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[Commentary] Comments on: "A perspective on impedance matching and resonance absorption mechanism for electromagnetic wave absorbing" by Hou et al. [Carbon 222 (2024) 118935]

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Abstract
This is a comment on the problems of the paper by Hou et al., which are related to wrong theories dominated in current research of microwave absorption. The problems involve the confusion between a film and a material represented by using the film parameter reflection loss to characterize the material, the wrong impedance theory, the wrong quarter wavelength theory, and the wrong absorption mechanism for the film. The wrong theories can be corrected easily from principles not beyond a college education and have already been clarified by several papers from different perspectives in a number of journals. However, the papers using these wrong theories are continuing to be published in huge quantities without mentioning the opposite views, and further works on the subject have often been rejected even without external review. Thus, a commenting letter is necessary to draw attention.

1. Introduction
A huge number of papers have been published [1]. Different from textbooks where correctness is essential, journals encourage new ideas since innovative ideas are healthy for the progress of science, whether they are correct or wrong, and science is not afraid of errors because questioning established conclusions is a characteristic of science. Thus, it is estimated that 90% of journal papers are incorrect [2, 3], which necessitates reviews of published results. However, it has become a hidden rule that manuscripts questioning established theory cannot be acceptable for publication [4]. As a result, review papers seldom point out serious mistakes in publications even though a great number of reviews were written by eminent people. Reviews should not just be a survey and a list of published results. They should find the main problems in publications and reveal insights from published data that others have not seen, such as those that occurred in the history of the proposal of the atomic theory from the law of definite composition, the law of multiple proportions, and the law of combining volumes of gases, and

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the proposal of the Balmer formula from published spectra data of hydrogen, and the revealing of theoretical logic in the formula.

One of the interesting phenomena is that wrong understanding can become dominant for long after the establishment of a correct theory. Misuse of a textbook principle has been identified 91 times among different publications by different research groups [5]. The problems in Le Chatelier's principle have been identified for long [6], but the wrong principle is still taught in modern classrooms. The concepts concerning the Gibbs–Duhem Equation were originally established correctly [7]. However, these concepts have been misunderstood, and manuscripts with the correct interpretations were rejected for publication, while those with the wrong understanding have been numerously published [8]. This has led to the related corrections becoming difficult [9]. Current theories of microwave absorption have confused film with material [1, 10] though the two are distinctively different [11, 12]. This confusion has resulted in the film parameter reflection loss *RL* being used to characterize the absorption of material [1, 10, 13-36] while it should be used to characterize the absorption from metal-backed film other than from material [11, 37, 38]. The confusion is caused by a misinterpretation of transmission line theory, though, when correctly used, it can provide the correct electromagnetic theory for microwaves. This confusion has caused many problems with the interpretation of experimental data, but in order to solve these problems, research has not been directed to correct the confusion but into developing wrong concepts such as those involving impedance matching theory, the quarter-wavelength theory, and the wrong absorption mechanism for film [11, 37, 39-43]. A large number of papers have been published in which experimental data has been used unconvincingly to support these wrong theories. Only recently have the problems been identified and solved by the establishment of the new wave mechanics theories for microwave absorption [11, 40, 42, 44] which has been shown to interpret experimental data more accurately than current theories [11, 37, 38, 40, 45]. In this work, problems in ref. [46] associated with the wrong theories are discussed in detail. Although these wrong theories have already dominated the field for a long time with a great number of papers published [1, 13, 14, 47-50], their corrections can be easily done from basic principles of wave mechanics at the college level, and the issues are important since the conclusions of those published results are not reliable.

2. Discussions

Many serious problems were demonstrated in the survey in the introduction of the paper by Hou et al [46] that "Xie et al. developed a hierarchical aerogel … that exhibits excellent EMW (electromagnetic wave) absorption capability with a remarkable attenuation of *up to - 73.2 dB*. Wu et al. prepared a heterobimetallic disulfide nanoparticles composite dispersed in CoS_2 hollow sea urchins … which exhibits excellent EMW absorption performance at a thickness of 1.97 mm with *an* RL_{min} *of - 75.23 dB … A perfect absorbing material is one with a relative complex permeability same as the relative complex permittivity*, so that its wave impedance is equal to that of air. *But this material is impossible to exist in nature* … A deeper understanding of *quarter-wavelength resonance* is urgently needed to produce *multi-frequency resonance* for designing *broadband* and strong absorption materials."

Reflection loss *RL*/dB is commonly used to characterize absorption by a material.
However, *RL*/dB is a property of a film, which can be used to characterize the absorption of a

film. The absorption of material cannot be characterized by this parameter [12] since more microwaves will be absorbed as the waves travel further into the material. Less microwaves may be absorbed by a film when its thickness is increased. [51] This is because the attenuation power of the material is responsible for the absorption of a material, while the absorption mechanism of the film originates from wave mechanics [11, 40].

As microwaves travel further into material, no absorption peak is possible, and thus the bandwidth of the absorption peak is irrelevant to the material. The multiple absorption peaks from the film do not originate from the multi-frequency resonance of the material but originate from the cancellation of beams r1 and r2 as shown in Fig. 1 [40, 52, 53], thus, there is no such thing as quarter-wavelength resonance. Perfect absorption can be achieved when the two beams are out of phase by π and, at the same time, their amplitudes are of the same value. Indeed, absorbing films were reported with *RL*/dB < - 40 dB where 99.99% of the incident microwaves have been absorbed.

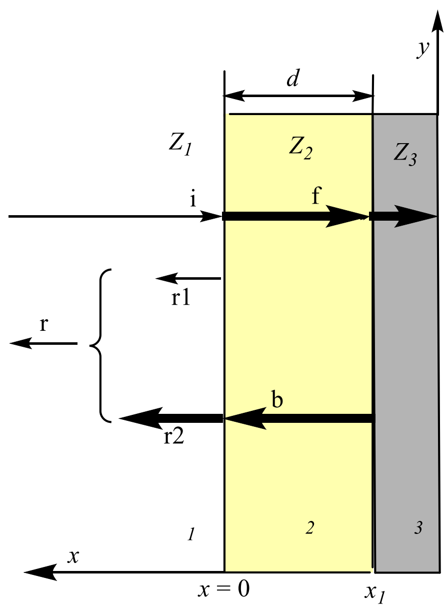

Fig. 1 i is the incident beam and r1 is the beam, reflected from the interface at x = 0. Beams f and b are the total beams reflected back and forth in layer 2. r2 is the transmitted beam from b. Z_l is the characteristic impedance for layer l, and ε_l and μ_l are the permittivity and permeability for layer l, respectively.

With reference to Fig. 1, Akinay et al. listed the following equations:

$$RL(x=0)/dB = 20\log\left|\Gamma_{12}\right| \tag{1}$$

$$s_{11}(x=0) = \frac{Z_{in}(x=0) - Z_1}{Z_{in}(x=0) + Z_1} \tag{2}$$

$$Z_{in}(x=0) = Z_2 \frac{Z_3 + Z_2 \tanh(j2\pi\nu \frac{\sqrt{\varepsilon_2 \mu_2} z'}{c})}{Z_2 + Z_3 \tanh(j2\pi\nu \frac{\sqrt{\varepsilon_2 \mu_2} z'}{c})} \quad (3)$$

where ν is frequency and c is the speed of light in vacuum. However, all these three above equations were wrong [44], where Γ_{12} in Eq. (1) is not the reflection coefficient Γ_{11} for layer 2 at $x = 0$. If $Z_3 = Z_1$, the input impedance at $x = 0$ is [45, 54]

$$Z_{in}(x=0) = Z_2 \frac{Z_2 + Z_1 \tanh(j2\pi\nu \frac{\sqrt{\varepsilon_2 \mu_2} d}{c})}{Z_1 + Z_2 \tanh(j2\pi\nu \frac{\sqrt{\varepsilon_2 \mu_2} d}{c})} \quad (4)$$

If $Z_3 = 0$, then

$$Z_{in}(x=0) = Z_2 \tanh(j2\pi\nu \frac{\sqrt{\varepsilon_2 \mu_2} d}{c}) \quad (5)$$

Equation (2) would be correct if Eq. (4) were used for the film without a metal back, and if Eq. (5) were used for metal-backed film.

For metal-backed film, the maximum absorption is indeed achieved when $Z_{in}(x = 0) = Z_1$ [55]. But this result does not validate impedance matching theory because the maximum penetration is ensured by $Z_2 = Z_1$ instead of $Z_{in} = Z_1$ [45]. Impedance matching theory cannot explain why all the incident microwaves are absorbed while not all of them enter the film. The theory cannot explain why $Z_{in} = Z_1$ cannot be achieved for most of the absorption peaks. The reason can be easily found from wave mechanical theory instead of the reason claimed by Hou et al [46] that Z_{in} is a complex number and Z_1 for open space is a real number. It is claimed that impedance matching can be achieved when $Z_{in}/Z_1 \approx \mu_2/\varepsilon_2 = Z_2^2/Z_1 = 1$ [47]. Z_{in} is a property of the film, and Z_2 is a property of the material. The confusion between $Z_{in} = Z_1$ and $Z_2 = Z_1$ represents the confusions between the film and the material and between the interface in the film and in its isolated state [39].

It is claimed that "A good EMW absorbing material can not only rarely reflect the electromagnetic wave, but also completely absorb the incident energy in the shortest possible distance" [46] and "In this system, Fe_3O_4/CNT is a typical absorption material with good impedance matching and attenuation constant" [14]. This is not true because absorption from the film is not determined by penetration and attenuation of material, but by wave mechanics [37].

Impedance matching theory is developed to explain the absorption peaks from film. However, there is no peak formed if $Z_2 = Z_1$ because the film behaves as a material at this circumstance [39]. The interface at $x = 0$ vanishes and beam r1 does not exist, where RL is only determined by the amplitude of beam r2 [40]. It can be demonstrated that the minima of RL/dB when $|Z_{in} - Z_1|$ reaches its maxima instead of its minima [41, 56].

It was claimed by Hou et al [46] that "When the sum of the reflected wave energy of the two interfaces is equal to the incident wave energy and their phases are opposite, the EMW will be completely absorbed," and this is a common mistake [57-63]. The absorption peaks originate from the wave cancellation between beams r1 and r2 instead of beams i and r. Another mistake [64, 65] is that the wave superposition refers to the amplitude of the beams instead of their energy [39, 66].

The impedance matching coefficients represented by Eqs. (4) and (5) in ref. [46] are for the film and for the interface, respectively [43], and they are equivalent to the wrong impedance matching theory because when these coefficients approach 1, the $Z_{in} = Z_1$ and $Z_M = Z_1$ in the impedance matching theory are achieved.

Equation (7) in ref. [46] is listed below

$$d = \frac{(2m+1)c}{nv}(\frac{1}{4} + \Delta), \qquad (m = 1, 2, 3...) \tag{6}$$

n is the refraction index, and Δ is the deviation of the absorption peak from $d = \lambda_l/4$, where λ_l is the wavelength in layer l. But this formula cannot be used generally as among the 11 cases listed in ref. [41], only one case with $\varepsilon_2 > \mu_2$ obeys the quarter-wavelength theory. For example, the absorption peaks for the film without a metal back occur at $d = \lambda_l/2$, which does not obey the quarter-wavelength theory. It was claimed in ref. [46] that refs. [67, 68] identified this result, but there was no such conclusion in these two claimed references, and the result can be found in refs. [41, 66]. The quarter-wavelength theory should be replaced by the inverse relationship between v and d if ε_2 and μ_2 are not sensitive to frequency [69]. The quarter-wavelength theory refers to absorption peaks, and these peaks from the film are formed by the wave cancellation of beams r1 and r2 rather than from the resonances of the material. Resonance peaks should be much sharper and stronger. Thus, the term "quarter-wavelength resonance" is misled.

Since there are absorption peaks at $d \approx \lambda_l/2$, all the following equations based on Eq. (6) would not achieve correct conclusions, and the mathematical problems on that will be presented in Appendix 1. There are other attempts based on the wrong impedance matching theory to investigate the deviations of absorption peak away from the phase difference of beams r1 and 2 at (2m + 1)π [70, 71]. When a theory is wrong, it is wrong from every aspect, even though the theory has dominated for a very long period in modern research. These approaches are not to the point and thus are tedious, and at the same time, such approaches cannot achieve positive results [39, 69].

It was concluded in [46] from Eq. (6) that $\Delta = 0$ if the tangent dielectric loss $\tan\delta_\varepsilon$ equals the magnetic loss $\tan\delta_\mu$. The conclusion has already been proved wrong [39, 41] since there is no absorption peak when $\varepsilon_2 = \mu_2$. It was claimed wrongly from the proof in [46] that $\Delta > 0$ when $\tan\delta_{\sqrt{\varepsilon_2\mu_2}} > \tan\delta_\mu$, and $\Delta < 0$ when $\tan\delta_{\sqrt{\varepsilon_2\mu_2}} < \tan\delta_\mu$, together with the conclusion that "the resonance thickness of the material dominated by dielectric loss is greater than $\lambda_2/4$, while that of the material dominated by magnetic loss is less than $\lambda_2/4$" [46]. These conclusions are not true. From the wave mechanics theory, the actual peak position shifts always occur at phase differences of beams r1 and r2 larger than $(2m + 1)\pi$ [40, 72]. From the angular effect of the film,

$|RL|$ decreases from $2m\pi$ to $(2m + 1)\pi$ and increases from $(2m + 2)\pi$ to $(2m + 1)\pi$, but the attenuation power of the material decreases $|RL|$ throughout the whole process. Thus, the minima of $|RL|$ can only be achieved at positions larger than $(2m + 1)\pi$ where the effects of angular and attenuation are balanced.

The correlation in the claim that "For an EMW absorber with a high loss material as a backplate, two interfacial reflections are similar to that with a metal backplate" [46] is not correct since all the incident microwaves on metal are complete reflected, while high values of ε_3'' and μ_3'' only imply the attenuation power of the material. It was reasoned that "The introduction of Δ in the resonant thickness allows to obtain a standing wave ratio (VSWR) equal to 1, when the reflection coefficient is equal to 0" [46], which is not true. When the reflection coefficient $RL = 0$, beam r is vanished, and standing wave is impossible since the only wave exists is beam i propagating in one direction. On the other hand, absorption deviation Δ is irrelevant to the standing wave ratio.

Conclusions about dielectric dispersion were obtained from Δ as "the dielectric dispersion relation of an ideal absorber can be determined by Eq. (13) and Eq. (14), which is the theoretical support for realizing multi-frequency resonance and can be used to guide the preparation of broadband EMW absorbing materials" [46]. The conclusion were wrong because Eq. (13) and Eq. (14) were derived from Eq. (6). In fact, the absorption peak shifts Δ are irrelevant to the occurrence of multiple absorption peaks and their intensities.

3. Conclusions

The main theories in current research are wrong. Although the correct theory has been rediscovered from transmission line theory and developed further to reveal the physics of films not realized before, it has not attracted the attention of the researchers, and papers using the wrong theories continue to be published in large quantities. The problems in published papers have been analyzed through the comment on the paper from Hou et al. [46] to attract the attention of the community. The issues discussed are important since the wrong theories still dominate the field. Although the wrong theories have a huge influence, the corrections can be made from simple principles covered at the college level.

Appendix 1 The problems in the mathematical derivations in ref. [46]

A1 Theoretical background

With reference to layer 2 in Fig. 1, we obtain

$$\sqrt{\varepsilon_2\mu_2} = \sqrt{(\varepsilon_2' - j\varepsilon_2'')(\mu_2' - j\mu_2'')} = \mathrm{Re}(\sqrt{\varepsilon_2\mu_{r2}}) - j\,\mathrm{Im}(\sqrt{\varepsilon_2\mu_2}) \quad (7).$$

Let k and the refraction index n be defined as

$$\begin{aligned} n &= |\mathrm{Re}(\sqrt{\varepsilon_2\mu_2})| > 0 \\ k &= |\mathrm{Im}(\sqrt{\varepsilon_2\mu_2})| > 0 \end{aligned} \quad (8),$$

We obtain

$$\sqrt{\varepsilon_2\mu_2} = n - jk \quad (9)$$

$$t = \left|\tan\delta_{\sqrt{\varepsilon_2\mu_2}}\right| = \frac{k}{n} = \frac{|\operatorname{Im}(\sqrt{\varepsilon_2\mu_2})|}{|\operatorname{Re}(\sqrt{\varepsilon_2\mu_2})|} \quad (10).$$

From wave mechanics [66] with layer 1 as a reference, open space

$$\frac{1}{\lambda_2} = \frac{\nu\,|\operatorname{Re}(\sqrt{\varepsilon_2\mu_2})|}{c} = \frac{\nu}{\upsilon} \quad (11)$$

$$\frac{c}{\upsilon} = \left|\operatorname{Re}(\sqrt{\varepsilon_2\mu_2})\right| = \frac{\lambda_1}{\lambda_2} \quad (12)$$

$$\lambda_2 = \frac{\lambda_1}{\left|\operatorname{Re}(\sqrt{\varepsilon_2\mu_2})\right|} = \frac{\lambda_1}{n} \quad (13)$$

From the properties of propagating waves, we define [45, 54]

$$\alpha_j = \frac{4\pi\nu\,|\operatorname{Re}(\sqrt{\varepsilon_2\mu_2})|}{c} = \frac{4\pi\nu n}{c} = \frac{4\pi}{\lambda_2} = \frac{4\pi n}{\lambda_1} \quad (14)$$

$$\alpha_P = \frac{4\pi\nu\,|\operatorname{Im}(\sqrt{\varepsilon_2\mu_2})|}{c} = \frac{4\pi\nu k}{c} = \frac{4\pi k}{\lambda_1} \quad (15)$$

The absorption *A* of a material can be defined as

$$A = -\ln\left|e^{-4\pi j\frac{\nu\sqrt{\varepsilon_2\mu_2}}{c}d}\right| = -\ln\left|e^{-\alpha_P d - j\alpha_j d}\right| = \alpha_P d \quad (16)$$

A2 The problems in the mathematical derivations of equation (8) in ref. [46]

From Eq. (5)

$$\frac{Z_{in}}{Z_2} = \frac{1 - e^{-j4\pi\nu\frac{\sqrt{\varepsilon_2\mu_2}d}{c}}}{1 + e^{-j4\pi\nu\frac{\sqrt{\varepsilon_2\mu_2}d}{c}}} \quad (17)$$

$$\frac{Z_2 - Z_{in}}{Z_2 + Z_{in}} = e^{-j4\pi\nu\frac{\sqrt{\varepsilon_2\mu_2}d}{c}} \quad (18)$$

$$j4\pi\nu\frac{\sqrt{\varepsilon_2\mu_2}d}{c} = -\ln\frac{Z_2 - Z_{in}}{Z_2 + Z_{in}} \quad (19)$$

In ref. [46], Eq. (6) has been inserted into Eq. (19)

$$j4\pi\nu\frac{\sqrt{\varepsilon_2\mu_2}}{c}\frac{(2m+1)c}{n\nu}\left(\frac{1}{4} + \Delta\right) = -\ln\frac{Z_2 - Z_{in}}{Z_2 + Z_{in}} \quad (20)$$

However, Δ cannot be solved from Eq. (20) since Z_{in} is defined from Δ, which signifies that Eq. (8) in ref. [46] cannot be obtained.

Conflict of Interest

The authors declare that they have no conflict of interest.

Data availability statement

Data sharing does not apply to this article as no new data were created or analyzed in this study.

The authors contribution statement

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

Ying Liu: Conceptualization, Methodology, Validation, Formal analysis, Investigation, Resources, Writing - Review & Editing, Supervision, Project administration

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

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