Chapter-10

Electromagnetic Wave Absorbers: A Brief Discussion

Dipangkar Borah

Department of Physics, Tezpur University, Napaam, 784028, Assam, India
E-mail: dip.borah1991@gmail.com

In this chapter, an overview of electromagnetic absorbers is briefly discussed. Emphasis is specially given on definitions, types and transmission line model of electromagnetic absorbers. Pros and cons of the absorbers are also discussed briefly. Finally advances of metamaterial absorbers, their advantages over conventional absorbers are also pointed out. Possible uses of metamaterial absorbers are also mentioned. The concluding section provides a summary and gives a future outlook of metamaterial absorbers.

1. INTRODUCTION

The science and technology of electromagnetics absorbers become a great deal of interest as the number of electronic and communication systems are increasing in different frequency regime in modern age. Because of rapid development of detection equipment, electromagnetic absorbers are also

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equally important in military stealth applications. Microwave absorbers are specially designed material to absorb electromagnetic wave incident on it and allows a very less amount of wave to reflect back from the incident surface and transmitted through it. The reflection is minimized by properly matching the impedance at the air-absorber interface while absorption is maximized by using lossy material in it [1-3].

In order to establish a common understanding, let's begin with some useful definition of electromagnetic absorber. There are numbers of definitions of EMI absorbers, however here few definitions will be quoted.

A electromagnetic shield can be defined as, "*a housing, screen, or other object, usually conducting, that substantially reduces the effect of electric or magnetic fields on one side thereof, upon devices or circuits on the other side*" [4]. This definition is not appropriate as it indirectly assumes the presence of the "victims". Also this definition is based on a misconception that the source and observation points are in opposite with respect to the shield or the absorber. In some cases, source and victims may present in the same direction of the shields and hence reliability of the definition is questionable [5].

Another definition is, "*any means used for the reduction of electromagnetic field in prescribed region is known as electromagnetic absorber*" [6]. This definition is also silent about the position of the shields, its shape and materials.

Most appropriately, an electromagnetic absorber can be defined as, "*a near unity electromagnetic absorber is a device in which all incident radiation is absorbed at the operating frequency and all other propagating channels i.e,*

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transmission, reflection and scatterings are disabled" [7]. This definition seems more appropriate because it tells about all the terms related to wave propagation in a medium. To understand it more specifically, a schematic diagram is presented in the Fig.1.

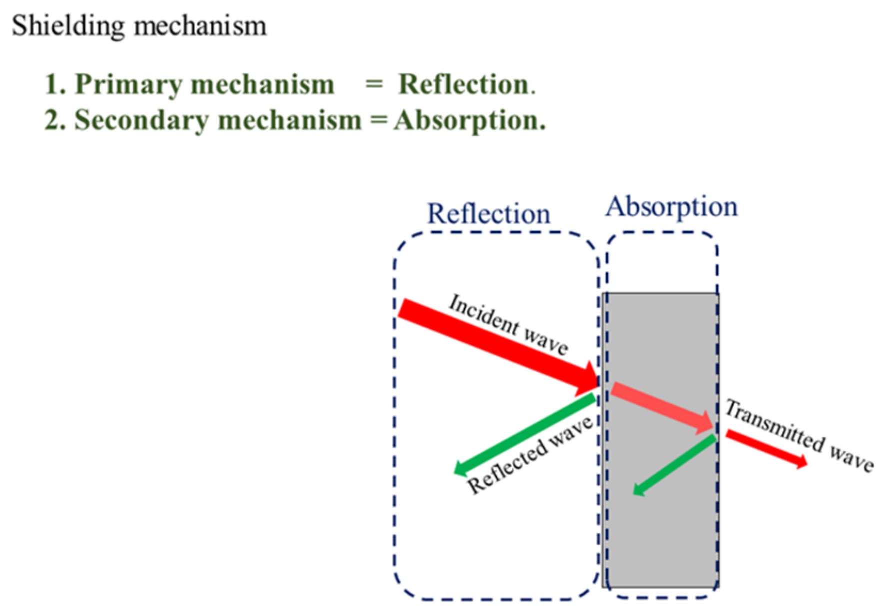

Fig. 1: Schematic diagram of absorber mechanism

In the Fig.1, the dark portion represent the absorber. When electromagnetic wave is incident on it, one part is reflected back while another part is entered into the absorber. Entered part undergoes secondary reflection at the absorber-air interface and one part is transmitted. If the percentage of transmission and reflection of electromagnetic wave is very less, then it represent an electromagnetic absorber.

In general, electromagnetic shield or absorber is an arsenal with which an electronic system designer can improve the electromagnetic compatibility

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(EMC) of the systems. Where, EMC is defined as "*ability of a system to function satisfactorily in its electromagnetic environment without introducing intolerable disturbance to that environment*" [IEEE standard dictionary of electrical and electronics terms] [8].

2. BRIEF HISTORY OF ELECTROMAGNETIC ABSORBER

The development of electromagnetic wave absorbers has been initiated in 1930's shortly after the advent of radar [9]. Before and during the Second World War, numbers of investigations of the interaction between electromagnetic radiations at radar frequencies with various materials were carried out. One aspect of these investigations being to find ways of reducing the returned signal. The first patent on radar absorbing materials was appearing in 1936 in Netherlands [10]. It was a quarter wave resonant type absorber and was designed using carbon black as lossy resistive material and Titanium Dioxide for its high permittivity to reduce the thickness of the absorber. During the World War II, Germans developed a coatings for their submarine periscopes, snorkels and conning towers which achieved a reflection decrease of almost 26dB in the 112 to 195 cm wavelength band. Their coating was basically carbonyl iron powder loaded rubber sheet, which was about 0.3 inches thick. The front surface of this material was waffled to produce a wide bandwidth. A number of physical shortcomings however, mainly the coating's lack of survivability in harsh environments, prevented the large scale implementation and deployment of this material [9]. During this period, America developed a material known as "HARP" for Halpern Anti-Radiation Paint [11]. It was basically disk shaped aluminium flaskes suspended in a rubber sheets that exhibits permittivity about 150. This material reduce the reflectivity upto 15-20 dB. Pyramidal absorber were another type of absorber developed in the same period. Because of the gradual change of impedance at the air-absorber interface, pyramidal absorber shows high attenuation and fined its place in different radar absorbing applications.

With progressive development of wireless technology, during the post-world war period (1945-1950), the need of broadband absorber became the major challenge. At the same time requirement of quality anechoic chamber for accurate indoor measurement came into the picture. Material investigated during this period were carbon loaded plaster of paris. Graphite, iron oxide, powdered iron and aluminium and copper. Various plastics and ceramics were used as binders to bind the powdered materials.

The 60’s and 70’s saw continuing work on circuit analog materials and absorber thickness were significantly reduced using ferrite underlayer [12]. During this period, number of absorber were designed and developed from foams, netlike structures, knitted structures, or honeycomb and coated with a paint containing particulate or fibrous carbon, evaporated metal or nickel chromium alloy.

The 1980’s. The absorber design process is improved by optimization techniques [13] in terms of thickness, material parameters and weight. Graded layers were used to achieve broad bandwidth. New composite materials were designed to be used as absorber by mixing different materials at different composite ratios and permittivity and permeability of

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these new materials are realized to the desired values. In the same time, conducting polymers appear as potential radar absorbing materials.

The 1990's and till today, optimization techniques like genetic algorithms are used for achieve more application oriented absorbers. Conducting polymers and composite materials find more attention for fabricating electronics and wireless devices.

3. TYPES OF ELECTROMAGNETIC ABSORBER

In this section, the types of the absorbers will be discussed from two prospect, one is material prospect i.e., material used to design the absorber and another one is nature of the absorbers. Depending on the material used to design the absorber and material's complex permittivity and complex permeability values, conventional electromagnetic absorbers can be classified as [14-19],

- Dielectric absorbers
- Magnetic absorbers
- Magneto-dielectric absorbers

Dielectric composite absorption depends on ohmic loss of energy, generally achieved by adding conducting fillers like carbon black, graphite. Dielectric absorber has no magnetic properties. They possess the advantages of being low cost and weight. Disadvantages are higher conductivity preventing usage in contact with electronic equipment and their lack of performance in most cavity resonance applications due to their lack of magnetic absorption. On the other hand, magnetic composite absorption depends on magnetic hysteresis effect of the magnetic materials like ferrites incorporated into the

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matrix materials. This gives the absorber a high permeability and high magnetic loss. Advantages include the ability to greatly compress the wavelength due to the high permeability enabling quarter wavelength resonant absorbers at a thickness that are a fraction of the free space wavelength. Also, magnetic absorbers are best for cavity resonance damping since the magnetic field is a maximum on the conductive surface where the absorber is placed. Disadvantages of magnetic absorber include weight and cost.

Depending on the nature and structure of the absorber, it can be classified as [7-9],

- Impedance matching absorbers
- Resonant absorbers
- Broadband absorbers

Impedance matching absorbers are basically graded interfaced absorbers. In these types of absorber, impedance of the air-absorber interface is matched to the impedance of the free space for minimizing the reflection of electromagnetic waves. Depending on nature of absorber, structure and the way of matching the impedance, impedance matching absorbers can be classified as flows [20-22],

- Pyramidal absorbers
- Tapered loading absorbers
- Matching layer absorbers

Pyramidal absorbers are typically thick materials. They have pyramidal or cone structure on the surface. These structure are placed perpendicular to the surface of the absorbers. They are developed in this way, so that they

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can present a gradual transition of impedance from air to that of the absorber. With proper optimization of the structure, they provide the best performance. However, the disadvantage of these kind of absorber is their thickness and tendency to be fragile. Fig.2 is showing typical pyramidal absorbers and its uses in anechoic chamber.

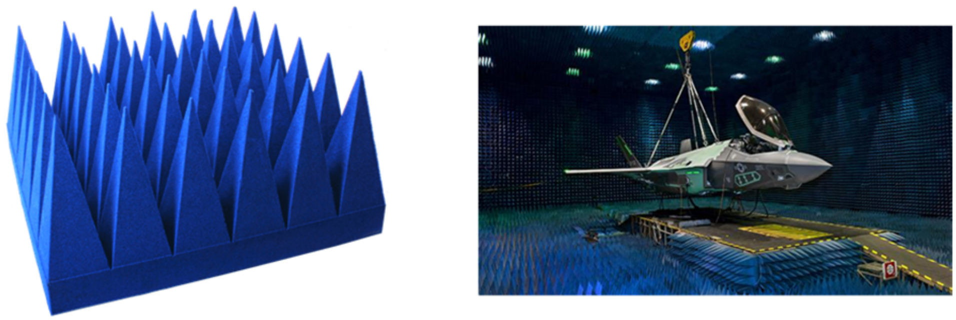

Fig. 2: Pyramidal absorber and their uses in anechoic chamber (Image courtesy: Google Images)

Tapered loading absorbers are basically plane slab made up of low loss material mixed with a lossy material. Lossy material are homogeneously mixed with increasing loading in the direction of propagation. They possess the advantage of being thinner than pyramidal absorber and disadvantage of poor performance.

Matching layer absorbers are basically graded layer absorber. Using gradual transition material, thickness of the absorbers are reduced in matching layer absorbers. Fig.3 shows the schematic diagram and developed absorber of the matching layer absorbers. The transition materials are placed between two impedances to be matched. Depending on the material parameters, thickness is calculated and impedance is matched to the desired level.

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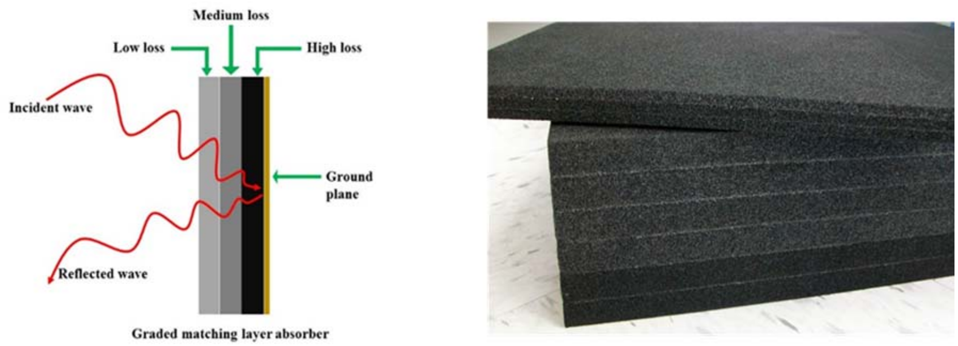

Fig 3: Schematic diagram and developed graded matching layer absorber (Image courtesy: Google Images)

Resonant absorbers are the mostly used absorber throughout the history. They employed multiple layers separated by a quarter of operation wavelength. For these reason they are also called as tuned or quarter wavelength absorbers. In transmission line theory, a metal plate acts like a short circuit, and when it is placed $\lambda_0/4$ behind any sort of "load," will act like an open circuit at the resistive sheet (i.e. conductance G = 0). Therefore, the incident wave sees just the admittance of the resistive sheet. When the load impedance matches free space, the reflectivity goes to zero. With the addition of loss, high absorption can be achieved. Resonant absorbers can be classified as [23-29],

- Dallenbach layer absorber
- Salisbury screen absorber
- Jaumann absorber
- Crossed grating absorber
- Circuit analog absorber

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Dallenbach absorber consists of a homogeneous layer in front of a ground plane. The material parameters mainly permittivity and permeability, thickness are adjusted to the desired value so that reflection can be minimized. The Dallenbach absorbers work on destructive interference of electromagnetic wave. Although different optimization techniques have employed over Dallenbach absorbers to increase the bandwidth, however, it is not possible to obtain a broadband absorber with only one layer. Bandwidth can be increased by stacking multiple layers together.

Salisbury screen, patented on 1952, is another resonant absorber. As Dallenbach absorber, it does not depend on permittivity and permeability of the bulk layers. In Salisbury screen a resistive sheet is placed $\lambda_0/4$ in front of a metal ground plane, usually separated by an air gap. Fig.4 is showing the schematic diagram of Salisbury screen.

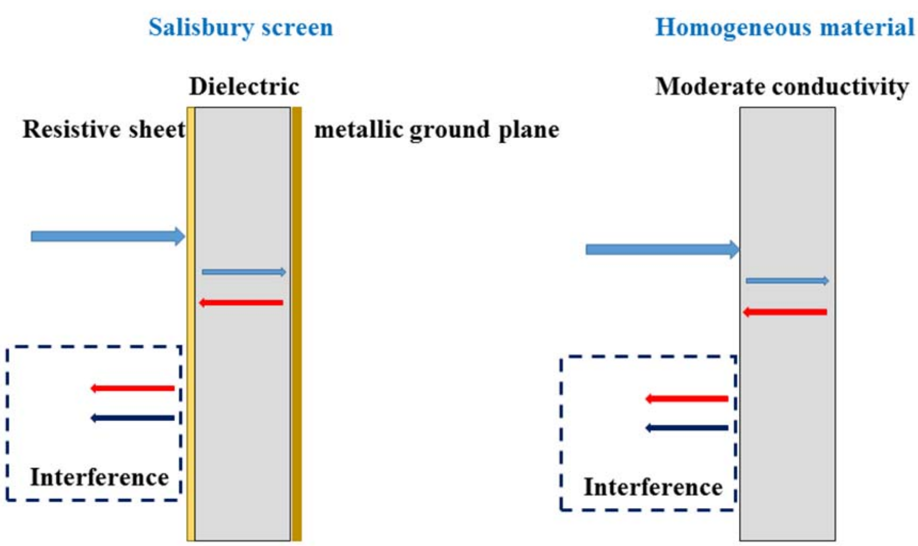

Fig. 4: Schematic diagram of Salisbury screen

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Jaumann absorber can conceptually be considered an extension of the Salisbury screen that consists of two or more resistive sheets in front of a single ground plane. All sheets are designed to operate at a distinct wavelength, and thus each sheet is separated by approximately $\lambda/4$, producing multiple reflection minimums around some center frequency λ_0. The effect is that it acts as a resonant absorber over multiple wavelengths, achieving a broadband response. Further, bandwidth can be possibly increased by placing suitable dielectric slabs in between the resistive sheets. Particularly, in front of the outer most resistive sheet. However, these absorbers have the undesirable effect of making the absorber thick and bulky.

Crossed grating absorber, uses a reflective metal plane with an etched shallow periodic grid. Resonance is created due to the interaction between the periodic grid and incident radiation, creating a period of anomalous diffraction. This absorber had developments as early as 1902 when R. W. Wood postulated the possible effects of anomalous diffraction. It was shown that anomalous diffraction is correlated to periods of enhanced absorption. The total absorption of polarized light with the use of these gratings was postulated in 1976 and was experimentally demonstrated soon after. Recently, this has been extended to unpolarized light with the use of doubly-periodic crossed diffraction gratings.

Circuit Analog (CA) absorbers, another type of resonant electromagnetic absorber that can be considered an extension of the Salisbury screen, consist of one or more sheets composed of both resistive and reactive components (i.e. a lossy frequency selective surface, FSS) arranged in a periodic array in

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front of a single ground plane. These components practically help to matching the impedance of the absorbers and provided small reflection maintaining small thickness. Like the previously mentioned resonant absorbers, the ground plane is a distance $\lambda_0/4$ behind the FSS. Modern designs of CA absorbers have achieved absorption at high angles of incidence and over broad bands. For simplicity both, Salisbury screen absorber and Jaumann absorber can be considered as circuit analog absorber.

4. IMPORTANT MATERIAL PARAMETERS OF ABSORBERS

Absorbers are characterized by their electric permittivity and magnetic permeability. The permittivity is a measure of the material's effect on the electric field in the electromagnetic wave and the permeability is a measure of the material's effect on the magnetic component of the wave. The permittivity is complex and is generally written as,

$$\varepsilon = \varepsilon' - j\varepsilon''$$

The permittivity arises from the dielectric polarization of the material. The quantity ε' is sometimes called the dielectric constant which is something of a misnomer when applied to absorbers as ε' can vary significantly with frequency. The quantity ε" is a measure of the attenuation of the electric field cause by the material. The electric loss tangent of a material is defined as,

$$\tan\delta_e = \frac{\varepsilon''}{\varepsilon'}$$

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The greater the loss tangent of the material, the greater the attenuation as the wave travels through the material. Analogous to the electric permittivity, the magnetic permeability is written as,

$$\mu = \mu' - j\mu''$$

With magnetic loss tangent defined as,

$$\tan\delta_m = \frac{\mu''}{\mu'}$$

The permeability is a measure of the material's effect on the magnetic field. Both components contribute to wavelength compression inside the material. Additionally, due to the coupled EM wave, loss in either the magnetic or electric field will attenuate the energy in the wave. In most absorbers, both permittivity and permeability are functions of frequency and can vary significantly over even a small frequency range. If the complex permittivity and permeability are known over a frequency range then the material's effect on the wave is completely known [30].

5. TRANSMISSION LINE MODELING OF ELECTROMAGNETICS ABSORBER

Plane electromagnetic waves propagating in bulk slabs can be modelled by transmission line equations. TLM is a numerical technique based on temporal and spatial sampling of electromagnetic fields. A transmission line carrying TEM wave is represented as distributed elements in a network having series impedance $Z = R + j\omega L$ and shunt admittance $Y = G + j\omega C$ per unit length as shown in Fig.5 [31].

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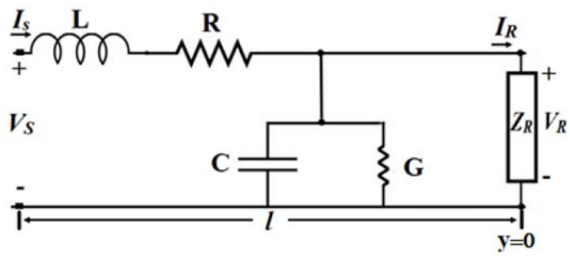

Fig. 5: Transmission line modeling of electromagnetic absorber

For a uniform transmission line having the constants R, L, C and G per unit length, the voltage and current equations can be written in the differential form as [32],

$$\frac{\partial \tilde{V}}{\partial y} + L\frac{\partial \tilde{I}}{\partial t} + R\tilde{I} = 0 \quad \text{------------------------------------(1)}$$

$$\frac{\partial \tilde{I}}{\partial y} + C\frac{\partial \tilde{V}}{\partial t} + G\tilde{V} = 0 \quad \text{------------------------------------(2)}$$

If the voltages and currents vary sinusoidally with time, the phasor notation of equations (1) and (2) become,

$$\frac{\partial V}{\partial y} + (R + j\omega L)I = 0 \quad \text{-------------------------------------(3)}$$

$$\frac{\partial I}{\partial y} + (G + j\omega C)V = 0 \quad \text{-------------------------------------(4)}$$

Differentiating equations (3) and (4) with respect to y and combining gives,

$$\frac{\partial^2 V}{\partial y^2} - (R + j\omega L)(G + j\omega C)V = 0 \quad \text{-----------------------------(5)}$$

$$\frac{\partial^2 I}{\partial y^2} - (R + j\omega L)(G + j\omega C)I = 0 \quad \text{-----------------------------(6)}$$

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A possible solution for these equations would be of the form,

$$V \; or \; I = Ae^{-\gamma y} + Be^{\gamma y} \qquad \text{----------------------------------(7)}$$

where $\gamma^2 = (R + j\omega L)(G + j\omega C)$

When the variation with time is expressed explicitly, the first term of the expression (7) represents a wave travelling in forward direction and the second term represents a wave travelling in reverse direction.

In hyperbolic function form, the solutions to equations (5) and (6) are,

$$V = A_1 cosh\, \gamma y + B_1 sinh\, \gamma y \qquad \text{--------------------------------(8)}$$

$$I = A_2 cosh\, \gamma y + B_2 sinh\, \gamma y \qquad \text{--------------------------------(9)}$$

The constants A_1, A_2, B_1 and B_2 are evaluated by applying boundary conditions,

$$V = V_{R,}\, I = I_R \quad at\; y = 0$$

$$V = V_{s,}\, I = I_s \quad at\; y = y_1$$

Substituting these boundary conditions in (8) and (9), the co-efficients are found as,

$$\left.\begin{aligned} &A_1 = V_R \\ &B_1 = -\sqrt{\frac{R+j\omega L}{G+j\omega C}}\, I_R \\ &\text{and} \\ &A_2 = I_R \\ &B_2 = -\sqrt{\frac{G+j\omega C}{R+j\omega L}}\, V_R \end{aligned}\right\} \qquad \text{--------------------------------(10)}$$

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The characteristic impedance (Z_0) of the transmission line is related to the primary constants R, L, G and C as,

$$Z_0 = \sqrt{\frac{Z}{Y}} = \sqrt{\frac{R+j\omega L}{G+j\omega C}} \quad \text{--------------------------------(11)}$$

The characteristic impedance (Z_0) is analogous to the intrinsic impedance of the wave given by equation,

$$\eta = \sqrt{\frac{j\omega\mu}{\sigma_s + j\omega\varepsilon}} \quad \text{----------------------------------(12)}$$

Considering the location of the terminating impedance ZR the reference point (y = 0), the other end is left of this reference point, i.e. in the –y direction as shown in Fig.5. Combining the equations (8) and (9) become,

$$V_S = V_R \cosh \gamma l + Z_0 I_R \sinh \gamma l \quad \text{--------------------------------(13)}$$

$$I_S = I_R \cosh \gamma l + \frac{V_R}{Z_0} \sinh \gamma l \quad \text{--------------------------------(14)}$$

The general expression for the input impedance of the transmission line is obtained by dividing equation (13) by equation (14),

$$Z_{in} = \frac{V_s}{I_s} = \frac{V_R \cosh \gamma l + Z_0 I_R \sinh \gamma l}{I_R \cosh \gamma l + \frac{V_R}{Z_0} \sinh \gamma l} \quad \text{--------------------------------(15)}$$

or

$$Z_{in} = Z_0 \frac{Z_R + Z_0 \tanh \gamma l}{Z_0 + Z_R \tanh \gamma l} \quad \text{--------------------------------(16)}$$

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The expression (16) gives the input impedance of the transmission line terminated by a load Z_R. The reflection coefficient is expressed as,

$$\Gamma = \frac{Z_{in} - Z_0}{Z_{in} + Z_0} \qquad \text{--------------------------------(17)}$$

As we know, impedance of free space is, Z0 = 377 Ω,

$$\Gamma = \frac{Z_{in} - 377}{Z_{in} + 377} \qquad \text{--------------------------------(18)}$$

By properly matching the input impedance to that of free space, Zin~377 Ω, reflection co-efficient can be minimized.

6. LIMITATION WITH CONVENTIONAL ELECTROMAGNETIC ABSORBERS

Although absorption could be achieved using conventional electromagnetic absorber, however some limitations are associated with it. Few of it, listed below,

- Dielectric absorbers are generally thick leading to bulky devices and has more impedance mismatch at the air-absorber interface.
- Magnetic absorbers reduce the impedance mismatch (as Zin=$\sqrt{\mu/\varepsilon}$) and are thinner than dielectric absorber, but are heavy. Again using metals like iron, cobalt as inclusions in the polymer matrix makes the absorber corrosive
- Ferrites are, however, a good alternative to metal fillings. But weight is still an issue to be handled. Replacement of bulk ferrites

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with nano inclusions reduce the weight and enhances absorption, but the use in larger quantity is limited by shrinkage level of polymer.

- Absorption bandwidth could be increased by multi-layering which may increase the thickness of absorber to some extent.
- Using flexible matrix can take care of conformal surfaces, but bending absorbers on complex conformal surfaces can lead to variation in the extent of absorption and hence the reliability of the shields.

7. METAMATERIAL ABSORBERS

Use of metamaterial based absorber could be a promising alternative of finding solutions to the above stated problems. Metamaterials are engineered material and have simultaneously negative permittivity and permeability [33], which can modify the EM properties of the incident wave. After successfully demonstration of perfect metamaterial absorber by N. I. Landy et.al in 2008, research on electromagnetic absorber based on metamaterials open a new field of investigation [33]. N. I. Landy's perfect absorber was based on Vesselago's theoretical proposal and Pendry's experimental validation. In 1967, Veselago theoretically proposed the electrodynamics of a medium having simultaneously negative permittivity and permeability [34]. Veselago predicted the following exotic properties for materials with negative index: reverse Cerenkov radiation, reverse Doppler shift, and opposite phase and group velocity, among others. After about 30 years, Pendry has experimentally demonstrated that circular split ring and wire structure can create negative permeability and permittivity

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respectively [35, 36]. The metamaterial absorbers have possessed the following advantages,

- Larger design and fabrication options for achieving impedance matching and high attenuation of incident EM wave. Different metamaterial's unit cells are presented in Fig.6.
- The in-plane geometry of metamaterial absorbers or two dimensional metaskin reduces the absorber thickness significantly.
- Multiple resonating structure in a single unit cells give a broader bandwidth absorber.
- No inclusions in the matrix or substrate reduces the weight considerably compared to the conventional EMI absorbers.

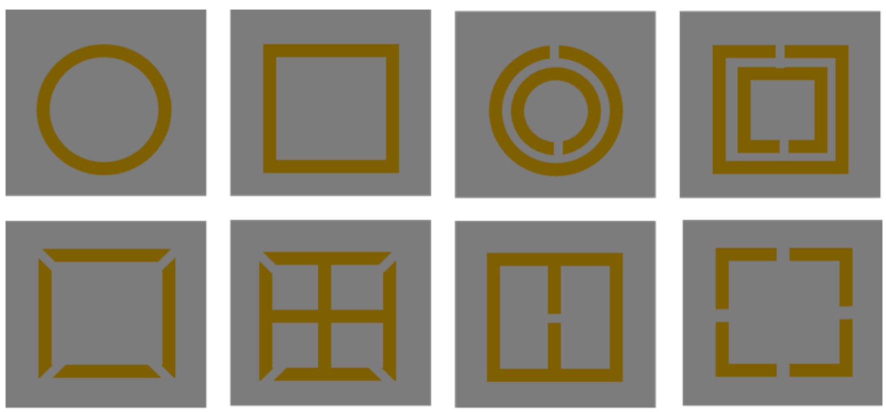

Fig. 6: Different metamaterial unit cells used as absorber

8. APPLICATION OF METAMATERIAL ABSORBERS

Other than their rich ability as a platform to study fundamental electromagnetic wave theory, MPAs offer a wide variety of practical applications. Although many of these applications are still in their infancy, a

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major goal since the creation of MPAs has been to integrate them into existing devices to boost their performance. The possible applications that are most studied in the fields are [37-43],

- Invisibility Cloaks
- Bolometers
- Efficient energy harvesting devices
- Thermo photovoltaic devices
- Solar cells

9. CONCLUSION AND DISCUSSIONS

In this chapter we have discussed the definition, classification, theory and brief history of conventional electromagnetic absorber. We have also discussed the limitation with the conventional absorbers and advantages of metamaterial based absorber over it. Besides, use metamaterial absorber for EMI reduction application, we have also mentioned few applications of metamaterial absorber. Because of the exotic properties of metamaterials, there are great prospects of metamaterial based absorber development. Although, metamaterial structure possesses some fabrication issues, however in future, there are multitude challenges are waiting for the researchers in each and every frequency band of electromagnetic spectrum. In fact, this will spark the merging of knowledge and expertise across different areas, further driving the astounding advance of metamaterials research. Within only ten years, we have witnessed many remarkable breakthroughs, such as negative refraction, superlens and invisible cloak. Many other fascinating discoveries and applications are waiting for us to explore. With the complete degree of freedom to control overall material properties, what we could do next is only limited by our imagination.

REFERENCES

[1] Tong, X. C. (2016). Advance Materials and Design for Electromagnetic Interference Shielding, Taylor and Francis, London, CRC Press.

[2] Hong, S. K., Kim, K. Y., Kim, T. Y., Kim, J. H., Park, S. W., Kim, J. H., & Cho, B. J. (2012). Nanotechnology, **23**(45), 455704.

[3] Oikonomou, A., Giannakopoulou, T., & Litsardakis, G. (2007). Journal of Magnetism and Magnetic Materials, **316**(2), e827-e830.

[4] IEEE 100, The Authoritative Dictionary of IEEE Student Terms, 7^{th} ed. New York, IEEE press, 2000.

[5] Celozzi, S., Araneo, R., Lovat G. Electromagnetic Shielding, A John Wiley & Sons. Inc.,

[6] C. Morris, ed. Academic Press Dictionary of Science and Technology, San Diego, Academic press, 1992.

[7] Watts, C. M., Liu, X., & Padilla, W. J. (2012). Advanced Materials, **24**(23).

[8] Tsaliovich, A. (1999). Electromagnetic shielding handbook for wired and wireless EMC applications. Kluwer.

[9] Saville, P. (2005). (No. DRDC-TM-2005-003). Defence research and development atlantic dartmouth (Canada).

[10] Machinerieen, N. V. Dispositif et procÃ©dÃ© pour l'amÃ©lioration de dispositifs de production et de rÃ©ception d'ondes Ã©lectriques ultra-courtes, French Patent 802 728, 1936.

[11] Halpern, O. (1960). **U.S. Patent No**. 2,923,934. Washington, DC: U.S. Patent and Trademark Office.

[12] Knott, E. F. (1993). In Radar Cross Section Measurements (pp. 1-26). Springer US.

[13] Fante, R. L., & Mccormack, M. T. (1988). IEEE transactions on antennas and propagation, **36**(10), 1443-1454.

[14] Thomassin, J. M., Vuluga, D., Alexandre, M., Jérôme, C., Molenberg, I., Huynen, I., & Detrembleur, C. (2012). Polymer, **53**(1), 169-174.

[15] Abbas, S. M., Chandra, M., Verma, A., Chatterjee, R., & Goel, T. C. (2006). Composites Part A: applied science and manufacturing, **37**(11), 2148-2154.

[16] Zhou, J., He, J., Li, G., Wang, T., Sun, D., Ding, X., & Wu, S. (2010). The Journal of Physical Chemistry C, **114**(17), 7611-7617.

[17] Guo, X., Deng, Y., Gu, D., Che, R., & Zhao, D. (2009). Journal of Materials Chemistry, **19**(37), 6706-6712.

[18] Koledintseva, M. Y., Razmadze, A. G., Gafarov, A. Y., Khilkevich, V. V., Drewniak, J. L., & Tsutaoka, T. (2011). Progress In Electromagnetics Research, **118**, 441-459.

[19] Koledintseva, M. Y., Xu, J., De, S., Drewniak, J. L., He, Y., & Johnson, R. (2011). IEEE Transactions on Magnetics, **47**(2), 317-323.

[20] Park, M. J., Choi, J., & Kim, S. S. (2000). IEEE transactions on magnetics, **36**(5), 3272-3274.

[21] Nornikman, H., Malek, M. F. B. A., Soh, P. J., Azremi, A. A. A. H., Wee, F. H., & Hasnain, A. (2010). Progress In Electromagnetics Research, **104**, 145-166.

[22] Neo, C. P., & Varadan, V. K. (2001). Smart materials and structures, **10**(5), 1107.

[23] Reinert, J., Psilopoulos, J., Grubert, J., & Jacob, A. F. (2001). Microwave and optical technology letters, **30**(4), 254-257.

[24] Gilbert, Roland A. "Thin, broadband salisbury screen absorber." **U.S. Patent No**. 6,538,596. 25 Mar. 2003.

[25] Fante, R. L., & Mccormack, M. T. (1988). IEEE transactions on antennas and propagation, **36**(10), 1443-1454

[26] Chambers, B., & Tennant, A. (1994). Electronics Letters, **30**(18), 1530-1532.

[27] Chambers, B., & Tennant, A. (1996). IEEE Proceedings-Radar, Sonar and Navigation, **143**(1), 23-30.

[28] Munk, B. A., Munk, P., & Pryor, J. (2007). IEEE Transactions on Antennas and Propagation, **55**(1), 186-193.

[29] Kejin, R., & Yi, G. (2000). Journal-university of electronic science and technology of china, **29**(1), 54-63.

[30] http://www.eccosorb.com/resource-white-papers.htm

[31] Jordan, Edward C., and Keith G. Balmain. 2nd edition, Prentice Hall Inc., USA (1968).

[32] Chen, L. F., Ong, C. K., Neo, C. P., Varadan, V. V., & Varadan, V. K. (2004). John Wiley & Sons.

[33] Landy, N. I., Sajuyigbe, S., Mock, J. J., Smith, D. R., & Padilla, W. J. (2008). Physical review letters, **100**(20), 207402.

[34] Veselago, V. G. (1968). Soviet physics uspekhi, **10**(4), 509.

[35] Pendry, J. B., Holden, A. J., Stewart, W. J., & Youngs, I. (1996). Physical review letters, **76**(25), 4773.

[36] Pendry, J. B., Holden, A. J., Robbins, D. J., & Stewart, W. J. (1999). IEEE transactions on microwave theory and techniques, **47**(11), 2075-2084.

[37] Schurig, D., Mock, J. J., Justice, B. J., Cummer, S. A., Pendry, J. B., Starr, A. F., & Smith, D. R. (2006). Science, **314**(5801), 977-980.

[38] Maier, T., & Brückl, H. (2009). Optics letters, **34**(19), 3012-3014.

[39] Wang, H., Sivan, V. P., Mitchell, A., Rosengarten, G., Phelan, P., & Wang, L. (2015). Solar Energy Materials and Solar Cells, **137**, 235-242.

[40] Ramahi, O. M., Almoneef, T. S., AlShareef, M., & Boybay, M. S. (2012). Applied Physics Letters, **101**(17), 173903.

[41] Wang, Y., Sun, T., Paudel, T., Zhang, Y., Ren, Z., & Kempa, K. (2011). Nano letters, **12**(1), 440-445.

[42] Wu, C., Neuner III, B., John, J., Milder, A., Zollars, B., Savoy, S., & Shvets, G. (2012). Journal of Optics, **14**(2), 024005.

[43] Liu, X., Tyler, T., Starr, T., Starr, A. F., Jokerst, N. M., & Padilla, W. J. (2011). Physical review letters, **107**(4), 045901.

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