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RESEARCH ARTICLE

High Efficiency Wide-Beam Antenna Array With H-Plane Beamwidth Enlargement and Filtering Properties for Millimeter-Wave Applications

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ABSTRACT

This manuscript presents a 1×4 wide-beam patch antenna array that is serially fed by a double-side substrate integrated suspended line (DSISL) for millimeter-wave applications. A novel wide-beam method with beam enlargement only in H-plane is proposed and very suitable for the serially-fed array. Two vertical patches in the special shape of inverted "T" are installed on both sides of radiation patch of antenna element to broaden the beamwidth only in H-plane. Antenna element with wide beamwidth only in H-plane can help the antenna array to obtain wide beamwidth in H-plane while achieve a lower side lobe level (SLL) in E-plane. In addition, benefiting from the features of low loss and good shielding effect, a DSISL is used to realize high efficiency property. Besides, the proposed antenna array is fed by the way of series with an open end to obtain filtering response. There are no extra filtering circuits so the antenna efficiency can be improved further. For demonstration, the proposed 1×4 antenna array working at 24 GHz is fabricated and measured. The measured results shows that the proposed antenna works from 23.7 to 24.4 GHz with the beamwidth of 140° in H-plane, total efficiency of 82.6%, and suppression level of 22.3 dB. Based on its features of wide beamwidth while keeping high efficiency and good filtering performances, the proposed antenna has great potential in wide-coverage mm-wave application.

1 | Introduction

With the rapid development of intelligent vehicle infrastructure cooperative systems, wide-beamwidth antennas are desired in different vehicle systems, such as vehicle-to-everything (V2X) communications system [1], vehicle radar system [2], and so on. Millimeter-wave (mm-wave) antennas featuring compact size are more suitable for vehicle systems compared with the antennas working at sub-6G band. Considering the high loss at mm-wave frequency band and electromagnetic interference (EMI) characteristics, the antenna with high efficiency and out-of-band filtering performances is also required.

Substrate integrated suspended line (SISL) as a low-loss transmission line has been utilized for high-efficiency antenna design, and the efficiencies are not less than 90% [3, 4]. In recent years, the SISL-based antennas with filtering response are presented [5–7]. But they suffer from narrow beamwidth or large size which are not suitable for the vehicle systems.

In general, there are four types of methods to realize wide beamwidth property of antennas. The first one is to integrate multiple modes to obtain wide beamwidth [8, 9]. The shape of DRA is changed to excite and integrate multiple high-order modes to obtain wide beamwidth, and the beamwidth is 250° and 209° in E- and H-plane, respectively [8]. The second method is reconfiguring the radiation patterns [10, 11]. This method is focused on changing the beam coverage by using PIN diodes to switch the working state of antennas. The third method is constructing wide beamwidth antennas [12–15]. A magnetic current source is designed to parallel with the GND and then a 180° beamwidth is achieved in E-plane [12]. The fourth method is utilizing parasitic structures [16–18]. Two parasitic vertical patches are installed in the front and back of the radiation patch elements, and then wide beamwidths of 221°and 168° are obtained in E- and H-plane, respectively. However, most of these antennas reported in [8–18] pay attention to achieve wide beamwidth in E-plane or in both E- and H-plane. But few antennas pay attention to achieve wide beamwidth only in H-plane. In the proposed antenna, a 1×4 series-fed antenna array is proposed with wide beamwidth in H-plane. In this situation, wide beamwidth in E-plane is unnecessary because wide beamwidth in E-plane will cause high side lobe level (SLL) in E-plane and low gain.

In this paper, a wide-beam 1×4 patch antenna array with high efficiency and filtering properties is proposed for the vehicle systems. Vertical patches in the special shape of inverted "T" are installed on both sides of antenna element, which helps obtain low SLL while keeps wide beamwidth in the antenna array. Besides, the feed line is bent in the proposed 1×4 patch antenna array to further reduce the SLL. To obtain high efficiency property, DSISL is utilized to design the feeding network due to its low-loss feature. DSISL comes from SISL but shows lower transmission loss [19]. The filtering response of the proposed antenna array is obtained by feeding the four patch elements in the way of series-fed with an open end. There are no filtering circuits to obtain the filtering response, which improves the antenna efficiency further.

2 | Antenna Design

In this section, configuration and principles of the proposed antenna will be described and analyzed.

2.1 | Antenna Configuration

The proposed 1×4 patch antenna is constructed with five substrates (Sub1–Sub5), eight metal layers (G1–G8) and eight

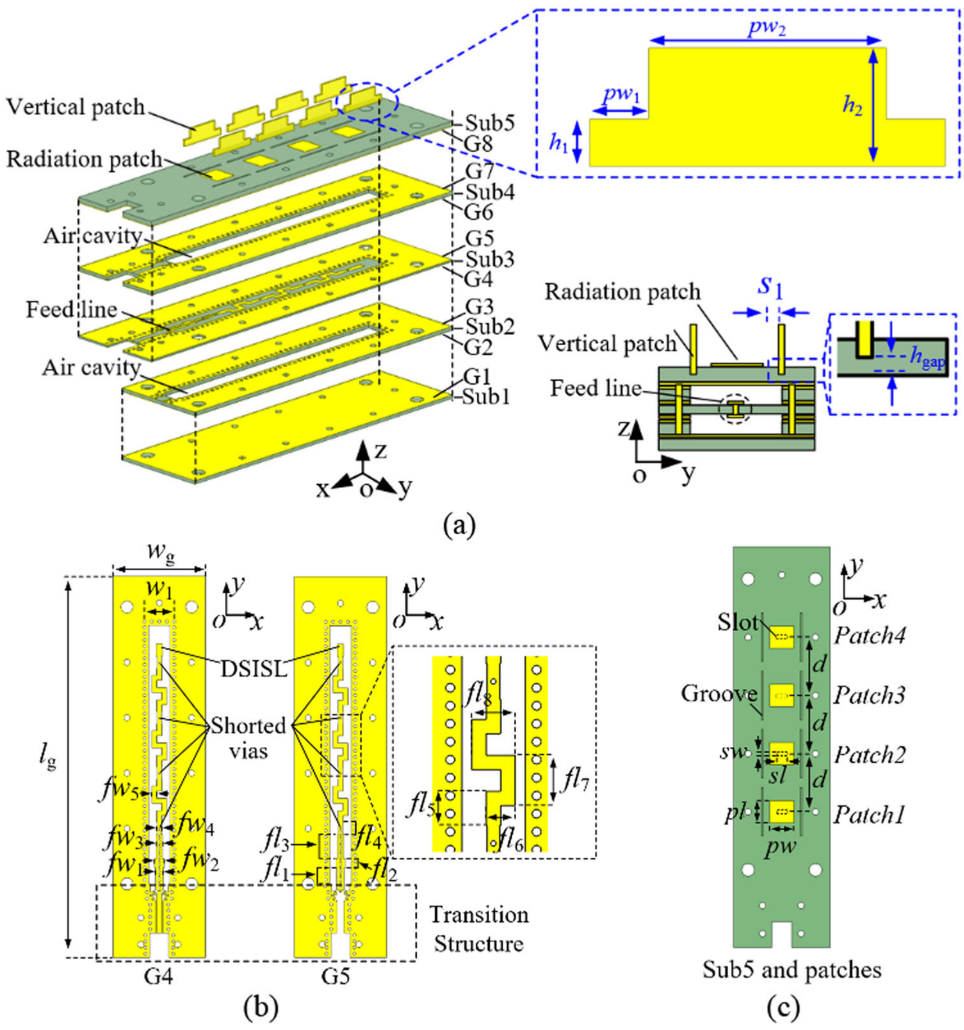

FIGURE 1 | Configuration of the proposed 1×4 patch antenna. (a) 3D view and front view. (b) G4 and G5 layers. (c) Sub5 and patches.

TABLE 1 | Parameters of the proposed DSISL 1 × 4 series-fed antenna array.

Parameter	L_G	W_G	W_1	FW_1	FW_2	FW_3	FW_4	FW_5	FL_1
Value (mm)	62	15	4.8	1.2	1.5	1	0.7	0.8	3.6
Parameter	FL_2	FL_3	FL_4	FL_5	FL_6	FL_7	FL_8	SW	SL
Value (mm)	1.5	3.9	2	1.9	1.6	2.8	2.4	0.25	2.2
Parameter	PW	PL	D	H_1	H_2	PW_1	PW_2	H_{GAP}	S_1
Value (mm)	3.75	3.45	9	0.25	2.5	1.25	5	0.381	1

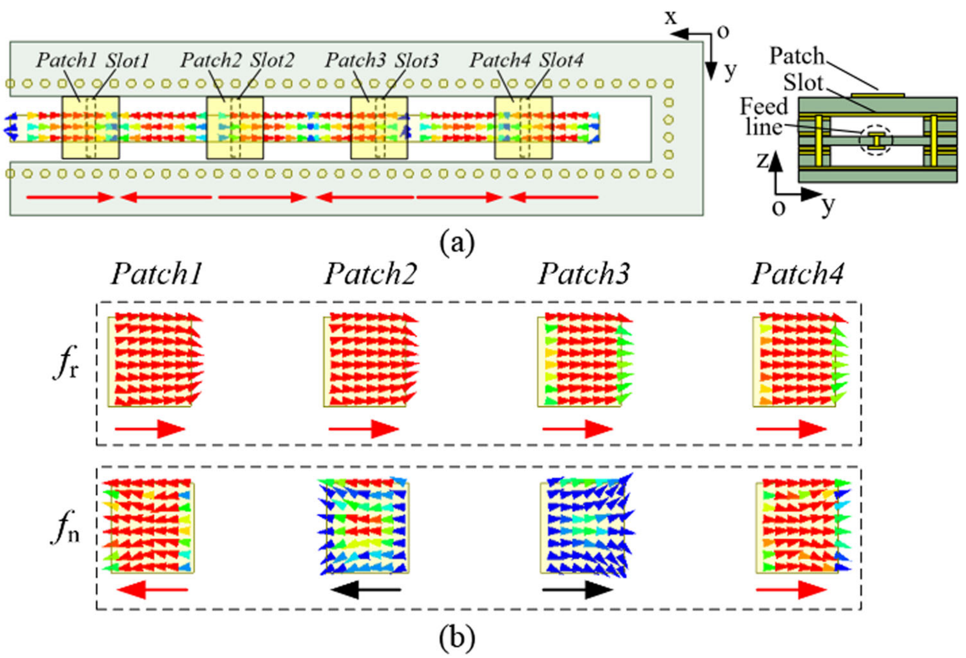

FIGURE 2 | Current distribution of DSISL and proposed antenna. (a) Current distribution of DSISL. (b) Patches current distribution of the proposed antenna at the frequency of resonance and one of radiation nulls.

inverted-"T"-shaped vertical patches, as shown in Figure 1. Sub1, Sub2 and Sub4 are FR4-epoxy with $h_1 = h_2 = h_4 = 0.5$ mm, $\varepsilon_r = 4.4$ and $\tan\delta = 0.02$. Sub3 and Sub5 are Rogers RT/duroid 5880 with $h_3 = 0.254$ mm, $h_5 = 0.787$ mm, $\varepsilon_r = 2.2$ and $\tan\delta = 0.0009$. The feed line is bent and printed on G4, G5 layers, and shorted by metal vias, as shown in Figure 1b. Sub2 and Sub4 are hollowed and surrounded by metal vias to form air cavities for low-loss purpose. Sub5 are etched with blind grooves for the installation of vertical patches, as shown in Figure 1c. Vertical patches are installed on both sides of radiation patches but not connected with the GND1 layer (G8), so there is a gap between vertical patches and G8, as shown in Figure 1a. The gap can help the vertical patches broaden the beamwidth, efficiently. For measurement purpose, a GCPW-Strip line-DSISL transition structure is designed in the input port. Bent line can help to further reduce the SLL of proposed 1 × 4 antenna array in E-plane (xoz). The detailed parameter values are shown in Table 1.

2.2 | Antenna Principles

1) *Principle of filtering response*:

It has been proved in [20] that series-fed antenna is equivalent to a second-order bandpass filtering circuit. In [21], a series-fed microstrip patch antenna is presented with good filtering response by adjusting the location of patches to control the current distribution on patches. According to [20] and [21], a way of series-fed with an open end is utilized to achieve filtering response based on DSISL in the proposed antenna. Similar to the microstrip patch antenna in [21], the proposed antenna achieves filtering response by adjusting the location of coupling slots (*Slot1-Slot4*) to control the current distribution on radiation patches, as shown in Figure 2a. After well design, the currents on radiation patches (*Patch1–Patch4*) are in-phase at resonant frequency f_r but out-of-phase at radiation-null frequencies f_n, as shown in Figure 2b. As a result, strong radiation is obtained at f_r while weak radiations are appeared at f_n, so filtering response is obtained in the proposed antenna.

2) *Principle of wide beamwidth in H-plane:*

To understand this principle, a DSISL patch antenna element installing with rectangular vertical patches is analyzed. The configuration and current distribution are shown in Figure 3a. When the radiation patch is excited, currents on one vertical patch have the same direction, and the currents are strongest on the center and weakest on the ends. Besides, the length l_v of vertical patch is about half waveguide wavelength. Therefore, the two vertical patches are regarded as two dipoles. Based on

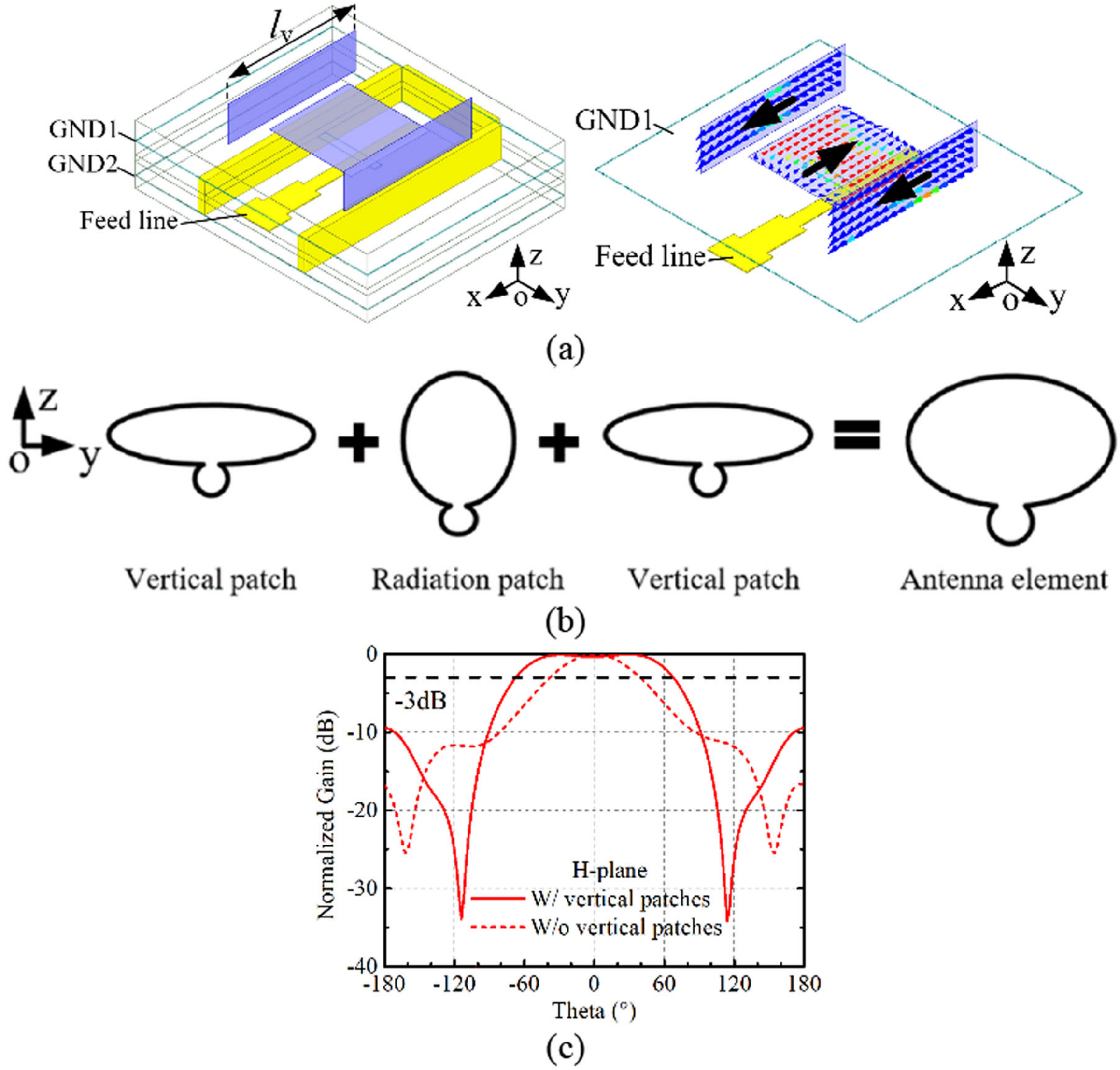

FIGURE 3 | Configuration, principle and radiation pattern of the DSISL patch antenna element installing rectangular vertical patch. (a) Configuration and current distribution at f_0. (b) Schematic diagram of wide beamwidth in H-plane. (c) H-plane radiation pattern comparison with and without vertical patches.

the radiation patterns of dipole, the vertical patch would show omnidirectional property in yoz-plane if there is no GND layer under it. In the DSISL patch antenna element, though the vertical patch doesn't show omnidirectional property in yoz-plane due to the top GND (GND1), it also owns wide beamwidth property in yoz-plane. Therefore, the element shows wide beamwidth in H-plane (yoz) based on the synthesis of radiation pattern, as shown in Figure 3b. Compared with the traditional DSISL patch element with a half-power beamwidth (HPBW) of 78°, the patch element installing with rectangular vertical patches shows a HPBW of 140°, which is almost two times of the HPBW of the traditional DSISL patch element.

To further understand the principle of wide beamwidth, the evolution of the proposed antenna element is given in Figure 4a. Antenna I is traditional DSISL patch antenna element. Antenna II is DSISL patch antenna element installing rectangular vertical patches, and the vertical patches are connected to the GND1. Antenna III has the similar structure with Antenna II but there is a gap between vertical patches and the GND1, which means that the vertical patches are not connected to the GND1. In the proposed antenna, the vertical patches are not also connected to the GND1 but the vertical patches are in the shapes of inverted "T."

As shown in Figure 4b,c, compared with Antenna I with the beamwidth of 78° in H-plane, Antenna II shows wider beamwidth of 108° in H-plane owing to the installation of rectangular vertical patches. But the beamwidth isn't wide enough. Because the currents on vertical patch of Antenna II are not strong and the current directions are nonuniform due to the connection of vertical patches with GND1. Compared with Antenna II, Antenna III shows much stronger currents, and its current directions are uniform, so Antenna III shows much wider beamwidth of 148° in H-plane, but it also shows much wider beamwidth of in E-plane which will cause high SLL and low gain in 1×4 series-fed antenna array. Besides, its front-to-back (FB) ratio is less than 10 dB. Compared with

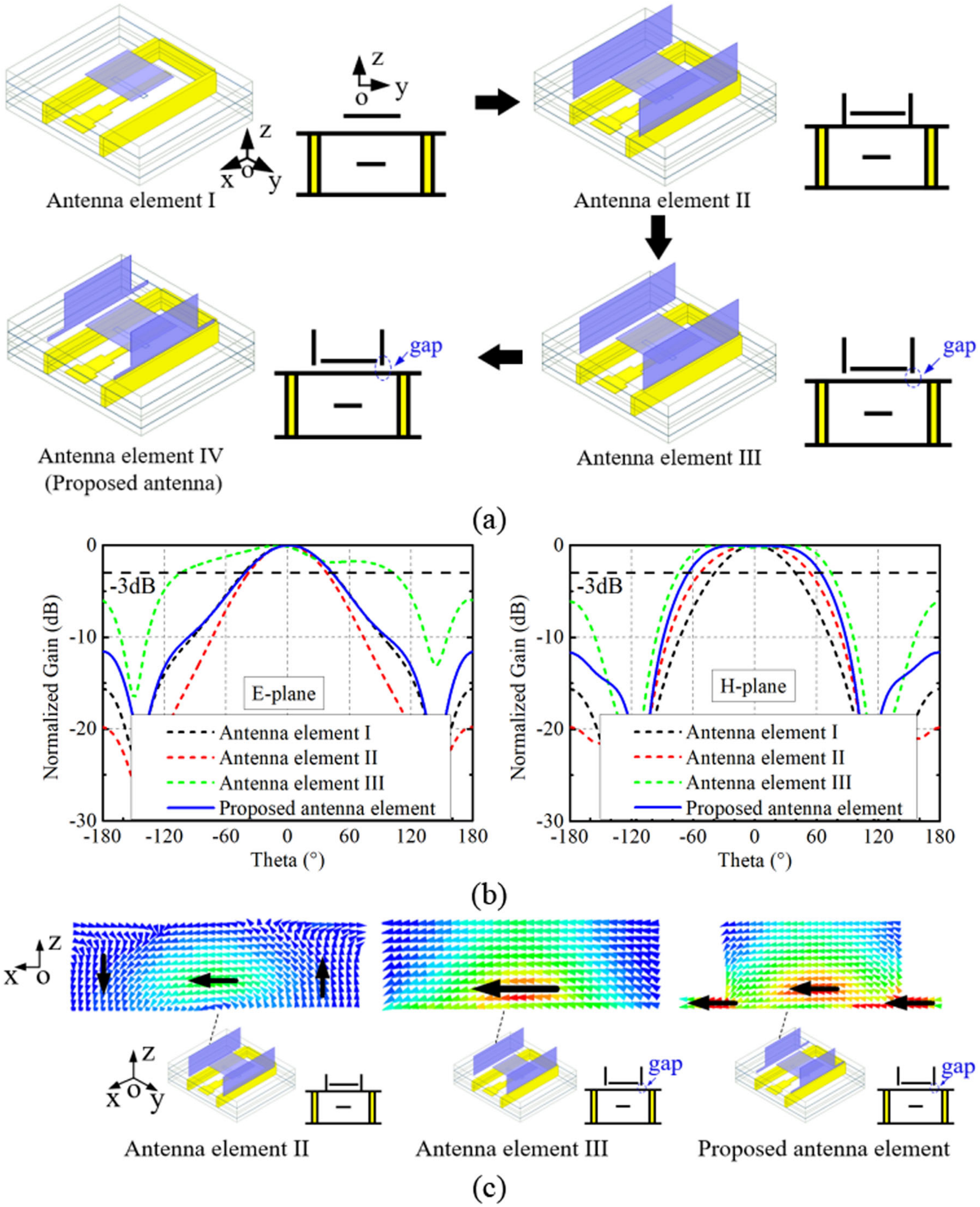

FIGURE 4 | (a) Evolution of the proposed antenna element. (b) Radiation comparison. (c) Current distribution.

Antenna III, the currents on the proposed antenna element are divided into three parts due to the inverted-"T"-shaped design, which can be regarded as three dipoles. As we all know, three-dipole antenna array (Proposed antenna element) shows narrower beamwidth compared with one-dipole antenna element (Antenna III). Therefore, the proposed antenna element shows narrower beamwidth in E-plane compared with Antenna III. Besides, the three parts of current on the proposed antenna are strong and show the same directions, so the proposed antenna also shows wide beamwidth of 128° in H-plane.

Based on the element analysis, the proposed 1×4 series-fed antenna array is designed, and the evolution of the antenna array is given in Figure 5a. Antenna III array is the array based on Antenna element III. Antenna array IV and the proposed antenna array are the arrays based on proposed antenna element. Antenna array IV is fed by straight line, but the proposed antenna array is fed by bend line so the element space is shortened to $0.78\lambda g$ which helps to further reduce the SLL. As shown in Figure 5b,c, Antenna array III suffers from high SLL and low FB ratio which is up to -0.6 dB and low to 2.4 dB due to its wide E-plane element.

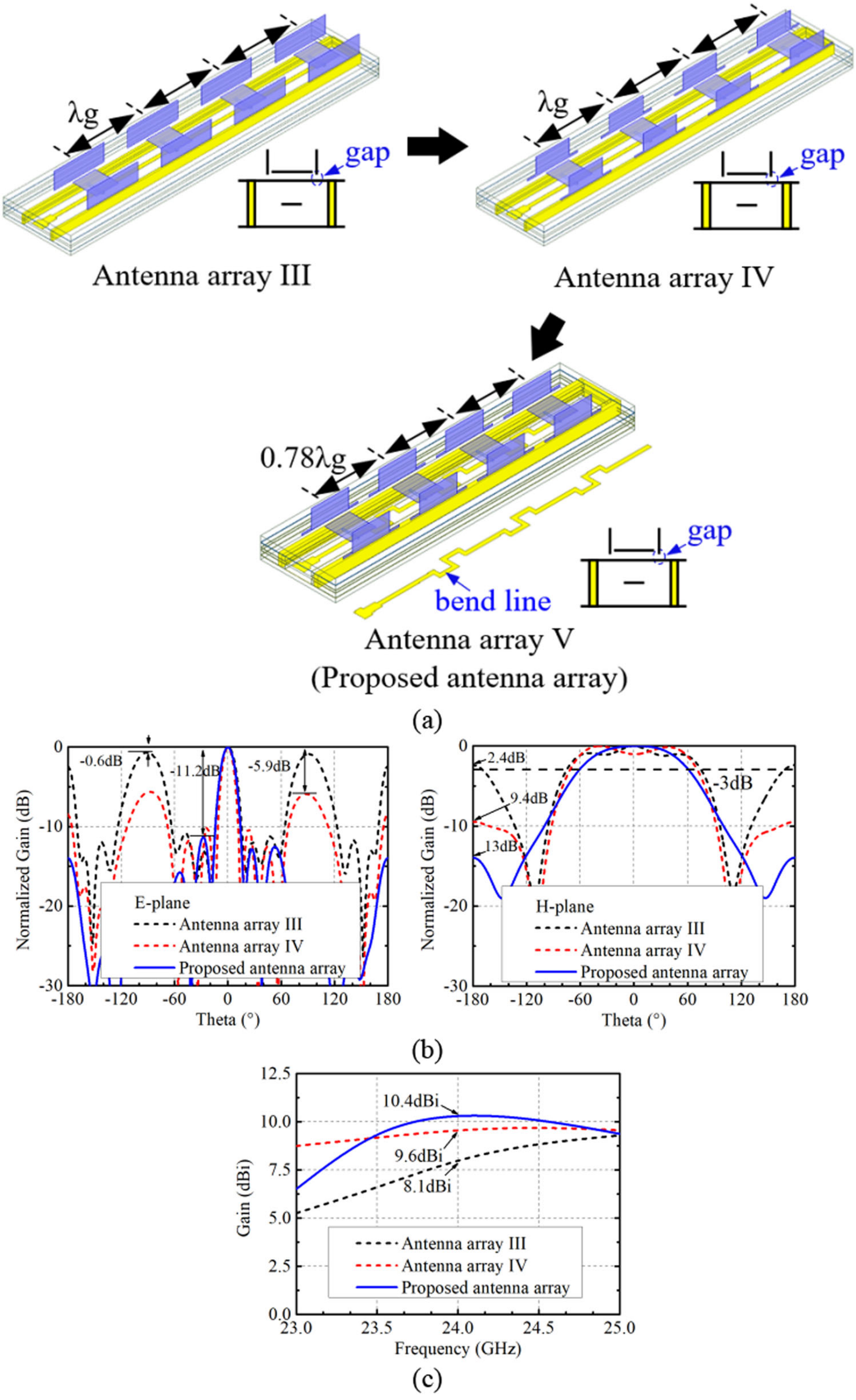

FIGURE 5 | (a) Evolution of the proposed antenna array. (b) Radiation pattern comparison. (c) Gain comparison.

Besides, Antenna array III also shows a low gain. Compared with Antenna array III, Antenna array IV shows better SLL, FB ratio and gain. However, though the proposed antenna element shows narrow beamwidth in E-plane, the SLL of Antenna array IV is higher than −10 dB due to the large element space. Therefore, in the proposed antenna array, the feed line is bent to further reduce the SLL. In the proposed antenna array, its beamwidth of 124° is less than the beamwidths of Antenna array III (150°) and antenna array IV (140°) in H-plane due to its shorten element space and stronger couple between elements.

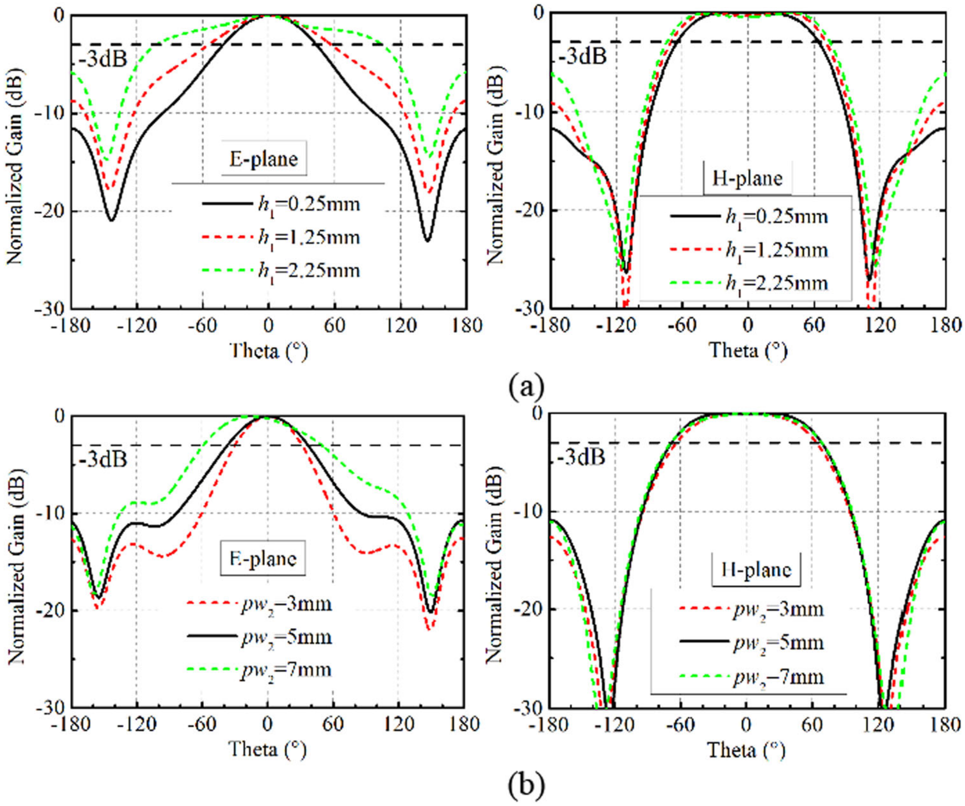

FIGURE 6 | Radiation patterns of the proposed antenna element with different (a) h_1 and (b) pw_2.

c) Parameter analysis:

To show the novelty of this wide-beamwidth method, the key parameters are investigated. As shown in Figure 6, the smaller h_1 and pw_2 is, the narrower beamwidth will be obtained in E-plane, while the beamwidths in H-plane are almost no changed in the proposed antenna element, which shows that the beamwidth in E-plane can be controlled independently. Based on Figure 6a, h_1 should be as small as possible, so the vertical patches are in the shape of inverted "T" but not rectangle and h_1 takes the smallest value of 0.25 mm in Figure 6a. Based on Figure 6b, pw_2 should also be as small as possible. However, when pw_2 is too small, an extra resonant point will be introduced into the low stop-band and affects the filtering performance, so pw_2 takes the middle value of 5 mm in Figure 6b.

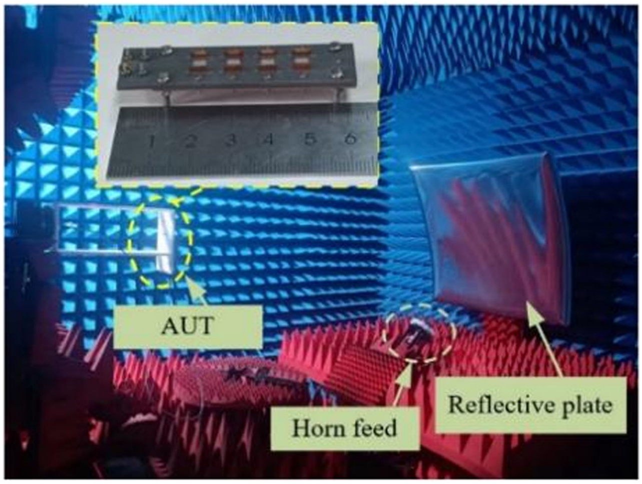

FIGURE 7 | Measurement setup and prototype of the proposed 1 × 4 series-fed antenna array.

3 | Antenna Measurement

To validate the proposed design philosophy, the proposed 1 × 4 series-fed antenna array has been designed, fabricated, and measured. Its simulated model is shown in Figure 1. Its fabrication prototype is also given and measured in the anechoic chamber, as shown in Figure 7. Screws are used to fit the substrates together, and inverted-"T"-shaped vertical patches are installed on both sides of radiation patches.

In Figure 8a, the measured $|S_{11}|$ shows that the proposed antenna array works from 23.7 to 24.4 GHz (−10 dB), and its center frequency is at 24 GHz. The measured $|S_{11}|$ agrees well with the simulated $|S_{11}|$ in the working band but shows fluctuations in low and high bands, which may be caused by the measured lines. In Figure 8b, the measured result shows that the proposed antenna array owns good filtering performance. It has a peak gain of 10.2 dBi and suppression level of 22.3 dB. Besides, it shows wide stop bands in both low and high frequencies. In Figure 8c, the measured result shows that the proposed antenna array owns an obvious filtering response. It has a peak total efficiency of 82.6%, and then drop fast in the low and high band. In Figure 8d,e, the proposed antenna array obtains a wide beamwidth of 140° in H-plane and a SLL of

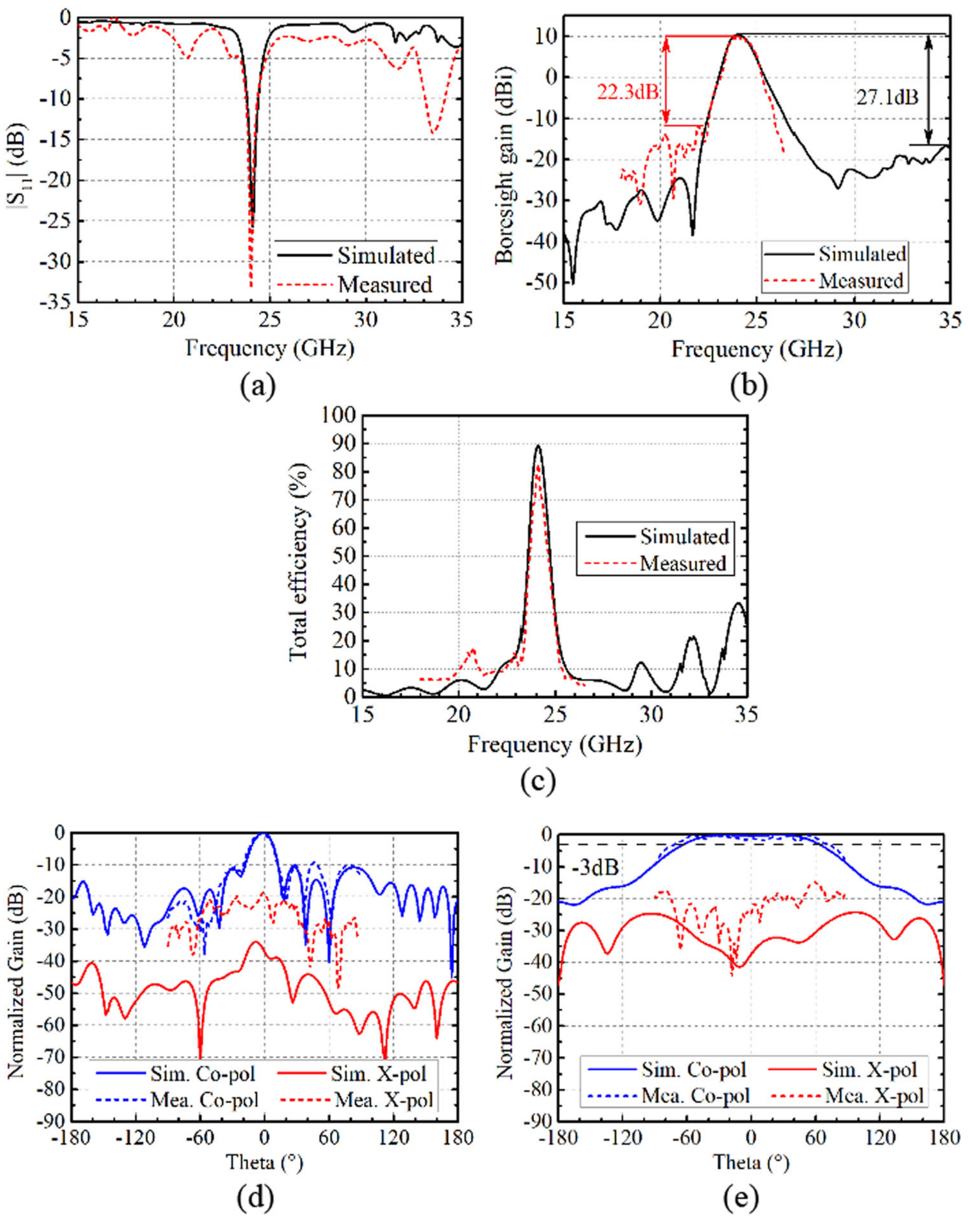

FIGURE 8 | Simulated and measured results of the proposed 1 × 4 series-fed antenna array. (a) $|S_{11}|$. (b) Boresight realized gain. (c) Total efficiency. (d) E-plane. (e) H-plane.

−9.3 dB in E-plane. Besides, its FB ratio is up to 20 dB. The measured X-polarization levels of −15 dB are higher than the simulated ones of −25 dB, which is mainly caused by the test environment setup. Compared with the antenna array without inverted-"T"-shaped vertical patches, the proposed antenna array broadens the beamwidth from 74° to 140° in H-plane. And compared with the antenna array installing rectangular vertical patches (Antenna array III) shown in Figure 5a with SLL of −0.6 dB and FB ratio of 2.4 dB, the proposed antenna array shows lower SLL of −9.3 dB in E-plane and higher FB ratio of 20 dB. In a word, the proposed antenna array shows wide beamwidth while keeps low SLL and high FB ratio.

A comparison with reported high efficiency or filtering or wide beamwidth antennas is also given, as shown in Table 2. In Table 2, most of reported antennas show good performances, such as high efficiency of 90% in [14], high suppression level of 30 dB in [15] and very wide beamwidth of up to 221°. However, most of them show disadvantage in other performances. Compared with the reported antennas, the proposed antenna array features wide beamwidth property of 140° while keeps high efficiency of 82.6% at mm-wave frequency band and high suppression level of 22.3 dB. The proposed antenna array shows competitive and balanced performances.

4 | Conclusion

In this study, the design strategy of one kind of wide-beam patch antenna with high efficiency and filtering properties is proposed based on DSISL. Wide beamwidth performance in H-plane is realized by installing vertical patches on both sides of the radiation patches. Besides, the beamwidth in E-plane can be easily controlled by adjusting some key parameters of vertical

TABLE 2 | Comparison with reported high efficiency or filtering or wide beamwidth antennas.

Ref.	Center frequency f_0 (GHz)	Feed line type	Antenna type	Efficiency	Suppression level (dB)	Gain (dBi)	HPBW (°)
[5]	4.9	SISL	2 × 1 patch antenna	77%	17.6	8.3	N.A
[6]	3.5	SISL	2 × 1 patch antenna	75%	17.8	11.4	N.A
[7]	3.5	SISL	1 × 1 patch antenna	62.35%	18.7	5.53	64.8
[14]	2.5	Coaxial probe	1 × 1 dipole antenna	90%	No filtering	3.8	100
[15]	8.15	Metal waveguide	1 × 1 DR antenna	72%	30	4.8	118
[16]	4	Coaxial probe	9 × 1 patch antenna	N.A	No filtering	13.8	221
[18]	3.25	Coaxial probe	4 × 1 patch antenna	88%	10	10	120
This study	24	DSIDL	1 × 4 patch antenna	82.6%	22.3	10.2	140

patch, while the beamwidth in H-plane is almost no changed. This shows that the proposed antenna has the ability of broadening beamwidth only in one plane or in both planes. Based on the low-loss transmission line DSISL, high efficiency is obtained in the proposed antenna. Filtering performance is realized just by the way of series-fed with an open end. There is no extra filtering circuits and antenna efficiency can be improved further. One 1 × 4 DSISL series-fed patch antenna array is designed, fabricated and measured for demonstration. The measured results show that the proposed antenna array features wide beamwidth of 140°, while maintaining high efficiency of 82.6% and good filtering properties with a suppression level of 22.3 dB. With above advantages, the proposed antenna array is potential in vehicle systems.

Acknowledgments

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Data Availability Statement

Data sharing not applicable to this article as no datasets were generated or analyzed during the current study.

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