Customized Compact Dielectric Lens to Improve Double-Ridge Horn Antenna Performance for Automotive Immunity EMC Test

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***Abstract*— In this paper we present a novel dielectric lens design placed in front of a double ridge horn (DRH) antenna to meet the technical requirements for Automotive Electromagnetic Compatibility (EMC) Immunity tests. ETS-Lindgren 3119 DRH is selected as the reference antenna for its superior wide frequency range. In the new lens design, the shape of the conventional Plano-convex lens is modified to accommodate two seemingly contradictory requirements - to increase the gain of the antenna system to meet a target average field strength (100 V/m @ 2m distance), and in the meantime, to maintain the antenna beamwidth for field uniformity (FU) to be better than 6dB over 80% of the total number of frequency points. Additionally, it is desirable to keep the lens size small to reduce the cost and weight. Both numerical simulation and measurements results are shown, indicating that the proposed lens with DRH antenna is well suited for ISO 11451-2 Automotive Immunity tests.**

Keywords—Automotive EMC Immunity test; dielectric Plano-Convex lens, field strength, field uniformity, double ridge horn antenna, ISO 11451-2

I. INTRODUCTION

Double Ridge Horn (DRH) antenna is an attractive antenna for EMC and automotive tests due to its wide frequency band, stable radiating characteristics, and small size [1]-[3]. However, similar to other ultra-wideband antennas (e. g. Vivaldi antennas), DRH antennas can suffer from reduced gains at the low-frequency end. Moreover, in some cases, gains are even insufficient at other frequencies in band (mid and/or high end), as a result, we cannot achieve the required field strength for immunity test (e. g. 100 V/m @ 2m distance). One method to achieve a higher field strength is using antennas with higher gain or applying beam focusing techniques to the reference antenna. However, for many automotive immunity tests, not only achieving a higher field strength is critical, but field uniformity (FU) must also be met. Higher antenna gain is associated with narrower beamwidth which may lead to FU deterioration. This contradictory behavior is one of the most challenging issues in designing antennas for Automotive EMC tests.

One of the widely used techniques to improve the antenna gain is to place a lens in front of the antenna [4]-[6]. Dielectric lens structures are commonly used due to their low loss and wide frequency range of operation. Several different designs are available, namely BiConvex, Plano-Convex, etc. Recently, ETS-Lindgren used a Plano-Convex lens manufactured by Matsing Pte. Ltd. [7] in front of an antenna to extend the quiet zone (QZ) size in a conical tapered chamber [8].

In this paper, we propose a new concept on a modified Plano-Convex dielectric lens in conjunction with a 3119 DRH antenna. The design is optimized for both field strength and FU requirements for ISO 11451-2 automotive EMC test in 1 - 5 GHz frequency range. Without loss of generality, we chose ETS Lindgren 3119 DRH as the reference antenna [9]. However, the proposed design technique is applicable to DRHs of other designs. Using a 3119 DRH antenna alone, because of the lower gain at lower frequency end, it requires impractically high input power to achieve 100 V/m average field (observed at 2 m from the transmit antenna and at 4 locations as required by ISO 11451-2). If we use a conventional Plano-Convex lens in front of DRH in our simulation model, it was observed that although the antenna gain improves drastically, the radiation pattern beamwidth also reduces significantly in higher frequencies such that we are not able to meet the FU requirement. The proposed technique tailors the lens shape so that we not only control the gain, but also the beamwidth at both elevation (E) and horizontal (H) planes. The E- and H-plane performance was affected mainly by defocusing the lens, and in particular the H-plane performance was adjusted further by truncating both sides of

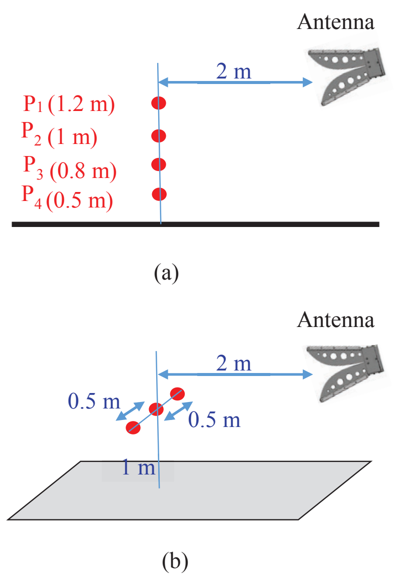


Fig. 1. Automotive EMC Immunity test setup, (a) Four probes average field strength, (b) FU of three probes

TABLE I. AVAILABLE POWER FOR AUTOMOATIVE EMC IMMUNITY TEST (100 V/M ELECTRIC FIELD @ 2 METER)

Frequency range (GHz)	*Available Power (W)*
1 – 2.5	300
2.5 – 4	180
4 – 5	100

lens. As an added benefit, the size reduction leads to lower cost and easier assembly for the DRH and lens combination. The electromagnetic modelling and simulations are done in CST MWS software [10]. The proposed lens was manufactured and provided by Matsing Pte. Ltd. The input power required to achieve 100 V/m average field strength are given in Table I. The requirement of 6dB uniform field over 80% of total number of frequency points was also achieved at three probe positions separated by 50 cm located at 1 m above ground (see Figure 1).

The organization of this paper is as follows. In section II, we discuss the ISO 11451-2 Automotive EMC immunity setup and requirements, and the results of 3119 DRH. In section III, the proposed lens along with simulation modelling results are presented. Experimental data of the proposed lens with 3119 DRH are provided in Section IV. Section IV contains conclusions.

II. AUTOMATIVE EMC IMMUNITY TEST SETUP

A. Test setup and Requirements

The test setup for Automotive EMC Immunity is shown in Fig. 1. Two main criteria need to be met. First, the average field from the four horizontal positions as shown in Fig. 1(a) must be at least 100 V/m. Second, field levels at three vertical locations (Fig. 1(b)) must be within 6dB covering 80% of the total number of frequency points. It should be noted that it is quite challenging

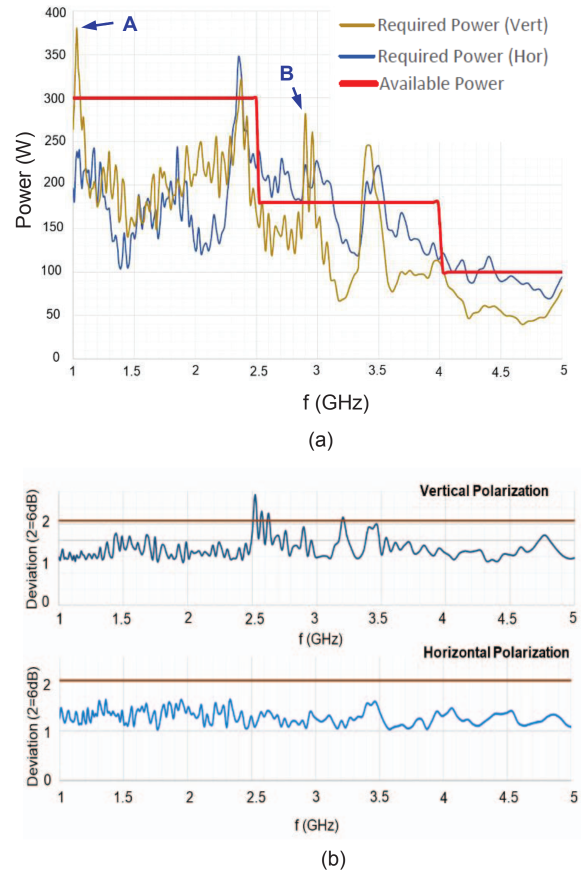
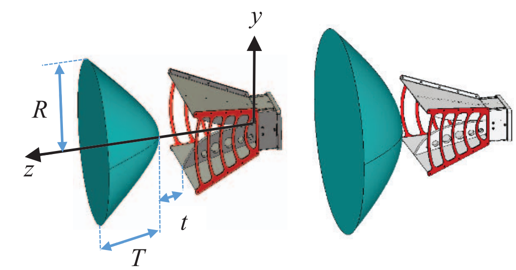


Fig. 2. Experimental results of 3119 DRH antenna, (a) required power for 100 V/m average field strength of four probes., (b) FU.

to maintain the average field strength requirement, especially for horizontally polarized field. Since the field values are measured close to a conducting ground (i. e. 50 cm and 80 cm above ground), the horizontal tangential field is quite low due to the ground cancelation. Therefore, using low- or medium-gain antennas may not provide enough field strength, whereas using a high-gain antenna may address the field strength criteria, but the narrower beamwidth of the higher gain antenna can compromise the FU requirement. Therefore, field strength and uniformity must be balanced.

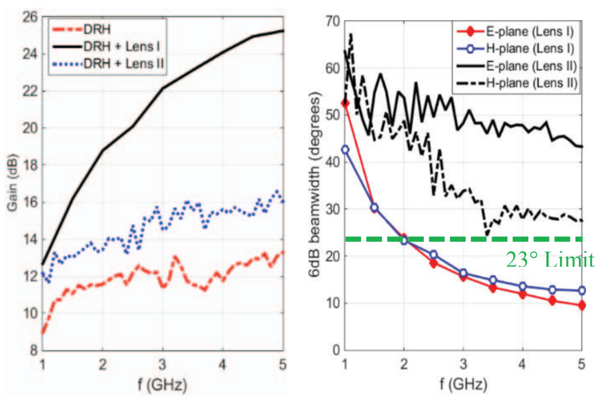
B. Experimental Results of 3119 DRH

According to the test setup shown in Fig. 1, we used 3119 ETS-Lindgren DRH as the reference antenna and the average four probe field strength is measured for both vertical and horizontal polarizations as displayed in Fig. 2(a). Measurements are done inside ETS-Lindgren FACT 3^{TM} anechoic chamber. It shows that the available power is not sufficient to generate 100 V/m average probe field over the low-end of the frequency band (around 1 GHz) and at a large number of frequency points between 2 and 5 GHz. This indicates that the antenna gain is not high enough for these frequencies. For example, as an approximation, if we want to achieve 100 V/m at points A and B (specified in Fig. 2(a)) with a 50 W margin deducted from the available power, the gain differential of the antenna at points A



(a) (b)

Fig. 3. EM model of 3119 DRH with Plano-Convex dielectric lens, (a) Lens I (shorter F), (b) Lens II (longer F).



(a) (b)

Fig. 4. Simulated results of 3119 DRH with lenses, (a) gain, (b) 6dB beamwidth.

and B should be *at least* ΔG = 1.8 dB and 3.3 dB higher, respectively. It can be estimated from

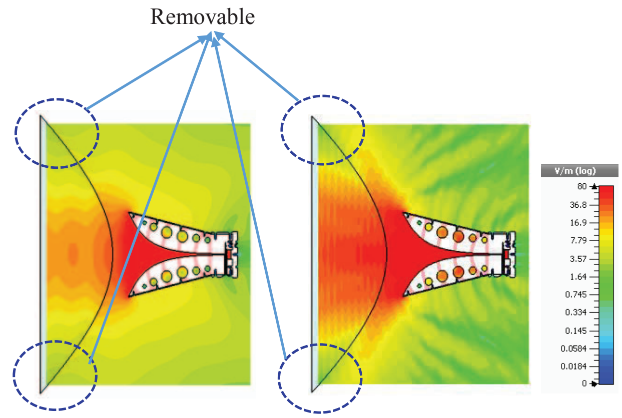
$$\Delta G = 10\log P_{meas} - 10\log\,(P_{max} - \Delta P_{mar}) \qquad (1)$$

where P_{meas} is the measured power, ΔP_{mar} is the margin power, and P_{max} is the maximum available power (e. g. P_{max} = 380 W @ point A and P_{max} = 180 W @ point B). Note that this calculation gives a general guidance, and is based on antenna gain in free space, and only a single probe field value is considered instead of the average of four probe values.

Figure 2(b) shows the measured FU of three probes separated by 50 cm (Fig. 1c) for both polarizations. The test passes FU requirement since more than 80% of frequency points satisfy FU ≤ 6 dB (or = 2) criterion.

III. DRH Antenna with Dielectric Lens

Because the DRH by itself cannot satisfy the field strength requirement with the given maximum available power, we need to improve the gain of DRH. It should be noted other commercially available DRHs with similar size and profile operating in the same frequency range show almost identical gain and radiation characters. Therefore the proposed technique in this section can be applied to other types of DRHs as well.



(a) (b)

Fig. 5. Field distribution at cross section (E-plane) of 3119 DRH with Lens II at (a) 1 GHz, and (b) 5 GHz.

As a starting point, we need to determine how much gain improvement is allowed which can still ensure the FU condition is met. This can be done by analyzing antenna far-field beamwidth based on the setup shown in Fig. 1(b). The far-field region of an antenna is defined by

$$d = 2\frac{D^2}{\lambda} \qquad (2)$$

In which D is the maximum size of the radiator and λ is the wavelength. It is known that for DRH, at very low-end frequency of operation the whole ridges act as radiator, but by increasing frequency the active area is more limited to the throat. Considering the maximum physical size of 3119 DRH (D = 62 cm) and 1 GHz as frequency of interest in (2), the far-field distance d = 2.5 m is obtained. It is quite close to the actual 2.4 m distance between the antenna (feed point) and probes. Hence, it is reasonable to assume the probes are at the far-field of the antenna. At higher frequencies probes would still remain in the far-field. As explained earlier the active radiating region becomes smaller as wavelength gets smaller. Far-field assumption simplifies our analysis, and design process. Under the far field condition, since the deviation of electric field magnitude for three probes should not exceed 6dB, we can relate that the 6dB power beamwidth of the antenna pattern at both E- and H-planes need to be greater than $2tan^{-1}\left(\frac{0.5}{2.4}\right) = 23^{\circ}$.

Figure 3 shows the EM model of 3119 DRH with two different Plano-Convex dielectric lenses. Figure 3(a) is the lens (Lens I) with a shorter focal distance resulting in stronger (more focused) lens (F = 30 cm, T = 27.6 cm, R = 30 cm,), and Fig. 3(b) is the lens (Lens II) with a longer focal distance leading to a weaker (less focused) lens (F = 120 cm , T = 26.6 cm, R = 46 cm,). The dielectric constant of lens is ε_r = 1.6. The profile of Plano-Convex dielectric lens is given by

$$z = \frac{nF}{n+1} + \sqrt{\left(\frac{F}{n+1}\right)^2 + \frac{y^2}{n^2-1}} \qquad (3)$$

where F is the focal distance and $n = \sqrt{\varepsilon_r}$ is the refractive index of the dielectric. The structure is simulated using CST MWS.

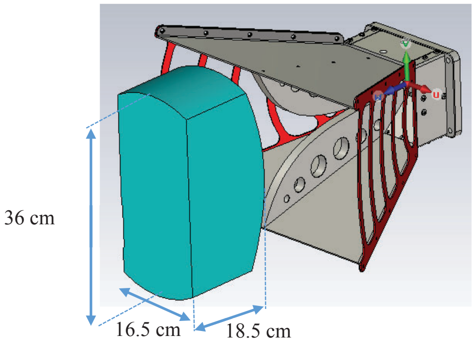
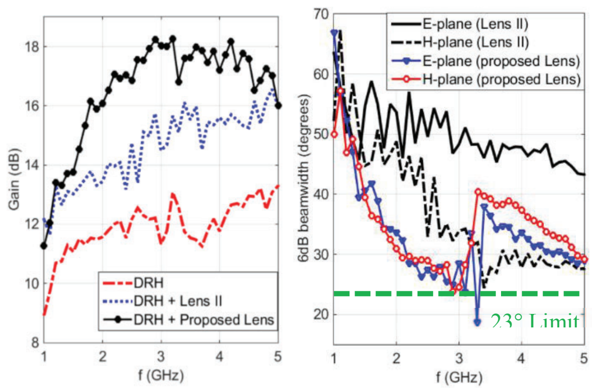


Fig. 6. 3119 DRH with the proposed lens.



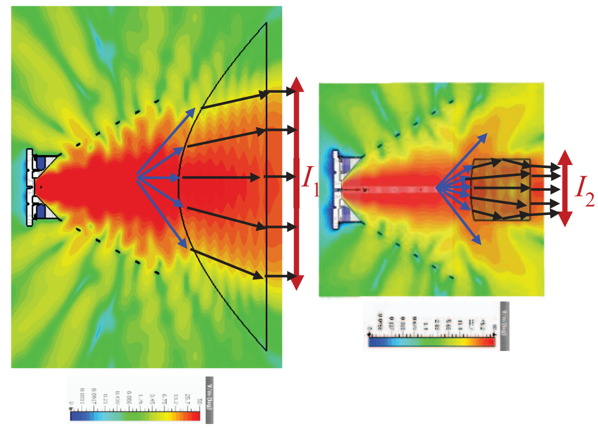
(a) (b)

Fig. 7. Simulated results for 3119 DRH with the proposed lens, (a) gain, (b) 6dB beamwidth

The gain of the DRH antenna with lenses I and II is compared with that of the DRH itself, as shown in Fig. 4(a). It is observed that gain enhancement is achieved over the whole frequency band by using lenses. As expected, gain enhancement is especially significant for Lens I. However, as displayed in Fig 4(b), the 6dB beamwidth of the DRH with Lens I drops below 23° over f > 2.2 GHz, indicating that FU requirement could not be satisfied. One way to control the gain is to defocus the lens as is done in the case for Lens II. Defocusing can be done by increasing the focal distance (F) and/or decreasing the distance between the antenna and lens. In other words, by reducing the ratio of t/F, defocusing can become more noticeable. As a result, the level of gain enhancement is reduced as we see for Lens II. However, there would be two issues with a defocused lens:

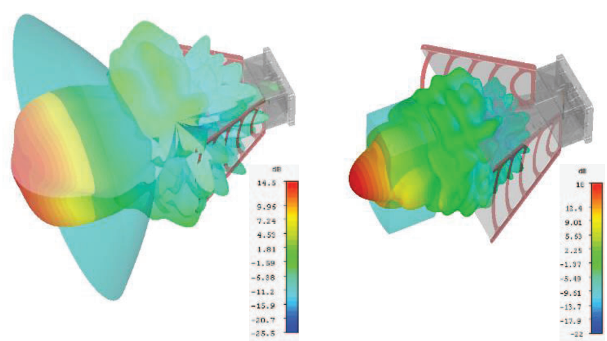
i) As shown in Fig. 4(b), the beamwidth of Lens II approaches the 23° limit for f > 3 GHz. However, we still need larger gain between 2-3.5 GHz (as indicated by the power spikes in Fig. 2(a)). If we further focus the lens (by shortening F), the gain will increase over the whole band and the beamwidth would decrease. It would be challenging to maintain the 6dB uniformity over 80% of total frequency points (since it may fail over f > 3GHz).

ii) Secondly, the size of the lens is large making the assembly difficult to maneuver in the actual use.



(a) (b)

Fig. 8. Field distribution at H-plane at 3 GHz, (a) Lens II, (b) proposed lens.



(a) (b)

Fig. 9. 3D radiation pattern of 3119 DRH with lenses: (a) Lens II, (b) proposed lens.

Here we propose a small dielectric lens by modifying lens II to addressing both size and performance issues. The initial step is to miniaturize the lens. Figure 5 shows the field distribution at x = 0 cross plane for DRH with Lens II at 1 GHz and 5 GHz. It is observed that the field strength is much weaker at the corner areas of the lens. We postulate that we can remove these parts (in a cylinder shape cut) without sacrificing much performance. As a second step, in order to adjust the performance, we remove lens materials on the sides at H-plane as shown in Fig. 6 such that most EM energy enters the lens while the rest passes besides the lens in air. The realized gain and 6dB beamwidth of the DRH with the truncated lens and the original Lens II are compared with those of DRH itself in Figs. 7(a), and (b). It is observed that for the proposed lens the 6dB beamwidth decreases to a minimum point at around 3 GHz and afterward increases (sidelobes become stronger) versus frequency. It can be seen that the gain of the truncated lens is higher (with a peak at around 3 GHz). It is caused by the internal reflections from the lens side walls. This leads to higher gain and smaller illumination area in front of the lens. This is illustrated in Fig. 8 where field distributions of DRH with Lens II and proposed lens are

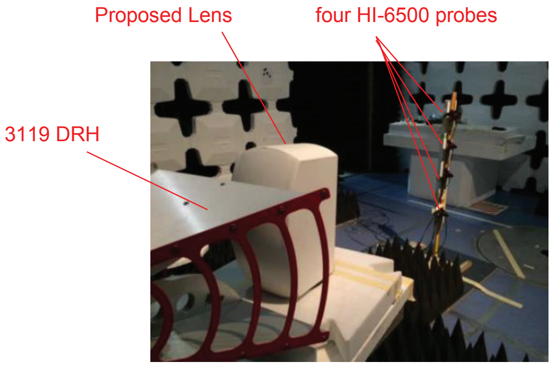


Fig. 10. Measurement setup of four probe average field strength for Automative Immunity EMC test using ETS-Lindgren 3119 DRH and the proposed lens.

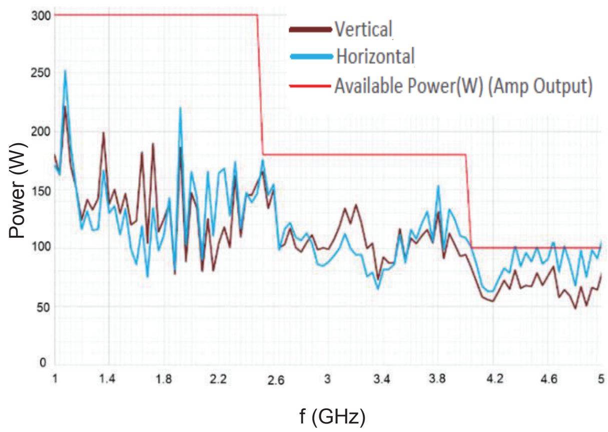


Fig. 11. Measured required power for 100 V/m average field strength of four probes.

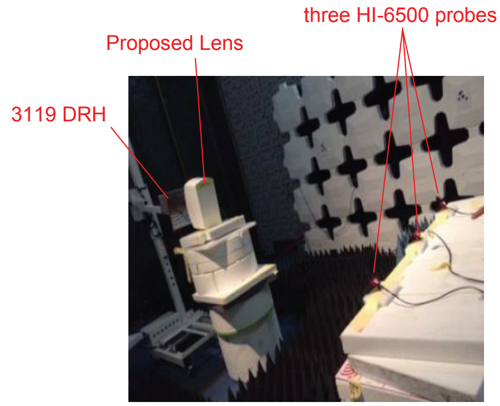


Fig. 12. Measurement setup of FU for Automative Immunity EMC test using ETS-Lindgren 3119 DRH and the proposed lens.

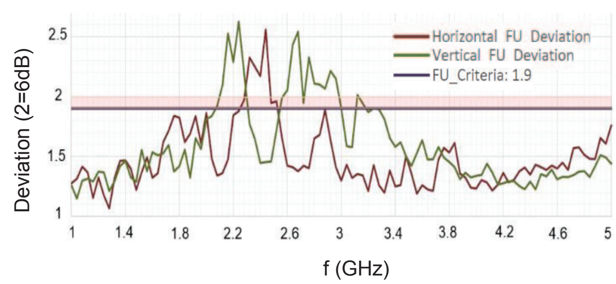


Fig. 13. Measured FU of three pobes.

compared in the H-plane at 3 GHz. The propagated wave in different directions are represented by small arrows indicating that the illumination area for the proposed lens (I_2) is much smaller than that of Lens II (I_1). Side wall reflections in truncated lens direct radial propagation inside the lens toward the front of the antenna, whereas a portion of energy passes through the sides, contributing to sidelobes in far-field pattern. Figure 9 displays the 3D far-field radiation pattern of the two cases (i.e., proposed lens and Lens II) at 3 GHz. Fig. 9 further illustrates that the radiation pattern of the proposed lens is narrower (or smaller illumination area) with some ripples (sidelobes) due to the truncation effect. The amount of lens truncation and lens thickness (T) are optimized to obtain a sufficiently large gain improvement to meet the field strength requirements (as displayed in Fig. 2(a)).

As shown in Fig. 7(b), the 6dB beamwidth of the 3119 DRH with proposed lens drops below 23° at around 3.2 GHz. It is therefore predicated that few frequency points may fail the FU requirement. However, it is expected less than 20% of total number of points will fail because beamwidth increases immediately after 3.2 GHz. As a result, we are able to increase the gain and maintain FU in a desirable manner. The other benefit of the truncation is the noticeable size reduction. The volume of the proposed lens is about 38% of a non-truncated conventional lens (Lens II).

IV. Experiments using Customized Lens

The final lens was manufactured by Matsing Pte. Ltd. The lens is made of a light metamaterial with a dielectric constant of approximately 1.6 over the entire frequency band. The measurement setup using four electric field probes is shown in Fig. 10. The field probes are ETS-Lindgren HI-6005 [11] which measure three x-, y-, and z-components of electric field at each probe location. Measurements are performed inside an ETS-Lindgren FACT 3^{TM} anechoic chamber. The antenna is placed at 1.46m height from ground and 2.1 m away from the probes. The average electric field of four probes is measured for both vertical and horizontal polarizations as displayed in Fig. 11. It is observed that we can achieve 100 V/m of average electric field with much less power, especially over 1-4 GHz rang compared to using DRH itself (Fig. 2(b)). Since the lens was not attached to the DRH with high precision in the prototype tests (it was supported in front of the antenna on a polystyrene foam block), there might be some slight misalignments which accounted for the less than expected improvement at high frequency end. We observed that a small adjustment in alignment and geometrical positions affects the high frequency performance.

The FU setup is shown in Fig. 12. Three HI-6005 probes are located at 1 m above ground and 50 cm away from each other.

The measured field uniformity is presented in Fig. 13. Instead of using 6dB as the FU criteria, we elected to use 5.5 dB to provide some safety margin. The percentage of failed number of points for vertical and horizontal polarizations based on 5.5 dB criteria is 20% and 3%, respectively, indicating that DRH with the proposed lens can meet the FU requirement. As discussed and predicted by the simulation in Fig. 7(b), it can be seen that FU is compromised around 3 GHz with affordable number of failed points.

V. CONCLUSION

A new compact dielectric lens is proposed to improve the performance of double-ridged horn (DRH) antennas to meet field strength and field uniformity requirements for ISO 11451-2 Automotive Immunity EMC test from1 to 5 GHz. It is shown that with the proposed lens combined with an ETS-Lindgren 3119 DRH, we can satisfy 100 V/m average field strength and 6dB field uniformity (over 80% of total points) requirements. In contrast, the 100 V/m field strength cannot be obtained with the DRH antenna itself. The lens structure is modified and optimized with considerations to both the gain and beamwidth. This was done by a combination of defocusing and truncation of lens. The size of the proposed lens is also reduced significantly to be only approximately 40% of a conventional Plano-Convex dielectric lens. The design process was aided using CST MWS. Experimental result validated the design concepts.

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