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ARTICLE

Reflection Loss is a Parameter for Film, not Material

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ABSTRACT

In studies of microwave absorption in the current literature, theories such as reflection loss, impedance matching, the delta function, and the quarter-wavelength model have been inappropriately applied. As shown in this case study, these problems need to be corrected as they are representative of similar work in the literature.

Keywords: Microwave absorption; Reflection loss; Impedance matching; Input impedance

1. Introduction

Analyses of experimental data which are based on flawed theories should always be corrected [1-3]. Here we highlight inadequacies in the theory that has been applied to experimental data concerned with microwave absorption in some recent papers [4-9] and provide detailed corrections that can be used to correctly understand such experimental data. While some authors are aware of our comments, they continued to use the current theory [8-14] despite our views being available in publications [15-24]. The problems addressed here are common in publications [25-28] and thus deserve serious attention. A theory can survive for several years after it has been proved wrong [29]. The purpose of this work is to draw attention to the subject and to shorten the period for the practice of the wrong theory. Nevertheless, journals are places where different ideas confront each other to push science forward.

2. Reflection loss should not be used to characterize material

The purpose of the paper by Du et al. [4] was to establish the amount of Mo_2C that would provide the best microwave absorption material based on $Mo_2C/Co/C$ composite. However, this was done by using reflection loss *RL*, a parameter for film rather

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than for material [15,18,20,24,30] thus following the common practice in modern research to characterize material [5,6,8-14,31-41].

The property of material should be characterized quantitatively using parameters such as permittivity or permeability while a portion of material can be characterized by extensive variables such as *RL*/dB. Layered material is an assembly of material and two parallel interfaces thus it behaves more like a film than a material [20,24].

RL is the scattering parameter s_{11} for metal-backed film defined in transmission-line theory and therefore, it is a parameter to characterize devices other than material [15,17-23]. Thus, using *RL* to characterize material is inappropriate and the conclusions obtained are misleading. For example, the MCC-50 sample was judged by *RL*/dB and impedance matching (im) theory to be the best microwave absorption composite [4]. MCC-50 and MCC-75 are materials for which *RL* is not applicable. However, it is clear from the data presented in the paper that when correctly interpreted from the properties of the relevant materials, the best microwave absorption composite is in fact MCC-75, a result that can be readily obtained from the innate properties of the materials [4]. Here parameters such as the imaginary part of the permittivity of the material should be used rather than *RL*/dB to characterize dielectric loss material [30] of the Mo_2C which dominated the functionality of the composites. Clearly, judging from the suitable parameters, MCC-50 can be the most suitable composite for microwave absorption film in order to obtain a result for specific applications at some specific frequency and film thickness d, but in general, it cannot be considered to be the best absorbing material.

In this context, the absorption mechanism for the device and material must be differentiated [22]. The film of the ternary Mo_2C/Co/C composite is a simple device. The material should be characterized by its innate properties such as permittivity ε_r and permeability μ_r [30]. But as the value of *RL* varies with film thickness d while keeping the material of the film unchanged [15,30], it cannot be used to characterize material. This is true since *RL* of film is correlated to R_M of interface [16,22]. R_M is used in Equation (1) for reflection coefficient of interface. Indeed, the ε_r and μ_r values of a material can be obtained from s_{11} and s_{21} of the film [22]. But using s_{11} and s_{21} to obtain ε_r and μ_r and to characterize material are not the same. For example, the equilibrium constant K is the innate property of the chemical equilibrium system. Although the equilibrium concentration C_i for species i in a particular equilibrium system can be calculated by using K, it cannot be used to characterize thermodynamic equilibrium since it varies when equilibrium is shifted. Similarly, ε_r and μ_r are constants for material but *RL* is not. When the thickness of the film d is changed, the values of *RL* change but those of ε_r and μ_r do not. The absorption mechanism of film is related to angular and amplitude effects unique to film [22]. Interestedly, it was proved theoretically [42] that ε_r is a function of d and this result was even established using experimental data [42], a result which seems inconsistent and shows that the theoretical proof presented in that paper was wrong [23,42].

Many experimentalists do not pay sufficient attention to theoretical results, so this work, which resolves problems easily overlooked from experimental data, based on theory from mathematical methods [15,17-24] is particularly pertinent. Using the wave cancellation method for microwave absorption film [20,22], the experimental data from voltage measurements for a whole frequency range can be reproduced from transmission-line theory using only constants appropriate to material [17,18,20,22,30]. This shows that the theoretical method of characterization of microwave absorption of film by *RL*/dB from ε_r and μ_r is feasible, i.e., *RL*/dB is obtained from voltage measurement experimentally with Equation (2) [17,22], but its values can also be obtained from d, ε_r and μ_r theoretically as shown by Equation (5) below [19-22]. The experimental results obtained from a linear device using different amount of incident microwaves can be accurately predicted by a theoretical model using a matrix of scattering s parameters arising from the innate properties of the device, and the theoretical results can be verified by experimental measurements [17,18,20]. These facts show that experimental results of film can be well assimilated by universally valid theory.

The results [4] are unexpected, as normally, the real part of permeability μ_r' should have lower values at low frequency and higher values at high frequency [30] rather than the contrary and in particular the values shown at high frequency range do not conform to the fact that Co is the main magnetic component. It is argued that energy can be generated by making the imaginary part of permeability μ_r'' negative. ("This induced electric field can generate an internal magnetic field and radiate some magnetic energy in turn. The radiation of magnetic energy will result in negative μ_r'' values. … Herein, these ternary composites have larger conductivities and smaller magnetic loss capabilities than binary Co/C composite, so that their inherent magnetic loss cannot offset the radiation of magnetic energy completely in high frequency range. " [4]) This explanation is unlikely to be true since it would be an effect symptomatic of a perpetual machine. In fact, the magnetic loss is determined by the absolute value of μ_r'' [21,43]. Thus, the absolute values should be used in that paper [4] for μ_r'' and the magnetic loss tangent, respectively. Contrary to the authors' conclusions [4], MCC-75 is the most efficient magnetic loss composite at high frequency. The material consumes energy if $\mu_r'' > 0$ while no energy will be consumed if $\mu_r'' = 0$. Thus, the authors assume that the composites generate energy when $\mu_r'' < 0$ and as a consequence it was concluded that MCC-75 is the least microwave consumption composite on the grounds that the most energy generating material is the one with the least energy consumption. Thus, the material can output useful work at high frequency without absorbing energy by making μ_r'' negative. Then switching to low frequency to restore the value of μ_r'' to 0 will not require any energy. In those circumstances, a perpetual machine against the laws of thermodynamics would be possible by a circulation of switching frequencies.

2.1 Input and the characteristic impedances

Z_0 was defined as the impedance of free space [5,44-46]. However, free space acts as part of the transmission line and the definition does not distinguish between input and characteristic impedances. Confusion between these two types has led to the imperfect theory of im for interface and for film [17,19] as with the statements: (a) "Ma et al. ever proposed a delta function to evaluate the matching degree of characteristic impedance between free space and transmission medium… When EM waves in space reach the front surface of the ring, the good impedance matching of MCC-50 will allow the transmission of EM waves in its interior rather than induce strong reflection at the interface" [4,44], (b) "If the characteristic impedance is poorly matched, there will be a strong reflection of incident EM waves at free space/MAMs interface… To achieve the condition of zero reflection, MAMs should have characteristic impedance as close as possible to free space. In recent works, a delta-function method was widely utilized to describe the matching degree of characteristic impedance between MAMs and free space" [5], and (c) "Recently, a Δ function has been proposed to feature the matching degree of impedance of MA materials with that of free space." [6]. Many of the confusing statements cited above are discussed below.

2.2 Impedance matching for interface and for film

Differentiating input from characteristic impedance is of crucial importance for the concept of perfect impedance matching (pim). Ignoring the difference between these two in the derivation of the Δ function [47] led to the development of the inaccurate theory of im for interface and for film. Equations (1) and (2) define reflection coefficient R_M for interface and reflection loss RL for film at position x_1 (**Figure 1**) in units of dB, respectively. All the incident beam i penetrates from free space into film without beam r when $Z_M = Z_0$, as shown by Equation (1), while beams r and t still exist although they cancel each other out when $Z_{in}(x_1^-) = Z_0$, as shown by Equation (2) [17], a fact often overlooked in publications [4-34].

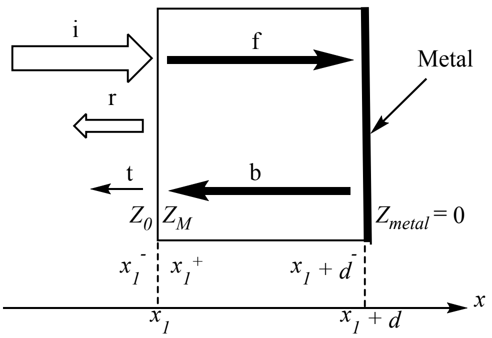

Figure 1. Metal-backed film of thickness *d*. Microwaves are reflected back and forth in the film. f is the total forward beam and b is the total backward beam in the film. i, r, and t represent incident, reflected, and the total transmitted beams, respectively. Z_0, Z_M, and Z_{Metal} are characteristic impedances of free space, material of the film, and metal, respectively. Superscripts – and + indicate immediately before and after a position, respectively.

$$R_M(x_1^-) = 20\log_{10}\left|\left[\left.\frac{V_r(x_1^-)}{V_i(x_1^-)}\right|_{V_b(x_1^+)=0}\right]\right| = 20\log_{10}\left|\frac{Z_M - Z_0}{Z_M + Z_0}\right| \quad (1)$$

$$RL(x_1^-) = 20\log_{10}\left|\left[\left.\frac{V_r(x_1^-)+V_t(x_1^-)}{V_i(x_1^-)}\right|_{V(x_1+d^+)=0}\right]\right| = 20\log_{10}\left|\frac{Z_{in}(x_1^-) - Z_0}{Z_{in}(x_1^-) + Z_0}\right| \quad (2)$$

$V_k(x)$ is the maximum amplitude of voltage at x for beam k in **Figure 1**. k can be i, r, or t.

It should be noted from Equations (1) and (2) that im for the interface cannot be achieved by adjusting Z_{in} or by changing the film thickness *d*. Thus, absorption might be related to $|Z_{in} – Z_0|$ in Equation (2), but penetration cannot be defined by it.

Nevertheless, penetration has been defined by $|Z_M – Z_0|$ from Equation (1) as in the claims: "In theory, the characteristic impedance of MAMs should be equal/close to that of the free space (377 Ω) to achieve zero-reflection at the front surface of the materials." [7], "Generally speaking, the closer the values of η_{in} are close to 377 Ω (wave impedance of free space), the better impedance matching is created." [8], and "In theory, the closer the η_{in} value is to 377 Ω (wave impedance of free space), and the better impedance is created, and the less incident EM wave will be reflected off at the boundary of MAMs, which means that more EM energy is possible to be consumed by the intrinsic attenuation ability of MAMs" [9]. In these quotes, η_{in} is Z_M for characteristic impedance. However, these claims led to the results that film can absorb more microwaves than the amount penetrated and that the energy reflected from the front interface can be drawn into the film by back-and-forth reflections in the film, illogical conclusions which show that im theory is flawed. It should be noted that wave cancellation theory [20,22] does not lead to these conclusions. The problem of im theory is that interface in film and in its isolated state are confused. Although the amplitude of the penetrated beam for film can be defined from Equation (1) [17,21], the penetrated energy for film cannot be defined.

2.3 The delta function

It follows that the widely used delta function [4-6,47-54] cannot be correct since it is based on im theory, even if the function can be fitted into experimental data from statistics, because it is applied improperly at $Z_{in}(x_1^-) \neq Z_0$, while being based on pim where $Z_{in}(x_1^-) = Z_0$ [47].

The peak of *RL* at pim is a strong narrow peak [15] which is rarely observed since the two conditions, $|Z_{in}(x_1^-)| = |Z_0|$ and that the phase of $Z_{in}(x_1^-)$ is equal to the phase of Z_0, must be met simultaneously, which is difficult to achieve. Even if the pim peak exists, it is likely to remain unobserved since the step Δf_m in the measurement is usually much larger than its width. f_m is frequency. All the reported *RL*/dB peaks are wide even for those where $|Z_{in}(x_1^-)|$ nearly equals to $|Z_0|$ [4]. For the majority of *RL*/dB peaks, $|Z_{in}(x_1^-)| \neq |Z_0|$. All the reported peaks occur where $Z_{in}(x_1^-) \neq Z_0$ and therefore the im theory is seriously flawed since the minima of *RL*/dB can occur when $|Z_{in}(x_1^-)|$ deviates far from $|Z_0|$ [20]. Impedance matching theory predicts only one sharp absorption peak at $|Z_{in}(x_1^-) = Z_0|$ which is not consistent with experimental data, while by contrast wave cancellation theory predicts a set of broad peaks whether $Z_{in}(x_1^-)$ and Z_0 are equal or not, a result which conforms to all the published experimental data.

The value of $|RL|$ is not necessarily smaller if $\delta = |Z_{in}(x_1^-)| - |Z_0|$ is smaller. In addition, the smaller of the two $|RL|$ peaks does not necessarily have a smaller value of δ [24]. An $|RL|$ peak can occur at a position with larger δ value, while there may be not a peak at all at a position with smaller value of δ [20]. These facts cannot be explained by using the delta function. In fact, im peaks are wide and they are caused by the fact that beams r and t in **Figure 1** are out of phase by π [20,22].

As in the following quote, it is believed that in order to establish RL/dB as the peak position, ε_r'' and μ_r'' must be large and that more incident microwave should have penetrated into the material. ("However, one should also notice that MCC-75 with the largest α values fails to produce the best EM absorption performance. This is because EM absorption efficiency is not only dependent on the overall loss capacity, but also on the impedance matching between free space and transmission medium. An imperfect impedance matching can account for strong reflection of incident EM waves at the front surface, which may invalidate the intrinsic loss capacity of the transmission medium." [4]) But this theoretical basis for RL/dB to decrease is only valid when ε_r'', μ_r'', or d is very large. Usually, these three parameters are small and as a result, the microwaves in the film are reflected back and forth many times. The strong peak for the film of MCC-50 is not caused by large values of ε_r'', μ_r'' [4], and the attenuation constants α, nor is it a result of im [20]. Rather, it is determined by how close are the two amplitudes of beam r reflected from the interface at x_1 and of beam t reflected from the interface at $x_1 + d$ in **Figure 1** when the two beams are out of phase by π, which is determined by the property of the film. The amplitude of beam r in **Figure 1** is determined by the reflection coefficient R_M for the interface at x_1. The amplitude of beam t is determined by R_M, d, and ε_r and μ_r, and reaches its maxima when RL/dB reaches its minima, a result that can be established from angular effects of film by energy conservation requirement [21,22]. On the other hand, the value of RL/dB changes when d increases, however, the microwave penetration characterized by Equation (1) and the attenuation power of the material characterized by ε_r'' and μ_r'' do not change.

It can be revealed from the inconsistencies [4] that im theory is wrong. The im is designed to find the minimum values of RL/dB. It is claimed that "the desirable delta value for good matching degree is less than 0.4" [4]. But there was no corresponding value for the first valley of RL [4], neither was for the second valley [4]. It is also noteworthy that the highest values of RL/dB do not have the highest delta values [4]. In addition, the region with $\Delta < 0.4$ includes values of RL/dB near 0 dB [4], which are the maximum instead of the minimum peak values of RL/dB. This is an example where evidence can be overlooked if not be equipped with suitable theory.

The formula for RL is simple and provides a clear picture from the wave superposition theory of General Physics while the formulae for the delta function are much more complex and as a result, their significance is vague. The delta function originated from statistical fitting and it does not lead to the correct solution of wave cancellation and therefore is not a suitable parameter to characterize RL/dB.

3. The quarter-wavelength model cannot be universally applied

The two interfaces introduced into material to form a film is responsible for the differences between film and material. However, the phase effects of the two interfaces have been neglected in the quarter-wavelength model [19,20,23]. What is more, the wavelength λ_m in film was calculated from frequency f_m and the velocity of light c in vacuum by Equation (3) [4].

$$\frac{n}{4}\lambda_m = \frac{nc}{4f_m\sqrt{|\varepsilon_r\mu_r|}} \qquad (n = 1,3,5...) \tag{3}$$

Equation (3) is wrong [19] though often applied in the field of microwave absorption material [4,34, 44,46,54-63]. The correct formula that should be used is shown in Equation (4) [19].

$$\lambda_m = \frac{c}{f_m\left|\mathrm{Re}(\sqrt{\varepsilon_r\mu_r})\right|} \tag{4}$$

The quarter-wavelength (λ/4) model claimed in the statement [4] "... which suggests that the attenuation of incident EM waves may be based on a quarter-wavelength (λ/4) matching model. In that case, if the phase difference at the air-medium interface between incident EM waves and reflected waves from a metal-backed layer is 180°, there will be intensive consumption of EM energy due to interference cancellation…" cannot be universally applied [17,19,20,23,64], even though it is widely accepted in publications [34-37,48]. The minima of *RL/dB* occur when the phase difference of beams r and t in **Figure 1** is 180° contrary to the claim [4,34] that the phase difference of beams r and i is 180° as "the phase difference between the incident wave and the reflective wave is 180°" [34]. In fact, as indicated by Equation (2), *RL*/dB is only related to the power ratio of the resultant beam (r + t) to the incident beam i. The power ratio is only related to the maximum amplitude of voltages but has nothing to do with the phase difference between beams (r + t) and i. However, the maximum amplitude of voltage for beam (r + t) is related to the phase difference between beams r and t [19].

It is stated that "It is very interesting that with the increase of coating thickness, the minimum *RL* peaks of all these composites gradually shift towards low-frequency region which suggests that the attenuation of incident EM waves may be based on a quarter-wavelength (λ/4) matching model" [4]. But this is neither interesting nor indeed true.

$$RL(x_1^-) = \frac{R_M(x_1^-)e^{2j\pi f_m \frac{\sqrt{\varepsilon_r \mu_r}}{c} d} - e^{-2j\pi f_m \frac{\sqrt{\varepsilon_r \mu_r}}{c} d}}{e^{2j\pi f_m \frac{\sqrt{\varepsilon_r \mu_r}}{c} d} - R_M(x_1^-)e^{-2j\pi f_m \frac{\sqrt{\varepsilon_r \mu_r}}{c} d}} \tag{5}$$

As can be seen from Equation (5), if $|RL(x_1^-)|$ achieves a minima at f_m and d, it will retain the same peak value when the frequency decreases to $f_m/2$ and the film thickness increases to $2d$ if both ε_r and μ_r are constants. In other words, the peak values will be found on the inverse curve of f_m and d if ε_r and μ_r are insensitive to frequency [23].

4. Conclusions

The criticisms included here are not just concerned with the work of Du et al. [4] as they can be applied to many other published works in this field. It is a general comment on the prevailing theories applied to microwave absorption including the application of *RL* to characterize material, the im theory, the delta function, and the quarter-wavelength model. Judged by the value of *RL*/dB, except in extreme cases, it is found that the material most suitable for microwave absorption film is not usually the one with the highest values of ε_r'', μ_r'', and the attenuation constants α of the material, nor the one which allows most of the incident microwaves to penetrate the film as supposed by the im theory. In fact, the most suitable material has the most balanced amplitudes at x_1^- for the two beams reflected from the two interfaces in the film when the two beams at x_1^- in **Figure 1** are out of phase by π. This work shows that the claim: "the most highly utilized method for determining material response to incident electromagnetic radiation in the microwave region" "appears to have been demonstrated experimentally" [65] is unjustified.

Author Contributions

Ying Liu: Conceptualization, Methodology, Validation, Investigation, Resources, Writing - Review & Editing, Supervision, Project administration, Funding acquisition.

Xiangbin Yin: Validation, Investigation.

Michael G. B. Drew: Conceptualization, Validation, Writing - Review & Editing, Supervision.

Yue Liu: Conceptualization, Methodology, Validation, Formal analysis, Investigation, Writing - Review & Editing, Visualization.

Conflict of Interest

There is no conflict of interest.

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