Relationships between Surface Wave Attenuation and the Reflection Properties of Thin Surface Wave Absorbing Layer

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Abstract— Compared and analyzed the surface impedance defined by the basic definition of surface wave and by the reflection coefficient of thin radar absorbing material (RAM) layers backed with a perfect electric conductor (PEC) plate, the relationships between its surface wave attenuation property and its reflection characteristics can be founded. Equivalent surface impedance for a perfect electrical conductor (PEC) plate coated by a thin layer of RAM can be easily obtained based on the reflection coefficient for an infinite plate coated with same thin RAM layers, which can be regarded as a function for computing the attenuation of surface wave in this RAM layers. In this paper, two kinds of reality RAM for single layer coating and two layers coating will be considered for verifying this approach respectively. For two layers coating, the mono-static radar cross section (RCS) reduction properties of a slab coated with this RAM are discussed for evaluating the attenuation of surface wave because the equivalent medium theory is not appropriated under this condition. The proposed approach is effective and advantageous especially for thin multi-layers RAM coating.

1. INTRODUCTION

In recent years, with the development of low observable technology, much interest has been shown in reducing the non-specular scattering caused by surface wave. Surface wave becomes one of the most important issues in RCS design since the main scattering sources such as specular reflections are effectively eliminated [1]. The control of surface wave has been utilized as the motivation for exploring new RAM as well as the shaping of edges and other electromagnetic discontinuities. Surface wave radiates energy at discontinuities such as edges of the target [2]. By reciprocity, surface wave will be excited by plane electromagnetic (EM) wave incident upon such a discontinuity [3]. Properties of surface wave in absorbing layers are widely investigated, such as the works done by Ufimtsev [4, 5], Paknys [6], and Neve [7]. In these literatures, fundamental characteristics of surface wave including attenuation and propagation constants, electric and magnetic losses, phase and energy velocities, etc., are analyzed. These works start with the definition of surface wave, but ignore the properties of surface wave in multi-layers RAM coating. The equivalent medium theory is not appropriated for computing the surface wave properties under this condition of multi-layers RAM coating. Thus, it is necessary to study another approach for evaluating the surface wave properties especially for the case of multi-layers RAM coating.

Based on the Collin's guided wave analysis method of dielectric plate [8], equivalent surface impedance of thin coating layers over which surface wave propagates is defined to predict the performances of surface wave attenuation. Reflection coefficient of an impedance-coated surface can be measured expediently at plane EM wave incidence from normal to near grazing incidence. Then, attenuation properties of surface wave in thin RAM at oblique incidence can be obtained. Relationships between the surface wave properties and the reflection characteristic of a grounded dielectric slab covered a doubly periodic array of metal patches was analyzed [9], but this problem is still needed further research.

In this paper, the relationships between its surface wave attenuation property and its reflection characteristics will be founded by compared surface impedance defined by the basic definition of surface wave and the reflection coefficient at plane EM wave incidence respectively. Single layer RAM coating and two layers RAM coating are considered respectively for analyzing this conclusion. For single layers RAM coating, an actual magnetic material is considered. For two layers RAM coating, two kinds of actual RAMs will be considered, in one of the materials exist only electric loss, in another exist simultaneously electric loss and magnetic loss, and their relative permittivity and relative permeability are obtained from measured data. Based on these intrinsic parameters, reflection properties of the entire coating layers can be computed for various combinations of coating thicknesses and coating orders according to the transmission line theory. For thin RAM layers, this planar coated structure is equivalent to an impedance-coated surface, and its surface impedance can be obtained based on computed reflection coefficient. The properties of surface wave in RAM layers have certain correspondence to its contributions to mono-static RCS reduction. According to this conclusion proposed in Ref. [10], the mono-static RCS reduction of a slab coated with corresponding thin RAM layers are calculated to validate the analysis of surface wave attenuation property in thin RAM layers based on their electromagnetic reflection characteristics.

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

2. DESIGN

2.1. The Attenuation of Surface Wave

We consider the two-dimensional (2-D) TM surface wave in thin homogeneous RAM layer backed up by a perfect conducting plane. Schematic of the problem is illustrated in Figure 1. In this figure, region 1 is free space; region 2 is a thin RAM layer with equivalent relative permittivity ε and equivalent relative permeability μ. The layer thickness is denoted by d. the wave number in free-space is denoted as $k_0 = \varpi\sqrt{\varepsilon_0\mu_0} = 2\pi/\lambda_0$, where ε_0, μ_0 is the permittivity and the permeability of free space respectively, ω is the angular frequency of harmonic oscillation and λ_0 is the free-space wavelength. The time dependence $\exp(-j\omega t)$ is assumed and suppressed below.

Based on Ref. [11], the surface wave attenuation can be obtained,

$$\beta'' = -k_0 \mathrm{Im}\left(\sqrt{1-\left(\frac{\eta_s^s}{Z_0}\right)^2}\right)\ (\mathrm{Np/m}). \tag{1}$$

where

$$\eta_s^s = \frac{E_{\tan}}{H_{\tan}} = -Z_0\frac{k_1}{k_0} \tag{2}$$

2.2. Reflection at the Interface of Free Space and the Thin RAM Layer Backed by Ground Plane

In the case of TM polarization, the electric field vector is parallel to the plane of incidence as shown in Figure 2. The wave is incident at an angle θ_i with respect to the surface normal $\overset{\Lambda}{n}$ and reflected at an angle θ_r. Region 1 is free space with parameters (ε_0, μ_0) and region 2 is the thin RAM layer with parameters (ε, μ).

Base on the Maxwell's equation, we obtain

$$\eta_s^r = -\frac{E_x^{inc} + E_x^{ref}}{H_x^{inc} + H_x^{ref}} = -\frac{\cos\theta_i Z_0(1-\Gamma)}{1+\Gamma} \tag{3}$$

where η_s^r represents the surface impedance based on the reflection coefficient. Eq. (2) is consistent with the Eq. (9.20) in Page 426 of Ref. [12].

η_s^s can be equivalent with η_s^r under the certain conditions, which is the main target in this paper.

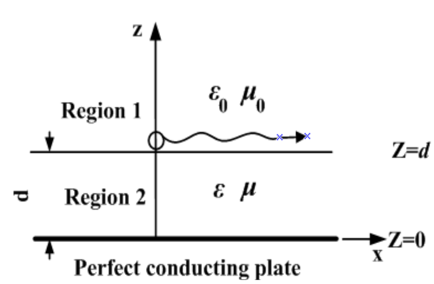


Figure 1: Model for surface wave analyzing.

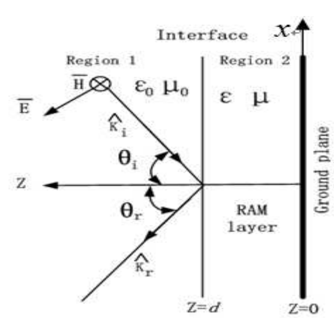
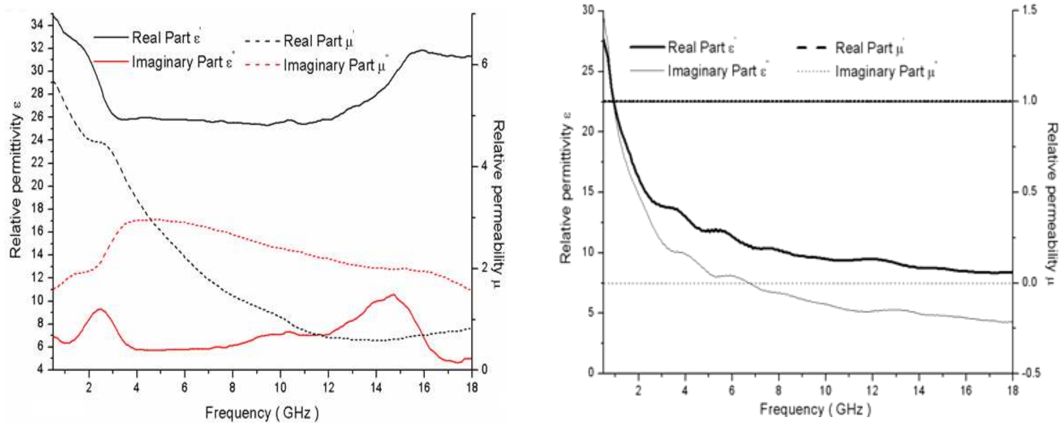


Figure 2: Plane wave incidence on a plane boundary.



(a) (b)

Figure 3: The relative permittivity and relative permeability dispersion characteristics. two actual absorbing materials: (a) RAM A, and (b) RAM B.

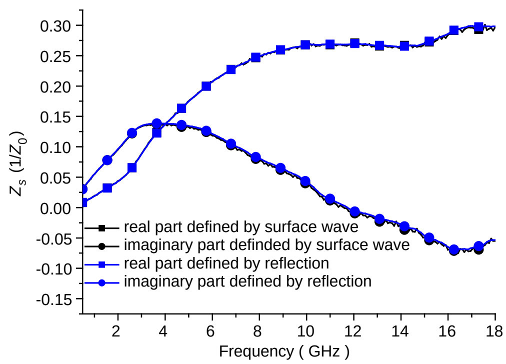


Figure 4: Surface impedance defined by surface wave characteristic and by the reflection coefficient of RAM A backed with a perfect electric conductor (PEC) plate, and its thickness is 0.5 mm.

3. RESULTS AND ANALYSIS

3.1. Single Layer RAM Coating

In this paper, two kinds of RAMs for single layer coating and two layers coating will be considered, RAM A is obtained on the basis of polymer composites filled with carbonyl iron and Co_2Z ferrite [13], but RAM B is obtained on the basis of Carbon black in polyethylene, which the relative permittivity ε and relative permeability μ shown in Figure 3 are gained from measured results. For single layer RAM coating, only RAM A is considered, and its thickness is 0.5 mm.

Based on the transmission line theory, the reflection loss determined in coating layer of RAM A with the thickness of 0.5 mm can be obtained for TM polarization, and the surface impedance defined by surface wave characteristic can be obtained based on the Formula (2), and the surface impedance defined by reflection coefficient at 30° of incidence angle is also proposed for comparison, just as shown in Figure 4. We can observe that the surface impedance defined by surface wave characteristic is exactly identical to that defined by reflection coefficient. That is to say, the evaluation of surface wave attenuation property in thin RAM layers based on their electromagnetic reflection characteristics is good enough.

3.2. Two Layers RAM Coating

Considered the propagation properties of surface wave, the equivalent medium theory is not appropriated for thin multi-layers RAM coating. Therefore, the evaluation of surface wave properties of thin multi-layers RAM coating is very difficult. In this paper, based on the relationships between the properties of surface wave in coated RAM layers and mono-static RCS reduction performances of the coated slab [10, 15], its surface wave characteristics can be easily obtained.

Double layers coating order is kept and as follow, the bottom layer is RAM A with the thickness of 0.5 mm, and the top layer is RAM B with the thickness of 1.0 mm. To this case, the surface

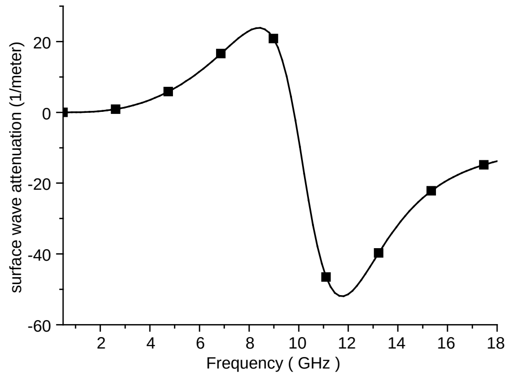


Figure 5: The surface wave attenuation defined by reflection coefficient.

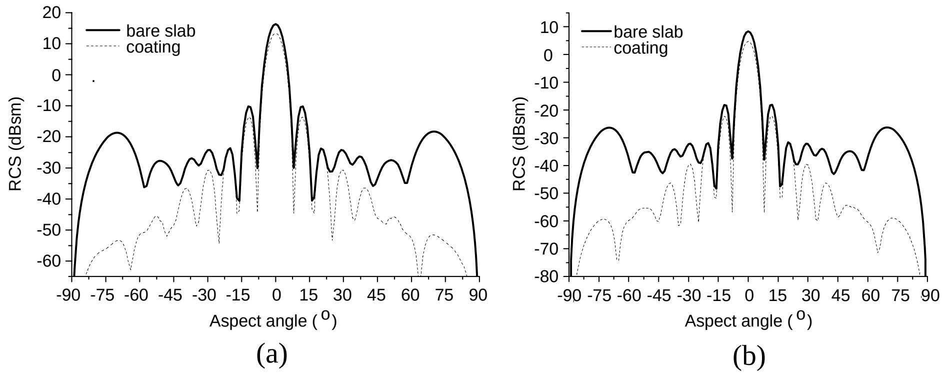


Figure 6: Mono-static RCS with TM polarization for different frequency ((a) 4 GHz, (b) 10 GHz).

impedance based on the reflection coefficient can obtained according to the Eq. (3). Supposed that the η_s^s can be equivalent with η_s^r, the surface attenuation of this structure can be obtained based on the Eq. (1), just as shown in Figure 5. In the following, the surface attenuation defined by reflection coefficient will be certified based on the relationships in between the travelling wave attenuation and the radar cross section reduction.

In this paper, a slab will be considered to lie in the xy-plane with a plane wave incident at an angle θ_i with respect to the z-axis, as shown in Figure 2. The flat plate (aluminum slab) of size $a \times b = 5\lambda \times 5\lambda$ (λ is the wavelength in free space) and thickness equal to 0 mm, has RAM coatings on the upper surface. Based on the definition of the RCS of surface traveling wave [15], the main-lobe of surface traveling wave is located at 75°.

Figure 6 shows the mono-static RCS with TM polarization at 4 and 10 GHz. Tapered R-card [16–18] was loaded to the edges of the considered metal slab to reduce its edge scatter. The mono-static RCS of uncoated slab is also provided for RCS reduction analysis. The differences between mono-static RCS for coated and uncoated cases are shown by RCS reduction values. Based the RCS reduction at the observe angle of 75°, the surface wave attenuation can computed, 3.82 Np/m and 9.82 Np/m for 4 GHz and 10 GHz respectively. Compared these results with Figure 5, good agreement is observed.

4. CONCLUSION

The surface wave attenuation property can be obtained based on the reflection coefficient of thin RAM layers backed with PEC ground plate. This approach is effective and advantageous especially for thin multi-layers RAM coating. The case of double layers RAM coating is analyzed in this paper, and the results verify this analysis effectively. In general, the thickness of surface wave absorbing materials layers should be much thinner than the effective wavelength, and its refractive index is large relative to free space, which is a prerequisite to using this approach. In conclusion, we verified that the surface impedance Z_s with near constant for all angles of incidence defined by reflection coefficient of plane wave incidence on it is practically identical to that defined by surface wave properties.

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