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# Simple Technique for Measurement of Complex Permittivity and Detection of Small Permittivity Change Using Partially Open Cavity

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**Abstract** – This letter presents a measurement methodology of the complex permittivity of liquid using a partially open cavity in narrow band. The partially open cavity (POC) can measure dielectric small changes caused by the temperature variation of the liquid inside the cavity as well. Using the resonance frequency and unloaded quality factor of the proposed POC, the complex permittivity is evaluated. The apertures on the walls of the cavity are designed to circulate the liquid inside to outside of the POC and located at the corner area of the cavity to minimize the disturbance of field distribution at the dominant mode. The results measured by the proposed POC were compared with those by the conventional open-ended probe and Cole-Cole equation. The POC showed better performance in measuring small dielectric constant changes than the open-ended probe.

**Keywords**: Cavity resonator, Permittivity, Dielectric material, Dielectric liquid

## 1. Introduction

With several methods and probes of many types such as coaxial and waveguide transmission lines (T/L), and cavity, many people have researched to know electrical properties such as permittivity and permeability of materials at microwave frequencies [1-5]. If we can know electrical properties of the materials in an area of interest, they will be utilized to predict and analyze electromagnetic effects. And the small change of the permittivity of the materials in the area will affect the electric and magnetic fields distribution, which means that the small change should be measured to increase the accuracy of the field analysis. Most materials have the potential for the permittivity change as the degradation process occurs or the temperature of the materials changes at normal circumstance.

It is difficult for the conventional T/L probes to measure such small permittivity changes because the permittivity variations may be less than the tolerance of them. The technique using T/L probes for permittivity measurement cannot give precise results of the permittivity change of a material because the measurement error is generated during a calibration process using the reference materials such as air, methanol and distilled water. The measurement error is about 6% and depends on a measurement method and calibration skill [1, 2]. Also it would have the irreversible deformation of the probe filled with Teflon when measuring the material at over 40°C [6].

Thus, we may need a more sensitive probe of the cavity type having high quality factor. In order to detect the small permittivity change, a cavity resonator would be desirable since the resonance frequency of a cavity resonator with high quality factor is noticeably shifted even if the permittivity of the material inside the cavity gets changed even below 0.1%. Thus, we have proposed a partially open cavity (POC), which partially has openings to circulate liquid materials at each corner, to measure complex permittivity. If a vector network analyzer to measure the resonance frequency can implement a narrower span over measurement frequencies, one may detect the smaller permittivity changes [7].

In this letter, the introduced partially open cavity probe can be applied to various monitoring systems for an insulating oil degradation, a temperature change of gas tank, and so on [8, 9]

## 2. Design of Partially Open Cavity

Fig. 1 shows the proposed rectangular POC fed by a coaxial line. It has four apertures at each corner wall whose opening area is 10 mm by t mm. We can put open apertures at each corner without disturbing the dominant mode field distribution of the rectangular cavity because the electric field intensities at each corner are weak enough. The apertures will allow the test material of liquid type to circulate easily inside to outside of the POC while measuring.

The return loss was simulated using HFSS according to the width (t) of the aperture, t=0~6 mm, and the resonant frequency of the dominant mode were compared in Fig. 2. In the EM simulation using HFSS, the test material of the cavity was distilled water whose dielectric constant is 81. As shown in Fig. 2, when t < 2mm, the resonant frequency

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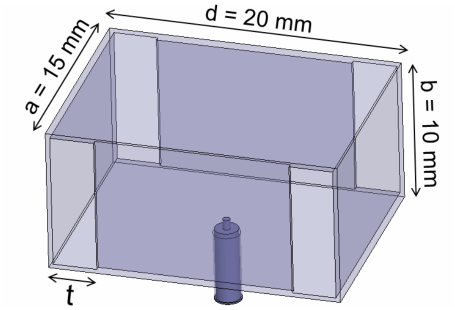


**Fig. 3.** Structure of partially open cavity

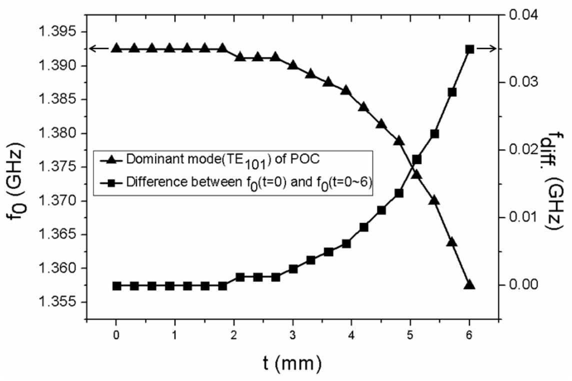


**Fig. 3.** Resonant frequencies of dominant mode according to *t*

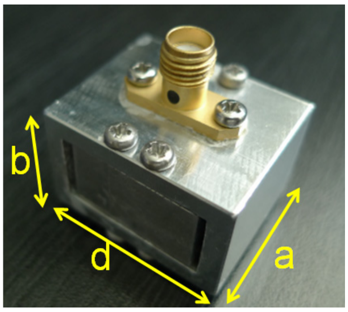


**Fig. 3.** POC with t=1 mm; a=21 mm, b=16 mm, and d=26 mm.

of the dominant mode is almost same as that of t=0 which is the entirely closed cavity. As the aperture width t increases, the field distributions are disturbed by the apertures because the electromagnetic power is leaked thru the apertures. The wider aperture allows test materials of liquid type to circulate easily, but it causes us to get inaccurate permittivity of the materials due to the distorted field distribution of $TE_{101}$ mode and leakage power.

Considering this trade-off, we have chosen the aperture width as 1 mm, which is about one twentieth of a guided wavelength of the 1st resonance mode. We assume that the cavity with the width, 1 mm, is the same as the entirely closed cavity when considering the graph of Fig. 2.

The picture of the proposed POC is shown in Fig. 3. It was made of aluminum plate whose the thickness is 3 mm, and was designed based on the structure in Fig. 1, but considered the thickness of aluminum plate.

## 3. Theory

### 3.1 Calculation for obtaining $\varepsilon_r'$

Consider a rectangular cavity whose dimensions are a, b and d filled with dielectric material whose dielectric and magnetic constants are $\varepsilon_r'$ and $\mu_r'$ , respectively. The resonant frequency of *mnl* mode of the cavity is given as (1).

$$f_{mn\ell} = \frac{ck_{mn\ell}}{2\pi\sqrt{\mu_r'\varepsilon_r'}} = \frac{c}{2\pi\sqrt{\mu_r'\varepsilon_r'}}\sqrt{\left(\frac{m\pi}{a}\right)^2+\left(\frac{n\pi}{b}\right)^2+\left(\frac{\ell\pi}{d}\right)^2} \tag{1}$$

where $k_{mnl}$ is a resonant wave number [10] and $m$=1, $n$=0, and $l$=1. Eq. (1) can be expressed as (2) including a calibration factor, $C_f$ that is to calibrate the square root term including the physical length factors such as a, b, and d, by multiplying $C_f$. It was difficult to precisely fabricate the POC, which is very small size, about 20 mm. Once we know the $\varepsilon_r'$ and $\mu_r'$ of a reference liquid inside the rectangular cavity and the resonant frequency $f$ are measured, the physical length error can be calibrated with the calibration factor, $C_f$.

$$\sqrt{\varepsilon_r'} = \frac{\dfrac{c\sqrt{\left(\frac{m\pi}{a}\right)^2+\left(\frac{n\pi}{b}\right)^2+\left(\frac{\ell\pi}{d}\right)^2}\times C_f}{2\pi\sqrt{\mu_r'}}}{f_{mn\ell}} \tag{2}$$

The reference liquid used in this letter is distilled water whose complex permittivity is calculated by Cole-Cole Eq. [1]. Once the resonant frequency is measured with the rectangular cavity, the $C_f$ would be derived.

One of the main drawbacks of the proposed technique is that it can be applied in a narrow band because of the use of cavity resonance.

### 3.2 Calculation for obtaining loss tangent

In order to obtain loss tangent of a test material inside a rectangular cavity, we used the critical-points method [11] which is to obtain unloaded $Q$ of a rectangular cavity including an electrical probe. Unloaded quality factor is that

$$\frac{1}{Q} = \frac{1}{Q_c} + \frac{1}{Q_d} \tag{3}$$

where $Q$ is unloaded quality factor, $Q_c$ is quality factor with lossy conducting walls, and $Q_d$ is quality factor with lossy dielectric filling. The $Q_d$ is the inverse number of loss tangent (tan$\delta$) and the $Q_c$ can be written as

$$\begin{aligned} Q_c &= k^3\eta \cdot \frac{(ad)^3 b}{2\pi^2 R_s} \cdot \frac{1}{(2\ell^2 a^3 b + 2bd^3 + \ell^2 a^3 d + ad^3)} \\ &= \left(\sqrt{\varepsilon_r}\right)^3 \frac{1}{\sqrt{\varepsilon_r}} \cdot s \\ &= \varepsilon_r' \cdot s \end{aligned} \qquad (4)$$

where

$$s = \frac{377(ad\omega)^3 b}{2\pi^2 R_s (2\ell^2 a^3 b + 2bd^3 + \ell^2 a^3 d + ad^3)}.$$

The unloaded Q can be derived as

$$\frac{1}{Q} = \frac{1}{\varepsilon_r' \cdot s} + \frac{\varepsilon_r''}{\varepsilon_r'}. \qquad (5)$$

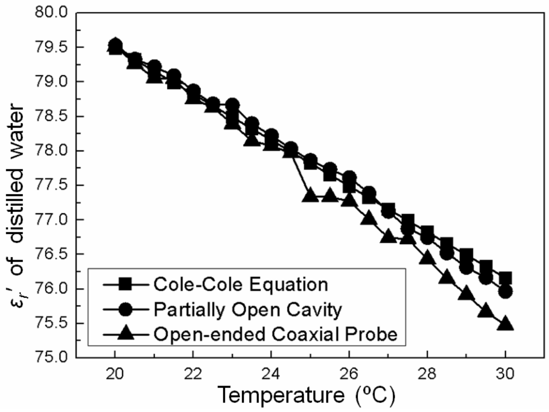
If the denominator of the first term in (5) is large enough, the loss tangent, the second term, can be obtained by only deriving unloaded $Q$ of a rectangular cavity.

## 4. Measurement

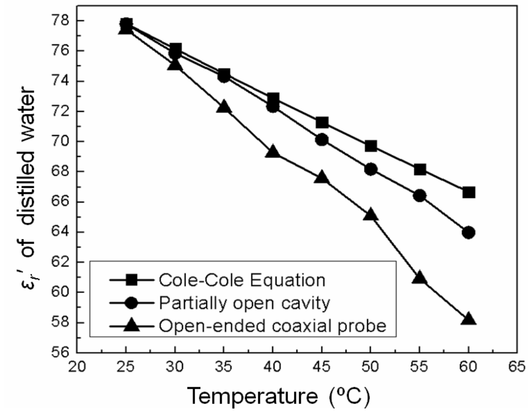
In this letter, we used saline as a test material that is a mixture of distilled water and NaCl and made three kinds of the test materials whose salinity are 0.3, 0.6 and 0.9%, respectively. The results, $\varepsilon_r'$ and tan$\delta$, measured by the POC were compared with those by open-ended coaxial probe and Cole-Cole equation as shown in Table 1.

We immersed the POC and open-ended coaxial probe into test materials, saline, in a beaker, and measured the return loss of those probes in order to measure complex permittivity. The proposed POC has a calibration process using only one reference material, distilled water, as (2), whereas the open-ended coaxial probe used three materials, air, methanol and distilled water for the calibration. The measurement of complex permittivity using the proposed method showed the error of less than about 6% [1].

And the POC can measure small change of $\varepsilon_r'$ with high accuracy as the temperature of a liquid in a beaker is rising, but the open-ended coaxial probe is difficult to identify the small change. We showed the fact in Fig. 4. As mentioned, the open-ended coaxial probe is filled with a dielectric material of Teflon that can be easily deformed due to high temperature. Both of the POC and open-ended coaxial probe used distilled water of 20°C for a calibration process and measured the distilled water of 20°C to 30°C and 25°C to 60°C as shown in Fig. 4(a) and (b). Fig.4(a) shows the open-ended coaxial probe has the error in measuring dielectric constant even if the irreversible deformation of the dielectric material in the coaxial cable due to high temperature was not present. However the results measured from the proposed POC showed a good agreement with those calculated using Cole-Cole Equation in the temperature of 20°C to 60°C.



(a) $\varepsilon_r'$ of distilled water at temperature of 20 ~ 30°C



(b) $\varepsilon_r'$ of distilled water at temperature of 30 ~ 60°C

**Fig. 4.** Measured and calculated ε r' as function of temperature

**Table 1.** Comparison of calculated and measured complex permittivity (at 23°C)

| Liquids (Salinity, %) | Frequency (GHz) | Cole-Cole Equation (Calculated) | | Measurement | | | |
|---|---|---|---|---|---|---|---|
| | | | | Partially Open Cavity | | Open-Ended Coaxial Probe | |
| | | $\varepsilon_r'$ | tan$\delta$ | $\varepsilon_r'$ | tan$\delta$ (1/Q) | $\varepsilon_r'$ | tan$\delta$ |
| Saline (0.3%) | 1.2489375 | 77.70 | 0.1604 | 78.20 | 0.1699 | 78.34 | 0.1574 |
| Saline (0.6%) | 1.2505 | 76.69 | 0.2534 | 78.01 | 0.2631 | 78.03 | 0.2570 |
| Saline (0.9%) | 1.2518125 | 75.71 | 0.3468 | 77.85 | 0.3343 | 77.63 | 0.3523 |

## 5. Conclusion

The measuring technique with a partially open cavity (POC) was introduced to measure complex permittivity in a narrow band and to monitor any small dielectric constant changes as the temperature is slowly rising; it also demonstrated its feasibility by comparing with the conventional technique using open-ended coaxial probe and Cole-Cole equation.

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## References

[1] A. Nyshadham, C.L. Sibbald, and S.S. Stuchly, "Permittivity measurements using open-ended sensors and reference liquid calibration - An uncertainty analysis," IEEE Trans. Microwave Theory & Tech., vol. 40, no. 2, pp. 305-314, Feb. 1992.

[2] Sangbok. Park, Young-seek Chung, Youngwoo Kwon, "A novel two-port probe for complex permittivity and permeability measurement of liquid and powder type materials," Microwave and Optical Technology Letters, vol. 51, no. 12, pp. 2977-2979, Dec. 2009.

[3] Nawaf N. Al-Moayed, Mohammed N. Afsar, Usman A. Khan, Sean McCooey, and Mahmut Obol, "Nano Ferrites Microwave Complex Permeablility and Permittivity Measurements by T/R Technique in Waveguide," IEEE Trans. Magnetics, vol. 44, no. 7, pp. 1768-1772, Jul. 2008.

[4] M. Jaleel Akhtar, Lambert E. Feher, and Manfred Thumm, "Noninvasive procedure for measuring the complex permittivity of resins, catalysts, and other liquids using a partially filled rectangular waveguide structure," IEEE Trans. Microwave Theory & Tech., vol. 57, no. 2, pp. 458-470, Feb. 2009.

[5] Atsuhiro Nishikata, "A swept-frequency measurement of complex permittivity and complex permeability of a columnar specimen inserted in a rectangular waveguide," IEEE Trans. Microwave Theory & Tech., vol. 55, no. 7, pp. 1554-1567, Jul. 2007.

[6] Namgon Kim, Jeonghoon Yoon, Sungjoon Cho, Jeiwon Cho, Changul Cheon, and Youngwoo Kwon, "An optimum design methodology for planar-type coaxial probes applicable to broad temperature permittivity measurements," IEEE Trans. Microwave Theory & Tech., vol. 56, no. 3, pp. 684-692, Mar. 2008.

[7] Lye Heng Chua, and Dariush Mirshekar-Syahkal, "Accurate and direct characterization of high-Q microwave resonators using one-port measurement," IEEE Trans. Microwave Theory & Tech., vol. 51, no. 3, pp. 978-985, March 2003.

[8] Maja Koncan Gradnik, "Physical-chemical oil tests, monitoring and diagnostics of oil-filled transformers," 2002 International Conference on Dielectric Liquids, pp. 242-247, July 2002.

[9] Sangbok Park, Young-seek Chung; Changyul Cheon, "A new method for measuring degradation level of insulating oil with temperature in microwave," IEEE 2010 Antennas and Propagation Society International Symposium, pp. 1-4, July 2010.

[10] D.M. Pozar, Microwave engineering, 3rd ed., New York: J. Wiley & Sons, 2003.

[11] En-Yuan Sun and Shuh-Han Chao, "Unloaded Q measurement - the critical-points method," IEEE Trans. Microwave Theory & Tech., vol. 43, no. 8, pp. 1983-1986, August 1995.

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