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Design of shorted parasitic rhombic array antenna for 24 GHz rear and side detection system

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Abstract: A novel microstrip patch antenna is proposed for automotive application. The antenna design has been investigated through both the parametric study and the demonstration of surface currents on the antenna structure. The surface currents related to the co-polarisation increased, and those related to the cross-polarisation is reduced by attaching shorted parasitic element. The four types of single antenna are designed to compare of gain and cross-polarisation level. The cross-polarisation level of proposed antenna has been reduced by 5.9 dB compared with the rhombic antenna. The rhombic array antenna and proposed array antenna were fabricated and tested for input reflection coefficient and radiation performance. The measured and simulated results have been presented and discussed.

1 Introduction

Making driving safer and more convenient has been one of the key promises for every new car generation during the past three decades [1]. The radar-based sensors have been identified as a key technology to further decrease the amount and severity of traffic accidents, as they are robust against weather conditions and other environmental influences [2–4]. A rapidly growing number of radar-based sensors are being integrated into new vehicles to allow driver assistance functions, such as adaptive cruise control, parking assistant system (PAS), lane change assist (LCA) and blind spot detection (BSD) for comfort and safety [5–6]. About 24 GHz Industrial, Scientific and Medical (ISM) (24.05–24.25 GHz) band was adopted for short range automotive radar sensor, being employed for rear and side detection (RASD) system, such as BSD, PAS and LCA [7, 8].

In spite of dielectric loss and conductor loss, microstrip antenna is preferred for automotive radar system due to their low cost, low profile, simple integration with systems and easy implementation in array structure [9–11]. However, the conventional microstrip antenna has high cross-polarisation level. It has to be improved to reduce the interference since the radar signals from cars travelling in adjacent lane are orthogonally polarised by using 45° polarisation [12, 13].

There are significant efforts going on at both the industry and academic institutions to reduce the cross-polarisation level. The previous research works on reducing the cross-polarisation have been focused on using the multi-layers and low frequency band [14–18], the complex feeding structure [19] and the defected ground structure [20]. However, the multi-layer structure and complex feeding structure have problems, such as the cost efficiency and manufacturing complexity; also the defected ground structure is also inadequate to apply into automotive radar system because the body of vehicle is considered to ground plane. A research on 24 GHz single-layer microstrip array antenna with 45° polarisation has been reported in [21]. It has a cross-polarisation level high up to −7 dB.

In this paper, we propose a novel low-cost microstrip patch antenna with fully covering 24 GHz ISM band (24.05–24.25 GHz). The cross-polarisation level has been reduced by using the shorted parasitic elements. The prototype antennas were fabricated and evaluated for the input reflection coefficient and radiation performances. The measurement and simulation results have been presented and discussed in this paper. The design and geometrical configurations of the proposed antenna have been explained in Section 2. The measurement results have been reported and discussed in Section 3 followed by conclusions in Section 4.

2 Antenna design

2.1 Design of single antenna element

The microstrip patch antenna is preferred choice for automotive radar system due to its well-known merits. The antenna for RASD system typically requires a low cross-polarisation level since the antenna uses the 45° slant polarisation to reduce the interference from the car travelling in an adjacent lane. The signals from other cars are orthogonally polarised by using 45° slant polarisation.

The design based on the rectangular patch antenna, such as Fig. 1*a* is conventionally used in the array antenna system. However, it has the problem in the 45° slant polarisation. When the radiation element and feeding line are rotated to make the 45° slant polarisation, the edge of the rectangular patch antenna becomes closer to the feeding network. It leads to not only additional feeding line but also disadvantage in a sub-array system due to the increased array distance. The array distance is preferable no larger than $\lambda/2$ between the adjacent sub-array elements to improve the angular resolution [22].

The rhombic patch antenna, such as Fig. 1*b* is made from the rectangular patch antenna by rotating the radiation element 45°. The problems being used as the rectangular patch antenna can be resolved by using this rhombic patch antenna. However, the rhombic patch antenna has high cross-polarisation level because the sides of radiation element are diagonal to direction of feeding line.

The high cross-polarisation level reduces the advantage of using the 45° polarisation antenna. Therefore, the parasitic rhombic antenna and the shorted parasitic rhombic antenna are proposed as shown in Figs. 1*c* and *d*, respectively. The parasitic rhombic antenna is made from the rhombic patch antenna by slitting both sides of the rhombic patch. These parasitic elements increase the currents related to the co-polarisation while decreasing the current those related to the cross-polarisation. The short pins at the centre of the parasitic element are inserted to reduce the current those

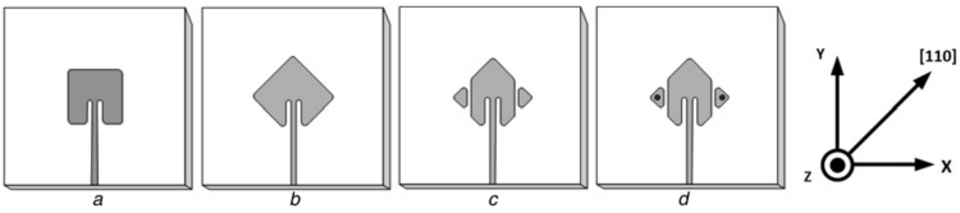

Fig. 1 *Single antenna elements*

a Rectangular patch antenna
b Rhombic patch antenna
c Parasitic rhombic patch antenna
d Shorted parasitic rhombic patch antenna

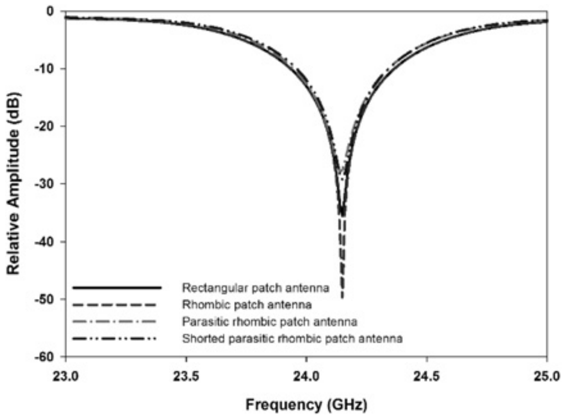

Fig. 2 *Simulated reflection characteristics of four type single antennas*

related to the cross-polarisation. These short pins have been used for interconnection of the top and bottom layers on the substrate.

The single antennas are designed to compare of reflection characteristic, the gain and the radiation pattern. There are designed on a substrate with a dielectric constant of 3.48 (loss tangent = 0.0031) and a thickness of 0.254 mm. The size of the substrate is 10×10 mm^2. The simulated reflection characteristic of single antennas is shown in Fig. 2. The result shows those antennas have similar bandwidth and the proposed antenna keeps the bandwidth compared with conventional patch antenna.

The simulated radiation pattern results of four type single antennas for *XZ*-plane, *YZ*-plane and 45°-plane are shown in Fig. 3. The four type single antennas have 6.1 dBi peak gain and the radiation patterns of the co-polarisation as shown in Figs. 3*a–c* are almost similar. Moreover, there is a slight asymmetry in the co-polarised radiation patterns of *YZ*-plane and 45°-plane because of the feeding line. However, the radiation patterns of the cross-polarisation have

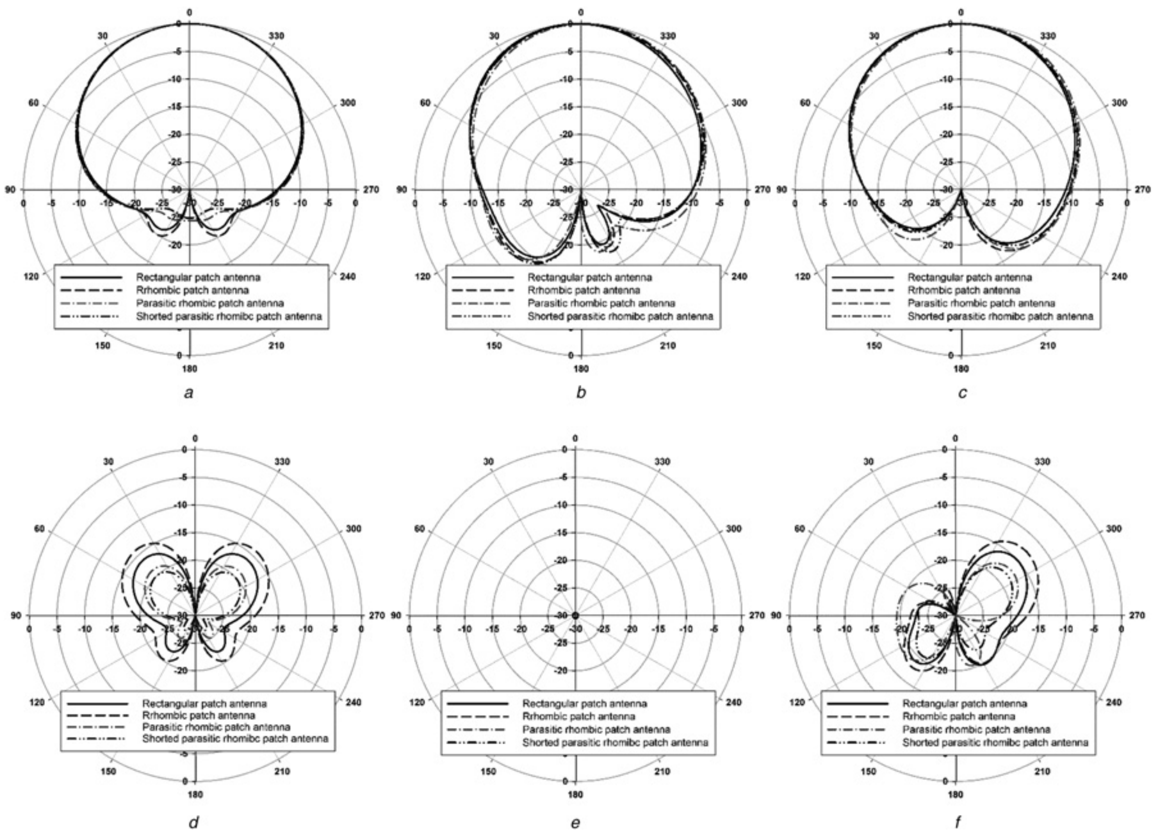

Fig. 3 *Simulated radiation pattern*

a XZ-plane radiation pattern (co-polarisation)
b YZ-plane radiation pattern (co-polarisation)
c 45°-plane radiation pattern (co-polarisation)
d XZ-plane radiation pattern (cross-polarisation)
e YZ-plane radiation pattern (cross-polarisation)
f 45°-plane radiation pattern (cross-polarisation)

Table 1 Comparison of the cross-polarisation level

Antenna	Gain, dBi	Cross-polarisation level (*XZ*-plane), dB	Cross-polarisation level (45°-plane), dB
rectangular patch antenna	6.1	−16.2	−15.0
rhombic patch antenna	6.1	−14.1	−12.8
parasitic rhombic patch antenna	6.1	−18.7	−17.0
shorted parasitic rhombic patch antenna	6.1	−20.0	−18.1

differences. The cross-polarisation level of four antennas have been summarised in Table 1. The cross-polarisation level of the proposed antenna has been reduced by 5.9 dB in *XZ*-plane and 5.3 dB in 45°-plane compared with the rhombic antenna. The cross-polarisation radiation patterns in *YZ*-plane are below −70 dB as shown in Fig. 3*e*, which is much lower than cross-polarisation level of *XZ*-plane and 45°-plane.

The cross-polarisation of radiation pattern has been investigated through the demonstration of surface currents on the antenna structure. The surface current of the rhombic patch antenna, parasitic rhombic patch antenna and the proposed antenna are shown in Fig. 4. The side of rhombic antenna has strong surface current in the diagonal direction ([110]-axis). Those of current have associated with not only the co-polarisation but also the cross-polarisation. However, the surface current in the diagonal direction is reduced by parasitic elements as shown in Fig. 4*b*. The current which is parallel to the co-polarisation is increased by the path those of both main patch and shorted parasitic elements. Moreover, the current inside the parasitic element is cancelled out by short pin as shown in Fig. 4*c*.

2.2 Design of array antenna

The Taylor pattern synthesis is widely used for reducing the sidelobe in array beam pattern. Taking into consideration a linear array of *N*-elements, the normalised weight factors (w_i) for Taylor array

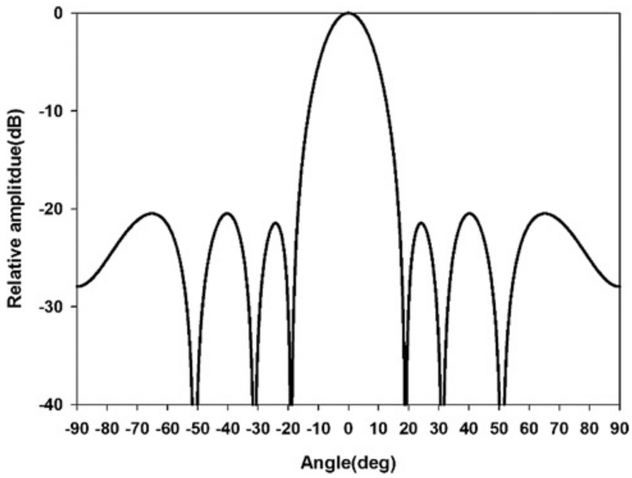

Fig. 5 *Array factor of Taylor pattern synthesis*

pattern synthesis is given by

$$w_i = \frac{1}{N}\left\{1 + 2\sum_{n=1}^{\bar{n}-1} f(n,\ A,\ \bar{n})\cos\left(\frac{2\pi n z_i}{N}\right)\right\}, \tag{1}$$

where the parameter $\bar{n}$ is the number used to define how many close-in sidelobes will be set as a constant sidelobe level. The coefficient parameter $f(n, A, \bar{n})$ represents samples for the Taylor pattern and can be obtained by

$$f(n,\ A,\ \bar{n}) = \frac{[(\bar{n}-1)!]^2}{(\bar{n}-1+n)!(\bar{n}-1-n)!} \times \prod_{m=1}^{n-1}\left[1 - \frac{n^2}{\pm\sigma^2\left(A^2 + (m-1/2)^2\right)}\right], \tag{2}$$

where $A = \dfrac{\cosh^{-1}R}{\pi}$, $\sigma^2 = \dfrac{\bar{n}}{A^2 + (\bar{n}-0.5)^2}$ and $R = 10^{\mathrm{SLL}/20}$.

The parameter sidelobe level (SLL) is the desired sidelobe level in decibel scale, relative to the peak value of the main beam.

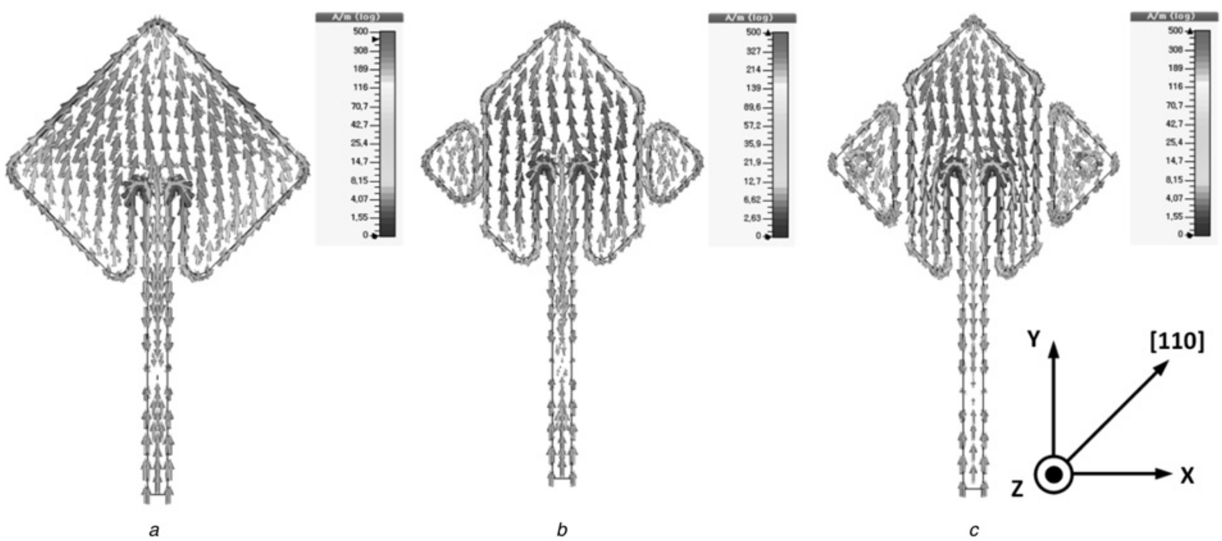

Fig. 4 *Surface current of single antenna*

a Rhombic patch antenna (Fig. 1*b*)
b Parasitic rhombic patch antenna (Fig. 1*c*)
c Shorted parasitic rhombic patch antenna (Fig. 1*d*)

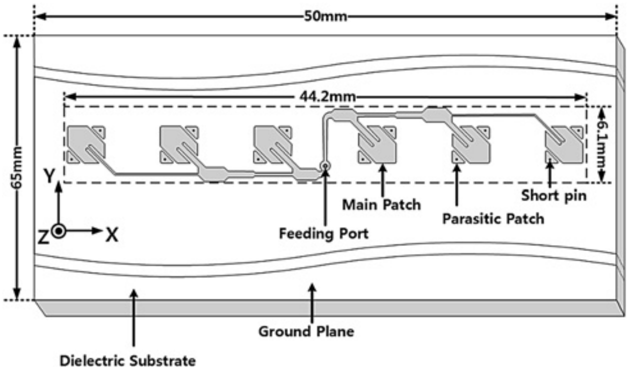

Fig. 6 *Design of the proposed array antenna*

The proposed antenna is designed using the Taylor pattern synthesis with a series-fed configuration to synthesise the radiation patterns in the *XZ*-plane. The weight factors of antenna elements are calculated to reduce the sidelobe level under −20 dB. The calculated weight factor ratio is 1:0.7512:0.5025 from centre element to outside element (all elements are in same phase). The calculated array factor is shown in Fig. 5.

The array antenna is designed to demonstrate the proposed antenna is suitable for RASD system. The structure of the proposed antenna is shown in Figs. 6 and 7. It is designed on a substrate with a dielectric constant of 3.48 (loss tangent = 0.0031) and a thickness of 0.254 mm. The size of the substrate is 50×65 mm^2, it is reasonable for half of the modern RASD system size (considering bi-static system). The proposed antenna occupies a dimension of 44.2×6.1 mm^2 and the total number of elements is 6. The shorted parasitic rhombic antenna is used for the radiating element. The radiating elements are inclined 45° from the feed network for the 45° polarisation requirement of the automotive radar system.

The antenna is fed using a *K*-band Sub Miniature version A (SMA) connector placed at the bottom side of the substrate. Those incident powers are divided into left and right sides and then delivered to each antenna element. The radiation and transmission coefficients of each antenna with a feeding network are calculated from the scattering parameters by an electromagnetic simulation software, computer simulation technology (CST) Microwave Studio [23] to obtain the optimum parameters when the antennas are connected in an array.

Table 2 Physical dimensions of the proposed antenna

Parameter	Value	Parameter	Value	Parameter	Value
AD	8.00	SW	0.23	DW4	1.19
AG	0.20	FW1	0.45	DW5	0.15
AL	3.20	FW2	0.45	DL1	2.20
AW	3.20	FW3	0.15	DL2	3.25
MW	0.30	DW1	1.00	DL3	2.30
FO	1.80	DW2	0.25	DL4	2.55
PL	1.21	DW3	0.50	DL5	7.12

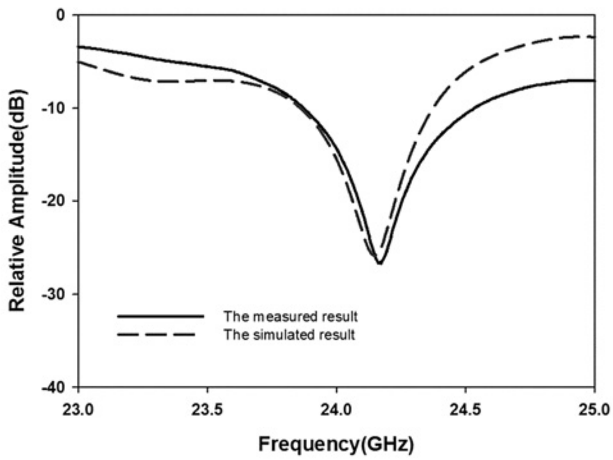

Fig. 9 *Reflection characteristics of the fabricated antennas*

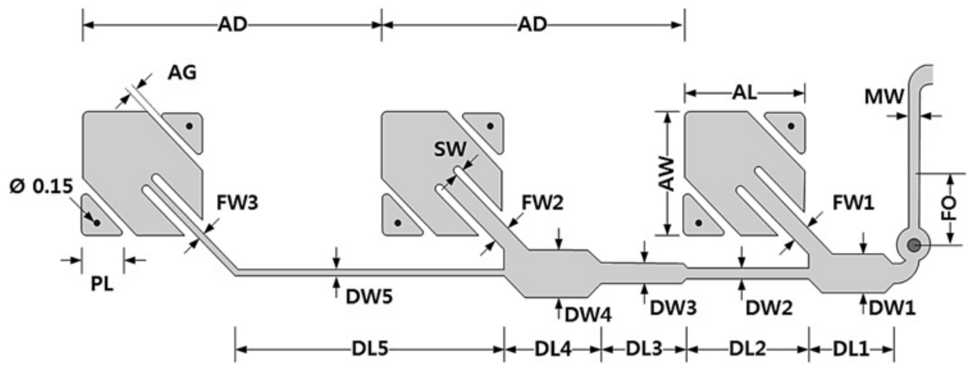

Fig. 7 *Dimensional details of the proposed array antenna*

Fig. 8 *Surface current of the proposed array antenna*

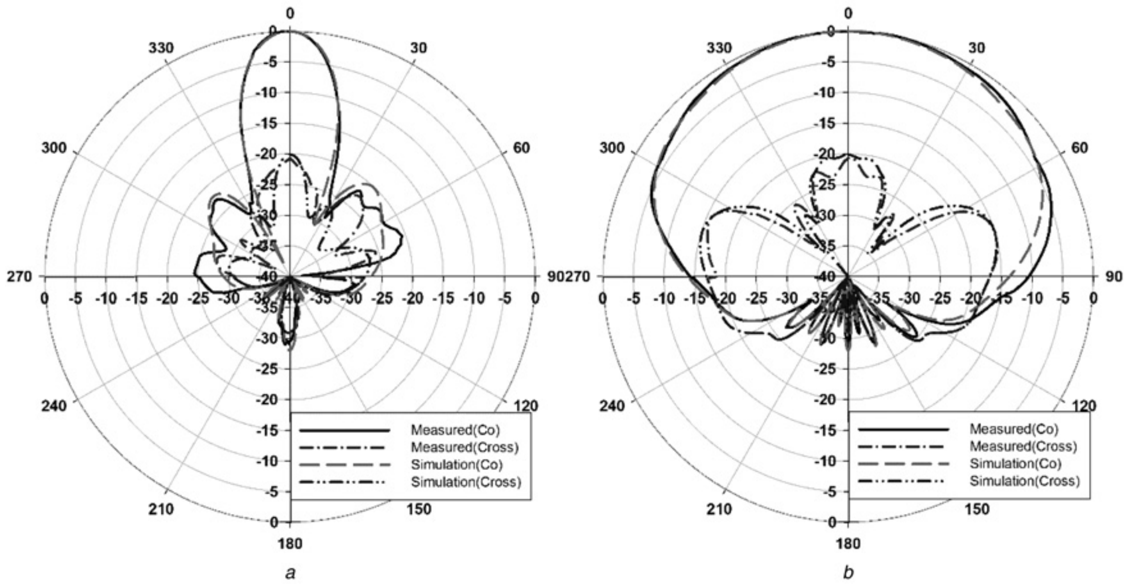

Fig. 10 *Normalised radiation patterns (co- and cross-polarisation) of the proposed antenna*
a XZ-plane
b YZ-plane

The radiating patch elements are arranged in 8 mm (0.645λ) array distance. Those of radiating elements have same dimensions, except only width of the feeding line to adjusting the weighting power. The location of the feed point has been positioned with 1.8 mm ($\lambda_g/4$) offset to make the phases of left and right sides inversely. The difference of delivered power due to length of the feeding line between the left side and right side is small enough to be negligible. The optimised dimensions of the complete antenna structure are listed in Table 2. The unit of all values in the table is in millimetres.

To explain the polarisation, the surface currents on the array structure have been shown in Fig. 8. The direction of strong surface currents can be clearly seen on the 45° slant polarisation. The mutual coupling between the elements and effects of feeding network can increase the cross-polarisation levels, in case of a series-fed linear array.

3 Measurement results and discussion

A prototype antenna was fabricated to verify the simulation results. The prototype antenna has been characterised by measuring input reflection coefficient and the radiation patterns. Comparison of the measured and simulated reflection coefficients for the proposed antenna is shown in Fig. 9.

The fabricated antenna is measured using a KEYSIGHT N5222A network analyser. Both the simulated and measured reflection coefficients are in agreement with each other in the target frequency band, whereas the slight discrepancy, especially in above 24.5 GHz, can be attributed to the manufacturing and assembling errors. The bandwidths have been calculated for −10 dB input reflection coefficient. The measured bandwidth is 660 MHz from 23.87 to 24.53 GHz which is sufficient to cover the ISM band.

The radiation patterns of the prototype antenna are measured using a ±45 inclined standard horn antenna for the polarisation characteristic in a radio frequency anechoic chamber of which dimensions are 16 m (length) × 11 m (width) × 9.5 m (height). The measured and simulated radiation patterns (both co-polarisation and cross-polarisation) are shown in Fig. 10.

There is a good agreement with each other. The difference of delivered power due to the lengths of the feeding line brings the slight asymmetry in the radiation pattern. Increased level of the cross-polarisation components is due to the feeding network in the array structure. The measured gain of the proposed antenna is 11.04 dBi and that of the cross-polarisation level is −20.73 dB. The cross-polarisation level is reduced by 5 dB due to the shorted parasitic patch. The cross-polarisation levels are increased in ±70 due to the current flowing along the large ground. However, it is negligible because those angles are out of angle of detection in automotive application. The sidelobe levels of the proposed antenna are −20.59 dB at 70° in the *XZ*-plane and the front to back ratio of the proposed antenna is −29.10 dB. The half-power beam width of the proposed antenna is 16.2° in the *XZ*-plane and 100.8° in the *YZ*-plane.

4 Conclusions

The design of a microstrip array antenna for RASD system has been discussed in this paper. The design of the proposed antenna is based on a shorted parasitic rhombic patch. The proposed antenna structure simply improves the cross-polarisation ratio up to −20 dB level. The antenna design has been explained through both the parametric study and the demonstration of surface currents on the antenna structure. Measured and simulated input reflection coefficients and radiation patterns have been presented and discussed. As a result, the proposed antenna is a good solution for RASD systems.

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