

A Nondestructive Method of Measuring Dielectric Properties of
Substrate at Microwave and Millimeter-wave Frequencies
using an Open-ended Coaxial Resonator Probe

Ryotaro INOUE^{AB*},

Kazuhiko MIWA^B, Haruhisa KITANO^B, Atsutaka MAEDA^B,

Yasuhiko Odate^C and Eiji TANABE^C

^A Japan Science and Technology Agency

4-1-8, Honcho, Kawaguchi-shi, Saitama 332-0012, Japan

^B Dept. of Basic Science, Univ. of Tokyo

Komaba 3-8-1, Meguro-ku, Tokyo 153-8902, Japan

^C AET Japan, Inc.

Manpukuji 1-2-3, Asao-ku, Kanagawa-shi, Kanagawa 215-0004, Japan

*e-mail: inoue@maeda1.c.u-tokyo.ac.jp, tel. fax.: +81-3-5454-6763

Abstract

A new measurement system of the local complex permittivity of insulating substrates at microwave and millimeter-wave frequencies is developed. This system enables accurate and nondestructive measurement by utilizing an open-ended coaxial resonator probe. An empirical formula for data analysis is deduced based on the experimental data and the numerical calculation of the three-dimensional electromagnetic fields. The measurement sensitivity for loss tangent is estimated to be $\tan \delta \sim 10^{-4}$, and the spatial resolution, which is now ~ 1 mm, can be increased to submicron order by making aperture hole size smaller.

KEYWORDS: new measurement technique, electricity and magnetism, microwave and millimeter-wave, nondestructive measurement, electromagnetic simulator

1 Introduction

Recent higher speed device technology requires an accurate and convenient method of estimating local dielectric properties at microwave and millimeter-wave region. Especially, nondestructive measurement of complex permittivity, $\hat{\epsilon} \equiv \epsilon' + i\epsilon''$, of insulating substrate is necessary.

We have developed a new measurement system to measure the local dielectric properties at microwave and millimeter-wave frequencies in a nondestructive manner, using an open-ended coaxial resonator probe. In this system, one puts an open-ended coaxial resonator probe on the smooth surface of the sample under test, and measures the resultant change of the quality factor and that of the resonant frequency of the resonator probe. By comparing the experimental result with the numerical simulation, the complex permittivity of the sample under test is obtained. We measured several reference materials and confirmed the potential possibility of this system. We also deduced the empirical formula for the data analysis which determines the complex permittivity of the sample, $\hat{\epsilon}$ from the complex frequency shift, $\Delta\hat{\omega}/\omega_0$.

The measurement sensitivity for loss tangent is estimated to be $\tan \delta \gtrsim 10^{-4}$, and, the spatial resolution, which is now ~ 1 mm, can be increased to submicron order by making aperture hole size smaller.

2 Experimental

Figure 1(a) shows the open-ended coaxial resonator probe made from brass and plated with copper. We used transverse electromagnetic (TEM) mode of the resonator probe at 0.80, 2.45, 4.00, 6.00 GHz for measurement. The resonant frequencies of TEM mode of the *simple* and *ideal* open-ended coaxial resonator are given as $f_n = (c/4L)(2n - 1)$, where c is the speed of light in vacuum, L is the length of the resonator, and, $n = 1, 2, \dots$, respectively. However, we covered thin top plate with a small aperture hole and sharpened the open end of the inner conductor for increasing the measurement accuracy and the spatial resolution as shown in Fig. 1(b). In order to achieve a fairly high quality factor ($\gtrsim 1200$) and desired measurement frequency, we optimized the geometrical design of the resonator probe by utilizing three-dimensional electromagnetic simulator, *CST MICROWAVE STUDIOTM*.

The resonator probe has two ports, and the complex transmission coefficient data are measured as a function of frequency by using vector network analyzers, Advantest R3767CH and Agilent E8364B. For

an accurate measurement of the conductivity of the low-loss materials, it is indispensable to determine the small change of the quality factor due to the putting of the sample. We developed a complex Lorentzian fit method [1] for accurate and *real-time* determining of the resonant frequency and the quality factor from the obtained complex transmission coefficient data.

In the numerical simulation, we used the eigen mode solver of three-dimensional electromagnetic simulator, *CST MICROWAVE STUDIOTM*, which is based on the finite integration method. The unique meshing algorithm called *Perfect Boundary ApproximationTM* enables the calculation of the electromagnetic fields for the arbitrary shapes even with round corners or tiny gaps without stair case approximation. We also prepared mesh with intervals of 1 μm around the aperture hole for accurate estimation of the electromagnetic fields.

3 Results and Discussions

As test samples, we prepared Teflon, acrylic plastic, quartz and alumina, and measured the complex frequency shift, $\Delta\hat{\omega}/\omega_0$, defined as $\Delta\hat{\omega}/\omega_0 \equiv \Delta f/f_0 - i\Delta(1/2Q)$. Here $\Delta f/f_0$ and $\Delta(1/2Q)$ represent the change of the reduced resonant frequency and the inverse of the twofold quality factor, respectively. Figure 2 shows the measurement results of test samples.

The sign-inversed resonant frequency shift, $(-\Delta f/f_0)$, increases as the dielectric constant, ϵ' increases. For the highly dielectric region, however, $(-\Delta f/f_0)$ shows the tendency to saturate in a limiting value. The change of the inverse of the twofold quality factor, $\Delta(1/2Q)$, increases as the loss tangent, $\tan\delta$ increases. The measurement sensitivity for loss tangent is estimated to be $\tan\delta \gtrsim 10^{-4}$. Although these behaviors can be explained quasi-quantitatively by the equivalent circuit theory [2], numerical simulation by three-dimensional electromagnetic simulator is necessary for data-analyzing [3].

For data-analyzing for the measurement results of low-loss materials, we first neglect the *imaginary* part of the permittivity, ϵ'' , and discuss the relation between the resonant frequency shift, $\Delta f/f_0$, and the dielectric constant i.e. the *real* part of the permittivity, ϵ' . Because we measure the insulating materials, the so-called loss tangent is much smaller than the unity, ($\epsilon''/\epsilon' \ll 1$), and the resonant frequency shift does not depend on ϵ'' .

The sign-inversed resonant frequency shift, $(-\Delta f/f_0)$, of the test sample is again plotted as a function

of the *real* part of the permittivity, ϵ' in Fig. 3, together with the numerical calculation shown as a solid curve. The experimental results coincides well with the numerical simulation data.

These behavior can be well described by the following empirical equation,

$$\frac{\Delta f}{f_0} \approx -\Gamma \frac{\epsilon' - 1}{\epsilon' + A}, \quad (1)$$

where Γ and A are the geometrical constants determined by the mode and the design of the resonator. In Fig. 4, we plot numerically calculated $(-\Delta f/f_0)^{-1}$ as a function of $(\epsilon' - 1)^{-1}$ for each TEM mode. A definite linear relation can be confirmed, and the geometrical factors, Γ and A , tabulated in Table 1 are obtained from the linear fitting.

This empirical equation can be extended easily to the equation for the finite loss materials by replacing the frequency shift and the dielectric constant by the complex form,

$$\frac{\Delta \hat{\omega}}{\omega_0} \approx -\Gamma \frac{\hat{\epsilon} - 1}{\hat{\epsilon} + A} \quad (2)$$

The geometrical factors can be determined experimentally by measuring the frequency shifts, $\Delta f/f_0$, of the two reference materials, whose dielectric constant, ϵ' , are known. If fairly lossy material ($\epsilon'' \gtrsim 0.01$) can be used for calibration, then only one reference material is sufficient. Once the geometrical factors, Γ and A , are determined, the data-analyzing process is very easy because the empirical formula (eqn. (2)) can be solved analytically for the complex permittivity, $\hat{\epsilon}$.

The physical interpretation of the empirical formula (eqn. (2)) is indispensable for increasing the measurement accuracy. This is still in progress. Comparing the results of numerical calculations for models with various geometrical designs, it is found that the geometrical factor, A , is strongly affected by the geometrical designs of the resonators rather than by the measurement modes. This implies that the geometrical factor, A , is determined by the aperture design and can be calculated *in principle* under quasistatic approximation. On the other hand, the geometrical factor, Γ , depends on the measurement modes as well as the geometrical designs of resonators, reflecting the fact that Γ is closely related to the stored energy of the resonator probe.

4 Conclusion

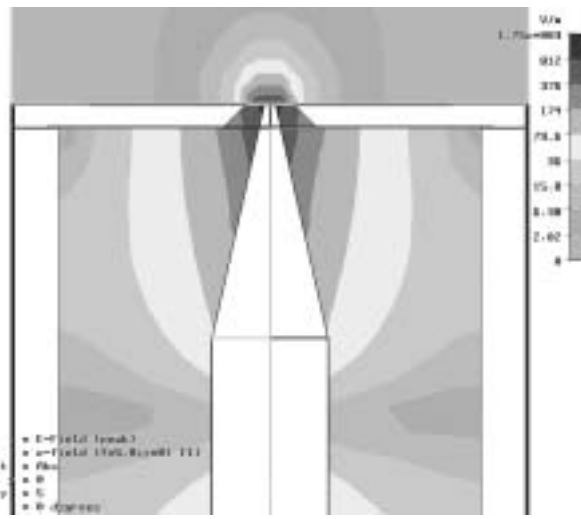
A new measurement system of the complex permittivity of insulating substrates at microwave and millimeter-wave frequencies is developed. This system enables accurate and nondestructive measurement by utilizing an open-ended coaxial resonator probe. An empirical formula for data analysis is deduced based on the experimental data and the numerical calculation of the three-dimensional electromagnetic fields. The measurement sensitivity for loss tangent is estimated to be $\tan \delta \gtrsim 10^{-4}$, and the spatial resolution, which is now ~ 1 mm, can be increased to submicron order by making aperture hole size smaller.

References

- [1] R. Inoue, K. Miwa, H. Kitano, A. Maeda, Y. Odate and E. Tanabe, *submitted to J. Appl. Phys.*
- [2] E. Tanabe and W. T. Joines IEEE Trans. Instrum. Meas., **IM-25**(1976)222
- [3] Y. Odate, R. Inoue, K. Miwa, H. Kitano, A. Maeda and E. Tanabe, *submitted to IEICE Trans. Electron.*



(a)



(b)

Figure 1: (a) Open-ended coaxial resonator probe. (b) The electric field distribution in the vicinity of the aperture.

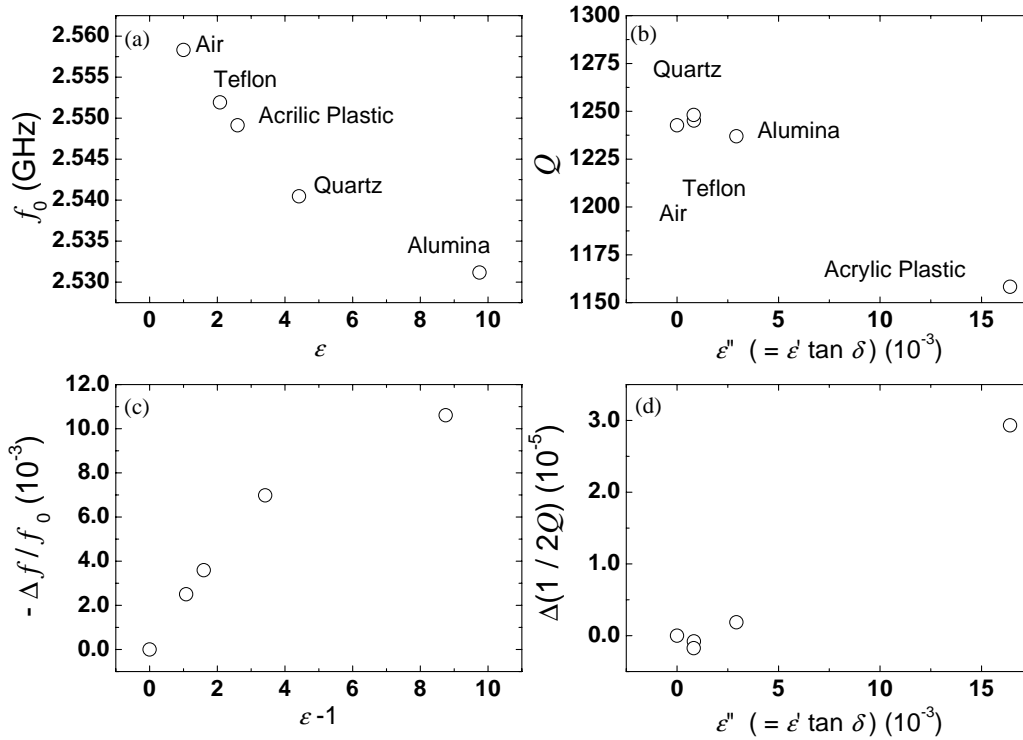


Figure 2: The measurement results of the test samples. (a) resonant frequency, (b) quality factor, (c)(d) complex frequency shift is plotted as functions of *real* or *imaginary* parts of the complex permittivity, ϵ' , or ϵ'' .

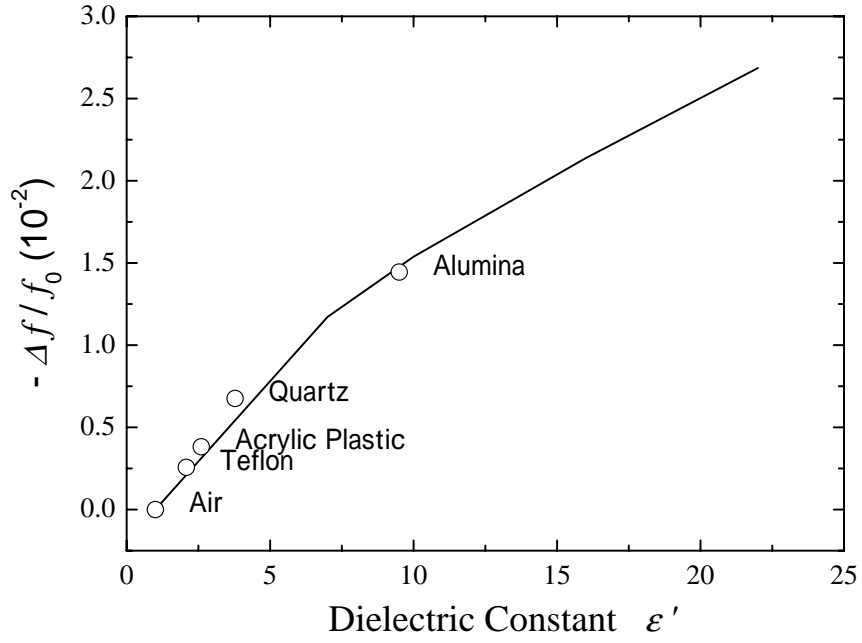


Figure 3: The sign-inversed frequency shift, $(-\Delta f/f_0)$, of the test samples as a function of the dielectric constant, ϵ' . The result of the numerical calculation is shown as a solid curve.

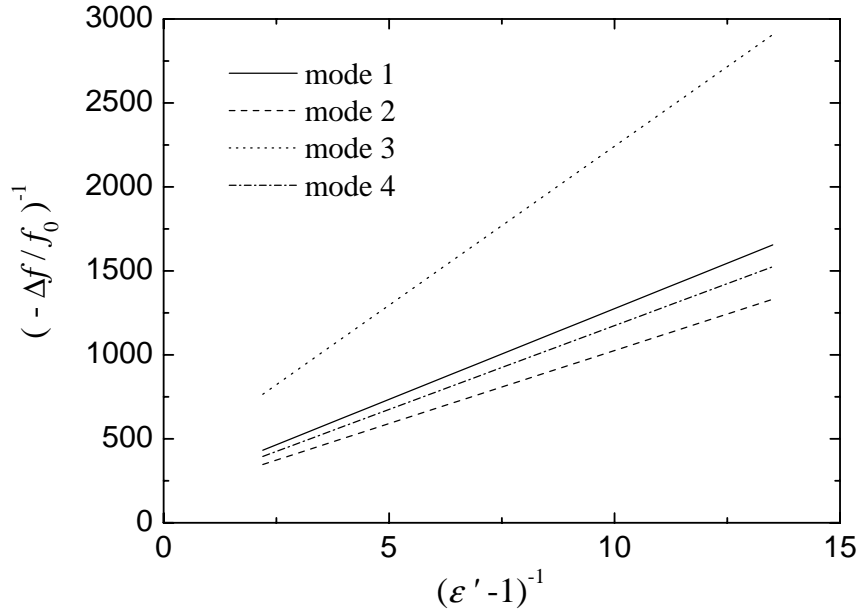


Figure 4: Numerically calculated $(-\Delta f/f_0)^{-1}$ as a function of $(\epsilon' - 1)^{-1}$ for each TEM mode.

mode	f	Γ	A
	(GHz)	($\times 10^{-3}$)	
1	0.80	5.138	7.978
2	2.45	6.412	8.008
3	4.00	2.865	7.817
4	6.00	5.699	8.153

Table 1: The geometrical factors of the coaxial resonator probe.