Influence of Sample Insertion Hole on Resonant Cavity Perturbation Measuring Method

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Abstract — **Influence of sample insertion holes in resonant cavity for a measuring fixture was investigated experimentally and numerically. Shift of the resonant frequency caused by loaded sample decreased when the cavity height decreased or dielectric constant of a sample increased. Employing tall cavity improved measurement error. Using commercial simulators, it was found that disturbance of electric field near the sample insertion hole caused deviation of resonant frequency from the ideally closed cavity. The simulation result was inspected from the viewpoint of physical rationality**

I. INTRODUCTION

Accurate evaluation of dielectric characteristics of the substrate material at the carrier frequency is essential for accurate design of microwave modules or components such as array antennas or filters. The cavity perturbation method [1] has become the most appropriate method to reconcile the accuracy with the flexibility of evaluating frequency selection, using digitalized equipment and appropriate data processing methods [2]. However, the problem of the error according to sample insertion hole, that was pointed out by Estin and Bussey in 1960 [3], has not been solved well yet.

Although they showed that the influence of the hole was not significantly large for the cavity about 50 mm tall and for permittivity smaller than 10, another area of cavity height and permittivity has not been investigated. Moreover, the equation proposed by them does not have continuity of electromagnetic field on the iris, and it lacks the singularity expected on the metal edge. Another works did not deal the problem of cavity height [4].

Recently, the authors showed that the permittivity calculated by the well-known perturbation equation gave a significant decrease when the height of the cavity decreased [5][6]. In this study, we show that the decrease is sufficient to prevent the optimum design of the resonance circuit for high permittivity materials and its solution. We also discuss the relationship between disturbance of the field near the sample insertion hole and the deviation of the resonant frequency shift, paying attention to the singularity on metal edge.

II. THORETICAL BACKGROUND

Principle of cavity perturbation method is as follows. When a small object is introduced into a resonant cavity, the resonant frequency shifts. If the magnetic field in the region where the object is loaded is small enough, the frequency change is expressed as follows according to the well-known perturbation theory.

$$\frac{\Delta\nu}{\nu_0} = \frac{(\varepsilon_s - 1)\int_{\Delta V} E E_0 dV}{2\int_V E E_0 dV} \tag{1}$$

$$\Delta\nu \equiv \nu_0 - \nu$$

where ΔV is the volume occupied by the sample, V is the whole volume of the cavity, E_0, ν_0 and E, ν is electric field and the resonant frequency in unperturbed and perturbed state, and ε_s is permittivity of the sample, respectively. Let us assume that the sample is set in the center of the cavity where TM_{0m0} mode is exited. When the cavity is a perfectly closed cylinder, the rod sample is equal in height to the cavity, and the radius of the sample is so small that the electric field can be regarded constant, equation (1) becomes a simple form as follows [1].

$$\frac{\Delta\nu}{\nu_0} = \frac{A(\varepsilon_s - 1)\Delta V}{V} = A(\varepsilon_s - 1)\frac{s}{S} \tag{2}$$

where s is cross section of sample, S is cross section of cavity, $A = 1/2J_1(\rho_{0m})^2 = 1.855190$ for TM_{010} mode, $J_n(x)$ means the n-th Bessel function, and ρ_{0m} means the m-th root of $J_0(x)$. Eq.2 does not imply dependence on cavity height.

Actual cavity has centered holes and tubular guides on both endplates in order to make it easy to insert a sample. At first sight it seems that influence of the hole can be ignored when the frequency is lower than cut off frequency. However, the disturbance of the electric field near the hole may cause a deviation of resonant frequency from the closed cavity, because integral region of the numerator of right side of equation 1 is limited in a small volume ΔV and disturbed field is localized in ΔV and the nearby.

In this geometry, electric field E and E_0 within ΔV is no longer constant. It is complicate function of position and permittivity. Although an analytical solution has been obtained for the problem of iris on thin metal plate [7], it is difficult to obtain simple analytical forms of E and E_0. Therefore experimental or numerical investigation is recommended.

III. EXPERIMENTAL RESULTS

Cavities with 140 mm, 50 mm, and 8mm height were made as shown in Fig. 1. In order to exclude a derangement such as the effect of higher term of the perturbation, another dimensions were fixed. Diameter of cavities was 229.5 mm.

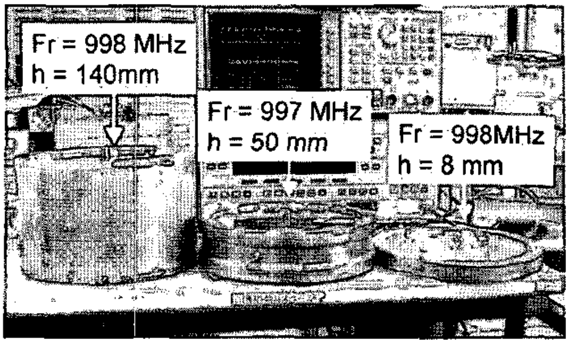

Fig. 1.Cavities having different height.

Diameter of sample insertion hole was 1.5 mm. Length of insertion guide was 15mm. Resonance frequency was about 1 GHz. Two driving loops were instructed at the side of cylinder so as to couple a magnetic flux of the TM010 mode in the resonator. The insertion loss was kept larger than 20 dB. A revised resonance curve area (RCA) method was used to determine the Q-factor and resonance frequency of the resonator to increase the accuracy [2]. Ceramic samples were fired in the temperature lower than melting point of silver, then fabricated to the rectangular rod

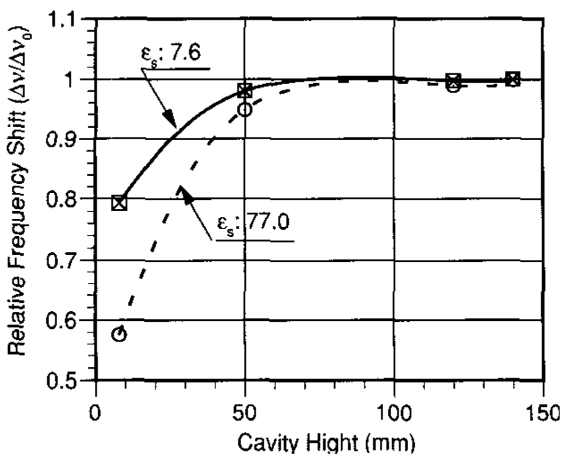

Fig. 2.Influence of cavity height on the frequency shift

Fig. 2 shows the influence of cavity height on the frequency shift Δv. The frequency shift is normalized by that in 140mm height cavity, Δv_0. The frequency shift caused by loaded sample decreased when the cavity height decreased, though conventional perturbation equation (2) does not suggest dependence on cavity height. In high permittivity sample, the frequency shift strongly depended on cavity height. Commercially available cavity having 1GHz resonant frequency has the height of 50 mm.

It provides the accuracy of the measurement within 1% of error when permittivity is 7.6. It has the deviation of 4% when the permittivity is 77. In the case of the height of 8 mm and the permittivity of 77, the relative frequency shift $\Delta v / \Delta v_0$ was 0.68. If we apply equation (2) to this experimental data, apparently small permittivity resulted as shown in Fig. 3.

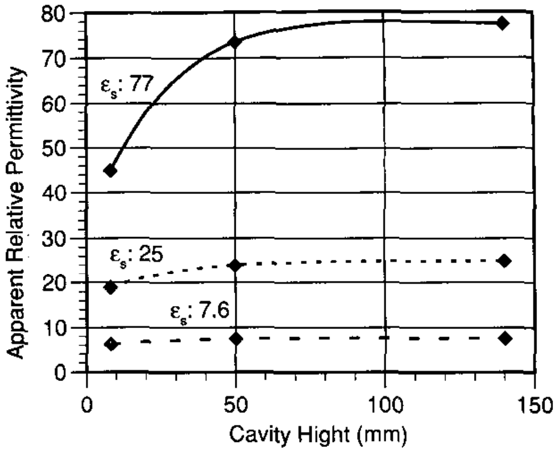

Fig. 3 Influence of cavity height on apparent permittivity calculated from equation 2

Accurate result was obtained for the sample with permittivity of 77 using the cavity 140mm tall. Influence of diameter of hole was investigated for 8mm height cavity with sample having the permittivity of 77.

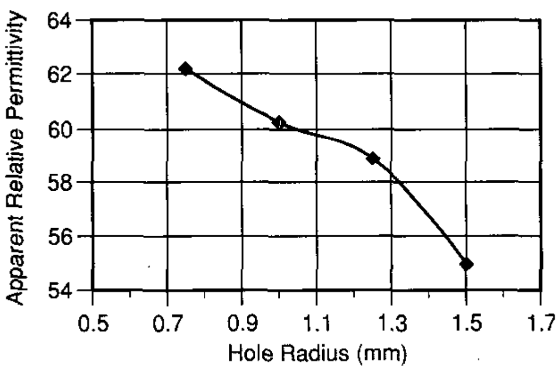

Fig. 4 Influence of diameter of hole for 8mm height cavity with sample having the permittivity of 76.

Apparent relative permittivity decreased when the diameter of hole increased as shown in Fig. 4.

IV. ELECTROMAGNETIC FIELD SIMULATION

Eigen mode analysis of the cavity with loaded dielectric was executed using various commercial simulators. Some simulators failed to execute this calculation. Let us discuss abut the results obtained from HFSS and MW-Studio. The geometry for simulation was as follows. The hole and the tubular sample guide were formed on both endplates. The radius of the hole was 1.5 mm, the height of the tubular guide was 50mm, the radius of the sample was 1 mm, and radius of the cavity was 100mm. The height of the cavity has been changed from 8 mm to 60 mm.

The permittivity of the loaded sample changed from 2.5 to 100. In HFSS, we have introduced magnetic walls on meridian plane every 2 degrees. *i.e.*, 180 times rotation symmetry was assumed. When the symmetry was not assumed, the calculation did not converge. In MW-Studio, calculation converged without any symmetry assumption.

We inspected the result from the viewpoint of physical rationality. Especially, the attention was paid to the singularity on metal edge. In the large, the basic mode was similar to TM_{010} mode in the closed cavity except the concentration of electric field near the hole.

When simulation conditions were not adequate, the calculation converged to improper solution. As shown in Fig. 5, electric field component longitudinal to the endplate of the cavity, E_z had singularity on the endplate, not on the edge. Moreover, E_z had finite quantity on inner surface of the guide though it was perfect conductor and parallel to E_z.

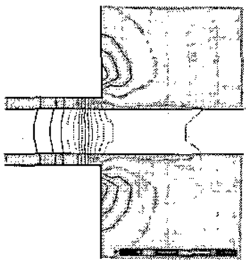

Fig. 5 An example of improper convergence Distribution of axial component of electric field E_z

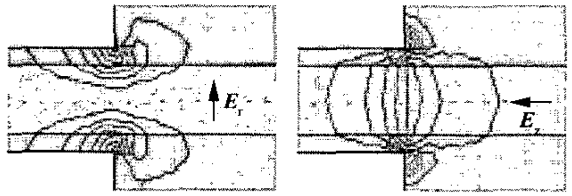

Fig. 6 An example of proper convergence Distribution of axial and tangential components of electric field E_z and E_r near a hole.

When the parameters were set appropriately, the solution almost satisfied boundary condition as shown in Fig. 6. The relationship between the relative frequency change $\Delta\nu/\Delta\nu_0$ and the cavity height is shown in Fig.7. In both simulators, the deviation of the resonant frequency from the ideally closed cavity increased when the height of the cavity decreased as shown in Fig. 8.

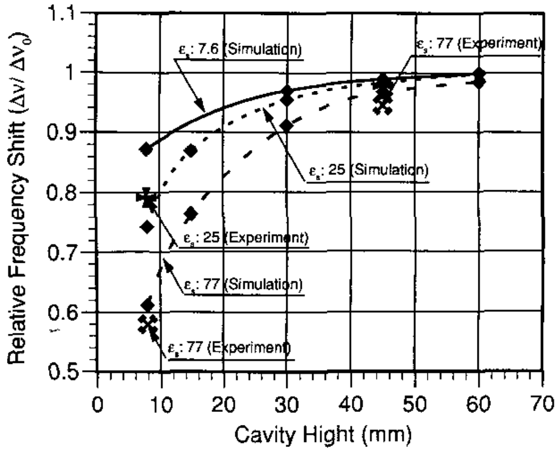

Fig. 7 Influence of the cavity height to relative frequency shift $\Delta\nu/\Delta\nu_0$: Simulation by MW-Studio

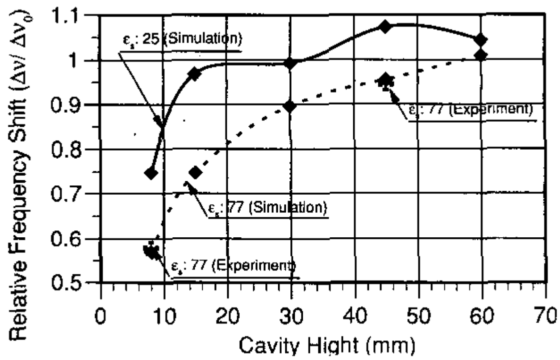

Fig. 8 Influence of the cavity height to relative frequency shiftt $\Delta\nu/\Delta\nu_0$: Simulation by HFSS

In the case of the height of 8 mm and the permittivity of 75, the relative frequency shift $\Delta\nu/\Delta\nu_0$ was 0.68 in the experiment and 0.61(MWS) and 0.57 (HFSS) in simulations. The deviation from the closed cavity increased when permittivity increased. This tendency accords with experimental results.

V. DISCUSSION

The results can be explained as follows. When the cavity height decreases, the ratio of disturbed domain near the hole to ΔV relatively increases. Therefore, the deviation of the frequency shift Δv from the closed cavity increases. Contributions of the disturbed field to $\Delta v / \Delta v_0$ are classified as follows. Let us express $\boldsymbol{E}$ and $\boldsymbol{E}_0$ in equation 1 as sum of the field in perfectly closed cavity $\boldsymbol{E}c$ and excess field $\boldsymbol{e}_0$ or $\boldsymbol{e}$.

$$\boldsymbol{E}_0 = \boldsymbol{E}_c + \boldsymbol{e}_o \tag{3}$$

$$\boldsymbol{E} = \boldsymbol{E}_c + \boldsymbol{e} \tag{4}$$

According to continuity of $\boldsymbol{E}_0$ and $\boldsymbol{E}$, numerator of equation (1) is expressed as following.

$$\int_{\Delta v} E\,E_0 dV = \int_{Cavity} E_C{}^2 dV + 2\int_{Cavity} E_C e_z dV + \int_{Cavity} e_{0z}{}^2 dV + \int_{Pipe} e_{0z}{}^2 dV + \int_{Cavity} e_{0r} e_r dV + \int_{Pipe} e_{0r} e_r dV \tag{5}$$

Where "Cavity" under integral symbol means the volume occupied by sample in cavity, "Pipe" does in guiding pipe. Subscripts z and r mean axial or tangential component of electric field. Notations in equations (3), (4) and (5) are explained schematically in Fig. 5.

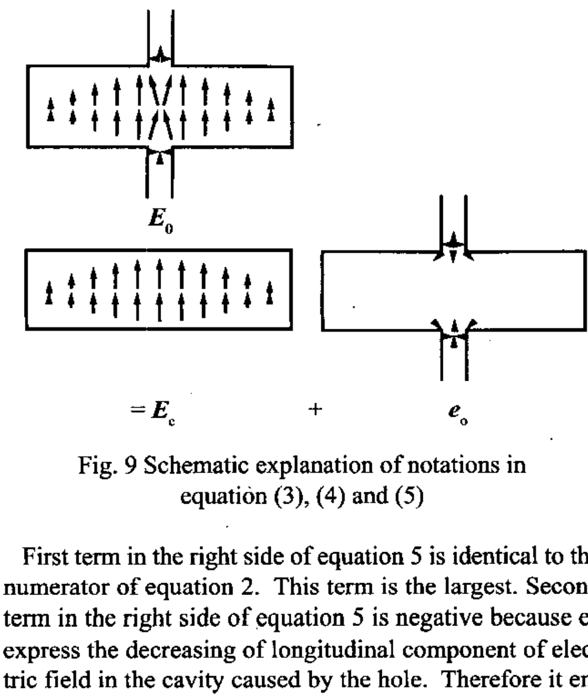

Fig. 9 Schematic explanation of notations in equation (3), (4) and (5)

First term in the right side of equation 5 is identical to the numerator of equation 2. This term is the largest. Second term in the right side of equation 5 is negative because ez express the decreasing of longitudinal component of electric field in the cavity caused by the hole. Therefore it enlarges resonant frequency (reduces Δv). This term is larger than following terms. They relax the effect of second term, but do not overcome it. Electric field energy within the sample in tubular guides domain is excess comparing to the closed cavity.

Therefore, it acts to reduce resonant frequency (enlarges Δv). This effect is small when the frequency is far lower than cut off frequency. Tangential component of electric field near edge is also excess. Its tail in the sample reduces resonant frequency (enlarges Δv). The tangential component is less excluded from the low permittivity sample than high permittivity one. It compensates the effect of last factor a little. Therefore, the deviation becomes small when permittivity is low.

VI. CONCLUSION

The frequency shift caused by loaded sample decreased when the cavity height decreased, though conventional perturbation equation does not suggest dependence on cavity height. In high permittivity sample, the frequency shift strongly depended on cavity height. The cavity 50 mm tall provides the accuracy of the measurement within 1% of error when permittivity is smaller than 25. Taller cavity improves measurement error for high permittivity sample. Cause of the deviation is the decrease of longitudinal component of electric field caused by the hole.

ACKNOWLEDGEMENT

The authors wish to acknowledge the ceramic sample preparation support of Mr. Kawada, Tomoaki of TDK Corporation.

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