

ANALYSIS OF SHIELDING EFFECTIVENESS OF SINGLE, DOUBLE AND LAMINATED SHIELDS FOR OBLIQUE INCIDENCE OF EM WAVES

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Abstract—Shielding prevents coupling of undesired radiated electromagnetic energy into equipment otherwise susceptible to it. In view of this, some studies on shielding effectiveness of different shields against angle of incidence with conductors and conductive polymers using plane-wave theory are carried out in this paper. The plane wave shielding effectiveness of new combination of these materials is evaluated as a function of angle of incidence for Single, Double and Laminated

Shields. Conductivity of the polymers, measured in previous investigations by the cavity perturbation technique, is used to compute the overall reflection and transmission coefficients of single and multiple layers of the polymers. With recent advancements in synthesizing stable highly conductive polymers, these light-weight mechanically strong materials appear to be viable alternatives to metals for EMI shielding. The analysis is done at a particular frequency for all three types of shields.

1. INTRODUCTION

Most of the difficult shielding problems occur in mobile systems in which many transmitters, receivers, and other sensitive equipment must be mounted closely together, and weight is minimized. Predicting the shielding effectiveness of any enclosure such as equipment package or screening the room is difficult. Therefore any theoretical treatment for problems of this nature is necessarily approximate only. A number of light-weight polymers, intrinsically nonconductive but made conductive upon doping, have been studied in recent years [1–3]. These materials have several potential applications, such as electromagnetic interference (EMI) shielding, microwave absorbers, gas sensors, display units, junction devices, etc. [4, 5]. The properties like conductivity variation over wide temperature range, light weight and high mechanical strength of the polymers make them attractive in high-frequency shielding applications. In previous investigations, thin films of two new polymeric materials, namely polyacetylene and poly-p-phenylene-benzobis-thiazole (PBT), have been doped with iodine either electrochemically or by ion implantation, and their conductivity measured using the cavity perturbation technique [2, 3]. Conductive polymers are useful as shielding materials in applications involving high data-rate electronics (e.g., supercomputers) and in aerospace applications where weight is a constraint.

The measured values of polyacetylene [1, 2] are also included in Table 1 for comparison. The conductivity of the material is given by $\sigma = 2\pi f_0 \epsilon_0 \epsilon''$ where f_0 is the resonant frequency of the cavity [3] and ϵ_0 is the permittivity of free space. The conductivity is found to increase with the dopant levels, with the Polymer E (Table 1, Mnemonic E) doped electrochemically with 80% by weight of iodine, yielding the highest conductivity. Therefore it can be used over a wide frequency range.

In this paper, an extension of plane-wave transmission line theory of shielding analysis of different shields with conductors and conductive polymers is presented. In this paper, the plane wave shielding behavior

Table 1. Measured complex Dielectric constant $\epsilon_r = \epsilon' - \epsilon''$ of Conductive Polymer Films Doped with Iodine various levels. The frequency of measurement is $f_o = 9.375$ GHz, i.e., the centre frequency of X-band.

Mnemonic	Material	Doping	$\epsilon_r = \epsilon' - \epsilon''$
A	PBT	Ion implantation to a fluence of 10^{16} ions/cm ²	$3 - j838$
B	PBT	Ion implantation of a fluence of 10^{17} ions/cm ²	$3 - j1158$
C	Polyacetylene cis-(CHI _{0.045}) _x	Electrochemical; 4.5% I ₂ by weight	$5 - j607$
D	Polyacetylene Trans-(CHI _{0.045}) _x	Electrochemical; 4.5% I ₂ by weight	$5 - j909$
E	Polyacetylene cis-(CHI _{0.8}) _x	Electrochemical; 80% I ₂ by weight	$5 - j4.E5$

of single, double and laminated shields constructed with polymer and materials like copper and aluminum for oblique incidence are analysed. The well-known formulation of reflection and transmission by a planar multilayer is applied to compute the shielding effectiveness of shields [6–8]. The analysis is done using the material polyacetylene, mentioned with mnemonic E in Table 1. This material is represented as Polymer E.

2. SHIELDING THEORY

Two basic mechanisms, reflection loss and absorption loss, are responsible for a major part of the shielding. Therefore shielding theory is based on transmission behavior through metals and reflection from the surface of the metal as in Figure 1.

2.1. Angle of Incidence

The reflection and transmission of electromagnetic waves in n -layered dielectric between two semi-infinite media are considered for a general incident angle as shown in Figure 2. Each medium is assumed to be homogeneous and isotropic with electrical constants of the j -th layer

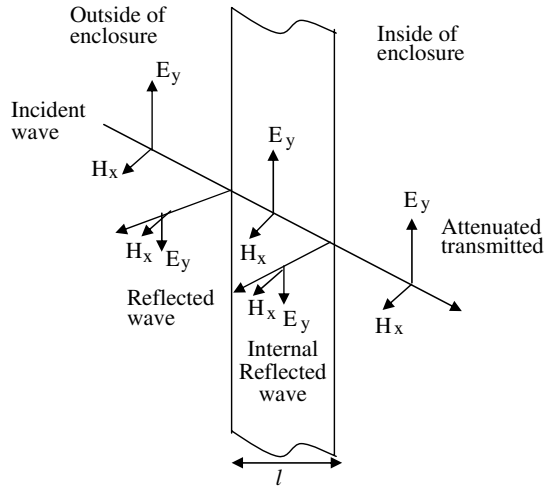


Figure 1. Representation of shielding mechanisms for plane-waves.

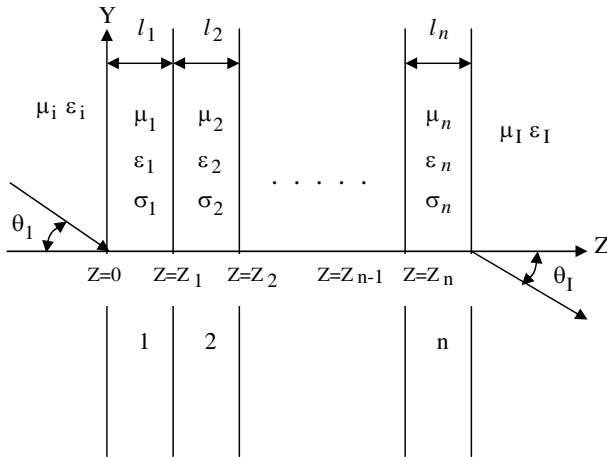


Figure 2. Oblique incidence of an EM wave on multilamina, n is the number of layers, and θ_1 is the incident angle.

ϵ_j , μ_j , and σ_j and thickness by l_j . The z -axis is the direction of stratification. θ_j , denotes incident angle of the j -th layer. Electric field components $E_y = E_z = 0$ for Transverse Electric wave, and magnetic field components $H_y = H_z = 0$ for Transverse Magnetic wave, respectively.

The impedance of shield material is [7] given by,

$$\eta = \sqrt{\frac{j\omega\mu}{\sigma}} = (1 + j)\sqrt{\frac{\pi\mu f}{\sigma}} \quad (1)$$

where μ is the permeability of the metal, σ is the conductivity of the metal and f is the frequency of operation. The impedance of the shield is varied according to the polarization as follows [8].

$$Z_j = \begin{cases} \frac{\eta_j}{\cos \theta_j} & \text{Transverse Electric polarisation} \\ \eta_j \cos \theta_j & \text{Transverse Magnetic polarisation} \end{cases} \quad (2)$$

Using Snell's law, we obtain $\cos \theta_j$ as [8]

$$\cos \theta_j = \left[1 - \left(\frac{K_1}{K_j} \right)^2 \sin^2 \theta_1 \right]^{1/2} \quad (3)$$

where in the j -th medium θ_j is the angle of refraction, and the wave number is

$$K_j = \omega [\mu_j (\epsilon_j + (\sigma_j/j\omega))]^{1/2} \quad (4)$$

and the intrinsic impedance is

$$\eta_j = \sqrt{\frac{j2\pi f \mu_j}{(\sigma_j + j2\pi f \epsilon_j)}} \quad (5)$$

2.2. Single Shield

The structure of single shield is as shown in Figure 1. If we interpret a shield as a transmission line, then input impedance normal to, and output fields of an infinite planar sheet of thickness l are

$$Z = \eta \frac{Z(l) \cosh \gamma l + \eta \sinh \gamma l}{\eta \cosh \gamma l + Z(l) \sinh \gamma l} \quad (6)$$

$$H(l) = \frac{\eta}{\eta \cosh \gamma l + Z(l) \sinh \gamma l} H(0) \quad (7)$$

$$E(l) = \frac{Z(l)}{Z(l) \cosh \gamma l + \eta \sinh \gamma l} E(0) \quad (8)$$

where $Z(l)$ is the impedance looking to the right of the plane $x = l$. At this plane, let E_i, H_i be the incident electric and magnetic fields; E_r, H_r the reflected fields, and E_t, H_t the transmitted fields as shown in Figure 1. Since the fields are continuous across the plane

$$E_i + E_r = E_t; \quad H_i + H_r = H_t \quad (9)$$

The reflected wave travels back to the source impedance for a sheet with a matched impedance at the plane $x = 0$. Thus

$$E_i = \eta H_i E_r = -\eta H_r, \quad E_t = -Z(l)H_t \quad (10)$$

When Equation (10) is substituted in (9) the following expressions are obtained for reflection coefficients:

$$\begin{aligned} q_E &= \frac{E_r}{E_i} = \frac{Z(l) - \eta}{Z(l) + \eta} \\ q_H &= \frac{H_r}{H_i} = \frac{\eta - Z(l)}{\eta + Z(l)} \end{aligned} \quad (11)$$

and for the corresponding transmission coefficients

$$\begin{aligned} p_E &= \frac{E_t}{E_i} = \frac{2Z(l)}{Z(l) + \eta} = 1 + q_E \\ p_H &= \frac{H_t}{H_i} = \frac{2\eta}{\eta + Z(l)} = 1 + q_H \end{aligned} \quad (12)$$

When two mismatches are considered as in a planar sheet, the net transmission coefficient is the product of the transmission coefficients across the two boundaries [9, 10].

$$p = p_E = p_H = p_E(0) \cdot p_E(l) = p_H(0) \cdot p_H(l) = \frac{4Z(l)\eta}{(Z(l) + \eta)^2} \quad (13)$$

By definition, the reflection loss is

$$R = -20 \log_{10} |p| \text{ dB} \quad (14)$$

When successive re-reflections are considered, the transmission coefficients across the sheet are

$$\begin{aligned} T_H &= \frac{H(l)}{H_i} = \frac{H(l)}{H(0)} \frac{H(0)}{H_i} \\ T_E &= \frac{E(l)}{E_i} = \frac{Z(l)}{Z_w} \frac{H(l)}{H_i} = \frac{Z(l)}{Z_w} T_H \end{aligned} \quad (15)$$

where $E(0)$, $H(0)$ and $E(l)$, $H(l)$ are the actual values at interfaces 0 and l , respectively, with reflection taken into account; Z_w is the impedance of the incident wave. With the use of Equations (11) to (13) and (15), the transmission coefficient can be expressed as

$$T_H = p_H \left(1 - q_H e^{-2\gamma l}\right)^{-1} e^{-\gamma l} \quad (16)$$

where

$$p_H = \frac{4Z_w\eta}{(Z_w + \eta)(Z(l) + \eta)}, \quad q_H = \frac{(Z_w - \eta)(Z(l) - \eta)}{(Z_w + \eta)(Z(l) + \eta)} \quad (17)$$

when $Z(l) = Z_w$, then $T_E = T_H$, or

$$T = p(1 - qe^{-2\gamma l})^{-1} e^{-\gamma l} \tag{18}$$

By definition, the total shielding effectiveness is

$$\begin{aligned} S &= -20\log_{10} |T| = 20\log_{10} \frac{|(1 - qe^{-2\gamma l}) e^{\gamma l}|}{|p|} \\ &= 20\log_{10} |e^{\gamma l}| - 20\log_{10} |p| + 20\log_{10} |(1 - qe^{-2\gamma l})| \\ &= A + R + B \end{aligned} \tag{19}$$

where A, R, B are the absorption loss, reflection loss and the correction term due to successive re-reflection and this expression is the complete formula for shielding effectiveness of a single shield.

2.3. Double Shield

A double shield is developed by considering two sheets separated by an air gap as shown in Figure 3.

Generally double shields are used to improve shielding effectiveness. Considering importance of two shielding sheets separated by an

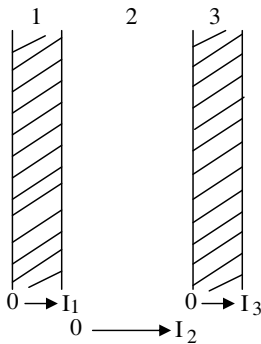


Figure 3. Double shield.

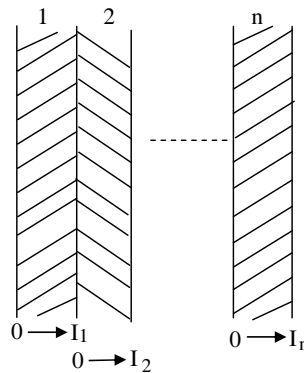


Figure 4. Multilamina shielding.

air space; $n = 3$, $\eta_2 = Z_w$, $\alpha_2 = 0$ and $\gamma_2 = \frac{j2\pi}{\lambda_0}$. Then

$$p = \frac{16Z_w^2\eta_1\eta_3}{(Z_w + \eta_1)^2(Z_w + \eta_3)^2} \quad (20)$$

$$Z(l_2) = \eta_3 \frac{Z_w \cosh \gamma_3 l_3 + \eta_3 \sinh \gamma_3 l_3}{\eta_3 \cosh \gamma_3 l_3 + Z_w \sinh \gamma_3 l_3} \quad (21)$$

$$Z(l_1) = Z_w \frac{Z(l_2) \cosh \beta_0 l_2 + jZ_w \sinh \beta_0 l_2}{Z_w \cosh \beta_0 l_2 + jZ(l_2) \sinh \beta_0 l_2} \quad (22)$$

$$q_1 = \frac{(\eta_1 - Z_w)[\eta_1 - Z(l_1)]}{(\eta_1 + Z_w)[\eta_1 + Z(l_1)]} \quad (23)$$

$$q_2 = \frac{(Z_w - \eta_1)[Z_w - Z(l_2)]}{(\eta_1 + Z_w)[Z_w + Z(l_2)]} \quad (24)$$

$$q_3 = \frac{(\eta_3 - Z_w)^2}{(\eta_3 + Z_w)^2} \quad (25)$$

where p is the transmission coefficient across the interfaces, q_1 , q_2 and q_3 are the reflection coefficients at the three interfaces and $Z(l_1)$ and $Z(l_2)$ are the impedances looking to the right of $x = l_1$ and l_2 plane and Z_w is the impedance of the free space.

The transmission coefficient across the double shield is given as

$$T = p \left[(1 - q_1 e^{-2\gamma_1 l_1}) (1 - q_2 e^{-2j\beta_0 l_2}) (1 - q_3 e^{-\gamma_3 l_3}) \right]^{-1} e^{-\gamma_1 l_1 - j\beta_0 l_2 - \gamma_3 l_3} \quad (26)$$

And the shielding effectiveness is given by

$$S = -20 \log_{10} |T| \quad (27)$$

2.4. Laminated Shield

To develop the theory for any number of multiple sheets or laminations of a single sheet, as illustrated in Figure 4, the approach beginning with Equation (20) may be extended.

Let the constants of a typical sheet be η_m , γ_m , l_m ; let the impedance looking to the right of each section be $Z(l_m)$; let Z_w be the characteristic impedance of the incident wave. Then the transmission coefficient for E or H field across the laminate is [11, 12]

$$T = p \left[(1 - q_1 e^{-2\gamma_1 l_1}) (1 - q_2 e^{-2\gamma_2 l_2}) \dots (1 - q_n e^{-\gamma_n l_n}) \right]^{-1} e^{-\gamma_1 l_1 - \gamma_2 l_2 \dots - \gamma_n l_n} \quad (28)$$

where

$$p = \frac{(2\eta_0)(2\eta_1) \dots (2\eta_n)}{(Z_w + \eta_1)(\eta_1 + \eta_2) \dots (\eta_n + Z_w)} \quad (29)$$

$$q_m = t \frac{(\eta_m - \eta_{m-1}) [\eta_m - z(l_m)]}{(\eta_m + \eta_{m-1}) [\eta_m + z(l_m)]} \tag{30}$$

3. RESULTS

In this paper copper, aluminum and conductive polymer are considered as materials of single and double shields. The laminated shields

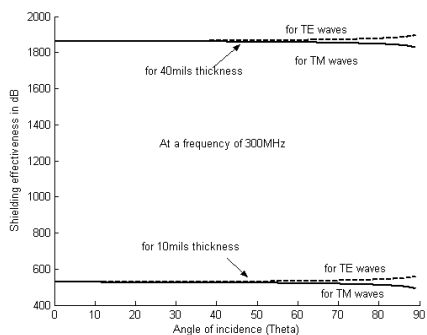


Figure 5. Variation of the shielding effectiveness with Angle of incidence of single shield of Aluminum with 10 mils & 40 mils thickness.

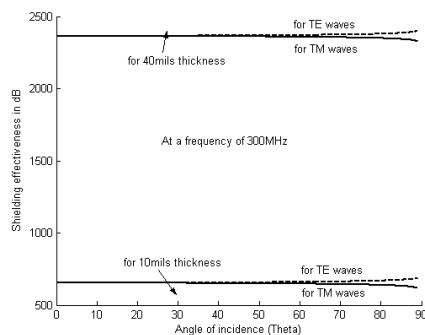


Figure 6. Variation of the shielding effectiveness with Angle of incidence of single shield of copper with 10 mils & 40 mils thickness.

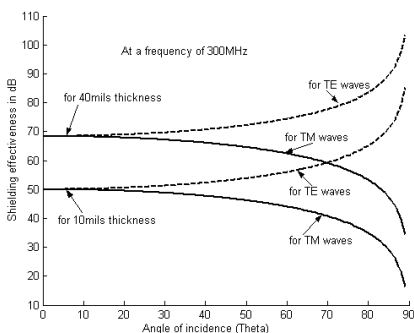


Figure 7. Variation of the shielding effectiveness with angle of incidence of single shield of polymer E with 10 mils & 40 mils thickness.

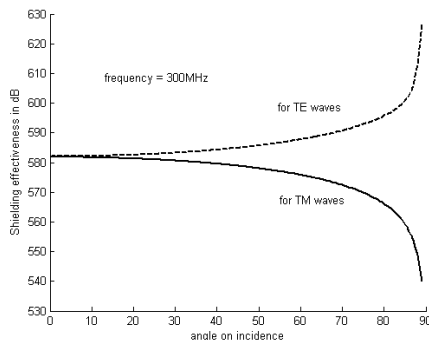


Figure 8. Variation of the shielding effectiveness with Angle of incidence of aluminium-free Space-Aluminium double shield with 5 + 10 + 5 mils thickness.

are considered as the combination of three layers constructed using conductive polymer, i.e., polyacetylene with mnemonic E listed in Table 1 and conducting materials like copper and aluminum. The angle of incidence of both Transverse Electric waves and Transverse Magnetic waves is considered for analyzing shielding effectiveness of all three types of shields.

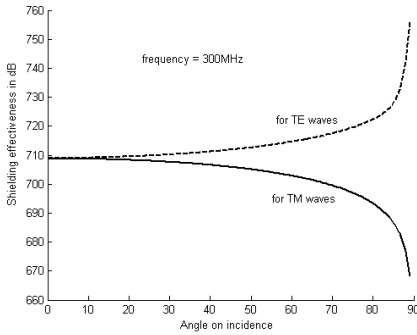


Figure 9. Variation of the shielding effectiveness with Angle of incidence of Copper-Free Space-Copper double shield with 5+10+5 mils thickness.

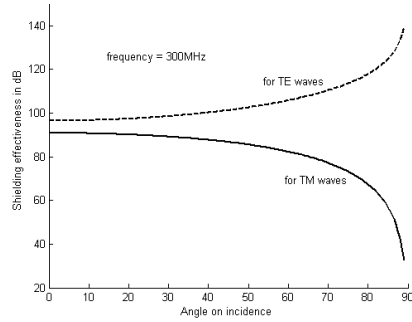


Figure 10. Variation of the shielding effectiveness with angle of incidence of Polymer E-Free Space-Polymer E double shield with 5 + 10 + 5 mils thickness.

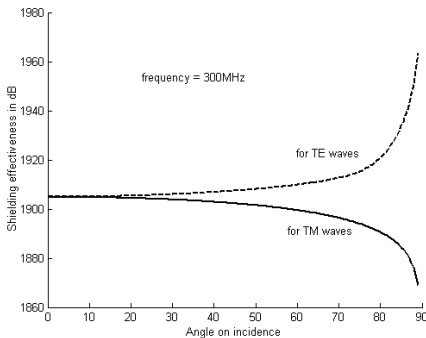


Figure 11. Variation of the shielding effectiveness with Angle of incidence of Aluminium-Free Space-Aluminium double shield with 20 + 10 + 20 mils thickness.

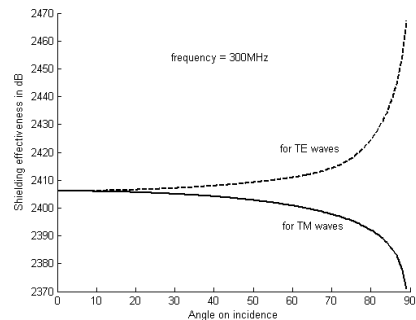


Figure 12. Variation of the shielding effectiveness with Angle of incidence of Copper-Free Space-Copper double shield with 20 + 10 + 20 mils thickness.

The shielding effectiveness of single and double shields is calculated against angle of incidence using Eqs. (19) & (27). Figures 5 to 7 depict the polarization and angle dependencies of the shielding effectiveness of single shields of copper, aluminum and conductive polymer with total thickness of 10 mils and 40 mils. In the same manner the analysis of double shields is done and is represented in Figures 8 to 13, both for perpendicular and parallel polarization.

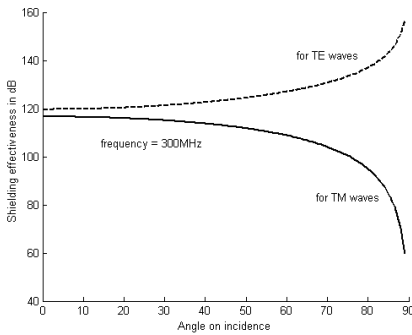


Figure 13. Variation of the shielding effectiveness with Angle of incidence of Polymer E-Free Space-polymer E double shield with 20 + 10 + 20 mils thickness.

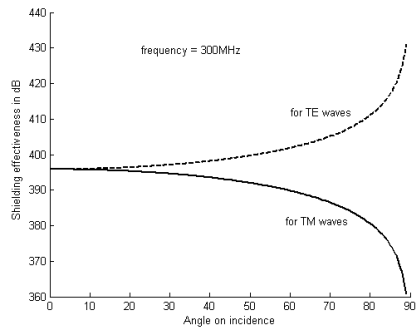


Figure 14. Variation of the shielding effectiveness with Angle of incidence of Copper-Polymer E-Copper laminate shield with 2.5 + 5 + 2.5 mils thickness.

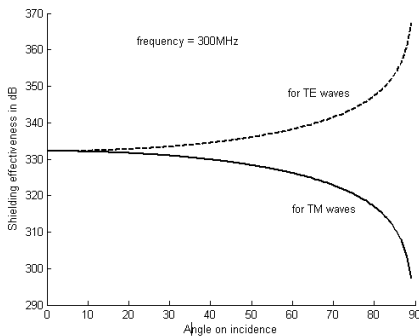


Figure 15. Variation of the shielding effectiveness with Angle of incidence of Al-Polymer E-Al laminate shield with 2.5 + 5 + 2.5 mils thickness.

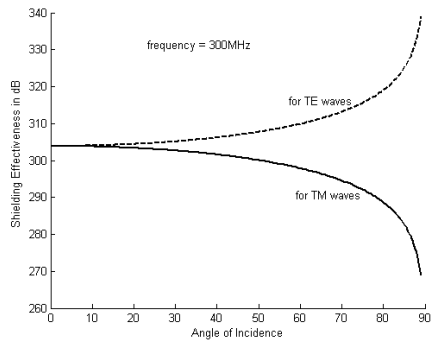


Figure 16. Variation of the shielding effectiveness with Angle of incidence of Polymer E-Al-Polymer E laminate shield with 2.5 + 5 + 2.5 mils thickness.

The shielding effectiveness of laminated shield is calculated against angle of incidence using Eq. (27). The angle dependence of the shielding effectiveness S computed for laminated shields constructed with thin sheets of the polymer with mnemonic E listed in Table 1 and conducting materials like copper and aluminum. These laminated shields considered as the combinations of copper-polymer E-copper, polymer E-copper-polymer E, aluminum-polymer E-aluminum and

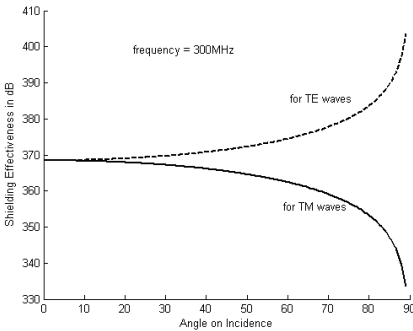


Figure 17. Variation of the shielding effectiveness with Angle of incidence of Polymer E-Cu-Polymer E laminate shield with 2.5 – 5 – 2.5 mils thickness.

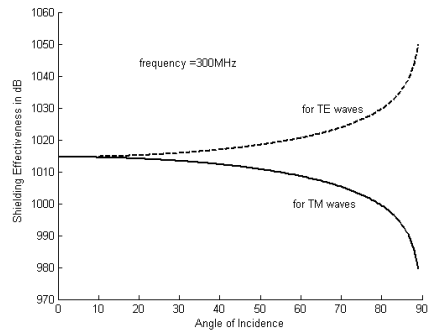


Figure 18. Variation of the shielding effectiveness with Angle of incidence of Al-Polymer E-Al laminate shield with 10 + 20 + 10 mils thickness.

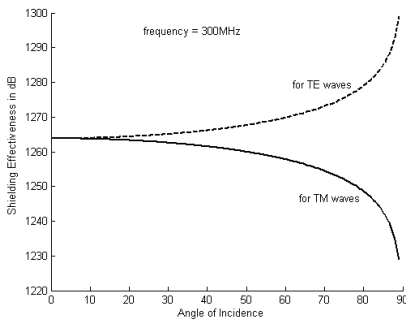


Figure 19. Variation of the shielding effectiveness with Angle of incidence of Copper-Polymer E-Copper laminate shield with 10 + 20 + 10 mils thickness.

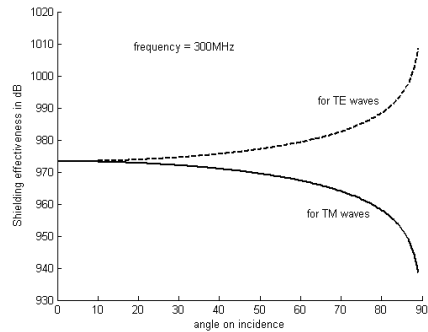


Figure 20. Variation of the shielding effectiveness with Angle of incidence of Polymer E-Al-Polymer E laminate shield with 10 + 20 + 10 mils thickness.

polymer E-aluminum-polymer E with the thickness of 40 mils (1 mm) and 10 mils. The frequency dependence of shielding effectiveness of all four types of laminated shields with total thickness of 1 mm and 10 mils are represented in Figures 18 to 21. In this analysis, the important consideration is that each laminated shield is constructed with equal thicknesses of polymer E and metal.

Table 2. The total variation of Shielding effectiveness for single, double and laminated shields of materials Aluminum, Copper and Polymer-E for different layer thicknesses of 10 mils and 40 mils at a frequency of 300 MHz for an oblique incidence of 0° to 89° for different polarizations.

Type of shield	Material considered	Total variation in shielding effectiveness in dB for different polarizations			
		Thickness 10 mils		Thickness 40 mils	
		Perpendicular	Parallel	Perpendicular	Parallel
Single shield	Aluminum	37	33	37	34
	Copper	36	35	34	34
	Polymer E	35	33	45	33
Double shield	Cu-free space-Cu	50	41	60	36
	Al-free space-Al	46	44	65	35
	polyE-freespace-polyE	42	60	40	58
Laminated shield	Al-polyE-Al	36	34	36	34
	polyE-Al-polyE	35	35	34	35
	Cu-polyE-Cu	34	35	35	35
	polyE-Cu-polyE	36	35	35	34

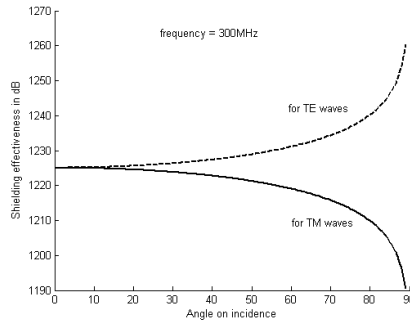


Figure 21. Variation of the shielding effectiveness with Angle of incidence of Polymer E-Cu-Polymer E laminate shield with 10+20+10 mils thickness.

4. CONCLUSION

The shielding effectiveness of single, double and laminated shields constructed with conductive polymer, metals such as copper and aluminum is evaluated using transmission line theory. Better shielding is possible for perpendicular polarization than for parallel polarization. Shielding effectiveness increases with the angle of incidence for perpendicular polarization and decreases for parallel polarization.

The shielding effectiveness is more than doubled for double shields when compared with single shields of same thickness. It is interesting to note that the shielding effectiveness is practically independent of the angle of incidence (less than 2 dB change) for angles from normal incidence to about 30° in both cases i.e., perpendicular and parallel polarizations.

The total variation in shielding effectiveness with respect to angle of incidence from 0° to 89° is represented in Table 2. The value of shielding effectiveness is increased from single to double and to laminated shield.

The computed results of the transmitted field as a function of angle of incidence for different combinations of materials indicate that the laminated shields perform well as EM1 shields over a substantial frequency band.

All four laminated shields exhibit less shielding effectiveness (approximately 400 dB) for a thickness of 10 mils, and it is drastically increased for a thickness of 40 mils. From Figures 18 and 20, it is observed that there is no much difference in the shielding effectiveness (approximately 40 dB) of laminated shields of Polymer E-Al-Polymer E or Al-Polymer E-Al.

When we compare metals with polyacetylene on a basis of the conductivity/weight ratio CW, it can be seen that laminated shields constructed with the combination of conductive polymers and metals like copper and aluminum have already reached the same level as many metals. Therefore laminated shields with conductive polymers appear to be a viable alternative to metals in lightweight shielding applications. From the above analysis an electromagnetic shield can easily be designed to achieve required shielding effectiveness against angle of incidence of an electromagnetic wave.

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REFERENCES

1. Naarman, H., "Synthesis of new conductive electronic polymers," *Proc. Int. Cong. Synthetic Metals*, Kyoto, Japan, June 1986.
2. Ehinger, K., S. Summerfield, W. Bauhofer, and S. Roth, "DC and microwave conductivity of iodine-doped polyacetylene," *J. Phys. C: Solid State Phys.*, Vol. 17, 3753–3762, 1984.
3. Naishadham, K. and P. K. Kadaba, "Measurement of the microwave conductivity of a polymeric material with potential applications in absorbers and shielding," *IEEE Trans. Microwave Theory Technol.*, Vol. 39, 1158–1164, July 1991.
4. William, J., "Shielding tests for cables and small enclosures in the 1- to 10-GHz range," *IEEE Trans. Electromagnetic Compatibility*, Vol. 12, 106–112, February 1970.
5. Konefal, T., J. F. Dawson, and A. C. Marvin, "Improved aperture model for shielding prediction," *IEEE International Symposium on Electromagnetic compatibility*, 187–192, 2003.
6. Prasad Kodali, V., *Engineering Electromagnetic Compatibility, Principles, Measurements and Technologies*, S. Chand & Company Ltd., 2000.
7. Paul, R. C., *Introduction to Electromagnetic Compatibility*, John Wiley Interscience, New York, 1992.
8. Yasumitsu, M. and T. Koki, "Electromagnetic absorption and

- shield properties of lossy composite multilayers,” *IEEE Trans. Electromagnetic Compatibility*, Vol. 32, 370–374, August 1990.
9. Schulz, R. B., V. C. Plantz, and D. R. Brush, “Shielding theory and practice,” *IEEE Trans. Electromagnetic Compatibility*, Vol. 30, 187–201, August 1988.
 10. Kiang, J.-F., “Shielding effectiveness of single and double plates with slits,” *IEEE Transactions on Electromagnetic Compatibility*, Vol. 39, No. 3, 260–264, August 1997.
 11. Jayasree, P. V. Y., et al., “Shielding effectiveness of laminated shields,” *Journal of Radio Engineering*, Vol. 17, No. 4, December 2008.
 12. Jayasree, P. V. Y., et al., “Shielding effectiveness of conductive polymers against EM fields — A case study,” *IE(I) Journal — ET*, Vol. 90, July 2009.