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Microwave Reflective Properties of Carbon Fiber-Epoxy Composites

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탄소섬유-에폭시 복합재료의 전파반사 특성

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초 록 탄소섬유-에폭시 복합재료의 전파 반사특성을 전파전송 이론에 근거하여 해석하였다. 탄소섬유 복합재료의 유전상수를 투과/반사법에 의해 4-12GHz 주파수 범위에서 측정하였다. 측정된 재료정수로부터 반사손실을 시편의 두께와 주파수의 함수로 계산하였다. 탄소섬유 복합재료는 높은 유전상수와 도전손실 특성에 의해 전파의 반사율이 매우 높았다. 그러나 파장에 비해 시편의 두께가 작은 경우 반사손실은 두께에 매우 민감하였으며, 이는 입력 임피던스의 변화에 기인하는 것으로 해석되었다. 이러한 결과로부터 전자파 차폐를 극대화시키기 위해서는 특히 저주파 대역에서 시편의 두께 조절이 매우 중요함을 제시할 수 있었다.

Abstract Microwave reflective properties of carbon fiber-epoxy composites are analyzed on the basis of wave propagation theory. Dielectric constant is determined by the reflection/transmission technique in 4-12 GHz frequency range. From the measured material constants, the microwave reflection loss has been calculated as a function of plate thickness and frequency. Because of high dielectric constant and conduction loss, the carbon fiber composites exhibit a relatively high microwave reflectance. However, large fluctuation in the reflection loss is predicted at a small normalized thickness with respect to the wavelength, which is attributed to the variation of input impedance with the plate thickness. It is suggested that the determination of plate thickness is important to obtain the maximum wave reflection especially in the low frequencies.

1. Introduction

Widespread use of electric and electronic circuits for various purposes makes it necessary for circuit designers to control the EMI (Electro-Magnetic Interference) problems. One of the EMI reduction technique is shielding the noise source to prevent the noise radition or shielding the equipment to prevent the noise infiltration from the outside[1]. Metallic sheets are commonly used as a shielding material. Recently many attempts were made to replace the metals by light-weighted and easily-workable polymer composites as a shielding material[2~3]. Ferrite powders with magnetic loss and conductive metal or carbon powders are used as the absorbent filler in a rubber or resin matrix[3~4]. Those fillers in the form of equiaxed powders have a lower microwave shielding capability due to the lower conduction loss. Continueous carbon fibers of high aspect ratio have advantages in both high electrical conductance and conduction loss along its longitudinal axis[5~6]. Therefore, the carbon fiber reinforced composites can be considered as a good candidate of the microwave shielding material. However, the experimental results and theoretical analysis on microwave properties (reflection, absorption) of carbon fiber reinforced composites are quite poor.

The purpose of this study is to investigate the microwave reflective properties of carbon fiber composite materials for the application to electromagnetic shielding at high frequencies. Dielectric constant and permeability spectrum was measured in 4-12 GHz frequency range. On the basis of theory of wave propagation in a lossy media, the reflection loss from the composite layer was predicted as a function of frequency and layer thickness.

2. Experimentals

Carbon fiber-epoxy composites were prepared by lamination technique with commercially available 8-harness fabric carbon fiber prepreg and Bisphenol-A type epoxy resins. The carbon fiber fabric was cut by 15x15 cm^2 and dipped in epoxy resin. The fiber content was about 60 wt%. After drying at 80 ℃ in vacuum oven, the prepregs were laminated using uniaxial press with automatic temperature and pressure controller. The lamination temperature was 130 ℃.

The dielectric constant and permeability were determined by using HP/8720B network analyzer. Measurements were made in the C and X-band frequencies (4–12 GHz). The precisely machined toroidal samples were inserted between the inner and outer conductors of standard coaxial line. The complex permittivity and permeability can be determined from the measured reflected and transmitted scattering parameters$^{7)}$.

3. Results and Discusson

Fig. 1 shows the complex permeability ($\mu_r' - j\mu_r''$) and permittivity ($\varepsilon_r' - j\varepsilon_r''$) spectra observed in the carbon fiber-epoxy composite specimen. High dielectric constant with considerable loss was observed in this specimen. Real part of permittivity (ε_r') is a slightly decreasing function of the frequency (from 24 at 4 GHz to 15 at 12 GHz). Imaginary part (ε_r''), which corresponds to the conduction loss, increses slightly with the increase of frequency (4 at 4 GHz, 8 at 12 GHz). Nearly constant value of μ_r' (equal to free-space permeability) was observed and μ_r'' is negligibly small, which is attributed to the nonmagnetic property of carbon fibers and epoxy resins. The observed high dielectric constant is coming from the space-charge polarization between the parallel carbon fibers and the longitudinal current flow along the fibers induces the large amount of conduction loss.

When a composite layer having a low characteristic impedance (low permeability and high dieletric constant as in carbon fiber composites) is illuminated by incident plane wave, a microwave reflection occurs at the front surface of the plate because of impedance-mismatching. The amplitude of the reflected wave (E_r) is related to the amplitude of the incident wave (E_i) by the reflection coefficient (Γ), defined by

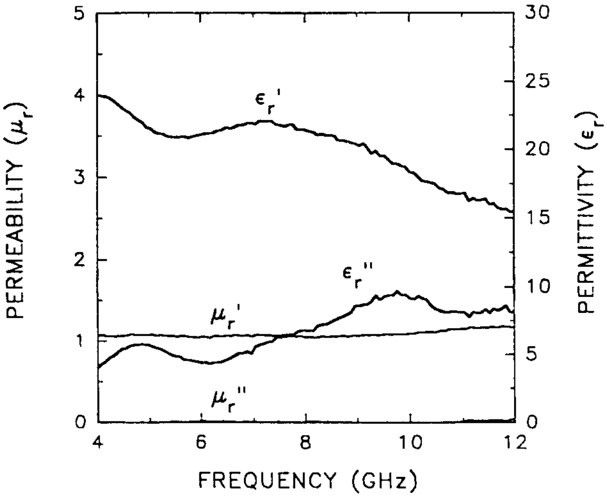

Fig. 1. Complex dielectric constant and permeability of carbon fiber-epoxy composite.

$$\Gamma = (E_r/E_i) \qquad (1)$$

The power reflectance, in decibels, is then given by

$$\text{reflection loss} = 20 \log |\Gamma| \qquad (2)$$

For normal-incidence, the reflection coefficient is determined by the input impedance at the layer surface (Z_{in}) and free-space impedance (Z_0= 376.7 Ω), which is given by

$$\Gamma = \frac{Z_{in} - Z_0}{Z_{in} + Z_0} \qquad (3)$$

where,

$$Z_{in} = Z_c \times \frac{Z_0 + Z_c \tanh \nu d}{Z_c + Z_0 \tanh \nu d} \qquad (4)$$

In Equation (4), Z_c is characteristic impedance, ν is a propagation constant, and d is the thickness of composite layer. Z_c and ν are functions of μ_r and ε_r, expressed as

$$Z_c = Z_0\sqrt{\frac{\mu_r}{\varepsilon_r}} \qquad (5)$$

$$\nu = j\omega\sqrt{\mu_0\varepsilon_0}\ \sqrt{\mu_r\varepsilon_r} \qquad (6)$$

where, ω is angular frequency, μ_0 and ε_0 are permeability and permittivity of free-space, respectively.

Fig. 2 shows the reflection loss calculated from the material constants by using the Equation (2). It is evident that the reflection loss is greatly dependent upon the plate thickness and frequency. The result is attributed to the variation of input impedance with the plate thickness and frequency as seen in the Equation (4). The variation of permittivity with frequency (shown in Fig. 1) gives rise to frequency-dependent characteristic impedance and propagation constant as seen in Equations (5) and (6), which, in turn, influence the microwave reflectance at a given thickness.

Fig. 3 shows the variation of reflection loss according to the different layer thickness at a given frequency. The reflection loss varies periodically with an average value of about -4 dB. The deviation from the average value is greater at a lower frequency and at a smaller thickness. The maximum wave reflection occurs at a

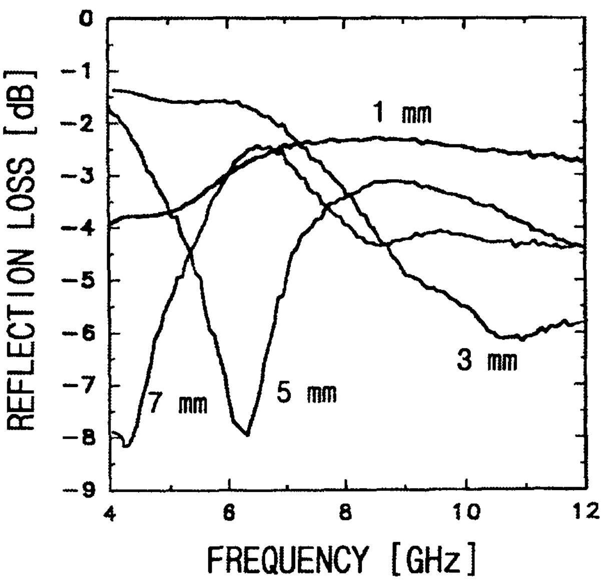

Fig. 2. The frequncy dependence of the reflection loss predicted in the carbon fiber-epoxy composite.

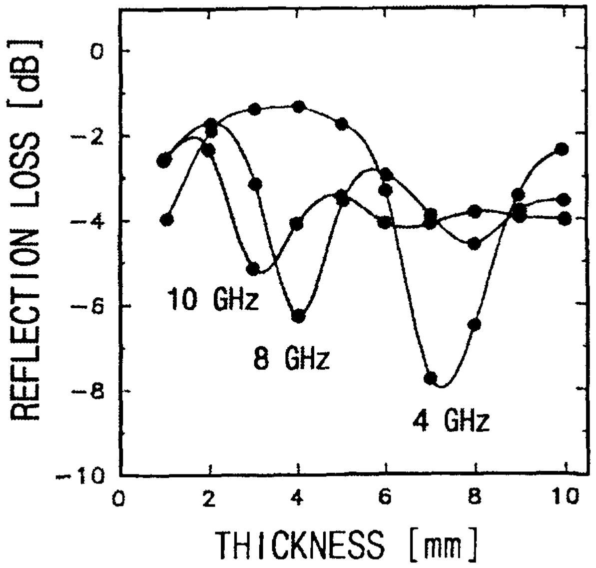

Fig. 3. The variation of reflection loss with the thickness of carbon fiber-epoxy composite.

middle point of the first half cycle (d= 3.5 mm at 4 GHz, d=2.0 mm at 8 GHz and d=1.5 mm at 10 GHz) and the minimum reflection loss is at the middle point of the second half cycle. The deviation decreases toward the average value as the thickness increases, which is more clearly seen at high frequency.

It can be seen from Equation (3) that the reflected power increases as the input impedance at the plate surface is reduced. Since the rear face of the sample is open to free space (which can be considered as a transmission line with the resistive load; $Z_o > Z_L$), the voltage minimum is at $\lambda/4$ distance from the load[8]. Therefore, the maximum wave reflection is expected when the plate has a quarter-electrical-wavelength thickness.

For a lossy media, the wavelength is expressed as[9]

$$\lambda = \frac{c}{\sqrt{2}f}[(\mu_r'^2 + \mu_r''^2)(\varepsilon_r'^2 + \varepsilon_r''^2) + (\mu_r'\varepsilon_r' - \mu_r''\varepsilon_r'')]^{-1/4} \quad (7)$$

where, f is frequency and c is velocity of light. Fig. 4 shows the calculated $\lambda/4$ value which is a decreasing function of frequency (5 mm at 4 GHz, 2 mm at 12

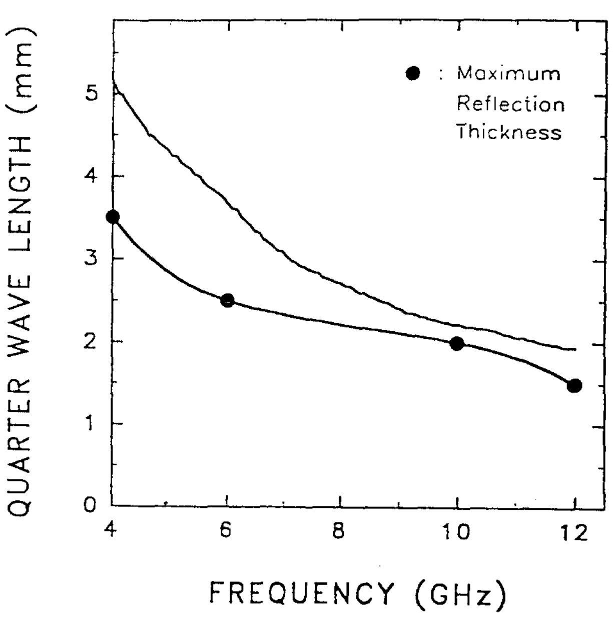

Fig. 4. The calculated $\lambda/4$ in carbon fiber-epoxy composite. The plate thickness with maximum wave reflections is also given.

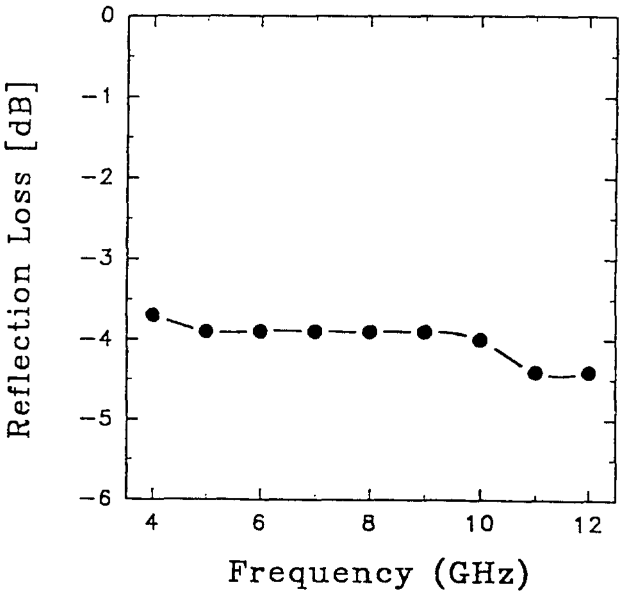

Fig. 5. The calculated microwave reflection from the carbon-fiber composite with large normalized thickness.

GHz). The layer thickness with maximum wave reflection is a little lower than the $\lambda/4$ value. The discrepancy needs a further consideration. However, the two curves exhibit a similar decreasing function of frequency.

When the plate thickness becomes large as compared to the wavelength ($d/\lambda \rightarrow \infty$), Z_{in} is equal to to the characteristic impedance ($Z_{in} = Z_c$) as seen in Equation (4). Therefore, the reflection loss is simplified into

$$reflection\ loss = 20\log \frac{Z_c - Z_o}{Z_c + Z_o} \qquad (8)$$

and thus the wave reflection is independent of thickness. Combining Equations (5) and (8) gives a result of reflection loss shown in Fig. 5. Nearly constant value of reflection loss about -4 dB is resulted. This value is consistent with the average value of reflection loss shown in Fig. 3.

4. Conclusion

This study has demonstrated that the microwave reflection from the carbon fiber composite materials is greatly dependent upon the plate thickness and frequency. Because of high dielectric constant and conduction loss, the carbon fiber composite exhibits a relatively high microwave reflectance (in average, -4 dB). However, large fluctuation in reflection loss is predicted at a smaller plate thickness as compared to the wavelength. The maximum wave reflection is expected at a specified thickness with the minimum input impedance (minimum voltage at the surface). This critical thickness is reduced as the frequency increases. When the plate thickness is large as compared to the wavelength, the reflection loss approaches the intrinsic value (about -4 dB). It can thus be suggested that the determination of plate thickness is important to obtain the maximum microwave reflection (high shielding effectiveness) especially in the low frequencies.

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