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Design of High-Gain Circularly Polarized Antennas Based on Vehicle Application Environment

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ABSTRACT In this paper, a novel circularly polarized (CP) antenna that achieves high gain by maximizing the radiation aperture utilization is proposed for vehicle applications. The realization of increasing the radiation aperture is based on the application environment, making full utilization of the vehicle roof, a large metal reflector beneath the antenna, which is indispensable in the vehicle application. Developed from the structure of typical microstrip patch antenna, the design extends the radiation patch to cover the side of the dielectric substrate, which increases the size of the radiating patch without increasing the antenna's outline size. To make CP antennas more suitable for special working environments with large reflecting surface, a sequential rotation feeding structure with 90° progressive phase difference is uniquely designed based on the active port impedance of the four-ended radiation structure. This co-design method introducing the active port impedance of a multi-port radiator into the design of feeding network as the loads can effectively guarantee the CP performance of the antenna, and can greatly simplify the optimization work in the subsequent stage. Based on this design idea, a prototype working at 1.48 GHz with a 50-MHz bandwidth is designed for vehicle satellite broadcasting application. Experimental results show that the antenna achieves a high CP gain greater than 7 dBic with a compact size of $50 \times 50 \times 10\ mm^3$ ($0.247\lambda_0 \times 0.247\lambda_0 \times 0.05\lambda_0$, λ_0 is the wavelength of working frequency in free space).

INDEX TERMS Vehicle satellite broadcasting, high gain, circular polarization, sequential rotation feeding, extreme radiation aperture.

I. INTRODUCTION

The continuous development of satellite communication has even more remarkable advantages, such as global coverage, unlimited geographical conditions, and large transmission capacity, thereby, satellite communications have reached wide applications [1]. As transportation becomes more and more popular, correspondingly, the satellite communications industry has also covered the vehicle mobile communication field. As an important component of the communication system, vehicle-mounted satellite antennas also received much attention. However, the car roof, a huge reflect plane, constructs a special working environment for the vehicle-mounted satellite antennas.

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Because the circularly polarized (CP) electromagnetic waves are relatively immune to interference, fading, polarization mismatches and Faraday rotation effects caused by the ionosphere [2], CP antennas are usually adopted in satellite communication. There are many CP antenna types proposed for satellite communications in existing works, including helical antennas [3], crossed dipole antennas [4], [5], parallel-plate slot antennas [6], patch antennas [7]–[10], among others. However, these designs are not satisfactory for vehicle applications due to the special working environment of vehicle-mounted antenna, particularly the huge reflect plane, that is compact and beautiful appearance.

There are also some works specially designed for vehicle application. In [11], a crossed dipole antenna for automotive applications was proposed. A pair of crossed non-equal length dipoles are adopted as the main radiator to achieve

CP radiation. The crossed dipole antenna structure is easy to fabricate and can improve the gain at low elevation angles by adjusting the distance between the main radiator and the huge reflector. However, the unacceptable height profile ($0.36\lambda_0$, λ_0 is the wavelength of working frequency in free space) limits its application in vehicle equipment. Helical CP antenna can adapt to the vehicle environment well and a 2 × 2 hemispherical helical antenna array is proposed in [12] for mobile vehicles, which achieves a low-profile and high gain. Higher antenna gain means better communication quality, especially for complex situations like vehicle communication, high gain is even more critical. The large-size problem caused by the array [12] makes it difficult to integrate into the vehicle.

There is an antenna type, CP patch antenna [13]–[17], widely adopted in satellite communications. Patch antennas have the advantages of a low profile, light weight and ease of manufacturing, and the inherent ground plane makes it very easy to be installed in a car. For example, in [15], a patch antenna integrating GPS and Satellite Digital Audio (SDARS) for automotive use is proposed, and for which the main radiator consists of an annular ring and a slot-loaded square patch. The design utilizes module integration to achieve a certain level of miniaturization to meet the space requirements of automotive applications, but a diameter of 126 mm makes it hard to stay compact. The integration on a vehicle with a decent appearance is difficult to attain.

Note that all these existing designs adopt the same design considerations. Firstly, design an entire CP antenna, then consider the adaptability of the design on the vehicle environment, and finally, achieve a specific performance through optimization. However, since the vehicle roof is an unavoidable huge reflecting plane, is it feasible to introduce a reflector into the design process of the CP antenna as a favorable factor?

In this paper, a novel CP antenna is designed by considering the metal sheet of vehicle as a necessary component, which is works as the reflector of the improved microstrip patch antenna to achieve the unidirectional radiation performance. Because of the huge reflector, the original ground plane can be reduced or made even smaller than the size of the radiation patch, which can realize the maximum use of antenna aperture, so excellent gain performance becomes possible. For a more compact structure and better for vehicle integration, the radiation patch of traditional microstrip antenna is extended to the side of the dielectric substrate. Multi-port CP antenna is less sensitive to the working environment, and is more suitable for use in vehicle application, so a four-ended model with sequential rotation feeding scheme is adopted in this design. Based on the co-design concept, the active port impedances of the four-ended antenna working on a huge reflector are extracted as the load to assist in the design of feeding networks. This method can greatly reduce the optimization work caused by the mismatch between the independently designed feed networks and the multi-port antennas. The fabricated prototype is working at 1.48 GHz with a 50-MHz bandwidth. Thanks to the extreme utilization of radiation aperture, the measured results show an excellent CP gain over 7dBic with a half-power beamwidth over 90° based on a compact size of $50 \times 50 \times 10\ mm^3 (0.247\lambda_0 \times 0.247\lambda_0 \times 0.05\lambda_0$, λ_0 is the wavelength of working frequency in free space).

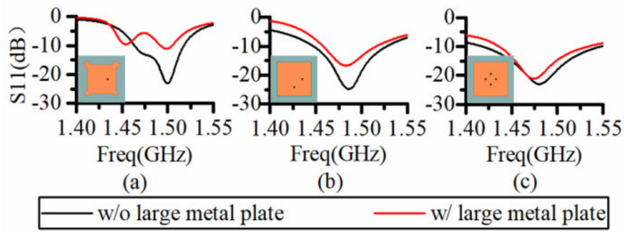

FIGURE 1. Comparison of the effects of different feeding forms on reflection coefficient. (a) single-end (b) double-end. (c) four-end.

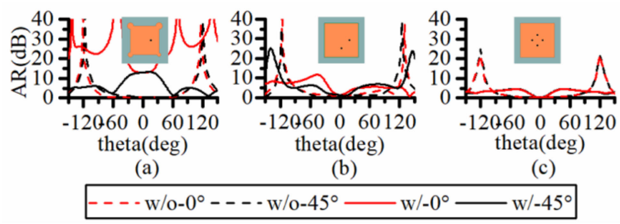

FIGURE 2. Comparison of the AR patterns of different feeding forms patch antenna on big ground plane. (a) single-end (b) double-end. (c) four-end.

II. ANTENNA DESIGN

A. FEEDING SCHEME

To determine the feeding form of the antenna, the working states of antennas with different feeding forms on the large reflection plane are explored first. Fig. 1 contrast shows the effects of the huge car roof (a square metal plate with a size of $500 \times 500\ mm^2$ is as a substitute [18].) on the reflection coefficients (Fig. 1(a)) and active reflection coefficients (Fig. 1(b) and (c)) of single-ended, dual-ended and four-ended CP microstrip antenna. Note that compared to the particular sensitivity of single-ended CP microstrip antenna, the dual-port antenna is more stable, and the four-port CP antenna is the most retarded model. In terms of radiation performance, the axial ratio (AR) (Fig. 2 (a)) of the single-ended CP antenna worsens when working on a huge metal plate. The gap between dual-ended model and the four-ended model is also clearer. The AR patterns of dual-ended CP antenna (Fig. 2 (b)) is extremely deteriorated on one side, while thanks to the balanced feeding scheme, the four-ended CP model always keeps acceptable symmetrical AR patterns(Fig. 2 (c)), although there is still a certain deterioration in value.

B. RADIATION STRUCTURE

Fig. 3 shows the evolution process, of which the original idea can be traced to the typical four- ended CP microstrip antenna. Although there is an inherently huge reflection plate providing guarantee for unidirectional radiation performance, it is not necessary to limit the radiation patch smaller than

FIGURE 3. Evolution process.

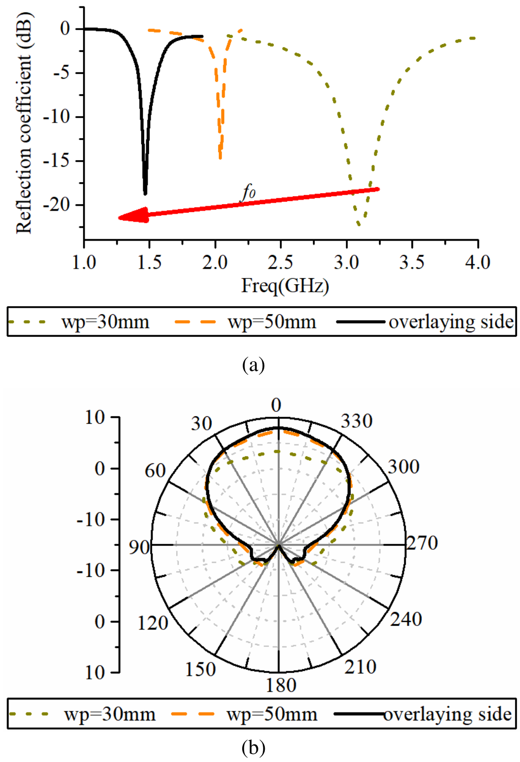

FIGURE 4. Comparison of (a) reflection coefficients and (b) radiation patterns based on the antennas with different patches, *wp* is the width of upper patch of the antenna.

the bottom patch. Extending the radiation patch to the same size as the ground patch can greatly expand the antenna aperture utilization, thereby improving antenna gain. The idea of extending the metal patch to the four sides of the dielectric substrate and reducing the size of the bottom patch of the microstrip antenna can further make the model more compact. As shown in Fig. 4 (a), the resonant frequency of the example model gradually approaches the low frequency end as the evolution progresses whereas the antenna gain is gradually increasing, especially when the radiation patch extends from a small patch to cover the entire substrate (Fig. 4 (b)).

Note that the huge ground plate is an indispensable part in the proposed design. If there is no large ground plane beneath the four-ended antenna, the performance of this antenna will be severely deteriorated. Fig. 5 (a) shows that both the resonant features and impedance match characteristics will change with it, especially, when cancelling the huge ground plate, the desired unidirectional radiation performance is completely lost and replaced by a quasi-omnidirectional

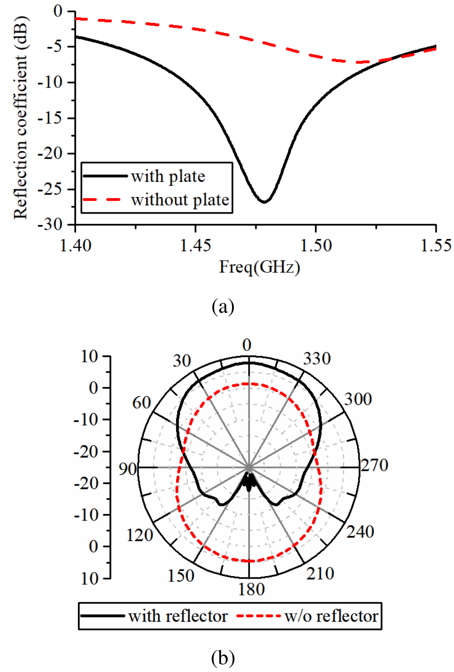

FIGURE 5. The performance of the presented four-ended element with and without the big ground plane. (a) reflection coefficient and (b) radiation patterns.

radiation pattern (Fig. 5 (b)). In by Fig. 5, the proposed four-ended CP antenna is not a component that can work independently. The design is a special customization for a specific environment — vehicle applications.

C. CO-DESIGN FEEDING NETWORK

Obviously, the four-ended CP antenna must be accompanied with a sequential rotation feeding structure. Typical sequential rotation feeding structures, as applied in [19], [20], are based on Wilkinson power divider with the unequal-length microstrip lines to provide phase shift. The advantages of this sequential rotation feeding type are the benefits from good ports isolation and that the slight mismatch between the antenna ports and the feeding network output port does not cause severe performance degradation. Compared to the feeding network constructed by the Wilkinson power divider, the simplified type directly constructed by unequal T-type microstrip power divider [21] is more succinct and without lumped components. In addition, the total length of the feeding network is shorter, which indicates less insertion loss and lower layout difficulty. However, the isolations between the output ports are not considered, so the performance of the simpler feeding network requires a high degree of port matching.

To reduce the optimization work caused by the port mismatch between the feeding network and the multi-port antenna, an active co-design method is considered. Because it is almost impossible to ensure the active working impedance to be exactly $50 + j0\Omega$, thereby, as shown in Fig. 6, the simulated active impedances ($39 + j0\Omega$ in this design) are extracted as the load impedances of the feeding network to improve the accuracy of the feeding network design.

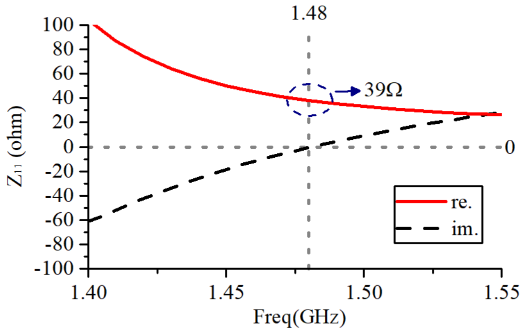

FIGURE 6. The active port impedance of the four-end element.

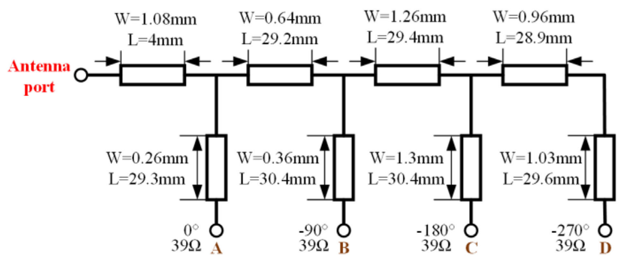

FIGURE 7. Detailed parameters of the feeding network. ***W*** is the width of the microstrip lines and ***L*** stands the length.

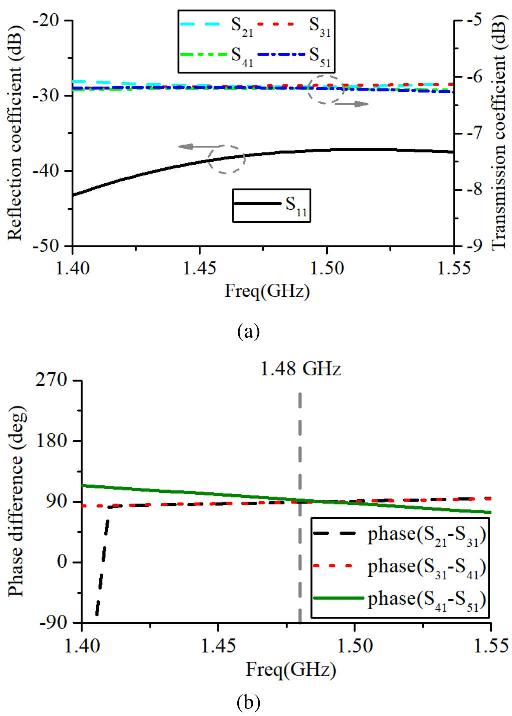

FIGURE 8. Simulated performance of ideal model of the feeding network. (a) Amplitude feature. (b) phase feature.

After simple optimization, an ideal feeding network circuit topology is achieved as shown in Fig. 7, which is designed based on the port impedance shown in Fig. 6 (39 + $j0\Omega$). The substrate adopted in the feeding network design is Rogers 4350 with a relative permittivity of $\varepsilon_r = 3.5$ and a thickness of 0.508 *mm*. Simulated results shows that port_A, port_B, port_C and port_D have the equal amplitudes (Fig. 8(a)) with a sequence 90° phase difference(Fig. 8(b)).

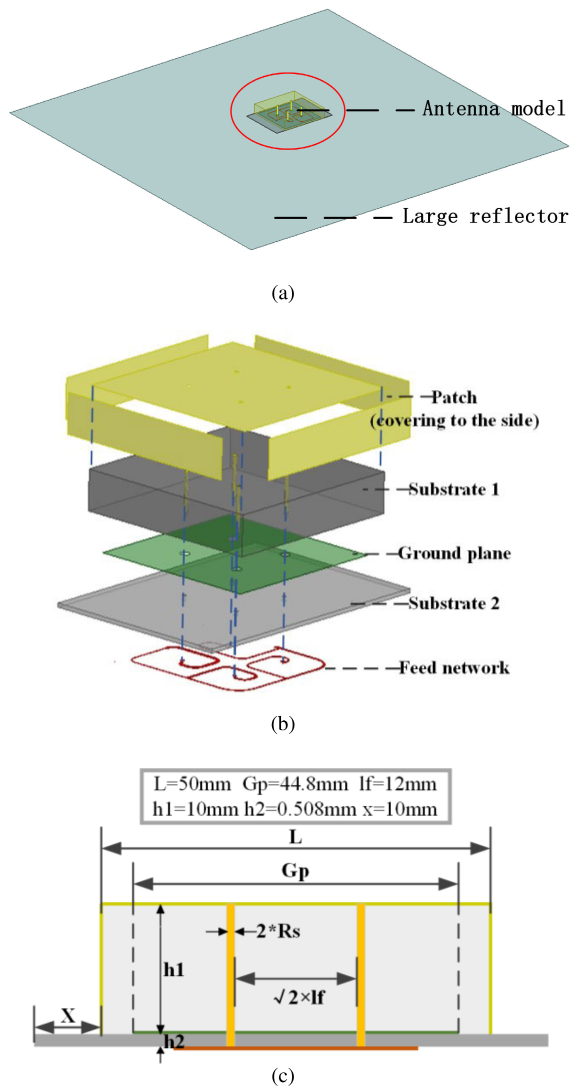

FIGURE 9. Geometry of the proposed CP antenna. (a) Perspective view. (b) explode view. (c) sectional view.

III. EXPERIMENTAL RESULTS

Integrating the sequential rotation feeding network to the pro- posed four-ended CP antenna by suitable layout, a complete high-gain CP antenna is completed (Fig. 9). Note that there is no more parameter optimization in this case after combining the feeding network with the radiation part, which fully illustrates the efficiency and effectiveness of this active co-design method. The radiation part of this proposed sequential rotation feeding CP antenna is built on a thick substrate with a relative permittivity of $\varepsilon_r = 3.5$, a tangent loss of 0.003 and a thickness of $h_1 = 10$ *mm*. The lower substrate is extend 10 *mm* to the edge of the upper substrate, which is for easy assembly and without relation to electrical performance.

To validate the simulation analysis, a prototype was fabricated and tested. Fig. 10 illustrates the top-view and

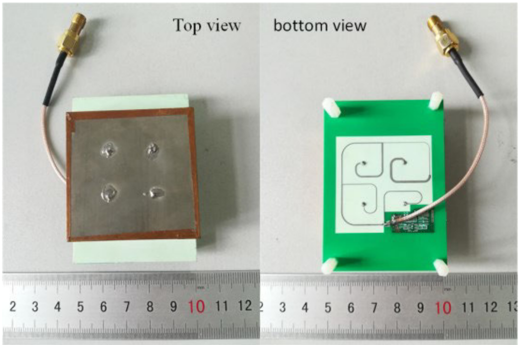

FIGURE 10. Photograph of the fabricated antenna prototype.

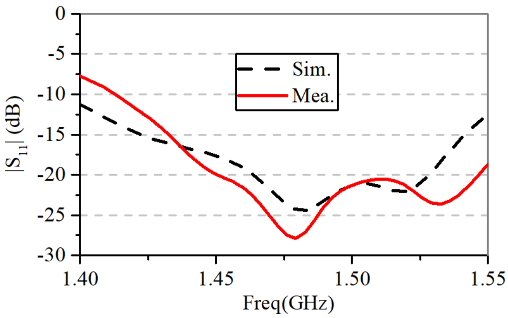

FIGURE 11. Simulated and measured S_{11}.

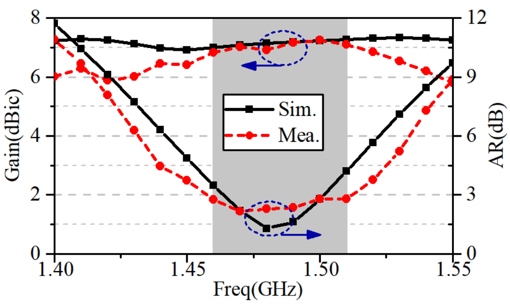

FIGURE 12. Simulated and measured AR and gain.

bottom-view photographs of the fabricated antenna prototype. The antenna consists of a dielectric substrate with five sides coated tin and a substrate with a printed feeding network on one side and a common ground plane on the other side.

The simulated and measured S_{11} carves are compared in Fig. 11, and an acceptable consistency between the measured results and simulated ones can be found. An impedance bandwidth over 10% (1.40 to 1.55 GHz) is confirmed based on the standard of $S_{11} < -10\ dB$. However, compared to the excellent impedance bandwidth, the AR bandwidth, shown in Fig. 12 is only about 50 MHz (1.46 - 1.51 GHz), while it is still satisfy the requirement (1.46 - 1.5 GHz) of the case for vehicle satellite broadcast application. Benefit from the extreme utilization of the aperture, the most prominent performance is the antenna gain. As shown in Fig. 12, measured results shows that the RHCP Gain extend to 7 dBic over the entire operating bandwidth, while the overall size of this module is only $0.247\lambda_0 \times 0.247\lambda_0 \times 0.05\lambda_0$.

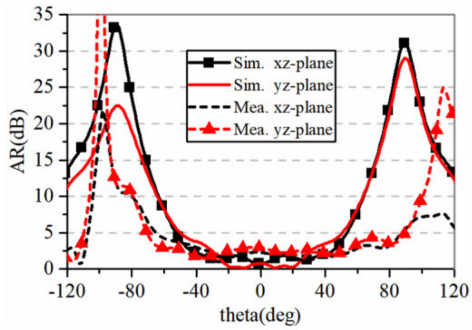

FIGURE 13. AR change with the pitching angle at 1.48 GHz.

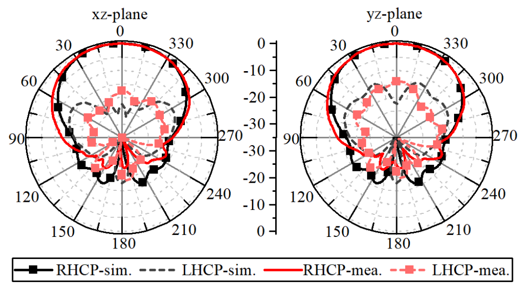

FIGURE 14. Simulated and measured normalized radiation patterns at 1.48 GHz.

TABLE 1. Comparisons Between This Work and Previous Circularly Polarized Antenna

Ref.	[10]	[8]	[5]	[16]	[17]	This work
Feeding scheme	single-end	dual-end	dual-end	four-end	four-end	four-end
Dimensionality	single-layer	multi-layer	3D	multi-layer	multi-layer	double-layer
Center Freq. (GHz)	1.58	1.61	1.575	1.1	1.64	1.48
Size ($\times\lambda_0$)	0.32× 0.32	0.21× 0.21	0.47× 0.47	0.27× 0.27	0.6 × 0.6	0.25× 0.25
Hight ($\times\lambda_0$)	0.026	0.03	0.38	0.07	0.15	0.05
Bandwidth	2.2%	5%	6.3%	6.8%	16%	3.4%
Gain(dBic)	4.65	5	4.14	5.4	8	7

Fig. 13 shows the simulated and measured AR patterns in the $xoz - plane$ and $yoz - plane$ at 1.48 GHz. The measured AR patterns have good consistency in the two planes and the 3-dB AR beamwidth is covering from $-60°$ to $60°$. The corresponding normalized radiation patterns of the proposed antenna in the $xoz - plane$ and $yoz - plane$ at 1.48 GHz are also shown in Fig. 14. Symmetrical radiation patterns are noticeable and measurement results agree well with the simulation results.

Compared to the other CP antennas (TABLE I), the proposed design achieved a relatively high gain based on a compact antenna size. Unlike conventional CP antennas for GNSS application that pursue wide coverage [5], [7], this antenna is designed for geostationary satellite broadcasting applications with a working frequency band of 1.467GHz - 1.492 GHz where the satellite antenna beam is directed to high latitudes area. The high CP gain can ensure the stability of the satellite link in low latitudes area where the satellite signal ground power coverage is weak, so that keeping a stable satellite link in a wider area.

IV. CONCLUSION

A sequential rotation feeding CP antenna with excellent gain performance has been proposed for vehicle satellite broadcast applications. To make the structure of the antenna more compact and easier to integrate into a limited vehicle environment, such as a shark fin-type radome, the radiation patch of the typical microstrip antenna is expanded to cover the side of the dielectric substrate. This operation can fully utilize the aperture to improve the radiation performance. Meanwhile, the inherent car roof, a metal reflector, can induce a unidirectional radiation feature. Thereby, the remarkable high gain can be realized with a restricted size. The active co-design concept is adopted for the design of sequential rotation feeding network. The active port impedance of the four-port radiator working on a huge reflector is extracted to assist the feeding network design as the loads of the ideal circuit model. This method can greatly reduce the parameter optimization work caused by the mismatch between the independently designed feed networks and the multi-port CP antennas. A prototype designed based on this concept is fabricated and tested. The measured results show a 3-dB axis ratio bandwidth of 50MHz, a 3-dB beamwidth of about 120°, and a high RHCP gain above 7 dBic based on a compact size of $0.247\lambda_0 \times 0.247\lambda_0 \times 0.05\lambda_0$.

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