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FREQUENCY DEPENDENT MODEL OF SHEET RESISTANCE AND EFFECT ANALYSIS ON SHIELDING EFFECTIVENESS OF TRANSPARENT CONDUCTIVE MESH COATINGS

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Abstract—A frequency dependent model of sheet resistance of transparent conductive mesh coatings is proposed based on transmission line theory and vilified by experiments. And the effect on shielding effectiveness of frequency dependent sheet resistance is analyzed. Simulation results of shielding effectiveness are compared with the experimental data of a mesh-coated window sample with equivalent parameters fabricated and measured by Exotic Electro-Optics. The agreement between experiment and simulated proves the validity of the proposed sheet resistance model. So it can be therefore concluded that the frequency dependent model can be used to reasonably evaluate sheet resistance and shielding effectiveness of transparent conductive mesh coated windows.

1. INTRODUCTION

Transparent conductive mesh coatings have been widely used for many years to provide electromagnetic interference (EMI) shielding on optical windows and domes while allowing visible and infrared radiation to pass through nearly unobstructed [1–3]. Proper and reasonable EMI shielding evaluation is very important in structural design and optimization of transparent conductive mesh coatings. Equivalent circuit and equivalent film methods are especially favored in the EMI shielding evaluation of transparent conductive mesh coatings for high calculation accuracy and efficiency comparing with full-wave analysis methods. And the sheet resistance is a key parameter governing shielding effectiveness. But none of work has been done to

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give a frequency dependent model of sheet resistance for transparent conductive mesh coating, and most researchers in this field have not paid attention to its effect on EMI shielding. For example, Kohin et al. [4] and Bright [5] ignored the effect of sheet resistance of mesh coatings in their analysis models. However, currently transparent conductive mesh coatings used on optical windows and domes are fabricated with fine linewidth, sub-millimeter and sub-micrometer thickness to ensure optical transmission, and especially voids or holes in the micro-size mesh pattern occasionally occur during the fabrication process. In this case, the sheet resistance of a transparent conductive mesh coating significantly increases and attenuates EMI shielding performance. Ulrich [6], Whitbourn and Compton [7], and Ciddor and Whitbourn [8] used an empirical resistance formula based on waveguide theory to analyze a mesh interference filter, but DC sheet resistance calculated using their formula is zero and inconsistent with the facts of no-zero DC resistance characteristics. Sarto et al. [9], D'Amore et al. [10], and Jacoby et al. [11] proposed a DC resistance model independent of frequency, but did not give a frequency dependent model of sheet resistance. So the above evaluation models are not suitable to describe the sheet resistance and EMI shielding of transparent conductive mesh coating. Therefore, it is very significant to propose a frequency dependent model of sheet resistance to evaluate shielding performance of transparent conductive mesh coatings.

In this paper, we proposed a frequency dependent model of sheet resistance for effective evaluation of EMI shielding of transparent conductive mesh coatings. And the proposed model is verified by experiments.

2. MODELING AND SIMULATION

2.1. Frequency Dependent Model of Sheet Resistance of Mesh Coating

As shown in Fig. 1, a transparent conductive mesh coating has a sub-millimeter period of g, a micrometer linewidth $2a$, and a sub-micrometer thickness t and can be equivalent to a lumped circuit model of series $R/2$ and parallel of $2C$ and $L/2$ according to transmission line theory, and R_{mesh}, L_{mesh} and C_{mesh} are equivalent sheet resistance, inductance and capacitance, respectively.

At low-frequency limit, the transparent conductive mesh coating performs as a continuous conductive film when plane waves incident. For a continuous conductive film, EMI shielding is determined by the energy it absorbs and reflects. When the thin film is much thicker than its skin depth and absorption dominates its EMI shielding. However, a

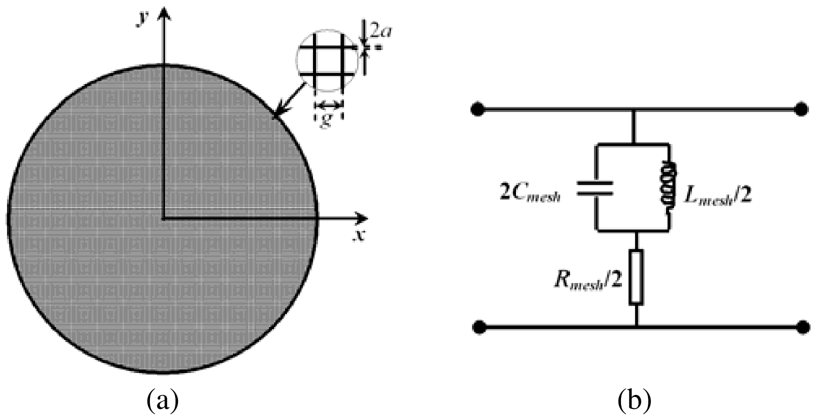


Figure 1. (a) Transparent conductive mesh coating and (b) corresponding transmission line model.

continuous conductive film is thinner than its skin depth, so reflection dominates the shielding effectiveness. EMI shielding is independence of frequency and can be characterized by DC sheet resistance of continuous conductive films.

DC sheet resistance is a reasonable indicator of how a continuous conductive film shields EMI at low frequency limit. DC sheet resistance is related with skin depth δ and thickness t for continuous conductive thin films. When the thickness of thin film is small with respect to skin depth δ, the sheet resistance is a function of conductivity σ and thickness t. While the thickness of thin film is much larger than the skin depth, the sheet resistance is a function of conductivity σ and skin depth δ, independence of thickness t and frequency. So the skin depth δ of conductive thin film is an important parameter in modeling sheet resistance and shielding effectiveness. The skin depth δ of a continuous conductive film is [12–14]

$$\delta = \sqrt{\frac{1}{\pi f \mu \sigma}} \tag{1}$$

where f is the frequency of incident plane wave, and μ and σ are the permeability and bulk DC conductivity of film metal.

The EMI frequency band ranges from low radio frequency to microwave frequency band 18 GHz. The skin depth δ of a gold film, with $\sigma = 4.1 \times 10^7$ mho/m in EMI frequency band ranging from 0 to 18 GHz is calculated and plotted in Fig. 2.

It can be seen from Fig. 2 that:

(1) The skin depth of a continuous conductive metal film decreases as the frequency increases. At the low frequency limit, the skin depth

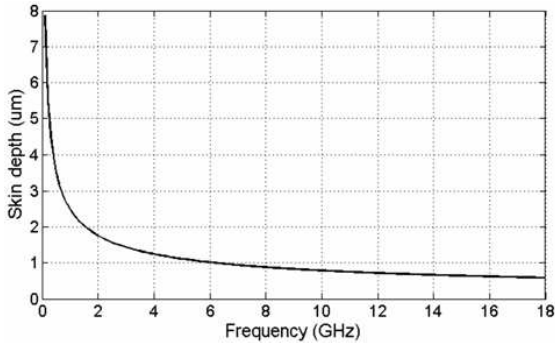


Figure 2. Skin depth of gold film VS frequency.

of a continuous conductive coating is infinite. However the thickness of mesh coatings is usually approximately 1 or 2 μm. In the case, the thickness of a mesh coating is much less than a skin depth δ, EMI shielding is almost entirely due to reflection of the incident plane wave at the air to mesh interface. And the DC sheet resistance R_{DC} of a continuous conductive coating is a function of the metal conductivity σ and thickness t according to transmission line theory [15–18].

$$R_{DC\text{-}film} = \frac{1}{\sigma t} \tag{2}$$

With consideration of the mesh duty factor ($\eta = g/2a$), Keith proposed a DC sheet resistance formula of a transparent conductive mesh coating.

$$R_{DC\text{-}mesh} = \frac{1}{\sigma t}\frac{g}{2a} \tag{3}$$

Keith's DC resistance formula is only suitable for calculating DC sheet resistance of a mesh coating when the thickness of a mesh coating is much less than a skin depth δ at low radiofrequencies, but it cannot be used to evaluate the frequency dependent sheet resistance characteristics at RF and microwave frequencies. So it is very necessary to develop a frequency dependent model of sheet resistance to evaluate SE all over entire EMI frequency band ranging from 0 to 18 GHz.

(2) As EMI frequency increases from 1 to 18 GHz, the skin depth of a continuous gold film is less than 2.5 μm, and transparent conductive mesh coatings are usually approximately 1or 2 μm, so the thickness is of the order of the skin depth for RF and microwave frequencies. The role of surface scattering becomes dominant when the thickness of mesh coating is of the order of the electron mean-free path [19]. In the case, we propose a frequency dependent model of sheet resistance

of continuous conductive metal film based on transmission line theory.

$$R_{film} = \frac{1}{\sigma\delta\left(1 - e^{-t/\delta}\right)} \tag{4}$$

From the point of view of mathematics of infinitesimal, expression (4) of film sheet resistance at lower frequency limit $f \to 0$ is consistent with famous DC sheet resistance model of thin metallic film of Eq. (2).

$$\lim_{f\to 0} R_{film} = \lim_{f\to 0} \frac{1}{\sigma\delta\left(1 - e^{-t/\delta}\right)} = \frac{1}{\sigma t} \tag{5}$$

With consideration of duty factor of period to linewidth ($\eta = g/2a$), a frequency dependent model of sheet resistance of transparent conductive mesh coating can be built below.

$$R_{mesh} = \frac{1}{\sigma\delta\left(1 - e^{-t/\delta}\right)} \frac{g}{2a} \tag{6}$$

In order to prove the validity of our proposed frequency dependent model of sheet resistance, we calculate the sheet resistance of a mesh coating versus frequency and compare the results and Ulrich's model based on waveguide theory in Fig. 3. The mesh coating is with gold film, and $t = 1\,\mu\text{m}$, $g = 300\,\mu\text{m}$ and $2a = 2\,\mu\text{m}$.

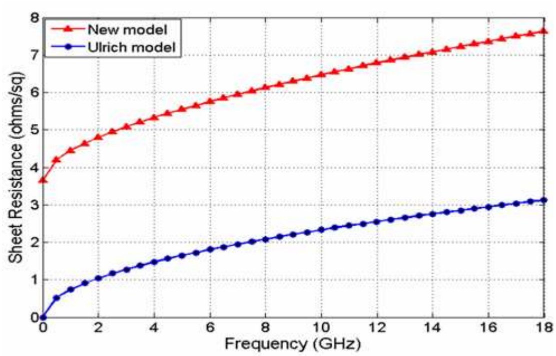
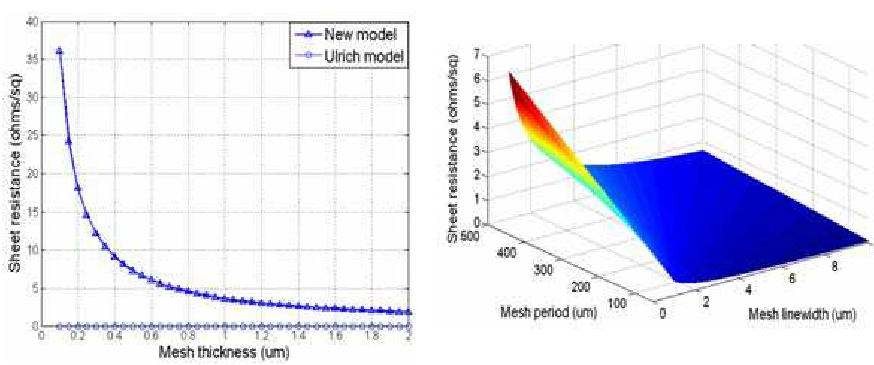


Figure 3. Comparison of sheet resistance versus frequency between new model and Ulrich's model.

Figure 3 shows that the sheet resistance of mesh coating increases as the frequency increases. However, there are obvious differences between our proposed new model and Ulrich model all over EMI frequency band (0 to 18 GHz). Especially, at low frequency limit, the sheet resistance of our proposed model is 3.65 ohms/sq, which is consistent with Keith's DC sheet resistance model. However, the calculated sheet resistance of Ulrich's model at low frequency limit is zero, which is inconsistent with the fact of non-zero DC sheet resistance. So Ulrich's model based on waveguide theory is not suitable to be used to evaluate the sheet resistance of transparent conductive mesh coatings.

Mesh thickness (t), period (g) and linewidth ($2a$) control sheet resistances of transparent conductive mesh coatings. According to our proposed new model, sheet resistances of mesh coating with $g = 300\,\mu\text{m}$, $2a = 2\,\mu\text{m}$, $t = 1\,\mu\text{m}$ at 1 GHz are calculated and plotted in Figs. 4(a) and (b) respectively.

It can be seen from Fig. 4(a) that the sheet resistance decreases as the mesh thickness increases. The sheet resistance only decreases 1.7 ohms/sq as the thickness of mesh coating decreases from $2\,\mu\text{m}$ to $1\,\mu\text{m}$; however, markedly decreases 32.5 ohms/sq as the mesh thickness decreases from $1\,\mu\text{m}$ to $0.1\,\mu\text{m}$. Meanwhile, Ulrich's model is not rational because of its independence of thickness. Fig. 4(b) shows that the sheet resistances of transparent conductive mesh coatings increase as the mesh linewidth increases, and increase as the mesh period decreases. In other word, thicker metal, increasing mesh linewidth and reducing mesh period can decrease the sheet resistance of mesh coatings and increase EMI shielding performance, especially at lower frequencies.



(a) (b)

Figure 4. (a) DC sheet resistances versus mesh thickness, and (b) versus period and linewidth at 1 GHz.

2.2. Experimental Validity of Sheet Resistance Model at Low Frequency Limit

In order to verify the validity of the proposed sheet resistance model, we fabricated transparent conductive mesh coating samples using a UV lithography technique and their DC sheet resistance was calculated and measured using a four-probe testing method. And we calculated and compared experimental results of sheet resistance of two mesh coating samples (No. 3* and 4*) from Refs. [6] and [11]. The calculated and measured results of DC sheet resistance of mesh coating samples are shown in Table 1.

Table 1. Simulation and measured results of DC sheet resistance.

Mesh Coating Sample		Dimension (μm)			Resistance (Ω/sq)	
No.	σ (siemens/m)	g	$2a$	t	Calculated	Measured
1	Aluminium (3.8e7)	250	5	0.3	5.48	5.5
2	Silver (6.1e7)	500	4	0.5	3.42	3.6
3*	Copper (5.8e7)	216	28.8	7	0.009	0.004
4*	Gold (4.1e7)	50	5	1	0.24	0.2

*Note: Measurement data of No. 3 and No. 4 samples is from Refs. [6] and [11] respectively.

It can be seen from Table 1 that the measured DC sheet resistance results agree with the calculated ones at low frequency limit, which verifies the validity of our proposed frequency dependent model of sheet resistance. So it can be concluded that the proposed sheet resistance model can be used to analyze EMI shielding performance of transparent conductive mesh coatings.

2.3. Effect on Shielding Effectiveness of Sheet Resistance of Mesh Coatings

At low frequency limit, a transparent conductive mesh coating performs as a continuous conductive film. For a thin continuous conductive film, the transmission coefficient and SE is independence of frequency and can be characterized by the sheet resistance of the transparent conductive mesh coating. Because the transparent conductive mesh coating has low intrinsic impedance compared to free space, ignoring the effects of the substrate, SE of a transparent conductive mesh coating is a function of DC sheet resistance $R_{DC\text{-}mesh}$

and the impedance of free space Z_0.

$$SE_{DC\text{-}mesh} = 20\log_{10}\left[\frac{1}{1+\frac{Z_0}{2R_{DC\text{-}mesh}}}\right] \tag{7}$$

where $Z_0 = (\mu_0/\varepsilon_0)^{1/2}$, ε_0 and μ_0 are the permittivity and the permeability of free space.

As the frequency increases, the frequency dependence of the transparent conductive mesh coating must be taken into account. So it is very necessary to model the plane wave transmittance and EMI shielding of transparent conductive mesh coatings as a function of frequency as well as the sheet resistance, the mesh geometry.

We proposed a frequency-dependent model for the impedance of the finitely conductive mesh coating based on the transmission coefficient analysis for arbitrary layered media incorporating mesh coatings. According to transmission line lumped circuit, Ciddor and Whitbourn [8] presented an equivalent film model and gave a transfer matrix M_{mesh} for metal grids with a normalized equivalent admittance Y_{mesh}.

$$M_{mesh} = \begin{bmatrix} A_{mesh} & B_{mesh} \\ C_{mesh} & D_{mesh} \end{bmatrix} = \begin{bmatrix} 1 & 0 \\ Y_{mesh} & 1 \end{bmatrix} \tag{8}$$

The normalized admittance Y_{mesh} is the reciprocal of the impedance Z_{mesh} of transparent conductive mesh coatings:

$$Y_{mesh} = \frac{1}{Z_{mesh}} \tag{9}$$

The normalized impedance Z_{mesh} of transparent conductive mesh coatings can be given by equivalent sheet resistance R_{mesh} and equivalent reactance X_{mesh}:

$$Z_{mesh} = R_{mesh}/Z_0 + iX_{mesh}/Z_0 \tag{10}$$

And the equivalent reactance X_{mesh} of transparent conductive mesh coating can be given by [6]:

$$\frac{X_{mesh}}{Z_0} = -\frac{g}{\lambda}\left[\ln\left(\sin\frac{\pi a}{g}\right)\right] \tag{11}$$

It can be seen from Fig. 5 that the sheet resistance (real part) and the equivalent reactance (imaginary part) of impedance of transparent conductive mesh coating have the same magnitude in the low frequency band ranging from 0 to 3 GHz, but the sheet resistance increases slowly relative to the equivalent reactance beyond 3 GHz. So the sheet resistance will obviously affect the shielding effectiveness at low frequencies, but slightly at high frequencies. Due to the impedance of mesh coatings Z_{mesh} is very small relative to free space; the transparent conductive mesh coating has low intrinsic impedance compared to free space; reflection is the dominant effect.

The transmittance of transparent conductive mesh coatings can be expressed:

$$T = \frac{Y_{mesh}}{1 + Y_{mesh}} = \frac{R_{mesh} + iX_{mesh}}{Z_0 + R_{mesh} + iX_{mesh}} \tag{12}$$

Shielding effectiveness (SE) is an attenuation of an incident EMI plane wave as it is transmitted through transparent conductive mesh coatings ignoring the effect of optical window substrate.

$$SE(\mathrm{dB}) = 20 \log_{10} \left(\frac{R_{mesh} + iX_{mesh}}{Z_0 + R_{mesh} + iX_{mesh}} \right) \tag{13}$$

EMI shielding performance of transparent conductive mesh coatings depends on frequency, sheet resistance and mesh parameters. According to above proposed model with consideration of sheet resistance, SE of transparent conductive mesh coating with gold film $t = 1\,\mu\mathrm{m}$, $g = 300\,\mu\mathrm{m}$ and $2a = 2\,\mu\mathrm{m}$ is calculated and shown in Fig. 6(a) in EMI frequency-band ranging from 0 to 18 GHz ignoring the effects of the substrate. And the effect on SE of sheet resistance is analyzed and shown in Fig. 6(b).

Figure 6(a) shows that EMI shielding decreases as frequency increases, and SE of both models beyond 4 GHz is consistent with each other. However, there is an obvious attenuation of more than 10 dB between our proposed model and Kohin's ignoring resistance model at low frequencies. So the effect on SE of sheet resistance is obvious, especially at low frequencies, but slight at high frequencies. As the frequency decreases, a point will be reached where the skin depth, a function of bulk conductivity, will be greater than mesh

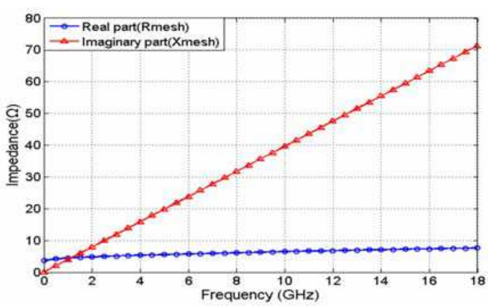
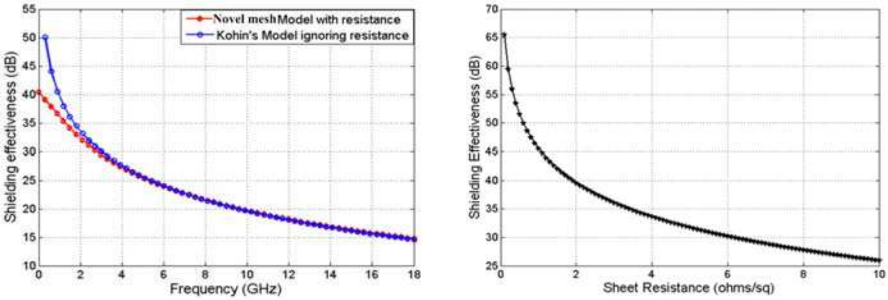


Figure 5. Real and imaginary parts of impedance of mesh coating.



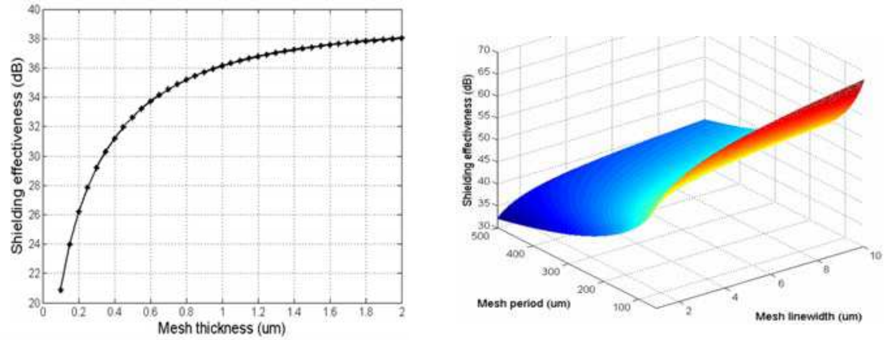
(a) (b)

Figure 6. (a) Shielding effectiveness versus frequency and (b) sheet resistance.

thickness. Shielding currents will consequently diminish allowing an increased transmission of energy. Fig. 6(b) shows that SE significantly decreases about 40 dB as the sheet resistance of mesh coating increases about 10 ohms/sq. From the plane wave theory of attenuation in the far field, when a radio wave propagates from a medium of high intrinsic impedance into a transparent conductive mesh coating with high conductivity, low resistance and low intrinsic impedance, the reflection coefficient is high and high EMI attenuation occurs. In other words, the increasing sheet resistance will attenuate EMI shielding lowering sheet resistance can enhance EMI shielding performance in the far field.

Several factors, such as mesh thickness, period and linewidth, control SE of transparent conductive mesh coatings. SE of a transparent conductive mesh coating with gold film $g = 300\,\mu\text{m}$, $2a = 2\,\mu\text{m}$ and $t = 1\,\mu\text{m}$ versus mesh thickness, period and linewidth at 1 GHz are shown in Figs. 7(a) and (b), respectively.

It can be seen from Fig. 7(a) that SE only decreases 2 dB as the mesh thickness decreases from 2 to 1 μm; however, markedly decreases 15 dB as the mesh thickness decreases from 1 to 0.1 μm. So the thickness of the transparent conductive mesh coating should be preferably designed greater than 1 μm to obtain lower sheet resistance and higher SE. Fig. 7(b) shows that SE of the transparent conductive mesh coating increases as the mesh linewidth increases, and mesh period decreases. In a word, thicker metal will decrease the effective sheet resistance of transparent conductive mesh coatings, increasing the shielding performance, especially at the lower frequency. Increasing mesh linewidth and reducing mesh period will also increase the shielding performance, but these changes will also attenuate the optical



(a) (b)

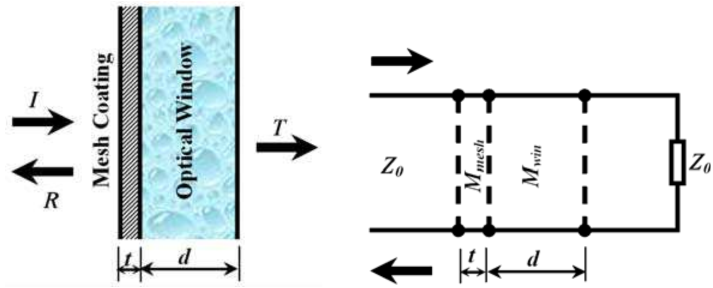
Figure 7. Shielding effectiveness versus mesh period, (a) linewidth and (b) thickness at 1 GHz.

(visible and infrared) transmittance and influence the imaging quality. EMI shielding and the optical transmittance of transparent conductive mesh coatings are a pair of inherent conflicts. It is the key to the optimization design to strike a good balance between them. Thicker mesh coating, finer mesh linewidth and rational mesh period can be optimized to obtain required SE and higher optical performance [19].

2.4. Validity of Sheet Resistance Model Using EEO's Experimental Data at EMI Frequency Band

As shown in Fig. 8, transparent conductive mesh coatings are deposited on optical window surface to improve its strength using a lithographic technique. Transparent conductive mesh coating can be equivalent as a layer of optical thin-film due to its unique zero order diffraction characteristics and so mesh-coated optical windows can be treated as a double-layer thin film. We build a SE model for mesh-coated windows based on multi-layer optical film theory.

Because mesh period is much smaller than the wavelength of incident EMI plane wave, transparent conductive mesh coatings have only zero order diffractive energy. According to transmission line and optical film theories, Ciddor and Whitbourn [8] presented an equivalent film model of mesh interference filter using Ulrich's empirical resistance formula based on waveguide theory, but DC sheet resistance calculated using their formula is zero and inconsistent with the facts of no-zero DC resistance of mesh coatings, so Ciddor's model is not suitable for describing the sheet resistance and EMI shielding of transparent conductive mesh coating. We substitute the proposed frequency



(a) (b)

Figure 8. (a) Mesh-coated optical window, and (b) equivalent double-layer film model.

independent model of sheet resistance into equivalent film matrix and obtain transfer matrix M_{mesh} of transparent conductive mesh coatings.

$$M_{mesh} = \begin{bmatrix} 1 & 0 \\ \frac{Z_0}{R_{mesh}+iX_{mesh}} & 1 \end{bmatrix} \tag{14}$$

The transfer matrixes of optical window substrate M_{win} can be obtained using a transfer matrix theory of optical thin-films [20–22].

$$M_{win} = \begin{bmatrix} \cos(\delta_{win}) & \frac{i}{\eta_{win}}\sin(\delta_{win}) \\ i\eta_{win}\sin(\delta_{win}) & \cos(\delta_{win}) \end{bmatrix} \tag{15}$$

where δ_{win} and η_{win} are the optical path difference and equivalent optical admittance of optical window substrate.

$$\delta_{win} = \frac{2\pi nd}{\lambda} \tag{16}$$

$$\eta_{win} = \sqrt{\frac{\varepsilon_o}{\mu_o}}n_{win} \tag{17}$$

The transfer matrix M of a mesh-coated window can be calculated by the products of the transfer matrixes of mesh coating M_{mesh} and optical window substrate M_{win}.

$$M = M_{mesh}M_{win} = \begin{bmatrix} A & B \\ C & D \end{bmatrix} \tag{18}$$

According to transmission matrix method of multi-layer optical film theory, the transmittance coefficient T of a mesh-coated window is

$$T = \frac{2}{A + B/Z_0 + CZ_0 + D} \tag{19}$$

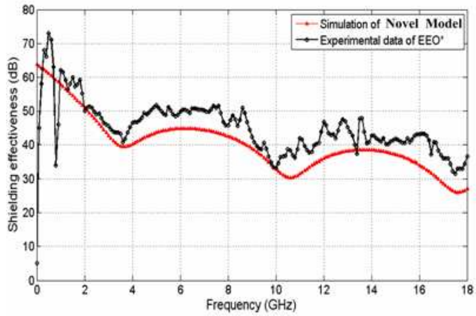


Figure 9. Comparison between simulation of our novel model and EEO's experimental data.

SE is the attenuation of an incident EMI plane wave as it is transmitted through a mesh-coated window.

$$SE(\mathrm{dB}) = 20\log_{10}(T) \tag{20}$$

In order to verify the validity of our proposed frequency dependent model of sheet resistance and SE model of mesh-coated optical windows, we compared the simulation results using the proposed model and experimental data published by Exotic Electro-Optics (EEO) in Fig. 9. EEO fabricated a patterned conductive mesh coating sample with 5 μm linewidth and 50 μm period and 1 μm thick gold film on a 0.25 inch thick polished sapphire window. And SE of the mesh coated window sample was measured from about 1 to 18 GHz using Horn antenna (double ridge guide) [11].

It can be seen from Fig. 9 that:

(1) The trend of the SE simulation results of our proposed frequency dependent model agree with EEO's experimental data of Ref. [11] from about 1 to 18 GHz. The agreement between measurement and simulation results verifies the validity of our proposed frequency dependent model of sheet resistance in EMI frequency band. The measured SE is slightly higher than our simulation results. The difference between the measurement and simulation results is caused by the small size of EEO's mesh-coated window sample and measurement aperture. The incident energy of the measured plane wave that passes through the small measurement aperture is low even there is no window present. Some of the incident energy of plane wave is blocked by the small measurement aperture. At the same time, the measurement is in the near field and not in the form of plane wave at low frequencies. So the measurement results of SE are higher than the predicted results.

(2) The EMI shielding of transparent conductive mesh coating is significantly periodically degraded at some frequencies when it is deposited on an optical window substrate. The SE degradation is due to the interference effect that radiation reflected from the upper surface of optical window interacts coherently with radiation reflected from the bottom one. When the optical thickness of the optical window substrate is an even multiple of quarter-wave (such as at 7 and 14 GHz), the SE is equal that of a free-standing mesh coating. However, at all other wavelengths, the SE is degraded, especially, the maximum of the SE degradation occurs when the optical thickness of the optical window is an odd multiple of quarter-wave (such as at 3.5, 10.5, and 17.5 GHz).

3. CONCLUSION

A frequency dependent model of sheet resistance of transparent conductive mesh coatings is proposed based on transmission line theory and verified by experiments. And the effect on shielding effectiveness of frequency dependent sheet resistance is analyzed. Thicker mesh metal, increasing mesh linewidth and reducing mesh period can decrease the sheet resistance of mesh coatings and increase EMI shielding performance, especially at the lower frequency. Simulation results of SE are compared with the experimental data of a mesh-coated window sample with equivalent parameters fabricated and measured by EEO. The agreement between experimental data and simulated results proves the validity of our proposed sheet resistance model. So it can be concluded that the frequency dependent model can be used to evaluate sheet resistance and shielding effectiveness of transparent conductive mesh coated windows.

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