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Preface

Due to their extensive applications in military stealth technology, most of the research on microwave absorbing materials has been kept secret and classified over the years. In the recent past, with increasing requirements for microwave absorbing performances of these materials and their prosperity in civil applications, new kinds of microwave absorbing materials have emerged, and either their absorbing mechanisms or their applications have attracted considerable attention and made pronounced progress.

This book presents a concise scope of modern microwave absorbing materials, also known as electromagnetic absorbing materials, and their absorption characterizations. The objective is to provide a sound understanding of the fundamentals and concepts of microwave absorbing theories, which also form the basis of the principles of microwave absorbing materials and their absorbing mechanisms.

The content in this book is presented in eight chapters. Chapter 1 is devoted to the fundamental aspects of interactions between electromagnetic waves and microwave absorbing materials. On the basis of principle theory, the crucial factors which may influence the absorbing performances of microwave absorbing materials, such as density, particle size, shape, chemical compositions, and stability, are also included. Chapters 2 to 5 discuss traditional microwave absorbing materials based on manganese oxides, iron matrix alloys, conductive polyanilines, and barium titanates. The preparation techniques and their electromagnetic characterizations are also dealt with. Chapters 6 to 8 give a description of hybrid microwave absorbers, cement matrix absorbing materials, and structural pyramidal materials. Chapter 6 also gives an overview of two main absorbers, absorbing coatings and absorbing structures. Several representative absorbing coatings and structures based on epoxide resin, polyurethane (PU) varnish, silicon rubber, and acrylonitrile-butadiene-styrene (ABS) are introduced briefly. Chapter 7 elaborates on the electrical and electromagnetic properties of cement-based composite materials filled with carbon materials, metal fillers, and porous fillers. On the basis of the microwave absorbing properties of cement composites filled with expanded polystyrene (EPS), the energy conservation law in electromagnetic fields has been proposed. In Chapter 8, we present the design philosophy of the pyramid absorbers widely used in most anechoic chambers. And also, we propose a new kind of resonant absorber based on carbon-coated EPS and discuss its absorbing mechanism in detail.

To give a more intuitive understanding of the materials in each chapter, we give a full list of references related to the main contents in that chapter. The readers can refer to these lists to get more information.

I would like, first, to thank gratefully my colleagues and students for their assistance and contribution to this book. These include Prof. Liu, Prof. Guan, Huifang Pang, Wei Liu, Yahong Zhang, Jin Liu, Qun Xi, LuLu Song, Gaihua He, Liyang Chen, Lidong Liu, Baoyi Li, Shuping Lv, Guangli Wu, Shuchao Gu, Jia Zhang, Hui Jin, He Ma, Zhuo Liu, Ming Wen, Long Wang, Junlei Chen, Jizhu Du, and Xiaodong Chen, who provided excellent expertise and support for the language and pictures, especially Prof. Guan, who gave many good suggestions on the design and polishing of the content. I am also deeply indebted to my family for their patience, encouragement, and support and for contributing so much to my confidence in dealing with the writing of this book.

Yuping Duan

May 2016

Chapter 1

Fundamentals of Electromagnetic Wave Absorbing Theory

Maxwell's equations indicate that the time-varying electromagnetic (EM) field is a rotational solenoidal field in the source-free space ($\rho = 0, \vec{J} = 0$). In other words, electric force lines and magnetic field lines are closed without any endpoints. The electric field and magnetic field cross-link and excite each other to generate EM waves, which are the main form for EM energy to propagate forward.

According to the shape of the phase surface (also known as the wave front plane), waves are classified into plane waves, spherical waves, and cylindrical waves. Among them, a plane wave is the simplest one in structure. In a small region far away from the radiating source, the spherical wave may be approximated as a plane wave. All the field quantities are in a plane normal to the direction of their propagation. The other forms of EM waves are created by mixing plane waves. If the amplitude and direction of the plane-wave electric field are identical on the whole equiphase surface, it can be defined as a uniform plane wave. Thus, it is very important to comprehend and master the transmission characteristics and basic properties of plane waves[1–5].

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1.1 Plane Electromagnetic Wave in Lossy Medium Space

In practice, there is more of the space consisting of lost media, although most of the time we think the space is lossy as an approximation. Next we will discuss the planar transmission characteristics of the source-free boundless plane waves in a lossy medium.

We assume the characteristic parameters of lossy medium are σ, ε, and μ in source-free boundless space, and the time-varying EM field satisfies Maxwell's equations as

$$\nabla \times \vec{H} = \sigma \vec{E} + j\varepsilon\omega\vec{E} \tag{1.1a}$$

$$\nabla \times \vec{E} = -j\omega\mu\vec{H} \tag{1.1b}$$

$$\nabla \cdot \vec{H} = 0 \tag{1.1c}$$

$$\nabla \cdot \vec{E} = 0 \tag{1.1d}$$

Rewrite Eq. 1.1 as

$$\nabla \times \vec{H} = j\omega\left(\varepsilon - j\frac{\sigma}{\omega}\right)\vec{E}$$

and

$$\varepsilon_c = \varepsilon - j\frac{\sigma}{\omega} = \varepsilon(1 - j\tan\delta) \tag{1.2}$$

ε_c is complex permittivity, and it is related to the frequency. $\tan\delta = \sigma/\varepsilon\omega$ is the loss angle tangent; then

$$\nabla \times \vec{H} = j\omega\varepsilon_c\vec{E} \tag{1.3}$$

This equation is in the same form as Maxwell's equation in an ideal medium. This means that the solution of plane EM waves can be obtained if ε in the relative equations of an ideal medium was replaced by ε_c.

Wave equations are

$$\nabla^2\vec{E} + \omega^2\mu\varepsilon_c\vec{E} = 0 \tag{1.4}$$

$$\nabla^2\vec{H} + \omega^2\mu\varepsilon_c\vec{H} = 0 \tag{1.5}$$

If $k_c^2 = \omega^2\mu\varepsilon_c$, then

$$k_c = \omega\sqrt{\mu\left(\varepsilon - j\frac{\sigma}{\omega}\right)} = \omega\sqrt{\mu\varepsilon}\sqrt{1 - j\tan\delta} = \beta - j\alpha$$

$$\alpha = \omega\sqrt{\frac{\mu\varepsilon}{2}\left(\sqrt{1+\tan^2\delta}-1\right)} \tag{1.6}$$

$$\beta = \omega\sqrt{\frac{\mu\varepsilon}{2}\left(\sqrt{1+\tan^2\delta}+1\right)} \tag{1.7}$$

If $\vec{E} = E_x\vec{a}_x$, we can obtain the values of the electric field and the magnetic field as

$$E_x = E_{xm}e^{-jk_z z} = E_{xm}e^{-\alpha z}e^{-j\beta z} \tag{1.8}$$

$$H_y = \frac{j}{\omega\mu}\frac{\partial E_x}{\partial z} = \sqrt{\frac{\varepsilon}{\mu}(1-j\tan\delta)}E_{xm}e^{-\alpha z}e^{-j\beta z} \tag{1.9}$$

On the basis of the equations above, in a lossy medium:

- As the transmitting range increases, the amplitudes of this field decreases. The attenuation constant is α.
- As the phase-moving constant β is related to frequency ω, we know the phase velocity also relates to it. This phenomenon is called dispersion.
- The phase of electric field intensity is different from that of magnetic field intensity, and the ratio of these two is known as complex wave impedance.

$$\eta_c = \sqrt{\frac{\mu}{\varepsilon_c}} = \sqrt{\frac{\mu}{\varepsilon(1-j\tan\delta)}} = \frac{\eta}{\sqrt{\varepsilon(1-j\tan\delta)}} \tag{1.10}$$

In this equation, $\eta = \sqrt{\mu/\varepsilon}$. In practical applications, the following two special situations always can be seen[6]: low-loss medium and high-loss medium.

1.1.1 Low-Loss Medium

Under this condition ($\tan\delta << 1$, that is, $\sigma << \omega\varepsilon$), using the binomial theorem

$$\begin{aligned} k_c &= \omega\sqrt{\mu\varepsilon}(1-j\tan\delta)^{1/2} \\ &= \omega\sqrt{\mu\varepsilon}[1-j\tan\delta/2+\cdots] \end{aligned}$$

And ignoring the higher-order term behind the quadratic term, we get

$$k_c \approx \omega\sqrt{\mu\varepsilon} - j\frac{\sigma}{2}\sqrt{\frac{\mu}{\varepsilon}} = \beta - j\alpha \tag{1.11}$$

Then

$$\beta \approx \omega\sqrt{\mu\varepsilon} \tag{1.12}$$

$$\alpha \approx \frac{\sigma}{2}\sqrt{\frac{\mu}{\varepsilon}} \tag{1.13}$$

$$\eta_c \approx \sqrt{\frac{\mu}{\varepsilon}} = \eta \tag{1.14}$$

Thus it can be seen that β and η_c have almost the same results as in an ideal medium; only they have an attenuation on amplitude, which is not serious. Then we can approximately take the low-loss medium as the ideal medium in practice.

1.1.2 High-Loss Medium

In this case $\tan\delta >> 1$, that is, $\sigma >> \omega\varepsilon$

$$k_c = \omega\sqrt{\mu\varepsilon}(1 - j\tan\delta)^{1/2} \approx \sqrt{\omega\mu\sigma}e^{-j\pi/4} \tag{1.15}$$

So we can get

$$\alpha = \beta = \sqrt{\frac{\omega\mu\sigma}{2}} \tag{1.16}$$

$$\eta_c = \sqrt{\frac{\mu}{\left(\varepsilon - j\dfrac{\sigma}{\omega}\right)}} \approx \sqrt{\frac{\omega\mu}{\sigma}}e^{j\pi/4} \tag{1.17}$$

From the above it is obvious that the higher the frequency of EM waves, the faster the transmission attenuation of EM waves in the medium, and the shorter the distance of transmission. Therefore, high-frequency EM waves only exist in the thin layer which is near the conductor surface. This phenomenon is said to be the skin effect whose level is characterized by skin depth (or penetrating depth).

Skin depth is defined as the distance traveled by waves in a conducting medium at which its amplitude falls to $1/e$ of its value on the surface of that conducting medium. It is represented as h, and obviously there is

$$h = \frac{1}{\alpha} = \sqrt{\frac{2}{\omega\mu\sigma}} = \frac{1}{\sqrt{\pi f \mu\sigma}} \tag{1.18}$$

As a good conductor has a high conductivity, there is a very small skin depth for high-frequency EM waves. Therefore, the metal has an excellent function of shielding radio waves.

1.2 Reflection and Refraction of Uniform Plane Waves

In practice, EM waves inevitably encounter the interfaces of various media where they are reflected and transmitted. In this section we start out from simple boundary problems to introduce the characteristics of reflection and refraction[7–10].

1.2.1 Vertically Incident, Uniform Plane Electromagnetic Waves on the Interface

As shown in Fig. 1.1, uniform plane waves are transmitted from medium 1 to medium 2 with the interface of infinite plane $z = 0$. The parameters of medium 1 are ε_1, μ_1, and σ_1 and those of medium 2 are ε_2, μ_2, and σ_2.

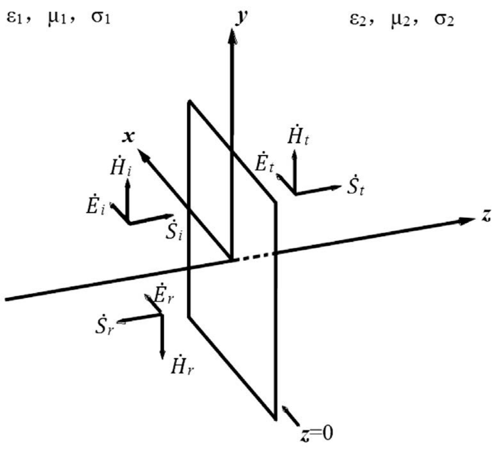

Figure 1.1 Vertical incidence of the boundary.

According to the characteristics of plane waves in lossy medium space mentioned in Section 1.1.1, we assume the electric field of incident waves in common media is

$$\vec{E}_{\mathrm{i}}(z)=\vec{a}_x E_{\mathrm{im}} e^{-jk_{\mathrm{c1}}z} \tag{1.19}$$

Then their magnetic fields are

$$\vec{H}_{\mathrm{i}}(z)=\vec{a}_y \frac{E_{\mathrm{im}}}{\eta_{c1}} e^{-jk_{c1}z} \tag{1.20}$$

And the reflected electric and magnetic fields are

$$\vec{E}_{\mathrm{r}}(z)=\vec{a}_x E_{\mathrm{rm}} e^{jk_{\mathrm{c1}}z} \tag{1.21}$$

$$\vec{H}_{\mathrm{r}}(z)=-\vec{a}_y \frac{E_{\mathrm{rm}}}{\eta_{\mathrm{c1}}} e^{jk_{\mathrm{c1}}z} \tag{1.22}$$

Electric and magnetic fields of transmitted waves in medium 2 are

$$\vec{E}_{\mathrm{t}}(z)=\vec{a}_x E_{\mathrm{tm}} e^{-jk_{\mathrm{c2}}z} \tag{1.23}$$

$$\vec{H}_{\mathrm{t}}(z)=\vec{a}_y \frac{E_{\mathrm{tm}}}{\eta_{\mathrm{c2}}} e^{-jk_{\mathrm{c2}}z} \tag{1.24}$$

In Eqs. 1.19–1.24

$$k_{\mathrm{c1}}=\omega\sqrt{\mu_1\varepsilon_1}(1-j\tan\delta_1)^{1/2}$$

$$\eta_{\mathrm{c1}}=\sqrt{\frac{\mu_1}{\varepsilon_1}}(1-j\tan\delta_1)^{-1/2}$$

$$k_{\mathrm{c2}}=\omega\sqrt{\mu_2\varepsilon_2}(1-j\tan\delta_2)^{1/2}$$

$$\eta_{\mathrm{c2}}=\sqrt{\frac{\mu_2}{\varepsilon_2}}(1-j\tan\delta_2)^{-1/2}$$

The composite electric and magnetic fields in medium 1 are

$$\vec{E}_1(z)=\vec{E}_{\mathrm{i}}(z)+\vec{E}_{\mathrm{r}}(z)=\vec{a}_x(E_{\mathrm{im}}e^{-jk_{\mathrm{c1}}z}+E_{\mathrm{rm}}e^{jk_{\mathrm{c1}}z}) \tag{1.25}$$

$$\vec{H}_1(z)=\vec{H}_{\mathrm{i}}(z)+\vec{H}_{\mathrm{r}}(z)=\vec{a}_y\left(\frac{E_{\mathrm{im}}}{\eta_{\mathrm{c1}}}e^{-jk_{\mathrm{c1}}z}-\frac{E_{\mathrm{rm}}}{\eta_{\mathrm{c1}}}e^{jk_{\mathrm{c1}}z}\right) \tag{1.26}$$

According to Eqs. 1.23–1.26 and the boundary conditions of the tangential electric field and the tangential magnetic field on $z = 0$

$$\vec{E}_1(z=0)=\vec{a}_x(E_{\mathrm{im}}+E_{\mathrm{rm}})=\vec{E}_{\mathrm{t}}(z=0)=\vec{a}_x E_{\mathrm{tm}}$$

$$\vec{H}_1(z=0)=\vec{a}_y\left(\frac{E_{\text{im}}}{\eta_{\text{c1}}}-\frac{E_{\text{rm}}}{\eta_{\text{c1}}}\right)=\vec{H}_t(z=0)=\vec{a}_y\frac{E_{\text{tm}}}{\eta_{\text{c2}}}$$

Combining these two equations above, we can get

$$E_{\text{rm}}=\frac{\eta_{\text{c2}}-\eta_{\text{c1}}}{\eta_{\text{c2}}+\eta_{\text{c1}}}E_{\text{im}} \tag{1.27}$$

$$E_{\text{tm}}=\frac{2\eta_{c2}}{\eta_{c2}+\eta_{c1}}E_{\text{im}} \tag{1.28}$$

For the convenience of analysis, we define the rate of reflection wave fields' amplitudes and incident wave fields' amplitudes as the reflection coefficient, in terms of Γ. Then there is

$$\Gamma=\frac{E_{\text{rm}}}{E_{\text{im}}}=\frac{\eta_{\text{c2}}-\eta_{\text{c1}}}{\eta_{\text{c2}}+\eta_{\text{c1}}} \tag{1.29}$$

Defining the rate of transmitted and incident wave fields' amplitudes as the reflection coefficient, in terms of τ, we get

$$\tau=\frac{E_{\text{tm}}}{E_{\text{im}}}=\frac{2\eta_{\text{c2}}}{\eta_{\text{c2}}+\eta_{\text{c1}}} \tag{1.30}$$

The reflection coefficient and the transmission coefficient are two of the most important parameters to analyze the transmission characteristics of EM waves in bounded space, and there is

$$1 + \Gamma = \tau \tag{1.31}$$

Let's substitute Γ and τ in Eqs. 1.23 and 1.25. Then the electric fields in medium 1 and medium 2 are

$$\vec{E}_1(z)=\vec{a}_x E_{\text{im}}(e^{-jk_{\text{c1}}z}+\Gamma e^{jk_{\text{c1}}z}) \tag{1.32}$$

$$\vec{E}_t(z)=\vec{a}_x \tau E_{\text{im}} e^{-jk_{\text{c2}}z} \tag{1.33}$$

For the common media, as η_{c1} and η_{c2} are complex, so the reflection coefficient and the transmission coefficient also should be complex items. It indicates that reflected and transmitted waves through the interface vary not only in the amplitudes but also in the phases and their variation is related to the medium parameters.

Next let's analyze two special conditions:

- Interface between an ideal medium and an ideal conductor
- Interface of an ideal medium

1.2.1.1 Interface between an ideal medium and an ideal conductor

We assume medium 1 is an ideal medium and medium 2 is an ideal conductor; that is, $\sigma_1 = 0$ and $\sigma_2 = \infty$. Then

$$k_{c1} = \omega\sqrt{\mu_1\varepsilon_1} = k_1$$

$$\eta_{c1} = \sqrt{\frac{\mu_1}{\varepsilon_1}} = \eta_1$$

$$k_{c2} = \infty$$

$$\eta_{c2} = 0$$

Let's substitute them in Eqs. 1.29, 1.30, 1.32, and 1.33; we obtain

$$\Gamma = -1 \tag{1.34}$$

$$\tau = 0 \tag{1.35}$$

$$\vec{E}_1(z) = -\vec{a}_x 2jE_{\text{im}} \sin k_1 z \tag{1.36}$$

$$\vec{H}_1(z) = \vec{a}_y \frac{2E_{\text{im}}}{\eta_1} \cos k_1 z \tag{1.37}$$

$$\vec{E}_{\text{t}}(z) = 0 \tag{1.38}$$

$$\vec{H}_{\text{t}}(z) = 0 \tag{1.39}$$

These equations state that there is no time-varying electric field in a perfect conductor. Besides, according to the boundary conditions of $\vec{n}\cdot\vec{E} = \rho_{\text{s}}$ and $\vec{n}\times\vec{H} = \vec{J}_{\text{s}}$, it can be known that there is no inductive charge on the surface of a perfect conductor. The surface inductive charge is

$$\vec{J}_{\text{s}} = -\vec{a}_z \times \vec{H}_1(z=0) = \vec{a}_x \frac{2E_{\text{im}}}{\eta_1} \tag{1.40}$$

To analyze the transmission characteristics in medium 1, we express the total electric field and the total magnetic field in the form of an instant. These are

$$\vec{E}_1(z,t) = \text{Re}[\vec{E}_1(z)e^{j\omega t}] = \vec{a}_x 2E_{\text{im}} \sin k_1 z \sin \omega t \tag{1.41}$$

$$\vec{H}_1(z,t) = \text{Re}[\vec{H}_1(z)e^{j\omega t}] = \vec{a}_y \frac{2E_{\text{im}}}{\eta_1} \cos k_1 z \cos \omega t \tag{1.42}$$

The space-time curves of Eqs. 1.41 and 1.42 are shown in Fig. 1.2. They indicate that electric and magnetic fields pulsate with time, but there are a fixed max point (wave antinode points) and zero point (wave nodal points) in the z direction. This kind of waves are called pure standing waves. The locations of electric field wave antinode points (magnetic wave nodal points) are $z=-\frac{(2n+1)\lambda}{4}$, n = 0, 1, 2, . . . The locations of electric wave nodal points (magnetic antinode point) are $z=-\frac{n\lambda}{2}$, n = 0, 1, 2, . . .

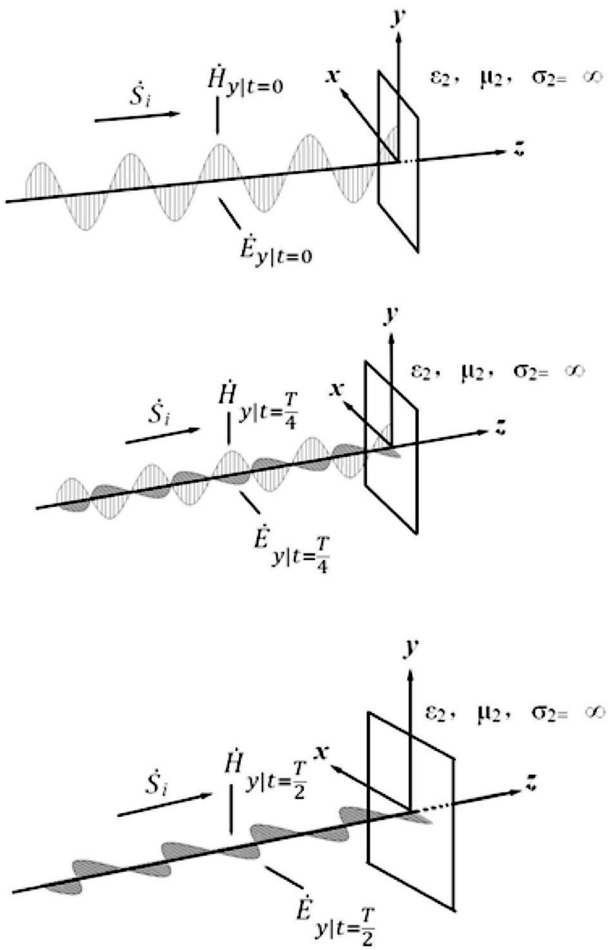

Figure 1.2 Space and time distributions of electric fields and magnetic fields in the case of perpendicular incidence.

The average synthesized energy flux density of magnetic waves in medium 1 is

$$\vec{S}_{\text{av}} = \frac{1}{2}\text{Re}[\vec{E}_1(z) \times \vec{H}_1^*(z)] = 0 \tag{1.43}$$

This equation indicates that pure standing waves can't be the method to transmit magnetic energy. Therefore, electric energy and magnetic energy mutually convert between the two nodal points with a 1/4 cycle.

1.2.1.2 Interface of an ideal medium

We assume $\sigma_1 = \sigma_2 = 0$, that is, media 1 and 2 are both ideal media. Then

$$k_{c1} = \omega\sqrt{\mu_1\varepsilon_1} = k_1$$

$$\eta_{c1} = \sqrt{\frac{\mu_1}{\varepsilon_1}} = \eta_1$$

$$k_{c2} = \omega\sqrt{\mu_2\varepsilon_2} = k_2$$

Substituting them in Eqs. 1.29, 1.30, 1.32, and 1.33,

$$\Gamma = \frac{\eta_2 - \eta_1}{\eta_2 + \eta_1} \tag{1.44}$$

$$\tau = \frac{2\eta_2}{\eta_2 + \eta_1} \tag{1.45}$$

$$\vec{E}_1(z) = \vec{a}_x E_{\text{im}}[(1+\Gamma)e^{-jk_1 z} + j\Gamma 2\sin k_1 z] \tag{1.46}$$

The first item in Eq. 1.46 expresses the magnetic waves with their amplitude of E_{im} $(1 + \Gamma)$ transmitting along the y direction; these kind of waves are called travelling waves. The second item expresses that of standing waves. In consequence, the waves $\vec{E}_1(z)$ containing both travelling wave components and standing wave components are named standing traveling waves (mixed waves). Standing traveling waves have fixed antinode points and nodal points. But compared to pure standing waves, their field intensity on antinode points is not zero. The transmitted waves are unidirectional, and their characteristics are similar to plane waves'. So it won't be discussed here.

For the standing traveling wave, the standing wave coefficient S (or standing wave ratio) is introduced to describe its characteristics, and it is defined as the rate of the maximum value and the minimum value in the standing wave electric field. It can be expressed as

$$S = \frac{|E|_{\max}}{|E|_{\min}} \tag{1.47}$$

To analyze the characteristics of a standing wave in medium 1, it can be rewritten as

$$\vec{E}_1(z) = \vec{a}_x E_{\text{im}} e^{-jk_1 z}(1 + \Gamma e^{j2k_1 z}) \tag{1.48}$$

For the ideal medium, η_1 and η_2 are both positive real numbers; so are Γ and τ. But as the relationship of η_1 and η_2 changes, Γ can be a positive real number or a negative one.

- Condition 1: $\Gamma > 0$, that is, $\eta_2 > \eta_1$.

On the basis of what is mentioned above, the maximum value of the electric field is

$$|E_1|_{\max} = E_{\text{im}}(1 + \Gamma) \tag{1.49}$$

The locations of the maximum value in the electric field are $2k_1 z = -2n\pi$:

$$z = -\frac{n\lambda_1}{2} \quad n = 0, 1, 2, \ldots \tag{1.50}$$

The minimum value in the electric field is

$$|E_1|_{\min} = E_{\text{im}}(1 - \Gamma) \tag{1.51}$$

The locations of the minimum value in the electric field are $2k_1 z = -(2n + 1)\pi$:

$$z = -\frac{(2n+1)\lambda_1}{4} \quad n = 0, 1, 2, \ldots \tag{1.52}$$

- Condition 2: $\Gamma < 0$, that is, $\eta_2 < \eta_1$.

Obviously, amplitudes of the maximum and minimum point are the same as those in condition 1, but they are at the opposite locations. Substituting Eqs. 1.49 and 1.51 in Eq. 1.47, we get

$$S = \frac{1 + |\Gamma|}{1 - |\Gamma|} \tag{1.53}$$

and

$$|\Gamma| = \frac{S+1}{S-1} \tag{1.54}$$

The standing wave ratio S is a real number and convenient to be measured; therefore we often get the reflection coefficient by computing S, which can be given from measurement. The EM energy flow densities in these two media are

$$\vec{S}_{1\mathrm{av}} = \frac{1}{2}\mathrm{Re}[\vec{E}_1(z) \times \vec{H}_1^*(z)] = \frac{E_{\mathrm{im}}^2}{2\eta_1}(1-\Gamma^2)\vec{a}_z \tag{1.55}$$

$$\vec{S}_{\mathrm{tav}} = \frac{1}{2}\mathrm{Re}[\vec{E}_{\mathrm{t}}(z) \times \vec{H}_{\mathrm{t}}^*(z)] = \frac{\tau E_{\mathrm{im}}^2}{2\eta_2}\vec{a}_z \tag{1.56}$$

It can be proved that the sum of the transmitted waves' and reflected waves' energy flow equals the incident waves' energy flow, which satisfies the law of conservation of energy.

1.2.2 Normal Incidence on the Interface of Multilayered Media

Multilayered media are very common in practical applications, such as composite materials, surface shielding materials, and absorbing coated materials. Taking the case of the three-layered medium let's discuss the problem of normal incidence of plane waves. The analysis model is shown in Fig. 1.3.

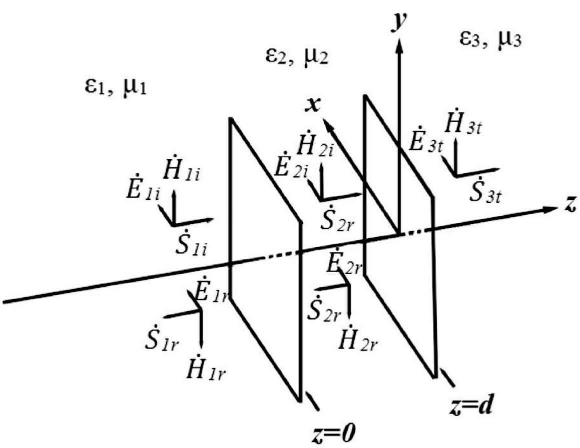

Figure 1.3 Normal incidence of interface of multilayered media.

According to the characteristics of plane waves, we can present the formulas of the superposed electric field and magnetic field. In medium 1

$$\vec{E}_1(z)=\vec{a}_x E_{1\mathrm{im}}(e^{-jk_1 z}+\Gamma_1 e^{jk_1 z}) \tag{1.57a}$$

$$\vec{H}_1(z)=\vec{a}_y \frac{E_{1\mathrm{im}}}{\eta_1}(e^{-jk_1 z}-\Gamma_1 e^{jk_1 z}) \tag{1.57b}$$

In medium 2

$$\vec{E}_2(z)=\vec{a}_x E_{2\mathrm{im}}(e^{-jk_2(z-d)}+\Gamma_2 e^{jk_2(z-d)}) \tag{1.58a}$$

$$\vec{H}_2(z)=\vec{a}_y \frac{E_{2\mathrm{im}}}{\eta_2}(e^{-jk_2(z-d)}-\Gamma_2 e^{jk_2(z-d)}) \tag{1.58b}$$

In medium 3

$$\vec{E}_3(z)=\vec{a}_x E_{3\mathrm{im}} e^{-jk_3(z-d)} \tag{1.59a}$$

$$\vec{H}_3(z)=\vec{a}_y \frac{E_{3\mathrm{im}}}{\eta_3} e^{-jk_3(z-d)} \tag{1.59b}$$

For interface 2, there is

$$\Gamma_2=\frac{\eta_3-\eta_2}{\eta_3+\eta_2} \tag{1.60}$$

When z = 0 on interface 1, the tangential components of the electric field and the magnetic field are continuous. They are

$$\vec{E}_1(0)=\vec{E}_2(0)$$

$$\vec{H}_1(0)=\vec{H}_2(0)$$

Dividing both sides of the two equations above and substituting the result in Eqs. 1.57 and 1.58, we can get

$$\eta_1\frac{1+\Gamma_1}{1-\Gamma_1}=\eta_2\frac{e^{jk_2 d}+\Gamma_2 e^{-jk_2 d}}{e^{jk_2 d}-\Gamma_2 e^{-jk_2 d}} \tag{1.61}$$

If there is

$$Z_\mathrm{p}=\eta_2\frac{e^{jk_2 d}+\Gamma_2 e^{-jk_2 d}}{e^{jk_2 d}-\Gamma_2 e^{-jk_2 d}}$$

Then substitute Eq. 1.60 into the equations above. Combining those with Euler's formula, we can get

$$Z_\mathrm{p}=\eta_2\frac{\eta_3+j\eta_2\tan k_2 d}{\eta_2+j\eta_3\tan k_2 d} \tag{1.62}$$

Z_p is the ratio of the electric and magnetic fields on $z = 0$ in medium 2. It has the same dimension as impedance; therefore we define it as the equivalent wave impedance on plane 1 in medium 2. Substituting Z_p in Eq. 1.61, one can get

$$\Gamma_1 = \frac{Z_p - \eta_1}{Z_p + \eta_1} \tag{1.63}$$

Equations 1.62 and 1.63 are very useful in the analysis of reflection and transmission characteristics. When there are n layers in the medium, starting from the layer $n - 1$ we can compute the reflection coefficient of these layers by recycling Eqs. 1.62 and 1.63. Then the electric and magnetic fields of all the layers can be computed.

Next we discuss two special cases of multilayers:

- Quarter-wave matching layer
- Half-wavelength dielectric window

1.2.2.1 Quarter-wave matching layer

As shown in Fig. 1.4, assuming the thickness of medium 2 is $\frac{\lambda_2}{4}$, $k_2 d = \frac{2\pi}{\lambda_2}\frac{\lambda_2}{4} = \frac{\pi}{2}$ and $\tan k_2 d = \infty$. Substituting them in Eqs. 1.62 and 1.63, one can get that the equivalent wave impedance and reflection coefficients are

$$Z_p = \frac{\eta_2^2}{\eta_3} \tag{1.64}$$

$$\Gamma_1 = \frac{\eta_2^2 - \eta_1\eta_3}{\eta_2^2 + \eta_1\eta_3} \tag{1.65}$$

That is to say there is no reflection on interface 1. It means that medium 2 transforms η_3 to $Z_p = \eta_1$ of interface 1, which counteracts the reflection and plays the role of impedance conversion. Thus medium 2 is termed the "quarter-wave matching layer." This property can be used in the design of absorbing coatings to improve the effects of absorbing materials.

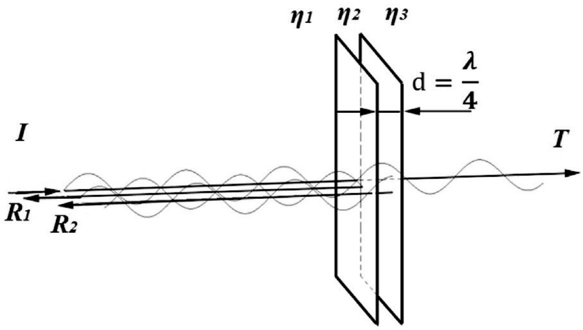

Figure 1.4 Quarter-wave matching layer.

1.2.2.2 Half-wavelength dielectric window

If the thickness of medium 2 is $\frac{\lambda_2}{2}$, $k_2 d = \frac{2\pi}{\lambda_2}\frac{\lambda_2}{2} = \pi$ and tan $k_2 d = 0$. Then $Z_p = \eta_3$. If we assume $\eta_3 = \eta_1$, medium 1 is the same as medium 3; then there is

$$\Gamma_1 = \frac{Z_p - \eta_1}{Z_p + \eta_1} = 0 \tag{1.66}$$

There is no reflection on interface 1 and it is easy to conclude $E_{3tm} = E_{1im}$. It indicates that incident waves transmit from medium 1 to medium 3 just like there is no medium 2. Thus we call it a "half-wavelength dielectric window." This property is extensively used in the design of radomes.

1.2.3 Oblique Incidence of Uniform Plane Electromagnetic Waves on the Interface

When an EM wave strikes a plane boundary with any arbitrary angle, we refer to it as oblique incidence. In this case, as the plane of electric and magnetic fields is not horizontal with the plane of the interface, the analysis is much more difficult, although the overall thought of analytical method is the same as the oblique incident before.

For the sake of convenient analysis, first we introduce the concept of an incidence plane and a reflection plane. Then we classify oblique incidence plane waves into parallel polarized waves and vertically polarized waves. As shown in Fig. 1.5, the plane which includes the normal to the boundary $\vec{n}$ and the incident ray is called the plane of incidence, θ_i is called the angle of incidence, the plane that includes the normal to the boundary $\vec{n}$ and the reflected ray is called the plane of incidence, θ_r is called the angle of reflection, and θ_t is the angle of transmission. When the field of the incident wave is normal to the incident plane, we called it the perpendicularly polarized wave; when the field of the incident wave is parallel to the incident plane, we called it the parallel polarized wave. The polarized waves of any orientation can be decomposed into parallel polarized waves and perpendicularly polarized waves.

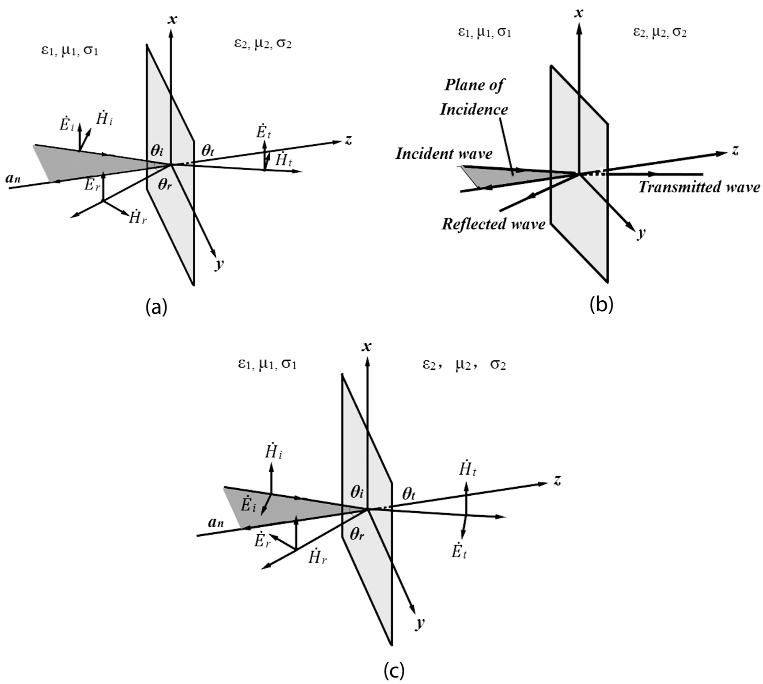

Figure 1.5 (a) Basic definition and the sketch map for (b) perpendicularly and (c) parallel polarized waves.

1.2.3.1 Oblique incidence on the surface of an ideal medium plane

For the sake of convenient analysis and in general, we assume $z = 0$ as the interface of the ideal medium and there is a coincidence between the incident plane and the coordinate plane. They are shown in Fig. 1.6. According to the boundary conditions, the components of the tangential electric and magnetic fields are continuous. This relationship must be satisfied on the whole interface. In other words, the transmit velocity components of incident, reflected, and transmitted waves along the interface must be equivalent. That is,

$$\frac{v_1}{\sin\theta_\mathrm{i}}=\frac{v_1}{\sin\theta_\mathrm{r}}=\frac{v_2}{\sin\theta_\mathrm{t}}$$

So

$$\theta_\mathrm{r} = \theta_\mathrm{i} \tag{1.67}$$

$$\frac{\sin\theta_\mathrm{i}}{\sin\theta_\mathrm{t}}=\frac{v_1}{v_2}=\frac{\sqrt{\mu_2\varepsilon_2}}{\sqrt{\mu_1\varepsilon 1}} \tag{1.68}$$

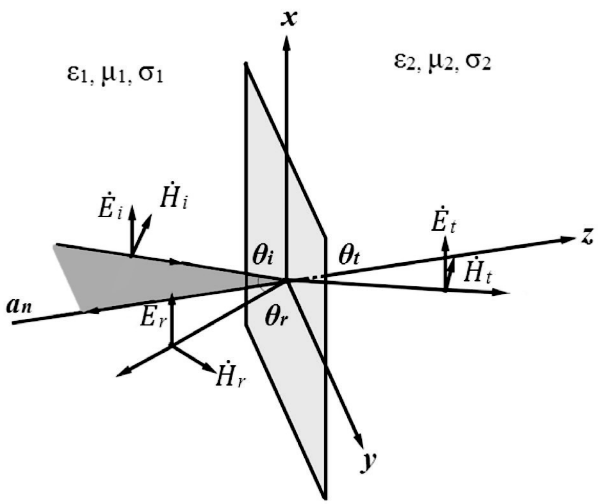

Figure 1.6 Oblique incidence on the surface of an ideal medium plane.

Equations 1.67 and 1.68 are Snell's laws of refraction and refraction, respectively. For general media, $\mu_1 = \mu_2 = \mu_0$. $n=\sqrt{\varepsilon_\mathrm{r}}$ is called the refractive index. Then Eq. 1.68 can be written as

$$n_\mathrm{t}\sin\theta_\mathrm{t} = n_\mathrm{i}\sin\theta_\mathrm{i} \tag{1.69}$$

That is the mathematical expression for the optic refraction law. For parallel polarized waves, boundary conditions of the tangential field are

$$E_{\mathrm{i}}\cos\theta_{\mathrm{i}} - E_{\mathrm{r}}\cos\theta_{\mathrm{r}} = E_{\mathrm{t}}\cos\theta_{\mathrm{t}} \tag{1.70a}$$

$$\frac{E_{\mathrm{i}}}{\eta_1} + \frac{E_{\mathrm{r}}}{\eta_1} = \frac{E_{\mathrm{t}}}{\eta_{\mathrm{t}}} \tag{1.70b}$$

Combining these two equations above, we can get

$$E_{\mathrm{r}} = \frac{\eta_1\cos\theta_{\mathrm{i}} - \eta_2\cos\theta_{\mathrm{t}}}{\eta_1\cos\theta_{\mathrm{i}} + \eta_2\cos\theta_{\mathrm{t}}} E_{\mathrm{i}} = \Gamma_{||} E_{\mathrm{i}} \tag{1.71}$$

$$E_{\mathrm{t}} = \frac{2\eta_2\cos\theta_{\mathrm{i}}}{\eta_1\cos\theta_{\mathrm{i}} + \eta_2\cos\theta_{\mathrm{t}}} E_{\mathrm{i}} = \tau_{||} E_{\mathrm{i}} \tag{1.72}$$

$\Gamma_{||}$, $\tau_{||}$ in the above equations are the reflection coefficient and transmission coefficient of parallel polarized waves, respectively. And

$$\Gamma_{||} = \frac{\eta_1\cos\theta_{\mathrm{i}} - \eta_2\cos\theta_{\mathrm{t}}}{\eta_1\cos\theta_{\mathrm{i}} + \eta_2\cos\theta_{\mathrm{t}}} \tag{1.73}$$

$$\tau_{||} = \frac{2\eta_2\cos\theta_{\mathrm{i}}}{\eta_1\cos\theta_{\mathrm{i}} + \eta_2\cos\theta_{\mathrm{t}}} \tag{1.74}$$

$$\tau_{||} = (1 + \Gamma_{||})\ \eta_2/\eta_1 \tag{1.75}$$

η_1 and η_2 are the wave impedance of medium 1 and medium 2, respectively. Similarly, for vertically polarized waves

$$\Gamma_{\perp} = \frac{\eta_2\cos\theta_{\mathrm{i}} - \eta_1\cos\theta_{\mathrm{t}}}{\eta_2\cos\theta_{\mathrm{i}} + \eta_1\cos\theta_{\mathrm{t}}} \tag{1.76}$$

$$\tau_{\perp} = \frac{2\eta_2\cos\theta_{\mathrm{i}}}{\eta_2\cos\theta_{\mathrm{i}} + \eta_1\cos\theta_{\mathrm{t}}} \tag{1.77}$$

$$\tau_{\perp} = 1 + \Gamma_{\perp} \tag{1.78}$$

- Condition 1: Total reflection and critical angle

  Total reflection is the special case for $|\Gamma| = 1$. When $\theta_{\mathrm{t}} = \pi/2$, from Eqs. 1.73 and 1.76, it can be known that $\Gamma_{||} = \Gamma_{\perp} = 1$. The incident angle of total reflection is named the critical angle; it can be expressed as θ_{C}. Thus it can be concluded from Eq. 1.65 that

  $$\theta_{\mathrm{c}} = \arcsin\sqrt{\varepsilon_2/\varepsilon_1} \tag{1.79}$$

  Obviously, only when $\varepsilon_1 > \varepsilon_2$, that is, EM waves move from a high-optical-density medium to a lower one, total reflection can be observed.

- Condition 2: Total transmission and Brewster angle

  The total transmitted wave is the special case for $|\Gamma| = 0$. For a parallel polarized wave, it can be concluded from Eq. 1.73 that $|\Gamma| = 0$, that is,

  $\eta_1 \cos\theta_\text{i} = \eta_2 \cos\theta_\text{t}$

  Substituting it into Eq. 1.69, we get

$$\theta_\text{i} = \theta_\text{B} = \arcsin\sqrt{\frac{\varepsilon_2}{\varepsilon_1 + \varepsilon_2}} \tag{1.80}$$

In the formula above, θ_B is known as the Brewster angle. We can also conclude from it that when parallel polarized waves are incident on the surface of an ideal medium with an angle of θ_B, the EM wave energy will pass totally into medium 2. Then the reflected energy is zero.

For a vertical polarization wave, the analysis above is equally applicable. If $\Gamma_\perp = 0$, there must be $\varepsilon_1 = \varepsilon_2$. Then we know these two media are the same, which means that the total transmission can't happen to vertical polarization waves.

1.2.3.2 Oblique incidence of an ideal conductor plane

Assume medium 1 is an ideal medium, μ_1, ε_1, $\sigma_1 = 0$ and medium 2 is an ideal conductor with $\sigma_2 = \infty$. The uniform plane wave is incident on the surface of the conductor with the incident angle of θ_i.

As shown in Fig. 1.7, for vertical polarization waves as $\sigma_2 = \infty$, $\eta_2 = 0$. From Eqs. 1.76 and 1.77 we can conclude that $\Gamma_\perp = -1$, $\tau_\perp = 0$, that is, there is total reflection. From the analysis, the composite electric and magnetic fields in the medium can be expressed as

$$E_1 = \vec{E}_\text{i} + \vec{E}_\text{r} = -\vec{a}_y j2E_\text{im} \sin(k_1 z\cos\theta_\text{i}) e^{-jk_1 x\sin\theta_\text{i}} \tag{1.81a}$$

$$\vec{H}_1 = \vec{H}_\text{i} + \vec{H}_\text{r} = -\vec{a}_x \frac{2E_\text{im}}{\eta_1}\cos\theta_\text{i}\cos(k_1 z\cos\theta_\text{i}) e^{-jk_1 x\sin\theta_\text{i}}$$

$$-\vec{a}_z \frac{j2E_\text{im}}{\eta_1}\sin\theta_\text{i}\sin(k_1 z\cos\theta_\text{i}) e^{-jk_1 x\sin\theta_\text{i}} \tag{1.81b}$$

It can be known from these equations that when a vertically polarized wave is incident on an ideal conductor surface, the EM wave in the medium area has the following features:

- In the z direction on the surface of the vertical conductor, composite waves distribute as pure standing waves with no EM energy transmission along this direction.
- The composite wave in the x direction is a traveling wave. From $e^{-jk_1 x \sin\theta_i}$, we can know the phase shift constant in the x direction is $k_1 \sin \theta_1$. Then the phase velocity in this direction is

$$v_{px} = \frac{\omega}{k_1 \sin\theta_i} = \frac{v_p}{\sin\theta_i} > v_p$$

In this equation, there is

$$v_p = \frac{1}{\sqrt{\mu_1 \varepsilon_1}}$$

- As the uniform amplitude plane z and equal phase plane x are both constants, the composite wave is a nonuniform plane wave.
- There are components of the magnetic field but no component of the electric field in the transmission direction (x direction). Such kind of wave is called a transverse electric (TE) wave.

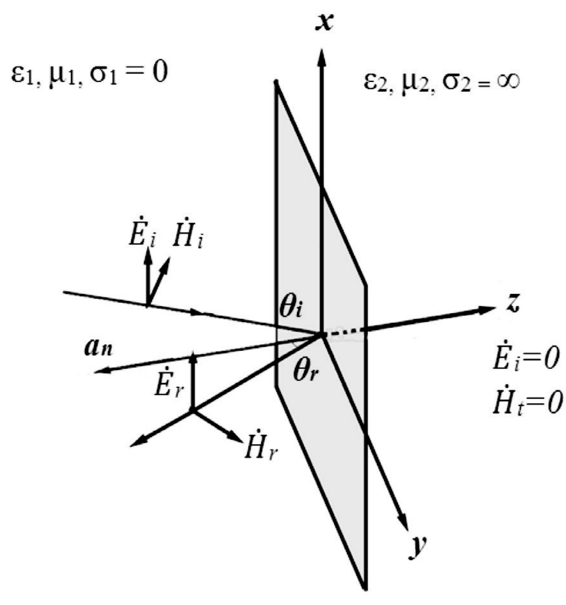

Figure 1.7 Oblique incidence of the ideal conductor plane.

For a parallel polarized wave, $\sigma_2 = \infty$ and $\eta_2 = 0$. From Eqs. 1.75 and 1.76 we can obtain that $\Gamma_{//} = 1$ and $\tau_{//} = 0$. Therefore

$$\vec{E}_1 = -\vec{a}_x j2E_{\text{im}} \cos\theta_{\text{i}} \sin(k_1 z \cos\theta_{\text{i}}) e^{-jk_1 x \sin\theta_{\text{i}}}$$

$$-\vec{a}_z 2E_{\text{im}} \sin\theta_{\text{i}} \cos(k_1 z \cos\theta_{\text{i}}) e^{-jk_1 x \sin\theta_{\text{i}}} \quad (1.82\text{a})$$

$$\vec{H}_1 = \vec{a}_y \frac{2E_{\text{im}}}{\eta_1} \cos(k_1 z \cos\theta_{\text{i}}) e^{-jk_1 x \sin\theta_{\text{i}}} \quad (1.82\text{b})$$

It can be found from Eq. 1.82 that when a parallel polarized wave is under oblique incidence to the surface of an ideal conductor, the features of EM waves in the medium area are the same as those of vertically polarized waves. There are components of the electric field but no component of the magnetic field in the transmission direction (x direction) at the moment. Such kind of wave is called a TE wave.

1.3 Theoretical Fundamentals of Absorbing Materials

According to the absorbing mechanism, absorbents can be divided into three classes: resistive-type absorbents, dielectric-type absorbents, and magnetic-type absorbents. Resistive-type absorbents absorb EM waves mainly by the interaction with the EM wave. The absorption rate of resistive-type absorbents depends on the conductance and permittivity of material. Resistive-type absorbents are primarily represented by carbon black (CB), metal powders, and silicon carbide. Dielectric-type absorbents absorb EM waves mainly through the dielectric polarization relaxed loss, such as barium titanate and ferroelectric ceramics. Magnetic-type absorbents play the role mainly from resonance and hysteresis loss, such as ferrite and carbonyl-iron (CI). In addition, absorbing coatings contain radioisotopes of high-energy particles can also attenuate EM waves by ionizing the air nearby. But, there are many difficulties to overcome in practical use of radioisotopes, such as complex process control and high cost.

The most important requirement of conventional absorbing materials is the high absorption property. But new absorbing materials are required for better properties, such as thinner thickness, less weight, wider absorption band, and higher strength.

For futuristic absorbing materials, more intensified requirements are raised. The restrictions of absorbents limit the development of EM absorbing materials. Therefore, it's very important to develop new absorbing materials.

With rapid development of modern science and technology, the advent of various increasing mature methods of new materials and new preparation methods is a beneficial guarantee for new absorbing materials. The current study of new absorbents includes nanometer-sized material, chiral materials, and conducting polymers.

1.3.1 Property Characterization of Absorbents

The study of absorbents is an important part of developing radar absorption materials (RAMs), and it is also the material base for studying the absorbing material and improving properties. A good understanding and an apt description of absorbents are of great importance and necessity for the research, production, and selection of RAMs.

1.3.1.1 Electromagnetic parameters and absorbing properties

EM parameters include permittivity (ε) and permeability (μ). They are both important parameters to represent EM properties. A RAM can absorb EM waves as much as possible by adjusting the EM parameters. From the point of a medium, the bigger the ε (ε', ε''), the bigger the μ (μ', μ''), and the better the properties of the RAM. But the characteristic impedance matching must be considered in the design. Therefore, there is an optimum value of ε and μ when we choose a proper material. It is important to balance the characteristic impedance matching and EM wave absorbing.

According to transmission line theory, for a single-layer absorbing material backed by a perfect conductor, the input impedance (Z_{in}) at the air–material interface is given by

$$Z_{in} = \sqrt{\frac{\mu}{\varepsilon}} \tanh\left(j\frac{2\pi}{\lambda} d\sqrt{\mu\varepsilon} \right) \tag{1.83}$$

where μ is the complex permeability ($\mu' - j\mu''$) and ε is the complex permittivity ($\varepsilon' - j\varepsilon''$).

When the incident wave is perpendicularly transmitted to the absorber, the reflection loss R is expressed as follows:

$$R = \frac{Z - 1}{Z + 1} \tag{1.84}$$

The propagation constant γ can be expressed as

$$\gamma = \alpha + j\beta = j\frac{2\pi f}{c}\sqrt{\varepsilon \cdot \mu} \tag{1.85}$$

$$\alpha = \frac{\pi f}{c}(\mu'\varepsilon')^{1/2}$$

$$\left\{2\left[\tan\delta_\varepsilon \tan\delta_{\mathrm{m}} - 1 + (1 + \tan^2\delta_\varepsilon + \tan^2\delta_m + \tan^2\delta_\varepsilon\delta_m)^{\frac{1}{2}}\right]\right\}^{\frac{1}{2}} \tag{1.86}$$

where α, β, c, and f denote the attenuation coefficient, the phase coefficient, the velocity of light, and the frequency of wave, respectively. $\tan\delta_\varepsilon = \varepsilon''/\varepsilon'$, and $\tan\delta_m = \mu''/\mu'$, are the dielectric and magnetic loss factors, respectively.

From Eqs. 1.83–1.86, you can draw this conclusion: To satisfy impedance matching and high absorption properties, a reasonable design of (ε, μ) must be chosen[13–15].

1.3.1.2 Confirmation of electromagnetic parameters

Representations of EM parameter determination are calculation methods and direct measurement methods. The calculation methods of EM parameters are the direct calculation method and the indirect calculation method. The direct calculation method estimates EM parameters on the basis of the magnetic polarization intensity and electric field intensity of the absorbent in the EM field[16]. The main indirect calculation methods are the transmission/reflection method and the multistate, multithickness method[17–22]. Measuring waveguides of samples and the S parameters of coaxial lines are widely employed in the transmission/reflection method; then complex permittivity ε and complex permeability μ are calculated according to the related formulas. Because measuring the amplitudes and phases of S_{11} and S_{21} simultaneously is difficult, changing the terminal states and thicknesses of samples is employed to measure the corresponding complex reflection coefficient and to obtain the complex permittivity and complex permeability through calculation.

There are two main direct testing methods. The first method is that the absorbent and binder are made into coatings or block samples to measure ε and μ. The measured parameters are actually the constants of the complex medium, that is, the relative dielectric constant and magnetic permittivity. Therefore, the quality, mixing ratio, and size dimension should remain the same in this method. The second method is the measurement of absorbent EM parameters ε and μ. The ε and μ measurement of a powder absorbent is the intuitional method to represent its EM properties. Therefore, a sample frame waveguide should be prepared. The two ends of the waveguide sealed with a high-transmission material slice form a rectangular vessel, and the above cover of the waveguide is opened to form the waveguide sample frame. The absorbent powder is filled into the frame according to apparent density and tap density, and the complex permittivity ε and complex permeability μ of the sample frame filled with absorbent are measured using the waveguide measuring system.

1.3.1.3 Electromagnetic parameters of absorbing materials with different absorbent content

Absorbing materials with different absorbents should be measured, and relational expressions should be summarized to obtain the accurate relationship between EM parameters of an absorbing material and the volume percentage of absorbents. μ', μ'', ε', and ε'' are the EM parameters of the absorbing material; μ_1', μ_1'', ε_1', and ε_1'' are the EM parameters of the absorbent; ε'_g and ε''_g are the dielectric constants of the matrix; V_1 and V_g are the volume percentages of the absorbent and the matrix, respectively; and f is the operating frequency. There are no dependencies among the above parameters[23]:

$$\begin{aligned} \mu' &= f_1(\mu_1', V_1, f) \\ \mu'' &= f_2(\mu_1'', V_1, f) \\ \varepsilon' &= f_3(\varepsilon_1', \varepsilon_g', V_1, V_g, f) \\ \varepsilon'' &= f_4(\varepsilon_1'', \varepsilon_g'', V_1, V_g, f) \end{aligned} \tag{1.87}$$

where μ_1', μ_1'', ε_1', and ε_1'' are the EM parameters when the quantity of the absorbent is 100% in the absorbing material. Absorbents are usually powder materials and can't be pressed into pure samples; therefore the values of μ_1', μ_1'', ε_1', and ε_1'' cannot be obtained through testing directly. It is feasible for us to calculate the values of V_1 and V_g and test the values of μ', μ'', ε', and ε'' as well as ε'_g and ε''_g for each absorbing material sample. Taking no account of the explicit function expression of the arguments in the above formulas, the numerical values of the parameters at different frequencies can be measured, and therefore, μ_1', μ_1'', ε_1', and ε_1'' can be calculated through four formulas.

However, as the functional relationships in the above formulas are unknown, multiple samples are needed to confirm the values of μ_1', μ_1'', ε_1', and ε_1''. If the given functions are correct, the obtained μ_1', μ_1'', ε_1', and ε_1'' from each sample should reach the same values. Actually, for the existence of measuring error and sample inhomogeneity, these values are just closed and a few values may have a larger difference. In the actual processing, the values with relatively larger deviations are rejected and then the average value is calculated. When these values are brought into the above functions, the relation curve between μ', μ'', ε', and ε'' and V_1 can be determined.

In the actual test, the volume fraction can be determined on the basis of the ratio of the density and weight of each component. If the densities of the absorbent and matrix are ρ_1 and ρ_g, respectively, the density of the absorbing material sample is ρ_s; the compound dielectric of the matrix is $\varepsilon_g' - j\varepsilon_g''$; and the weight ratios of the absorbent and matrix are G_1 and G_g, respectively, and $G_1 + G_g = 1$. The volume percentages of the absorbent, matrix, and air are V_1, V_g, and V_k, respectively, and they can be calculated according to the following formulas:

$$
\begin{aligned}
V_1 &= \rho_s G_1/\rho_1 \\
V_g &= \rho_s G_g/\rho_g \\
V_k &= 1 - V_1 - V_g
\end{aligned}
\tag{1.88}
$$

1.3.2 Density of Absorbents

The density of an absorbent includes apparent density, tap density, and true density. Apparent density is the density obtained when the powder fills up the specified standard container freely. If the container is shaken to make it tight during the powder-filling process, then the obtained density is called tap density. The true density is measured by a pycnometer. The EM parameters measured with different densities are generally varied; hence, the referring EM parameters must be a numerical value under specific test conditions. In addition, the density of the absorbent will have a great influence on the entire EM wave absorption effect. In a composite material, the density of the absorbent is the percentage composition of the absorbent. On the basis of the EM parameter and impedance matching, the density of an absorbent has an optimum value on microwave absorption performance.

1.3.3 Particle Size of Absorbents

The particle size of an absorbent has a large influence on the EM wave absorbing performance and the selection of absorbing frequency. Nowadays there are two choice trends of the absorbent grain size: First, the particle size of absorbing agents trending toward miniaturization and nanocrystallization is the research focus at present. When a particle is refined to a nanoparticle, owing to the small size and large specific area, the atoms on the nanoparticle's surface and the dangling chemical bonds are numerous and the activity of the nanomaterial is enhanced. Interfacial polarization and multiple scattering are the main reasons that nanomaterials show the microwave absorption property[24]. Second, the absorbing units are discontinuous. The percolation point of the absorbent in the matrix appeared relatively early after refining, and the absorbent formed a conductive network, which is effective to reflect the EM wave strongly and make it difficult for the EM wave to enter the material. It is insufficient to fully absorb EM wave when the absorbent content is controlled under the percolation point. Therefore, the discontinuous millimeter-level absorbing unit should be formed in the absorber, and the content of the absorbent in each absorbing unit should be increased as much as possible. The absorber matches the impedance of free space favorably, the EM wave enters the material maximally in this way, and then the absorbing band is broadened and the absorption efficiency is improved enormously.

1.3.4 Shapes of Absorbents

An absorbent is the crux to obtain a high-performance absorbing material. Besides the particle content, particle size, and aggregate