Minimization of Microwave Reflections from EC-Coated Glass Slabs

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***Abstract*— This study reports measurements and analysis of microwave reflections from the uncoated surfaces of glass slabs coated with electrically conductive (EC) films. The results show that these reflections can be minimized by varying the sheet resistance of the EC films. General design formulas to calculate such optimizing sheet resistance are given.**

***Index Terms*— Electroconductive-coated dielectric slabs, EMC/EMI, heat-reflective glass.**

I. Introduction

ELECTRICALLY conductive (EC) thin films coated on glass or other dielectric substrates are used to reflect and attenuate incident electromagnetic waves in applications such as electromagnetic pulse (EMP) and electromagnetic interference (EMI) protection as well as heat (infrared) reflection to reduce the air-conditioning load for buildings. These coated EC films are put to face the incident electromagnetic waves when used for EMP and EMI protection applications [1], [2] and are put on the interior side of the glass panels for heat-reflective applications [3]. Metal films with high electrical conductivity in the order of 10^7 S/m such as gold are used as EC-films in EMP and EMI protection applications, whereas metal oxide and metal nitride films with electrical conductivity in the order of 10^5 S/m or less are used in high-performance heat reflective glass (HPHRG).

Klein [2] gave formulas for the upper and lower limits for the effective shielding performance of an EC-coated dielectric slab, corresponding to quarter- and half-wavelength thickness of the substrates. To reduce "ghost" image effect, Niwa *et al.* [3] investigated TV signal reflections from HPHRG over the frequency range 100–800 MHz, reporting that high sheet resistance of the EC coating is needed to reduce the reflection level from the HPHRG. In this letter, we report a study on the general microwave reflection performance of the EC-coated dielectric slabs. In particular, we found that the reflections from the uncoated surfaces of EC-coated dielectric slabs can be minimized by varying the sheet resistance of EC-coating.

II. Minimization of Reflections

The structure of EC-coated glass is shown in Fig. 1(a). The EC coating can be metallic, metal nitride, or metal oxide thin films. Due to its small thickness (in the range of a few hundred

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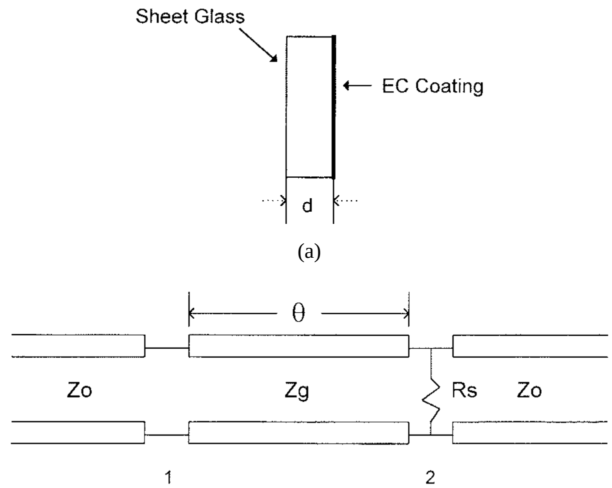

(a)

(b)

Fig. 1. (a) EC-coated glass and (b) transmission line model.

Angstroms) as compared to the microwave wavelength and its good electrical conductivity, the EC thin films can be characterized by sheet resistance R_S [2]. Therefore, we use the transmission line model shown in Fig. 1(b) to study microwave reflection and transmission properties of the EC-coated glass slabs. We denote the uncoated surface as port 1 and the coated surface as port 2.

From the transmission line theory and using the transmission matrix technique [4], we can determine the reflection coefficients from both sides of the EC-coated glass, the transmission coefficient, and the insertion loss (IL), as given below:

$$S_{11} = \frac{-G_S Y_g \cos\theta + j(Y_o^2 - Y_g^2 + G_S Y_o)\sin\theta}{(G_S Y_g + 2Y_o Y_g)\cos\theta + j(Y_o^2 + Y_g^2 + G_S Y_o)\sin\theta} \quad (1)$$

$$S_{22} = \frac{-G_S Y_g \cos\theta + j(Y_o^2 - Y_g^2 - G_S Y_o)\sin\theta}{(G_S Y_g + 2Y_o Y_g)\cos\theta + j(Y_o^2 + Y_g^2 + G_S Y_o)\sin\theta} \quad (2)$$

$$S_{21} = S_{12} = \frac{2Y_o Y_g}{(G_S Y_g + 2Y_o Y_g)\cos\theta + j(Y_o^2 + Y_g^2 + G_S Y_o)\sin\theta} \quad (3)$$

$$IL = 1.0 - |S_{11}|^2 - |S_{22}|^2 \quad (4)$$

where and Y_o and Y_g are the wave admittance of air and glass, respectively, and θ is the electrical phase shift of the slab. For uncoated glass, let $G_S = 0$ to use in the above formulas.

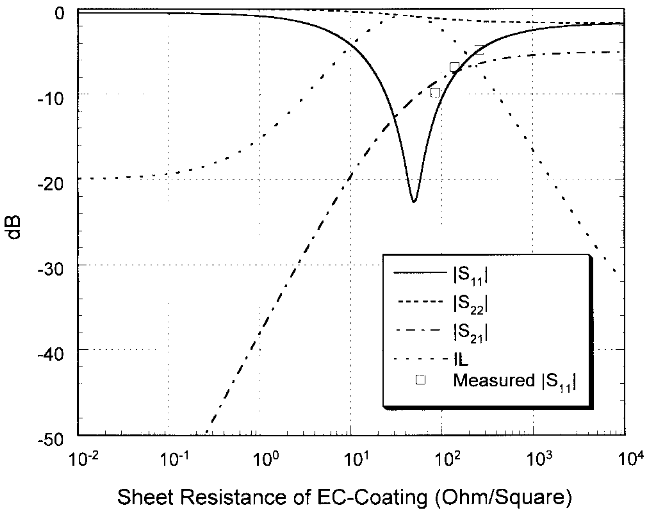

Fig. 2. Reflection, transmission, and insertion loss through EC-coated glass for TE_{10} mode at 5 GHz.

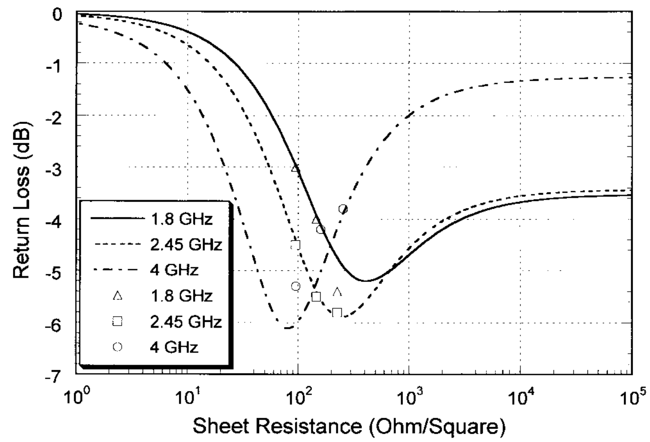

Fig. 3. Return loss of 5.75-mm HPHRG with TiN coating of 250, 300, 450 A. Experimental results: Δ, $\Box$, and O.

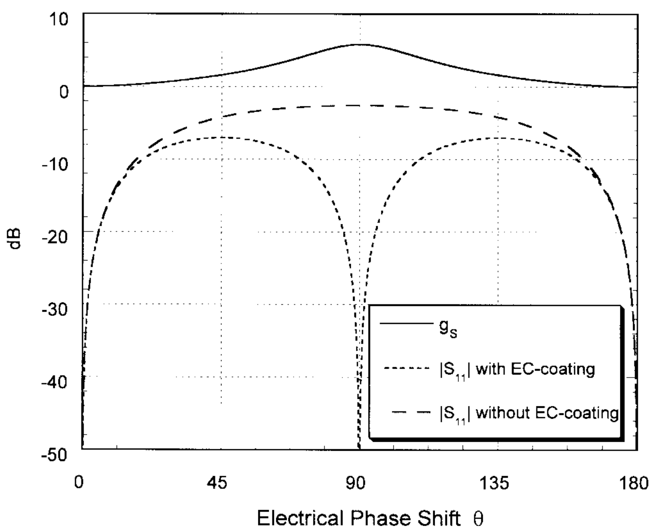

Fig. 4. Optimized g_S (numerical values) and reflection coefficient (in decibels) from the uncoated surface for normal incident plane wave on EC-coated glass with $\varepsilon_r = 6.8$.

To examine the effect of the EC-coatings on the reflection properties, we note that the only difference between S_{11} and S_{22} is the imaginary part of the numerators. For normal dielectric materials $\varepsilon_r > 1$, i.e., $Y_g > Y_o$, we can show that $|S_{22}| > |S_{11}|$, meaning that the reflection from the coated side is always higher than that from the uncoated side. Thus, the EC-films are arranged to face the incident electromagnetic waves so as to increase the return loss in EMI shielding applications.

In Fig. 2 we plot the reflection, transmission, and insertion loss of TE_{10} mode at 5 GHz in a G-band waveguide (WR-187) for a high-performance heat-reflective glass (HPHRG) as the sheet resistance of EC-film is varied. The experimental points for our three glass samples are shown to fit the curve quite well. The glass substrates used are AMG green float of thickness 5.75 mm with relative permittivity $\varepsilon_r = 6.8$ and dielectric loss tangential $\delta = 0.016$. The EC-coatings are magnetically sputtered titanium nitride films of thickness of about 250, 300, 450 A with corresponding sheet resistance of 255, 140, and 95 $\Omega/\Box$, respectively.

It is seen that there exists a minimum point about -24 dB near $R_S = 49\ \Omega/\Box$ for the reflection from the uncoated surface of the HPHRG sample. Compared to the reflection coefficient without the EC-coating of about -2 dB where $R_S = \infty$, we observe that the return loss has been reduced by about 22 dB. At this minimum point, the insertion loss peaks -0.9 dB while the transmission is about the -10.5 dB. As the EC-coating approaches the perfect electrical conductor ($R_S \to 0$), the return loss $|S_{11}|$ and the insertion loss become constants of -0.46 and -20 dB, respectively. That is caused by the dielectric loss of the glass sample.

To further verify the phenomena of minimization of reflection due to the sheet resistance of EC coating, we plot in Fig. 3 the theoretical and experimental return loss from 5.75-mm HPHRG versus R_S at three different frequencies of 1.8, 2.45, and 4 GHz. As R_S increases up to 255 $\Omega/\Box$, the return loss is reduced for frequencies 1.8 and 2.45 GHz, but increased for 4 GHz. It is clear that the EC coating can be used to minimize the microwave reflections from the uncoated surface of HPHRG.

As observed in Fig. 3, the difference between the return loss level at the minimum point and $R_S = \infty$ becomes smaller as the frequency decreases. In addition, the sheet resistance for the minimum return loss becomes larger for lower frequency. Niwa *et al.* [3] pointed out that larger sheet resistance in the order of a few kilohms is needed to reduce the reflection level for VHF and UHF bands, but they were apparently not aware of existence of a minimum reflection point.

III. Optimized Sheet Resistance

By making $(\partial|S_{11}|^2)/(\partial G_S) = 0$, we have derived the formula for calculating the optimum sheet resistance for the lossless case, as given by

$$g_S = y_g\sqrt{\frac{1 + y_g^2\tan^2\theta}{y_g^2 + \tan^2\theta}} - 1 \qquad (5)$$

where $G_S = G_S/Y_o$ and $y_g = Y_g/Y_o$. It is noted that (5) can be applied to TEM (normal or oblique) or waveguide modes as long as the appropriate formulas for characteristic admittance and propagation constant are used.

For normal plane wave incidence onto a lossless glass slab of $\varepsilon_r = 6.8$, the optimized $g_S = G_S/Y_o$ and the corresponding return loss are shown in Fig. 4, with the return loss for without EC-coating for comparison. It is observed that the EC-coating can be utilized to reduce the return loss from the uncoated surface. There are two special cases worthy of mention. When the phase shift is π (half wavelength resonance), the required $g_S = G_S/Y_o$ is zero and no reflection occurs. Any EC-coating would cause reflection. On the other hand, when the phase shift is $\pi/2$ (quarter wavelength transformer), the return loss without the EC-coating reaches the maximum −2.6 dB, while the optimized coating gives no return loss. In fact, at $\theta = \pi/2$, we simply have $g_S = \varepsilon_r - 1$.

From Fig. 4, it is also seen that the reduction of the return loss using EC-coating is not so useful when the phase shift is close to zero or π. The reduction of reflection by the EC-coating is most effective when the electrical phase shift is around $\pi/2$.

IV. Conclusions

EC-coating affects the microwave reflections from both uncoated and coated surfaces of EC-coated dielectric slabs. The reflection coefficient from the coated surface is always larger than that from the uncoated surface. We can vary the sheet resistance of the EC-films to minimize the reflection from the uncoated surface. The formula to calculate optimum sheet resistance has been derived. This work has applications in radar cross-section reduction and reduction of multipath problems in TV broadcast as well as in wireless communications.

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