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STUDY ON THE PROPERTIES OF SURFACE WAVES IN COATED RAM LAYERS AND MONO-STATIC RCSR PERFORMANCES OF A COATED SLAB

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Abstract—Relationships between the properties of surface waves in radar absorbing materials (RAM) layers and mono-static radar cross section reduction (RCSR) performances of a coated slab are studied. In this paper, two kinds of RAM were employed for double-layer coating. By changing the thickness of each layer and the order of RAMs, mono-static RCSR performances of the coated slab are studied. Simultaneously mono-static RCSR performances of a slab coated with equivalent medium of the considered RAMs in situ are calculated and compared with the previous ones in regard to the properties of surface waves. It is found that surface waves in between layers for various coated projects can be evaluated. Our results suggest that the optimal coated order for RAMs exists, and the method may be efficient for coating strategy with various kinds of RAMs. Electromagnetic scatterings of the equivalent medium exclude the effect of surface waves in between layers. Therefore, the equivalent medium theory is not appropriated for the research of electromagnetic scattering on lossy mediums.

1. INTRODUCTION

Electromagnetic scattering from finite coated surface arises in many physical contexts [1–4]. In most applications, the transmitter and receiver are located on the same platform and frequently share the same antenna. In this case, the radar is mono-static. Therefore, it is desirable to study the properties of surface waves in coated RAM layers and mono-static RCSR performances of the coated slab. In the past researches of RCSR of a target using RAM,

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some important electromagnetic scattering problems including the quantitative interrelationships between the coating materials sorts, coating layers, coating thickness and the shaping design such as curvature adjustment, have been extensively investigated by M. Hossein [5], F. C. Smith [6], You-lin Geng [7], et al.. Yet the intrinsic electromagnetic characteristics of the coated RAMs are rarely concerned. Since the mono-static RCS of the coated slab can be mainly benefited from edge effectiveness generated by surface wave, properties of surface waves in absorbing layers are widely researched, such as Pyotr Ya. Ufimtsev [8–10], Robert Paknys [11], Michael J. Neve [12], Y. H. Xu [13], F. Terracher [14], et al.. In these literatures, all basic characteristics of surface waves are analyzed, including attenuation and propagation constants, electric and magnetic losses, phase and energy velocities, etc. However, the contributions of surface waves to the mono-static RCSR of the coated target and the properties of surface waves in between absorbing layers are seldom considered. Thus, it is necessary to study the properties of surface waves in RAM layers and mono-static RCSR performances of the coated slab.

In this paper, two kinds of actual RAMs will be considered, and their relative permittivity and relative permeability are obtained from measured data. Based on these intrinsic parameters, the electromagnetic characteristics parameters of entire coated layers can be computed for various combinations of alternating thickness and order according to the equivalent medium theory. Therefore, the properties of surface waves in equivalent radar absorbing layers can be considered, but the analysis is limited to the attenuation and propagation properties for TM surface waves in equivalent RAM layers, since the analysis of TE surface waves is wholly similarity, which will be regarded as a guide for mono-static RCSR of a coated target. The properties of surface waves in between RAM layers are also considered for obtaining an optical coated order.

By coating a given target with optical RAM layers, the RCS can be reduced and it is of interest to investigate the resulting RCSR. The mono-static RCS patterns of a target with RAM coating for horizontal polarization plane wave are calculated using a uniform geometrical theory of diffraction for loss surfaces. The properties of surface waves in coated RAM layers will be obtained from numerical calculations using the equivalent medium theory. In this paper, two kinds of RAM for double-layer coating will be considered. By changing the thickness of each layer and the order of RAMs, the properties of surface waves in RAM layers and mono-static RCSR performances of the coated slab can be studied. Mono-static RCSR performances of a slab coated with equivalent medium of the considered RAMs in situ are calculated and compared with the previous ones in regard to the properties of surface waves to obtain the optimal coating order. Finally, the relationships between the properties of surface waves in coated RAM layers and the mono-static RCSR characteristics of the coated slab are discussed in detail.

2. DESIGN

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. The flat plate of size ($a \times b = 10\lambda \times 10\lambda$) where λ is the wavelength of incidence plane wave. As for the loaded RAMs, we consider two kinds of stratified isotropic mediums characterized by their thickness d_1, d_2 (but infinite in-plane), dielectric permittivity $\varepsilon_{r1} = \varepsilon'_{r1} + j\varepsilon''_{r1}$, $\varepsilon_{r2} = \varepsilon'_{r2} + j\varepsilon''_{r2}$ and magnetic permeability $\mu_{r1} = \mu'_{r1} + j\mu''_{r1}$, $\mu_{r2} = \mu'_{r2} + j\mu''_{r2}$. The assumed time dependence is $\exp(j\omega t)$. The frequencies of 1, 4, 8, and 18 GHz, representing L, S, X, and Ku wave bands characters respectively, are discussed, in two polarizations; which has the electric field vector perpendicular to the plane of incidence (VV-polarization) or parallel to the plane of incidence (HH-polarization). Similarly, only the results of HH-polarization are proposed corresponding to the analysis of TM surface waves.

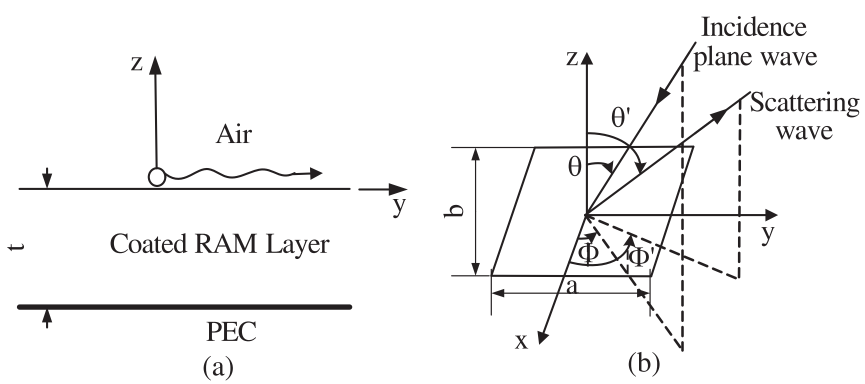

Figure 1. (a) Model of the proposed target. (b) Geometry and coordinate system of the coating RAM layer. t represents the thickness of the coating RAM layer. $a = b = 10\lambda$ represents the length and width of the proposed target, and λ is the wavelength of free space.

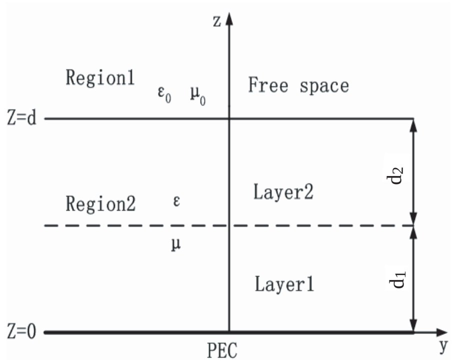

Figure 2. Schematic for surface waves analysis.

In this work, we consider the two-dimensional (2-D) TM surface waves in homogeneous RAM layers backed up by a perfectly conducting plane. Schematic of the problem is illustrated in Fig. 2. In this figure, region 1 is free space; region 2 is an equivalent RAM layer with equivalent relative permittivity ε and equivalent relative permeability μ obtained from the equivalent medium theory. The layer thickness is denoted by $d = d_1 + d_2$.

TM surface waves in a homogeneous layer are described by the following expressions [9]: Above the layer ($z \geq d$)

$$H_x = e^{ik_1(z-d)} e^{i\beta y}$$
$$E_z = -\frac{\beta}{k_0} Z_0 H_x, \quad E_y = \frac{k_1}{k_0} Z_0 H_x \tag{1}$$

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

$$H_x = \frac{\cos(k_2 z)}{\cos(k_2 d)} e^{i\beta y}$$
$$E_z = -\frac{\beta}{k_0 \varepsilon} Z_0 H_x, \quad E_y = i\frac{k_2}{k_0 \varepsilon} Z_0 H_x \tan(k_2 z) \tag{2}$$

where $Z_0 = \sqrt{\varepsilon_0/\mu_0}$ is the impedance of free space, the complex quantities $k_1 = k_1' + jk_1''$ and $k_2 = k_2' + jk_2''$ are the transverse wave numbers of the wave field outside and inside layer, respectively. The complex quantity $\beta = \beta' + j\beta''$ is the longitudinal wave number, or the propagation constant. These wave numbers meet the following relations:

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

According to Eq. (3), and the continuity boundary condition E_y satisfied, we can obtain the dispersion equation:

$$\sqrt{k_0^2\varepsilon\mu-\beta^2}\tan\left(d\sqrt{k_0^2\varepsilon\mu-\beta^2}\right)+i\varepsilon\sqrt{k_0^2-\beta^2}=0 \qquad (4)$$

Based on Eq. (4), the attenuation and propagation properties of TM surface waves in RAM layers can be obtained. Moreover, in order to calculate the properties of surface waves in between layers, Eq. (4) must be transformed into another form:

$$\sqrt{k_0^2\varepsilon_2\mu_2-\beta^2}\tan\left(d_1\sqrt{k_0^2\varepsilon_2\mu_2-\beta^2}\right)+i\varepsilon_2\sqrt{k_0^2\varepsilon_1\mu_1-\beta^2}=0 \qquad (5)$$

where the Subscript 1 and 2 represents the lower and upper RAM layer dividing broken line, just as shown in Fig. 2, respectively. d_1 represents the lower-RAM layer thickness. In general, the properties of surface waves in between layers can not be directly calculated using formula Eq. (5) because ε_1 and μ_1 representing the equivalent electromagnetic parameter for the upper absorbing materials and free space can not be obtained easily.

In this paper, two kinds of RAM for double-layer coating are considered, and four cases are proposed to realize the two schemes: One is that the thickness of each layer is the same but RAMs are alternated, and named as case 1 and case 2 respectively; the other is that the thickness is apparent different but RAMs are unchanged, and named them as case 3 and case 4 respectively. Table 1 summarizes the considered four cases. All results presented in this paper are obtained from two actual absorbing materials denoted RAM A and RAM B, and their relative permittivity ε and relative permeability μ are gained from measured results, just as shown in Fig. 3. The RAM is coated on the surface of a copper slab, with four combinations shown in Table 1.

Table 1. RAM layers for the $10\lambda \times 10\lambda$ conducting slab.

	Layer order	Layer RAM	Layer thickness d (mm)
Case 1	1	RAM B	$d_1 = 0.5$
	2	RAM A	$d_2 = 0.5$
Case 2	1	RAM A	$d_1 = 0.5$
	2	RAM B	$d_2 = 0.5$
Case 3	1	RAM A	$d_1 = 3.4$
	2	RAM B	$d_2 = 0.1$
Case 4	1	RAM B	$d_1 = 0.1$
	2	RAM A	$d_2 = 3.4$

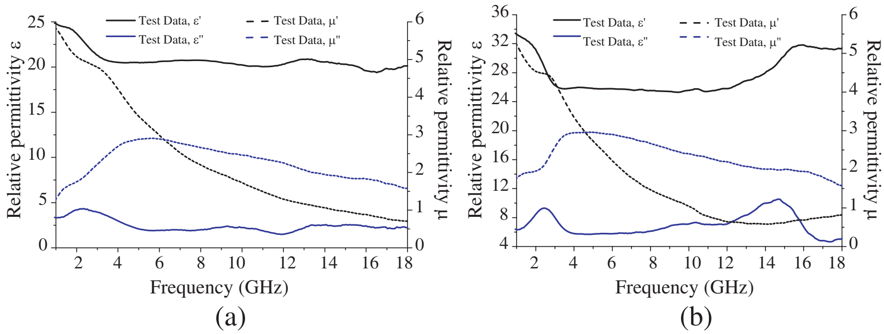

Figure 3. The electromagnetic parameters of two actual absorbing materials, as a function of frequency. (a) Relative permittivity and relative permeability of RAM A. (b) Relative permittivity and relative permeability of RAM B.

The equivalent electromagnetic parameters can be obtained based on the equivalent medium theory. In order to obtain the equivalent permittivity and permeability of the coating RAM multilayer, we characterize it as an equivalent homogeneous medium and resort to the transmission line theory [15]. The S parameters are related to refractive index n and impedance z by

$$S_{11} = \frac{R_{01}\left(1 - e^{ink_0 d}\right)}{1 - R_{01}^2 e^{i2nk_0 d}}, \tag{6}$$

$$S_{21} = \frac{\left(1 - R_{01}^2\right) e^{ink_0 d}}{1 - R_{01}^2 e^{i2nk_0 d}}, \tag{7}$$

where $R_{01} = (z-1)/(z+1)$, S_{11} and S_{21} are the reflection and transmission coefficient respectively, d is the thickness of the considered medium.

Just as the Ref. [16, 17] pointed out, the refractive index n and the impedance z can be obtained by inverting Eqs. (6) and (7), yielding

$$z = \pm\sqrt{\frac{(1+S_{11})^2 - S_{21}^2}{(1-S_{11})^2 - S_{21}^2}}, \tag{8}$$

$$e^{ink_0 d} = \frac{1-S_{11}^2+S_{21}^2}{2S_{21}} \pm \frac{i}{2S_{21}}\sqrt{[S_{11}^2-(1-S_{21})^2][(1+S_{21})^2-S_{11}^2]}, \tag{9}$$

The permittivity ε and permeability μ meet the following relations:

$$\varepsilon = nz, \tag{10}$$

$$\mu = n/z, \tag{11}$$

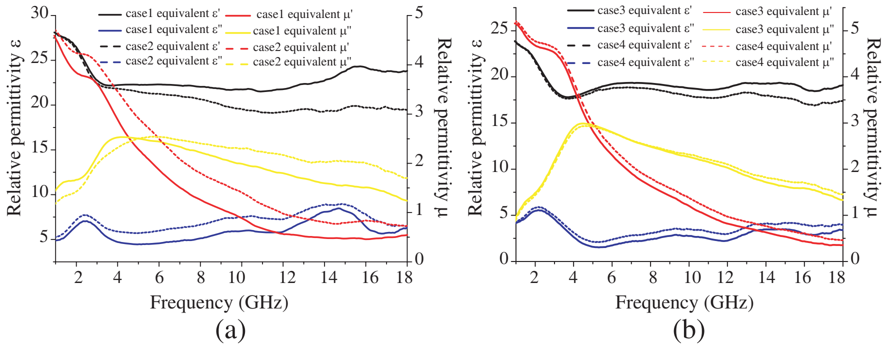

Figure 4. Equivalent electromagnetic parameters of the considered four cases, as a function of frequency. (a) Equivalent relative permittivity and relative permeability of case 1 and case 2. (b) Equivalent relative permittivity and relative permeability of case 3 and case 4.

Therefore, the real part and imaginary part of ε and μ can be obtained by solving equations from (8) to (11). In this paper, the equivalent permittivity and permeability of four cases under consideration can be determined using the method proposed above, just as shown in Fig. 4. To compare the performances of mono-static RCSR with the properties of surface waves in absorbing layers, case 1 and case 2 are regarded as a group, whereas case 3 and case 4 are the other one.

Mono-static RCS considerations are carried out at the frequencies of 1, 4, 8 and 18 GHz. In each frequency, the target conducts RCS calculation is conducted by changing pitching angle. The calculations are made in the principal plane and the radar cross section values are presented in decibels relative to one square wavelength (dB). The incidence angle θ is defined in Fig. 1, with 0° incidence perpendicular to the target surface.

3. RESULTS AND ANALYSIS

In most cases, the mono-static RCS of a target is due to the electrical or magnetic discontinuity existed within the structure of the target. Surface wave must be considered when the electrical or magnetic discontinuity happens. The mono-static RCS patterns are computed for the uncoated slab and RAM coated slab under the horizontal polarization of incidence plane wave. The mono-static

RCSR performances of a slab coated with the equivalent medium of RAM layers are calculated, and their surface wave properties are also considered. As for the properties of surface waves in between layers, a direct calculation can not be found because the coated RAMs are commonly complex loss materials. The optimal design is highly necessary based on genetic algorithm (GA) to meet the target of our research.

3.1. Equal Thickness Research

In this scheme, case 1 and case 2 are the targets of our research. The mono-static RCS patterns are given for the uncoated slab and RAM coated slab under the horizontal polarization of incidence plane wave, and the mono-static RCSR performances of a slab coated with the

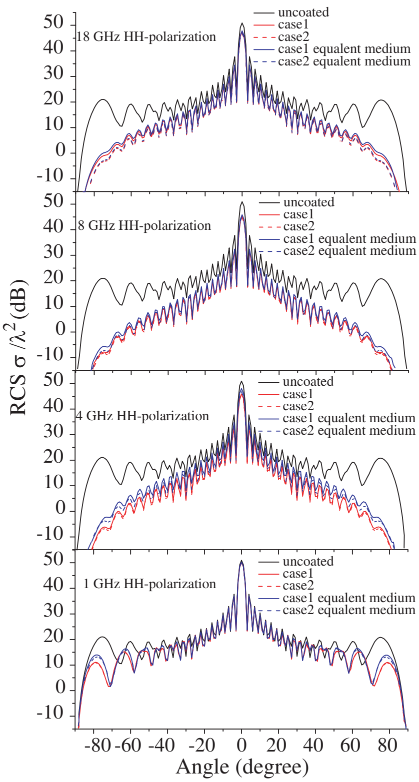

Figure 5. HH-polarization mono-RCS diagram for case 1 and case 2 for at 1, 4, 8, and 18 GHz respectively.

equivalent medium for the considered cases are also proposed, just as shown in Fig. 5. All the results demonstrate a distinction between the actual cases and their equivalents. The distinction is relatively large at low frequencies, and decreases with the increasing frequencies. For every frequency region, the distinctions for case 1 are larger than those for case 2, so the attenuation properties of surface waves in between layers for case 1 superior to those for case 2. Based on Eq. (5), the layer order adopted in case 1 is an optimal parameter.

Based on the definition of surface wave and the theory of electromagnetic field, attenuation characteristic of the equivalent mediums for considered RAMs is obtained for the 1 mm thickness by numerical calculation, just as shown in Fig. 6. For corresponding to the analysis of surface waves, only transverse magnetic (TM) waves are considered for target's RCS pattern. The characteristics of surface waves are dependent on the values of the attenuation and phase constants, and their transmission mechanisms are rally complicated. In the figure, the positive values of the attenuation constant $\beta'' = \mathrm{Im}(\beta)$ relate to propagating surface waves while the negative values with regard to nonphysical waves. The frequency, at which the imaginary part of the wave number becomes naught can be interpreted as the upper cutoff frequency. Transformation of surface waves into nonphysical waves happens at the upper cutoff frequency near to 9.6 GHz. As for the electromagnetic scattering originated from nonphysical waves, we will discuss in following research. The dispersion properties of surface waves are also illustrated in Fig. 7

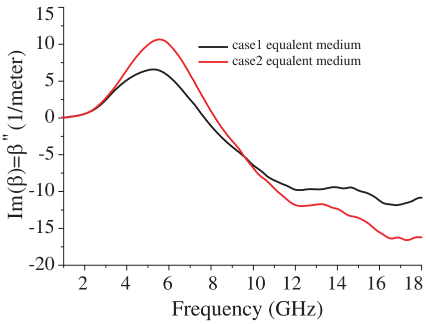

Figure 6. Attenuation constants of TM surface waves in absorbing layers with equivalent ε and μ shown in Fig. 4(a).

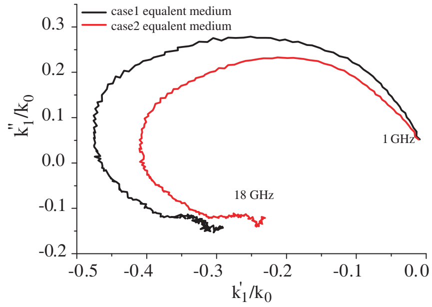

Figure 7. Trajectories of the transverse wave number of fundamental TM surface waves in absorbing layers with equivalent ε and μ shown in Fig. 4(a).

for the equivalent absorbing mediums of considered case 1 and case 2. Transformation of TM surface waves into nonphysical waves can also be evidenced. The oscillation frequency ranges from 1 GHz at the upper end of each trajectory in Fig. 7 to 18 GHz at its lower end. The peak of surface waves attenuation can achieve 10 and 5 neper/m at 5.8 GHz for case 2 and case 1, respectively.

From Figs. 5–7, we can observe that the attenuation and dispersion properties of surface waves for the case 2 equivalent mediums are superiority over those for the case 1 equivalent. Good agreement between the mono-static RCSR patterns and the properties of surface waves is observed.

3.2. Equal Reflection Properties Research

By optimal design, case 3 and case 4 are provided equal reflection properties at low frequency range. From Fig. 4(b), we can observe that the equivalent electromagnetic parameters for case 3 and case 4 are very similar at the low frequency range. Therefore, the considered

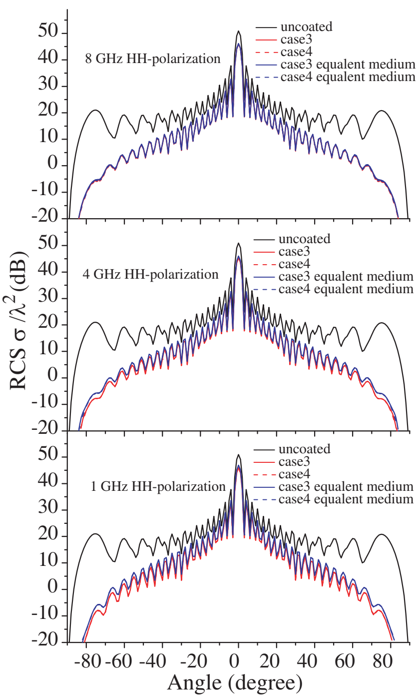

Figure 8. HH-polarization mono-RCS diagram for case 3 and case 4 for at 1, 4, and 8 GHz respectively.

frequency bands are limited to below 12 GHz. The mono-static RCS patterns for HH-polarization are proposed, just as shown in Fig. 8. The mono-static RCS trajectories of the considered two cases and their equivalent mediums are wholly superposing respectively, but the distinctions between the actual cases and their equivalent are still existent. The properties of surface waves in between layers can be obtained using the distinctions based on Eq. (5). Accordingly, we can concluded that the layer order adopted by case 4 is an optimal selection. Comparing Fig. 5 with 8, we can observe that the distinctions between the actual cases and their equivalent will be gradually eliminated with the increasing frequency. According to these, I presume that the equivalent medium theory may be used to analysis the electromagnetic scatter of loss absorbing materials at certain frequency range.

The attenuation properties of surface waves for the two equivalent cases are proposed in Fig. 9, and the dispersion properties of surface waves are also illustrated in Fig. 10. Similarly, the attenuation and dispersion properties of surface waves can keep consistent for the two cases below 12 GHz. Transformation of surface waves into nonphysical waves happens at the upper cutoff frequency near to 2.2 GHz.

From Figs. 5–10, we can observe that the relationships between the mono-static RCS performances of a slab coated with RAM and the properties of surface waves in absorbing layers can be founded. The properties of surface waves for case 3 and case 4 are apparently superior to those for case 1 and case 2, and so the mono-static RCSR performances are.

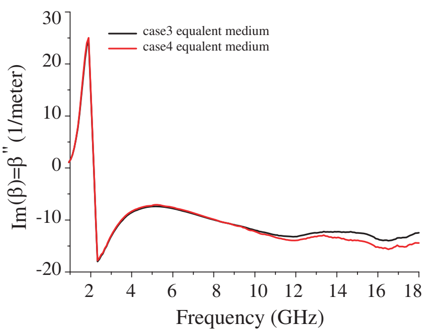

Figure 9. Attenuation constants of TM surface waves in absorbing layers with equivalent ε and μ shown in Fig. 4(b).

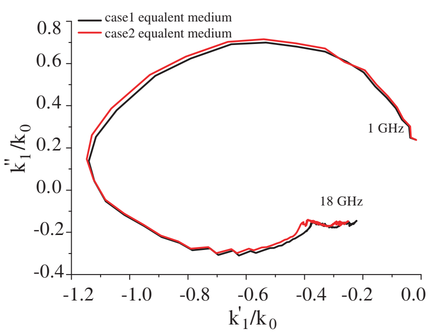

Figure 10. Trajectories of the transverse wave number of fundamental TM surface waves in absorbing layers with equivalent ε and μ shown in Fig. 4(b).

4. CONCLUSION

We have studied the relationships between the mono-static RCSR performances of a coated target and the properties of surface waves in RAM layers. The mono-static RCS performances show a distinction between the actual cases and their equivalent. The distinction result in the contribution from the attenuation of surface waves in between layers. For equal RAM thickness, the properties of surface waves in between layers are apparently different when the coated orders are changed. The layer order adopted by case 1 and case 4 will be an optimal selection. In general, electromagnetic scatterings of the equivalent medium exclude the effect of surface waves in between layers. Therefore, the equivalent medium theory is not appropriated for the research of electromagnetic scattering on the loss medium. From Figs. 5–10, we can observe that the mono-static RCS patterns approach superposition for two cases of every scheme in certain frequency ranges. The electromagnetic scattering can be analyzed using the equivalent medium theory in certain frequency ranges. Surface wave is very important in RCSR design. Attenuation constant is the most important one in all basic characteristics of surface wave, and it can qualitatively reflect the effect of mono-static RCSR for the considered RAM. The properties of surface waves in RAM layers have certain correspondence to its contributions to mono-static RCSR.

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