A Cone Shaped Tapered Chamber for Antenna Measurements Both in Near Field and Far Field in the 200 MHz to 18 GHz Frequency Range and Extension of the Quiet Zone using an RF Lens

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***Abstract*–**Traditionally, tapered chambers are constructed using a square based pyramidal shaped taper. The taper is then shaped into an octagon and finally transformed into a cylindrical launch section. This approach is related to the manufacturability of different absorber cuts. This paper introduces a chamber where the conical shape of the launch in continued throughout the entire length of the tapered chamber. The results of the free space VSWR test over a 1.5 m diameter quiet zone (QZ) are presented at different frequencies. The conical taper appears to have a better illumination wave front and better QZ levels even at frequencies above 2 GHz than the standard traditional approach. This design was implemented in Singapore and the actual chamber was designed to have a secondary near field range for planar and spherical scans. As with all antenna chambers, as the frequency increases, the usable or far field illuminated QZ is reduced. At a 12 m distance from the feed to the turntable, the quiet zone at 8 GHz is reduced to 45 cm. The chamber includes a near to far field range to allow the use of the chamber at higher frequencies when testing electrically large antennas. Another solution implemented to extend the quiet zone at high frequency is to use a large dielectric lens to improve the phase distribution of the field. A light weight, broadband lens with a diameter of 2 m was developed by Matsing Pte Ltd. The parameters of the lens were specially customized for the tapered chamber built. The RF lens, weighing just 35 kg, has a focal length of 10 m. It was installed in front of the turn table. The performance of the tapered chamber with the RF lens is presented. The usable far field QZ was increased by using a dielectric RF lens that allows for electrically larger antennas to be measured in the tapered range of the chamber.

***Index Terms*–**Antenna range design, metamaterials, quiet zone, RF lens, and tapered chamber.

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I. INTRODUCTION

Tapered anechoic chambers have been around for almost 50 years [1-2]. The reason for the introduction of these chambers was the issues present on rectangular chambers at frequencies below 500 MHz [3-4]. At lower frequencies, the antennas used in an antenna measurement range become physically very large. These antennas can be difficult to handle inside an anechoic chamber. Less directive antennas are used. These less directive antennas will radiate more energy to the side walls, ceiling and floor of the chamber. To reduce the reflections, thicker absorbers are required. To accommodate the thicker absorbers, the chamber must be larger. Tapered anechoic chambers were introduced to solve this low frequency issue. Instead of trying to eliminate the specular reflections into the quiet zone, the specular area is brought closer to the measuring antenna and the specular reflections are used to create the illumination in the QZ [2, 5]. Traditionally, tapered anechoic chambers were built having a square based pyramid as the taper (see Figs. 1 and 2). To better accommodate different feed antennas, the square section may be changed to a cylindrical cross section taper. These changes in cross section require a lot of special cuts of absorber to make the transition from the conical section to the square section as smooth as possible. As was reported in [2-5], the absorber reflections are used to create the illumination in the QZ.

Fig. 1. A typical tapered anechoic chamber.

The concept presented in this paper introduces a conical taper. The entire tapered structure maintains a constant angle and a circular cross section. Figure 3 shows a picture of the conical tapered chamber of the new type of chamber. The tapered section shown in Fig. 3 is about 10 m in total length. The results for the free-space VSWR [6] of the range are presented in the next section where they are compared with similar chambers that use the traditional design.

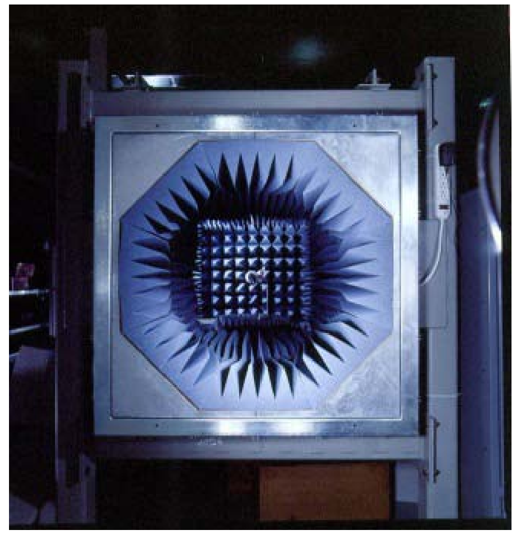

Fig. 2. Shaping from square to octagonal cross-section at the feed section.

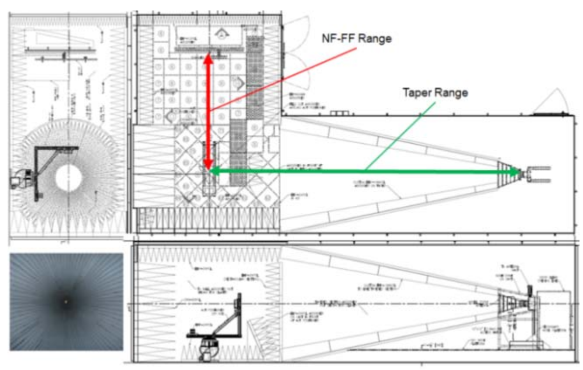

Fig. 3. The conical tapered anechoic range.

II. MEASURED RESULTS

The manufactured chamber, using the conical taper, had its QZ scanned using the free space VSWR tests [6]. The tests were performed at a series of frequencies from 200 MHz up to 18 GHz. The chamber was lined with 60" (152 cm) curvilinear absorbers on the back (i.e., receive) wall and a combination of 24" (61 cm) pyramidal absorbers and 36" (91.44 cm) on the sidewalls, floor and ceiling. The tapered section has a specially cut wedge material that lines the tapered section from the feed location to the QZ area. The wedges ranged from 18" (45.72 cm) at the QZ end to 8" (20.32 cm). Figure 4 shows a picture of the conical treatment.

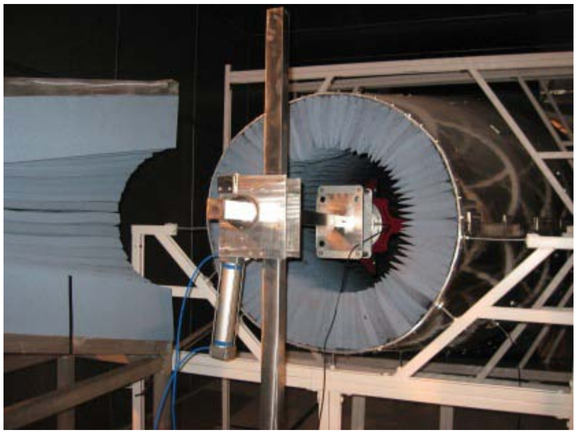

Fig. 4. The tapered section seen from the feed location. The tapered section was built inside an RF shielded room to avoid outside interference during measurements.

The source antenna was an ETS-Lindgren model 3164-06 dual linearly polarized open boundary quad-ridge horn [7], rated from 300 MHz to 6 GHz. In this application, the antenna was used from 200 MHz. Attenuators were used at the feed of the antenna to reduce the effects of the high VSWR. The QZ was scan with an ETS-Lindgren model 310 6B dual ridge horn. The scanning antenna and source antenna are shown in Fig. 5.

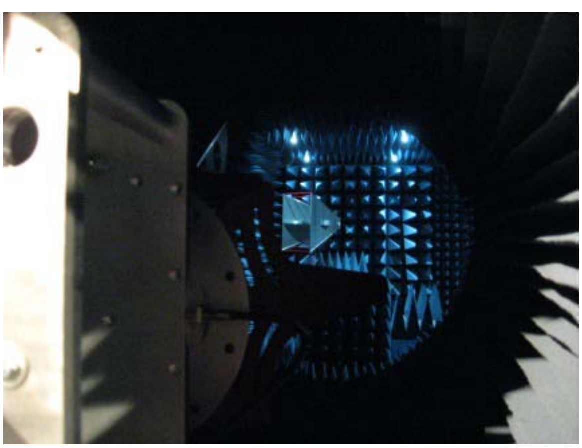

Fig. 5. The scanning antenna at the QZ viewed from a point right behind the source antenna at the apex of the taper.

Figure 6 shows the reflectivity levels of the QZ versus direction for horizontal and vertical polarizations. Results are shown for 200 MHz, 400 MHz, 800 MHz, and 1,000 MHz. All these results were measured with the source antenna at a fixed position in the apex of the taper. Commonly, the antenna is moved as frequency changes to maintain the phase center close to the reflections and keep a QZ illumination free of ripples [3-4].

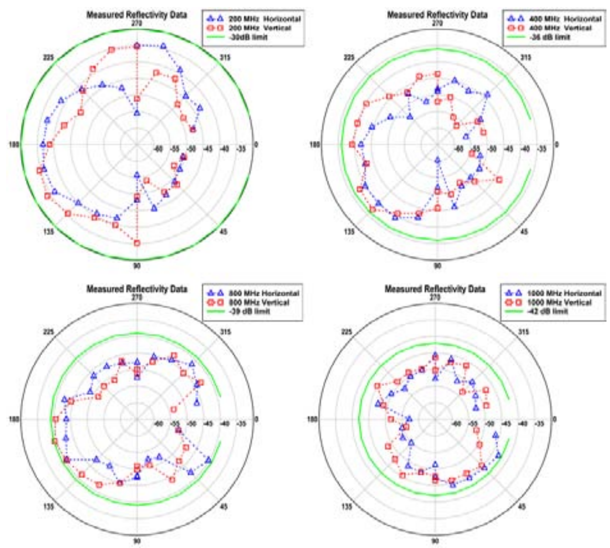

Fig. 6. Reflectivity results for the conical tapered chamber.

For frequencies above 2 GHz, a different horn, an ETS-Lindgren 3164-05 dual linearly polarized open boundary quad-ridge horn, rated from 2 GHz to 18 GHz, was used. For scanning the QZ, a series of standard gain horns were used with gains ranging from 10 dBi to 20 dBi. Additionally, since a smaller horn was used as the source, the horn was positioned inside an extension of the conical taper. Figure 4 shows one of the two halves that made up this high frequency extension.

Figure 7 shows the results of the scans at high frequencies. As discussed in [5], tapered chambers are better suited for low frequencies and care must be taken to properly position the source antenna. However, it is possible to use them at these high frequencies once the chamber is properly characterized.

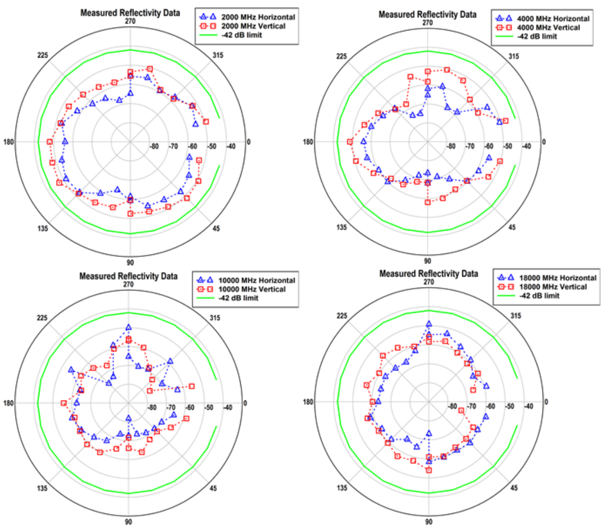

Fig. 7. Reflectivity levels in the QZ versus angle at four different frequencies.

III. COMPARISON WITH TRADITIONAL CHAMBERS

Comparison with traditional chambers is difficult. There are no two identical chambers with the exact same absorber treatment with the only difference being the taper geometry. So a qualitative comparison is done. When compared with traditional chambers, there seem to be some advantages in the new design. In traditional chambers, antennas with gains of 16 dBi and above are required to get adequate illumination at the QZ. It appears to be one of the advantages of the conical taper that lower gain antennas can be used to illuminate the QZ. At 10 GHz, the source antenna has a directivity of 12 dBi [7]. On the other hand, the conical quad ridge horn used in many traditional tapered anechoic chambers has a directivity of 14 dBi at 10 GHz.

The open boundary ridge horn was successfully used in the conical chamber design. However, in the past, when it was used in a traditional chamber, a smooth amplitude taper was not achieved as seen in Fig. 8. In Fig. 9, a comparison of the reflectivity of the conical tapered chamber and a traditionally implemented chamber is shown for 400 MHz. At this frequency, there is a slight difference on the back wall reflectivity between the chambers (180°) but this is related to the difference in absorber treatment between the chambers. One can notice the large variation in horizontal polarization as the direction changes from 15° to 60° on either side of the source antenna. The reflectivity swings by about 10 dB. These variations are not seen in the conical tapered chamber.

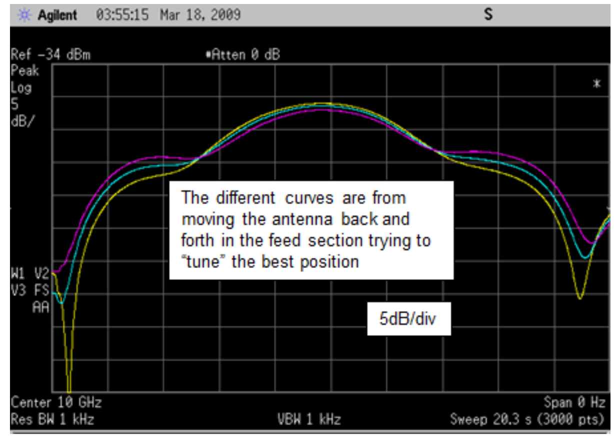

Fig. 8. Data for a transverse scan of a traditional chamber using the same horn used in the conical design.

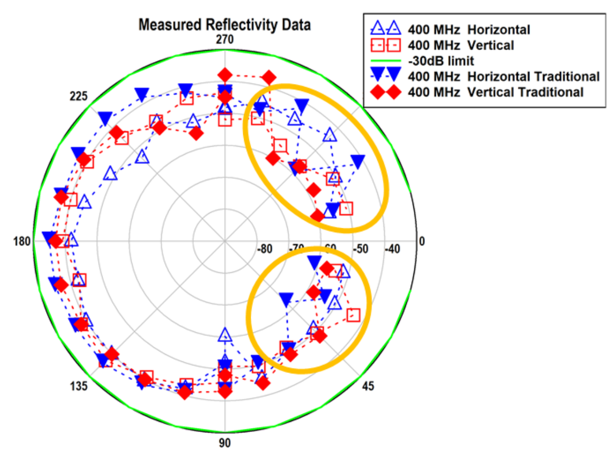

Fig. 9. Comparison with a traditional chamber.

The chamber was implemented with two ranges, a far field tapered range and an NF-FF planar and spherical range. Figure 3 shows the chamber plan with the two ranges. The antenna under test uses the same positioner for both ranges, and the QZ is the same for both ranges. For the spherical range the probe is located between the QZ and the planar scanner on the opposite wall. The planar scanner can be used for testing high gain arrays. These arrays can be positioned at the QZ or closer to the scanner mounted on a tripod depending on the frequency of operation or the size of the scanner.

IV. INCREASING THE QZ SIZE

As mentioned above, the tapered chamber is used to overcome some of the limitations of the standard rectangular chamber for antenna testing at lower frequencies. However, like in rectangular chamber, the size of the quiet zone in a tapered chamber reduces significantly as the frequency increases. For example, the tapered chamber installed at the National University of Singapore (NUS) has a quiet zone of 1.4 m at 500 MHz but only 45 cm at 8 GHz. To increase the quiet zone at the higher frequencies, it was proposed to integrate a customized RF lens inside the chamber. The authors are not aware of other methods to increase the quiet zone without physical alterations to the original chamber.

V. DESIGN OF THE RF LENS

The design of the RF lens is based on the principle of optical refraction to transform a spherical wave from a point source to a planar wave. By precisely controlling the dielectric constant of the lens, the focal length of the lens can be customized based on the lens aperture.

A plano-convex RF lens was designed and integrated into tapered chamber at NUS (see Fig. 10). Its focal length, *f*, of 10 m is equal to the distance between the source antenna and the end of the tapered section of the chamber. The diameter of the lens was chosen to be 2 m in order to cover a large area of the aperture of the tapered chamber while allowing easy mobility of the lens inside the chamber.

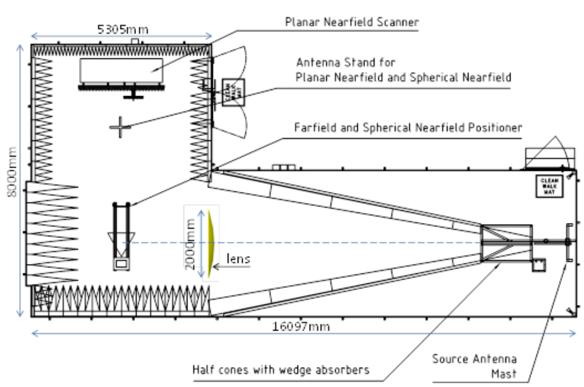

Fig. 10. Placement of lens in tapered chamber.

The lens has a comparatively high ratio of the size of the planar wave front to the lens diameter (a factor of about 0.7 *D*, where *D* is the diameter of the lens). Hence, a 2 m diameter lens can produce a 1.4 m plane wave-front. The profile $P(x,y)$ of the lens was designed using the following equations [8],

$$x = \frac{r}{\tan\theta_m} - \frac{y}{\tan\theta} \quad (1)$$

where

$$y = \rho \sin\theta, \quad (2)$$

and

$$\rho = \frac{f(\sqrt{\varepsilon}-1)}{\sqrt{\varepsilon}\cos\theta - 1}, \quad (3)$$

with

$$h = \frac{r}{\sqrt{\varepsilon}-1}\left(\frac{1}{\sin\theta_m} - \frac{1}{\tan\theta_m}\right). \quad (4)$$

The variables are defined in Fig. 11.

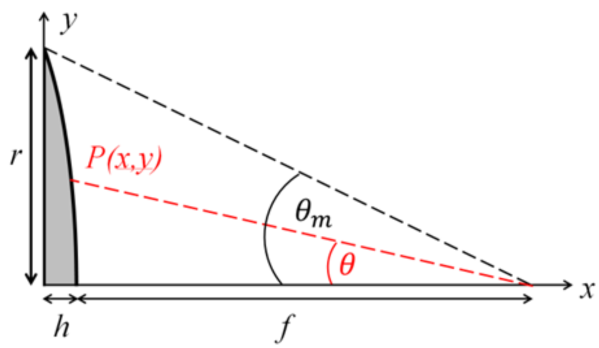

Fig. 11. Lens geometry.

Due to the proposed size of the RF lens (2 m), the lens cannot be manufactured with traditional dielectric materials as it will be difficult to control the dielectric permittivity throughout the lens to a high degree of accuracy. Furthermore, if the lens is manufactured with traditional dielectric material, it will be extremely heavy (≈ 1,000 kg), making it difficult to install and requiring a special support structure, which may cause undesirable diffractions.

To overcome these challenges, a new low-loss, light weight metamaterial manufactured by Matsing Pte Ltd was used. The material allows the control of the dielectric permittivity to a high degree of accuracy. It has extremely low-loss ($\varepsilon'' < 10^{-4}$). It slow density (40 kg/m^3) means that the 2 m lens weighs only 35 kg, allowing the lens to be portable and easily installed. Furthermore, the material is isotropic and broadband, so that the lens is operable for both vertical and horizontal polarizations on a range of frequencies.

VI. NUMERICAL ANALYSIS

The performance of the designed lens was first evaluated using FEKO. A half-wavelength dipole was placed at the focal length of the 2 m lens. The focal length corresponds to the distance (of 10 m) between the feed and aperture of the tapered chamber. The field was observed at a vertical plane at 2 m (corresponding to the quiet zone region) on the other side of the lens. For simplicity, the lens and the dipole were simulated in free-space without the tapered chamber as the primary aim of the simulation was to ensure that for the given length of the taper, the lens would provide the best possible illumination. Including the chamber with its absorbers in the simulation model would drastically increase the problem size and complexity beyond the capability that the numerical package could handle at these high frequencies.

Figure 12 shows the predicted fields (for a quadrant) at 8 GHz. The circles in the plots represent the outline of the 2 m lens. Cuts of the fields along the lens diameter are shown in Figs.13 and 14 for 2 GHz and 8 GHz, respectively. The fields of the dipole in the absence of the lens are superimposed in the figures for reference. For ease of comparison, the magnitudes are normalized to their respective mean values while the phase without the lens is normalized to its peak value and the phase with the lens is normalized to its mean value. From these figures, it is observed that the field with the lens deviates slightly from the dipole field due to mainly diffraction from the lens. However, the lens reduces significantly the large phase variation of the dipole field. Thus, the designed lens was shown to produce a reasonably good plane wave in the vicinity of the quiet zone of the tapered chamber.

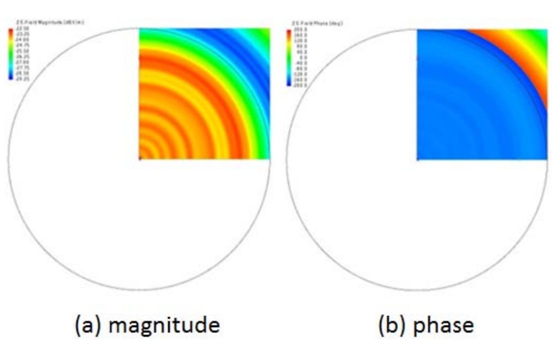

Fig. 12. Predicted field distribution at 8 GHz, both in (a) magnitude and (b) phase.

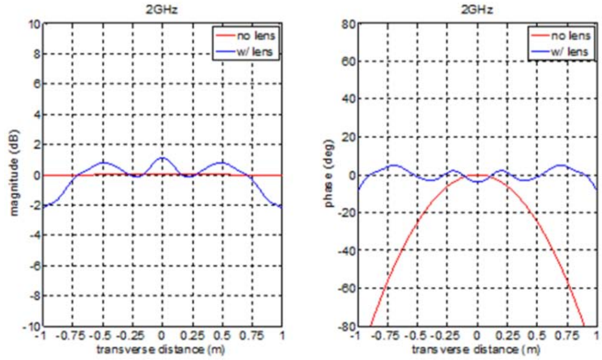

Fig. 13. Computed field distribution at 2 GHz.

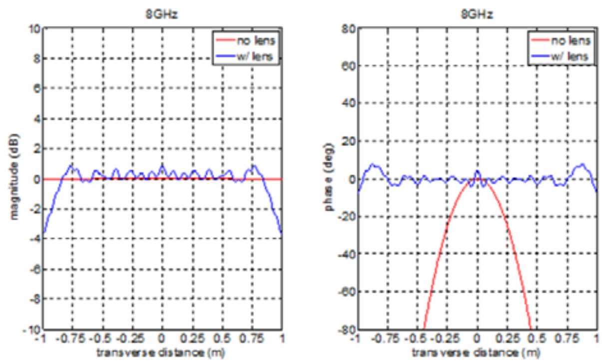

Fig. 14. Computed field distribution at 8 GHz.

VII. MEASURED PERFORMANCE

The manufactured lens is installed at the aperture of the tapered chamber as shown in Fig. 15. A special frame was made from low reflection material to hold and easily place the lens in the tapered chamber.

For the field measurement of the quiet zone of the tapered chamber, a simple linear scanner was set up as shown in Fig. 16. A broadband dual-ridged horn was used as the probe antenna. The field was measured along an axis transverse to the lens axis at about 2 m from the lens. The lens was then removed and the measurement repeated.

The results at 2 GHz and 8 GHz are shown in Figs. 17 and 18, respectively. The magnitudes and phases are “normalized” in the same manner as the numerical results were. Note that the transverse distance in these figures, unlike that of Figs.13 and 14, is relative to the start of the measurement position at 0 m. The plots show that the lens has indeed improved the phase significantly without adversely affecting the amplitude. The size of the quiet zone for ±10° phase variation with and without lens is summarized in Table I. Thus, the lens has significantly improved the phase performance of the tapered chamber.

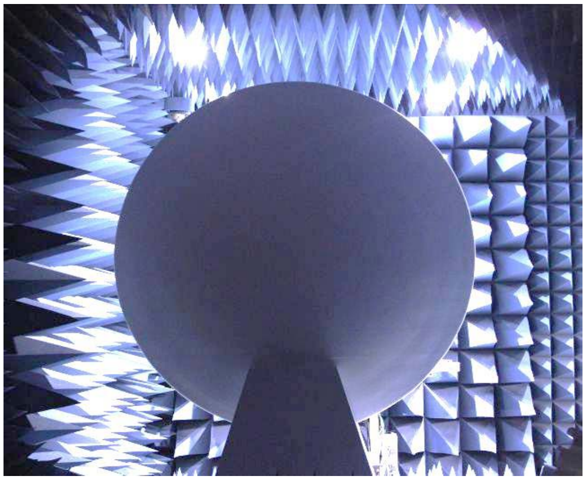

Fig. 15. View of the lens from the source antenna.

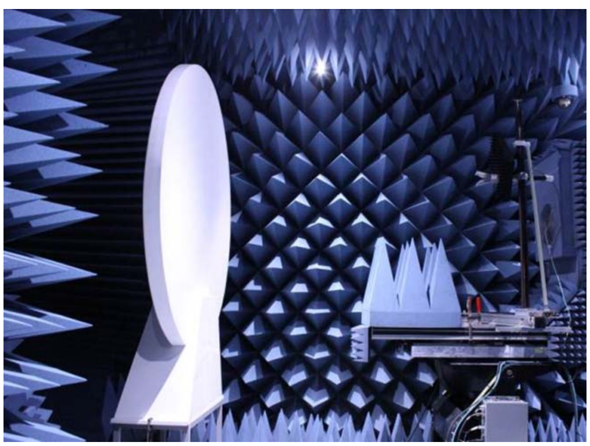

Fig. 16. The QZ scanned with the lens in place at the end of the taper section.

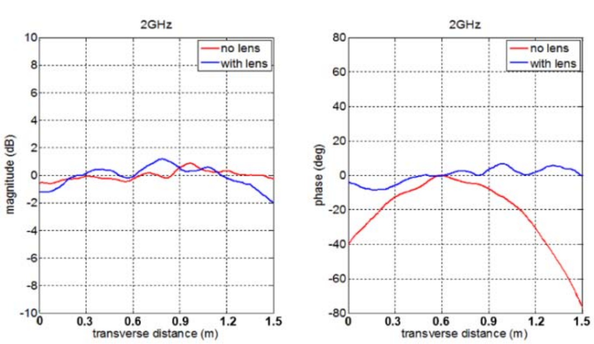

Fig. 17. Measured field distribution at 2 GHz.

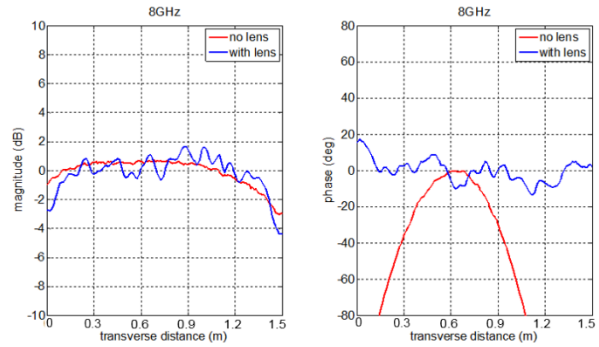

Fig. 18. Measured field distribution at 8 GHz.

Measurements were also done from 500 MHz to 1 GHz to confirm that the lens did not affect the original quiet zone of the chamber at low frequency.

Table I: Size of quiet zone (in cm) for ±10° phase variation with and without lens.

***f* (GHz)**	**2**	**4**	**6**	**8**	**10**
Without lens	95	65	55	45	40
With lens	140	140	140	140	140

VIII. CONCLUSION

The paper has introduced a new approach to the manufacturing of tapered anechoic chambers. This approach has shown that it provides good QZ reflectivity results over wide frequency ranges. Additionally, the new design appears to allow the use of lower directivity antennas than the ones used in traditional chambers. These lower directivity antennas provide a smaller amplitude taper across the QZ, which reduces the errors during gain measurements. With the addition of the RF lens, the phase of the quiet zone of the tapered chamber at higher frequency (2 GHz–10 GHz) has been improved significantly. The lens provides a quick and easy way to enhance the performance of the tapered chamber, allowing the user to easily install it due to its light-weight construction. The NUS tapered chamber with the RF lens is now capable of far-field measurement of relatively large antennas from 0.3 MHz to 10 GHz.

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Dr. Rodriguez is the author of more than fifty publications. Dr. Rodriguez holds patents for hybrid absorber and dual ridge horn antennas. Dr. Rodríguez is a Senior Member of the IEEE and several of its technical societies, including the EMC society where he serves as Distinguished Lecturer of the Society for the years 2013 and 2014. He is also a Senior Member of the Antenna Measurements Techniques Association (AMTA). He served as Meeting Coordinator and Vice-President in the board of directors of AMTA. Dr. Rodriguez is an active member of the Applied Computational Electromagnetic Society (ACES). He is an Associate Editor of the ACES Journal and has served as a reviewer for the ACES Journal and for the Journal of Electromagnetic Waves and Applications (JEWA). Dr. Rodriguez currently serves as the Dean Appointee to the School of Engineering Advisory Board at the University of Mississippi. Dr. Rodriguez is a Full member of the Sigma Xi Scientific Research Society and of the Eta Kappa Nu Honor Society.

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In 1995 Dr. Matitsine joined the research and development group at Singapore Technologies Aerospace as Technical Director and later holding the position of Chief Engineer. In parallel, since 2001, Dr. Matitsine has also been working at Temasek Laboratories of the National University of Singapore as an Adjunct Senior Principal Research Scientist. He is also the Chairman and Technical Director of MatsingPte Ltd.

His research interests include electromagnetic materials, metamaterials, smart materials, multi-beam antennas, antenna measurement techniques, and most recently, lightweight, large-size RF Lenses. He has more than 60 publications in these areas, including four patents.

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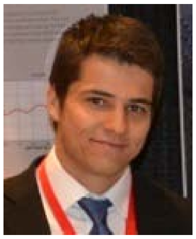
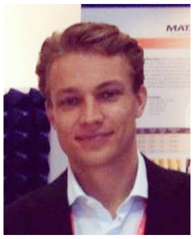
Pavel Lagoiski received his B.S E.E. from the National University of Singapore in 2010. Since then he has held the position of Engineer at Matsing Pte Ltd. His current research interests include antenna measurement system and RF Lenses.



Leo Matytsine received his B.Sc. from the University of Southern California in 2009 and his MBA from the Australian Global School of Management in 2013. He has been with Matsing Pte Ltd since 2009 and currently holds the position of Director. His interests include RF convex lenses and antenna measurement systems.



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