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Recognizing Problems in Publications Concerned with Microwave Absorption Film and Providing Corrections: A Focused Review

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Abstract

Errors common in publication have been analyses in details. Serious consequences have been resulted in, such as the establishments of the wrong impedance matching theory and wrong absorption mechanism, since these errors have not been corrected in time. Material scientists continue the practice of the wrong theories when the correct new wave mechanics theory for microwave absorption film had been developed to replace those wrong theories, just because they have become deeply ingrained in the wrong concepts built up from those errors.

Key words

Microwave absorption; concept clarification; film physics.

1. Introduction

Many scientific journals encourage new ideas since they are healthy for the progress of science. Unlike textbooks where consistent and accepted accuracy is required, scientific papers can often include speculation which can be accepted or denied over the course of time. Thus, it has been

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estimated that 90% of journal papers contain some unconfirmed material [1, 2], which necessitate reviews on published results. However, contrary to this ideal, all too often manuscripts questioning established theory are not accepted for publication [3, 4]. Reviews should not just contain an uncritical survey of relevant papers [5-8] but rather should be used to critically assess publications, establish any significant problems and reveal insights from published data that were remained unrecognized [9-13]. As a consequence, due to some extent of the prevalence of uncritical reviews, wrong theories can persist for far longer than they should and valid corrections can take a long time to be accepted [9, 14, 15].

In current theories of microwave absorption, the properties of film and material have become confused [6, 7, 16] despite the two being distinctively different [17-19]. This confusion has resulted in the film parameter reflection loss *RL* being used to characterize the absorption of material [5-8, 20-41] while it should only be used to characterize the absorption from metal-backed film [17, 42, 43]. 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, not corrected in time, has caused many problems in understanding the physics intrinsic in experimental data, and subsequently has led to the development of a wrong theoretical framework involving impedance matching theory [42, 44-46], the quarter wavelength theory [47-50], and the wrong absorption mechanism for film [9, 51]. A large number of papers [6] have been published in which experimental data have been used unconvincingly to support these wrong theories. Only recently have the problems in microwave absorption theories been identified [9, 17, 42, 45, 50, 51] and corrected by the development of wave mechanics theories which can be used to comprehend experimental data more accurately [9, 17, 42, 52]. Although the problems have been corrected across several years from different perspectives among many journals, and the subject have attracted attention indicated by the number of views and downloads, the subject is dealt with only by our single group and the practice of using the wrong theories continues without mention of opposite views [5-8]. It is interesting that the research community does not accept the new theories even though the background is not beyond fundamental physics at college level, the only difficulty is that many new concepts are involved when wave mechanics is applied to the film. As evident from the Supplementary Materials, material scientists are likely to reject the work without comments on the main contents of such manuscripts [53] and not given the authors the opportunity in defensing [2, 54].

In this work, recent publications [55-62] have been used in section 2 to demonstrate the problems in current microwave absorption that have arisen from confusing characteristic and input impedances [52], and interface and film [45]. The theoretical background is introduced in section 2.1. The confusion between the input Z_{in} and the characteristic Z_M impedances in refs. [55-57] has been addressed in section 2.2. The absorption of metal-backed film can be characterized by the reflection coefficient of the film RL in units of dB. However, by confusing the film with the material, the reflection coefficient of interface R_M has been wrongly used in place of RL to characterize the absorption in film which is incorrect since the interface does not absorb microwaves [63] and thus R_M cannot be used to characterize absorption. Section 2.3 concerns refs. [58-62]. In this section, it is clarified that the condition $Z_{in} = Z_0$ is fulfilled by complete cancellation of beams r1 and r2 in Fig. 1 [44], where beam r is vanished rather than both beams r1 and r2 are vanished, simultaneously. The significance of this issue is that wave mechanics [9, 51, 64, 65] should be used to replace impedance matching theory [42, 44-46] and wave superposition involves amplitude of individual beam rather than its energy [45, 47].

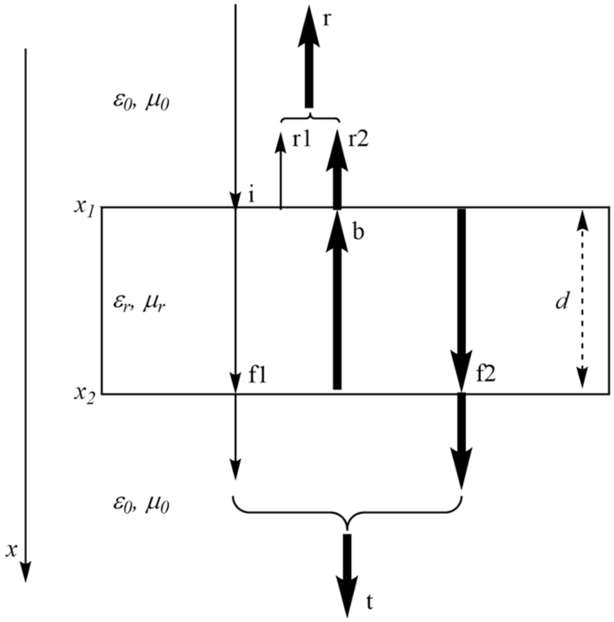

Fig. 1 Film with thickness d from material with relative electric permittivity ε_r and magnetic permeability μ_r; ε_0 and μ_0 are the permeability and permittivity in open space. i is the incident beam for the microwave signal; r1 and f1 are the reflected and transmitted beams from beam i for the interface at x_1. Beam f1 is reflected back and forth in the film, and (f1 + f2) is the total forward beam, while b is the total backward beam. The reflected beam r2 from the rear interface at x_2 is transmitted from beam b; beam r represents the superposition of beams r1 and r2. Beam t is transmitted from beam (f1 + f2). There are no incident microwaves from the interface at x_2.

The impedance matching theory is designed to explain the absorption peaks from the film. The essential of the theory requires more penetration of the incident microwaves and more attenuation power of material for more efficient absorption. But the theory has proved to be wrong. The criteria of penetration are confused between $Z_{in} = Z_0$ and $Z_M = Z_0$ [52]. Indeed, all the incident microwaves enters the film when $Z_M = Z_0$, but contrary to impedance matching theory, in such a case there is no absorption peak at all. The film behaves as material [42, 51] at this circumstance since the thicker the film, the more the absorption, i.e. the amplitude of the microwave beam in the film is a monotonic decaying function of film thickness at fixed frequency [44, 45]. It is true that the film absorbs all the incident microwaves when $Z_{in} = Z_0$ [44]. However, $Z_{in} = Z_0$ cannot ensure that $Z_M = Z_0$, and beam r1 in Fig. 1 still presents when $Z_M \neq Z_0$. Thus, the impedance matching theory cannot explain why all the incident microwaves have been absorbed while not of them penetrated. For film with thickness increasing, judged from impedance matching theory, the incident microwaves enter the film is fixed since the front interface is fixed. And the attenuation power of the material is fixed since the material of the film is the same for different film thickness. But the absorption of the film can be become larger or smaller as d increases. The result cannot be explained by impedance matching theory [42].

Contrary to the impedance matching theory, wave mechanics theory has developed for absorption in the film [9, 51]. Although the film does not absorb microwaves if its material does not absorb [66], the absorption mechanism of film is different from that of material [17, 42].

Almost all the reported absorption peaks cannot be achieved at $Z_{in} = Z_0$ as predicted by impedance matching theory. As indicated in section 3, the reason was attributed wrongly to that Z_{in} is a complex number and Z_0 is a real number [16]. This problem is representative because the formation of absorption peak was also attributed the resonance of material [16, 60] and concluded that no such material with $Z_{in} = Z_0$ exists [60]. The issue indicates that the real absorption mechanism is not identified in current theory. In fact, Z_{in} can take real number, and the absorption peak is a result of the cancellation of beams r1 and r2 rather than the resonance of material. The correct answer has been provided by wave mechanics theory [46] from the inward spiral shape of the amplitude of beam r2 in polar coordinate system [9]. The standing wave from beams i and r propagating in opposite directions has been confused with the wave superposition of beams r1 and r2 in ref. [16] which is common among publications to attribute absorption to the standing wave instead of the amplitude of beam r [67-73]. This mis-concept is responsible to the difficult in recognizing the real absorption mechanism. The wrong quarter-wavelength theory has been used to derive an equation for the deviation of absorption peak positions from their ideal positions in ref. [16] and the same mistake occurs elsewhere [74, 75]. This mistake has resulted in the wrong conclusion that the permittivity ε_r and permeability μ_r are functions of film thickness, which was also claimed in many other publications [74, 76, 77]. The shifts of absorption peak positions have been accoutered theoretically by wave mechanics theory [9, 66].

It is claimed wrongly in ref. [16] that the absorption peak was a result of material resonance which is the common view in current theory [7, 60]. An alternative view is that the absorption of film is a result of the attenuation power of material along the zig-zag optical path from the back-and-forth reflections in the film. But this is proved untrue [17]. The absorption peak is a result of wave cancellation from beams r1 and r2. Beam r1 is the reflection of the incident microwaves from the front interface and interface does not absorb microwaves [63]. Thus, the amplitude of beam r1 has nothing to do with material attenuation. Material attenuation does make the amplitude of beam r2 an inward spiral in polar coordinate system as film thickness *d* is increase at constant frequency [9], but the amplitude of beam r2 still possesses a wave form in Cartesian coordinate system because of the angular effect unique to film [51]. Thus, even the amplitude of beam r2 cannot be used to characterize the absorption of material since the amplitude of microwaves propagating in material must be a monotonic decaying function as more microwaves are absorbed when the waves travel further into the material [19]. The so called "the quarter-wavelength theory" under the condition $\varepsilon_r > \mu_r$ [48] is governed by the inverse relationship when both ε_r and μ_r are insensitive to frequency [49]. It should be noted "the quarter-wavelength theory" is not applicable to muti-layered film [50] and many other cases such as film without metal-back [48].

It is true that the problems discussed in this work are not complicated. However, they are representative of the mistakes that commonly occur in the literature. It is just these simple misunderstandings that have led to the current wrong theories and to the failure to accept the new physics of film based on wave mechanics [9, 17, 42, 45, 48-51] (See the supplementary materials). This review based on our previous work is intended to attract attention to the problems of current theories.

2. Corrections of common errors in current theories of microwave absorption caused by confusing input and characteristic impedances

2.1 Theoretical background

Figure 1 shows a film without a metal back with thickness *d*. The voltages for beams i, r1, and r2 at time *t* and position $x \le x_1$ are [78]:

$$\begin{aligned} V(\mathrm{i},t,x \le x_1) &= V(\mathrm{i},x_1)e^{2\pi\nu j[t-\sqrt{\varepsilon_0\mu_0}(x-x_1)]} \\ &= V(\mathrm{i},x_1)e^{2\pi j[\nu t-\frac{\nu}{c}(x-x_1)]} = V(\mathrm{i},x_1)e^{2\pi j(\nu t-\frac{x-x_1}{\lambda})} \end{aligned} \tag{1}$$

$$\begin{aligned} V(\mathrm{r1},t,x \le x_1) &= V(\mathrm{r1},x_1)e^{2\pi\nu j[t+\sqrt{\varepsilon_0\mu_0}(x-x_1)]} \\ &= V(\mathrm{r1},x_1)e^{2\pi j(\nu t+\frac{x-x_1}{\lambda})} \end{aligned} \tag{2}$$

$$\begin{aligned} V(\mathrm{r2},t,x \le x_1) &= V(\mathrm{r2},x_1)e^{2\pi\nu j[t+\sqrt{\varepsilon_0\mu_0}(x-x_1)]} \\ &= V(\mathrm{r2},x_1)e^{2\pi j(\nu t+\frac{x-x_1}{\lambda})} \end{aligned} \tag{3}$$

$V(k, t, x)$ is the voltage amplitude at time t and position x for beam k, and $V(k, x)$ is its maximum amplitude. ν is frequency, and λ is the wavelength in open space. c is the velocity of light in vacuum. For the beams within the film:

$$\begin{aligned} & V(\mathrm{f1},t,x_1 \le x \le x_2) = V(\mathrm{f1},x_1)e^{2\pi\nu j[t-\sqrt{\varepsilon_0\varepsilon_r\mu_0\mu_r}(x-x_1)]} \\ & = V(\mathrm{f1},x_1)e^{2\pi j[\nu t-\frac{\nu\sqrt{\varepsilon_r\mu_r}}{c}(x-x_1)]} \\ & = V(\mathrm{f1},x_1)e^{-\frac{\alpha_P}{2}(x-x_1)}e^{j2\pi\nu t-j\frac{\alpha_j}{2}(x-x_1)} \\ & = V(\mathrm{f1},x_1)e^{-\frac{\alpha_P}{2}(x-x_1)}e^{2\pi j(\nu t-\frac{x-x_1}{\lambda_M})} \end{aligned} \tag{4}$$

$$\begin{aligned} & V(\mathrm{f2},t,x_1 \le x \le x_2) = V(\mathrm{f2},x_1)e^{2\pi\nu j[t-\sqrt{\varepsilon_0\varepsilon_r\mu_0\mu_r}(x-x_1)]} \\ & = V(\mathrm{f2},x_1)e^{2\pi j[\nu t-\frac{\nu\sqrt{\varepsilon_r\mu_r}}{c}(x-x_1)]} \\ & = V(\mathrm{f2},x_1)e^{-\frac{\alpha_P}{2}(x-x_1)}e^{j2\pi\nu t-j\frac{\alpha_j}{2}(x-x_1)} \\ & = V(\mathrm{f2},x_1)e^{-\frac{\alpha_P}{2}(x-x_1)}e^{2\pi j(\nu t-\frac{x-x_1}{\lambda_M})} \end{aligned} \tag{5}$$

$$\begin{aligned} & V(\mathrm{b},t,x_1 \le x \le x_2) = V(\mathrm{b},x_1)e^{2\pi\nu j[t+\sqrt{\varepsilon_0\varepsilon_r\mu_0\mu_r}(x-x_1)]} \\ & = V(\mathrm{b},x_1)e^{2\pi j[\nu t+\frac{\nu\sqrt{\varepsilon_r\mu_r}}{c}(x-x_1)]} \\ & = V(\mathrm{b},x_1)e^{\frac{\alpha_P}{2}(x-x_1)}e^{j2\pi\nu t+j\frac{\alpha_j}{2}(x-x_1)} \\ & = V(\mathrm{b},x_1)e^{\frac{\alpha_P}{2}(x-x_1)}e^{2\pi j(\nu t+\frac{x-x_1}{\lambda_M})} \end{aligned} \tag{6}$$

λ_M is the wavelength within the film; α_P is the power attenuation coefficient and α_j is the wave propagation coefficient. Wavelength is a result of the phase factor in wave mechanics. However, this relationship between λ_M and α_j was ignored in the quarter-wavelength theory [47]. For beam t:

$$\begin{aligned} V(\mathrm{t},t,x \geq x_2) &= V(\mathrm{t},x_2)e^{2\pi\nu j[t-\sqrt{\varepsilon_0\mu_0}(x-x_2)]} \\ &= V(\mathrm{t},x_2)e^{2\pi j[\nu t-\frac{\nu}{c}(x-x_2)]} = V(\mathrm{t},x_2)e^{2\pi j(\nu t-\frac{x-x_2}{\lambda})} \end{aligned} \tag{7}$$

The microwave absorption *A*(ν) from a device at frequency ν can be expressed by Eq. (8) if the microwaves are incident only from the front end of the device.

$$A(\nu) = 1 - R(\nu) - T(\nu) \tag{8}$$

For a film without a metal back as shown in Fig. 1, the microwave powers reflected *R*(ν) and transmitted *T*(ν) from the film of thickness *d* are related to the *s* parameters [63] when there are no incident microwaves from the other side of the film [52]. It should be note that the reflected beam b from the rear interface of the film is not the incident beam from the rear side of the film.

$$\begin{aligned} R(\nu) &= |s_{11}(\nu,d)|^2 = \left|\frac{V(\mathrm{r1},t,x_1)+V(\mathrm{r2},t,x_1)}{V(\mathrm{i},t,x_1)}\right|^2 \\ &= \left|\frac{V(\mathrm{r1},x_1)+V(\mathrm{r2},x_1)}{V(\mathrm{i},x_1)}\right|^2 \end{aligned} \tag{9}$$

$$\begin{aligned} T(\nu) &= |s_{21}(\nu,d)|^2 = \left|\frac{V(\mathrm{t},t,x_2)}{V(\mathrm{i},t,x_1)}\right|^2 \\ &= \left|\frac{V(\mathrm{t},x_2)}{V(\mathrm{i},x_1)}\right|^2 \end{aligned} \tag{10}$$

For a film with a metal back, $s_{21}(\nu, d) = 0$ and $s_{11}(\nu, d)$ is defined as the reflection loss *RL*(ν, *d*) in the field of microwave absorption material.

$$RL(\nu,d) = \frac{Z_{in}(\nu,d)-Z_0}{Z_{in}(\nu,d)+Z_0} \tag{11}$$

$Z_{in}(\nu, d)$ is the input impedance of the film, and Z_0 is the characteristic impedance of open space. The interface can be regarded as a film with $d = 0$. The reflection $R_M(\nu)$ and transmission $\gamma_M(\nu)$ coefficients of an interface are defined as

$$R_M(\nu) = \frac{Z_M(\nu) - Z_0}{Z_M(\nu) + Z_0} \tag{12}$$

$$\gamma_M(\nu) = \frac{2Z_M(\nu)}{Z_M(\nu) + Z_0} \tag{13}$$

$$1 + R_M(\nu) = \gamma_M(\nu) \tag{14}$$

$R_M(\nu)$ and $\gamma_M(\nu)$ are respectively the s_{11} and s_{21} parameters for an interface [46, 63]. Z_M is the characteristic impedance for a device [51, 78, 79], and it is also the characteristic impedance for the material of the normal film [80].

The relationships of the voltages between the different beams shown in Fig. 1 are:

$$V(\mathrm{r1}, t, x_1) = R_M(x_1)V(\mathrm{i}, t, x_1) \tag{15}$$

$$V(\mathrm{f2}, t, x_1) = -R_M(x_1)V(\mathrm{b}, t, x_1) \tag{16}$$

$$V(\mathrm{b}, t, x_2) = -R_M(x_1)[V(\mathrm{f1}, t, x_2) + V(\mathrm{f2}, t, x_2)] \tag{17}$$

$$V(\mathrm{f1}, t, x_1) = \gamma_M(x_1)V(\mathrm{i}, t, x_1) \tag{18}$$

$$V(\mathrm{r2}, t, x_1) = \frac{2Z_0}{Z_M + Z_0}V(\mathrm{b}, t, x_1) \tag{19}$$

$$V(\mathrm{t},t,x_2)=\frac{2Z_0}{Z_M+Z_0}[V(\mathrm{f1},t,x_2)+V(\mathrm{f1},t,x_2)] \tag{20}$$

The input impedance is associated with the s_{11} parameter whether the device is a film or refers to an interface.

$$\frac{Z_{in}(\nu,d)}{Z_0}=\frac{1+s_{11}(\nu,d)}{1-s_{11}(\nu,d)} \tag{21}$$

2.2 The confusion between Z_{in} and Z_M

This section is concerned with errors found in specific papers [55-57] which are related to common errors in current theories. For an interface, $Z_{in}(\nu, d)$ is reduced to Z_M [52]. The film parameters *RL* and Z_{in} are related to film thickness. However, their values have been quoted in ref. [56] without reference to the thickness of the film at which these values were obtained, as if they were the properties of the material.

In many papers [6, 55, 56, 59, 81-84] the input and the characteristic impedances are only vaguely defined as impedance. In addition, Z_0 is sometimes wrongly defined as input impedance [85-87]. It should be noted that the characteristic impedance Z_M and Z_0 are distributive properties which are only related to the forward or backward signal, while Z_{in} is a circuit parameter that is related to the total of the forward and backward signals and thus is associated with film thickness [52]. Since the real and imaginary axes of $\sqrt{\varepsilon_r\mu_r}$ had mistakenly been taken as the axes of the geometry of the film in ref. [88], the formula of Z_M was wrongly presented there.

This specific mistake regarding Z_{in} and Z_M is related to the common confusion between film and material in impedance matching theory [17, 18, 43, 52]. However, such confusion has been used to claim that the confusion did not occurred in the current theory of impedance matching in ref. [60].

Specific problems associated with Eqs. (8) and (14) can be identified in publications. Equation (14) can only be applied to an interface rather than to a film. However, Singh et al. [56] specified R_M in Eq. (14) as being equivalent to *RL*, thus confusing R_M of an interface with s_{11} or *RL* of a film. Hardianto et al. [57] have also used R_M/dB in place of *RL*/dB, a problem associated with the common error of confusing Z_{in} with Z_M, as found in impedance matching theory [42, 45, 46]. It should be noted that R_M is the reflection coefficient of an interface, which is unrelated to absorption because an interface does not absorb [46, 63], while *RL* is the reflection coefficient of a metal-backed film, and its value in dB is obtained from $|RL|^2$, which is directly related to microwave absorption, so *RL*/dB represents reflection loss. R_M was also used in place of *RL* in other references [57] to characterize absorption, which is incorrect because an interface does not absorb microwaves [46, 63]. Although *RL*/dB can be used to characterize the absorption of a metal-backed film, R_M/dB cannot be used similarly.

Similar problems can be identified concerning Eq. (8), even though the equation can be applied to both film and interface. When using Eq. (8), Saikia et al. [55] have specified that $T(\nu) = 0$ for metal-backed film and applied the equation $R(\nu) = |R_M(\nu)|$ associated with the interface, which is incorrect not only because parameters for interface and film have been mixed up but also because, although γ_M is the s_{21} for the interface, the interface does not absorb microwaves, and therefore Eq. (22) should be used rather than Eq. (10) [46, 63] even if $R(\nu) = |R_M(\nu)|^2$ was used.

$$T(\nu) = \frac{Z_0}{Z_M}\gamma_M^2(x_1^+) \tag{22}$$

The above errors are related to the common confusion between interface and film, which has led to the establishment of the mistaken impedance matching theory and wrong absorption mechanism for film [42, 45]. These mistakes led to the wrong conclusion, as stated in [89] that "A further benefit afforded by MMs (metamaterials) is the ability to construct a single unit cell with $\mu(\omega) = \varepsilon(\omega)$ over an extended frequency range. Thus, this unit cell can achieve zero $R(\omega)$ since it can have an impedance equal to the free space value $Z = \sqrt{\mu / \varepsilon} = 1$." This claim, however, cannot be justified because the two conditions $Z_{in} = Z_0$ and $Z_M = Z_0$ are confused [52].

For material, the amplitude of microwaves is a monotonic decaying function without absorption peaks as the waves travel further into the material. For metal-backed film shown in Fig. 1, beam r1 vanishes when $\varepsilon_r = \mu_r$. In such a case, the film behaves as a material, and the amplitude of beam r2 is a monotonic decaying function without absorption peaks as the film thickness d increases [44, 45, 48]. Thus, the conclusion quoted above from ref. [89] cannot be justified.

The confusion between Z_{in} of the film and Z_M of the material [52] represents the confusion between film and material [17] which leads to the wrong impedance matching theory [45]. However, the confusion between $Z_{in} – Z_0$ and $Z_M – Z_0$ has been used wrongly to assert that impedance matching theory has taken account of the difference between film and material [60]. Although the predictions from impedance matching theory can sometimes appear consistent with experimental results, predictions can be completely different in other circumstances [48]. Even in those rare cases where the predictions consistent with experimental results, the logic underlying the reasoning is still wrong [17, 46].

2.3 Common errors related to the confusion between Z_{in} and Z_M

Despite the specific errors discussed above, common problems in the current theories still occur. It is commonly believed that absorption from a film is caused by the attenuation power of its constituent material along the zig-zag optical path traveled in the film. Thus, absorption of the film is attributed to microwave penetration and material attenuation [56, 82] where first and second reflection losses have been defined from beams r1 and r2, respectively [58]. Thus, the disappearance of both beams r1 and r2 simultaneously is attributed to maximum absorption from the film [58-61] though the actual absorption mechanism for absorption peaks should be described by the cancellation of the two beams [9, 48, 51, 64, 65] since microwave absorption from the film is defined from the amplitude of beam r from wave superposition rather than from that of either beam r1 or r2 based on impedance matching theory [17, 42, 51, 66]. When all the incident microwave enters the film, as required by impedance matching theory as a condition for the absorption peak with RL/dB = - ∞, r1 disappears and absorption is only determined by the amplitude of beam r2. When the film thickness d approaches infinity, r2 indeed disappears by the attenuation power of the material. However, in such conditions, the film behaves as a material, and the amplitude of beam r2 is a monotonic decaying function of d from which no absorption peak can be obtained, thus showing that the logic of impedance matching theory is flawed.

Related to the definitions of first and second reflection loss [58] are the definitions of energy for beams r1 and r2 as "it was concluded that the intensity of the reflection loss peak is determined by the energy difference of the two waves" [62] and "the RL peak value is determined by the energy difference of the two waves reflected from the air–absorber interface and the absorber–metal plate interface" [90]. The mistakes originate from the confusion between film and material since the energies of beams r1 and r2 cannot be defined for a film [45, 47]. The reflection coefficient of a metal-backed film is defined as reflection loss since its value in units of dB is related to $|RL|^2$ and therefore to the energy loss of the film [63].

Indeed, the absorption of the film is related to the energy of beam r rather than the energies of beams r1 and r2 [45] and is a result of wave mechanism rather than the attenuation power of the material from the zig-zag optical path traveled by microwaves [9, 17]. It should be noted that the effect of material attenuation on film absorption has already been considered by including the parameter α_P in the wave mechanics theory. When beams r1 and r2 are in phase, the absorption apparently originates from a property unique to the film, which is related in some extent to α_P. This is demonstrated by the fact that even at those positions where the two beams are in phase, the absorption minima of the film are not represented by the attenuation powers of material along the zigzag optical path [17] though the absolute absorption values are increased as d increases [51] and as a consequence the next maximum peak of $|RL(x_1^-)|$ is always lower than the previous maximum. The amplitude of beam r1 is not related to the attenuation power of the material since it is only related to ε_r and μ_r but not to α_P as the interface does not absorb microwaves [63]. Although the amplitude of beam r2 is affected by α_P [9, 65], it is not solely determined by the attenuation power of the material since the amplitude of beam r2 is mainly determined by the angular effect from energy conservation unique to the film, since beam r2 [63] results from the microwaves being reflected back-and-forth in the film [17]. Although the amplitude of beam r2 is an inward spiral in the polar coordinate system [9], it still has its wave form in Cartesian coordinate system if α_P is not vary large [45, 51]. The amplitude of the absorption from the film is suppressed when $\alpha_P d$ becomes large [17]. This is because the behavior of thick film approaches material [42] rather than that the absorption of the film can be attributed to material.

The above problems are connected to the confusion between Z_{in} and Z_M as the former is a property characterizing a film and the latter is a property characterizing a material or an interface. Therefore, the condition that $Z_{in} = Z_0$ for film with RL/dB = - ∞ cannot ensure that $Z_M = Z_0$ represents complete penetration [17, 42, 45, 51, 52]. However, it is assumed in impedance matching theory that the best condition for absorption peaks is $Z_{in}/Z_0 \approx \mu_r/\varepsilon_r = (Z_M/Z_0)^2 \approx 1$ [91]. Where α_P is a property characterizing the attenuation power of material and RL/dB characterizes absorption from metal-backed film. However, despite many attempts [56, 59, 81, 92-98], no correlation has ever been found between these two Z parameters.

As a result of the confusion between film and material, research efforts have been directed wrongly to explore the structural effect of the nano-particles in the material of the interface on absorption [5, 7, 8, 21-41]. Thus, properties of the material such as dielectric and magnetic loss tangents, conductivity, and polarization have been inappropriately attributed as the reasons for absorption peaks in the film [56], which in fact are due to the properties of the film that force its constituent material to absorb the required amount of microwaves rather than the attenuation power of the material to force the film to absorb the required amount. In other words, it is the film forcing the absorbed energy to be distributed among the various absorption mechanisms of the material rather than the absorption mechanisms of the material forcing the film to absorb the required amount of microwaves [9, 17]. The correct research strategy therefore needs to be based on first, how the structures of the material affect the values of ε_r and μ_r and second, how the values of ε_r and μ_r affect the absorption of the film, characterized by RL/dB by wave cancellation from beams r1 and r2, rather than directly on how the structures of the material affect the absorption of the film [66].

In current theory, impedance matching is used to explain the experimental results from absorption of film. The experimental data provided in ref. [56] were used to support the impedance matching theory. By contrast, the data, when used properly, disprove the theory but were still used to support it, a situation representative of current publications. In fact, all the published data support the new theory of microwave absorption based on wave mechanics [9, 17, 42, 45, 64, 65].

For metal-backed film, $V(\mathrm{f1}, x_1)$ can be larger than $V(\mathrm{i}, x_1)$ [63]. The penetrated beam f1 is reflected back-and-forth in the film and returned to open space as beam r2. However, $V(\mathrm{r2}, x_1)$ can be larger than $V(\mathrm{f1}, x_1)$ and even larger than $V(\mathrm{i}, x_1)$, which seems contrary to common sense. What is surprising is that, contrary to the current theory, $V(\mathrm{r2}, x_1)$ achieves its maxima when absorption reaches its maxima [42, 51]. It is wrongly believed that $V(\mathrm{r2}, x_1)$ is minimized when the absorption of the film reaches its maxima [58, 59, 61]. In fact, the expressions of energy conservation for the film, interface, and material are all different [45, 51, 63] and the above correct results have been identified by theoretical research [42, 51] and verified by experimental data. In fact, all the relevant experimental data reported in the literature are consistent with these results. These data have been available for a considerable time and should have provided a source for the development of a more consistent theory before now. However, it is only now, with the application of wave mechanics, that a successful theory has been established and confirmed by experimental data.

3. A case study

Ref. [16] is used here to demonstrate the problems in current theory. Many serious problems were apparent in the introduction of the paper by Hou et al [16] where it was stated 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." (our italics)

Reflection loss *RL*/dB is commonly used to characterize absorption by 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 [18] 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 [19]. This is because the attenuation power of the material is responsible for absorption in a material, while the absorption mechanism of the film originates from wave mechanics [9, 17].

As microwaves travel further into material, no absorption peak is possible, and thus discussion of its bandwidth of the absorption peak in material is irrelevant. The multiple absorption peaks from the film do not originate from the multi-frequency resonance of the material, but from the cancellation of beams r1 and r2 as shown in Fig. 2 [9, 64, 65] thus, the often-discussed quarter-wavelength resonance does not occur. Perfect absorption can be achieved when the two beams are out of phase by π and, at the same time, their amplitudes are equivalent. Indeed, absorbing films have been reported with *RL*/dB < - 40 dB where 99.99% of the incident microwaves have been absorbed.

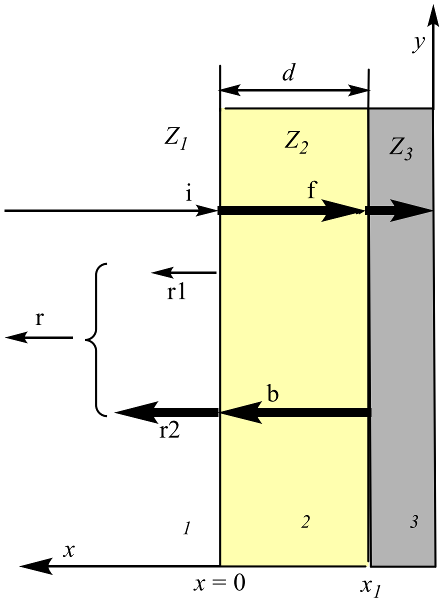

Figure 2 i is the incident beam and r1 is the beam reflected from the interface at $x = 0$. Beams f and b are the total beams reflected back and forth in layer 2. r2 is the transmitted beam from b. Z_l is the characteristic impedance for layer l, and ε_l and μ_l are the permittivity and permeability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

With reference to Figure 2, Akinay et al. [6] listed the following equations:

$$RL(x=0)/dB = 20\log\left|\Gamma_{12}\right| \tag{23}$$

$$s_{11}(x=0) = \frac{Z_{in}(x=0) - Z_1}{Z_{in}(x=0) + Z_1} \tag{24}$$

$$Z_{in}(x=0) = Z_2 \frac{Z_3 + Z_2 \tanh(j2\pi\nu \frac{\sqrt{\varepsilon_2\mu_2}z'}{c})}{Z_2 + Z_3 \tanh(j2\pi\nu \frac{\sqrt{\varepsilon_2\mu_2}z'}{c})} \tag{25}$$

where ν is frequency and c is the speed of light in vacuum. However, all these three above equations were inappropriate [50], because Γ_{12} in Eq. (23) is not the reflection coefficient Γ_{11} for layer 2 at $x = 0$. The input impedance at $x = 0$ can be obtained from Eq. (26) if no incident microwaves to the interface at $x = x_1$ [52].

$$Z_{in}(x=0) = Z_2 \frac{Z_3 + Z_2 \tanh(j2\pi\nu \frac{\sqrt{\varepsilon_2\mu_2}d}{c})}{Z_2 + Z_3 \tanh(j2\pi\nu \frac{\sqrt{\varepsilon_2\mu_2}d}{c})} \tag{26}$$

However, Eq. (26) cannot be applied to the intermediate layer shown in Fig. 2 since there are incident microwaves from both sides of the layer [50]. Equation (26) can be applied to a single layered film without metal-back where $Z_3 = Z_1$ [19, 52, 80, 99]. For metal-backed film, $Z_1 \neq Z_3 = 0$, and then

$$Z_{in}(x=0) = Z_2 \tanh(j2\pi\nu \frac{\sqrt{\varepsilon_2\mu_2}d}{c}) \tag{27}$$

Equation (24) would only be correct if Eq. (26) were used for a film without metal back, and if Eq. (27) were used for metal-backed film. For metal-backed film, the maximum absorption is indeed achieved when $Z_{in}(x = 0) = Z_1$ [44]. But this result does not validate impedance matching theory because the maximum penetration is ensured by $Z_2 = Z_1$ instead of $Z_{in}= Z_1$ [52]. It cannot be explained in impedance matching theory why all the incident microwaves are absorbed while not all of them enter the film and also why the condition that $Z_{in} = Z_1$ cannot be achieved for most of the absorption peaks. On the other hand, there is no absorption peak when $Z_2 = Z_1$. However, the reasons can be easily found from wave mechanical theory and not by the reason claimed by Hou et al [16] that Z_{in} is a complex number and Z_1 for open space is a real number. It was also claimed that impedance matching can be achieved when $Z_{in}/Z_1 \approx \mu_2/\varepsilon_2 = Z_2^2/Z_1 = 1$ [91] where Z_{in} is a property of the film and Z_2 is a property of the material. The confusion between the two alternative conditions, $Z_{in} = Z_1$ and $Z_2 = Z_1$, mirrors the confusion between the film and the material and between the interface in the film and in its isolated state [45].

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" [16] and "In this system, Fe_3O_4/CNT is a typical absorption material with good impedance matching and attenuation constant" [5]. Both these statements need correcting because absorption from the film is not determined by penetration and the attenuation of material, but by wave mechanics [42].

Impedance matching theory has been developed to explain the absorption peaks from the film. However, there is no peak formed if $Z_2 = Z_1$ because at these circumstances the film behaves as a material [45]. The interface at $x = 0$ vanishes and beam r1 does not exist so that RL is only determined by the amplitude of beam r2 [9]. It can be demonstrated that the minima of RL/dB can be achieved when $|Z_{in} - Z_1|$ reaches its maxima instead of its minima because the mathematics of complex numbers is different from that of real numbers [43, 48].

The impedance matching coefficients represented by Eqs. (4) and (5) in ref. [16], not quoted here, are for the film and for the interface, respectively [46] and they are equivalent to impedance matching theory because when these coefficients approach 1, the conditions $Z_{in} = Z_1$ and $Z_2 = Z_1$ are fortuitously achieved, despite confusing the film with the material, and the film with the interface.

The thin film behaves as the film and the thick film behaves as the material [42] since the attenuation power of the material overrides the angular effect of the film when the film thickness d is large [51]. The behavior of the film approaches that of the material when d become larger since then the amplitude of beam r2 represented by $|R_2|$ becoming a monotonic decaying function and the amplitude of oscillation for the absorption of the film is suppressed by the attenuation power of material. However, just as energy penetration cannot be defined for the film [45], the absorption of film cannot be attributed to the attenuation power of the material along the zigzag optical path because the film forces its material to absorb the required amount of microwave energy [17].

Equation (7) in ref. [16] is listed below as Eq. (28)

$$d = \frac{(2m+1)c}{n\nu}(\frac{1}{4}+\Delta), \qquad (m=1,2,3...) \tag{28}$$

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 11 cases listed in ref. [48], only one case with $\varepsilon_2 > \mu_2$ for metal-backed film obeys this. For example, the absorption peaks for the film without a metal back occur at $d = \lambda_l/2$, [47, 48, 50] which does not obey the quarter-wavelength theory. It was claimed in ref. [16] that refs. [77, 100] identified this result, but there was no such conclusion in these two references.

It is obvious therefore that the quarter-wavelength theory should be replaced by the inverse relationship between ν and d when ε_2 and μ_2 are not sensitive to frequency [49]. In the quarter-wavelength theory it is presumed that peaks from the film are formed from the resonances of the material [16] rather than by the wave cancellation of beams r1 and r2. However, resonance peaks should be much sharper and stronger. The resonance frequencies of the material cannot shift with the change of film thickness d while the frequency of an absorption peak of a film shifts if d is different [49]. Thus, the term “quarter-wavelength resonance” is misleading. The mechanism of absorption peak formation is wave cancellation instead of impedance matching theory [48, 51]. The mechanism of the so-called “quarter-wavelength theory” is neither wave cancelation nor resonance from material. This “quarter-wavelength theory” is about the shift of the position of the absorption peak for the film and its mechanism is governed by the inverse relationship when both ε_r and μ_r are invariant with respect to frequency [49].

Since there are absorption peaks at $d \approx \lambda_l/2$, all the equations in ref. [16] based on the above Eq. (28) give rise to incorrect conclusions which are revealed mathematically in Appendix 1. There are other unsuccessful attempts, also based on the wrong impedance matching theory, to explain why absorption peaks occur in different positions from those predicted by the quarter-wavelength theory [74, 75]. But when a theory is wrong, it is wrong in every aspect, and even when it is dominant in modern research, this does not make it right. Thus, this searching for new conditions which are intended to predict the shifts in the positions of absorption peaks are not to the point and are tedious, and at the same time, cannot achieve positive results [45, 49].

It was concluded in [16] from Eq. (28) 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 [45, 48] since there is no absorption peak when $\varepsilon_2 = \mu_2$. It was claimed wrongly from the proof in [16] 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 $\lambda_2/4$” [16]. But from the wave mechanics theory, it is clearly shown that these conclusions are invalid as the shifts in the actual absorption peak position always occur when the phase differences between beams r1 and r2 are larger than $(2m + 1)\pi$ [9, 50, 66]. From the angular effect of the film, $|RL|$ decreases from the phase difference of $2m\pi$ to $(2m + 1)\pi$ and increases from $(2m + 1)\pi$ to $(2m + 2)\pi$ but the attenuation power of the material decreases $|RL|$ throughout the whole process when d increases. Thus, the minima of $|RL|$ can only be achieved at positions where the phase differences between beams r1 and r2 are 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" [16] is incorrect since all the incident microwaves on metal are completely reflected while high values for 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" [16], which is also untrue. When the reflection coefficient $RL = 0$, beam r has vanished by cancellation, and a standing wave is impossible since the only wave that exists is beam i propagating in one direction. On the other hand, absorption deviation Δ is irrelevant to the standing wave ratio. It was claimed by Hou et al [16] 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 [67-73] as the absorption peaks originate from the wave cancellation between beams r1 and r2 rather than from wave superposition between beams i and r. In this context, the term wave superposition also mistakenly refers to their energy instead of the amplitude of the beams [45, 47], a common mistake [62, 101]. It should be noted that the standing wave from beams i and r is completely different from the result of the wave cancellation from beams r1 and r2.

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" [16]. But these conclusions were wrong because Eq. (13) and Eq. (14) were derived from Eq. (28).

In fact, the absorption peak shifts *Δ* are irrelevant to the occurrence of multiple absorption peaks and their intensities as they are mainly related to the balance of angular effects from film and attenuation power from material, or other phase effects from the amplitudes of individual beams [66].

It is often believed that theories are more likely to be wrong than experimental results, but this judgement is only superficially true [102]. When the conclusions from theory and experiments are in conflict, the conditions under which the experimental data were obtained needs to be carefully checked before the theory should be investigated [103]. Theory is a high level recapitulate of different experimental phenomena. Theory is the real nature abstracted from different experimental phenomena. The purpose of experiment is to achieve theoretical understanding. Thus, theory makes it easy to grasp different experimental phenomena.

In the paper of Hou et al. [16], experimental data were presented to support their result from wrong equations. Another wrong equation for *Δ* was also presented by Li et al. [75] and much experimental data were presented in their paper to support it. However, it has been shown that such support is not achievable [49]. It was claimed that "Fig. 4 shows the frequency dispersion of

ε_r', ε_r'' and Tanδ of ideal absorbing materials with different thickness" [16]. This wrong result obtained shows that the method to obtain the results is wrong. Experimental results supporting the theory that ε_r is a function of film thickness d have also been reported [74] and also with the conclusion that "The measured permittivity and permeability can be affected by many factors such as the thickness of the tested sample consisting of paraffin and absorbent, and the content and orientation of absorbent" [76]. The experimental result that ε_r and μ_r were functions of film thickness was also assumed to be true using simulations from Hou et al. [77]. However, permittivity and permeability are distributive properties of material which are irrelevant to the thickness of film [52] and all the theories such as the transmission line theory for *RL* are established from this simple assumption. Those claims based on the wrong experimental methods do not only show that film and material are confused in modern research, but also show that experimental results can be wrong when they conflict with correct theory. Any experimental design for a perpetual machine cannot work since the design conflicts to the theoretical law, the second law of thermodynamics. Currently, there are many different views on the importance of theoretical research. While many believe that theoretical research is an important part of scientific work, others believe that experimental research should be paramount since they take such results as scientific facts. It is our view that the importance of experimental research has become over-emphasized and that the importance of new theories has become downgraded [10]. Theory is not just an explanation of experiment phenomena. It is the level we have achieved in understanding the nature.

4. Conclusions

The main theories in current research concerned with microwave absorption are inadequate. Although the correct theory has been rediscovered from transmission line theory and been developed further to reveal the physics of the film, it has not attracted the attention of researchers and papers using the wrong theories continue to be published. The problems in recent published papers have been analyzed 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.

5. Appendix 1 The problems in the mathematical derivations in ref. [16]

A1 Theoretical background

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

$$\sqrt{\varepsilon_2\mu_2} = \sqrt{(\varepsilon_2^{'} - j\varepsilon_2^{''})(\mu_2^{'} - j\mu_2^{''})} = \mathrm{Re}(\sqrt{\varepsilon_2\mu_{r2}}) - j\,\mathrm{Im}(\sqrt{\varepsilon_2\mu_2}) \tag{29}.$$

Let *k* and the refraction index *n* be defined as

$$\begin{aligned} n &= |\mathrm{Re}(\sqrt{\varepsilon_2\mu_2})| > 0 \\ k &= |\mathrm{Im}(\sqrt{\varepsilon_2\mu_2})| > 0 \end{aligned} \tag{30}.$$

We obtain

$$\sqrt{\varepsilon_2\mu_2} = n - jk \tag{31}$$

$$t = \left|\tan\delta_{\sqrt{\varepsilon_2\mu_2}}\right| = \frac{k}{n} = \frac{|\mathrm{Im}(\sqrt{\varepsilon_2\mu_2})|}{|\mathrm{Re}(\sqrt{\varepsilon_2\mu_2})|} \tag{32}.$$

From wave mechanics [47] with layer 1 as a reference open space

$$\frac{1}{\lambda_2} = \frac{\nu\,|\mathrm{Re}(\sqrt{\varepsilon_2\mu_2})|}{c} = \frac{\nu}{\upsilon} \tag{33}$$

$$\frac{c}{\upsilon} = \left|\mathrm{Re}(\sqrt{\varepsilon_2 \mu_2})\right| = \frac{\lambda_1}{\lambda_2} \tag{34}$$

$$\lambda_2 = \frac{\lambda_1}{\left|\mathrm{Re}(\sqrt{\varepsilon_2 \mu_2})\right|} = \frac{\lambda_1}{n} \tag{35}$$

From the properties of propagating waves, we define [52, 80]

$$\alpha_j = \frac{4\pi\nu\,|\,\mathrm{Re}(\sqrt{\varepsilon_2 \mu_2})\,|}{c} = \frac{4\pi\nu n}{c} = \frac{4\pi}{\lambda_2} = \frac{4\pi n}{\lambda_1} \tag{36}$$

$$\alpha_P = \frac{4\pi\nu\,|\,\mathrm{Im}(\sqrt{\varepsilon_2 \mu_2})\,|}{c} = \frac{4\pi\nu k}{c} = \frac{4\pi k}{\lambda_1} \tag{37}$$

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

$$A = -\ln\left|\, e^{-4\pi j \frac{\nu\sqrt{\varepsilon_2 \mu_2}}{c} d} \,\right| = -\ln\left|\, e^{-\alpha_P d - j\alpha_j d} \,\right| = \alpha_P d \tag{38}$$

A2 The problems in the mathematical derivations of equation (8) in ref. [16]

From Eq. (27)

$$\frac{Z_{in}}{Z_2} = \frac{1 - e^{-j4\pi\nu\frac{\sqrt{\varepsilon_2 \mu_2} d}{c}}}{1 + e^{-j4\pi\nu\frac{\sqrt{\varepsilon_2 \mu_2} d}{c}}} \tag{39}$$

$$\frac{Z_2 - Z_{in}}{Z_2 + Z_{in}} = e^{-j4\pi\nu\frac{\sqrt{\varepsilon_2 \mu_2} d}{c}} \tag{40}$$

$$j4\pi\nu\frac{\sqrt{\varepsilon_2 \mu_2}\, d}{c} = -\ln\frac{Z_2 - Z_{in}}{Z_2 + Z_{in}} \tag{41}$$

In ref. [16], Eq. (28) has been inserted into Eq. (41)

$$j4\pi\nu\frac{\sqrt{\varepsilon_2\mu_2}}{c}\frac{(2m+1)c}{n\nu}(\frac{1}{4}+\Delta)=-\ln\frac{Z_2-Z_{in}}{Z_2+Z_{in}} \tag{42}$$

However, Δ cannot be obtained from Eq. (42) since Z_{in} is defined from Δ. The minima of $|RL|$ are not only related to the value of $|Z_{in} - Z_1|$ but also to that of $|Z_{in} + Z_1|$ and thus $Z_{in} = Z_1$ is not always achievable at the minimum positions of $|RL|$. What is more, the minima of $|RL|$ can be achieved at the maxima of $|Z_{in} - Z_1|$ [48]. Thus, Eq. (8) in ref. [16] cannot be obtained.

Preprints

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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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