# 1

# Fundamentals of Electromagnetic Wave Absorbers

Needless to say, learning the theory and application of wave absorbers entails learning the fundamentals of electromagnetic (EM)-wave engineering itself. In short, this means learning about a broad range of basic matters such as the following:

(a) Transmission line theory, which will aid in understanding the fundamental phenomena of EM waves;
(b) Analytical methods to learn EM-wave reflection and transmission phenomena;
(c) Various behaviors of EM waves;
(d) Theory of EM-wave analysis by computer simulation;
(e) Basic knowledge of EM-wave materials;
(f) Measurement of EM-wave material constants;
(g) The EM-wave environment associated with wave absorbers;
(h) Fundamental concepts of artificial materials;
(i) Knowledge of EM-wave absorbers that can be assimilated with artificial intelligence (AI) technology, and other matters.

Even if called just an "EM-wave absorber," its application fields are broadly extended. Particularly, in recent years, higher frequency applications in various kinds of communication systems have advanced rapidly. However, as the frequency region becomes higher, measures against EM scattering and diffracted waves are inevitably required.

Also, as is well known, EM waves are widely used in fields ranging from communication technologies to medical applications. Therefore, the existence of a radio wave absorber plays an important role ranging from preservation of such communication environment safety down to human body protection [1].

In this chapter, in order to make it easier to understand the contents of this book, basic matters on EM-wave absorbers are arranged from various perspectives.

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After first defining what an EM-wave absorber is, Section 1.1 briefly describes the history of EM-wave absorber development along with the application fields.

In Section 1.2, the quantitative representation method of the EM-wave absorption characteristic, namely, the reflection coefficient is defined. In Section 1.3, the EM-wave absorbers are classified and described from the viewpoint of appearance, composition form, material, and frequency characteristics; these are summarized in a table. In Section 1.4, various applications of EM-wave absorbers are introduced together with the literature. Finally, new wave absorber technologies described in the later chapters are briefly introduced.

## 1.1 Introduction to Electromagnetic-Wave Absorbers

As the name of the EM-wave absorber, "radio wave absorber," is often interpreted conventionally. However, the expressions "electromagnetic wave absorber" or, more simply, "absorber" are, except for a special case, adopted in this book. The EM-wave absorber refers to structures that can absorb an incident EM wave based on the principles of transforming the incident EM-wave energy into Joule heat or canceling mutually the phases between the incident EM wave and the reflected wave.

An object that completely absorbs all light wavelengths is known as a black body, and carbon is considered as nearly a black body. As for sound wave environments, sound-absorbing materials have been often utilized, and glass fibers, rock wools, etc. have been used as materials that absorb sound waves well. Thus, even before the EM-wave absorber was developed, objects that can be referred to as "absorbers" have been used in various scenarios in our daily lives.

The study of wave absorbers is said to date back to the study of EM-wave absorbers for the 2-GHz band carried out in the mid-1930s at the Naamlooze Vennootschap Machinerieen in the Netherlands [2].

Ever since the various types of EM-wave absorbers were developed, mostly for anechoic chamber applications, they basically have been composed of carbon-based materials.

During World War II, research began to be carried out, associated with the deep interest in wave absorbers for military use. For example, in the German Schornsteinfeger Project, two types of wave absorbers used for radar camouflage by mounting them on the periscope and snorkel of a submarine were developed [3]. One of the wave absorbers was made of a material called "Wesch," in which a carbonyl iron material is dispersed in a rubber sheet. The other, namely, the Jaumann absorber [3], was one in which a resistance sheet and a dielectric (plastic plate) were alternately superimposed, as shown in Figure 1.1d in Section 1.3. In addition, in the United States, in a project organized by O. Halpern at the MIT Radiation Laboratory, with the aim of realizing a coating-type wave absorber, the Halpern antiradar paint (HARP) was developed.

This was an EM-wave absorber using an artificial dielectric with a thickness of approximately 0.6 mm. It had a high-performance wave absorber with a resonance characteristic at the X-band. Furthermore, the “Salisbury screen absorber” was also developed at the same time in the Radiation Laboratory [4]. This was a resonant-type wave absorber, as shown in Figure 1.1b, and its structure was composed of the resistive sheet with a resistance value of 377 Ω, which was placed in a location $\lambda/4$ away from the back conductor plate.

In addition, from a practical standpoint, such as for performing measurements related to electronic devices and antenna characteristics, there is a need for an anechoic chamber. For this countermeasure, a pyramidal wave absorber capable of absorbing broadband EM waves was developed by Neher et al. in 1953. Owing to the development of this kind of a wave absorber, high accuracy has been achieved in experiments such as in the measurement of antenna radiation patterns in an anechoic chamber [5].

From a theoretical approach viewpoint, scattering waves from a planar multilayer absorber and a wedge-type absorber aimed at use for broadband wave absorbers for anechoic chambers were analyzed. This kind of analysis was conducted by G. Franceschetti and colleagues, who introduced an approximate analysis method of Riccati differential equations and optical approximation [6].

Currently, as wave absorbers based on new concepts, autonomously controllable wave absorbers [7, 8] have been promoted aggressively. In addition, wave absorbers based on the idea of a left-handed metamaterial [9] have been proposed.

In the next section, the EM-wave absorber is explained in detail from various viewpoints.

## 1.2 Fundamentals of Absorber Characteristics

The ideal wave absorber is able to absorb all incident EM-waves, regardless of the incident wave direction, polarization, and frequency. In other words, it is an object that does not cause any reflection waves. In practice, however, an ideal EM-wave absorber does not exist. Therefore, the performance of EM-wave-absorbing characteristics has been defined by the method of providing beforehand the allowable value assigned as the reflection coefficients. Usually, the reflection coefficient is defined to be −20 dB or less; when high performance is required, it is assumed to be −30 dB or less, as shown in Table 1.1 [10].

As the quantitative value that indicates the EM absorption performance, the reflection coefficient is represented generally in decibels. This reflection coefficient can be also regarded as return loss. A value of −20 dB corresponds

**Table 1.1** Representations of reflection coefficient in wave absorbers.

| Reflection coefficient (dB) | Electric-field reflection coefficient (S) | Electric-field standing-wave ratio (VSWR) | Power reflection coefficient[a), b)] |
|---|---|---|---|
| −20 | 0.1 | 1.2 | 0.01 |
| −30 | 0.03 | 1.06 | 0.001 |

a) −20 dB means that 99% of the EM-wave energy incident on the absorber is absorbed if converting to energy.
b) At −30 dB, 99.9% of energy is absorbed.

to an electric-field reflection coefficient of 0.1 or a power reflection coefficient of 0.01.

From an energy viewpoint, a value of −20 dB means also that 99% of the EM-wave energy that is incident on the wave absorber is absorbed. Also, for a reflection coefficient of −30 dB, 99.9% of the incident EM-wave energy to the EM-wave absorber is absorbed. Conventionally, the absorption amount of the EM-wave absorber was evaluated using a voltage standing-wave ratio (VSWR). Recently, the reflection coefficient or return loss mentioned earlier has been used. For the VSWR value, −20 dB is equivalent to 1.2. As a special case, in the wireless local area network (LAN) field, which has led to increased demand for wave absorbers, the acceptable reflection coefficient is regarded as −6 dB or less.

## 1.3 Classifications of Absorbers

As is well known, EM-wave absorbers are classified according to various factors such as the structure, the material to be used, and the frequency band to be applied, as listed in Table 1.2. In this section, the wave absorbers related to an incident wave radiated from a far oscillator are explained – that is, the absorber against a plane wave case.

### 1.3.1 Classifications by Appearance

First, let us classify the EM-wave absorbers from their appearance [10]. There are various types of EM-wave absorbers, such as those shown in Figure 1.1.

#### 1.3.1.1 Single-layer-type Absorber

As shown in Figure 1.1a, a flat-plate-type wave absorber is composed of a structure in which the wave absorber surface against the normal incident EM-wave direction is flat. A typical example of this type of wave absorber is a ferrite wave absorber.

**Table 1.2** Classifications of wave absorbers.

| Classification | Item | Remarks |
|---|---|---|
| *1. Material classification* | | |
| | 1) Conductive material | 1) Carbon materials such as carbon black or graphite have become a major material. Also, metal-based material, or the like, having a resistance is used |
| | 2) Dielectric material | 2) Carbon rubber, carbon-containing foamed urethane, and carbon-containing foamed polystyrene, which are made by mixing carbon into rubber or urethane |
| | 3) Magnetic material | 3) Ferrite or carbonyl iron material is used mainly |
| | 4) Metamaterial | 4) Metamaterials called as left-handed are used |
| | 5) Special material | 5) Special material |
| | a) Materials based on equivalent transformation method of material constant | a) By means of combinations or modifications of existing materials, the wave absorber materials create new characteristics |
| | b) Substrate-type material mounting an integrated circuit | b) Wave-absorbing material consisting of a microwave integrated circuit substrate |
| | c) Substrate-type material equipped with autonomous-control-type circuit | c) Material composed of active elements, sensors, and a microchip computer, on the same substrate |
| *2. Classification by configuration form* | | |
| (I) Classification from the number of layers | 1) Single-layer-type wave absorber | 1) EM-wave absorber which is made from a single layer |
| | 2) Two-layer-type wave absorber | 2) EM-wave absorber which consists of two layers having different material constants |
| | 3) Multilayered wave absorber | 3) Wave absorber which is constituted of three or more layers |

| | | |
|---|---|---|
| (II) Classification by shape | 1) Flat plate-shaped wave | 1) Flat configuration of radio wave incident surface |
| | 2) Quarter-wavelength wave absorber | 2) Wave absorber having the configuration where the film-shaped resistor is placed in quarter wavelength apart from a conductive plate |
| | 3) Multilayered wave absorber | 3) Wave absorber having configurations of different layered material constants |
| | 4) Jaumann absorber | 4) Wave absorber superimposing alternating resistive sheet and the dielectric plate |
| | 5) Chevron-shaped wave | 5) Wave absorber composed of chevron shape at radio wave incident surface |
| | 6) Pyramidal wave absorber | 6) Wave absorber composed of tapered pyramidal structure at incident side |
| (III) Classification by frequency characteristics | 1) Narrowband-shaped wave absorber | 1) Wave absorber having the fractional bandwidth $f/f_0 = 10\text{–}20\%$ approximately. |
| | 2) Broadband-type wave absorber | 2) $P$ value is more than 20%, and a wave absorber having peak or twin peaks. |
| | 3) Ultra-wideband-shaped wave absorber | 3) In more than a certain lower limit frequency, the wave absorber shows an allowable reflection attenuation characteristic or less |

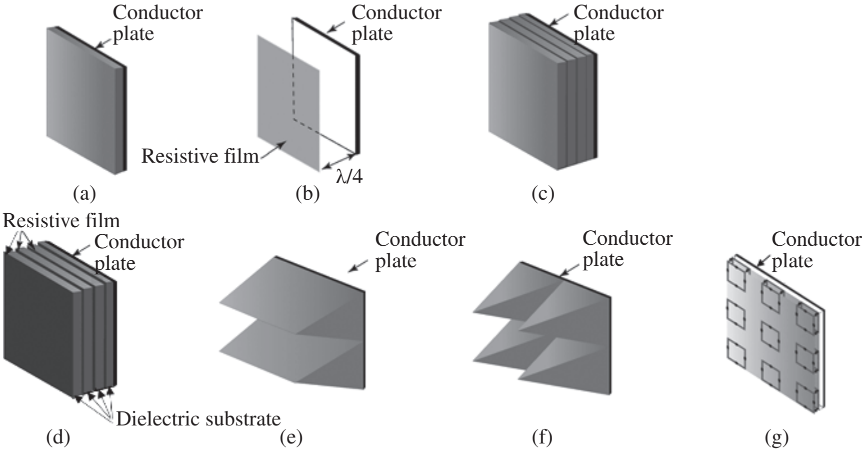

**Figure 1.1** Main classifications of the wave absorber. (a) Plane type, (b) $\lambda/4$ type, (c) multilayer type, (d) Jaumann absorber, (e) sawtooth type, (f) pyramidal type, and (g) metamaterial type.

#### 1.3.1.2 Quarter-wavelength-type Absorber

A quarter-wave-type wave absorber is constructed by placing a conductor plate in a position a quarter wavelength away from the film-shaped resistor, as shown in Figure 1.1b.

#### 1.3.1.3 Multilayered Absorber

As illustrated in Figure 1.1c, multilayered wave absorbers are constructed by layering the absorbing materials to obtain the matching characteristic by adjusting each input impedance for each material stepwise.

#### 1.3.1.4 Jaumann Absorber

As shown in Figure 1.1d, a Jaumann absorber consists of a configuration in which alternating resistive sheets and dielectric plates are superimposed.

#### 1.3.1.5 Sawtooth-shape Absorber

This EM-wave absorber surface is a sawtooth type and has a kind of tapered shape, as shown in Figure 1.1e. Because of this configuration, this absorber shape has been called a chevron-shaped absorber. Although this is a single-polarization-type EM-wave absorber, it becomes possible to absorb EM waves over a wide frequency band efficiently, as with the pyramid type, which is treated next.

#### 1.3.1.6 Pyramidal Wave Absorber

As shown in Figure 1.1d, because the pyramidal wave absorber adopts a pyramidal shape from the EM-wave incident side, this absorber exhibits EM-wave absorption characteristics over a wide frequency band to both polarized EM waves. This wave absorber is made by impregnating urethane foam, Styrofoam, or the like with a carbon material. This absorber has been widely put into practical use.

#### 1.3.1.7 Absorbers by Artificial Materials and Special Materials

Recently, as described later, wave absorbers related to left-handed metamaterials have been proposed.

### 1.3.2 Classifications of Material

#### 1.3.2.1 Conductive Absorber Material

Wave-absorbing materials that have been used since the wave absorber was invented include lossy conductive metal materials, resistive powders, and resistive films. These can be said to be typical EM-wave absorbers. This is because they are based on the principle of changing the currents generated in the absorber by the incident wave into Joule heat. As conductive wave-absorbing materials, there exist materials having predetermined resistance values. These are composed mainly of carbon-based materials such as carbon black or graphite. They are widely used in the form of platelike or filmlike materials for the conductive type of wave absorber material. Furthermore, excellent EM-wave-absorbing characteristics are realized if using a specific conductive fabric. A typical example of an EM-wave absorber using a resistive conductive material is a $\lambda/4$-type wave absorber, which is a basic EM-wave absorber configuration.

#### 1.3.2.2 Dielectric Absorber Material

Examples of dielectric wave-absorbing materials are carbon rubber, carbon-containing urethane foam, and carbon-containing expanded polystyrene. These materials are made by mixing carbon material with rubber, urethane, etc. This kind of material is used to realize broadband absorption characteristics and is applied to multilayer-structure, wedge, or pyramid types of wave absorbers, as described earlier.

#### 1.3.2.3 Magnetic Absorber Material

A thin wave absorber configuration can be realized using ferrite, carbonyl iron, and the like, which are magnetic loss materials available at frequencies higher than the very high frequency (VHF) band. In this case, the EM-wave-absorbing characteristic is strongly governed by the frequency dispersion characteristic of magnetic material and, thus, by permeability value.

#### 1.3.2.4 Metamaterial

Recently, wave absorbers have been proposed as one of the applications of the metamaterial that is called “left-handed.” Exploiting the idea of the left-handed metamaterial has made possible new types of absorbers that do not require a back conductor plate [9], and terahertz band absorbers have been suggested. Further, EM-wave absorbers based on a novel configuration concept have been proposed, and they are summarized as follows.

(a) To realize new EM-wave-absorption characteristics, an absorber based on the idea of equivalently converting material constants by means of loading some kind of metal pattern on an existing material surface or making small holes, and the like has been proposed (see Chapter 9). These methods are unified as the "equivalent transformation method of material constants." By introducing this concept, wave absorbers much thinner than the conventional ones can be realized [11, 12].
(b) A new wave absorber is a type composed of a microwave integrated circuit. This wave absorber has a simple, yet lightweight, structure, and the broadband-absorbing characteristics can be realized effectively, even beyond the microwave frequencies [13, 14].
(c) An autonomously controllable metamaterial-type wave absorber is a wave absorber based on a completely new material concept; thus, its structure is composed of a type of artificial material that is equipped with the active element circuit, sensors, and microchip computer on the same substrate [7, 8, 15–17].

The concept of this material configuration is based on the autonomy of living tissue, as is described in Chapter 10.

### 1.3.3 Classifications by Configuration Forms

Furthermore, the wave absorber is categorized from the viewpoint of the "number of layers" constituting each absorber layer and the "shape of appearance" in the absorber structure.

#### 1.3.3.1 Classification from Layered Numbers

(a) Single-layer-type absorber
An absorber made from a single-layer material is called a "single-layer-type wave absorber." Normally, a metal plate made of aluminum, copper, or the like is attached to the back of an absorber. This type of EM-wave absorber can be seen in those using ferrite, carbonyl iron material, and other such materials.
(b) Two-layer-type absorber
This is a wave absorber that has two layers composed of different material constants. This configuration is often introduced when aiming at improving a single-layered absorber's characteristic to realize a more broadband absorber characteristic.

(c) Multilayered absorber

The multilayered wave absorber is usually a wave absorber consisting of three or more layers. In the multilayered wave absorber, the wideband characteristics are obtained by increasing the number of layers, and this kind of absorber can be used, for example, for an anechoic chamber.

### 1.3.4 Classifications by Frequency Characteristics

Regarding the quality of the EM-wave absorber characteristic, the "goodness of absorption characteristic" is defined by introducing the idea of a "figure of merit [10]."

For example, when evaluating a reflection coefficient below −20 dB as a good EM-wave absorber, if the bandwidth cut by the level of −20 dB values is assumed to be $\Delta f$, by dividing the bandwidth values $\Delta f$ with the center frequency $f_0$, the figure of merit can be defined as $\Delta f/f_0$. This characteristic is mainly classified into the three types shown in Figure 1.2.

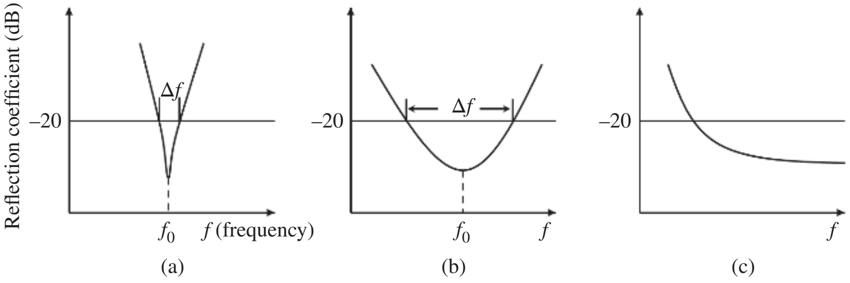

**Figure 1.2** Classification by frequency band. (a) Narrowband type, $\Delta f/f_0 \times 100 = 10-20\%$; (b) broadband type $\Delta f/f_0 \times 100 = 20-30\%$; and (c) ultra-wideband type $\Delta f/f_0 \times 100 = 30\%$ and above [10].

#### 1.3.4.1 Narrowband-type Absorber

This is usually associated with the case of the characteristic that can be found in a single-layer wave absorber, or the like. In this case, if the figure of merit is expressed as a percentage, it is approximately 10–20%, as illustrated in Figure 1.2a. When a narrow frequency band is needed, as in the case of a radar application, this type of absorber is used.

#### 1.3.4.2 Broadband-type Absorber

Notice that the distinction between the case of the wideband and the narrowband types is not clearly defined. In the case where the percentage of $\Delta f/f_0$ is not less than 20%, the EM-wave absorbers often show a peak or twin-peak characteristic, as shown in Figure 1.2b. These cases are generally referred to as "broadband wave absorbers."

#### 1.3.4.3 Ultra-wideband-type Absorber

This type of absorber possesses a wideband-absorbing characteristic in the above-assigned absorbing frequency, which is set beforehand. This results in an absorption characteristic of a type in which the lower limit frequency of the allowable reflection coefficient to the EM-wave absorber meets the specified frequency.

In other words, it is an EM-wave absorber with broadband characteristics that can absorb EM waves above a frequency determined beforehand, as depicted in Figure 1.2c. Of course, because $\Delta f/f_0$ becomes infinite, the definition of the figure of merit cannot be used in this case. In general, the multilayer absorber, wave absorber of the saw-tooth shape, and pyramidal shape exhibit this kind of property.

## 1.4 Application Examples of Wave Absorbers

The examples of the main application of the wave absorber and the related materials used therein are given in Table 1.3. As shown in Table 1.3, the EM-wave absorber application fields are expanding along with the development of communication technologies.

As shown in Table 1.3, with respect to the wave absorbers of the anechoic chamber described previously, many studies have been conducted, and much research that incorporates the latest analysis has been published. For example, with respect to the pyramid-type or wedge absorbers, research based on theory and experiments [18], the moment method [19, 20], and the frequency-domain finite-difference method [21] have been reported. Further, careful experimental studies have been conducted to study the anechoic chamber [22–24].

In addition, as one of the main application fields of the EM-wave absorber, the topic of radar technology improvement has been examined. Particularly, applications of the EM-wave absorber associated with radar problems have been studied from the early stages of wave absorber development [25–30]. Countermeasures to the problem of false images that occur on a radar screen, caused by radar waves reflected from a large bridge over the strait, have been in demand. For high-rise buildings, wave absorber walls were developed in Japan, because the reflection of the TV EM wave from a building wall surface causes a TV ghost (see Chapter 8). Furthermore, from the viewpoint of EM environment conservation in various consumer electronics products and wireless LAN environments, EM-wave leakage measures have been considered, leading to the development of various types of wave absorbers. In addition, measures to reduce noises generated from printed circuit boards are needed from the standpoint of absorber material and are an issue in recent EM compatibility research.

As for these countermeasures, a thin plate-shaped sheet made of a magnetic material called a noise-suppressing element, fine ferrite beads, etc. has been

**Table 1.3** Examples of main wave absorber use.

| **Application examples** | **EM-wave absorber, and material used** |
|---|---|
| For anechoic chamber (more than 30 MHz) | • Wave absorber of combination multilayer structure with carbon-based material and ferrite<br>• Pyramid-type wave absorber material being produced by mixing carbon in urethane foam material, or wave absorber in which sawtooth type unit absorbers made of a carbon material are arranged alternately in vertical and horizontal directions.<br>• Ferrite single-layer wave absorber (simplified type)<br>• Electromagnetic-wave absorber material that is composed of a combination of a dielectric comprising metal fiber material and a ferrite |
| Improvement of radar characteristics | • Absorber material using sintered ferrite<br>• Absorber material of rubber ferrite<br>• Absorber material composed of a nonwoven fabric and metal fibers |
| For high-rise building wall (TV ghost prevention measures, 100 MHz – an example of the old analog broadcasting) | • Absorber material of ferrite tile<br>• Absorber material using ferrite and dielectric combination<br>• Absorber material mixing ferrite grains into concrete |
| For electromagnetic interference prevention (for prevention of leakage wave of a microwave oven, wireless LAN measures) (2.45 and 5.2 GHz) | • Wave absorber using rubber ferrite<br>• Wave absorber using resin ferrite<br>• Wave absorber composed of carbon-based dielectric material and building materials<br>• Wave absorber composed of resistance film-based materials and building materials<br>• Wave absorber composed of ferrite and building materials |
| Countermeasure for electronic circuit noise (10 MHz to 5 GHz) | • Sheets composed of special magnetic materials and electrically conductive material<br>• Insulation sheet which has ferrite powder mixed with polymer<br>• Composite material made from metallic flat powder<br>• Small cylindrical-shaped ferrite |
| For mobile communication (malfunction prevention measures of electronic automatic billing system, 5.8 GHz) | • Wave absorber material consisting mainly of ferrite<br>• Foam material containing a conductive material<br>• Wave absorber material containing metal fiber in nonwoven fabric<br>• Wave absorber material coated with a conductive paint on synthetic fibers<br>• Paved road wave absorption material consisting of carbon fiber and asphalt material |

developed. Furthermore, malfunction prevention measures based on EM-wave scattering in the site of an electronic automatic billing system are an example of the application of EM-wave absorbers for mobile communications.

Moreover, EM-wave absorbers are expected to play an important role also from the viewpoint of communication control in the automated driving vehicle technology, which has been rapidly developing recently, and in infrastructure development related to this area of research. Thus, the application fields of EM-wave absorbers are expanding in response to the recent development of communication technology, as shown in Table 1.3.

## References

**1** Vandrer Vorst, A., Rosen, A., and Kotsuka, Y. (2006). *RF/Microwave Interaction with Biological Tissue.* Wiley Interscience.

**2** Naamlooze Vennootschap Machinerieen, French Patent 802 728, Feb. 19, 1936.

**3** Schade, H.A. (1945). Schornsteinfeger. U.S. Tech. Mission to Europe, *Tech. Rep. 90-45 AD-47746*.

**4** W. W. Salisbury, "Absorbent body for electromagnetic waves," US patent 2599944, filed May 11, 1943, granted Jun. 10, 1952.

**5** Emerson, W. (1973). Electromagnetic wave absorbers and anechoic chambers through the years. *IEEE Trans. Antennas Propag.* 21 (4): 484–489.

**6** Franceschetti, G. (1964). Scattering from plane layered media. *IEEE Trans. Antennas Propag.* 12: 754–763.

**7** Kotsuka, Y. and Amano, M. (2004). New concept for functional electromagnetic cell material for microwave and millimeter use. *IEEE MTT-S International Microwave Symposium Digest*.

**8** Kotsuka, Y., Murano, K., Amano, M., and Sugiyama, S. (2010). Novel right-handed metamaterial based on the concept of autonomous control system of living cells and its absorber applications. *IEEE EMC Trans.* 52 (3): 556–565.

**9** Landy, N.I., Sajuyigbe, S., Mock, J.J. et al. (2008). Perfect metamaterial absorber. *Phys. Rev. Lett.* 100: 207402.

**10** Shimizu, Y. (Editorial Committee Chairman) (1999). *Electromagnetic Waves Absorption and Shielding*, 123. Tokyo: Nikkei Gijyutu Tosho.

**11** Amano, M. and Kotsuka, Y. (2003). A method of effective use of ferrite for microwave absorber. *IEEE Trans. Microwave Theory Tech.* 51 (1): 238–245.

**12** Amano, M. and Kotsuka, Y. (2015). Detailed investigations on flat single layer selective magnetic absorber based on the equivalent transformation method of material constants. *IEEE Trans. Electromagn. Compat.* 57 (6): 1398–1407.

**13** Kotsuka, Y. and Amano, M. (2003). Broadband EM-wave absorber based on integrated circuit concept. In: *IEEE MTT-S International Microwave Symposium Digest*, vol. 2, 1263–1266.

**14** Kotsuka, Y. and Kawamura, C. (2005). Proposal of a new EM-wave absorber based on integrated circuit concept. *IEICE Trans.* J88-C (12): 1142–1148.

**15** Kotsuka, Y. and Amano, M. (2003). Microwave Functional Material for EMC. *Tech. Rep. of IEICE, EMCJ 3003-40*, pp. 13–18.

**16** Kotsuka, Y. and Amano, M. (2004). A new EM-wave absorber using functional electromagnetic cell material. In: *Proceedings of the EMC'04 Sendai*, vol. 1, 301–304.

**17** Kotsuka, Y., Sugiyama, S., and Kawamura, C. (2007). Novel computer control metamaterial beyond conventional configuration and its microwave absorber application. In: *IEEE MTT-S International Microwave Symposium Digest*, 1627–1630.

**18** Dewitt, B.T. and Burnsid, W.D. (1988). Electromagnetic scattering by pyramidal and wedge absorber. *IEEE Trans. Antennas Propag.* 36 (7): 971–984.

**19** Yang, C.F., Burnside, W.D., and Rudduck, R.C. (1992). A periodic moment method solution for TM scattering from lossy dielectric bodies with application to wedge absorber. *IEEE Trans. Antennas Propag.* 40 (9): 652–660.

**20** Yang, C.F., Burnside, W., and Rudduck, R.C. (1993). A doubly periodic moment method solution for the analysis and design of an absorber covered wall. *IEEE Trans. Antennas Propag.* 41 (5): 600–609.

**21** Sun, W., Liu, K., and Balanis, C.A. (1996). Analysis of singly and doubly periodic absorbers by frequency-domain finite-difference method. *IEEE Trans. Antennas Propag.* 44 (6): 798–805.

**22** Tofani, S., Ondrejka, A.R., and Hill, D.A. (1991). Bistatic scattering of absorbing materials from 30 to 1000 MHz. *IEEE Trans. Electromagn. Compat.* 34 (3): 304–307.

**23** Tofani, S., Ondrejka, A., and Kanda, M. (1991). A time-domain method for characterizing the reflection coefficient of absorbing materials from 30 to 1000 MHz. *IEEE Trans. Electromagn. Compat.* 33 (3): 234–240.

**24** Johnk, R.T., Ondrejka, A., Tofani, S., and Knada, M. (1993). Time-domain measurement of the electromagnetic backscatter of pyramidal absorber and metallic plates. *IEEE Trans. Electromagn. Compat.* 35 (4): 429–433.

**25** Bhattacharyya, A.K. (1989). Electromagnetic scattering from a flat plate with rim and RAM saving. *IEEE Trans. Antennas Propag.* 37 (5): 659–663.

**26** Wong, P.T.C., Chambers, B., Anderson, A.P., and Wright, P.V. (1992). Large area conducting polymer composites and use in microwave absorbing material. *Electron. Lett.* 28 (17): 289–290.

**27** Chambers, B. (1995). Symmetrical radar absorbing structures. *Electron. Lett.* 31 (5): 404–405.

**28** Knott, E.F. (1997). Suppression of edge scattering with impedance strings. *IEEE Trans. Antennas Propag.* 45 (12): 1768–1773.

**29** Williams, T.C., Stuchly, M.A., and Saville, P. (2001). Modified transmission-reflection method for measuring constitutive parameters of thin flexible high-loss materials. *IEEE Trans. Microwave Theory Tech.* 51 (5): 1560–1566.

**30** Matous, K. and Dvorak, G.J. (2003). Optimization of electromagnetic absorption in laminated composite plates. *IEEE Trans. Magn.* 39 (3): 1827–1835.