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Theoretical Insights Manifested by Wave Mechanics Theory of Microwave Absorption

Yue Liu [1,*], Michael G. B. Drew [2] and Ying Liu [1]

[1] College of Chemistry and Chemical Engineering, Shenyang Normal University, Shenyang, P. R. China,110034

[2] School of Chemistry, The University of Reading, Whiteknights, Reading RG6 6AD, UK

* Correspondence: author; yueliusd@163.com; ORCID: Yue Liu: https://orcid.org/0000-0001-5924-9730; Michael G. B. Drew: https://orcid.org/0000-0001-8687-3440; Ying Liu: https://orcid.org/0000-0001-9862-5786

Abstract: The wrong theory of impedance matching theory has dominated microwave absorption research for a long time because it was believed that the theory was supported by experimental reports over the years and transmission line theory which is fundamental in electromagnetism. Thus, when the correct wave mechanics theory for microwave absorption opposing impedance theory was recently developed, pointed out that the wrong theory involved a misunderstanding of transmission line theory, and in fact the published experimental data disproved the theory rather than supporting it, the wrong theory still dominates the field and material scientists are reluctant to acknowledge the new theory. Further evidence is demonstrated here that in contrast to impedance matching theory, the new wave mechanics theory rediscovers the real microwave absorption mechanism that had already been revealed by transmission line theory and now has been developed further with many new concepts. This work also reveals that theoretical research is important to correct the wrong conclusions obtained from experimental observations.

Keywords: wave mechanics theory; transmission line theory; microwave absorption film; theoretical insights

1. Introduction

In the field of microwave absorption material, the film and the material have been confused [1–7], characterized by not distinguishing the input impedance Z_{in} of film from the characteristic impedance of material Z_M [8,9] and represented by confusing the interface in its isolated state from that in film [10] and the two parallel interfaces in a film from the interfaces between material particles [11]. Wrong theories such as impedance matching theory [10,12–14] and the quarter wavelength theory [15–18] were used to develop the wrong absorption mechanisms for film and material [19–21] which have been established over the years since the inadequacies were not recognized and corrected. Over the years, many experiments have been carried out which are described as supporting the wrong theories instead of correcting them even though the inconsistences should have been easy to spot. Material scientists believe that their theories are based on transmission line theory and thus do not accept they are wrong.

Recently a new theory of wave mechanics has been developed for microwave absorption for film [18,20,22] which identifies the problems in current theories. Indeed, it is found that the experimental data reported previously were in fact inconsistent with the wrong theories which were based on misunderstanding transmission line theory. However, the scientific community continues using the wrong theories within a large number of publications with only a few exceptions [23–25] mentioning the opposite new theory [26–32]. Discrediting commonly accepted ideas is often difficult to achieve in a scientific community [33], particularly when the theory has been accepted for many years.

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To address this important issue, this work focuses on showing that the wave mechanics theory conforms with transmission line theory while the wrong theories originate from a misunderstanding this fundamental electromagnetic theory. Many people believe that theory must be wrong if theory and experimental conclusions are in confliction. However, this work demonstrates another perspective of scientific research that conclusion from numerous repeated experimental data might be wrong and not easily identified when the correct theory has not been established, which shows the importance of theoretical research in science.

2. Discussions Based on Transmission Line Theory

2.1. The Transmission Line Theory-Based Wave Mechanics Theory of Microwave Absorption

As shown by Figure 1, the incident microwaves represented by i enter the metal-backed film and the entered beam is reflected back-and-forth between the top and the bottom interfaces. r1 the is the reflected beam from the top interface and r2 is the total beam reflected from the bottom interface. Beam r is obtained from the superposition of beams r1 and r2.

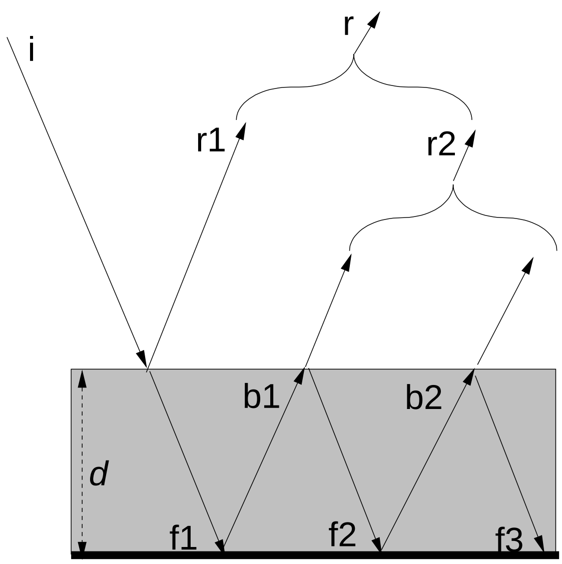

Figure 1. A metal backed film with thickness *d*. i indicates the incident beam and r1 is the reflected beam from the top interface. Part of the incident microwaves enters the film and reflected back-and-forth between the top and bottom interfaces. f1, f2, f3. etc. are the forward beams and b1, b2, etc. are backward beams in the film. r2 is the total reflected beam from the bottom interface. Beam r is the superposition of beams r1 and r2.

In transmission line theory, reflection coefficient RL is obtained from the superposition of individual beams [15,16,34] shown in Figure 1 as

$$RL = \frac{V_r}{V_i} = \frac{Z_{in} - Z_0}{Z_{in} + Z_0} \tag{1}$$

$$\begin{aligned} Z_{in} &= \sqrt{\frac{\mu_0 \mu_r}{\varepsilon_0 \varepsilon_r}} \tanh\left(j \frac{2\pi \nu d \sqrt{\varepsilon_r \mu_r}}{c}\right) \\ &= Z_M \tanh\left(j \frac{2\pi \nu d \sqrt{\varepsilon_r \mu_r}}{c}\right) \end{aligned} \tag{2}$$

Z_{in} is the input impedance of the film. Z_M and Z_0 are the characteristic impedances of material and free space, respectively. The permittivity ε_0 and the permeability μ_0 are of free space, and ε_r and the

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μ_r are the relative permittivity and permeability of material. ν is the frequency, c is the velocity of light in a vacuum. V_k is the voltage of beam k.

In microwave absorption research, ε_r and the μ_r of the material is first measured from s_{11} and s_{21} of a film without metal-back, then they are used in Eqs. (1) and (2) to calculate the value of RL. [19] For the material CA3.5-4 reported by Guangbin Ji et al [35], ε_r = 12.35 – j3.08 and μ_r = 1.14 – j0.12 at ν = 4.00 GHz, and ε_r = 9.51 – j3.85 and μ_r = 1.16 – j0.014 at ν = 11.00 GHz. The $|RL|$ values calculated using Eqs. (1) and (2) from these experimental data of ε_r and μ_r are plotted in Figure 2.

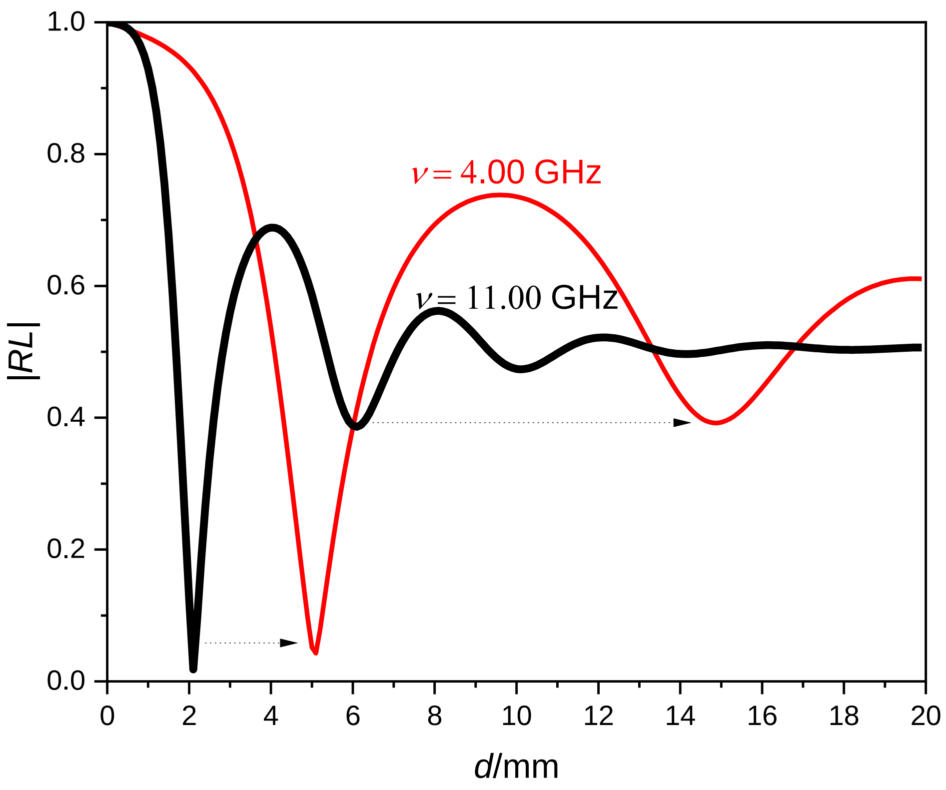

Figure 2. $|RL|$ for the material CA3.5-4 reported by Guangbin Ji et al [35] measured at 4.00 and 11.00 GHz, respectively.

The incident energy is reflected back to the free space represented by $|RL|^2$. The rest is absorbed by the film represented by A(Film) and thus

$$A(\text{Film}) = 1 - |RL|^2 \tag{3}$$

The lowest peaks in $|RL|$ in Figure 2 represent the strongest absorptions by the film where beam r is at its weakest positions. It is claimed in the wave mechanics theory of microwave absorption that the absorption peaks occur when beams r1 and r2 are out of phase by π and this condition ensures that beam r is at its local weakest. This result can be verified by numerical calculations using Eqs. (4) - (6), which confirms that $|RL|$ peaks do occur when the phase difference between the reflection coefficient R_M of the top interface and that R_2 of the bottom interface in Figure 1 is indeed π. [16,19]

$$R_M = \frac{V_{r1}}{V_i} = \frac{Z_M - Z_0}{Z_M + Z_0} \tag{4}$$

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$$R_2 = \frac{V_{r2}}{V_i} = RL - R_M = \frac{(R_M^2 - 1)e^{-\frac{j4\pi vd\sqrt{\varepsilon_r\mu_r}}{c}}}{1 - R_M e^{-\frac{j4\pi vd\sqrt{\varepsilon_r\mu_r}}{c}}} \tag{5}$$

$$Z_M = Z_0\sqrt{\frac{\mu_r}{\varepsilon_r}} = \sqrt{\frac{\mu_0\mu_r}{\varepsilon_0\varepsilon_r}} \tag{6}$$

The result shows that the new mechanics theory conforms to transmission line theory using the wave superposition derivation of the formula of *RL*.

2.2. The Misunderstanding of Transmission Line Theory

In the current dominant theory, it is believed from Eq. (1) that when Z_{in} - Z_0 = 0, all the incident microwaves enter the film. Therefore, in the theory it is required by the absorption mechanism that most incident microwaves enter the film and that it is necessary to use material with significant attenuation to absorb the microwave energy along the optical path in the film. However, this theory is untrue [14,29] and it is based on a misinterpretation of transmission line theory. It is true that *RL* = 0 when Z_{in} =Z_0. [12] However, it has been proved that the absorption peak can occur when $Z_{in} \neq Z_0$ and can occur when $|Z_{in} - Z_0|$ reaches its maximum value if the peak is achieved at $Z_{in} \neq Z_0$. [16] The reason is that being a complex number, the denominator (Z_{in} + Z_0) in Eq. (1) cannot be neglected if $Z_{in} \neq Z_0$. [16] It has further been proved that the absorption mechanism of film is not the same as that of material. The absorption of film does not originate from the attenuation power of the material along the zig-zag optical path. The absorption by the material along the optical path in the film should be *A*(Material) defined by Eq. (7) other than Eq. (3). [22] The differences between the absorption of film and the attenuation power of material along its optical path are shown in Figure 3. The absorption of thick film approaches the attenuation power of material [14] as the angular effects of the film are suppressed when *d* becomes large [19] since beam r2 is vanishing when *d* is large.

$$A(\text{Material}) = (1 - |R_M|^2)(1 - e^{-2\alpha_P d}) \tag{7}$$

$$\alpha_P = \text{Re}(|\, j\frac{4\pi vd\sqrt{\varepsilon_r\mu_r}}{c}\,|) \tag{8}$$

Re(x) is the real part of x.

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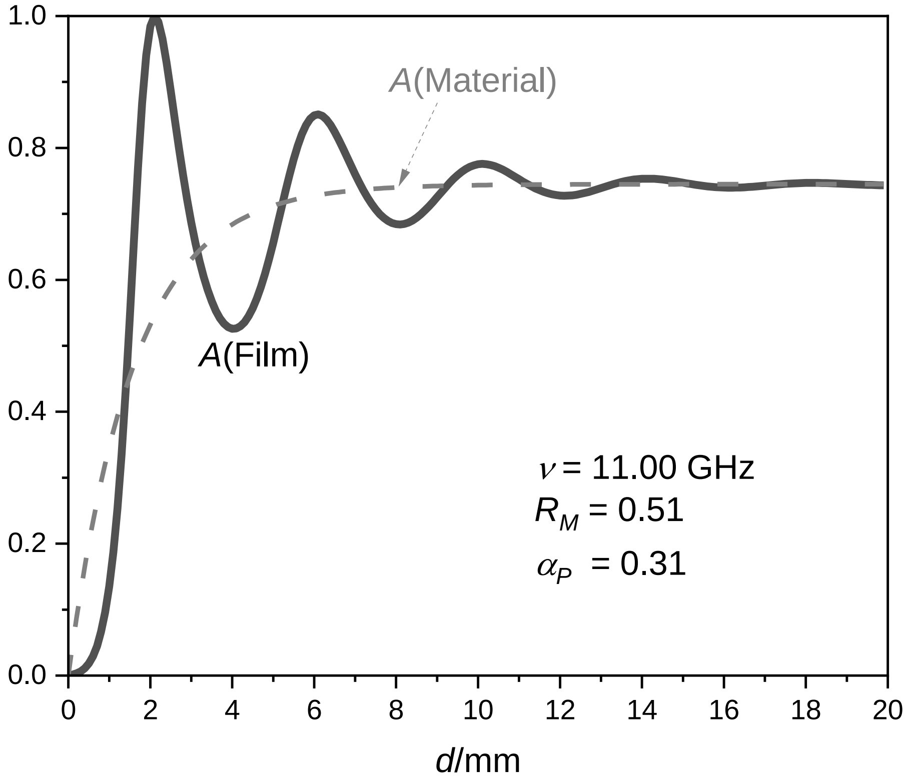

Figure 3. The difference between the absorption of metal-backed film A(Film) of material CA3.5-4 [35] and the attenuation power of its material A(Material) along the optical path.

The power of wave mechanics theory can be demonstrated by the fact that it can simply explain why the absorption peak does not occur exactly when the phase difference of beams r1 and r2 is π [18,20,29]. It can also be proved from the wave mechanics theory that film absorbs microwave and interface does not [27].

2.3. The Flaws in Impedance Matching Theory Revealed from the Mechanics Theory

The problems of the current theories were not identified until the establishment of the wave mechanics theory. In the current theory it is claimed that all the incident microwaves enter the film when $Z_{in} = Z_0$ and define this condition as impedance matching. However, this theory confuses Z_{in} and Z_M. [8] When $Z_M = Z_0$, the top interface in Figure 1 disappears and all the incident microwaves enter the film while it cannot ensure that all the incident waves enter the film since Z_M and Z_0 can be different even when $Z_{in} = Z_0$. [9] When $Z_M \neq Z_0$, the top interface still exists and not all the incident waves enter the film. The impedance matching theory uses the attenuation power of material to explain the absorption results represented by $|RL|$ and thus it does not account for the fact that all the incident microwaves have been absorbed when $Z_{in} = Z_0$ while not all of the waves enter the film since $Z_M \neq Z_0$,.

As shown by Figure 3, beam r2 vanishes and $|RL| = |R_M|$ when d approaches infinity. Beam r1 vanishes and $|RL| = |R_2|$ when $Z_M = Z_0$. As shown by Figure 4, $|RL|$ is a monotonic decay function of d at 11 GHz when $\varepsilon_r = \mu_r = 5.51 - j3.85$ and $\varepsilon_r = \mu_r = [(9.51 - j3.85)(1.16 - j0.014)]^{1/2}$ to ensure $Z_M = Z_0$.

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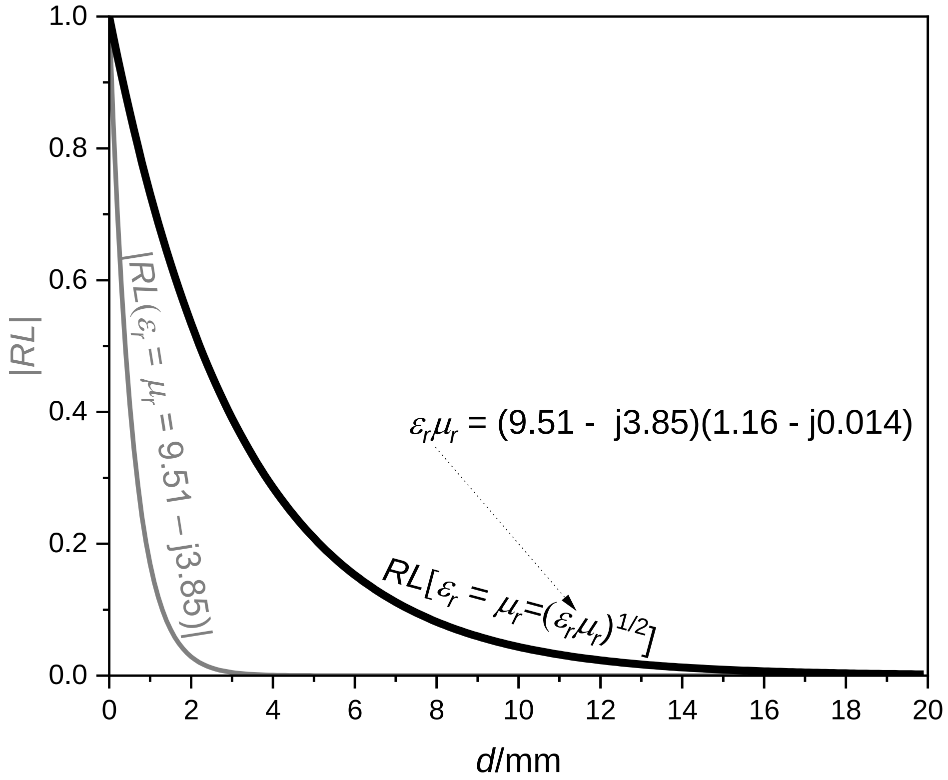

Figure 4. |*RL*| calculated by Eq. (1) or (5) with $\varepsilon_r = \mu_r = 9.51 - j3.85$ and $\varepsilon_r = \mu_r = [(9.51 - j3.85)(1.16 - j0.014)]^{1/2}$ at 11 GHz. [9].

It can be proved generally that |*RL*| is a monotonic decay function when $\varepsilon_r = \mu_r$ where $R_M = 0$, as shown by Eq. (9). [10,16] Although there may be an absorption peak with $Z_{in} = Z_0$ for film, |*RL*| = 0 with $Z_{in} = Z_0$ for material can only be achieved when *d* is infinity.

$$\begin{aligned} |RL(\varepsilon_r = \mu_r)| &= \left| \frac{R_M - e^{-\frac{j4\pi v d\sqrt{\varepsilon_r\mu_r}}{c}}}{1 - R_M e^{-\frac{j4\pi v d\sqrt{\varepsilon_r\mu_r}}{c}}} \right| = e^{-4\pi v d\varepsilon''/c} \\ = |R_2(\varepsilon_r = \mu_r)| &= \left| \frac{(R_M^2 - 1)e^{-\frac{j4\pi v d\sqrt{\varepsilon_r\mu_r}}{c}}}{1 - R_M e^{-\frac{j4\pi v d\sqrt{\varepsilon_r\mu_r}}{c}}} \right| = e^{-4\pi v d\mu''/c} \end{aligned} \tag{9}$$

where ε_r'' and μ_r'' are the imaginary parts of ε_r and μ_r, respectively.

The impedance matching theory was established to explain absorption peaks when $Z_{in} \neq Z_0$. However, as shown by Figure 2, the absorption of the film has a wave shape with absorption peaks while as shown by Figure 4, the accumulated attenuation of material is a monotonic decay function without absorption peak. When $Z_{in} \neq Z_0$, the absorption peak of the film usually cannot be achieved at the minimum of $|Z_{in} - Z_0|$ since the amplitude and the phase conditions for $Z_{in} = Z_0$ cannot be achieved simultaneously [13,28].

It is believed by the current theory that the absorption peaks shown in Figure 2 are the resonance absorptions of the material [36,37]. This wrong concept leads to the investigation of the relationship between material structure and the value of |*RL*|, which is not relevant and to the investigation of

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the relationship between the attenuation power of material α_P and the value of $|RL|$, although in practice these terms are independent. Correct research should be based on clarifying the relationship between material structure and the values of ε_r and μ_r, and then what values of ε_r and μ_r, can ensure the required value of $|RL|$ [14]. There is no simple relationship between material structure and the value of $|RL|$. There is no simple relationship relating α_P to $|RL|$ as qualitatively discussed in the literature except the complex relationship represented by Eq. (1). For example, at constant frequency, α_P is a constant while $|RL|$ is a function of d.

As can be seen from Figure 2 there is an absorption peak at d = 2.10 mm and ν = 11.00 GHz with $|RL|$ = 0.018. If this peak originates from material resonance, then it will become stronger if d increases to 5.10 mm. However, the value of $|RL|$ increases to 0.56 at d = 5.10 mm and ν = 11.00 GHz, which indicates a decrease in absorption with increase of film thickness.

This phenomenon can be understood by the wave mechanics theory. There is an absorption peak at d = 2.10 mm and ν = 11.00 GHz because the phase difference of beams r1 and r2 is π. When d increases with fixed ν, this phase difference is no longer π. To keep the phase difference at π, the frequency must decrease to ν = 4.00 GHz when d increases to 5.10 mm according to the inverse relationship between d and ν. [17] Thus, the origin peak at d = 2.10 mm and ν = 11.00 GHz shifts to the position at ν = 4.00 GHz with $|RL|$ = 0.043 when d increases from 2.10 to 5.10 mm. Similarly, the absorption peak at d = 6.10 mm and ν = 11.00 GHz with $|RL|$ = 0.39 shifts to d = 14.90 mm and ν = 4.00 GHz with $|RL|$ = 0.39.

3. Conclusions

There is enough evidence that microwave absorption is rooted in transmission line theory while the current dominant theories originate from a misinterpretation of this electromagnetism theory. The wave mechanics theory is a much more powerful theory for microwave absorption whether the film behaves as material or not. Unfortunately, the practice of using the wrong theories continues in modern research without open debate on the opposing wave mechanics theory because the wrong concepts have dominated the field for long.

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