Progress In Electromagnetics Research M, Vol. 26, 1–9, 2012

ANALYSIS OF MULTIPLE WEDGES ELECTROMAGNETIC WAVE ABSORBERS

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Abstract—To improve the reflection performance of absorbers used in anechoic chambers, several different electromagnetic wave absorber geometries similar to conventional wedge absorber structures are proposed in this study. Design basics are examined by using the reflection and absorption of electromagnetic waves. The return loss characteristics of each absorber structure which is illuminated by a TE polarized plane wave have been obtained using well-known simulation software for several incidence angles. Comparisons of the simulation results of the conventional wedge and proposed absorbers are presented. The results show that new absorber shapes provide better absorption characteristics than a conventional wedge across almost all frequency ranges especially for normal and near normal incidence cases.

1. INTRODUCTION

Accurate measurement of EMC according to published EMC Standards has always been a major problem. These measurements are performed in anechoic chambers which have similar conditions to open field in a closed area. All chamber walls must be covered by an absorber structure to provide open field conditions in this closed area. The absorption performance of the absorber structure is important to suppress unwanted signals such as reflections and interference. Wedge and pyramid arrays and other absorber structures are used to cover

Received 12 July 2012, Accepted 24 August 2012, Scheduled 6 September 2012

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chamber walls. Low reflection over a wide frequency range and a small thickness are preferred for the absorbers [1].

The first researches on absorbers were conducted at the Naamlooze Vennootschap Machinerieen, Netherlands in 1936, but the first study on the development of a pyramidal shape absorber was performed by Neher during his work at the MIT Radiation Laboratory [2–4]. To achieve a broadband absorber, the idea of gradually tapered materials dominated in the 1945–1950 period. Many individuals and organizations studied this idea during the same period [5, 6]. Various surface geometries such as pyramids, cones, hemispheres and wedges were studied experimentally.

The bandwidth and absorption performance of the absorber depend on various parameters. These parameters are incidence angle of the electromagnetic wave, geometry of the absorber, dielectric permittivity and magnetic permeability of the material used in the absorber [7]. The main purpose of research on absorber shapes is to provide EM energy absorption via multiple reflections in cases of both normal and oblique incidence [8].

In this study, a new absorber shape which has better absorption performance than a conventional wedge while the other parameters remain the same is developed. A structure similar to a wedge which has multiple tip points to obtain a narrower apex angle is proposed. The theoretical background is examined in Section 2. Conventional wedge and new shaped absorbers were analyzed at frequency range of 0.5–3 GHz by using HFSS simulation software for normal and oblique incidence cases of TE mode plane waves. A comparison of results is presented in Section 3.

2. THEORY

2.1. Reflection and Refraction of EM Waves

The plane wave incidence to free space dielectric boundary is pictured in Fig. 1. Medium 1 is assumed as free space with dielectric permittivity ε_0 and magnetic permeability μ_0. Medium 2 has complex dielectric and magnetic parameters.

Incident and reflected fields for the TE polarized plane electromagnetic wave are as follows:

$$\mathbf{E_i} = E_i\hat{\mathbf{y}}e^{-j\beta_0(x\sin\theta_i+z\cos\theta_i)} \tag{1}$$

$$\mathbf{H_i} = \frac{1}{\eta_0}E_i\left(-\hat{\mathbf{x}}\cos\theta_i+\hat{\mathbf{z}}\sin\theta_i\right)e^{-j\beta_0(x\sin\theta_i+z\cos\theta_i)} \tag{2}$$

$$\mathbf{E_r} = E_r\hat{\mathbf{y}}e^{-j\beta_0(x\sin\theta_r-z\cos\theta_r)} \tag{3}$$

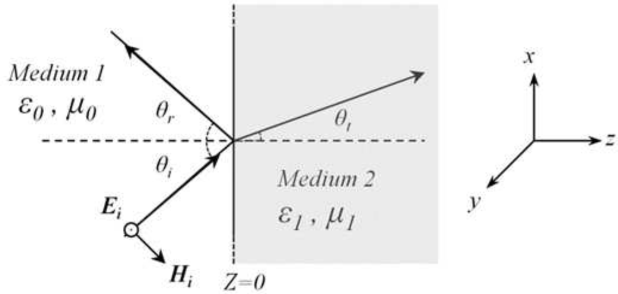


Figure 1. Plane wave incidence on lossy dielectric.

$$\begin{aligned}
\mathbf{H_r} &= \frac{1}{\eta_0} E_r \left(\hat{\mathbf{x}} \cos\theta_r + \hat{\mathbf{z}} \sin\theta_r\right) e^{-j\beta_0 (x \sin\theta_r - z\cos\theta_r)} && (4)\\
\mathbf{E_t} &= E_t \hat{\mathbf{y}} e^{-\gamma_1 (x \sin\theta_t + z \cos\theta_t)} && (5)\\
\mathbf{H_t} &= \frac{1}{\eta_1} E_t \left(-\hat{\mathbf{x}} \cos\theta_t + \hat{\mathbf{z}} \sin\theta_t\right) e^{-\gamma_1 (x \sin\theta_t + z \cos\theta_t)} && (6)
\end{aligned}$$

where θ_i, θ_r and θ_t are incidence, reflection and refraction angles, respectively. η_0 and η_1 are wave numbers of free space and Medium 2, respectively. β_0 is the phase constant in free space and γ_1 is the propagation constant in Medium 2. From the continuity of tangential components at the boundary and phase matching, the reflection coefficient for the TE polarization case is written as:

$$\Gamma_{TE} = \frac{\eta_1 \cos\theta_t - \eta_0 \cos\theta_i}{\eta_1 \cos\theta_t + \eta_0 \cos\theta_i} \tag{7}$$

Note that the incidence and reflection angles are equal. According to Snell's law of reflection, the angle of reflection is equal to the angle of incidence, $\theta_i = \theta_r$ [9].

2.2. Apex Angle Dependence on Multiple Reflections and Absorption of EM Energy

Wedge geometry provides multiple reflections in the direction of the wedge apex similarly to pyramid geometry. As a natural result of Snell's law of reflection, the wedge surface provides more reflections than a flat surface due to the angle between the propagation direction of the EM wave and the surface normal. Reflection of the EM wave many times between the wedge surfaces before being scattered back outward results in a loss of EM wave energy on each reflection. Absorbed portion of the EM wave energy for a single reflection can be given as:

$$A = \frac{1}{2}\sigma E^2 + \frac{1}{2}\omega\varepsilon_0\varepsilon_R E^2 + \frac{1}{2}\omega\mu_0\mu_R H^2 \tag{8}$$

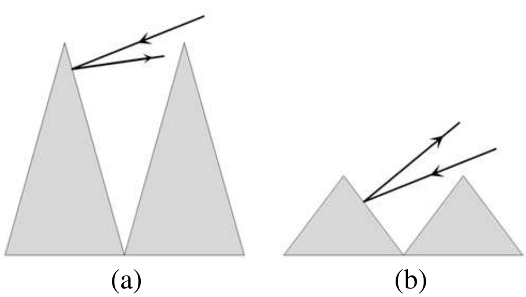
where A (W/m^3) is the electromagnetic energy absorbed per unit volume. According to this equation, electromagnetic wave absorption materials absorb the energy as magnetic loss and convert that energy to heat [7]. For the case of multiple reflection between the surfaces of the wedge absorber, the electromagnetic wave decays with each reflection. Reflected portion of the incidence electromagnetic waves is determined by the reflection coefficient of the absorber surface. The total reflection coefficient for multiple reflections is given as follows [10, 11]:

$$\Gamma = \Gamma_1\Gamma_2\Gamma_3\ldots\Gamma_n \tag{9}$$

where Γ_i is the i-th reflection coefficient, $i = 1, 2, 3, \ldots, n$. A large enough number of these reflections will cause a very low net scattered wave overall [12]. The advantage of pyramidal geometry on reflection was discovered and a pyramidal absorber was patented by Neher in 1945 [3]. Pyramidal absorber geometry was first used for practical measurement by the MIT Radiation Laboratory [4].

From the information given above, it is clear that a wedge with a narrower apex angle will provide more reflections than a wedge with a wider apex angle.

Fig. 2 shows how the apex angle of a wedge absorber affects the number of multiple reflections of the electromagnetic wave. The EM wave's incidence to the wedge absorber in Fig. 2(a) will provide more reflection than the wedge absorber in Fig. 2(b). It is clear that the number of reflections of the incident wave depends on the apex angle of the wedges for a certain incidence angle.



(a) (b)

Figure 2. Reflection of electromagnetic waves for different apex angles of wedge structures, (a) wedges with a narrow apex angle, and (b) wedges with a large apex angle.

2.3. Multiple Wedges

To obtain more reflection without changing the base width and material, increasing the height of the wedge absorber is needed (i.e., a wedge absorber with a narrower apex angle).

The new absorber shapes shown in Figs. 3(b), (c) and (d), which are a combination of multiple wedges, are proposed to achieve this goal. Fig. 3 shows a conventional wedge absorber and the proposed alternative absorbers. These new absorber shapes have the same height, base width and material as the conventional wedge absorber but they have multiple tip points with narrower apex angles. The apex angles of the multiple tips are equal to each other and provide more reflections than a conventional wedge.

2.4. Frequency Limitation

The reflection behavior of low frequency EM waves from absorber structures which have electrically small dimensions is different. It depends on the ratio between the wavelengths of the waves and the physical dimensions of the absorber array. For higher frequencies, the wavelengths of the waves are small compared to the physical dimensions of the absorber array. The absorber structure is considered as a rough surface and the EM wave is reflected between the surfaces of the absorber. For lower frequencies, the wavelengths of the waves are large compared to the physical dimensions of the absorber array. The absorber structure is considered as a rough surface and the EM waves are reflected similarly to a flat surface.

The low frequency limit for the reflection from the absorber can be determined by using Rayleigh's roughness criterion. This

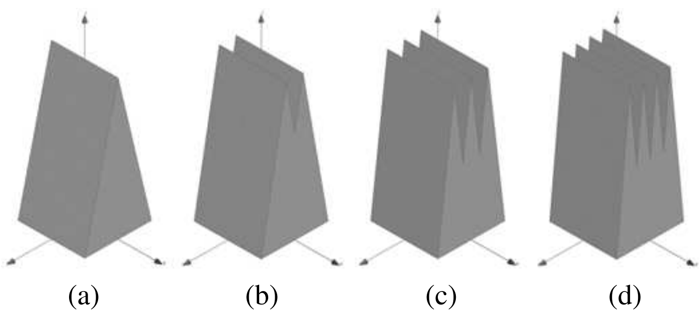


Figure 3. Unit cells of different wedge absorber arrays, (a) wedge arrays, (b) double wedge arrays, (c) triple wedge arrays, and (d) quadruple wedge arrays.

criterion was first studied by Lord Rayleigh and is commonly used as a tool for determining the degree of electromagnetic roughness of a surface [13–15]. According to this criterion, if the phase variations of the wave reflected by the surface are less than $\pi/2$, the waves interfere constructively, and the surface can be considered as slightly rough or nearly flat. If the phase variations of the wave reflected by the surface are greater than $\pi/2$, the waves interfere destructively, and the surface can be considered as rough [16]. Phase variations depend on the wave number inside the medium (k_1), height variation ($\delta\zeta_A = \zeta_A - \langle\zeta_A\rangle$) and the incidence angle of EM wave (θ_i) and can be written as $\delta\Phi_r = 2k_1\delta\zeta_A\cos\theta_i$. $\langle\zeta_A\rangle$ is the mean value of the rough surface height.

3. SIMULATION RESULTS

In this section, a comparison of simulation results between a conventional wedge absorber and double wedge absorber arrays is presented for different incidence angles of plane electromagnetic waves. They are analyzed by using a well-known commercial simulator Ansoft's HFSS software. HFSS utilizes a 3D full wave finite element method to compute the electrical behavior of high frequency components. Results are obtained for different absorber structures and different incidence angles of EM waves. A lossy dielectric material which has relative dielectric permittivity $\varepsilon = 1.46 + 0.35i$ for 1000 MHz is used [17]. Magnetic permeability is assumed as in free space, i.e., $\mu = \mu_0 = 4\pi \times 10^{-7}$ H/m for the lossy dielectric material. The base width of the absorber structures (period of absorber array) is $p = 7.6$ cm. The height of the absorber structures is $h = 16.2$ cm. Phase variation of the wave reflected from 16.2 cm height absorbers for 60 degrees angle of incidence at 500 MHz is approximately 1.696 (radians) which is greater than $\pi/2$. This height satisfies the Rayleigh roughness criterion between 0–60 degrees incidence angle range. For the incidence angles between 60–90 degrees, phase variation of the reflected wave is less than $\pi/2$ and does not satisfy the roughness criterion but this does not significantly affect absorption performance since most of the anechoic chambers have a rectangular shape and their length/width ratios are not so large, and the incidence angles of the EM waves emitted from the wave source are usually less than 60 degrees. So Snell's law of reflection is valid for the analysis of the wedge absorber and proposed absorbers.

The double wedge absorber has better performance at frequency range of 0.5–3 GHz for 0 degree angle of incidence, as shown in Fig. 4.

The double wedge absorber has better performance almost all

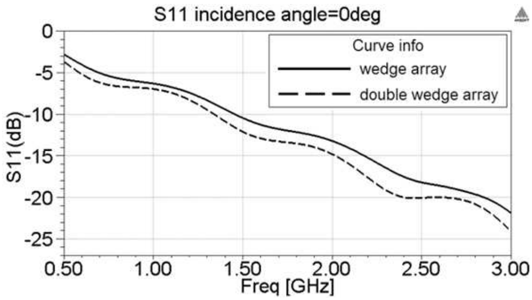


Figure 4. Comparison of wedge and double wedge array reflection coefficients for the 0 degree angle of incidence at frequency range of 0.5–3 GHz.

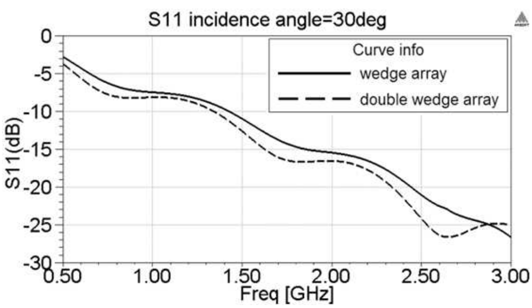


Figure 5. Comparison of wedge and double wedge array reflection coefficients for the 30 degrees angle of incidence at frequency range of 0.5–3 GHz.

frequencies at frequency range of 0.5–3 GHz for 30 degrees angle of incidence, as shown in Fig. 5.

Absorption performance of the double wedge absorber is almost same as the wedge absorber at frequency range of 0.5–3 GHz for 60 degrees angle of incidence, as shown in Fig. 6. It has better values than the wedge absorber for some frequencies, but worse values for some other frequencies.

Triple and quadruple wedge absorbers are also analyzed and the results show that their absorption performances are better than the wedge absorber for 0 and 30 degrees and almost the same as the wedge absorber for 60 degrees incidence angle of the plane electromagnetic waves at frequency range of 0.5–3 GHz. For simplicity, the results of the double wedge absorber geometry were analyzed in this study.

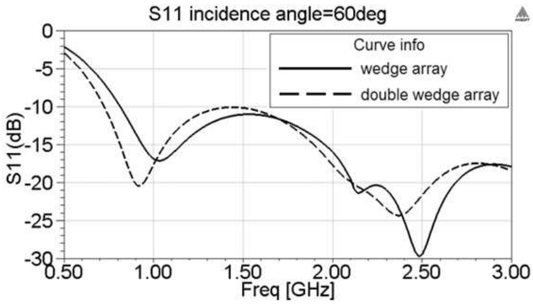


Figure 6. Comparison of wedge and double wedge array reflection coefficients for the 60 degrees angle of incidence at frequency range of 0.5–3 GHz.

4. CONCLUSIONS

This study shows that a better absorption performance is obtained by using multiple wedge structures than conventional wedge ones. *TE* mode uniform plane electromagnetic waves are used to analyze structures.

The results show that the proposed multiple wedge structures provide higher reflection loss than conventional wedge arrays. Multiple wedge structures can be ideal to use as an absorber for anechoic chamber applications since they provide quite good absorption properties especially for normal and near normal incidence angles and they contribute positively to the reduction of antenna measurement errors. Multiple wedge structures which have more tips than a double wedge and the optimum number of tips for providing the best absorption performance are not discussed in this work.

REFERENCES

1. Kent, S. and M. Kartal, "Dielectric absorber design for wide bandwide oblique incidence angle," *Int. J. Electron. Commun. (AEÜ)*, Vol. 61, 398–404, 2007.
2. Nornikman, H., F. B. A. Malek, P. J. Soh, A. A. H. Azremi, F. H. Wee, and A. Hasnain, "Parametric study of pyramidal microwave absorber using rice husk," *Progress In Electromagnetics Research,* Vol. 104, 145–166, 2010.
3. Neher, L. K., "Nonreflecting background for testing microwave equipment," U.S. Patent, 2 656 535, Oct. 20, 1953.
4. Emerson, W. H., "Electromagnetic wave absorbers and anechoic

chambers through the years," *IEEE Trans. Antennas Propagat.,* Vol. 21, 484–490, 1973.

5. Demotte, F. E., "Electromagnetic radiation absorbing means," U.S. Patent Application, 769 710, Aug. 20, 1947.
6. Tanner, H. A., "Fibrous microwave absorber," U.S. Patent, 2 977 591, 1952.
7. Tong, X. C., *Advanced Materials and Design for Electromagnetic Interference Shielding*, 237–255, Taylor & Francis Group, 2009.
8. Chung, B. and H. Chuah, "Modeling of RF absorber for application in the design of anechoic chamber," *Progress In Electromagnetics Research*, Vol. 43, 273–285, 2003.
9. Ishimaru, A., *Electromagnetic Wave Propagation, Radiation, and Scattering*, 31–75, Prentice Hall, 1991.
10. Bell, R. J., K. R. Armstrong, C. S. Nichols, and R. W. Bradley, "Generalized laws of refraction and reflection," *J. Opt. Soc. Am.*, Vol. 59, 187–189, 1969.
11. Cheng, D. K., *Field and Wave Electromagnetics*, 2nd edition, 411–417, Addison Wesley, 1989.
12. Kuester, E. and C. Holloway, "A low-frequency model for wedge or pyramid absorber arrays — I: Theory," *IEEE Transactions on Electromagnetic Compatibility*, Vol. 36, No. 4, 300–306, 1994.
13. Rayleigh, L., "On the dynamical theory of gratings," *Proceedings of the Royal Society of London. Series A, Containing Papers of a Mathematical and Physical Character,* Vol. 79, No. 532, 399–416, Aug. 1907.
14. Rayleigh, L., *The Theory of Sound*, Dover, New York, 1945, Originally Published in 1877.
15. Pinel, N., J. Saillard, and C. Bourlier, "Extension of the roughness criterion of a one-step surface to a one-step layer," *Journal of Electromagnetic Waves and Applications*, Vol. 24, Nos. 8–9, 1195–1205, 2010.
16. Pinel, N., C. Bourlier, and J. Saillard, "Degree of roughness of rough layers: Extensions of the Rayleigh roughness criterion and some applications," *Progress In Electromagnetics Research B,* Vol. 19, 41–63, 2010.
17. Holloway, C. L., R. R. DeLyser, R. F. German, P. McKenna, and M. Kanda, "Comparison of electromagnetic absorber used in anechoic and semi-anechoic chambers for emissions and immunity testing of digital devices," *IEEE Trans. Electromagnetic Compatibility,* Vol. 39, 33–47, 1997.