Science and Technology of
Advanced Materials

Measurement method of complex permittivity and permeability for a powdered material using a waveguide in microwave band

To cite this article: Hidetoshi Ebara *et al* 2006 *Sci. Technol. Adv. Mater.* **7** 77

ELSEVIER

Science and Technology of Advanced Materials 7 (2006) 77–83

SCIENCE AND TECHNOLOGY OF ADVANCED MATERIALS

www.elsevier.com/locate/stam

Measurement method of complex permittivity and permeability for a powdered material using a waveguide in microwave band

Hidetoshi Ebara *, Takao Inoue, Osamu Hashimoto

College of Science and Engineering, Aoyama Gakuin University, 5-10-1 Fuchinobe, Sagamihara-shi, Kanagawa 229-8558, Japan

Received 10 September 2005; received in revised form 11 November 2005; accepted 14 November 2005
Available online 2 February 2006

Abstract

This paper proposes the measurement method of the complex permittivity and permeability for a powdered material based on measuring the effective permittivity and permeability using a waveguide in the microwave band. The powder of the silica and the ferrite were prepared for the verification of the proposed measurement method. In order to measure the *S*-parameter of these powdered materials, two open-ended waveguides infilled with a Teflon at the waveguide end and the sample holder, which is constructed from the same material as the waveguide, are fabricated. The powdered materials are filled into the sample holder in a number of volume ratios, which represent the ratio between the silica and air, the ferrite and air, respectively. The effective permittivity and permeability of the powdered materials are measured using the vector network analyzer for each volume ratio of the powdered materials in the frequency range from 4.0 to 5.8 GHz. The relationship between the volume ratios of the powdered material and the measured effective permittivity and permeability is derived for each measurement frequency. Then, the complex permittivity and permeability of the powdered materials are estimated by using the measured effective permittivity and permeability and the Lichtenecker's formula. In our measurement method, the Lichtenecker's formula, which is generally used for deriving the effective permittivity and permeability of a mixture, is applied to the estimation of the complex permittivity and permeability of only the material constituting the powder. We confirmed that the measurement results are in comparatively good agreement with the effective permittivity and permeability derived using Lichtenecker's formula. The proposed measurement method is considered to be effective as the measurement, which can be performed easily for a powdered material in the microwave band.

Keywords: Complex permittivity; Complex permeability; Powdered material; Waveguide; Lichtenecker's formula

1. Introduction

Since the wireless communications such as wireless local area network (LAN) and intelligent transport system (ITS) are expanding in recent years, various kinds of wave absorbers aiming at reducing unnecessary electromagnetic waves have been developed in the microwave band. In order to develop the wave absorber, which has the desired absorption characteristics on the target frequency, it is necessary to measure the complex permittivity and permeability of the material used for fabricating a wave absorber. When the material is solid in the measurement of the complex permittivity and permeability, the *S*-parameter method employing a waveguide or a coaxial line is applied [1,2]. Additionally, a free space method using horn antennas is also applied in the high frequency more than the microwave band. Furthermore, the nondestructive measurement methods using an open-ended waveguide and an open-ended coaxial line were previously proposed for a solid lossy material [3–8]. On the other hand, although a powdered material is also used for fabricating a wave absorber, the measurement method of the complex permittivity and permeability for a powdered material is not fully examined and is not established as a general measurement method [9]. Additional proposals about the measurement method of the complex permittivity and permeability for a powdered material are still needed.

The aim of this study is to propose the measurement method of the complex permittivity and permeability for a powdered material in the microwave band. Firstly, the measurement system using a waveguide for measuring the effective permittivity and permeability of a powdered material are constructed. Then, the experimental studies using the powder of the silica and the ferrite are conducted at 5 GHz band, which is used by wireless LAN or ITS. The effective permittivity and permeability are measured using the vector network analyzer

* Corresponding author. Tel.: +81 42 759 6298; fax: +81 42 759 6526.
E-mail address: ebara@ee.aoyama.ac.jp (H. Ebara).

1468-6996/$ - see front matter © 2005 Elsevier Ltd. All rights reserved.
doi:10.1016/j.stam.2005.11.019

for a number of volume ratios of the powdered silica and the powdered ferrite in the frequency range from 4.0 to 5.8 GHz. The relationship between the volume ratios and the measured effective permittivity and permeability is derived for each measurement frequency. Next, the complex permittivity and permeability of only the silica and the ferrite are estimated using the measured effective permittivity and permeability and the Lichtenecker's formula. In our measurement method, the Lichtenecker's formula, which is generally used for deriving the effective permittivity and permeability of the composite material, e.g. a wave absorber [10], is applied to the estimation of the permittivity and permeability of only the material constituting the powder. The measurement results of the powdered silica and the powdered ferrite correspond to the effective permittivity and permeability derived using the Lichtenecker's formula. The proposed measurement method is considered to be effective as the measurement, which can be performed easily for a powdered material in the microwave band.

2. Proposed measurement method

In order to measure the complex permittivity and permeability of a powdered material, the measurement method by the *S*-parameter method employing a waveguide is proposed as described below.

2.1. Measurement system and method of the effective permittivity and permeability

The measurement system is constructed as shown in Figs. 1 and 2. Two open-ended waveguides (Japanese Industrial Standard WRJ-5) infilled with the Teflon at the waveguide end and the sample holder, which is constructed from the same material as the waveguide, are fabricated. The dimension of the cross-section of the waveguide is 47.55 mm×22.15 mm. The length of the sample holder is 15 mm. The sample holder infilled with a powder material is inserted into two waveguides. In order to measure the *S*-parameter using the vector network analyzer (E8364A, Agilent Technologies, USA) when the powdered material is in the sample holder, the measurement system is calibrated by Thru–Reflect–Line (TRL) calibration.

The procedures of TRL calibration using the fabricated waveguides are mentioned below. First, Thru calibration is performed by measuring the transmission coefficient (S_{21}, S_{12}) in the state where there is no sample holder and two waveguide ends are connected as shown in Fig. 3(a). Next, Reflect calibration is performed by measuring the reflection coefficient (S_{11}, S_{22}) in the state where metal plates are set at the end of each waveguide, respectively, as shown in Fig. 3(b). Finally, Line calibration is performed in the state where the straight waveguide, which has $\lambda/4$ of the length at the center frequency of the measurement frequency band, is set between two waveguides as shown in Fig. 3(c).

After TRL calibration, the powdered material is filled up into the sample holder. The weight of only a powdered material is derived by measuring the weight of only a sample holder and the whole weight of the sample holder filled up with the

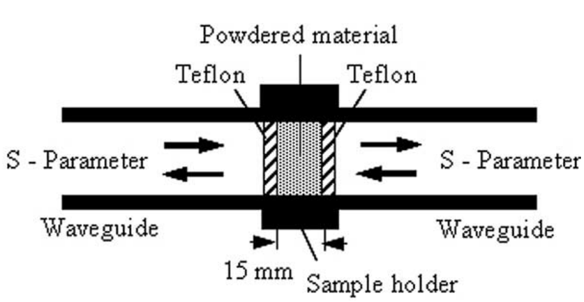

Fig. 1. Composition of measurement system.

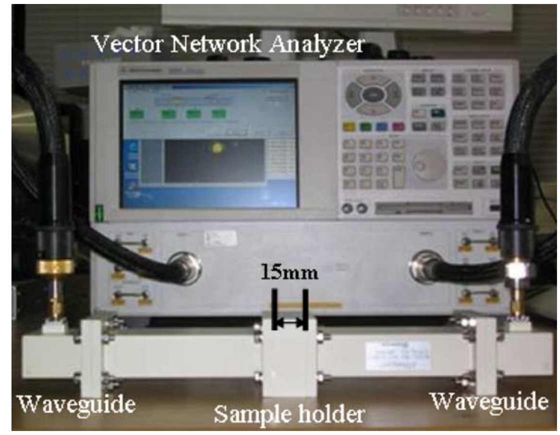

Fig. 2. Photo of measurement system.

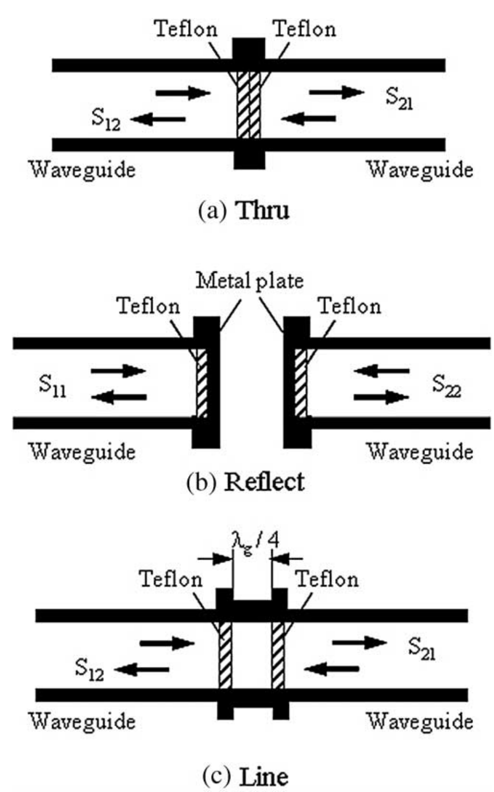

Fig. 3. TRL calibration using the fabricated waveguides.

powdered material. Then, the volume of the powdered material is calculated using the specific gravity. The sample holder filled up with a powdered material is inserted into two waveguides as shown in Figs. 1 and 2. The reflection coefficient and the transmission coefficient are measured using the vector network analyzer in the frequency range from 4.0 to 5.8 GHz. The effective permittivity and permeability of the powdered material are derived using Newton method by comparing the measured *S*-parameter values with the theoretical *S*-parameter values of the equivalent circuit, which is transformed from the composition as shown in Fig. 1 [11]. By the above method, the effective permittivity and permeability of the powdered material, which has the specific volume ratios, can be measured. Several effective permittivity and permeability of the powdered materials are measured at each volume ratio by filling up the sample holder with powdered materials in different volume ratio.

2.2. Estimation method of the complex permittivity and permeability

The complex permittivity and permeability of the powdered material is estimated using the measured effective permittivity and permeability and the Lichtenecker's formula [12]. In a lot of cases, this formula is used for deriving the effective permittivity and permeability of a mixture, which is mixed two substances. However, in our measurement method, the complex permittivity and permeability of each substance are conversely calculated from the effective permittivity. This formula is given hereafter.

$$\log \varepsilon_{\text{eff}} = v_1 \log \varepsilon_1 + v_2 \log \varepsilon_2 \tag{1}$$

$$\log \mu_{\text{eff}} = v_1 \log \mu_1 + v_2 \log \mu_2 \tag{2}$$

$$v_1 + v_2 = 1 \tag{3}$$

If a mixture can be replaced into a powdered material, each term in above formula is defined as follows. Term ε_{eff} is the effective permittivity of the powdered material. Terms ε_1 and ε_2 represent the complex permittivity of only the material and air, respectively. Term μ_{eff} is the effective permeability of the powdered material. Terms μ_1 and μ_2 represent the complex permeability of only the material and air, respectively. Terms v_1 and v_2 represent the volume of only the material and air, respectively.

The procedures of the estimation method are mentioned below. First, the relationship between the volume ratios of a powdered material (v_1/v_2) and the measured effective permittivity and permeability is obtained at each measurement frequency by the measurement as mentioned in Section 2.1. Next, the squares of the residual errors between the measured effective permittivity, $\varepsilon_{\text{eff-meas}}$, and the effective permittivity derived using Lichtenecker's formula, $\varepsilon_{\text{eff-calc}}$, are calculated for each volume ratio by varying the complex permittivity ε_1 in appropriate steps using Formulas (1) and (3). In the same way, the squares of the residual errors between the measured effective permeability, $\mu_{\text{eff-meas}}$, and the effective permeability derived using Lichtenecker's formula, $\mu_{\text{eff-calc}}$, are calculated for each volume ratio by varying the complex permeability μ_1 in appropriate steps using Formulas (2) and (3). Then, when the least sum of the squares of the residual errors is evaluated, the complex permittivity ε_1 and permeability μ_1 are determined as the estimated result at each frequency.

3. Complex permittivity of the powdered silica

In order to verify the effectiveness of the proposed measurement method in the microwave band, the powder of the silica is prepared. The powdered silica is filled up into the sample holder. The volume ratio of silica and air in the sample holder can be calculated using the specific gravity of 2.20 g/cm^3. The measurements of the effective permittivity for the powdered silica, which has 44.42, 45.49, 46.55, 47.73, 48.74, 50.21, 51.30, 52.22, 53.72, 54.72, 56.68, 56.93, 75.00, 80.92% of volume ratios, are performed using the measurement method as mentioned in Section 2.1, respectively. The total of measurements is 14 patterns. Since, the imaginary part in the complex permittivity of the silica is very small, which is approximately 0, the examination about the proposed measurement method is performed only paying attention to the real part in the complex permittivity.

The real part in the measured effective permittivity of the powdered silica is shown in Fig. 4. The results show that the real part is increasing with the increase in the volume ratio of the silica. Since the homogeneity of the powdered silica in the sample holder is easy to be maintained when the volume ratio is high, it is thought that the influence of a measurement error decreases. Therefore, when the volume ratio is low, some variations exist in the measurement result. It is conceivable that this variation can be reduced by performing two or more measurement in a comparable volume ratio. Additionally, it turned out that there is almost no frequency dependency in the complex permittivity of the silica in the measurement frequency band.

Then, the relationship between the effective permittivity and the volume ratios of the powdered silica is derived from these measurement results for each frequency. As mentioned in

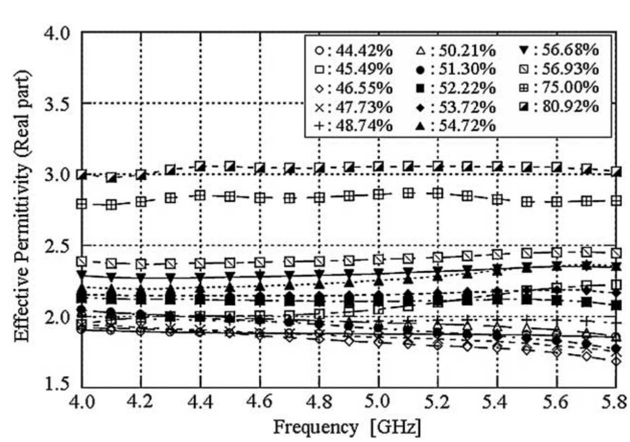

Fig. 4. Effective permittivity of powdered silica.

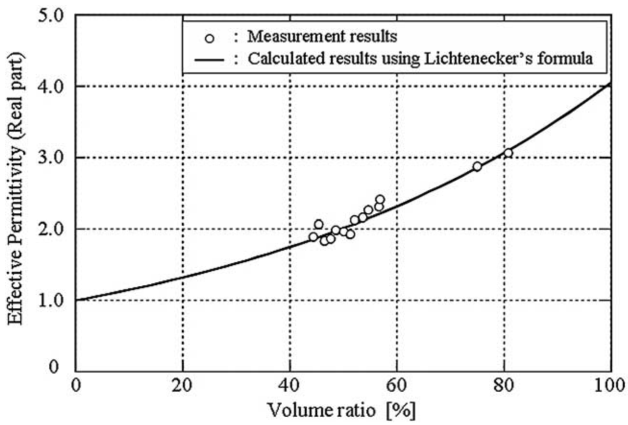

Fig. 5. Relationship between volume ratio and effective permittivity of powdered silica (5.0 GHz).

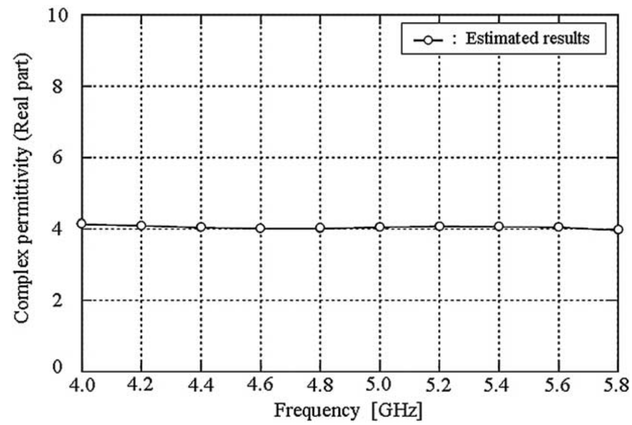

Fig. 6. Frequency characteristics of estimated permittivity of silica.

Section 2.2, the effective permittivity is derived using Lichtenecker's formula. For example, the relationship between the effective permittivity and the volume ratios at 5.0 GHz is shown in Fig. 5. The measured effective permittivity of the powdered silica is in comparatively good agreement with the effective permittivity derived using Lichtenecker's formula. The measurement results show the tendency to follow Lichtenecker's formula. The real part in the complex permittivity of the silica is estimated in the frequency range from 4.0 to 5.8 GHz by using the estimation method shown in Section 2.2. The estimated results are shown in Fig. 6. For example, the estimated result at 5.0 GHz is 4.06. The estimated complex permittivity of the silica has almost no frequency dependency in the measurement frequency band.

In order to confirm the validity of the estimated complex permittivity of the silica, the complex permittivity of the solid silica, which is prepared apart from the powdered silica, is measured at 5.8 GHz using the resonator method employing the cylindrical cavity resonator (manufactured by KEAD Co., Japan). The inside dimensions of the cylindrical cavity resonator is that the radius is 90.8 mm and the height is 29.5 mm. Three solid silicas from which the size differs are prepared (1.70 mm × 1.70 mm × 60.0 mm, 1.80 mm × 1.80 mm × 60.0 mm, 1.90 mm × 1.90 mm × 60.0 mm). The resonance frequency and *Q* value are measured three times for three solids silica, respectively. Then, the complex permittivity of the solid silica is estimated using the measurement results. As a result, the real part of the measured complex permittivity is 3.71. The estimated result at 5.8 GHz using the proposed measurement method is 3.97, so that the difference between the estimated result using the proposed measurement method and the measurement result using the resonator method is 6.5% at 5.8 GHz. If it takes into consideration that the silica used for each measurement is not the same at all, these results are in good agreement. By the above examination, the proposed measurement method is considered to be effective as the measurement, which can be performed easily for a powdered material in the microwave band.

4. Complex permittivity and permeability of the powdered ferrite

In order to apply the measurement method to the measurement of the complex permittivity and permeability of a powdered material, the powder of the ferrite is prepared. The powdered ferrite is filled up into the sample holder. The volume ratio of the ferrite and air in the sample holder can be calculated using the specific gravity of 2.82 g/cm^3. The measurements of the effective permittivity and permeability for the powdered ferrite, which has 36.40, 40.38, 43.22, 48.34, 51.18, 56.30, 58.01, 61.42, 67.73, 74.86, 82.51, 89.48% of volume ratios, are performed using the measurement method as mentioned in Section 2.1, respectively. The total of measurements is 12 patterns.

The measurement results of the real and imaginary parts in the effective permittivity are shown in Figs. 7 and 8. The results show that the real part is increasing with the increase in the volume ratio of the ferrite. On the other hand, the variations exist in the measurement result of the imaginary part. Since, the amount of imaginary part is very small quantity, it is thought that the measurement error attributed to the nonuniformity of the powdered ferrite has an effect on the measurement results. Additionally, the measurement results of the real and

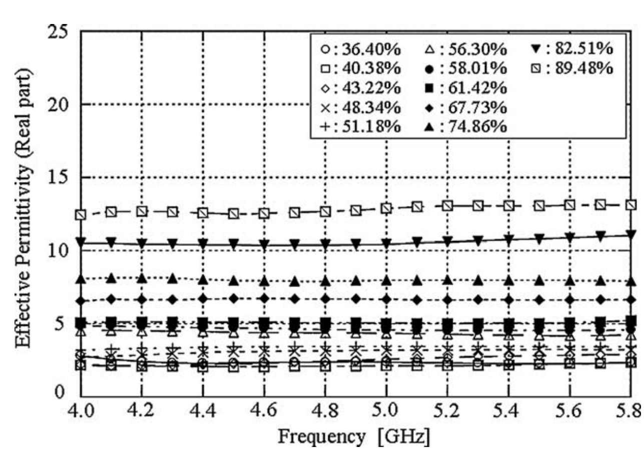

Fig. 7. Real part in effective permittivity of powdered ferrite.

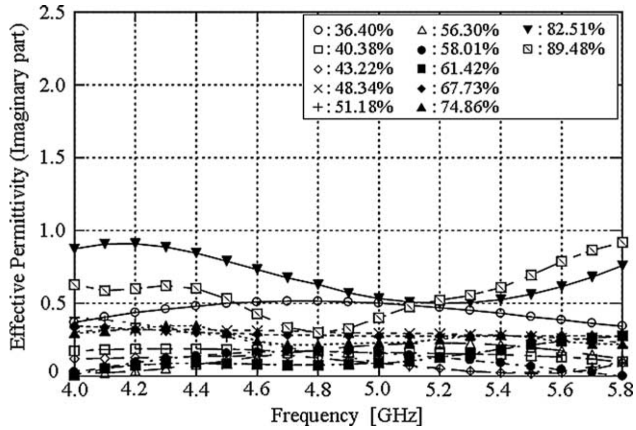

Fig. 8. Imaginary part in effective permittivity of powdered ferrite.

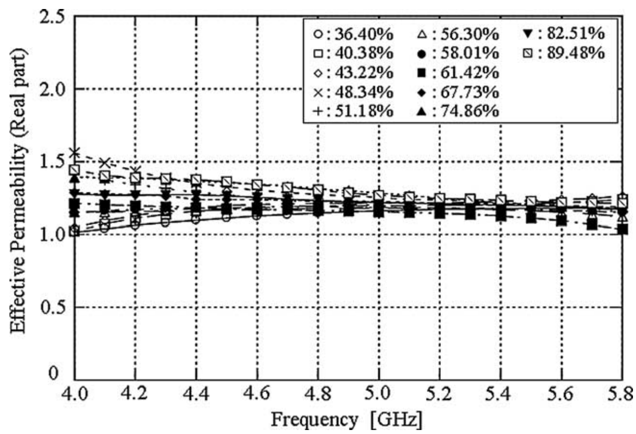

Fig. 9. Real part in effective permeability of powdered ferrite.

imaginary parts in the effective permeability are shown in Figs. 9 and 10. The results show that the real and imaginary parts are slightly increasing with the increase in the volume ratio of the ferrite. Although the measurement value of the real part is varied with the measurement frequency, the amount of variation is very small quantity.

Then, the relationship between the effective permittivity and the volume ratios of the powdered ferrite is derived from these

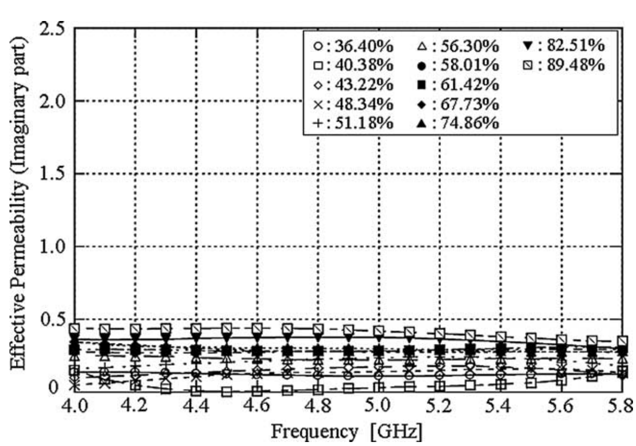

Fig. 10. Imaginary part in effective permeability of powdered ferrite.

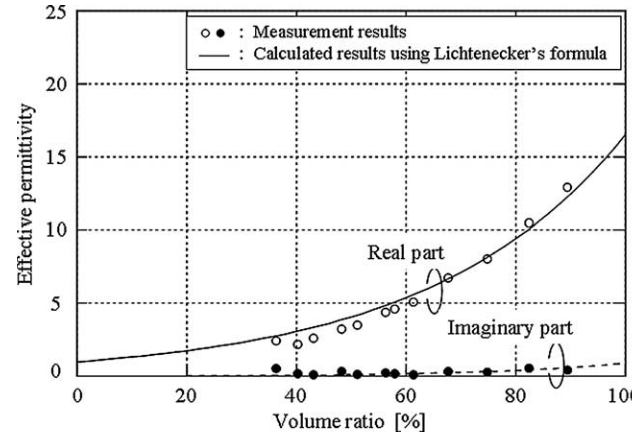

Fig. 11. Relationship between volume ratio and effective permittivity of powdered ferrite (5.0 GHz).

measurement results for each frequency. As mentioned in Section 2.2, the effective permittivity is derived using Lichtenecker's formula. For example, the relationship between the effective permittivity and the volume ratios at 5.0 GHz is shown in Fig. 11. The measurement results of the real and imaginary parts are in comparatively good agreement with the effective permittivity derived using Lichtenecker's formula. The measurement results show the tendency to follow Lichtenecker's formula. Additionally, the relationship between the effective permeability and the volume ratios of the powdered ferrite is derived in the same way. For example, the relationship between the effective permeability and the volume ratios at 5.0 GHz is shown in Fig. 12. Also in this case, the measurement results show the tendency to follow Lichtenecker's formula.

The real and imaginary parts in the complex permittivity are estimated in the frequency range from 4.0 to 5.8 GHz by using the estimation method shown in Section 2.2. The estimated results are shown in Fig. 13. For example, the estimated result at 5.0 GHz is $16.53 - j\,0.90$. The real and imaginary parts in the complex permeability are estimated in the frequency range from 4.0 to 5.8 GHz in the same way. The estimated results are

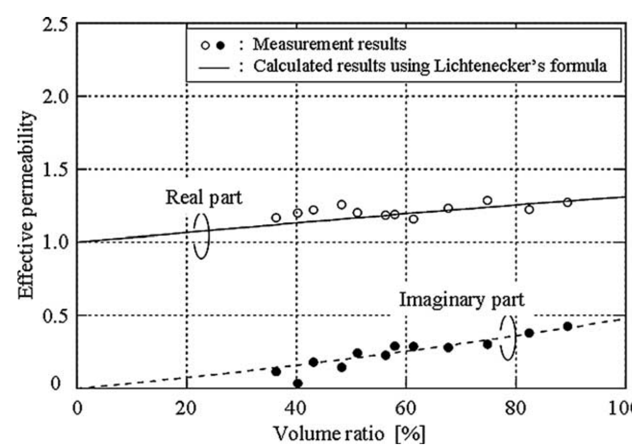

Fig. 12. Relationship between volume ratio and effective permeability of powdered ferrite (5.0 GHz).

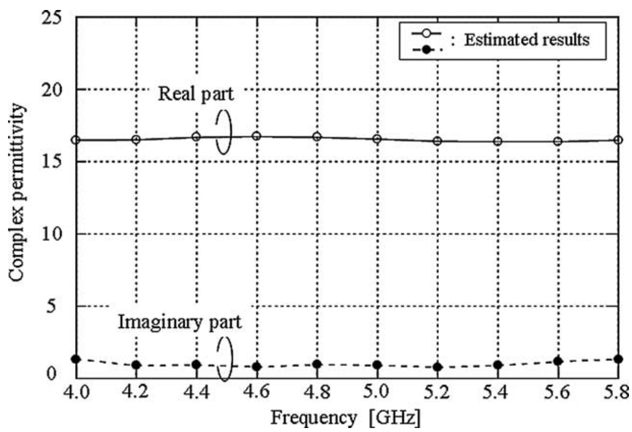

Fig. 13. Frequency characteristics of estimated complex permittivity of ferrite.

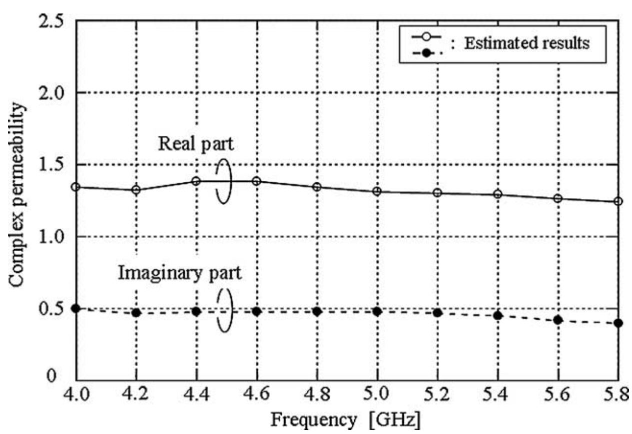

Fig. 14. Frequency characteristics of estimated complex permeability of ferrite.

shown in Fig. 14. For example, the estimated result at 5.0 GHz is $1.31 - j\ 0.48$. It turned out that the estimated complex permittivity and permeability of the ferrite has almost no frequency dependency in the measurement frequency band. Since, the measurement results are comparatively good agreement with the effective permittivity and permeability derived using Lichtenecker's formula, the estimated results are thought to be effective.

5. Conclusion

This paper proposed the measurement method of the complex permittivity and permeability for a powdered material based on measuring the effective permittivity and permeability using a waveguide in the microwave band. The powder of the silica and the ferrite were prepared for the verification of the proposed measurement method. In order to measure the *S*-parameter of these powdered materials, two open-ended waveguides infilled with a Teflon at the waveguide end and the sample holder, which was constructed from the same material as the waveguide, were fabricated. The effective permittivity and permeability of the powdered materials were measured using the vector network analyzer for each volume ratio of the powdered materials in the frequency range from 4.0 to 5.8 GHz. The relationship between the volume ratios of the powdered material and the measured effective permittivity and permeability was derived for each measurement frequency. Then, the complex permittivity and permeability of the powdered materials were estimated by using the measured effective permittivity and permeability and the Lichtenecker's formula. In our measurement method, the Lichtenecker's formula, which was generally used for deriving the effective permittivity and permeability of a mixture, was applied to the estimation of the permittivity and permeability of only the material constituting the powder.

The measured effective permittivity of the powdered silica corresponded to the effective permittivity derived using the Lichtenecker's formula. As a result, the estimated result at 5.8 GHz using the proposed measurement method is 3.97. The real part of the measured complex permittivity using the resonator method is 3.71, so that the difference between the estimated result using the proposed measurement method and the measurement result using the resonator method is 6.5% at 5.8 GHz. If it takes into consideration that the silica used for each measurement was not the same at all, these results were in good agreement. Additionally, the measured effective permittivity and permeability of the powdered ferrite also corresponded to the effective permittivity and permeability derived using the Lichtenecker's formula. Since, the measurement results were in comparatively good agreement with the effective permittivity and permeability derived using Lichtenecker's formula, the proposed measurement method were considered to be effective as the measurement which can be performed easily for a powdered material in the microwave band.

Acknowledgments

This work was partially supported by a Grant-in-Aid for 21st COE Program from the Ministry of Education, Culture, Sports, Science and Technology (MEXT) of the Japanese Government.

References

[1] A. Saito, A. Nishikata, Complex permeability and complex permittivity measurement of anisotropic lossy sheets composed of soft magnetic metal powder and rubber by waveguide S-parameter method, IEICE Trans. Electron. E85-C-9 (2002) 1684–1691.
[2] K.M. Lim, M.C. Kim, A. Lee, C.G. Park, Electromagnetic wave absorption properties of amorphous alloy-ferrite-epoxy composites in quasi-microwave band, IEEE Trans. Magn. 39 (3) (2003) 1836–1841.
[3] M.C. Decreton, F.E. Gardiol, Simple nondestructive method for the measurement of complex permittivity, IEEE Trans. Instrum. Meas. IM-23-4 (1974) 434–438.
[4] S. Bakhtiari, S.I. Ganchev, R. Zoughi, Open-ended rectangular waveguide for nondestructive thickness measurement and variation detection of lossy dielectric slabs backed by a conducting plate, IEEE Trans. Instrum. Meas. 42 (1) (1993) 19–24.
[5] M. Hirano, M. Takahashi, M. Abe, A measurement of complex permittivity of lossy dielectrics by using flanged rectangular waveguide, IEICE Trans. Electron. J82-C-I-11 (1999) 642–649.

[6] K. Shibata, O. Hashimoto, K. Wada, Estimation of complex permittivity using rectangular waveguide with flange by FDTD method, IEICE Trans. Electron. E84-C-7 (2001) 977–980.
[7] Y. Hayashi, G. Mishima, K. Hirayama, Y. Hayashi, Simultaneous measurement of permittivity and permeability of lossy sheet using flanged rectangular waveguide, IEICE Trans. Electron. J85-C-9 (2002) 810–818.
[8] H. Sawaumi, O. Hashimoto, K. Shibata, A fundamental study on measurement of complex permittivity by lossy sheet on rectangular waveguide with circular flange, IEICE Trans. Commun. J87-B-1 (2004) 98–100.
[9] S.O. Nelson, Open-ended coaxial-line permittivity measurement on pulverized materials, IEEE Trans. Instrum. Meas. 47 (1) (1998) 133–137.
[10] T. Kondo, K. Asano, S. Yoshikado, Development and evaluation of the composite electromagneticwave absorbers, IEE Jpn 120-A-2 (2000) 211–217.
[11] K. Shibata, K. Tani, O. Hashimoto, K. Wada, Measurement of complex permittivity for liquid phantom by transmission line method using coaxial line, IEICE Trans. Electron. E87-C-5 (2004) 689–693.
[12] H. Ebara, K. Tani, T. Onishi, S. Uebayashi, O. Hashimoto, Method for estimating complex permittivity based on measuring effective permittivity in radio frequency band, IEICE Trans. Commun. E88-B-8 (2005) 3269–3274.