# Corrections of Common Errors in Current Theories of Microwave Absorption Caused by Confusing Film and Material

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

[1]College of Chemistry and Chemical Engineering, Shenyang Normal University, Shenyang, P. R. China,110034, yingliusd@163.com (Ying Liu), yueliusd@163.com (Yue Liu)

[2]School of Chemistry, The University of Reading, Whiteknights, Reading RG6 6AD, UK, m.g.b.drew@reading.ac.uk

* Corresponding author

## Abstract

Film and material have been confused in the current theory of microwave absorption, which has led to some specific problems in publications and common errors in current theories. These specific problems and errors have been identified and corrected by using wave mechanics to develop new theories to describe the physics of microwave absorption in film.

## Key words

Microwave absorption; concept clarification; film physics.

## 1. Introduction

Current theories of microwave absorption have confused film with material [1, 2] though the two are distinctively different. This confusion has resulted in the film parameter reflection loss *RL* being used to characterize the absorption of material [1-26] while it should be used to characterize the absorption from metal-backed film other than from material [27-29]. 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 been directed into developing wrong concepts such as those involving impedance matching theory, the quarter wavelength theory, and the wrong absorption mechanism for film [27, 28, 30-34]. 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 [27, 31, 33, 35], which has been shown to interpret experimental data more accurately than current theories [27-29, 31, 36].

In this work, exemplified from recent publications [37-44] the problems from confusing characteristic and input impedances [36], and interface and film [30] have been addressed. The absorption of metal-backed film can be characterized by the reflection coefficient of the film *RL* in units of dB. However, by confusing film with material, the reflection coefficient of interface $R_M$ has been used in publications to characterize the absorption in film. This is incorrect since the interface does not absorb microwaves [45]. It should be noted that the absorption mechanism of the film involves wave mechanics rather than impedance matching theory [27-30, 32, 33].

https://doi.org/10.32388/QQ1MFF

## 2. Discussions

### 2.1 Theoretical background

Figure 1 shows a film without a metal back with thickness *d*.

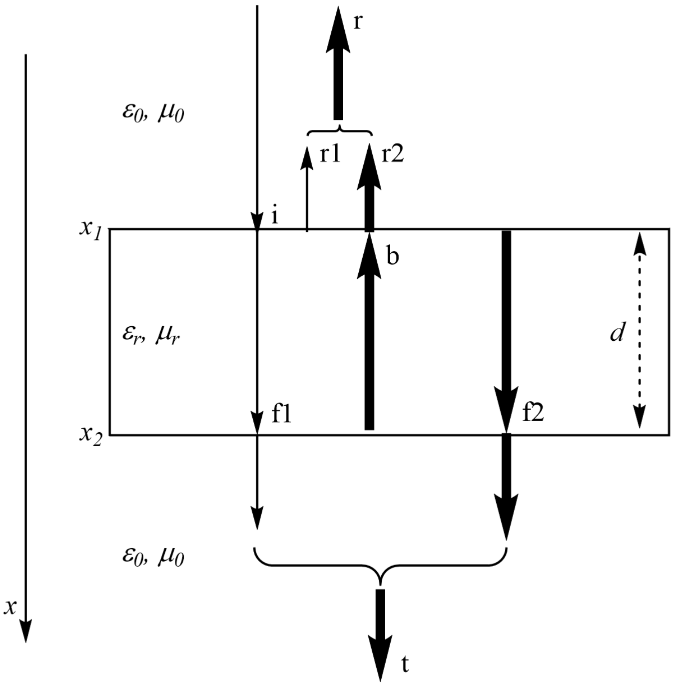

Fig. 1 Film with thickness *d* from material with relative electric permittivity $\varepsilon_r$ and

magnetic permeability $\mu_r$; $\varepsilon_0$ and $\mu_0$ 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 voltages for beams i, r1, and r2 at time *t* and position $x \le x_1$ are [46]:

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

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

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

*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. $\nu$ is frequency, and $\lambda$ is the wavelength in open space. c is the velocity of light in vacuum. For the beams within the film:

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

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

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

$\lambda_M$ is the wavelength within the film; $\alpha_P$ is the power attenuation coefficient and $\alpha_j$ is the wave propagation coefficient. For beam t:

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

The microwave absorption $A(\nu)$ from a device at frequency $\nu$ 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 $R(\nu)$ and transmitted $T(\nu)$ from the film of thickness $d$ are related to the $s$ parameters [45].

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

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

For a film with a metal back, $s_{21}(\nu, d) = 0$, and $s_{11}(\nu, d)$ is defined as reflection loss $RL(\nu, d)$ 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 [45, 47]. $Z_M$ is the characteristic impedance for a device [33, 46, 48], and it is also the characteristic impedance for the material of the normal film.

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 [37, 38, 40] which are related to common errors in current theories. For an interface, $Z_{in}(\nu, d)$ is reduced to $Z_M$ [36]. The film parameters *RL* and $Z_{in}$ are related to film thickness. However, their values have been quoted in ref. [38] 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 [2, 37, 38, 41, 49-52] the input and the characteristic impedances are only vaguely defined as impedance. In addition, $Z_0$ is sometimes wrongly defined as input impedance [53-55]. 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 [36].

This specific mistake regarding $Z_{in}$ and $Z_M$ is related to the common confusion between film and material in impedance matching theory [27, 29, 36, 56]. However, such confusion has been used to claim that the confusion did not occurr in the current theory of impedance matching [42].

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. [38] 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. [39] 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 [30, 34, 47]. 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 microwaves [34, 45], 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 [39] to characterize microwave absorption, which is incorrect because an interface does not absorb microwaves [34, 45]. 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. [37] 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 the interface and film have been mixed up, but also because, although $\gamma_M$ is the $s_{21}$ for the interface, the interface does not absorb microwaves, and therefore Eq. (22) should be used rather than Eq. (10) [34, 45] 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 [30, 47]. These mistakes led to the wrong conclusion, as stated in [57], 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 [36].

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 [30, 32, 58]. Thus, the conclusion quoted above from ref. [57] cannot be justified.

The confusion between $Z_{in}$ of the film and $Z_M$ of the material [36] represents the confusion between film and material [27] which leads to the wrong impedance matching theory [30]. 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 [42]. Although the predictions from impedance matching theory can sometimes appear consistent with experimental results, predictions can be completely different in other circumstances [32]. Even in those rare cases where the predictions from impedance matching theory are consistent with experimental results, the logic underlying the reasoning is still wrong [27, 34].

### 2.3 Common errors

Despite the specific errors discussed above, common problems in the current theories 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 [38, 50] where first and second reflection losses have been defined from beams r1 and r2, respectively [40]. Thus, the disappearance of both beams r1 and r2 simultaneously is attributed to maximum absorption from the film [40-43] though the actual absorption mechanism for absorption peaks should be described by the cancellation of the two beams [31-33, 59, 60] 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 [27, 28, 33, 47]. When all the incident microwave enters the film, as required by impedance matching theory as a condition for the absorption peak, 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 [40] 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" [44] 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" [61]. The mistakes originate from the confusion between film and material since the energies of beams r1 and r2 cannot be defined for a film [30, 62]. 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 thus is related to the energy loss of the film [45].

Indeed, the absorption of the film is related to the energy of beam r rather than the energies of beams r1 and r2 [30] and is a result of wave superposition rather than the attenuation power of the material from the zig-zag optical path traveled by microwaves [27, 31]. It should be noted that the effect of material attenuation on film absorption has already been considered by including the parameter $\alpha_P$ 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 $\alpha_P$. The amplitude of beam r1 is not related to the attenuation power of the material since it is only related to $\varepsilon_r$ and $\mu_r$, but not to $\alpha_P$, as the interface does not absorb microwaves [45]. Although the amplitude of beam r2 is related to $\alpha_P$ [31, 60], it is not solely determined by the attenuation power of the material since the amplitude of beam r2 is mainly determined by energy conservation unique to the film, since beam r2 [45] results from the microwaves being reflected back-and-forth in the film [27, 29].

As a result of the confusion between film and material, research efforts have been directed wrongly to explore the interface structure effect of the nano-particles from the material on absorption [1, 4-26]. 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 [38], 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. 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 [27, 31]. The correct research strategy therefore needs to be based on first, how the structures of the material affect the values of $\varepsilon_r$ and $\mu_r$, and second, how the values of $\varepsilon_r$ and $\mu_r$ 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 [47].

In current theory, impedance matching is used to explain the experimental results from absorption of film. The experimental data provided in ref. [38] 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 [27, 28, 30, 31, 59, 60].

For metal-backed film, $V(\text{f1}, x_1)$ can be larger than $V(\text{i}, x_1)$ [45]. The penetrated beam f1 is reflected back-and-forth in the film and returned to open space as beam r2. However, $V(\text{r2}, x_1)$ can be larger than $V(\text{f1}, x_1)$ and even larger than $V(\text{i}, x_1)$, which seems contrary to common sense. What is surprising is that, contrary to the current theory, $V(\mathrm{r}2, x_1)$ achieves its maxima when absorption reaches its maxima [28, 33]. It is wrongly believed that $V(\mathrm{r}2, x_1)$ is minimized when the absorption of the film reaches its maxima [40, 41, 43]. In fact, the expressions of energy conservation for the film, interface, and material are all different [30, 33, 45] and the above correct results have been identified by theoretical research [28, 33] 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. Conclusions

Film and material have been confused in the current theory of microwave absorption, which led to many problems and errors with the establishment of the wrong theories of impedance matching, the quarter wavelength, and the wrong absorption mechanism of the film. Some of the specific problems and common errors have been analyzed in this work based on the new theory of wave mechanics for microwave absorption film.

## 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

## References

[1] J. Cheng, H. Zhang, M. Ning, H. Raza, D. Zhang, G. Zheng, Q. Zheng, R. Che, Emerging Materials and Designs for Low- and Multi-Band Electromagnetic Wave Absorbers: The Search for Dielectric and Magnetic Synergy?, Advanced Functional Materials, 32 (2022) 2200123.
[2] Y. Akinay, U. Gunes, B. Çolak, T. Cetin, Recent progress of electromagnetic wave absorbers: A systematic review and bibliometric approach, ChemPhysMater, 2 (2023) 197-206.
[3] Z. Ma, K. Yang, D. Li, H. Liu, S. Hui, Y. Jiang, S. Li, Y. Li, W. Yang, H. Wu, Y. Hou, The Electron Migration Polarization Boosting Electromagnetic Wave Absorption Based on Ce Atoms Modulated yolk@shell FexN@NGC, Advanced Materials, (2024) 2314233.
[4] Z. Zhao, Y. Qing, L. Kong, H. Xu, X. Fan, J. Yun, L. Zhang, H. Wu, Advancements in Microwave Absorption Motivated by Interdisciplinary Research, Advanced Materials, 36 (2023) 2304182
[5] Q. An, D. Li, W. Liao, T. Liu, D. Joralmon, X. Li, J. Zhao, A Novel Ultra-Wideband Electromagnetic-Wave-Absorbing Metastructure Inspired by Bionic Gyroid Structures, Advanced Materials, 35 (2023) 2300659.

[6] G. Chen, H. Liang, J. Yun, L. Zhang, H. Wu, J. Wang, Ultrasonic Field Induces Better Crystallinity And Abundant Defects at Grain Boundaries to Develop Cus Electromagnetic Wave Absorber, Advanced Materials, 35 (2023) 2305586.
[7] J. Ma, J. Choi, S. Park, I. Kong, D. Kim, C. Lee, Y. Youn, M. Hwang, S. Oh, W. Hong, W. Kim, Liquid Crystals for Advanced Smart Devices with Microwave and Millimeter-Wave Applications: Recent Progress for Next-Generation Communications, Advanced Materials, (2023).
[8] J. Yan, Q. Zheng, S.P. Wang, Y.Z. Tian, W.Q. Gong, F. Gao, J.J. Qiu, L. Li, S.H. Yang, M.S. Cao, Multifunctional Organic–Inorganic Hybrid Perovskite Microcrystalline Engineering and Electromagnetic Response Switching Multi-Band Devices, Advanced Materials, 35 (2023) 2300015.
[9] B. Zhao, Z. Yan, Y. Du, L. Rao, G. Chen, Y. Wu, L. Yang, J. Zhang, L. Wu, D.W. Zhang, R. Che, High-Entropy Enhanced Microwave Attenuation in Titanate Perovskites, Advanced Materials, 35 (2023) 2210243.
[10] I. Huynen, N. Quiévy, C. Bailly, P. Bollen, C. Detrembleur, S. Eggermont, I. Molenberg, J.M. Thomassin, L. Urbanczyk, T. Pardoen, Multifunctional hybrids for electromagnetic absorption, Acta Materialia, 59 (2011) 3255-3266.
[11] W. Yang, Y. Zhang, G. Qiao, Y. Lai, S. Liu, C. Wang, J. Han, H. Du, Y. Zhang, Y. Yang, Y. Hou, J. Yang, Tunable magnetic and microwave absorption properties of Sm1.5Y0.5Fe17-xSix and their composites, Acta Materialia, 145 (2018) 331-336.
[12] R.H. Fan, B. Xiong, R.W. Peng, M. Wang, Constructing Metastructures with Broadband Electromagnetic Functionality, Adv Mater, 32 (2020) 1904646.
[13] L. Liang, W. Gu, Y. Wu, B. Zhang, G. Wang, Y. Yang, G. Ji, Heterointerface Engineering in Electromagnetic Absorbers: New Insights and Opportunities, Adv Mater, 34 (2022) 2106195.
[14] Q. Liu, Q. Cao, H. Bi, C. Liang, K. Yuan, W. She, Y. Yang, R. Che, CoNi@SiO2 @TiO2 and CoNi@Air@TiO2 Microspheres with Strong Wideband Microwave Absorption, Adv Mater, 28 (2016) 486-490.
[15] H. Sun, R. Che, X. You, Y. Jiang, Z. Yang, J. Deng, L. Qiu, H. Peng, Cross-stacking aligned carbon-nanotube films to tune microwave absorption frequencies and increase absorption intensities, Adv Mater, 26 (2014) 8120–8125.
[16] Z. Wu, H.W. Cheng, C. Jin, B. Yang, C. Xu, K. Pei, H. Zhang, Z. Yang, R. Che, Dimensional Design and Core-Shell Engineering of Nanomaterials for Electromagnetic Wave Absorption, Adv Mater, 34 (2022) 2107538.
[17] C.M. Watts, X. Liu, W.J. Padilla, Metamaterial electromagnetic wave absorbers, Advanced Materials, 24 (2012) OP98-OP120.
[18] H. Yao, J. Yang, H. Li, J. Xu, K. Bi, Optimal design of multilayer radar absorbing materials: a simulation-optimization approach, Advanced Composites and Hybrid Materials, 6 (2023) 43.
[19] N. Yang, S. Xu, D. Zhang, C. Xu, Super-Wideband Electromagnetic Absorbing TiC/SiOC Ceramic/Glass Composites Derived from Polysiloxane and Titanium Isopropoxide with Low Thickness (<1 mm), Advanced Engineering Materials, 25 (2023) 2201508.
[20] W. Zhou, L. Long, G. Bu, Y. Li, Mechanical and Microwave-Absorption Properties of Si3N4Ceramic with SiCNFs Fillers, Advanced Engineering Materials, 21 (2018) 1800665.
[21] M.S. Cao, X.X. Wang, M. Zhang, J.C. Shu, W.Q. Cao, H.J. Yang, X.Y. Fang, J. Yuan, Electromagnetic Response and Energy Conversion for Functions and Devices in Low-Dimensional Materials, Advanced Functional Materials, 29 (2019) 1807398.
[22] P. Liu, Y. Wang, G. Zhang, Y. Huang, R. Zhang, X. Liu, X. Zhang, R. Che, Hierarchical Engineering of Double-Shelled Nanotubes toward Hetero-Interfaces Induced Polarization and Microscale Magnetic Interaction, Advanced Functional Materials, 32 (2022) 2202588.

[23] P. Liu, G. Zhang, H. Xu, S. Cheng, Y. Huang, B. Ouyang, Y. Qian, R. Zhang, R. Che, Synergistic Dielectric–Magnetic Enhancement via Phase‐Evolution Engineering and Dynamic Magnetic Resonance, Advanced Functional Materials, 33 (2023) 2211298.
[24] J.C. Shu, M.S. Cao, M. Zhang, X.X. Wang, W.Q. Cao, X.Y. Fang, M.Q. Cao, Molecular Patching Engineering to Drive Energy Conversion as Efficient and Environment‐Friendly Cell toward Wireless Power Transmission, Advanced Functional Materials, 30 (2020) 1908299.
[25] Y. Xia, W. Gao, C. Gao, A Review on Graphene‐Based Electromagnetic Functional Materials: Electromagnetic Wave Shielding and Absorption, Advanced Functional Materials, 32 (2022) 2204591.
[26] F. Ye, Q. Song, Z. Zhang, W. Li, S. Zhang, X. Yin, Y. Zhou, H. Tao, Y. Liu, L. Cheng, L. Zhang, H. Li, Direct Growth of Edge-Rich Graphene with Tunable Dielectric Properties in Porous Si3N4 Ceramic for Broadband High-Performance Microwave Absorption, Advanced Functional Materials, 28 (2018) 1707205.
[27] Y. Liu, Y. Liu, M.G.B. Drew, Wave mechanics of microwave absorption in films - Distinguishing film from material, Journal of Magnetism and Magnetic Materials, 593 (2024) 171850.
[28] Y. Liu, Y. Ding, Y. Liu, M.G.B. Drew, Unexpected Results in Microwave Absorption -- Part 1: Different absorption mechanisms for metal-backed film and for material, Surfaces and Interfaces, 40 (2023) 103022.
[29] Y. Liu, X. Yin, D.M.G.B. Drew, Y. Liu, Microwave absorption of film explained accurately by wave cancellation theory, Physica B: Condensed Matter, 666 (2023) 415108.
[30] Y. Liu, M.G.B. Drew, Y. Liu, A physics investigation of impedance matching theory in microwave absorption film— Part 2: Problem analyses, Journal of Applied Physics, 134 (2023) 045304.
[31] Y. Liu, Y. Liu, M.G.B. Drew, The wave mechanics for microwave absorption film-Part 1: A short review, 10.21203/rs.3.rs-3256944/v1, Research Square, (2023).
[32] Y. Liu, Y. Liu, M.G.B. Drew, A theoretical investigation of the quarter-wavelength model-part 2: verification and extension, Physica Scripta, 97 (2022) 015806.
[33] Y. Liu, Y. Liu, M.G.B. Drew, A Re-evaluation of the mechanism of microwave absorption in film – Part 2: The real mechanism, Materials Chemistry and Physics, 291 (2022) 126601.
[34] Y. Liu, M.G.B. Drew, Y. Liu, A theoretical exploration of impedance matching coefficients for interfaces and films, Applied Physics A, 130 (2024) 212.
[35] Y. Liu, Y. Liu, M.G.B. Drew, The wave mechanics for microwave absorption film-Part 3: Film with multilayers, 10.21203/rs.3.rs-3256342/v1, Research Square, (2023).
[36] Y. Liu, M.G.B. Drew, H. Li, Y. Liu, An experimental and theoretical investigation into methods concerned with "reflection loss" for microwave absorbing materials, Materials Chemistry and Physics, 243 (2020) 122624.
[37] S. Saikia, H. Saikia, N.S. Bhattacharyya, Revertible wideband hydrogel-based meta-structure absorber, Applied Physics A, 130 (2024) 189.
[38] P.P. Singh, A.K. Dash, G. Nath, Dielectric characterization analysis of natural fiber based hybrid composite for microwave absorption in X-band frequency, Applied Physics A, 130 (2024) 171.
[39] Y. Prima Hardianto, R. Nur Iman, A. Hidayat, N. Mufti, N. Hidayat, S. Sunaryono, T. Amrillah, W. Ari Adi, A. Taufiq, A Facile Route Preparation of Fe3O4/MWCNT/ZnO/PANI Nanocomposite and its Characterization for Enhanced Microwave Absorption Properties, ChemistrySelect, 9 (2024) e202304748.
[40] W. Andriyanti, M.A. Choir Hidayati Nur, D.L. Puspitarum, T. Sujitno, H. Suprihatin, S. Purwanto, E. Suharyadi, Microstructures, magnetic properties and microwave absorption of ion-implanted bismuth ferrite thin films, Physica B: Condensed Matter, 676 (2024) 415690.
[41] D. Zuo, Y. Jia, J. Xu, J. Fu, High-Performance Microwave Absorption Materials: Theory, Fabrication, and Functionalization, Industrial & Engineering Chemistry Research, 62 (2023) 14791-14817.

[42] A.A. Abu Sanad, M.N. Mahmud, M.F. Ain, M.A.B. Ahmad, N.Z.B. Yahaya, Z. Mohamad Ariff, Theory, Modeling, Measurement, and Testing of Electromagnetic Absorbers: A Review, physica status solidi (a), 221 (2024) 2300828.
[43] M. Cao, C. Han, X. Wang, M. Zhang, Y. Zhang, J. Shu, H. Yang, X. Fang, J. Yuan, Graphene nanohybrids: excellent electromagnetic properties for the absorbing and shielding of electromagnetic waves, Journal of Materials Chemistry C, 6 (2018) 4586-4602.
[44] T. Wang, R. Han, G. Tan, J. Wei, L. Qiao, F. Li, Reflection loss mechanism of single layer absorber for flake-shaped carbonyl-iron particle composite, Journal of Applied Physics, 112 (2012) 104903.
[45] Y. Liu, Y. Liu, M.G.B. Drew, A Re-evaluation of the mechanism of microwave absorption in film – Part 1: Energy conservation, Materials Chemistry and Physics, 290 (2022) 126576.
[46] Y. Liu, M.G.B. Drew, Y. Liu, Chapter 4: Fundamental Theory of Microwave Absorption for Films of Porous Nanocomposites: Role of Interfaces in Composite-Fillers, in: S. Thomas, C. Paoloni, A.R. Pai (Eds.) Porous Nanocomposites for Electromagnetic Interference Shielding, Elsevier, 2024, pp. 59 - 90.
[47] Y. Liu, Y. Ding, Y. Liu, M.G.B. Drew, Unexpected results in Microwave absorption -- Part 2： Angular effects and the wave cancellation theory, Surfaces and Interfaces, 40 (2023) 103024.
[48] Y. Liu, H. Yu, M.G.B. Drew, Y. Liu, A systemized parameter set applicable to microwave absorption for ferrite based materials, Journal of Materials Science: Materials in Electronics, 29 (2018) 1562-1575.
[49] X. Guo, Z. Wu, J. Chang, D. Niu, A. Ren, Y. Xu, P. Li, H. Zhou, Construction of the N, S co-doped C/FeS2 materials for low thickness and high-efficiency microwave absorption, Surfaces and Interfaces, 46 (2024).
[50] H. Zhao, X. Ma, X. Song, H. Zheng, H. Yan, Study on the optimization of wave absorption of glass substrate indium tin oxide film composite building materials, Journal of Materials Science: Materials in Electronics, 35 (2024).
[51] B. Zhang, J. Cui, D. He, J. Zhang, L. Yang, W. Zhu, H. Lv, Transparent electromagnetic absorption film derived from the biomass derivate, Journal of Materials Science & Technology, 185 (2024) 98-106.
[52] S. Tabar Maleki, M. Babamoradi, Microwave absorption theory and recent advances in microwave absorbers by polymer-based nanocomposites (carbons, oxides, sulfides, metals, and alloys), Inorganic Chemistry Communications, 149 (2023) 110407.
[53] Y. Liu, S. Zhang, X. Su, J. Xu, Y. Li, Enhanced microwave absorption properties of Ti3C2 MXene powders decorated with Ni particles, Journal of Materials Science, 55 (2020) 10339-10350.
[54] J. Qiao, D. Xu, L. Lv, X. Zhang, F. Wang, W. Liu, J. Liu, Self-Assembled ZnO/Co Hybrid Nanotubes Prepared by Electrospinning for Lightweight and High-Performance Electromagnetic Wave Absorption, ACS Applied Nano Materials, 1 (2018) 5297-5306.
[55] D. Chen, F. Luo, W. Zhou, D. Zhu, Effect of Ti3SiC2 addition on microwave absorption property of plasma sprayed Ti3SiC2/NASICON coatings, Journal of Materials Science: Materials in Electronics, 29 (2018) 13534-13540.
[56] Y. Liu, X. Yin, M.G.B. Drew, Y. Liu, Reflection Loss is a Parameter for Film, not Material, Non-Metallic Material Science, 5 (2023) 38 - 48.
[57] N.I. Landy, S. Sajuyigbe, J.J. Mock, D.R. Smith, W.J. Padilla, Perfect Metamaterial Absorber, Physical Review Letters, 100 (2008) 207402.
[58] Y. Liu, M.G.B. Drew, Y. Liu, A physics investigation of impedance matching theory in microwave absorption film—Part 1: Theory, Journal of Applied Physics, 134 (2023) 045303.
[59] Y. Liu, Y. Ding, Q. Chen, Y. Liu, Preparation of NiFe2-xMxO4(M=Ce,Sm,Gd) and microwave absorption properties of its films, Journal of Shenyang Normal University (Natural Science Edition), 41 (2023) 98 - 103.
[60] Y. Liu, Y. Liu, Microwave absorption mechanism for film, Journal of Molecular Science, 39 (2023) 521 - 527.

[61] T. Wang, H. Wang, G. Tan, L. Wang, L. Qiao, The Relationship of Permeability and Permittivity at the Perfect Matching Point of Electromagnetic Wave Absorption for the Absorber Filled by Metallic Magnetic Particles, IEEE Transactions on Magnetics, 51 (2015) 2800405.
[62] Y. Liu, Y. Liu, M.G.B. Drew, A theoretical investigation on the quarter-wavelength model — Part 1: Analysis, Physica Scripta, 96 (2021) 125003.