A Compact, Band-Notched Ultra-Wideband Fully-Recessed Antenna With Pattern Diversity for V2X Communications

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ABSTRACT In this paper, a compact, band-notched ultra-wideband (UWB) fully-recessed antenna with pattern diversity is proposed and demonstrated for vehicle-to-X communications. The antenna is composed of a multi-port central radiator fully embedded inside a bowl-shaped ground structure with a flush top. The multi-port central radiator consists of a top circular plate, four split-quarter conical monopoles, four vertically- and horizontally-orientated strips, a central metallic cylinder, and a bottom cylinder. Moreover, four F-shaped monopoles are loaded to the multi-port central radiator for producing two narrow notched bands. The integrated antenna achieves a form factor of 0.23λ3/λL, where λL is the free space wavelength at the lowest working frequency. The proposed antenna was fabricated and characterized, achieving a measured S11 < -10 dB band ranging from 1.7 to 6 GHz with two stopbands at around 2.5 and 5.15 GHz for all four ports. Moreover, the measured mutual coupling is smaller than -15 dB, while the envelope correlation coefficients (ECCs) are below 0.1 between different input ports. A vertically-polarized (VP) omni-directional pattern can be supported when all four ports are excited simultaneously, whereas four directional patterns pointing towards different directions in the azimuthal plane can be realized when the four ports are excited individually. The demonstrated antenna is a promising candidate in multiple-input multiple-output communication systems for a wide variety of platforms.

INDEX TERMS Multiple-input multiple-output (MIMO) antennas, pattern diversity, recessed antenna, ultra-wideband (UWB), vehicular communications.

I. INTRODUCTION

In vehicular communication networks, the concept of vehicle-to-X (V2X) communication refers to the information exchange between a vehicle and other external communication nodes, e.g., base stations, vehicles, pedestrians, infrastructures, and so on [1], [2]. In such a rapid-evolving network, three requirements are put forward for vehicle-mounted antennas to ensure a high signal quality. First, multiple services should be supported in the sub-6 GHz regime, i.e., Long Term Evolution (LTE), Third-/Fourth-/Fifth-Generation (3G/ 4G/ 5G), Bluetooth, WiFi, and V2X (5905 – 5925 MHz). To this end, an ultra-wideband (UWB) antenna covering these frequency bands can significantly reduce the overall form factor of the device, as compared to using multiple antennas each with a different operational band [3], [4]. Secondly, a multiple-input multiple-output (MIMO) diversity antenna would be more desirable for simultaneously achieving a reliable link, a wide coverage, and/or a high channel capacity [5], [6]. As shown in Fig. 1 (a), if a vehicle needs to communicate with other...
In [30], a wideband MIMO antenna, with a profile of radiating elements with different and orthogonal patterns. Pattern diversities can be enabled by employing multiple pattern diversity. Broadband VP omni-directional patterns, they cannot support a grounded cross-plate [27], and a capacitive-coupled with a grounded parasitic ring [25], meandered wires [26], have been proposed, such as a cone monopole antenna loaded low-profile and wideband three-dimensional (3D) antennas achieving VP omni-directional radiation, including printed file. Several planar antennas have been reported for coated monopoles [14], [15], suffer from a high profile. Vertically-polarized (VP) antennas can provide a wide coverage for ground communications since the VP waves have lower path loss when they are propagating along the earth ground as compared to horizontally-polarized waves. On the other hand, omni-directional radiation can provide a wide coverage [11], [12]. Conventional single-port VP omni-directional antennas, such as narrow-band quarter-wave monopoles [13] and wideband metasurface-coated monopoles [14], [15], suffer from a high profile. Several planar antennas have been reported for achieving VP omni-directional radiation, including printed monopoles [16], [17], [18], slot loops [19], circular patches loaded with annular rings [20] or shorting pins [21], and metasurface-enabled radiators [22], [23], [24]. However, the bandwidths are narrow due to their high Q values. Recently, low-profile and wideband three-dimensional (3D) antennas have been proposed, such as a cone monopole antenna loaded with a grounded parasitic ring [25], meandered wires [26], a grounded cross-plate [27], and a capacitive-coupled patch [28], [29]. Although single-port antennas can provide broadband VP omni-directional patterns, they cannot support pattern diversity.

For multi-port VP omni-directional MIMO antennas, pattern diversities can be enabled by employing multiple radiating elements with different and orthogonal patterns. In [30], a wideband MIMO antenna, with a profile of 0.65λL, was proposed, consisting of four VP F-shaped monopoles sequentially rotated by 90°. The antenna achieves a bandwidth of 105% by introducing parasitic stubs and a high port isolation by etching slots and adding metallized walls. In [31], a two-port VP MIMO antenna composed of a probe-fed cone monopole at the center and a ring radiator (consisting of four linear dipoles) around the cone was reported, exhibiting a bandwidth of 108% and a profile of 0.11λL. A 4-channel MIMO antenna based on four probe-fed dielectric-loaded horns sharing a common top plate was proposed for achieving VP radiation within the sub-6 GHz bands [32]. By introducing shorting pins connecting the outer ring and ground plane, the antenna profile is reduced to 0.06λL. On the basis of the transverse electromagnetic (TEM) horns [33], an eight-element circular array was also proposed to realize omni-directional radiation within a bandwidth of 153% [34]. However, the 3D-structures of these reported antennas all have a protruding part, which would cause unwanted aesthetic and/or electrical problems.

To address the protruding problem, the radiator can be designed to recess inside a concave ground structure. In [35], an eye-shaped monopole antenna partially recessed inside a shaped ground plane was described, achieving a bandwidth of 148% and a profile of 0.2λL. However, the top part of the radiator still protrudes out from the plane of the ground. To further reduce the volume of the protruding part, several fully-recessed antennas have been proposed, including narrow-band designs, e.g., patch and/or ring antenna [36], and slot antenna [37], as well as wideband designs, e.g., cone monopolar antennas [38], Vivaldi antenna [39], and TEM horn [40]. In [41], a material-based design approach of embedded-monopole was reported theoretically based on transformation optics, with a two-dimensional (2D) demonstrating prototype realized by negative-index metamaterials operating over a narrow frequency range [42]. Therefore, antenna designs that have fully-recessed radiators without any protruding parts are highly desirable in vehicular communications, particularly for roof-mount communication modules, which, however, have not been achieved yet.

In this paper, the design and experiments of a compact four-port band-notched UWB fully-recessed antenna with pattern diversities is reported. The proposed antenna is composed of a multi-port central radiator fully recessed inside a bowl-shaped ground structure, covering a broad frequency range from 1.7 to 6 GHz. In addition, F-shaped monopoles are loaded to generate two notched stopbands at 2.4 and 5.2 GHz for inter-system interference suppression. The antenna can support omni-directional patterns when all four ports are excited simultaneously, and four directional patterns pointing towards different directions when the four ports are excited individually. The paper is organized as follows. In Section II, the antenna configuration and design procedure are presented. The impacts and optimization of the key design parameters are described in Section III. Section II shows the simulated and measured performance of the UWB diversity antenna with dual notched bands. Finally, concluding remarks are drawn in Section VI.
II. ANTENNA DESIGN

A. ANTENNA STRUCTURE

As depicted in Fig. 2, the configuration of the proposed fully-recessed antenna includes two metallic parts – a multi-port central radiator and a bowl-shaped ground structure, where the former one is fully embedded at the center of the latter one. The two parts have a flush top such that no structure is protruding out. The multi-port central radiator, as shown in Fig. 3, is composed of a top circular plate, four split-quarter conical monopoles, four horizontally-orientated strips, four vertically-oriented strips, a central metallic cylinder, and a bottom cylinder. Among them, the radius and thickness of the top circular plate are \( r_1 \) and \( h_1 \), respectively, wherein a sunken circular cylinder with a radius of \( r_2 \) and a height of \( h_2 \) is located at the center. On the top circular plate, four U-shaped slots are cut along the mirror-symmetry lines between adjacent split-quarter conical monopoles with side lengths of \( l_{u1} \) and \( l_{u2} \), and a width of \( w_{u1} \). Underneath the top circular plate, four split-quarter conical monopoles are distributed symmetrically around the center, each with a flare angle of \( \varphi_f \) and a radius of \( r_m \). Their curved generates follow the exponential function: 

\[
z = 0.316 \times e^{0.074y} - 10.58 \times e^{-0.0816y},
\]

with the value of \( y \) varying from 30 to 60 mm. In addition, four horizontally-orientated strips \((l_1 \times w_1)\) and vertically-orientated strips \((l_2 \times w_2)\) are attached to the top circular plate and four split-quarter conical monopoles, respectively. In the vertically- and horizontally-orientated strips, the inverted L-shaped slots with lengths of \((l_{f1} + l_{f2})\) are cut and parasitic strips with lengths of \( l_{f2} \) are loaded to form F-shaped monopoles for producing two resonances. Moreover, a central metallic cylinder with a height of \( l_3 \) and a diameter of \( d_3 \) is loaded at the center and a bottom cylinder with a diameter of \( d_p \) is used as the pedestal of the multi-port central radiator, which are used for improving port isolation. Four 50 Ω coaxial probes, each with a distance of \( d_f \) away from the center, are connected to the four split-quarter conical monopoles at the bottom through small circular holes etched out on the bowl-shaped ground structure. It should be noted that a gap with a height of \( g_f \) existing between the feeding position and bottom of the ground plane directly relates to the working bandwidth of the antenna.

For the ground plane, a bowl-shaped metallic structure is formed by cutting a cone out of a metallic cylinder with a height of \( h_g \) and a radius of 150 mm. The top and bottom radii of the bowl-shaped ground are \( r_a \) and \( r_b \), while the curved generatrix follows the exponential function of 

\[
z = 39.18 \times \exp(- (y - 142.9)^2/38.32^2),
\]

with the value of \( y \) varying from 72.3 to 120 mm. As it can be seen from Fig. 2(a), on the bottom of the bowl-shaped ground, four crescent slots, with a largest width of \( d_m \), and a central cylindrical aperture with a diameter of \( d_c \), were cut out for improving the isolation between all the input ports. The crescent shape was chosen for the slots since it can elongate the current path within a compact area, thereby improving the mutual coupling induced by direct current flow between ports. The outer and inner lines of the crescent slots, i.e., \( y_1 \) and \( y_2 \), follow the circular functions of 

\[y_1 = \sqrt{d_s^2/4 - (x - ds/2)^2}\]

and 

\[y_2 = d_m + \sqrt{d_s^2/4 - (x - ds/2)^2}\]

with the values of \( x \) both varying from 0 to 38 mm. The high frequency structure simulator (HFSS) was used for numerically evaluating the properties of the antenna.

B. DESIGN PROCEDURE

In this section, the design procedure of the proposed antenna structure is exhibited, evolving gradually from a simple vertically-orientated monopole to the final design. The inset in Fig. 4, i.e., ANT I, shows that the proposed antenna starts with a pin-fed monopole with \( h_{i1} = 34 \) mm placed on a finite ground plane with \( R_{gnd} = 150 \) mm. The simulated \( S_{11} \) curve exhibits a single resonance at around 2 GHz with a −10 dB impedance bandwidth of about 290 MHz, when the length of the pin-fed monopole is about a quarter wavelength (see ANT I). An additional resonance can be identified at 6.3 GHz due to the occurrence of the first higher-order resonant mode. In order to broaden the operational bandwidth, the thin monopole was re-shaped into a modified cone, named as ANT II. The top diameter \( d_{i2} \) and height \( h_{i2} \) of the modified conical monopole are 32 and 27 mm, respectively. The smooth generatrix follows the function of 

\[
z = 0.78 \times e^{0.21y},
\]

with \( y \in [0.5, 16] \). It can be seen from Fig. 4 that the impedance bandwidth of ANT II is broadened significantly, possessing a simulated \( S_{11} < -10 \) dB band ranging from 1.92 to...
which is referred to as the split-quarter conical monopole. Therefore, ANT II is split into four parts, each containing the overall array would appear bulky with poor isolation. An array of four elements that are arranged into a circular array, form factor. If ANT II is used as a single element of a MIMO array especially at low frequencies, which would affect the radiation characteristics. Pattern diversities can be achieved by using a multiport multimode antenna that radiate different and orthogonal patterns, which can enable a reliable link and/or a higher channel capacity. Here, four ANT III-2 elements are distributed annularly with a sequential rotation of 90° that constitute a MIMO antenna array (see ANT IV-1 in Fig. 7(a)), implying that an omni-directional coverage could be supported when all the elements are excited in phase. In this process, the four elements are moved outward away from the center by \( d_{\psi} \), similar to an exploded modified conical monopole each with a flare angle of \( \psi_1 \). As shown in Fig. 7, the simulated \( S_{11} \) curves indicate that the −10 dB impedance bandwidth of ANT IV-1 ranges from 1.9 to 5.4 GHz, with an impedance match worse than that of ANT III-2 at higher frequencies.

In this configuration, the radius, height, and generatrix of ANT III-1 are the same as those of ANT II. It can be seen that the \( S_{11} < -10 \) dB bandwidth of ANT III-1 is nearly the same as that of ANT II, indicating that the splitting action has no influence on the UWB characteristics of the radiator. However, the radiation pattern of ANT III-1 in the \( \theta \)-plane becomes more directive as compared to that of ANT II. Moreover, in the \( \psi \)-plane, a larger gain is obtained within the angular range of 60° ≤ \( \theta \) ≤ 90° [see Fig. 6].

On the other hand, a number of platforms require VP non-protruding antennas that are fully embedded below the horizon of the platform roof. To this end, the flat ground is modified into a bowl-shaped ground such that the split-quarter conical monopole at the center becomes a recessed radiator (see the inset of Fig. 5 for ANT III-2). The top and bottom radii of the bowl-shaped ground are \( r_{b3} \) and \( r_{b3} \), respectively. It should be noted that the inner generatrices of the bowl-shaped ground structures are kept the same throughout the paper. The inner wall of the bowl-shaped ground functions partially as a reflector especially at low frequencies, which would affect the impedance matching of the antenna, causing a resonant frequency blueshift. As shown in Fig. 6, the loading of the bowl-shaped ground only has a minor influence on the radiation patterns in the \( \psi \)-plane, demonstrating that the fully-recessed topology would not significantly change the radiation characteristics.

Pattern diversities can be achieved by using a multiport multimode antenna that radiate different and orthogonal patterns, which can enable a reliable link and/or a higher channel capacity. Here, four ANT III-2 elements are distributed annularly with a sequential rotation of 90° that constitute a MIMO antenna array (see ANT IV-1 in Fig. 7(a)), implying that an omni-directional coverage could be supported when all the elements are excited in phase. In this process, the four elements are moved outward away from the center by \( d_{\psi} \), similar to an exploded modified conical monopole each with a flare angle of \( \psi_1 \). As shown in Fig. 7, the simulated \( S_{11} \) curves indicate that the −10 dB impedance bandwidth of ANT IV-1 ranges from 1.9 to 5.4 GHz, with an impedance match worse than that of ANT III-2 at higher frequencies. This is because the distance between the split-quarter conical monopole and curved inner wall of the bowl-shaped
ground becomes smaller, yielding an increased capacitance in the input impedance of the radiator at frequencies from 4 to 6 GHz. To enable a better integration and extend the low frequency end of the operational band, a metallic circular plate with a radius of $r_{p1}$ and a thickness of $h_{p1}$ is loaded on the top of the four elements. When each element is excited, the other three can be considered as parasitic loadings that lengthen the current path, thereby inducing extra resonances at frequencies below 2 GHz and broadening the bandwidth [see Fig. 7(a)]. Moreover, comparing to ANT IV-1, the mutual coupling between adjacent ports of ANT IV-2, i.e., $S_{13}$, is reduced from $-11.7$ to $-15.6$ dB, while the mutual coupling between opposite ports, i.e., $S_{15}$, is increased slightly from $-14.3$ to $-12.1$ dB, which could be improved by other de-coupling techniques [see Fig. 7(b)]. At the same time, there is almost no difference between ANT IV-1 and ANT IV-2 in terms of the radiation patterns.

To ensure a mechanical robustness between the multi-port central radiator and bowl-shaped ground, a central cylinder is added at the center of the ground to support the multi-port central radiator. Moreover, four vertically- and horizontally-orientated strips connecting to the inner edges of the four split-quarter conical monopoles are introduced for impedance matching at higher frequencies. As shown in Fig. 8, the $S_{11}$ of ANT V is smaller than $-10$ dB from 1.5 to 6 GHz, exhibiting a much broader impedance bandwidth than that of ANT IV-2. It should be noted that the improved impedance match at high frequencies is primarily attributed to the vertically- and horizontally-orientated strips, bringing inductive effects for promoting the impedance matching. The mutual coupling between adjacent ports, i.e., $S_{12}$, is smaller than $-15$ dB within the entire operational band, whereas the port isolation between the opposite ports, i.e., $S_{13}$, reaches $12.7$ dB at $1.7$ GHz. This increased mutual coupling at $1.7$ GHz mainly results from the surface currents directly flowing between ports. In contrast, the mutual coupling at $3.1$ GHz is drastically reduced from $-15$ dB of ANT IV-2 to $-31$ dB of ANT V, which is due to the existence of the central metallic cylinder that suppresses direct spatial-wave coupling between adjacent and opposite ports.

To further improve the port isolation between adjacent and opposite ports, a slot-cutting technique for blocking the direct current paths is used. On the bottom of the bowl-shaped ground, four counter-clockwise crescent-shaped slots and a central circular hole with a diameter of $d_c$ are cut out [see Fig. 2]. It can be seen from Fig. 9 that while the $S_{11}$ of ANT VI are all smaller than $-10$ dB within the band of interest, i.e., $1.7 - 6$ GHz, the mutual coupling between adjacent and opposite ports are reduced from $-15$ to $-18.1$ dB and from $-12.7$ to $-14.7$ dB, respectively. It should be noted that the presence of the crescent slots would cause slight increasement of the back radiation towards the lower half-space with a maximum level of no more than $-10$ dB.

Since WLAN communication bands (2.4 /5.2 GHz) are widely used for in-vehicle entertaining systems, it would be beneficial for vehicle-mounted antennas to have narrow notched-bands to physically suppress crosstalk between in-car and out-of-car communications. By integrating resonant structures into the antenna, two narrow notched bands at 2.4 and 5.2 GHz can be achieved. In general, the notched bands can be realized by etching slots in the patch [45], [46] and loading additional resonators around the planar monopole [47], [48]. As shown in Fig. 10, ANT VII is obtained by loading four F-shaped monopoles on the vertically-oriented strips and four U-shaped slots on the top circular plate of ANT VI. First, the four inverted L-shaped slots in the vertically- and horizontally-strips, where the strong currents occur, are cut to form the longer-length arms of the F-shaped monopole with an electrical length ($l_f1 + $
First, antennas with a low profile are always desirable for various platforms, such as vehicles, for electrical as well as aesthetic considerations. In the premise of no protruding part, the integrated antenna profile, i.e., $h_g$, should be optimized. It can be seen from Fig. 11(a) and (b) that, when the value of $h_g$ increases, the notched band at 5.2 GHz would shift towards low frequencies, due to the elongated electrical length of the longer-length arm caused by the increased profile, while the notched band at 2.4 GHz remains almost unchanged. Since the shifting of the stopband at 5.2 GHz would also affect the input impedance at the 5.9 GHz V2X band, as a balance of impedance matching and mutual coupling, $h_g$ is chosen to be 29 mm.

Secondly, the radius of the top circular plate, i.e., $r_1$, primarily determines the miniaturization degree of the multi-port central radiator. As shown in Fig. 11(c) and (d), by varying $r_1$ from 58 to 62 mm, the impedance match becomes better in the band from 2.5 to 5 GHz, while it shows an opposite trend at frequencies around 5.9 GHz. Moreover, for achieving an $S_{11}$ of smaller than $-13$ dB within the low band of interest at frequencies around 1.7 and 1.9 GHz, $r_1 = 60$ mm was selected. Meanwhile, the mutual coupling is almost unaffected by $r_1$, where $S_{12}$ and $S_{13}$ are smaller than $-13.5$ and $-12.5$ dB for all three values of $r_1$, respectively.

Thirdly, resonances at 2.4 and 5.2 GHz are excited by loading two quarter-wavelength monopole structures for generating two stopbands, respectively. Thus, the locations of the notched bands are determined by the length of the two arms of the F-shaped monopoles, i.e., $l_{f1}$ and $l_{f2}$. As shown in Fig. 12(a) and (b), by increasing $l_{f1}$, the notched band at 2.4 GHz with a peak $S_{11}$ value of about $-2$ dB experiences a redshift, while the $S_{11}$ magnitude at 5.2 GHz is only slightly affected. The mutual coupling between ports, i.e., $S_{12}$ and $S_{13}$, remain almost unchanged. For the notched band at 5.2 GHz, when $l_{f2}$ increases, the resonance under-goes a redshift towards lower frequencies [see Fig. 12(c) and (d)]. Similarly, the change of $l_{f2}$ has almost no influence on the properties of the low-frequency stopband and port isolation. After optimization, $l_{f1}$ and $l_{f2}$ are chosen to be 16 and 10 mm, respectively.

### IV. SIMULATED AND EXPERIMENTAL RESULTS

#### A. S-PARAMETERS AND RADIATION PATTERNS

To validate the performance of the integrated fully-recessed band-notched UWB diversity antenna, the multi-port central radiator and bowl-shaped ground were fabricated separately using a high-precision cutting machine and assembled into an integrated fully-recessed antenna structure [see Fig. 13(a)-(c)]. Four mini-coaxial cables, which are directly soldered to the bottom of the vertically-orientated strips, are used for feeding the multi-port central radiator (not shown here). Fig. 13(d) shows a photograph of the fully-recessed band-notched UWB diversity antenna mounted on the car roof.

The $S$-parameters of the antenna were characterized by a vector network analyzer. During the measurement, when

| Ref. | Frequency (GHz) | Bandwidth | Diversity | Gain (dBi) | Notched band |
|------|----------------|-----------|-----------|------------|--------------|
| [10] | 1.65           | 103%      | No        | >2.5       | No           |
| [38] | 0.32           | 76%       | No        | >3         | No           |
| [39] | 13             | 77%       | No        | >8         | No           |
| [40] | 4.5            | 111%      | No        | >5         | No           |
| [36] | 1.18 / 1.58    | 7.2% / 3.4% / 10.6% | Yes | 5 / 5 / 7 | No |
| [37] | 1.472 / 2.339  | 2.7% / 0.5%  | Yes | >2 >2 | No |
| [49] | 2.2            | 47%       | Yes       | >6         | No           |
| This work | 3.85      | 112%      | Yes       | >6         | Yes          |
two of the four ports were excited, the remaining ports were terminated by 50 Ω matched loads. Fig. 14 depicts the measured reflection coefficients of all four input ports, as well as the mutual coupling between adjacent and opposite ports, showing a good agreement between the simulated and measured results. For Port 1, the measured $S_{11}$ values are below -10 dB band ranges from 1.7 to 6 GHz, with two narrow bands spanning from 2.4 to 2.64 GHz and from 4.98 to 5.6 GHz. The peak $S_{11}$ values in the two narrow stopbands for all four ports are around -2.8 and -3 dB at 2.5 and 5.15 GHz, respectively. The measured mutual coupling between adjacent and opposite ports, i.e., $S_{12}$ and $S_{13}$, are smaller than -15 dB throughout the entire band.

The radiation patterns and gain values of the integrated fully-recessed band-notched UWB diversity antenna prototype were measured in a spherical near-field anechoic chamber. It also should be noted that when one port is excited, the other three ports should be terminated by 50 Ω matched loads. Fig. 15 reports the normalized radiation patterns at 1.7, 1.9, 3.5, and 5.9 GHz in the $x\z$, $y\z$, and $x\y$-planes when Port 1 is excited, exhibiting a good correspondence between the simulated and measured results. In the $y\z$-plane, the patterns indeed show that majority of the power is radiated towards the upper region of +z-direction with a cross-polarization level of smaller than -26 dB and a maximum level of less than -10 dB towards the lower half-space for all frequencies. At first, the main beams radiate towards the directions in between +z- and $y$-directions at 1.7 GHz. As frequency increases to 5.9 GHz, the main beam shifts towards $y$-direction gradually. Moreover, in the $x\y$-plane, when Port 1 is excited, the main beams point to the $y$-direction with a cross-polarization level of smaller than -20 dB. When four ports are excited in phase simultaneously, the beams corresponding to four input ports merge into omni-directional patterns. In the measurement, for communications with the base station, quasi-omni-directional patterns are achieved in the horizontal planes with different elevation angles, i.e., $\theta =$ 60°, 70°, 80°, and 90° [see Fig. 16]. The gain deviations are smaller than 3, 3, 2, and 4.7 dB at 1.7, 1.9, 3.5, and 5.9 GHz, while the realized gain levels are higher than -5 dBi in between $\theta =$ 60° and $\theta =$ 90° for all frequencies. It also should be noted that the antenna placed on the Teflon pedestal is not perfectly perpendicular to the ground plane during the assembly process, which would slightly affect the impedance matching and pattern symmetry.

For a better illustration of the operating principle of the antenna, the current distributions on the proposed fully-recessed antenna due to Port 1 excitation at 1.7, 1.9, 3.5, and 5.9 GHz are displayed in Fig. 17. At low frequencies of 1.7
and 1.9 GHz, the current propagates along the y-direction on the top circular plate, generating broadside patterns in the yz-plane [see Fig. 17(a) and (b)]. Particularly, at 1.9 GHz in the yz-plane, slot radiation between the rim of the top circular plate and top edge of the ground structure can be identified, resembling a half-wavelength resonant mode. Moreover, the currents between the top circular plate and bowl-shaped ground radiate towards +z-directions, indicating that the inner wall of the bowl-shaped ground functions as a metallic reflector. At 3.5 and 5.9 GHz, stronger currents can be found on the split-quarter conical monopole rather than the top circular plate, which implies that the radiation is mainly attributed to the travelling wave propagating in between the curved ground plane and split-quarter conical monopole [see Fig. 17(c) and (d)].

In order to understand the stopband generation of ANT VII, the surface current distributions at 2.4 and 5.2 GHz are displayed in Fig. 18. It can be seen that strong currents are concentrated along the longer-length arm of the F-shaped monopole, which has a length of about a quarter wavelength at 2.4 GHz. Meanwhile, as revealed by the weak currents on the top circular plate, the U-shaped slots make little influence on the low frequency stopband. The second stopband centered at 5.2 GHz is generated by the shorter-length arm of the F-shaped monopoles on which the fields are concentrated [see Fig. 18(b)]. At 5.9 GHz, strong fields can be found around the U-shaped slots, implying that the introduced capacitive effects indeed help improving the impedance matching (not shown here).

Fig. 19 depicts the measured peak realized gains of ANT VII versus the frequency when the four ports are excited individually, which shows that the measured results agree well with the simulated results. Apart from the two narrow frequency bands near 2.5 and 5.15 GHz, the gain varies between 6 and 9.5 dBi in the majority of the bands. At 2.5 GHz, the realized gain is about 3 dBi, whereas the realized gain is about 2 dBi at 5.15 GHz. The discrepancy can be attributed to fabrication tolerance and the assembling errors.

B. DIVERSITY PERFORMANCE

The envelope correlation coefficient (ECC) was calculated for validating the diversity performance of the antenna, which can be expressed based on the radiation patterns of the antenna in an isotropic propagation environment as [50], [51]

$$\rho_e = \frac{\left|\int_{4\pi} F_{Porti}(\theta, \varphi) \ast F_{Portj}(\theta, \varphi) \, d\Omega\right|^2}{\int_{4\pi} |F_{Porti}(\theta, \varphi)|^2 \, d\Omega \int_{4\pi} |F_{Portj}(\theta, \varphi)|^2 \, d\Omega},$$

(1)

where $F_{Porti}(\theta, \varphi)$ represents the complex 3D far-field pattern for Ports $i$, $j$, and the symbol “$\ast$” denotes the Hermitian product. The second alternative method for ECC calculation is based on the scattering parameters, which can be expressed as [52]

$$\rho_e = \frac{|S_{ii}^2 + S_{jj}^2 - 2S_{ij}S_{ji}|^2}{(1-|S_{ii}|^2)(1-|S_{jj}|^2)},$$

(2)

where $S_{ij}, (i \neq j)$, and $i, j = 1, 2, 3$ represents the complex S-parameters for Port $i$ and/or Port $j$.

Fig. 20 shows the ECC curves calculated by the simulated and measured complex 3D radiation patterns and scattering parameters for adjacent and opposite ports, i.e., Ports
1, 2, and 3. It can be seen that the ECC values calculated by the simulated and measured radiation patterns and scattering parameters agree well with each other within the entire band, which are all below 0.05 from 1.7 to 6 GHz, except for frequencies near the two stopbands around 2.5 and 5.15 GHz. In short, the simulated and measured results demonstrate its low correlation for ensuring good channel characteristics.

V. CONCLUSION

In summary, a compact, band-notched UWB fully-recessed antenna with pattern diversities is proposed and demonstrated for V2X communications. The antenna is composed of a multiport central radiator fully embedded at the center of a bowl-shaped ground structure. The notched bands are achieved by incorporating four F-shaped monopoles that produce two resonances at 2.4 and 5.2 GHz. The mutual coupling reduction is realized by cutting crescent slots on the bottom of the bowl-shaped ground. The proposed antenna is fabricated and characterized, achieving an $S_{11} < 10$ dB band from 1.7 to 6 GHz with two notched bands centered at 2.5 and 5.15 GHz for all four ports, a mutual coupling of less than $-15$ dB, and an ECC below 0.1. The antennas provide omni-directional patterns when all four ports are excited in phase, and four directional beams when the four ports are excited individually. The demonstrated fully-recessed diversity antennas are promising candidates for MIMO multisevice devices in vehicles and other non-protruding platforms.

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