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Dk and Df Characterization of Low-loss Dielectric Liquid by Cylindrical Cavity Resonator

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***Abstract*—A novel cylindrical cavity resonator-based measurement method was developed to characterize the dielectric property of the low-loss dielectric liquid in the paper. The proposed method can be used to accurately measure the dielectric constant (Dk) and the loss tangent (Df) of the low-loss coolant for signal integrity analysis. The cylindrical cavity resonator works at tangential magnetic (TM_{010}) mode is used in the paper to demonstrate the proposed method. A cylindrical cavity resonator apparatus was designed and investigated using full-wave simulations at first. The relative error of Dk and Df extractions based on the designed apparatus are less than 1% and 5% from simulation results, respectively. In addition, the designed apparatus was manufactured to verify the proposed method through measurements. Measurements demonstrate the high accuracy and repeatability of the proposed method for low-loss dielectric liquid characterization. The measurement uncertainty for Dk could be less than 1%.**

***Keywords*—Cavity resonator, coolant, dielectric constant (Dk), loss tangent (Df), liquid characterization, measurement apparatus, TM_{010} mode.**

I. Introduction

The development of high-performance data centers and cloud computing brings a big challenge in efficiently cooling network servers. Immersion cooling, also known as liquid cooling, is the method of submerging electrical and electronic devices such as data center servers and storage systems, in a thermally conductive, but not electrically conductive liquid [1], as shown in Fig. 1. This cooling eliminates the need for fans, resulting in power saving. However, the use of coolant may have adverse effects on the electrical performance of exposed connectors, components, and microstrip lines on the printed circuit board (PCB) [2, 3]. Extracting the electrical properties of the coolant is crucial during the early design phase of the PCB. Typically, the coolant is a material with very low loss to minimize its impact on the PCB loss.

Several methods have been developed for characterization of dielectric material, these can be classified into non-resonant methods, such as transmission line-based techniques [4], coaxial probe method [5], parallel plate method [6], free space method [7], and resonant methods, e.g. cavity resonator method [8], resonator sensor [9]. Non-resonant methods generally have the capability to characterize materials over a wide bandwidth, particularly for the lossy materials. While the resonant methods measure the material properties at either a single frequency or multiple frequencies. Compared to non-resonant methods, the resonant method provides more accurate measurement of very low loss material property. Resonator can operate at different modes allowing for the characterization of PCB material inhomogeneity [10, 11]. Additionally, the standard IEC 60247 was proposed for the accurate characterization of dielectric liquids [12]. However, existing methods still face limitations in accurately measuring materials with a loss tangent below 0.001.

This paper introduces a novel measurement method based on a cylindrical cavity resonator for the precise characterization of the dielectric constant (Dk) and the loss tangent (Df) of low-loss dielectric liquids. Different from existing cavity resonator-based methods, the cavity resonator is fully filled by the liquid

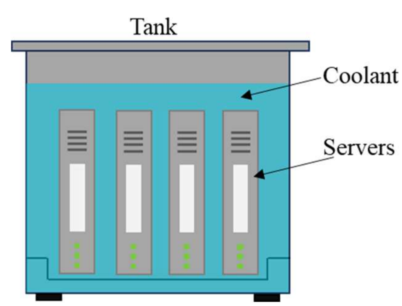


Fig. 1. Schematic image of immersion cooling solution for data centers with dielectric liquid coolant

under test from the proposed method, which makes it more sensitive to materials. The cylindrical cavity resonator works at TM_{010} mode is used in the paper to demonstrate the proposed method. The Dk and Df of the dielectric liquid can be extracted by the proposed method at the cavity resonance frequency. A resonator apparatus was designed and introduced in this study. The proposed technique is initially verified based on full-wave simulations. The designed apparatus was manufactured for measurements, which also verified the accuracy and the effectiveness of the proposed method. The application range of the manufacturing apparatus was evaluated based on the lowest Q-factor can be accurately measured by the vector network analyzer (VNA). The measurements demonstrated the proposed method's capability to accurately characterize a coolant with an extremely low loss tangent of approximately 0.0005.

II. Proposed Cylindrical Cavity Resonator Method

The proposed cylindrical cavity resonator method is introduced in this section. The cylindrical cavity resonator can work in different modes e.g. transverse electric (TE) mode and transverse magnetic (TM) modes. Here TM_{010} mode resonator is used as an example to clarify the proposed method for the low-loss coolant characterization.

A. Cylindrical Cavity Resonator Works at TM_{010} Mode

The geometry size of the cylindrical cavity is shown in Fig. 2. The resonance frequency of the cylindrical cavity resonator works at TM_{010} mode can be calculated based on the formula below [13].

$$f_{010}^{TM} = \frac{c}{2\pi\sqrt{\varepsilon_r}}\frac{x_{01}}{a} \quad (1)$$

where ε_r is the Dk of the dielectric in the cavity, c is the light speed in the free space, $x_{01} = 2.405$ is the ordered zeros of $J_0(x)$ and a is the radius of the cavity.

The Q-factor of the cylindrical cavity can be calculated based on the material property inside the cavity and the cavity size by the analytical formula below [14].

$$Q_{010}^{TM} = 1/\left(\frac{2\sqrt{\varepsilon_r}R_s\left(1+\frac{a}{h}\right)}{x_{01}}\sqrt{\frac{\varepsilon_0}{\mu_0}} + \frac{1}{tan\delta}\right) \quad (2)$$

where ε_0 and μ_0 is the permittivity and the permeability of the air separately, $R_s = \sqrt{\mu_0 \pi f_{010}^{TM}/\sigma}$ is the surface resistance of the cavity conductor and h is the cavity height. σ is the conductivity of the cavity conductor and $tan\delta$ is the Df of the material inside the cavity.

B. The Proposed Method

An apparatus was designed to verify the proposed method, as shown in Fig. 3. The designed apparatus consists of the cavity and the printed circuit board (PCB) probes used to measure the resonance and the Q-factor of the cavity. The lid of the cavity can be manually opened for filling or shifting the measured material. The PCB probe is a magnetic-field probe which typically used for the near-field scanning [14]. There are two small feeding holes on the side wall of the cavity for the probe insertion. The PCB probes and the holes would impact the resonance frequency and the Q-factor of the cavity itself. In other words, the designed cavity is not an ideal cylindrical cavity as shown in Fig. 1. It is very difficult to get the analytical model of the apparatus with the holes and the probes. Here the equivalent theory-based method is proposed. The apparatus is equivalent to an ideal cylindrical cavity without the probes and the holes. The size and the conductor conductivity of the equivalent ideal cavity would be different from the size and the conductor conductivity of the fabricated apparatus. In other words, the impact of the probes and the holes need to be compensated or calibrated by the size and the conductor conductivity of the ideal cylindrical cavity. Before characterizing material properties, the equivalent radius of the designed cavity should be extracted based on the measured resonance frequency when the cavity is empty. The equivalent radius of the designed cavity apparatus can be calculated below.

$$a_e = \left(\frac{cf_e}{2\pi}\right)^2 / x_{01} \quad (3)$$

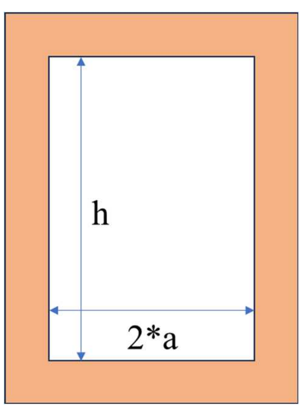


Fig. 2. Cross section view of cylindrical cavity.

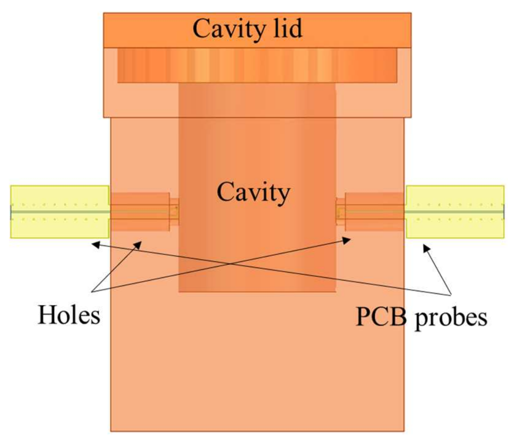


Fig. 3. Cross section view of the designed apparatus.

where f_e is the measured resonance frequency of the designed cavity when the cavity is empty. The impact of the probe and the hole on the cavity resonance frequency is compensated by the equivalent cavity radius.

The Q-factor of the designed apparatus is actually the loaded Q-factor Q_L, which includes the Q-factors of the probe and the hole. The Q_L can be calculated as

$$\frac{1}{Q_L} = \frac{1}{Q_{010}^{TM}} + \frac{1}{Q_p} + \frac{1}{Q_h} \quad (4)$$

where Q_p and Q_h are the Q-factor of the probe and the feed hole respectively. It is difficult to identify the Q-factors of the probe and the feed hole. The equivalent conductivity of the cavity conductor is used here to compensate or calibrate for the impact of the probe and the feed hole. The equivalent conductor conductivity should be extracted based on the measured Q-factor when the cavity is empty. The equivalent conductor conductivity can be calculated as

$$\sigma_e = \frac{\mu_0 \pi f_e}{\left(\frac{x_{01}}{Q_e(1+\frac{a_e}{h})}\sqrt{\frac{\mu_0}{\varepsilon_0}}\right)^2} \quad (5)$$

where Q_e is the measured Q-factor of the designed apparatus when the designed cavity is empty, h is the cavity height of the designed apparatus, which can be measured directly.

When the designed apparatus is fully filled by the coolant under test, the resonance frequency f_L and the Q-factor Q_L can be measured by the VNA. After that, the Dk and the Df of the coolant under test can be extracted based on the measured f_L and Q_L.

Table I. The actual size and conductor conductivity of the simulated apparatus and the equivalent size and conductor conductivity of the equivalent model

	Simulated apparatus	Equivalent model
Cavity radius	$a = 11.3\ mm$	$a_e = 11.13\ mm$
Cavity height	$h = 30\ mm$	$h = 30\ mm$
Conductor conductivity	$\sigma = 6500000\ s/m$	$\sigma_e = 5430000\ s/m$
Simulated f_e and Q_e	$f_e = 10.307,\ Q_e = 3818$	

$$Dk = \left(\frac{c}{2\pi f_L}\sqrt{\frac{x_{01}}{a_e}}\right)^2 \quad (6)$$

$$Df = 1/\left(\frac{1}{Q_L} - \frac{2\sqrt{Dk}\left(1+\frac{a_e}{h}\right)}{x_{01}}\sqrt{\frac{\varepsilon_0 \pi f_L}{\sigma_e}}\right) \quad (7)$$

The Dk and Df of the coolant can be extracted by the formulas (3-7) based on the measured f_e, Q_e, f_L and Q_L for the empty apparatus and the apparatus fully filled by the coolant under test.

III. Verification and Analysis

In this section, the proposed resonator method was verified based on full-wave simulations and measurements. The accuracy and effectiveness of the proposed resonator method were investigated based on full-wave simulation and measurement results.

A. Full-wave Simulation Verification

The designed apparatus was simulated by the standard high-frequency simulation software (HFSS). Fig. 2. shows the simulation model of the designed apparatus. The cavity is excited by the PCB probes. The actual size and the conductor conductivity of the apparatus are listed in Table I. The f_e and Q_e of the apparatus at TM_{010} mode can be simulated directly, which are shown in Table I. The equivalent radius of the apparatus can be calculated based on the simulated f_e, which is also listed in

Table II. Simulation verification of the proposed method by sweeping the Dk of the material.

Input Dk and Df of the material	Dk = 2 Df = 0.002	Dk = 3 Df = 0.001	Dk = 5 Df = 0.0007	Dk = 7 Df = 0.0005	Dk = 10 Df = 0.0003	Dk = 20 Df = 0.0001	Maximum Relative error
Simulated f_L (GHz)	7.268	5.938	4.597	3.885	3.25	2.298	-
Extracted Dk	2.01	3.01	5.03	7.04	10.06	20.12	-
Relative error of Dk	0.5%	0.3%	0.6%	0.6%	0.6%	0.6%	0.6%
Simulated Q_L	423	761	898	1065	1285	656	-
Extracted Df	0.00205	0.00097	0.000721	0.000512	0.000312	0.000105	-
Relative error of Df	2.5%	3%	3%	2.4%	4%	5%	5%

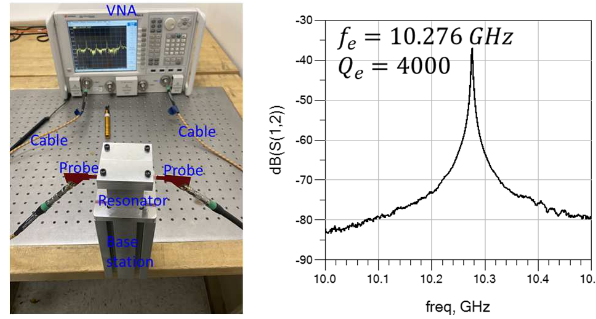
Table I for clarifying the impact of the probes and the holes on the resonance frequency. Similarly, the equivalent conductor conductivity can also be calculated based on the simulated and Q_e. The actual conductor conductivity and the equivalent conductor conductivity of the cavity are compared in Table I to clarify the impact of the probes and the holes on the Q-factor.

To verify the proposed method, the f_L and Q_L of the apparatus fully filled by the material were simulated, which are listed in Table II. The input Dk and Df are the material properties inside the cavity used in the simulation. According to the simulated f_L and Q_L, the Dk and Df of the material inside the cavity used in the simulation can be calculated based on equations (6) and (7). The relative error is used to clarify the accuracy of the proposed method, where $relative\ error = \frac{input - extracted}{input} \times 100\%$. From the data in Table II, it can be found that the relative error of Dk and Df extractions could be less than 1% and 3% separately. That means the accuracy of the proposed method is good based on the simulation.

B. Measurement Verification

The designed apparatus was manufactured for measurements. The measurement setup of the resonance frequency and the Q-factor of the manufactured apparatus is shown in Fig. 4 (1). The VNA is connected to the PCB probes of the apparatus. The resonance frequency and the Q-factor of the apparatus can be extracted based on the measured S-parameter S_{21}. The resonance frequency of the manufactured apparatus can be roughly predicted based on the apparatus cavity size and the equation (2) before the measurement, which can help the setup of the measurement frequency bandwidth. The measured S21 is shown in Fig. 4 (b).

To verify the proposed method, the Dk and Df of the known materials, e.g. Mineral oil, was measured by the manufactured apparatus at room temperature. The extracted results are listed



(a) (b)

Fig. 4. (a) Measurement setup, (2) The measured S_{21}.

in Table III. The Dk and Df of Mineral oil from other publications are also listed in Table III for comparison, which can be used to verify the proposed resonator method. From the Table III, it can be found that the Dk and Df of the mineral oil extracted by the proposed method have a good correlation with the results from the reference papers [15] and [16]. From the measurement of the mineral, the accuracy of the proposed method is verified. The proposed method will be verified by more different liquid materials in the future.

Moreover, the Dk and Df of the synfluid coolant from different vendors were extracted by the manufactured apparatus. The extracted results by the proposed method are compared with the results from the vendor in Table IV. The measured Dk of the coolant by the proposed method is same as the data provided by the vendors. The measured Df of the liquid FECC7 SYNTH is 0.00115 which is also same as the data from the vendor. The vendor cannot provide the Df of the coolant when the Df is very small, because they do not have an accurate method to extract the Df of the very low-loss coolant. But the proposed method can measure the Df of those very low-loss liquid. The measured

Table III. Measurement of the known material Mineral oil

Known material: Mineral oil				
	f_L	**Q_L**	**Dk**	**Df**
Proposed method	**6.9666 GHz**	**1496**	**2.171 ± 0.02**	**3.6e-4 $\pm$ 4%**
Parallel-plate method [15]	**-**	**-**	**2.2**	**0.32e-4 -- 3.35e-4**
Electrode method [16]	**1 – 100KHz**	**-**	**2.16**	**1e-5 – 4e-4**

Table IV. Measurement of the synfluid coolant from two different vendors

Vendor	**Liquid name**	**Measured Dk @ 7 GHz**	**Measured Df @ 7 GHz**	**Dk from vendor**	**Df from vendor**
A	**FECC7 SYNTH**	**2.095 ± 0.01**	**0.00115 $\pm$ 1%**	**2.11**	0.0011
B	**PAO4**	**2.099 ± 0.01**	**0.00046 $\pm$ 3%**	**2.11**	-
C	**SYN4**	**2.096 ± 0.01**	**0.00047 $\pm$ 5%**	**2.1**	**-**

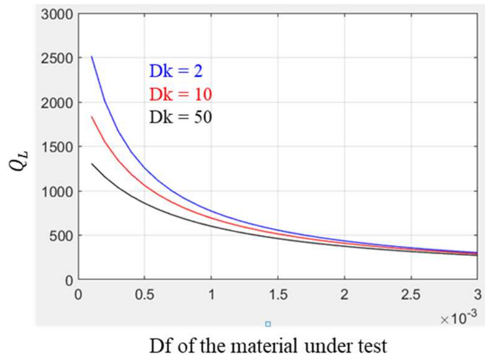


Fig. 5. Q_L of the manufactured apparatus fully filled by different material.

Df of the coolants is about 0.0005 which verified the effectiveness of the proposed method for the very low-loss dielectric liquid characterization. The measured coolant Df by the proposed method would effectively help to evaluate the impact of the coolant on the PCB of the data center. Moreover, the measurement uncertainty was also evaluated based on six times measurements, where the measurement uncertainty of Dk is less than 0.01 and the measurement uncertainty of Dk is less than 5%, which shows a good measurement repeatability of the proposed method.

C. *Applciation Range of the Manufactured Apparatus*

Theoretically, the manufactured apparatus can be used to characterize any dielectric materials with any Dk and Df. However, there is a limitation to the real measurement of the Q-factor. In other words, the measurement accuracy cannot be maintained if the Q-factor of the apparatus fully filled the material is too small. The Q-factor of the apparatus is related to the cavity conductor conductivity, the cavity radius, the probe loss, the probe factor, and the Dk and Df of the material under test. The application range of the manufactured apparatus can be evaluated by sweeping the Dk and Df of the material filled in the cavity. Fig. 5. shows the relationship of the Q_L of the apparatus and the Dk and Df of the liquid material under test. Assuming the lowest Q-factor that can be accurately measured is 400, the max Df of the material that can be measured by the manufactured apparatus is about 2.2×10^{-3} from the plot when the Dk of the material is larger than 2. For example, when the Dk of the material is 10, the max Df of the material is 2.1×10^{-3} which can be characterized by the manufacture apparatus.

IV. Conclusion

A cylindrical cavity resonator-based method was proposed in the paper, which can be used to characterize the low-loss dielectric liquid. The methodology of the proposed resonator-based method was introduced and verified, where the cylindrical cavity resonator works at TM_{010} mode. Different from other cavity resonator-based methods, the proposed method is more sensitive to the material under test because the cavity resonator is fully filled by the material. Besides, the impact of the external probes and the holes is calibrated by applying the equivalent cavity radius and conductivity, which guarantees the accuracy of the proposed method. Because the proposed method is calibrated based on the air, it could be more accurate for the low permittivity material measurement than other methods that use water to be calibration.

An apparatus of the cylindrical cavity resonator works at TM_{010} mode was designed and manufactured. The accuracy of the proposed method was investigated based on full-wave simulations at first, where the relative errors of the material Dk and Df extraction are less than 1% and 5%, respectively. The proposed method was also verified by comparing it with other methods for the measurement of the Mineral oil. Moreover, the coolant with a Df of 0.0005 can be accurately measured by the proposed method, where a good measurement repeatability was achieved. The measured permittivity of low-loss coolant in the paper can help signal integrity engineers to accurately analyze the impact of the coolant or select the appropriate coolant for their products.

Although the proposed method was only demonstrated based on the TM_{010} mode cylindrical cavity resonator. Theoretically, the proposed resonator-based method can work at any resonance mode. As a resonator method, the Dk and Df of the material under test can only be measured at the specific resonance frequency. However, the measurement frequency bandwidth can be improved by designing multiple different-size resonators. In the future, a resonator that works at multiple resonance modes or multiple resonators with different cavity sizes will be investigated.

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