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IMPROVEMENT OF SURFACE ELECTROMAGNETIC WAVES ATTENUATION WITH RESISTIVE LOADING

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Abstract—Electromagnetic properties of conventional radar absorbing materials (RAM) make it difficult to use them to provide remarkable surface electromagnetic waves (SEMW) attenuation with thin thickness at low radar frequencies such as in the UHF and L bands. In this paper, a composite structure realized by a grounded RAM slab covered by a resistive sheet is proposed. The use of a resistive sheet results in a significant increase of SEMW attenuation performance at low frequency, but almost no increase in its thickness. The electromagnetic scattering properties for a target coated with the RAM with/without covered by a resistive sheet are considered for interpreting the improvement of SEMW attenuation with resistive loading. Using a method-of-moments (MoM) computational scheme, we explore the performance of the proposed composite structure as radar backscattering suppression for a metal slab at low radar frequencies. It is found that the RAM with resistive loading has significantly increased SEMW attenuation at low frequencies, and advances the large incidence angle or grazing angle mono-static radar cross section (RCS) reduction of the coating slab further than the RAM without resistive loading case.

1. INTRODUCTION

Experimental evidence (e.g., impulse response of a flat plate) indicates that edges are a major potential scattering source of stealth objects after the typical ones such as specular reflection, cavity or ducting scattering, and angular scattering are effectively controlled [1].

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Although edge scattering could be alleviated by indenting the edge discontinuity [2, 3], this is not always effective due to other requirement such as meeting the aerodynamic. Under this special condition, edge scattering can be reduced by employing SEMW absorbing materials for effect attenuating the surface waves before it reached the edge discontinuity [4]. The control of surface electromagnetic waves are the most important issues in RCS management since the main scattering sources are effect restrained. The standard objective for the surface electromagnetic waves absorbing materials design is to obtain the materials with the least thickness and the significant SEMW attenuation, but thin layer and low-frequency surface electromagnetic wave absorbing materials are difficult to realize. Thus, it is necessary to study the methods for improving the attenuation of SEMW at low frequencies.

Because of their applications in microstrip antennas, traveling wave antennas, frequency selective surfaces, and scattering from coated objects, SEMW have been widely studied for the past few decades. Ufimtsev et al. [5–7], Paknys and Jackson [8], and Neve and Paknys [9] have analyzed the fundamental characteristics of SEMW in loss coating layer including attenuation and propagation constants, electric and magnetic losses, phase and energy velocities, etc.. SEMW suppression employing resonance-type periodic structures are reported by a number of investigators [10–12]. Richmond [13], and Shivelyd [14] have examined the theory of surface waves propagation on a thin resistive sheet, and this theory would be useful in analyzing the scattering properties of thin resistive strips.

In this paper, an effective solution for improving SEMW attenuation at low frequencies that is realized by a grounded RAM slab covered by a resistive sheet. The analytical study of surface electromagnetic waves is made possible by assuming the thickness of the resistive sheet is an infinitely thin. With this assumption, it is possible to resolve the dispersion equations by employing the discontinuity boundary conditions [15]. To further validate our special design for improvement SEMW attenuation with resistive sheet loading, electromagnetic scattering of a metal slab loaded this proposed composite structure, is studied for various azimuth angular of the incidence plane wave at low frequencies.

In the following discussion, unless otherwise indicated, the analysis is limited to the attenuation and propagation property of transverse magnetic (TM) SEMW in thin RAM layer, since the analysis of transverse electric (TE) SEMW is similar.

2. DESIGN

In this paper, we consider the two-dimensional (2-D) TM SEMW in homogeneous RAM layer covered by a resistive sheet, backed up by a perfectly conducting plane. Schematic of this problem is illustrated in Fig. 1(a). In this figure, region 1 is free space; region 2 is a coated RAM layer with the relative permittivity ε and the relative permeability μ. The layer thickness is denoted by t. The square resistance value of the loaded resistive sheet is R.

TM SEMW in a homogeneous layer are described by the following expressions [16]: above the layer $(z \geq t)$

$$\begin{aligned} &H_x^1 = Ae^{ik_1 z}e^{i\beta y}, \\ &E_z^1 = -\frac{\beta}{k_0}Z_0 H_x^1, \quad E_y^1 = \frac{k_1}{k_0}Z_0 H_x^1. \end{aligned} \tag{1}$$

and inside the layer $(0 < z < t)$,

$$\begin{aligned} &H_x^2 = B\cos(k_2 z)e^{i\beta y}, \\ &E_z^2 = -\frac{\beta}{k_0\varepsilon}Z_0 H_x^2, \quad E_y^2 = \frac{ik_2}{k_0\varepsilon}Z_0 H_x^2 \tan(k_2 z). \end{aligned} \tag{2}$$

where the Subscript 1 and 2 represents free space and coated RAM layer dividing resistive sheet, just as shown in Fig. 1, respectively. A and B represent the relative amplitude of field in region 1 and region 2 respectively. $Z_0 = \sqrt{\mu_0/\varepsilon_0}$ is the impedance of free space, the complex quantities $k_1 = k_1' + ik_1''$ and $k_2 = k_2' + ik_2''$ are the transverse wave numbers of the wave field outside and inside layer, respectively. The complex quantity $\beta = \beta' + i\beta''$ is the longitudinal wave number, or

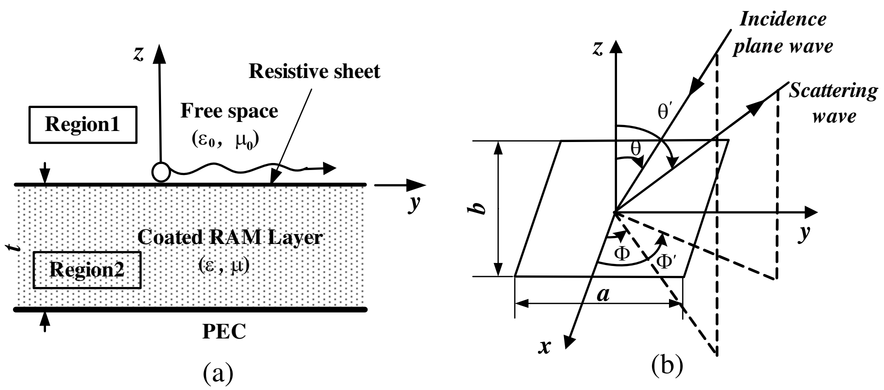

Figure 1. (a) Model of the proposed target; (b) Geometry and coordinate system of the coating RAM layer.

the propagation constant. These wave numbers meet the following relations:

$$k_1^2 + \beta^2 = k_0^2, \quad k_2^2 + \beta^2 = k_0^2 \varepsilon\mu. \tag{3}$$

The boundary conditions at $z = t$ are

$$E_y^1(z = t) = E_y^2(z = t), \quad H_x^2(z = t) - H_x^1(z = t) = J_s. \tag{4}$$

where J_s is the surface electric current on the resistive sheet, and is given by

$$J_s = \frac{E_y^1(z = t)}{R_\diamondsuit} = \frac{k_1 Z_0}{k_0 R_\diamondsuit} H_x^1. \tag{5}$$

According to Eqs. (1) to (5), the dispersion equation can be obtained

$$\sqrt{k_0^2\varepsilon\mu - \beta^2}\left(1 + \frac{\sqrt{k_0^2 - \beta^2}Z_0}{k_0 R_\diamondsuit}\right)\tan\left(\sqrt{k_0^2\varepsilon\mu - \beta^2}t\right) + i\varepsilon\sqrt{k_0^2 - \beta^2} = 0. \tag{6}$$

Based on Eq. (6), the attenuation and propagation properties of TM SEMW in RAM layers with resistive loading can be obtained. As $R_\diamondsuit$ is zero, $\beta = k_0$ must be met, and Eq. (6) becomes the propagation equation of parallel plate waveguide. As $R_\diamondsuit$ is infinity, Eq. (6) reduces to the correct equation

$$\sqrt{k_0^2\varepsilon\mu - \beta^2}\tan\left(\sqrt{k_0^2\varepsilon\mu - \beta^2}t\right) + i\varepsilon\sqrt{k_0^2 - \beta^2} = 0. \tag{7}$$

Equation (7) is consistent with the Eq. (4) in Ref. [16].

In this paper, the electromagnetic scattering properties presented by coated slab are discussed. In all of the following discussion, unless otherwise indicated, the slab is considered to lie in the xy-plane with a plane wave incident at an angle θ with respect to the z-axis, as shown in Fig. 1(b).

3. RESULTS AND DISCUSSION

For very thin thickness of coated RAM layer, purely dielectric RAM is not as efficient at attenuating SEMW as RAM with magnetic properties [17]. In the following discussion, we study only magnetic materials or composite materials. Panorama analysis method is to depict the relationship of parameters of absorbing material using the viewpoint of system and digital method, which is employed to study the distribution set of the electromagnetic parameters for the thin coated RAM. Based on the good representative sample of a wide class of available RAM proposed in Ref. [18], a sample absorbing material is selected, and its permittivity is constant ($\varepsilon' = 15$, $\varepsilon'' = 5$) in considered frequency band, but its permeability (μ', μ'') is variable from 0 to 15. The thickness of the sample RAM is $t = 0.5$ mm. Based on the Eq. (7), the contours are presented for analyzing the relationships between the electromagnetic parameters and the attenuation of TM-polarized SEMW (and its unit is dB/m) at the frequencies of 1, 2 and 10 GHz respectively, just as shown in Figs. 2–4.

From the Fig. 2, the attenuation of SEMW is very low in 0.5 mm thickness at the frequency of 1 GHz, no matter how the electromagnetic parameters of the sample RAM changes. In terms of conventional RAM, it is difficult to realize the electromagnetic parameters as mentioned above. The maximum attenuation of SEMW is only 0.44 dB/m, which can not be effect for suppression of the scattering mechanism of surface waves.

Contour of the attenuation of SEMW in the sample RAM layer at the frequency of 2 GHz is proposed in Fig. 3. The maximum attenuation reaches 3.6 dB/m, which is still not effect for suppression of the scattering mechanism of surface waves.

From the Fig. 4, the attenuation of SEMW is remarkable enhanced. The effect attenuation of surface waves can be obtained in most regions of the electromagnetic parameters. That is to say, it is very easy that we realize some actual RAM for providing high attenuation of SEMW.

From the Figs. 2–4, we can observe that the significant SEMW attenuation, but thin layer and low-frequency surface electromagnetic wave absorbing materials are difficult to realize. On the contrary, the remarkable attenuation of surface waves can be obtained comfortably with thin thickness at high frequencies range.

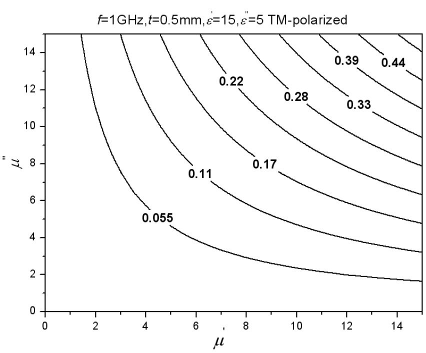

Figure 2. Contour of the attenuation of SEMW in the sample RAM layer at the frequency of 1 GHz.

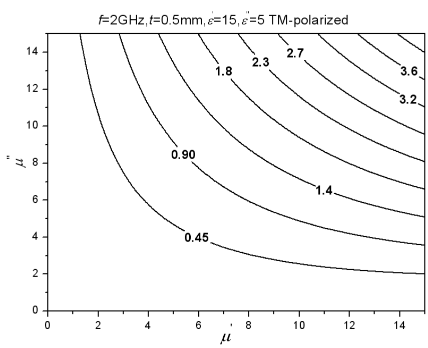

Figure 3. Contour of the attenuation of SEMW in the sample RAM layer at the frequency of 2 GHz.

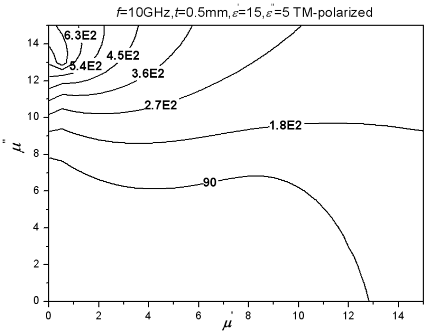

Figure 4. Contour of the attenuation of SEMW in the sample RAM layer at the frequency of 10 GHz.

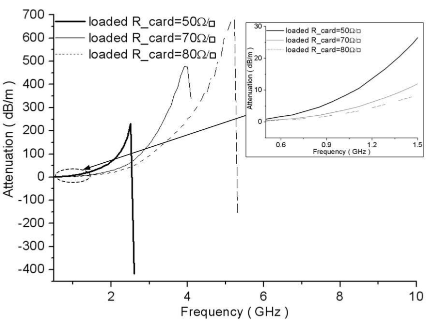

Figure 5. Attenuation constants of TM-polarized SEMW in the actual RAM with resistive loading.

Next, some actual absorbing material will be considered, and its electromagnetic parameters including the relative permittivity and the relative permeability are proposed by measured data, just as shown in Fig. 3(b) in Ref. [16]. This material is obtained on the basis of polymer composites filled with carbonyl iron and Co_2Z ferrite. This type of material is often used as SEMW waves absorbing coatings. Its thickness is selected as $t = 0.5$ mm. Based on the Eq. (6), the attenuation of TM-polarized SEMW in this actual RAM covered by resistive sheet with variable square resistance values is proposed, just as shown in Fig. 5.

The attenuation of TM-polarized SEMW in this actual RAM covered by resistive sheet with variable square resistance values is proposed, just as shown in Fig. 5. The attenuation of SEMW can be remarkably improved when a resistive sheet is introduced at low frequencies ranges. The cutoff frequencies of TM-polarized fundamental mode are 2.6, 4.1, and 5.23 GHz for the loaded resistive sheet of 50, 70 and 80 $\Omega/\square$, respectively. With the increasing of the resistance of loaded resistive sheet, the up cutoff frequencies will increase gradually, but the attenuation of SEMW will decrease rapidly at low frequencies ranges. To solve the issue of contradiction, the resistive sheet of 200 $\Omega/\square$ is selected by optimization. The dispersion curve of this case is shown in Fig. 6, and the attenuation property of the actual RAM unloaded resistive sheet is also proposed for comparison.

Just as shown in Fig. 6, we can observe that the attenuation of SEMW in the actual RAM with resistive loading is significant improved, but its cutoff frequencies is not changeable. Transformation of SEMW into nonphysical waves happens at the upper cutoff

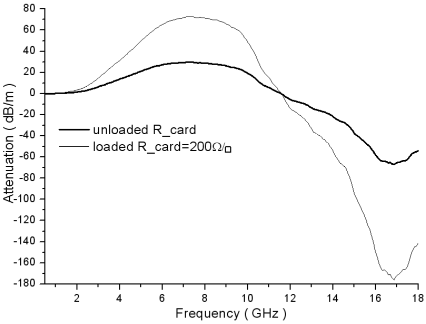

Figure 6. Attenuation constant of TM-polarized SEMW in the actual RAM with/without resistive loading (R_card = 200 Ω/□).

frequency near to 11.8 GHz for the two cases (that is to say, the actual RAM layer with/without resistive loading). Negative values of attenuation constant from the Fig. 6 show the amplification of the field, which mean that surface wave can not be excited and thus no propagation occurs under these conditions.

To verify the above analysis, we study the mono-static radar cross section reduction (RCSR) properties of a slab coated with the proposed actual RAM with/without resistive loading by the multilevel fast multipole method (MLFMM). Fig. 7 shows the mono-static RCS with TM polarization at 1, 2 and 4 GHz. Tapered R-card [19] is loaded to the edges of the considered metal slab to reduce its edge scattering [20]. Considered resistive sheet loading for improving surface electromagnetic wave attenuation at low frequency, the square resistance of resistive sheet is 70 Ω/□.

The properties of surface waves in RAM layers have certain correspondence to its contributions to mono-static RCSR. From the Fig. 7, we can observe that the effect of mono-static RCSR can improve when the coated actual RAM is covered by a resistive at the frequencies of 1 and 2 GHz, but the case is on the contrary for the frequency of 4 GHz. The improved attenuation of SEMW can be observed from the Fig. 5, but the deteriorated effect of mono-static RCSR is shown in Fig. 7 for the coated RAM with resistive loading at the frequency of 4 GHz, which seems to be contradictory. As we known, the characteristic of surface waves are dependent on the values of the attenuation and phase constants, their mechanisms are rather complicated. Moreover, the radar cross-section of a finite slab with a RAM coating depends on several physical mechanisms. In addition to the residual reflection after absorption in this RAM layer, according to the transmission line model, there will be a contribution arising from

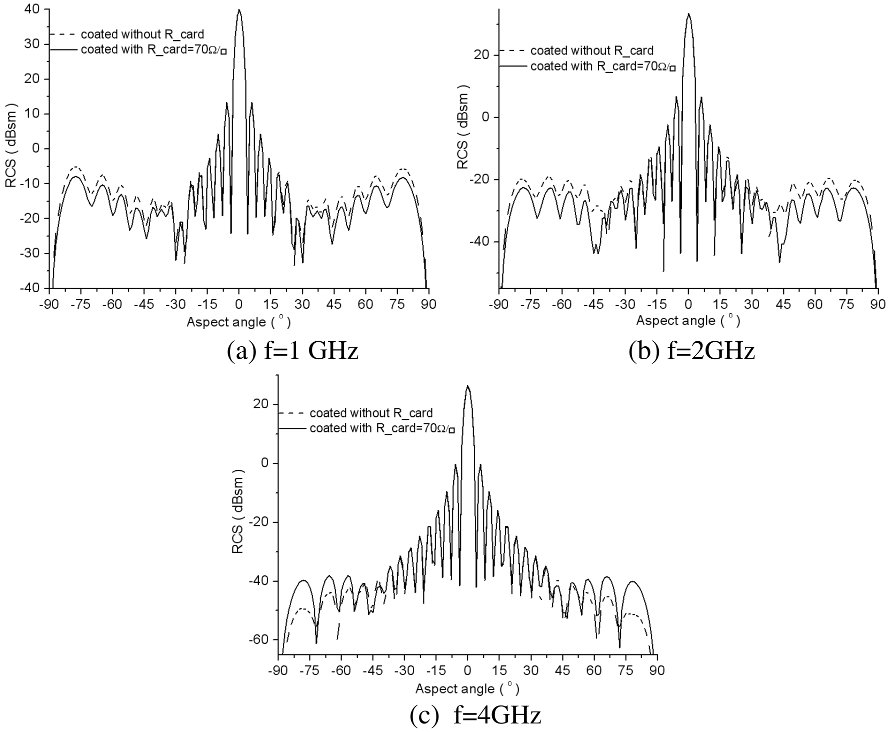

Figure 7. TM-polarized mono-static RCS diagram for a slab coated with the proposed actual RAM with/without resistive loading at the frequencies of 1, 2, and 4 GHz respectively.

diffraction at the slab edges. Part of this contribution involves the launching of a surface wave at these edges. Thus surface waves can be extracted from the multiple scattering mechanisms of a finite slab with a RAM coating, which can be carried out in future study.

4. CONCLUSION

According to the Panorama analysis method, the relationships between the electromagnetic parameters including the relative permittivity and the relative permeability in respective frequencies and the thickness of a sample RAM, and the attenuation of SEMW are presented. For thin layer and conventional surface waves absorbing materials, the significant attenuation of SEMW can not be obtained at low radar frequencies such as in the UHF and L bands. The resistive sheet is employed for the improvement of attenuation property of SEMW in a surface waves absorbing layer at low radar frequencies, but almost no increase in its thickness. With the increasing of the resistance values of loaded resistive sheet, the up cutoff frequencies will increase gradually, but the attenuation of SEMW will decrease rapidly at low frequencies ranges. The issues of combination of both the up cutoff frequencies and the attenuation property of SEMW must be considered. The monostatic radar cross section properties of a slab coated with the proposed actual RAM with/without resistive loading are studied for verifying the proposed method. The improvement of RSCR can obtained when the coated actual RAM is covered by a resistive sheet at low frequencies.

For future study, one may extend this investigation to explore the graphical resistive sheet employing all kinds of frequency selective surface (FSS) elements, and study a method for surface waves extracting from the multiple scattering mechanisms of a finite slab with a RAM coating. These topics are now under investigation.

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