Short Papers

A Systematic Design Method of Multilayer Composite-Glass with Thin Metallic Layer

B. F. Wang, W. J. Zhang, and Wai-Kai Chen

***Abstract*— A new design method for multilayer composite glass with absorbing thin film is presented. This composite glass has a high microwave reflective factor and good transparency in the visible light region. It is useful in vehicle stealth technology and microwave protection of a large-capacity microwave transmission system.**

***Index Terms*—Multilayer, thin film.**

I. The Layered-Media Wave Theory

A multilayer composite glass with good performance characteristics is important in a stealth control cabin and in personal protection from microwave rays. A dielectric multilayer filter with an absorbing thin layer plays an important role in this respect. Although much has been reported previously on the design of dielectric multilayer filters (thin-film filters) in the optical and microwave regions, this paper presents a composite glass that has a high microwave reflective factor and good transparency in the visible light region. A complete admittance-matrix representation of a multilayer system with absorbing thin film can be obtained by using layered-media wave theory [1].

Let L be the number of layers in a multilayer system, resulting in an $L+2$ media. The multilayer is bounded by a substrate and an outer boundary, $L+1$. A relationship between the electric and magnetic vectors in the incidence medium to those in the substrate can be expressed as follows:

$$\begin{bmatrix} \hat{k}\times E_0 \\ H_0 \end{bmatrix} = [M_1][M_2]\cdots[M_m]\cdots[M_L]\begin{bmatrix} \hat{k}\times E_{L+1} \\ H_{L+1} \end{bmatrix} \tag{1}$$

where $\hat{k}$ is the unit vector along the z-axis and $[M_m]$ can be written in a matrix as

$$[M_m] = \begin{bmatrix} \cos\delta_m & j\sin\delta_m/\eta_m \\ j\eta_m \sin\delta_m & \cos\delta_m \end{bmatrix} \tag{2}$$

where η_m, a modified admittance, is

$$\eta_m = \begin{cases} N_m \cos\theta_m, & \text{for TE (or S) wave} \\ N_m/\cos\theta_m, & \text{for TM (or P) wave} \end{cases}$$
$$\delta_m = (2\pi N_m/\lambda) d_m \cos\theta_m$$

where λ is the wavelength of the incident plane wave. The intrinsic dimensionless parameter of the medium N_m can be written in Gaussian units as

$$N_m^2 = \epsilon_m \mu_m - j\frac{4\pi\sigma_m\mu_m}{\omega} \tag{3}$$

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where ω is the angular frequency of wave and ϵ, μ, and σ are the permittivity, permeability, and conductivity of the medium, respectively. For simplicity, we define the admittance of the layer structure Y as follows:

$$Y = \left|\frac{H_0}{\hat{k}\times E_0}\right|. \tag{4}$$

Equation (1) can be written as

$$(\hat{k}\times\overline{E}_0)\begin{bmatrix} 1 \\ Y \end{bmatrix} = \begin{bmatrix} B \\ C \end{bmatrix}(\hat{k}\times\overline{E}_{L+1})$$
$$\begin{bmatrix} B \\ C \end{bmatrix} = [M]\begin{bmatrix} 1 \\ \eta_{L+1} \end{bmatrix} = \prod_{m=1}^{L}\begin{bmatrix} \cos\delta_m & \sin\delta_m/\eta_m \\ \eta_m\sin\delta_m & \cos\delta_m \end{bmatrix}\begin{bmatrix} 1 \\ \eta_{L+1} \end{bmatrix} \tag{5}$$

where $[B, C]^t$ is defined as the characteristic matrix of the layered structure. We obtain

$$Y = \frac{C}{B}. \tag{6}$$

In fact, the reflectance R, the transmittance T, and the absorptance A are found to be

$$R = \frac{(\eta_0 B - C)(\eta_0 B - C)^*}{(\eta_0 B + C)(\eta_0 B + C)^*} \tag{7}$$

$$T = \frac{4\eta_0\eta_{L+1}}{(\eta_0 B + C)(\eta_0 B + C)^*} \tag{8}$$

$$A = (1-R)\left[\frac{\eta_{L+1}}{\mathrm{Re}\,(BC^*)}\right]. \tag{9}$$

II. Antireflection (AR) Coatings for Visible Region

In order to have a high reflective factor over 8–12 GHz and good transparency in the visible region, some common metal thin films, such as silver, aluminum, copper, and gold, are often used in a multilayer composite glass structure. As we know, a good conductor is a medium for which the permittivity ϵ is complex and the propagation constant γ is given by

$$\gamma = \alpha + j\beta = \frac{1+j}{\sqrt{2}}\sqrt{\omega\mu\sigma}. \tag{10}$$

The order of the magnitude of $|\alpha|$ and $|\beta|$ for silver is about 1.56×10^6 m^{-1} at 10 GHz. The electromagnetic wave is attenuated very rapidly in the silver medium and reflected strongly from the interface between the dielectric glass and thin metallic film. On the other hand, for silver at 550 nm with $n - jk = 0.055 - j3.30$, the reflectance is approximately 96.2%. In order to have good transparency in the visible region, the thickness of the metal thin film should be chosen to be much less than the depth of penetration. In so doing, the reflectance will drop off in the visible region. The only complication that usually exists is a reflection loss in the optical passband region due to the high refractive index of the film. This problem can be readily solved by placing suitable antireflection (AR) coatings between the substrate and the metallic thin film, so that the transparency can be enhanced over the visible region [2].

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The matrix method is used for the design of AR coatings. Expression (5) is of prime importance in optical thin-film work and forms the basis of almost all calculations. Generally, in practice, the refractive index is not a parameter that can be varied at will. Choices of material suitable for use as thin films are very limited, and the designer has to take what is available. A more rewarding method is to use more layers, specifying obtainable refractive indexes for all layers at the start, to achieve good transparency in the visible region and maximal reflectance in the microwave band. For most purposes a few layer of coatings are quite adequate. In fact, if the optical admittance Y of the multilayer with a thin metallic film is equal to η_0, the corresponding optical reflectance will be zero.

III. High-Reflectance Performance in the Microwave Band

As noted above, the metal layers have considerable absorption loss and reflection, which can be used to reflect a major portion of the incident wave in the microwave region. The sole requirement is that the specular reflectance should be as high as conveniently possible, although there are specialized conditions under which not only should the reflectance be high in the microwave band, but also the transparence should be appropriately big enough over the visible region. So, the construction of the composite glass, especially the thickness of metal thin film, has to be chosen appropriately. For some microwave protection applications where the reflectance must be higher than that achieved with a simple metallic layer, its reflectance can be boosted by the addition of extra dielectric layers. In that case, layered-media wave theory combined with the microwave filter theory [3] can be used to design a microwave band-reject filter (BRF) and transform it to the multilayer structure.

The design procedure of a BRF consists of two steps: frequency transformation and resonator transformation. Frequency transformation is a conventional method of transforming a given LC low-pass prototype to an LC-BRF with a given rejection band that extends from ω_1 to ω_2. It is straightforward to show that we need only to compute the rejection band width $2\Delta\omega = \omega_2 - \omega_1$ and the center frequency $\omega_0 = \sqrt{\omega_1 \omega_2}$ and to replace each inductor with inductance L in the low-pass realization by a parallel combination of a resonator with inductance L_{e1} and a capacitor with capacitance C_{e1} and each capacitor with capacitance C by a series combination of a resonator with inductance L_{e2} and a capacitor with capacitance C_{e2}, whose values are given by

$$\begin{aligned} L_{e1} &= 2\Delta\omega L/\omega_0^2 \\ C_{e1} &= 1/2\Delta\omega L \\ L_{e2} &= 1/2\Delta\omega C \\ C_{e2} &= 2\Delta\omega C/\omega_0^2. \end{aligned} \tag{11}$$

This replacement process is illustrated in Fig. 1.

Resonator transformation transforms each resonator of the BRF to the corresponding multilayer resonator (MLR) by cascading these in tandem. The resonator transformation is also illustrated in Fig. 1.

IV. Optimal Design Consideration

In order to have a good performance for vehicle cabin design and microwave protection in a large-capacity microwave transmission system, consideration must be given to both the optical and microwave characteristics of the composite glass with absorbing thin film. The schematic diagram shown in Fig. 2 is the block diagram representation of the composite glass system with a manipulable multi-input driving the system from the given restricted conditions to produce the consequent multi-output. The Simplex method combined with the Monte Carlo method is used to obtain the optimal parameters of the composite glass system

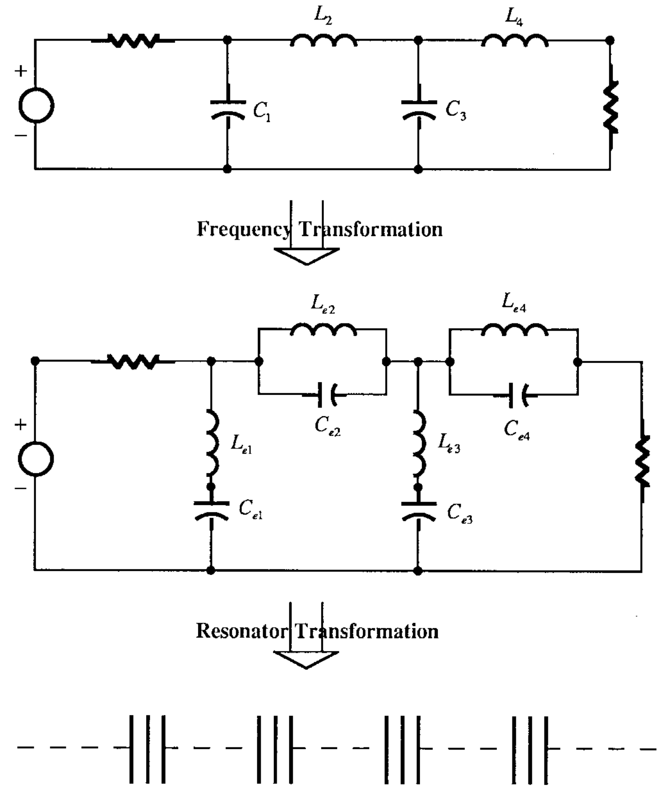

Fig. 1. Frequency and resonator transformations.

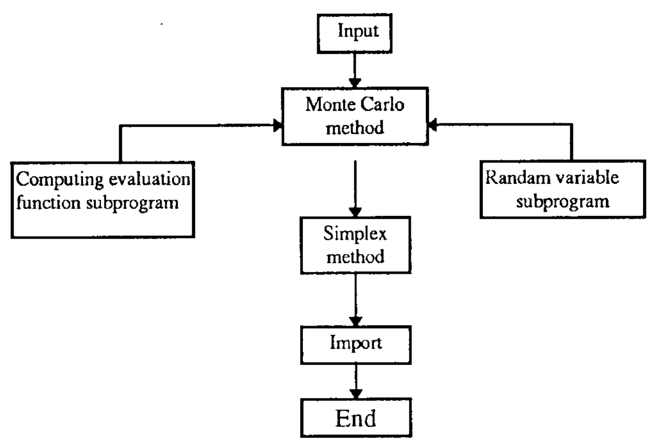

Fig. 2. The flowchart of computation.

In applying the Monte Carlo method, we first compute randomly a set of values of the evaluation function in a given independent variable region. Based on these values, we next narrow a new independent variable region from which a new set of values of the evaluation function is computed, and so forth, until a satisfactory result is reached when the computation is terminated. In using the Simplex method, a Simplex geometry is formed near a given point in an independent variable region, and the function values on the acme of the geometry and their average value are next computed. These values are compared, and the point whose function value is larger than the average value is determined in the chosen direction of the geometry. Using these, a new Simplex geometry is formed near the point, and so forth, until a satisfactory result is reached when the computation is terminated. In the concrete, after some peak regions of the function are located by the Monte Carlo method, the computation

TABLE I
NUMBER OF LAYERS, MATERIAL, AND THICKNESS

Number of layers	Material	Thickness
1	aero glass	5.00 mm
2	TiO_2	39 nm
3	Ag	14 nm
4	TiO_2	39 nm
5	PVB glass	2.00 mm
6	aero glass	8.00 mm
7	PVB glass	2.00 mm
8	aero glass	8.00 mm

TABLE II
REFRACTIVE INDEX AND EXTINCTION COEFFICIENT FOR SILVER OVER THE VISIBLE REGION

λ (nm)	n	k
400	0.075	1.93
450	0.062	2.40
500	0.050	2.87
550	0.055	3.30
600	0.060	3.76
650	0.068	4.15
700	0.075	4.62
750	0.083	5.00

of which is amenable to the digital approximation program of the Simplex method, the optimization process proceeds in each of the peak regions. These peak values are compared, and the largest one is selected, being the maximum value of the function in a given independent variable region [4].

A practical example of a multilayer composite glass system was designed. There are two specialized conditions for which the transparency of this system should be larger than 0.75 in the visible light region and the microwave reflectance of this system should be larger than -1.0 dB in 8–12 GHz. The glass materials are restricted to aeronautic glass and PVB glass. The permittivity ϵ and refractive index n of the aeronautic glass are 6.7 and 1.52, respectively. The permittivity ϵ and refractive index n of PVB glass are 2.8 and 1.49, respectively. An actual example of an optimized composite glass is a layered structure consisting of eight layers. Its structure parameters are listed in Table I. Table II shows the refractive index n and the extinction coefficient for silver over the visible region. The conductivity σ_{Ag} is 1.306×10^7 $(\Omega\text{-}m)^{-1}$. The refractive index $n_{\mathrm{TiO_2}}$ is 2.12.

The experimental and theoretical curves are shown in Figs. 3 and 4. In these figures, R and R_0 represent the microwave reflectances of the composite glass with and without silver thin film, respectively. The solid line is the experimental curve, and the dashed line is the theoretical curve.

From these figures we see that the reflectance R and the visible light transmittance T can be up to -1 dB (8–12 GHz) and 75%, respectively. The theoretical results are in close agreement with the measured data. The validity of this systematic design method for multilayer composite glass is verified by a simple working example.

Table III gives some other optimal parameters of the composite glass system. In Table III, DF represents a silver film and two

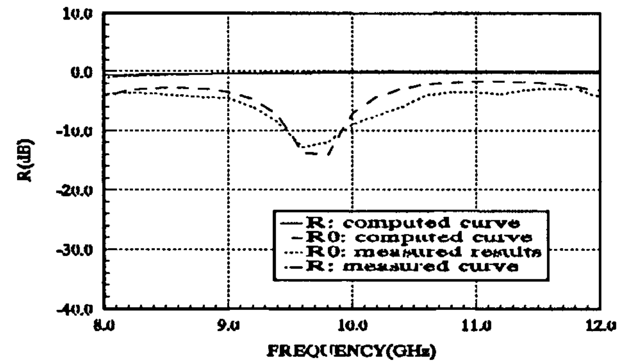

Fig. 3. The microwave performance for a given multilayer structure.

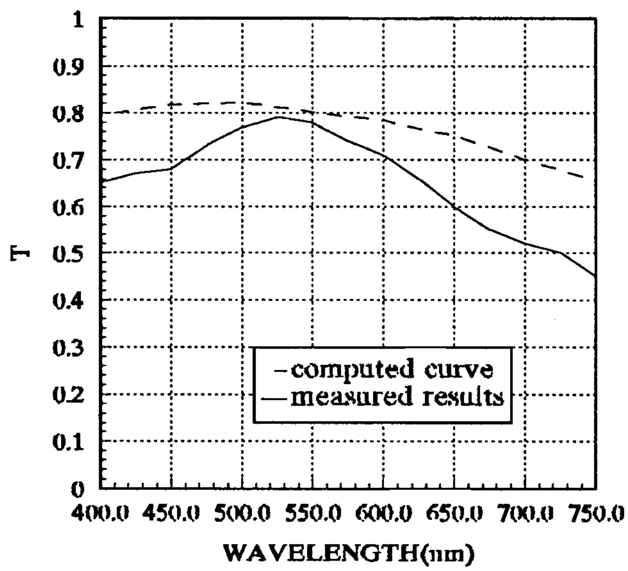

Fig. 4. The transmittance T as a function of wavelength.

TABLE III
SOME OTHER OPTIMAL PARAMETERS OF THE COMPOSITE GLASS SYSTEM

Frequency (GHz)	Thickness of each layer (mm)								D_{total} (mm)	FRf (dB)
	D_1	D_2	D_3	D_4	D_5	D_6	D_7	D_8		
8~12	2.85	4.42	DF	2.83					10.10	−1.00
	2.84	3.34	1.00	DF					7.18	−1.23
	5.00	DF	2.00	8.00	2.00	8.00			25.00	−1.37
	2.86	4.44	2.87	4.44	DF	2.82			17.44	−0.60
	2.85	4.43	2.87	3.36	1.00	DF			14.51	−0.76
	2.85	4.43	2.87	4.42	DF	3.24	6.32	10.82	34.94	−0.60
	11.80	4.40	2.87	4.44	2.88	4.45	DF	14.56	45.41	−0.52

TiO_2 films, f is the frequency in gigahertz, $D_1, D_2, \cdots, D_L$ are the thickness of the layers (mm), and FRf represents the evaluation function defined by

$$FRf = \sum_{i=0}^{8} R[D_1,\ D_2, \cdots, D_L,\ f = (8 + 0.5i)]. \qquad (12)$$

V. CONCLUSION

A design principle has been proposed to obtain a composite glass with a thin absorbing film which serves as a high-reflective multilayer BRF on a microwave band and as a high transmittance over the visible light region. It can be used to design stealth vehicle cabins to protect personnel from microwave radiation in a large-capacity microwave transmission system. The method's feasibility was confirmed with a design example. The actual composite multilayer glass characteristics depend on the accuracy of the thickness and refractive index of the layers, especially for cases where a large number of layers are involved.

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Duality Transformation for Nonreciprocal and Nonsymmetric Transmission Lines

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***Abstract*—Duality transformation is introduced to the theory of generalized (nonreciprocal and nonsymmetric) transmission lines making it possible to find solutions to problems in terms of solutions to dual problems without having to go through the solution process. The generalized transmission lines have emerged when more general media have been introduced to classical waveguide geometries, for example, microstrip lines on chiral substrates. It is seen that there actually exist two duality transformations and the self-dual voltage and current solutions are propagating waves in the transmission line. The transformation can be, e.g., applied to transform a nonsymmetric transmission line to a symmetric one.**

I. Introduction

Duality transformation in electromagnetic theory is based on the symmetry of electric and magnetic quantities in the Maxwell equations. It can be applied to obtain a solution for the dual problem through transforming the solution of the original problem [1]. A careful study for fields and sources in isotropic media showed that there are always two duality transformations of equal importance, [2], [3], and that there exist self-dual quantities invariant to the transformation, which have special physical significance. The theory was later generalized to bi-isotropic media [4] and certain bi-anisotropic media [5].

In circuit theory, the concept of duality has been applied to transform voltages to currents, impedances to admittances, inductances to capacitances, and series circuits to parallel circuits, for example [6], [7]. In transmission-line theory, the line parameters are changed correspondingly in the transformation. It is the purpose of this paper to define the duality transformation to the generalized transmission-line theory introduced recently [8], [9], applicable, e.g., to planar transmission lines on chiral and bi-isotropic substrates [10].

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II. Theory

Let us consider a transmission line with time–harmonic (complex) current $I(x)$ and voltage $U(x)$ functions satisfying the generalized transmission-line equations

$$\frac{d}{dx}\begin{pmatrix}U(x)\\ I(x)\end{pmatrix} + \begin{pmatrix}a & z\\ y & b\end{pmatrix}\begin{pmatrix}U(x)\\ I(x)\end{pmatrix} = \begin{pmatrix}u(x)\\ i(x)\end{pmatrix}. \tag{1}$$

Here we denote the distributed transmission-line circuit parameters by $a,\ z,\ y,\ b$ and the distributed series generator voltage and shunt generator current functions by $u(x)$ and $i(x)$, respectively. The quantities z and y are the distributed series impedance and shunt admittance, respectively. a and b are parameters defining the symmetry and reciprocity of the line [8]. In fact, $a = b$ implies that the impedance parameters of a line section satisfy the symmetry condition $Z_{11} = Z_{22}$. On the other hand, $a = -b$ implies that the impedance parameters satisfy $Z_{12} = Z_{21}$, whence the line is reciprocal [11, p. 158]. The symmetric and reciprocal line with $a = b = 0$ is called the conventional transmission line.

It was also seen [8] that the line is lossless if the parameters satisfy

$$z^* = -z \quad y^* = -y \quad a^* = -b \quad b^* = -a. \tag{2}$$

If we define

$$a = s + d \quad b = s - d \quad s = \frac{a+b}{2} \quad d = \frac{a-b}{2} \tag{3}$$

the quantities $z,\ y$, and s are seen to be imaginary while d is real for a lossless transmission line.

A. The Duality Transformation

The duality transformation is a linear map of the voltage–current pair

$$\begin{pmatrix}U_d\\ I_d\end{pmatrix} = \mathcal{D}\begin{pmatrix}U\\ I\end{pmatrix} = \begin{pmatrix}A & B\\ C & D\end{pmatrix}\begin{pmatrix}U\\ I\end{pmatrix} \tag{4}$$

where $A \cdots D$ are constant (complex) scalar quantities. Operating (1) by the matrix $\mathcal{D}$, we can write the transmission-line equation for the transformed line. The transformation rules for the sources are, then

$$\begin{pmatrix}u_d\\ i_d\end{pmatrix} = \begin{pmatrix}A & B\\ C & D\end{pmatrix}\begin{pmatrix}u\\ i\end{pmatrix} \tag{5}$$

and those for the line parameters

$$\begin{pmatrix}a_d & z_d\\ y_d & b_d\end{pmatrix} = \begin{pmatrix}A & B\\ C & D\end{pmatrix}\begin{pmatrix}a & z\\ y & b\end{pmatrix}\begin{pmatrix}A & B\\ C & D\end{pmatrix}^{-1}. \tag{6}$$

Let us require that the duality transformation be an involution, i.e., $\mathcal{D}^{-1} = \mathcal{D}$, [3]. This gives a set of conditions for the parameters $A \cdots D$. Ignoring the trivial transformations $\mathcal{D} = \pm\mathcal{I}$, where $\mathcal{I}$ denotes the unit matrix, the conditions are

$$A = -D = \sqrt{1 - BC} \tag{7}$$

implying $\det\mathcal{D} = -1$. Let us introduce the notation

$$A = -D = \sin\theta \quad B = \tau\cos\theta \quad C = \tau^{-1}\cos\theta \tag{8}$$

which takes care of the condition (7) and leaves us two parameters, τ and θ.

Let us now specify the transformation parameters $\tau,\ \theta$ by requiring that a given transmission line (the reference line) with parameters

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