of shorting pins increases.

4 Experiment results

In this section, two antennas, omnidirectional and elliptically radiating antennas with enhanced gain, are simulated and measured. Both simulated and measured results show that the proposed antennas have good matching property and about 3 dB enhanced gain in the horizontal plane within the DSRC band.

4.1 Omnidirectional patch antenna with gain enhancement

The fabricated omnidirectional antenna is shown in Fig. 10a. The return loss and the radiation patterns of the proposed antenna are shown below.

The reflection coefficients are shown in Fig. 11a. The simulated bandwidth of the proposed antenna covers 5.86–6.07 GHz, while the measured bandwidth starts from 5.80 to 5.99 GHz. Both the simulated and measured bandwidth cover the whole DSRC band (5.85–5.925 GHz).

The radiation patterns of the proposed omnidirectional antenna at 5.9 GHz are shown in Fig. 11. The monopole-like radiation patterns are realised and the measured radiation patterns match...
well with the simulated results. The maximum gain in the horizontal plane is 0.97 dB. The simulated cross-polarisation is as low as a value below −40 dB and the measured cross-polarisation is only below −20 dB. The difference between the simulated and measured results may be mainly due to the fabrication errors and the dielectric coefficient variations of PCB. Both the simulated and measured gain in the H-plane of the omnidirectional antenna with a finite ground are shown in Table 2. The simulated results of the proposed omnidirectional antenna with an infinite ground are also shown for comparison. The gains in the H-plane of the omnidirectional antenna with the finite ground are all around 1 dB, and increase by over 3 dB compared with the SCPRA within the DSRC band.

### Table 2 Simulated and measured gains of the omnidirectional antenna in the horizontal plane

<table>
<thead>
<tr>
<th>Frequency, GHz</th>
<th>5.85</th>
<th>5.875</th>
<th>5.9</th>
<th>5.925</th>
</tr>
</thead>
<tbody>
<tr>
<td>simulated gain in the H-plane of SCPRA, dB (Fin)</td>
<td>−2.04</td>
<td>−2.04</td>
<td>−2.04</td>
<td>−2.04</td>
</tr>
<tr>
<td>simulated gain in the H-plane of the proposed omnidirectional antenna, dB (Fin)</td>
<td>0.77</td>
<td>0.87</td>
<td>1.06</td>
<td>0.93</td>
</tr>
<tr>
<td>simulated gain in the H-plane of the proposed omnidirectional antenna, dB fabricated on lossless FR4 (Fin)</td>
<td>3.25</td>
<td>3.41</td>
<td>3.60</td>
<td>3.81</td>
</tr>
<tr>
<td>simulated gain in the H-plane of the proposed omnidirectional antenna, dB (Inf)</td>
<td>4.34</td>
<td>4.51</td>
<td>4.64</td>
<td>4.71</td>
</tr>
<tr>
<td>measured gain in the H-plane of the proposed omnidirectional antenna, dB (Fin)</td>
<td>0.60</td>
<td>0.86</td>
<td>0.97</td>
<td>0.69</td>
</tr>
</tbody>
</table>

Owing to the diffraction effects of the finite ground plane [24], the gain of the antenna with the finite ground is 3 dB lower than that of the antenna with infinite ground (4 dB). It should be noted that in our design, we apply FR4 as the substrate for economical purpose. However, the dielectric loss tangent of FR4 is high (0.02), which harms the radiation performance of the proposed antenna. As shown in Table 2, the horizontal gains of the proposed antenna fabricated on common FR4 are nearly 3 dB less than those values of the simulated antenna fabricated on lossless FR4. This means that we can employ low-loss substrate to enhance the proposed antenna's horizontal gain.

#### 4.2 Elliptically radiating patch antenna with gain enhancement

In this subsection, the desirable radiation patterns for DSRC communication are discussed and an elliptically radiating antenna is designed for the application.

When the vehicle tries to communicate with the vehicles and the roadside units in front of it, the communication path is normally long. Therefore, the gain on the front and back sides of the DSRC antenna is expected to be large. On the contrast, when the telecommunication link is built between the vehicle and other units on the object’s two flanks, the communication distance is much shorter; hence, it is normally not necessary to be large for the gain on the two flanks of the DSRC antenna. Therefore, the elliptically radiating antenna is more desirable for the DSRC applications.

To satisfy the requirements of DSRC communications, an elliptically radiating patch antenna is proposed as shown in Fig. 10. The dimensions of the elliptically radiating patch antenna are the same as those of the omnidirectional antenna except the reduced number of gain enhancement elements in two opposite groups. To verify the performance of the elliptically radiating patch antenna, the fabricated antenna has been tested. The antenna has a bandwidth starting from 5.79 to 5.97 GHz, which is slightly narrower than the simulated results as shown in Fig. 12a.

The radiating characteristics at 5.9 GHz are simulated and measured, and the results are shown in Fig. 12. The quasi-elliptical radiation patterns in the horizontal plane are achieved and its gain at 5.9 GHz is 1.70 dB. The measured cross-polarisation of the proposed antenna is below −15 dB. As shown in Table 3, both the simulated and measured gains within the DSRC band are larger than those of the omnidirectional antenna, which is in line with our expectation. Therefore, the elliptically radiating antenna can realise relatively longer communication distance in front and back direction. Furthermore, the simulated gain in the horizontal plane of the elliptically radiating antenna with the infinite ground is also shown in Table 3. Its value is 4 dB larger than that of the antenna with the finite ground.
patterns in the horizontal plane

Fig. 12

Simulated and measured results of the proposed elliptically radiating circular patch antenna
(a) Reflection coefficients, (b) Radiation patterns in the vertical plane, (c) Radiation patterns in the horizontal plane

Table 3

Simulated and measured gains of the elliptically radiating antenna in the horizontal plane

<table>
<thead>
<tr>
<th>Frequency (GHz)</th>
<th>5.855</th>
<th>5.875</th>
<th>5.9</th>
<th>5.925</th>
</tr>
</thead>
<tbody>
<tr>
<td>Simulated gain in the H-plane of the elliptically radiating antenna, dB (Fin)</td>
<td>1.56</td>
<td>1.65</td>
<td>1.70</td>
<td>1.50</td>
</tr>
<tr>
<td>Simulated gain in the H-plane of the elliptically radiating antenna, dB (Inf)</td>
<td>5.20</td>
<td>5.37</td>
<td>5.50</td>
<td>5.43</td>
</tr>
<tr>
<td>Measured gain in the H-plane of the elliptically radiating antenna, dB (Fin)</td>
<td>1.25</td>
<td>1.86</td>
<td>1.10</td>
<td>1.50</td>
</tr>
</tbody>
</table>

5 Conclusions

In this paper, we employed a curved half-width microstrip line with two flanks shorted and one edge open to the SCPRA to guide the TM wave along the horizontal surface and increase the gain in the horizontal plane. The gain enhancement element has been fully analysed both in mathematical analysis and cavity mode. A circuit model of SCPRA has been built, which gives the guidelines to improve the proposed antenna’s matching property. Two types of antennas, the omnidirectional and the elliptically radiating patch antennas, have been designed, simulated, and measured. The latter kind of antenna achieves the elliptically radiation patterns and higher gain up to 1.7 dB in the horizontal plane at 5.9 GHz, making it as a good candidate for the DSRC communications.

6 References


