4 July 2024, Preprint v1 ·
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Research Article

Review of Wave Mechanics Theory for Microwave Absorption by Film

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The clear distinction between film and material have been ignored in current microwave absorption theory. This confusion has led to the establishment of the wrong theory of impedance matching and as a consequence the development of the wrong absorption mechanism. These problems are detailed and corrected, and the current mechanism is highlighted in this review.

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1. Introduction

Microwave absorption is a subject intensively studied [1]. In current research, the results obtained by applying reflection loss *RL* to metal-backed film have been used to characterize the material of the film [2][3][4][5]. Based on such applications, both impedance matching theory and the quarter-wavelength theory have been established as the microwave absorption mechanism [6][7][8][9][10][11][12][13][14][15][16][17][18][19][20][21][22][23]. However, the theoretical framework for these theories has been recently challenged [24][25][26] and a wave mechanics theory has been developed to replace them [27][28][29][30][31][32][33][34][35][36][37][38][39][40][41][42]. This is a review on recent developments in this subject.

In recent years, our research group has focused on addressing fundamental errors in the current theories of microwave absorption, specifically the confusion between film and material. This new manuscript builds upon those works by reviewing the wave mechanics theory and its development, exploring its impact on microwave absorption theory. Any overlap in content between these manuscripts is intentional, as we believe it is necessary to ensure the continuity and comprehensiveness of our research.

doi.org/10.32388/ZKKEZF

Additionally, given the significant departure of our work from established theories, a high degree of self-citation is regrettably inevitable. Our group is the primary contributor to this new theoretical framework, and referencing our previous publications is essential to provide a complete and coherent narrative. We believe this approach is crucial to drawing the scientific community's attention to these important findings.

We understand the concerns that perceived redundancy and self-citation may raise in the academic landscape. Therefore, we welcome constructive feedback from reviewers and the community. If there are specific concerns about these issues, we are open to suggestions on how best to present our work without compromising its integrity and clarity.

2. The wave mechanics theory for microwave absorption film

2.1. The film and the material are different

In the field of microwave absorption, the permittivity ε_r and permeability μ_r of the material are first obtained from the s_{11} and s_{21} parameters of a film without metal-back [34][43]. Then the reflection coefficient *RL* for the metal backed film is calculated from Eq. (1) which is obtained from transmission line theory [37][38].

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

where V_k is the voltage for beam k in Fig. 1 and Z_0 is the characteristic impedance for the open space. Z_{in} is the input impedance for the film with metal-back and is given by Eq. (2) [24][44].

$$Z_{\text{in}} = Z_M \tanh\left(j 2\pi v d \sqrt{\varepsilon_r \mu_r}/c\right) \tag{2}$$

$$Z_M = \sqrt{\frac{\mu_r}{\varepsilon_r}} \tag{3}$$

Z_M is the characteristic impedance of the material. *d* is film thickness, *v* frequency and *c* the speed of light in vacuum.

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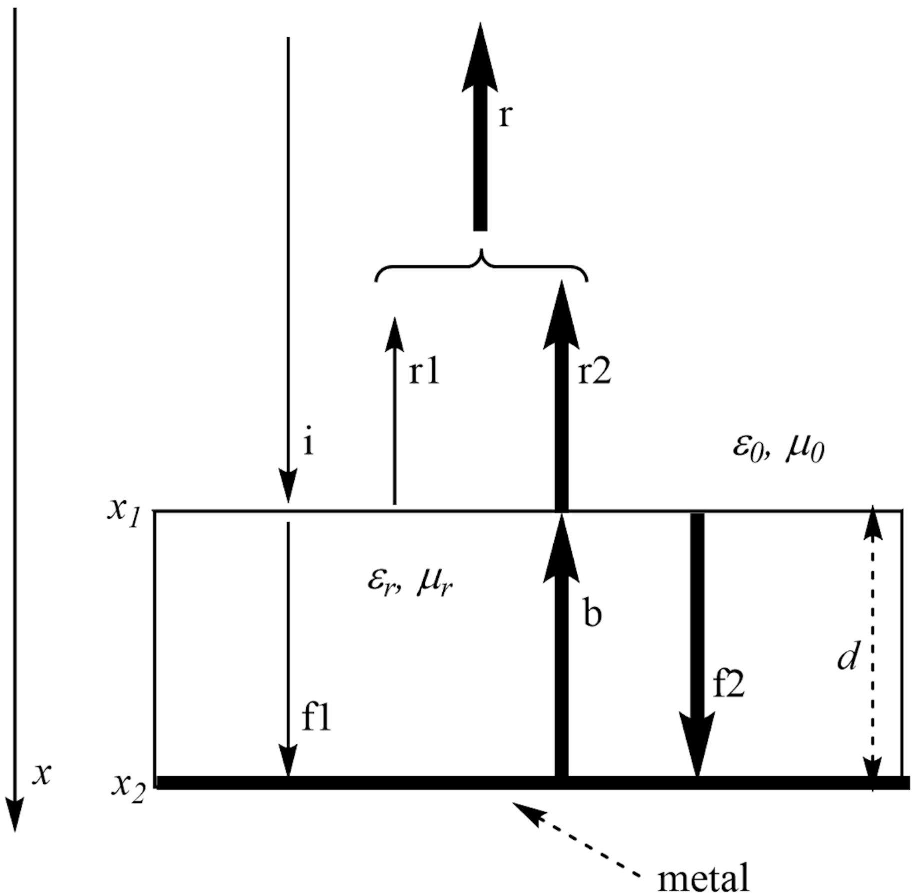

Fig. 1. A metal-backed film of thickness *d*, composed by material with permittivity ε_r and permeability μ_r. ε_0 and μ_0 are the permittivity and permeability of open space, respectively. i is the incident beam, r1 the reflected beam from beam i from the interface at x_1, and f1 the transmitted beam from beam i through the interface. Beam f1 is reflected back-and-forth in the film and b is the total backward beam while (f1 + f2) is the total forward beam in the film. r2 is the transmitted beam from beam b. r is the total beam from beams r1 and r2.

Inserting Eq. (2) into Eq. (1) we obtain Eq. (4) [38].

$$RL = \frac{R_M - e^{-j\frac{4\pi vd}{c}\sqrt{\varepsilon_r\mu_r}}}{1 - R_M e^{-j\frac{4\pi vd}{c}\sqrt{\varepsilon_r\mu_r}}} = \frac{R_M - e^{-(\alpha_P + j\alpha_j)d}}{1 - R_M e^{-(\alpha_P + j\alpha_j)d}} \quad (4)$$

$$R_M = \frac{V_{r1}}{V_i} = \frac{Z_M - Z_0}{Z_M + Z_0} \quad (5)$$

doi.org/10.32388/ZKKEZF

R_M is the reflection coefficient for the interface at x_1. α_P is power absorption coefficient, α_j is the wave propagation coefficient. When the reflection coefficient RL is expressed in the units of dB as shown by Eq. (6), it is also called reflection loss since the value of RL/dB is related to the power reflected from the film shown by Fig. 1.

$$\begin{aligned} RL/dB &= 20\log_{10}\left|\frac{V_r}{V_i}\right| \\ &= 10\log_{10}\left|\frac{V_r}{V_i}\right|^2 = 10\log_{10}\left|\frac{P_r}{P_i}\right| \end{aligned} \tag{6}$$

P_k is the power of beam k. From energy conservation, the absorption A by the metal-backed film is related to the reflection coefficient RL by Eq. (7) [35].

$$A = 1 - |RL|^2 \tag{7}$$

The curve of $|RL|$ obtained using experimental data from the metal-backed film of Ag/$NiFe_{1.92}Ce_{0.08}O_4$ [34] at constant frequency of 8.65 GHz has been shown in Fig. 2. The absorption curve possesses a wave form which signifies that the absorption from the film is very different from the attenuation power of the material. For uniform material, the attenuation power is a constant everywhere and the accumulative effect is a monotonic decay function represented by exp(-$\alpha_P d$) [30] as shown in Fig. 2. The microwaves are weakened as the waves travel further into the material [25].

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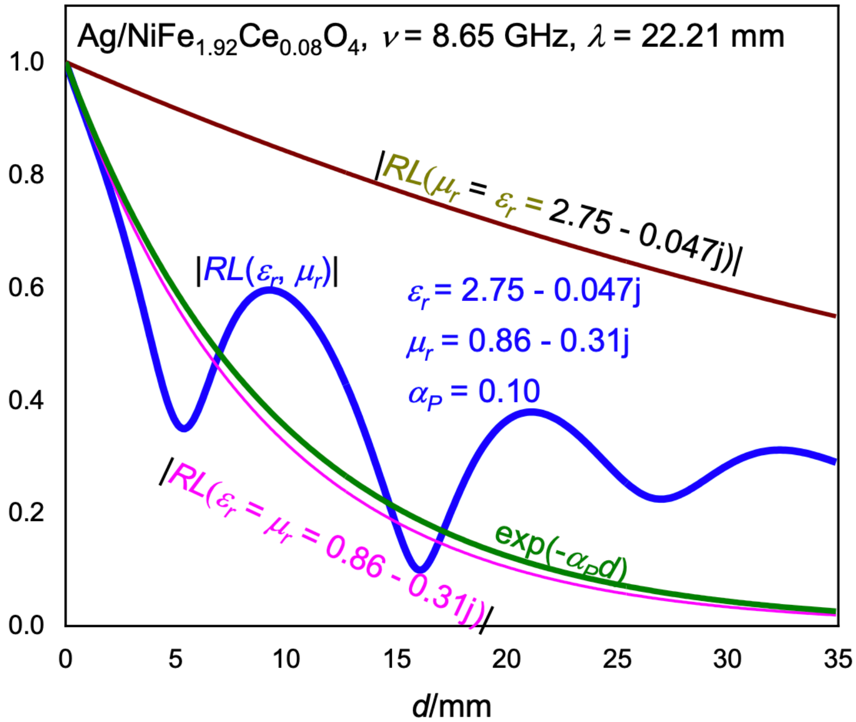

Fig. 2. The difference between $|RL|$ for metal-backed film of $Ag/NiFe_{1.92}Ce_{0.08}O_4$ at 8.65 GHz and the material attenuation power represented by $\exp(-\alpha_P d)$.

When $\varepsilon_r = \mu_r$, then $R_M = 0$ and the film behaves as a material since

$$|RL| = \left| e^{-j\frac{4\pi v d}{c}\left(\varepsilon_r{}' - j\varepsilon_r{}''\right)} \right| = e^{-\frac{4\pi v d}{c}|\varepsilon_r{}''|} = e^{-\frac{4\pi v d}{c}|\mu_r{}''|} \tag{8}$$

The curves of $\varepsilon_r = \mu_r = 0.86 - 0.31j$ and $\mu_r = \varepsilon_r = 2.75 - 0.047j$ have also been shown in Fig. 2, which shows that the film behaves as material when $\varepsilon_r = \mu_r$. This is because beam r1 vanishes when $R_M = 0$ and only beam r2 exists.

$$R_2 = \frac{V_r - V_{r1}}{V_i} = RL - R_M = \frac{\left(R_M^2 - 1\right) e^{-j\frac{4\pi v d}{c}\sqrt{\varepsilon_r \mu_r}}}{1 - R_M e^{-j\frac{4\pi v d}{c}\sqrt{\varepsilon_r \mu_r}}} \tag{9}$$

When $\varepsilon_r = \mu_r$,

$$|R_2| = \left| e^{-j\frac{4\pi v d}{c}\sqrt{\varepsilon_r \mu_r}} \right| = e^{-\frac{4\pi v|\varepsilon_r{}''|d}{c}} = |RL| \tag{10}$$

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It should be noted that the reflection coefficients RL, R_2 and R_M of film and interface are equal to their values of s_{11} when there are no incident microwaves from the other side of the devices [26]. Beam b which is reflected from the rear interface is not the incident microwaves. s_{11} is a constant for its device and thus RL, R_2 and R_M are independent on the intensity of the incident beam i [38].

$$\begin{aligned} A(\mathrm{M}-\mathrm{MB}) &= \frac{P_{\mathrm{i}}-P_{\mathrm{r}}}{P_{\mathrm{i}}} \\ &= \left(1-\left|R_M^2\right|\right)\left(1-e^{-2\alpha_P d}\right) \end{aligned} \tag{11}$$

Figure 2 shows that the absorption of film represented by RL is different from the attenuation power of material represented by exp(-$\alpha_P d$). The absorption of metal-backed film A can be calculated from $|RL|$ using Eq. (7). The absorption of the material of this film along the zigzag optical path traveled in the film, A(M-MB), can be obtained from Eq. (11) [28] and the curves for A and A(M-MB) have been shown by Fig. 3.

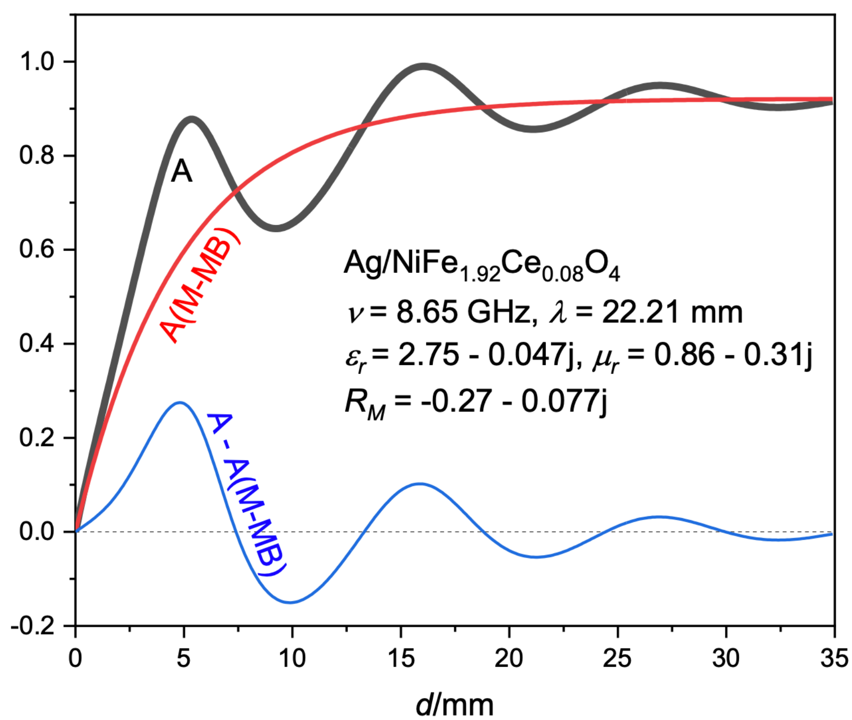

Fig. 3. The absorption of metal-backed film and of its the material with their difference.

It is clear from Fig. 3 that the absorption of metal-backed film is not same as absorption by the innate property of its material. It is true that the absorption of the film approaches that of material as d increases. However, this is because thick film behaves as material since the angular effect unique to film

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is suppressed [32]. The angular effect is a term introduced [34] to describe how the values of $|RL|$ and $|R_2|$ are affected by their phases and is dominant for thin film. As d increases, this effect is suppressed by the attenuation power of material since $\alpha_P d$ becomes large. The mechanism of absorption of the film is different from that of material and the fact that the absorption of film approaches the absorption of material at large d is not an indication that the absorption of film originates from the attenuation power of material. Just as an interface in film has different properties from those in its isolated state [31], the absorption of the film cannot be attributed to the absorption of material.

Z_{in} is a property of film while Z_M is a property of material [26]. However, the two are often confused in the literature [45][46][47] which has caused the current confusion between the film and the material [48]. It should be noted that film, interface, and material are all different. The interface does not absorb microwaves even though the imaginary parts of ε_r and μ_r are not zero [35].

2.2. The absorption mechanism of the film is different from that of the material

The absorption of the film is different from that of its material. More microwaves are absorbed when they travel further into material [25] and no absorption peak is possible. The absorption of the film is a wave like function as shown by Fig. 3 and the absorption peak is formed by wave cancellation from beams r1 and r2 [34][38].

The absorption of the metal-backed film is represented by the wave mechanics theory involving the superposition of beams r1 and r2 to form the total beam r [34][37][38]. The amplitudes of these beams can be represented by R_M, R_2, and RL [27][34] as shown by Fig. 4b.

As shown in Figs. 4a and 4b, the first absorption peak is formed when point P reaches position B where the phase difference ϕ between the two beams r1 and r2 is π. The maxima of $|RL|$ are achieved when point P reaches points C and E where $\phi = 0$ and $- 2\pi$, respectively. The second and the third absorption peaks are achieved at points D and F when $\phi = -\pi$ and $- 3\pi$.

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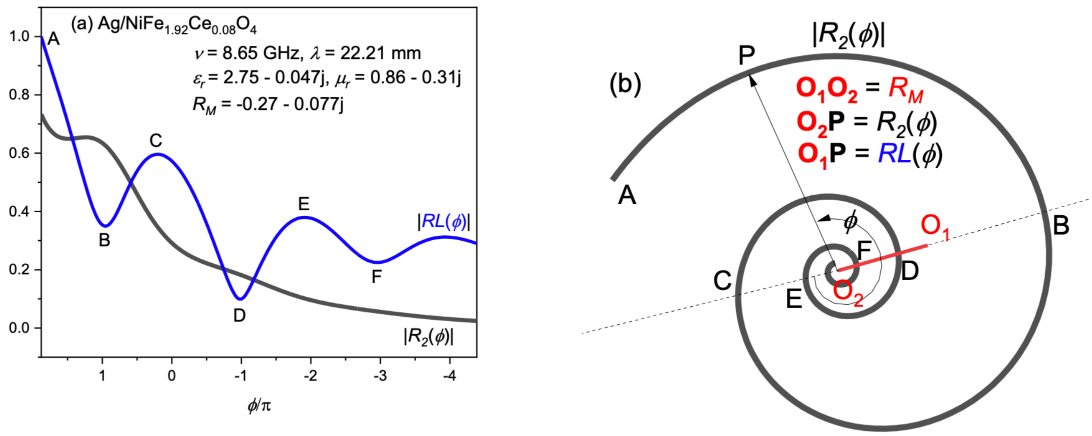

Fig. 4. The absorption peak formation mechanism for metal-baked film. ϕ is the phase difference between beams r1 and r2. (a) for Cartesian system and (b) for polar system.

2.3. The flaws in impedance matching theory

Based on Eq. (1) it is argued in impedance matching theory that perfect impedance matching, where all incident microwaves penetrate into the film, is achieved when $Z_{in} = Z_0$ so that the maximum absorption is achieved where $|RL| = 0$ and it therefore follows that absorption peaks occur for similar reasons at conditions where $Z_{in} \neq Z_0$. It is claimed that this theory is based on transmission line theory since Eq. (1) is derived rigorously using it, but in fact it is only generated by misinterpreting that theory.

Indeed, it is true that $Z_{in} = Z_0$ when $|RL| = 0$ [30]. However, only the condition $Z_M = Z_0$ and not the condition $Z_{in} = Z_0$ can ensure that all the incident microwaves enter the film. This error in impedance matching theory is due to confusion between the film and the material [26]. Furthermore, it is argued that the maximum absorption at $Z_{in} = Z_0$ takes place when both beams r1 and r2 have vanished [49][50][51][52]. However, for the film, beam r vanishes when $Z_{in} = Z_0$ but beams r1 and r2 still exist even though they cancel each other out.

All the reported absorption peaks do not occur exactly at $Z_{in} = Z_0$. Impedance matching theory is intended to offer an explanation for absorption peaks not occurring at $Z_{in} = Z_0$ by involving the amount of microwaves penetrating the film. In fact, all the incident microwaves enter the film when $\varepsilon_r = \mu_r$ or $Z_M = Z_0$. As seen from Fig. 2, the film behaves like material and there is no absorption peak as d increases, a fact which indicates that the logic of impedance matching theory is flawed. When $Z_M \neq Z_0$, penetration of

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the microwaves should not be defined by the amplitudes of individual beams but by energy penetration. However, the behavior of interface in film is not the same as that in its isolated state and thus the energy penetration for film cannot be defined, which signifies that (Z_M - Z_0) cannot be used as a criterion for microwave penetration in film [31].

When Z_{in} = Z_0 and $Z_M \neq Z_0$, beam r vanishes but beam r1 still exists. It cannot be explained using impedance matching theory why all the incident microwaves have been absorbed by the film while not all penetrate. It should be noted that impedance matching theory is a misinterpretation of transmission line theory since mathematics involving complex numbers is very different from that using real numbers. When Z_{in} is a complex number, the denominator Z_{in} + Z_0 in Eq. (1) cannot be neglected.

It is argued that RL/dB = - ∞ cannot be reached because Z_{in} is a complex number and Z_0 is a real number [53]. But this is not true because Z_{in} can also be a real number. It is also claimed that the reason why the condition RL/dB = - ∞ is not usually achieved is that there is no known material with that property ("An ideal EMW absorber would absorb all incident EMWs without any reflection waves … IM theory also specifies the condition for ideal penetration of EMW across the front interface of the absorber structure (i.e.,

zero occurrences of r, r1 and r2) [49]") and the absorption peaks are attributed to the quarter-wavelength resonance of the material [53]. This claim indicates that the absorption mechanism has not been understood in current theory since the absorption peaks originate from wave cancellation instead of the innate properties of material [27][34].

2.4. The inverse relationship

The quarter wavelength theory has been widely used in current microwave absorption research but the theory is wrong [37][38] because the phase effects from interfaces have been neglected [30][31]. The theory cannot be applied to the intermediate layer in a multilayered film since microwaves are incident from both sides of the layer [29]. The absorption peaks can also occur at $d = n\lambda/2$ where n is an integer [38]. What is more, there is no absorption peak when $\varepsilon_r = \mu_r$ where the quarter wavelength theory is irrelevant [38].

A transmission line with a length of a quarter wavelength has often been used as an impedance convertor [49][54][55] but it cannot be used to support the quarter wavelength theory in microwave absorption [40] which needs to be replaced by a mechanism involving wave cancellation from beams r1 and r2 where the shift of peak position of absorption is governed by the inverse relationship between v and d [36].

2.5. The deviation of absorption peak positions

In theory, the positions of absorption peaks for film should occur exactly at $d = (2n + 1)\lambda/4$ or $n\lambda/2$. However, in practice the reported peaks always deviate from these ideal positions. Efforts have been done to identify the reasons for this [53][56] but the methods used are inappropriate and as a consequence the conclusions are incorrect [36][57]. The method also has led to the conclusion that ε_r is a function of film thickness but this is not the case [53][58][59]. The phase effects from the imaginary parts of ε_r and μ_r will cause the peak positions to deviate from $d = (2n + 1)\lambda/4$ or $n\lambda/2$ but they should still occur exactly at phase difference $\phi = (2n + 1)\pi$ between beams r1 and r2. However, as shown by Table 1, the peaks also deviate from $\phi = (2n + 1)\pi$.

$|R_2|$ should increase by the angular effect when the phase difference between beams r1 and r2 ϕ approaches π from 2π and decrease when ϕ approaches 0 from π [34]. However, the maximum value 0.65 of $|R_2|$ in Fig. 4 is achieved at $\phi = 1.23\pi$ where point P has not yet reached $\phi = \pi$. This is because the attenuation power of material is constant and thus it reduces $|R_2|$ as d or ϕ increases. $|R_2|$ achieves its maximum when the effects of the angular and the attenuation power are balanced where P has not arrived at $\phi = \pi$ [27][33]. As P passes the position where $\phi = \pi$ and decreases ϕ further, $|R_2|$ becomes a monotonic decaying function since the effect from the attenuation power of material overrides the angular effect which makes this parameter of $|R_2|$ behaving more like a property of material. However, as long as both beams r1 and r2 are present, $|RL|$ is still influenced by the angular effect as ϕ is reduced from 2π to π, 0 to $-\pi$, and -2π to -3π, etc. and increased when ϕ decreases from π to 0, $-\pi$ to -2π, and -3π to -4π, etc [34]. Since the attenuation power of material reduces $|RL|$ as d or ϕ increases, $|RL|$ reaches its minimum when point P passes the positions where $\phi = \pi$, and its maxima when point P has not reached positions where $\phi = 0, -2\pi$. The results have been demonstrated by Fig. 4 and summarized in Table 1 for these positions where the contributions of the angular effect and the attenuation power are balanced. At large values of d, the attenuation effect represented by $\alpha_P d$ becomes dominant and the minima of $|RL|$ occur at positions D and E where point P has not reached $\phi = -\pi$ and -3π [27][33]. When the angular effect is weakened, other effects such as the amplitude effect on phase should be considered [30][33].

doi.org/10.32388/ZKKEZF

	B	C	D	E	F
ϕ	0.95	0.21	−0.99	−1.91	−2.96
$\|RL\|$	0.35	0.60	0.10	0.38	0.22

Table 1. The positions and values of the minima and maxima $|RL|$ for metal-backed film of $Ag/NiFe_{1.92}Ce_{0.08}O_4$ at 8.65 GHz (Data taken from Fig. 4)

2.6. Newly established concepts

When wave mechanics is used to explain microwave absorption, many new concepts are established. In contrast to the current theory, the film and the material have been differentiated. From impedance matching theory, more penetration and stronger attenuation power of material are required to increase absorption, however, it is revealed by wave mechanics that absorption of metal-backed film can be increased by less penetration and less attenuation power of material [32]. From current theory, a weaker beam r2 indicates a stronger microwave absorption, but this has been proved not to be the case for thin film where the strongest absorption occurs at the maximum of $|R_2|$ [32][34]. By wave mechanics, it is easily shown that the interface never absorbs microwaves [35], that the energy penetration cannot be defined for film [31], that the absorption mechanism of the film is different from that of material [27][28][34][38], and as a consequence the quarter wavelength theory should be replaced by a theory based on the inverse relationship between v and d [36]. It is also shown that the voltage of beams f1 and r2 can be larger than that of the incident beam i [35]. $|RL|$ is still a function of its phase angle and this is also true for $|R_2|$ [34][36].

When classical mechanics is combined with wave mechanics, quantum mechanics has established many useful concepts. Both the quantum mechanics and the wave mechanics theory for microwave absorption film demonstrate the power of wave mechanics in revealing the real nature behind experimental phenomena by establishing new concepts.

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3. Conclusions

Wave mechanics theory has been established in recent years. The real mechanism of absorption was made clear by transmission line theory as shown by the derivation of the formulae related to reflection loss *RL*. However, the results from transmission line theory have been misinterpreted in current research for too long. The real mechanism was rediscovered by the application of wave mechanics and the theory was further developed with many new concepts established. This new development includes representing the microwave absorption mechanism by the superposition of beams r1 and r2. Many new features ignored previously have been identified.

Conflict of Interest

The authors declare that they have no conflict of interest.

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Supplementary data: available at https://doi.org/10.32388/ZKKEZF

Declarations

Funding: No specific funding was received for this work.

Potential competing interests: No potential competing interests to declare.