Shielding Effectiveness Analysis of Multilayer Carbon-Fiber Composite Materials

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Abstract

In this paper, the plane-wave shielding effectiveness (SE) of multilayer composite materials is investigated. The SE of multilayer composite laminates is obtained analytically by using the equivalent anisotropic model of each layer along with the transmission matrix method (TMM). The SE sensitivity analysis is performed as a function of fiber orientation and plane wave polarization. Moreover, the experimental results of three fabricated composites are reported to evaluate the effect of orientation pattern on the shielding properties.

1. Introduction

Recently, advanced composite materials have been used in many industrial and military applications as a good replacement for metals. A typical fiber composite material is composed of a resin reinforced by oriented fibers. In addition to low fabrication cost, composites have a higher strength-to-weight ratio compared to metals. However, due to the limited conductivity, the SE of composite materials is much less than that of metals. Hence, the shielding properties of composite materials should be analyzed in detail. From the electromagnetic compatibility (EMC) point of view, since for most applications the shielded device is under far electromagnetic field exposure, the plane wave shielding effectiveness is adequate for analysis. The SE of multilayer composites highly depends on the fabrication process, distribution and the kind of fibers (long or short fibers) in the composite structure. Moreover, the full-wave numerical solutions use a very fine discretization step which leads to a very time-consuming process. Therefore, due to the complex structure of composites, the high-accurate equivalent model is defined and characterized to calculate SE and electrical parameters in the desired frequency range [1-5]. Volski obtains the SE of arbitrarily oriented fiber carbon composites by proposing the equivalent periodic model of crossed strips [1]. In [2], a lossy isotropic model for multilayer conductive composites has been introduced. In [3], Lin and Chen calculate the plane wave shielding properties of multilayer reinforced composites using the homogeneous anisotropic model of the structure. In [4, 5], the more accurate inhomogeneous anisotropic model is introduced for each layer which can capture resonances at higher frequencies. As discussed in [3-5], the composite layer reinforced by oriented conductive fibers shows the anisotropic behavior along the orientation direction. As a result, the anisotropic model of layers enables us to calculate the SE of reinforced composites with fast computational time and acceptable accuracy. For design purposes and to achieve a good shielding behavior, it would be very useful to carry out a parametric study on the composites performance. This can be performed by evaluating the effect of physical parameters of composites (e. g. fiber diameter, separation distance between fibers, fiber orientation, layer thickness, etc.) and incident wave parameters (angle of incidence and wave polarization) on the shielding performance.

In this paper, we evaluate the effect of fiber orientation pattern and incident plane wave parameters on the SE of multilayer composites. Following [3-5], we consider the homogeneous anisotropic model of the structure for SE calculations. Furthermore, the measured SE of some fabricated samples with different orientation patterns is reported. The organization of this paper is as follows. In section 2, the multilayer anisotropic model and transmission matrix method (TMM) are discussed briefly. In section 3, the parametric study and measurement results are reported. Finally, the paper is concluded in section 4.

2. Anisotropic Equivalent Model

A typical multilayer (*N*-Layer) reinforced composite consisting of resin and oriented fibers is displayed in Fig. 1(a). The fibers are reinforced in the desired orientation in each layer. The layers are modeled by the anisotropic medium with appropriate electrical parameters tensor as shown in Fig. 1(b). In the anisotropic model of layer *i*, the orientation effect of the reinforced fibers is accounted for in the related permittivity tensors ($\bar{\varepsilon}_i, \bar{\sigma}_i$) by applying a

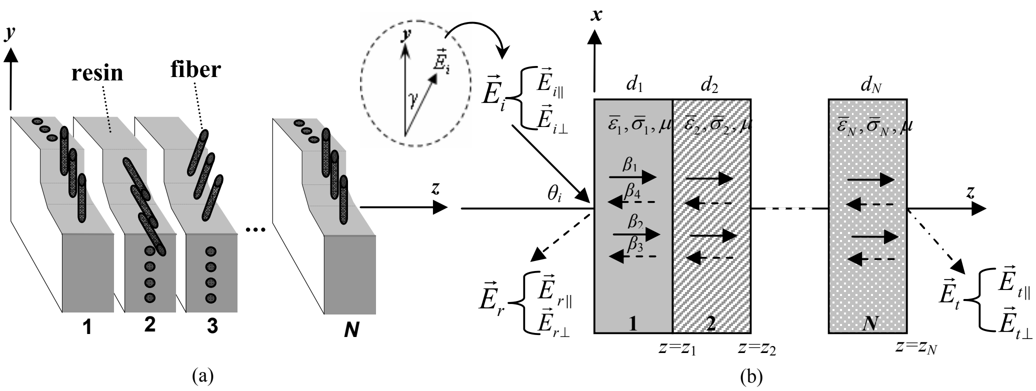


Fig. 1. (a) Typical reinforced multilayer composite, (b) Anisotropic model.

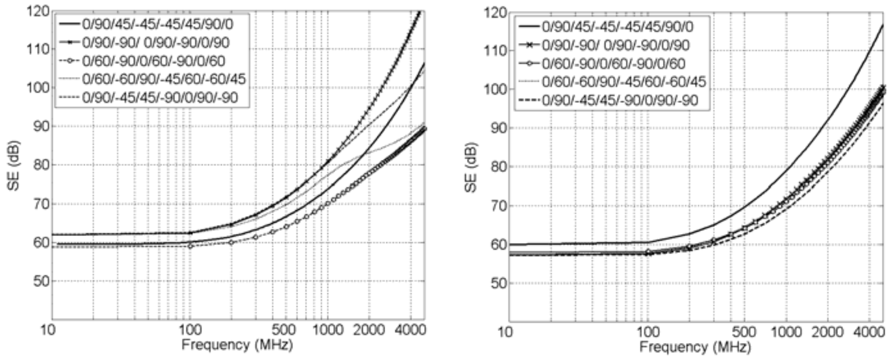
coordinate transform matrix [3]. The incidence and polarization angle of plane wave are θ_i and γ, respectively. When $\gamma = 0^\circ$, the electric field is perpendicular to the plane of incidence ($E\perp$). Similarly, for $\gamma = 90^\circ$ the electric field is parallel to the plane of incidence ($E_{\|}$). The TMM [6] is used to obtain the transmitted fields ($\vec{E}_{t\|}, \vec{E}_{t\perp}$) in terms of incident field components ($\vec{E}_{i\|}, \vec{E}_{i\perp}$). In a multilayered anisotropic media, the electromagnetic field consists of four propagated waves with β_1, β_2, β_3 and β_4 propagation constants. This is due to the anisotropy property of the media which leads to the coupling between propagating modes. Therefore, we have 4×4 matrix formulation using the TMM rather than 2×2 matrices for the isotropic case. The electric field in each layer can be expressed as follows,

$$\vec{E} = \sum_{i=1}^{4} C_{im}\, \vec{e}_{im}\, e^{-j(\alpha x + \beta_{im}(z - z_m) - \omega t)}\ ,\ m = 1, 2, ..., N \tag{1}$$

where $\vec{e}_i$ and C_i are the polarization vector and unknown coefficients of the electric field, respectively. The polarization vector $\vec{e}_i$ and propagation constants (β_i) are calculated from the wave equation in each layer. The magnetic fields can be obtained from Maxwell equations. By imposing the boundary conditions for tangential components of the electric and magnetic fields at different interfaces ($z = z_i$), the C_i coefficients and subsequently the relation among transmitted and incident waves can be derived.

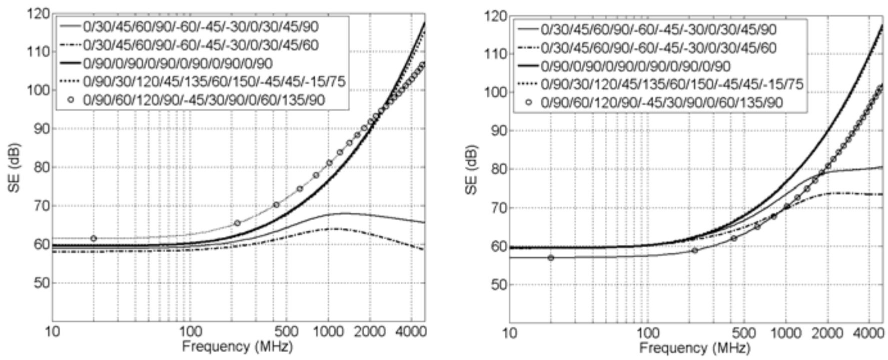
3. Numerical and Experimental Results

Using the equivalent anisotropic model, the SE of 1mm-thick 8-layer and 12-layer composites are calculated for different fiber orientation patterns in Figs. 2 and 3, respectively. The dielectric constant is considered as 3.3 for all layers and the conductivity tensor in principal coordinate is $\bar{\sigma} = (10000, 0.1, 0.2)\, S/m$ for all cases. It can be observed that at frequencies greater than 1 GHz, we have more than 10 dB difference between SE for various orientation patterns in both $E\perp$ and $E_{\|}$ cases. It can be explained as follows. Due to the coupling between modes in anisotropic layers, both electric field E_x and E_y components always exist independent of incident plane wave polarization. Hence, the different orientation patterns have different effect on the attenuation of these components. On the other hand, the orientation of fibers can be used to control the shielding effectiveness of multilayer composites at the frequency range of interest. It should be noted that the SE calculated in Figs. 2 and 3 is just for $E\perp$ and $E_{\|}$ modes which are correspond to $\gamma = 0^\circ$ and $\gamma = 90^\circ$, respectively. In Fig. 4(a), the effect of the polarization angle (γ) is evaluated on SE of two typical 8-layer (0/30/60/90/90/60/30/0) and 12-layer (0/30/45/90/-45/-30/0/30/45/90/-45/-30) composite materials. It can be seen that the SE changes considerably at higher frequencies with the polarization angle γ. The effect of incident angle (θ) on SE is calculated for $E\perp$ and $E_{\|}$ modes in Figs. 5(a) and (b), respectively. It is observed that SE decreases for $E_{\|}$ and increases for $E\perp$ as the incident angle increases. The reflection coefficient between air and a highly lossy material decreases in $E_{\|}$ case by increasing the incident angle from zero up to the angles close to the grazing incidence [7]. As a result, the power transmission increases for $E_{\|}$ mode versus incident angle. Contrarily, the transmission coefficient and as a result SE decreases in $E\perp$ case versus incident angle. Furthermore, SE of three fabricated composite samples is measured using coaxial cable fixture as shown in Fig. 6. The samples are two 4.5mm-thick 12-layer and one 6mm-thick 24-layer reinforced composites. Even though the thickness of 24-layer sample is greater than the 12-layer samples, the SE of 24-layer composite is much less than 12-layer ones. It is owing to this fact that the fiber orientations of all layers in 24-layer sample are in the same direction which is not suitable to attenuate electric field components appropriately.



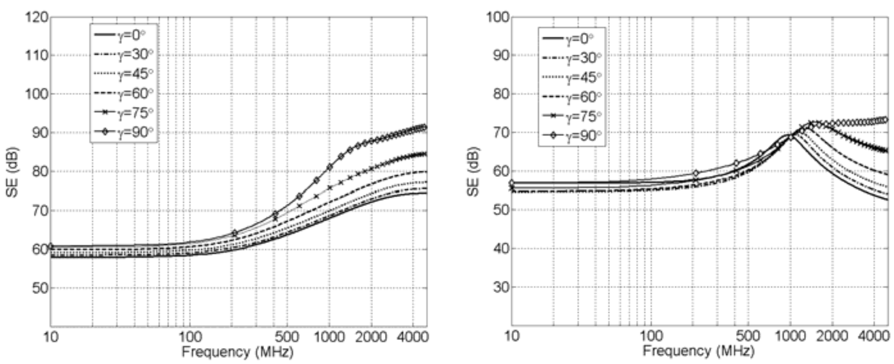
(a) (b)

Fig. 2. SE of 8-layer reinforced composite material, (a) perpendicular *E*-field ($E\perp$), (b) parallel *E*-field ($E_{\|}$).



(a) (b)

Fig. 3. SE of 12-layer reinforced composite material, (a) perpendicular *E*-field ($E\perp$), (b) parallel *E*-field ($E_{\|}$).

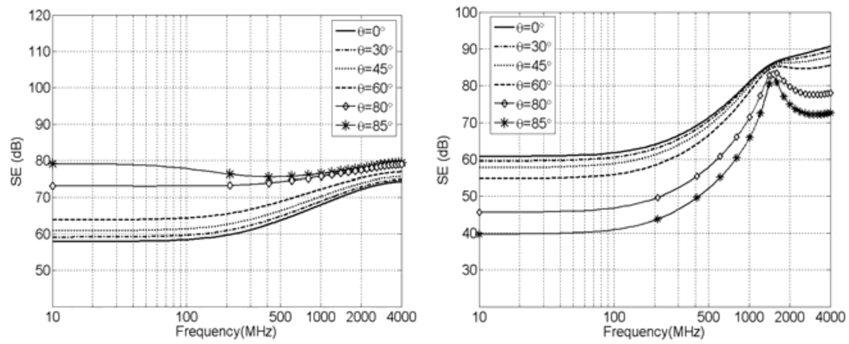


(a) (b)

Fig. 4. The effect of polarization angle on SE, (a) 12-layer and (b) 8-layer composites.

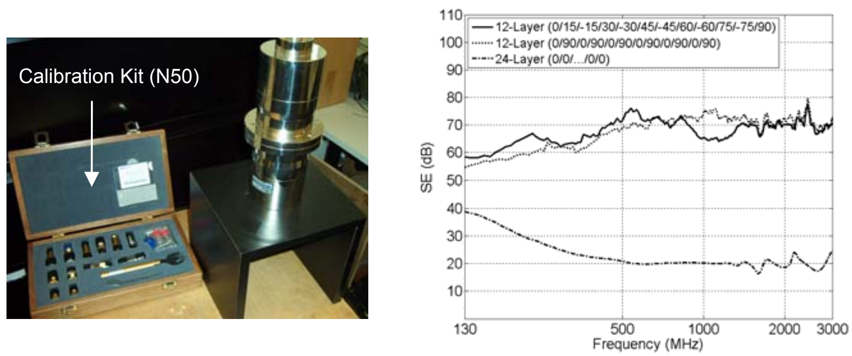
4. Conclusion

The effect of orientation pattern and incident plane wave parameters on shielding effectiveness of multilayer composites is studied in this paper. Due to the complex structure of the reinforced composites and to avoid the time-consuming full-wave methods, the equivalent transmission line model of structure is used to analyze the shielding characteristics. It is shown, both numerically and experimentally, that using different orientation patterns in the multilayer composites controls the shielding properties of the structure. The effect of incident angle is different on the shielding of perpendicular ($E\perp$) and parallel ($E_{\|}$) modes. Moreover, the effect of incident plane wave polarization angle was evaluated for two typical multilayer composites. It is observed that shielding effectiveness varies considerably at higher frequencies for different polarization angles.



(a) (b)

Fig. 5. The effect of incident angle on SE, (a) $E_\perp$ and (b) $E_\parallel$.



(a) (b)

Fig. 6. (a) Coaxial cable fixture, (b) Measured SE of fabricated samples.

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6. References

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