A Method of Effective Use of Ferrite for Microwave Absorber

Mitsuhiro Amano and Youji Kotsuka, *Senior Member, IEEE*

***Abstract*—To meet the demand for various electromagnetic-wave absorbers, a method for effective use of conventional ferrite in microwave absorbers is investigated both through finite-difference time-domain analysis and experiments. The matching characteristic is expanded to encompass a broad range from 1 GHz to over 4 GHz, using only a single magnetic material with a thickness of 6.5 mm. This is accomplished by simply punching small holes in a conventional magnetic absorber. The effects of various kinds of parameters for a rubber ferrite absorber with multiholes are clarified and general design charts are also presented, principally for normal incidence cases. The method of laser perforation is investigated for use in practical production. A desirable condition for obtaining a good matching characteristic in the present frequency range from 1 to 4 GHz is derived. A thin microwave absorber with a thickness of 3.0 mm at 2.45 GHz is presented as an application of punching small holes in a layer of conventional ferrite attached to a layer of carbonyl iron.**

***Index Terms*—Finite-difference time-domain (FDTD) methods, ferrites, permeability, permittivity, reflection.**

I. Introduction

RECENTLY, the demand for various kinds of electromagnetic (EM)-wave absorbers has increased, particularly in industries equipped with high-speed wireless data communication systems operating at 1.9 GHz for personal handyphone system (PHS) and 2.4 GHz for wireless local area networks (LANs) to suppress the delay spread due to multireflected waves. This kind of system is also employed in mobile communication fields such as the electric toll collection (ETC) system at 5.8 GHz, where it prevents incorrect operation.

To quickly respond to these demands and to effectively use conventional ferrite materials, a simple method of controlling the matching frequency of microwave is necessary. In the case of ferrite absorbers, however, it has been a challenge to develop an EM-wave absorber at the desired matching frequency. This is due to the fact that ferrite material is manufactured though a complex process involving such conditions as controlled sintered temperature, pressure, and a specific ratio of composite materials.

This paper describes a simple method of changing and improving the matching characteristics by punching out small holes in rubber ferrite. This is achieved not by adjusting the processing conditions to produce a new ferrite material, but by adjusting the geometrical shape of the holes. To avoid the complex process of producing absorbing materials, the authors have proposed simple methods for changing and improving the matching frequency characteristics with regards to effective use of conventional ferrite material. One method involves a weakly magnetized ferrite absorber [1], the other an absorber with two different kinds of materials distributed periodically in a checkerboard pattern [2], [3].

In this paper, the detailed matching characteristics of a multiholed rubber ferrite absorber is investigated, principally for a normal incidence case. By punching out small holes in the ferrite, the matching characteristics of the absorber are changed and improved. This principle is reached intuitively based on the resonant phenomena in the transmission line equivalent to a ferrite absorber (see the Appendix). An EM-wave absorber with a similar shape can be found in [4]. In that case, sintered ferrite was used in VHF and UHF frequency regions, but no theoretical system was established. Few experimental data were presented. The authors' earlier goal was to study EM-wave absorbers with random holes, with an eye to developing an ornamental stained-glass-type absorber for use in a microwave or in a millimeter LAN system to be installed in buildings [5]. In the course of their study, however, the authors found that this construction was important because of both its effective use of ferrite materials and because it provided a method for changing and improving the matching characteristics.

For the theoretical investigation of the present matching characteristics, finite-difference time-domain (FDTD) analysis is introduced for the first time here. Both from the analysis and experiments, detailed design charts for matching characteristics taking into consideration various parameters such as hole size, adjacent hole space, permeability, permittivity, and rubber ferrite thickness are presented. Optimum material constants necessary to obtain a good matching characteristic in the present frequency are clarified. The method of laser perforation is investigated for use in practical production. As an example of the application, a thin absorber below −20 dB in reflection coefficient with multiholes is obtained at 2.45 GHz with a thickness of 3 mm, based on the theoretical data.

II. Fundamental Construction and Analysis

Fig. 1 shows the fundamental construction of a multiholed EM-wave absorber. Small holes are punched in the rubber ferrite absorbing material and the back is attached to a conductive plate.

It is difficult to investigate the present matching characteristics from a purely experimental viewpoint due to the numerous parameters. Accordingly, FDTD analysis is applied theoretically for the first time to the present problem in order to clarify

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The authors are with the Department of Communications Engineering, Tokai University, Kanagawa 259-1292, Japan

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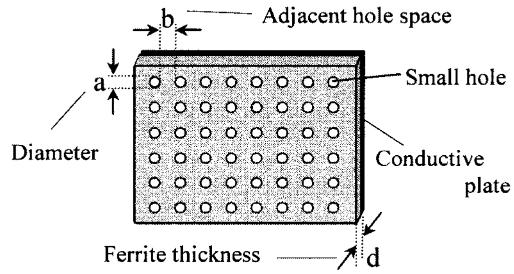

Fig. 1. Fundamental construction of multihole microwave absorber.

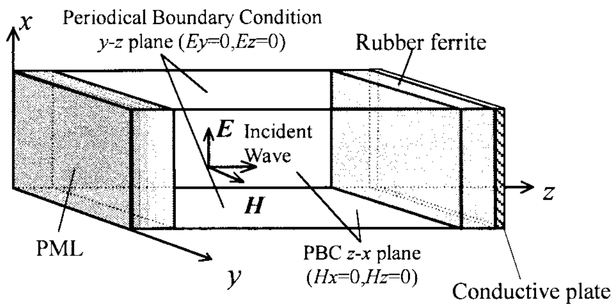

Fig. 2. Model for analysis.

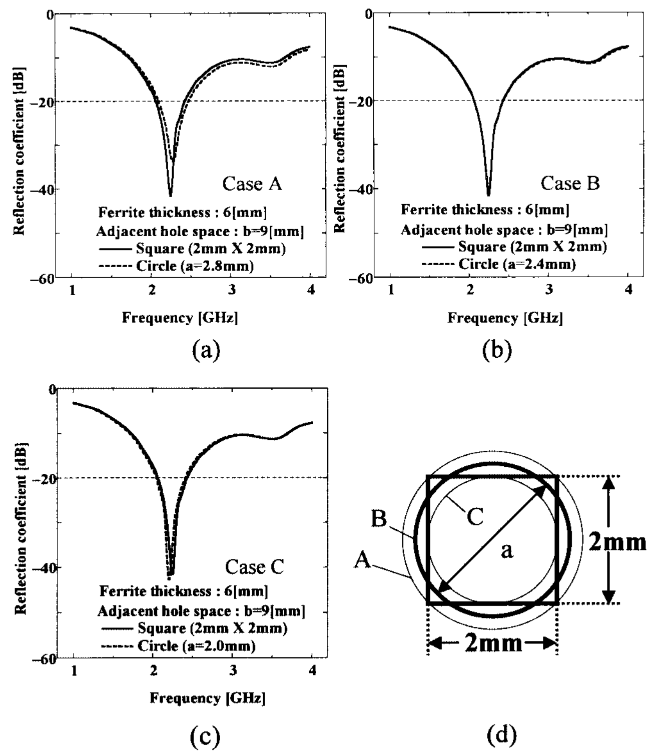

Fig. 3. Validity of approximation.

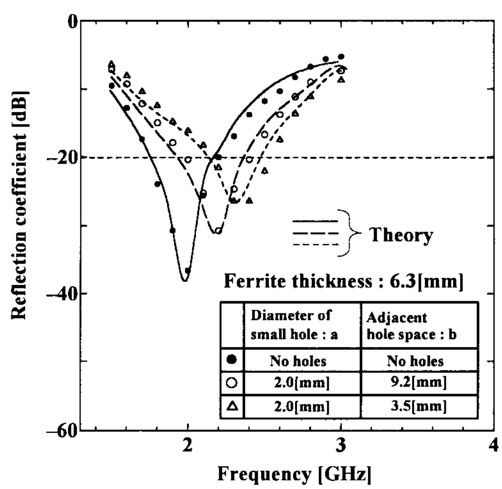

Fig. 4. Comparison of measurement with calculation.

the matching characteristics. The model of a slab waveguide in Fig. 2 analyzes reflection coefficients.

Since the present absorber has a periodical structure, periodical boundaries are adopted. On the opposite side of the ferrite absorber, a 16-layer perfectly matched layer (PML) absorbing boundary is set up. The periodical boundaries are important because of periodical construction. Therefore, when checking the accuracy of the periodical boundary, we find that it is entirely reliable in the newly developed program. The maximum number of cells is fundamentally approximately a 855 576 cell size being $\Delta x = 0.2$ mm, $\Delta y = 0.2$ mm, and $\Delta z = 1.0$ mm.

In the course of theoretical analysis, we find that a circular hole can be approximated by a square hole because the size of the holes is smaller than the wavelength. This is necessary from the standpoint of reducing the memory size and processing time for the computer analysis. Circular holes, however, are more easily manufactured than are square holes. Accordingly, circular holes are adopted in practical use. Fig. 3 shows the validity of this approximation. We find that a good approximation is obtained in middle-sized circular holes, as shown in Fig. 3(b).

In the above approximation, there is a tendency for the margin of error to increase as both the hole diameter and adjacent space increase simultaneously with the increase in frequency. When the hole diameter and adjacent hole space are both 7 mm, the margin of error in the amount of reflection coefficient is 7.7%; the margin in a central matching frequency deviation is 0.051% in the present frequency range from 1 to 4 GHz. Since the central matching frequency deviation is relatively small, we take the maximum size of 7 mm in both hole diameter and the adjacent space into account in the subsequent theoretical investigation.

Fig. 4 illustrates the comparison of calculated and measured results in matching characteristics. The dotted circles represent the measured matching characteristic without holes. In the case of 2-mm-diameter holes, the blank circles and triangles represent the measurement result of 9.2- and 3.5-mm spaces between adjacent holes, respectively. A 20D shorted coaxial waveguide where the diameters of the inner and outer conductors are 8.66 and 19.94 mm, respectively, is used in the present measurement of the reflection coefficient by mounting a cylindrical, multiholed piece of rubber. Dotted and solid lines represent theoretical values in the cases with and without holes, respectively, using measured permeability and permittivity. We find that the theoretical and experimental matching characteristics coincide closely.

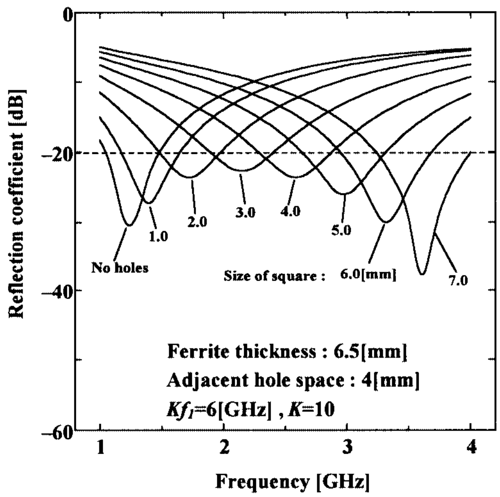

Fig. 5. Effect for size of small holes.

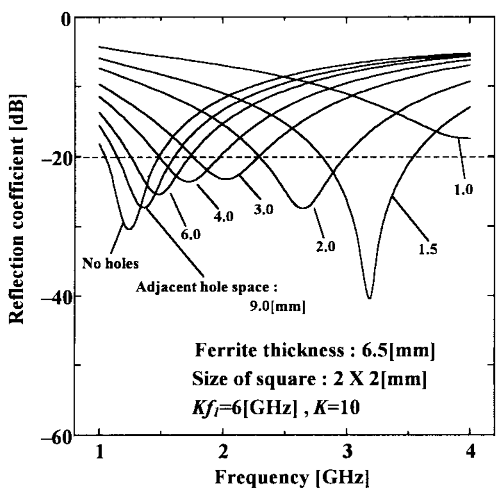

Fig. 6. Effect for adjacent hole of small holes.

III. Investigation of Matching Characteristics

A. Effect of Hole Size

Fig. 5 depicts the matching characteristics when the size of the square hole is taken as a parameter, other parameters being constant. The space between adjacent holes is 4 mm and the ferrite thickness is 6.5 mm. Fig. 6 shows the matching characteristic when the adjacent hole space is taken as a parameter. Throughout this investigation, a frequency-dispersion equation of permeability has been used as the value of permeability, as explained in Section III-B.

To summarize the theoretical results checked by these measurements, by simply punching holes in the rubber ferrite: 1) the matching frequency characteristic is shifted toward a higher frequency region as the size of the hole increases and 2) moreover, the matching frequency characteristic is shifted toward a higher frequency region as the adjacent hole space decreases [7] (see the Appendix).

B. Effect of Permeability

In order to evaluate the matching characteristics, we introduce the frequency-dispersion equation of permeability [6]. The

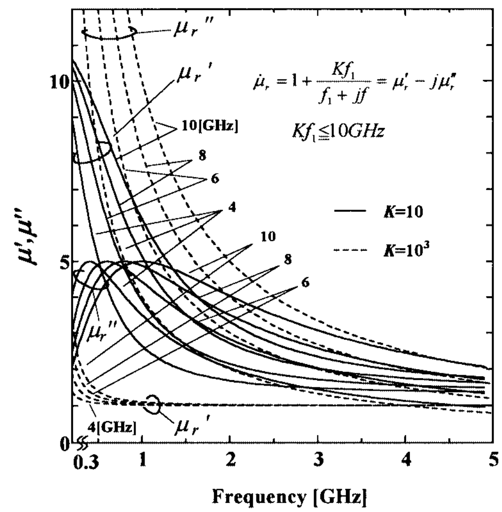

Fig. 7. Frequency characteristics of permeability.

frequency-dispersion equation is given by the following expression:

$$\dot{\mu}_r = 1 + \frac{Kf_1}{f_1 + jf} = \mu_r' - j\mu_r'' \tag{1}$$

where K is the value of static magnetic susceptibility when f is zero, f is the operating frequency, and the limit of Kf_1 is defined as the following expression derived from experimental investigation:

$$Kf_1 \leq 10\ \text{GHz} \tag{2}$$

In this expression, if Kf_1 takes on a greater value, the imaginary part of relative permeability tends to take on a greater value as well. That is, the effect of changing Kf_1 is mainly reflected in the value of the imaginary part of permeability. The change in the value of K primarily effects the real part of the permeability. If K takes on a greater value, the real part of permeability is almost 1.0 in the present frequency region. When K takes on a lower value, the real part of permeability is greater than 1.0. Fig. 7 shows the cases in which Kf_1 is taken as parameters and K is assumed to take extreme values being 10 and 10^3.

Fig. 8 shows the matching characteristics with holes when Kf_1 is taken as the parameter, the value of K being 10 and 10^3. It becomes clear that we obtain good matching characteristics when the value of K is low, even if Kf_1 is changed.

Further, as the value of Kf_1 increases in more than 7 GHz when relative permittivity is 14, the matching frequency characteristics deteriorate in the present frequency region. Common rubber ferrite has a maximum value between $Kf_1 = 6\,\text{GHz}$ and $Kf_1 = 7\,\text{GHz}$ and with a low K value. Inversely, however, when using sintered ferrite, the matching is taken in the VHF and UHF regions when K takes on a greater value. This is one reason why the authors chose a rubber ferrite in the present microwave frequency.

Fig. 9 shows general design charts illustrating the matching frequency characteristic of hole size versus hole space. Since the frequency characteristic of permeability in the present rubber ferrite coincides with the case where $Kf_1 = 4.5$ and $K = 3$,

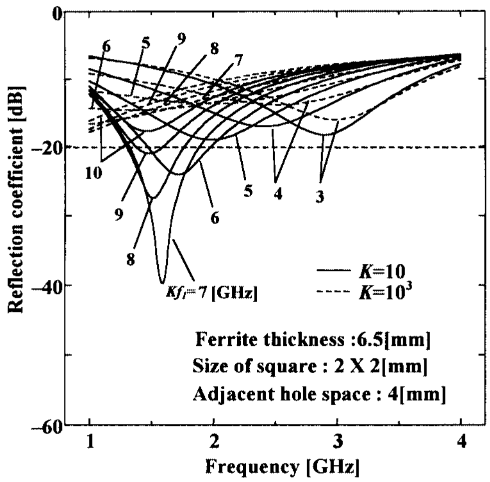

Fig. 8. Matching characteristics taking Kf_1 as a parameter in cases of $K = 10$ and 10^3.

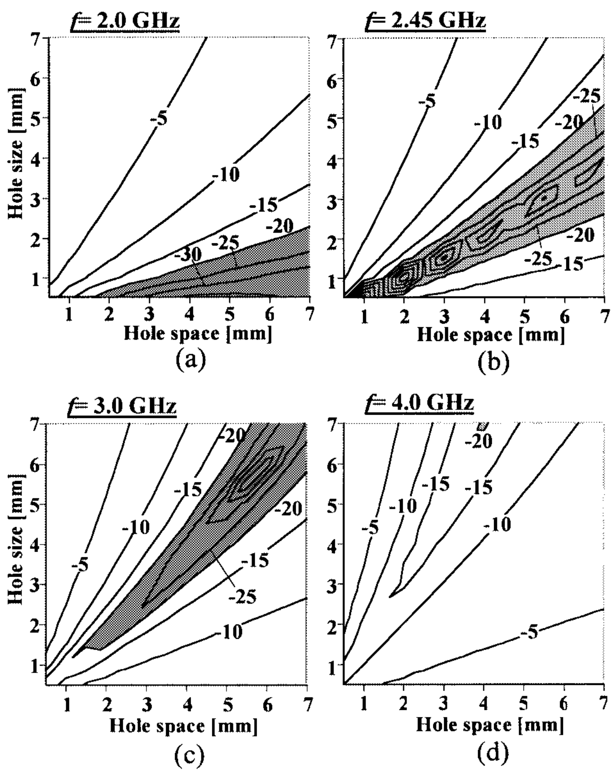

Fig. 9. Matching characteristics taking the value of permeability as a parameter ($Kf_1 = 4.5$ GHz, $K = 3$, $\varepsilon_r = 14$, $d = 6.0$ mm).

we introduce these values as standard in the subsequent discussions. The gray area represents reflection coefficient value below −20 dB. The difference between the contour lines is −5 dB. We find that we obtain a good matching characteristic if numerous closed loops or contour lines exist within the gray area. In Fig. 9, ferrite thickness, d and relative permittivity, ε_r are 6 mm and 14, respectively. We can conclude that good matching is obtained at around 2.45 GHz by adjusting the hole size and adjacent space. Fig. 10 shows the case in which Kf_1 takes on a greater value (6.0 GHz). Matching characteristics are inferior to the previous case in Fig. 9 where ferrite, at thicknesses such as 6.0 mm, is used.

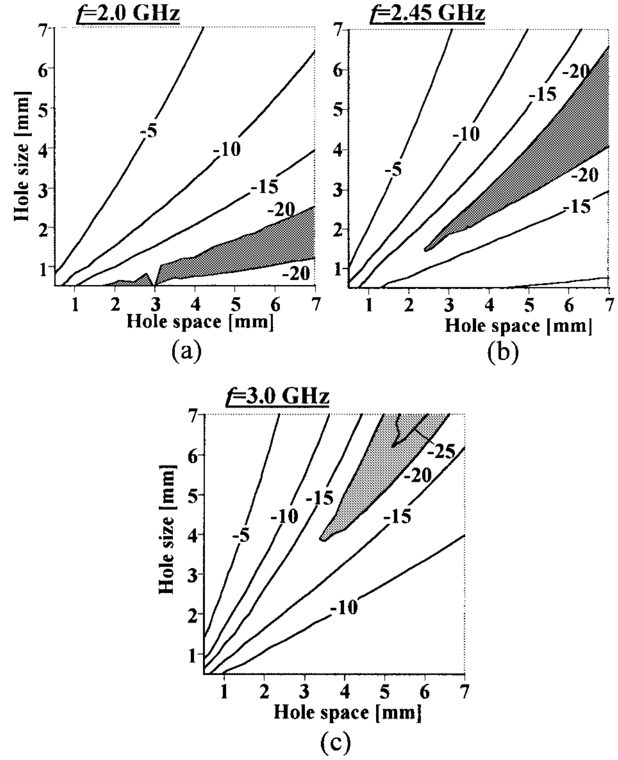

Fig. 10. Matching characteristics taking the value of permeability as a parameter ($Kf_1 = 6.0$ GHz, $K = 3$, $\varepsilon_r = 14$, $d = 6.0$ mm).

C. Effect of Permittivity

To investigate the effect of permittivity, we calculate general design charts by changing the relative permittivity. Fig. 11 illustrates the cases in which the real part of relative permittivity takes the value of 10 and 25 at the frequencies of 2.45, 3.0, and 4.0 GHz, respectively. These permittivity values are the usual limits for rubber ferrite. If the rubber ferrite accounts for a large imaginary part of permittivity, we do not obtain a good matching characteristic. In this study, rubber ferrite with a small imaginary part has been introduced from the outset. These data show an example in which the value of $Kf_1 = 4.5$ GHz and $K = 3$ in (1), where the ferrite thickness is 6 mm. From these design charts, we find that a larger permittivity value $(\varepsilon_r' = 25)$ is effective when the matching frequency is lower [see Fig. 11(a) and (d)]. On the contrary, when the matching frequency is higher, a smaller permittivity value is effective for obtaining good matching characteristics [see Fig.11 (c) and (f)].

D. Effect of Ferrite Thickness

Figs. 12 and 13 represent examples of general design charts taking the ferrite thickness as a parameter at both frequencies of 2.45 and 4.0 GHz. It becomes clear that ferrite thickness must be reduced to 4 mm at the frequency of 4.0 GHz, as shown in Fig. 13(c), if a matching characteristic of around −20 dB is needed. However, when the matching characteristic is allowed to be −15 dB, the matching ferrite thickness becomes 3.5 mm at the same frequency of 4.0 GHz, as depicted in Fig. 13(d).

If rubber ferrite with a large value such as $Kf_1 = 7.5$ GHz and a large value of permeability and a relatively large permittivity value around 18 were available, the matching thickness

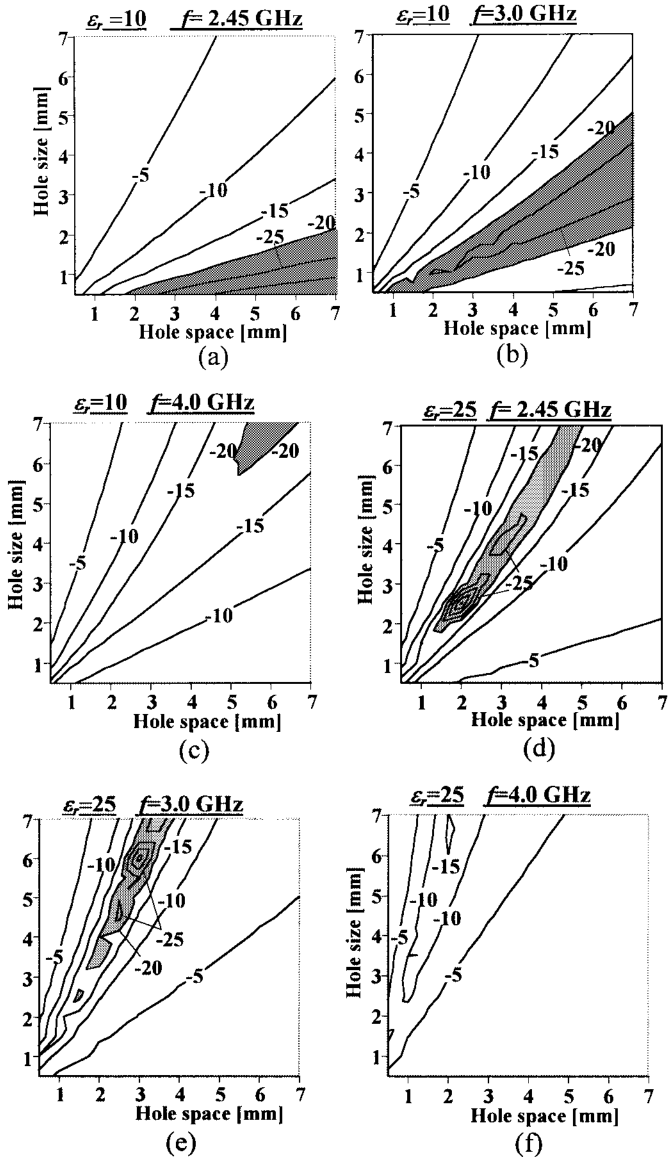

Fig. 11. Matching characteristics taking the value of permittivity as a parameter ($Kf_1 = 4.5$ GHz, $K = 3$, $d = 6.0$ mm)

would be reducible to 3.0 mm at 4 GHz, as shown in Fig.14(b). This result suggests a desirable condition for the present absorber and, at the same time, the conditions for obtaining a thin absorber in the frequency region from 1 GHz to around 4 GHz. To summarize the results mentioned herein, a thinner absorber is obtained when the values of real and imaginary part of permeability and the real part of permittivity take on greater values, as shown in Fig. 14(a) and (b).

E. Example of Oblique Incident Characteristic

The authors examined the theoretical and fundamental characteristics of oblique incidence. An FDTD computer analysis for oblique incidence was developed. The validity of the computer analysis was checked against the values of strict theoretical analysis for oblique incidence of a plane (without holes) ferrite absorber. It was confirmed that the result of computer analysis for oblique incidence coincides completely with the theoretical analysis.

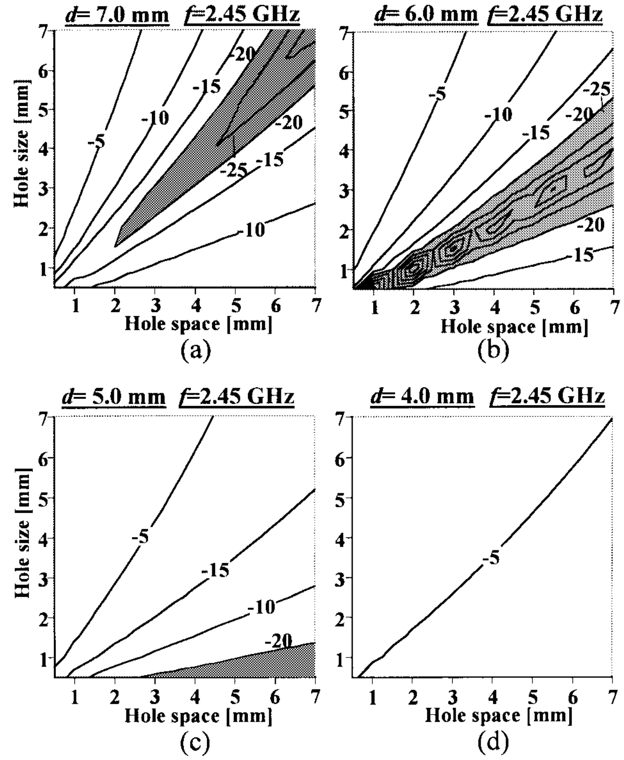

Fig. 12. Matching characteristics taking ferrite thickness as a parameter ($f = 2.45$ GHz, $Kf_1 = 4.5$ GHz, $K = 3$, $\varepsilon_r = 14$).

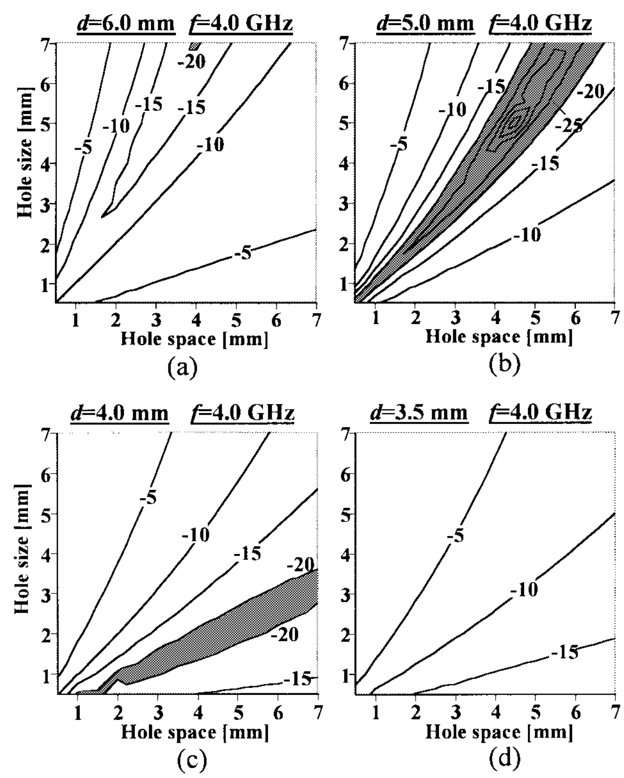

Fig. 13. Matching characteristics taking ferrite thickness as a parameter ($f = 4.0$ GHz, $Kf_1 = 4.5$ GHz, $K = 3$, $\varepsilon_r = 14$)

Fig. 15(a) and (b) shows examples of the matching characteristics for reflection coefficient versus incident angles. These matching characteristics correspond to the case in Fig. 5.

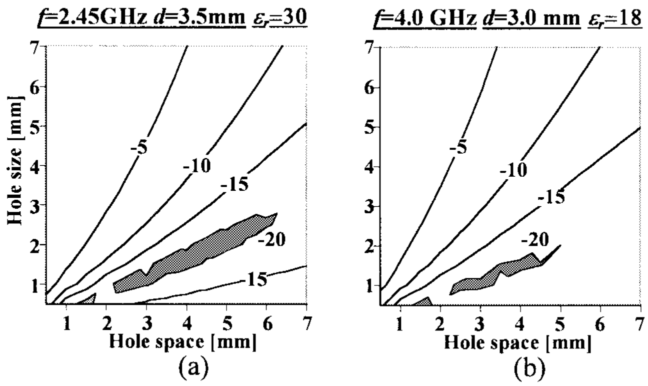

Fig. 14. Evaluation of matching thickness ($Kf_1 = 7.5$ GHz, $K = 3$).

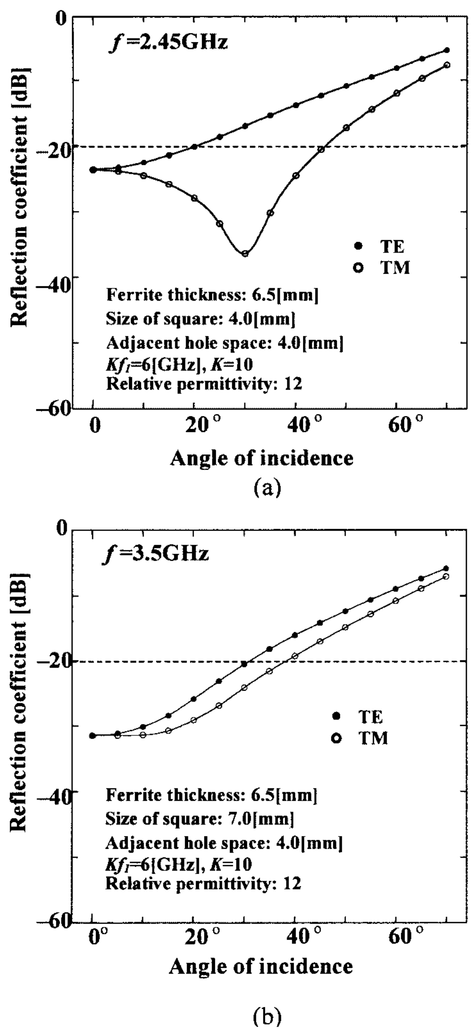

Fig. 15. Matching characteristics of oblique incidence.

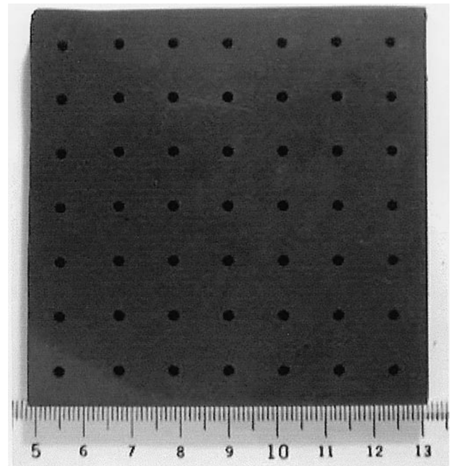

Fig. 16. Example of rubber ferrite absorber with multiholes using a Rofin SC × 20 Laser ($d = 2.0$ mm).

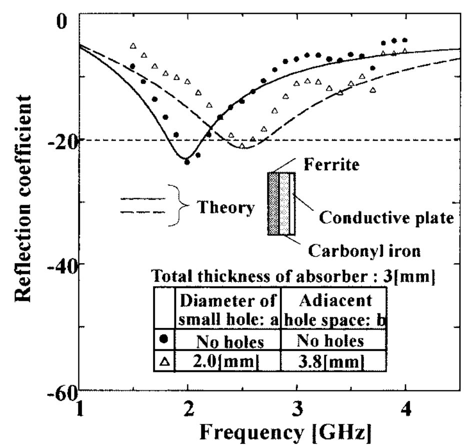

Fig. 17. Matching characteristics of double layer absorber.

Fig. 15(a) illustrates the case where hole size and adjacent hole space are both 4 mm, with a ferrite thickness of 6.5 mm at 2.45 GHz, as shown in Fig. 5. Fig. 15(b) illustrates the case where hole size and adjacent hole space are 7 and 4 mm, respectively, with a ferrite thickness of 6.5 mm at 3.5 GHz. From Fig. 15, we find that the oblique incident matching characteristic of the TE wave deteriorates earlier than those of the TM mode. The tendencies of present oblique incidence are similar to the cases of a plane rubber ferrite absorber.

IV. Method of Perforation

It is important to establish an accurate methodology for controlling the hole diameter for this rubber absorber. For this purpose, the authors investigated a laser perforation method.

Fig. 16 shows an example of holes with a diameter of 2 mm and adjacent hole spaces of 9 mm. The circular holes are formed with a CO_2 laser with a maximum power output of 200 W and a continuous wave (CW) maximum pulse frequency of 10 kHz (Rofin Sinar Laser, SC20). The diameter accuracy is checked using a profile projector (Nikon, V-12). At present, holes with an error factor of less than ±0.1 mm can be formed. Further, smaller diameter perforation is also examined. We find that a 0.1-mm hole diameter can be formed even when sintered ferrite is used. This accurate perforation method will be important when the present absorber is used in the millimeter frequency region where a small diameter is required.

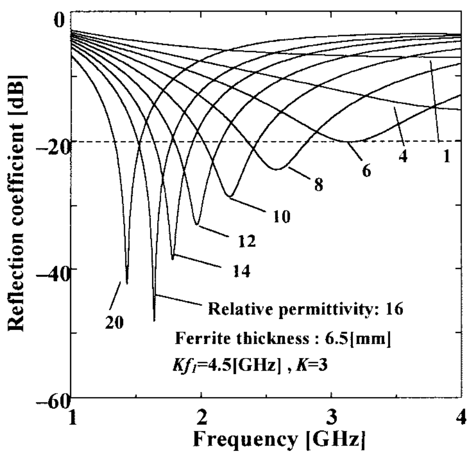

Fig. 18. Effect for relative permittivity.

V. Example of Application

On the basis of the investigations mentioned herein, a thin absorber at the frequency 2.45 GHz is designed by applying the idea of multiholes to a double-layered absorber. Carbonyl iron material is selected for the second material because it maintains a large permeability value, particularly its imaginary part, in the present frequency region. This is because when a ferrite absorber becomes a perfect absorber, the matching thickness d_m is approximately given by the following expression [2]:

$$d_m = \frac{\lambda}{2\pi\mu_r''}$$

where λ is the wavelength and μ_r'' is the imaginary part of permeability. Hence, if μ_r'' is high, d_m can be reduced. To adjust the present matching frequency characteristic around 2.45 GHz, holes are punched out of the double-layer absorber based on the findings of the theoretical simulation.

Fig. 17 shows the matching characteristic with holes of 2-mm diameter and adjacent hole spaces of 3.8 mm. The thickness of both rubber ferrite and carbonyl iron is 1.5 mm. In the same way, we obtain a 1.6-mm-thick absorber with a reflection coefficient of −20 dB at 5.8 GHz.

VI. Conclusion

In the effort to use ferrite effectively for microwave absorbers, detailed matching characteristics using a multihole rubber ferrite absorber have been investigated through both FDTD analysis and experiments. The main points are summarized as follows.

1) By making small holes in conventional ferrite: a) the matching frequency is shifted toward a higher frequency region as the hole diameter increases, but on the other hand, as the adjacent hole space decreases, the other parameters being constant, b) the matching thickness can be reduced.
2) The effect of various parameters on the matching characteristics have been examined, particularly for the behavior of permeability, and general design charts have been presented.
3) It has been shown that a desirable condition for a thin perforated absorber in the frequency region from 1 to 4 GHz is when the values of permeability and the real part of permittivity takes on a greater value.
4) As an application example, a double-layer absorber consisting of rubber ferrite and carbonyl iron was attained with a thickness of 3 mm at 2.45 GHz. The detailed matching characteristics in oblique incidence must be the subject of further study.

Appendix

The reason for the matching characteristics being changed and improved is intuited using a transmission-line theory equivalent to the ferrite absorber. That is, the equivalent circuit of a conventional ferrite absorber is represented by simply using resistance and inductance. Capacitance, however, is added to the equivalent circuit when holes are punched out in the ferrite material. Therefore, with the appropriate capacitance value, the circuit acts like a resonant phenomena. As a result, the matching frequency can be raised to a higher frequency region by adjusting the size of small holes; moreover, the matching characteristic can be improved due to this resonant phenomena. This principle is also explained using the material constant. That is, the equivalent value of permittivity is decreased by punching small holes in the ferrite. As a result, the matching frequency is raised to a higher frequency region. Fig. 18 depicts a simulation in which the value of permittivity is taken as a parameter in the case where the values of other parameters are shown in this figure. We find that the matching frequency characteristics are raised to higher frequency regions.

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Mitsuhiro Amano was born in Chiba, Japan, on March 24, 1978. He received the B.E. and M.E. degrees in telecommunications engineering from Tokai University, Kanagawa, Japan, in 2000 and 2002, respectively.

He is currently with the Department of Communications Engineering, Tokai University. Since 1996, he has been engaged in the research of EM-wave absorbers.

Mr. Amano is a member of the Institute of Electronics, Information and Communication Engineering (IEICE), Japan.

Youji Kotsuka (M'74–SM'99) was born in Kanagawa, Japan, on April 30, 1941. He received the Dr. Eng. degree from the Tokyo Institute of Technology, Tokyo, Japan, in 1980.

In 1974, he was a Lecturer with Tokai University, Tokyo, Japan, where he is currently a Professor of telecommunications engineering. From 1995 to 1996, he was a Visiting Professor with Harvard University, Cambridge, MA. He has been involved in the development of EM-wave absorbers using ferrite, shield techniques, RF dielectric and inductive applicators for deep hyperthermia, EM theory on scattering from random rough surfaces, and propagation in anisotropic media with loss.

Dr. Kotsuka is a member of the IEEE Microwave Theory and Techniques Society (IEEE MTT-S) Steering Committee, Tokyo Chapter, and the National Commissions A and K of the URSI. He was a chair of a Committee on Biological Effects of Electromagnetic Waves and Medical Application and Measurement Techniques with Radiated Waves of the Institute of Electrical Engineering, Japan.