Dielectric Measurement of Liquids After Calibration of S_{11} Using a Stepped Cut-off Circular Waveguide

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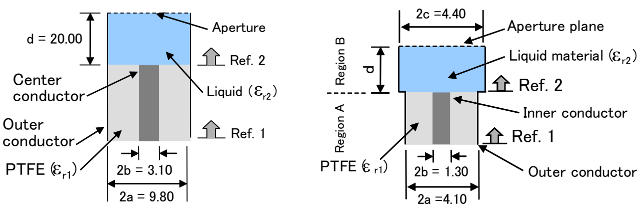
Measurement Procedure [1]

1. The jig is attached to a measurement cable connected to a VNA (vector network analyzer).
2. Calibration of S_{11} (input impedance) is performed at the tip of a coaxial line using SOM (short, open and reference material).
3. Input impedance is measured using a vector network analyzer at the front of the sample material when it is inserted into the measurement jig.
4. The complex permittivity of the sample material is computed based on an inverse problem to coincide with the calculated input impedance and the result of a measurement.

The Setting Condition of the Vector Network Analyzer

In this study, an HP 8720C analyzer (Keysight Technologies) was used to measure S_{11} with an IF bandwidth of 100 Hz and an averaging factor of 10 based on the relationship with factors such as sweep speed. Then, various liquids was inserted into the jig.

Numerical Calculation for Analytical Model [2]



Analytical model (coaxial loaded cut-off circular waveguide)

$$\boldsymbol{\Gamma}_1 = \boldsymbol{S}_{11} = \boldsymbol{V}_1 - 1 \ , \quad \boldsymbol{V}_m = \boldsymbol{Y}_{mn}^{-1} \cdot \boldsymbol{I}_m \ , \quad \boldsymbol{I}_m = \frac{2 \cdot \delta_{m1}}{\eta_0}$$

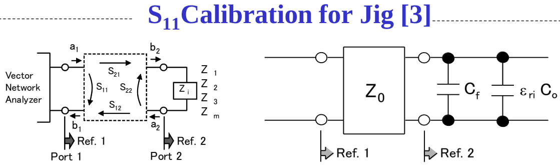
$$\boldsymbol{Y}_{mn} = \frac{\delta_{mn}}{\eta_{n-1}} - j\omega\varepsilon \sum_{i=1}^{I} \frac{F_{ni} F_{mi}}{\xi_i \tan(\xi_i \cdot d)} \ , \quad \eta_n = \frac{\gamma_n}{j\omega\varepsilon_0} \quad (n \geq 1)$$

$$\gamma_n = \sqrt{{k_n}^2 + {\gamma_0}^2} \quad (n \geq 1) \quad J_0(k_n \cdot b) \cdot Y_0(k_n \cdot a) - J_0(k_n \cdot a) \cdot Y_0(k_n \cdot b) = 0$$

$$\xi_i = \sqrt{\omega^2 \varepsilon\mu - P_i^2}$$

$$N_n = \frac{1}{\sqrt{\pi(\alpha_n^2 - \beta_n^2)}} \qquad F_{ni} = \begin{cases} \dfrac{\sqrt{2} \cdot [J_0(P_i b) - J_0(P_i a)]}{P_i \cdot c \cdot J_1(P_i c) \sqrt{\ln(a/b)}} & (n = 1) \\[2ex] \dfrac{-2\sqrt{\pi} \cdot N_{n-1} \cdot P_i \cdot [J_0(P_i a) \cdot \alpha_{n-1} - J_0(P_i b) \cdot \beta_{n-1}]}{c \cdot J_1(P_i c)[{k_{n-1}}^2 - P_i^2]} & (n > 1) \end{cases}$$

S_{11} Calibration for Jig [3]



$$\dot{\Gamma}_{corr} = \frac{a_2}{b_2} = \frac{\dot{\rho}_{meas} - \dot{E}_{DF}}{\dot{E}_{RF} + \dot{E}_{SF} \cdot (\dot{\rho}_{meas} - \dot{E}_{DF})} \ , \quad E_{RF} = E_{DF} \cdot E_{SF} + \gamma$$

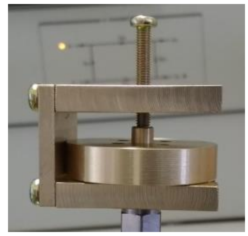
$$E_{SF} = \frac{\dot{\rho}_2 - \dot{\rho}_3 + \gamma \cdot (\dot{\Gamma}_3 - \dot{\Gamma}_2)}{\dot{\Gamma}_2 \cdot \dot{\rho}_2 - \dot{\Gamma}_3 \cdot \dot{\rho}_3} \ , \quad E_{DF} = \dot{\rho}_1 - \dot{\Gamma}_1 \cdot (E_{SF} \cdot \dot{\rho}_1 + \gamma)$$

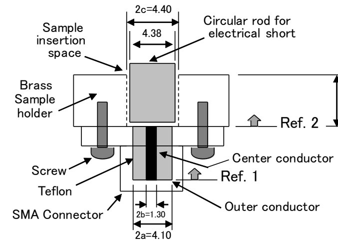
$$\gamma = \frac{(\dot{\rho}_2 - \dot{\rho}_1) \cdot (\dot{\Gamma}_2 \cdot \dot{\rho}_2 - \dot{\Gamma}_3 \cdot \dot{\rho}_3) + (\dot{\rho}_2 - \dot{\rho}_3) \cdot (\dot{\Gamma}_1 \cdot \dot{\rho}_1 - \dot{\Gamma}_2 \cdot \dot{\rho}_2)}{(\dot{\Gamma}_3 - \dot{\Gamma}_2) \cdot (\dot{\Gamma}_2 \cdot \dot{\rho}_2 - \dot{\Gamma}_1 \cdot \dot{\rho}_1) + (\dot{\Gamma}_1 - \dot{\Gamma}_2) \cdot (\dot{\Gamma}_3 \cdot \dot{\rho}_3 - \dot{\Gamma}_2 \cdot \dot{\rho}_2)}$$

$$\dot{\Gamma}_i = \frac{\dot{Z}_{\Gamma i} - Z_0}{\dot{Z}_{\Gamma i} + Z_0} = \frac{1 - j\omega C_0 \cdot \dot{\varepsilon}_{ri} \cdot Z_0 - j\omega C_f \cdot Z_0}{1 + j\omega C_0 \cdot \dot{\varepsilon}_{ri} \cdot Z_0 + j\omega C_f \cdot Z_0}$$

Here, ρ_i and Γ_i are the measured reflection coefficient for Ref. 1 and the theoretical reflection coefficient for Ref. 2

Auxiliary Jig to Ensure Electrical Shorting for S_{11} Calibration

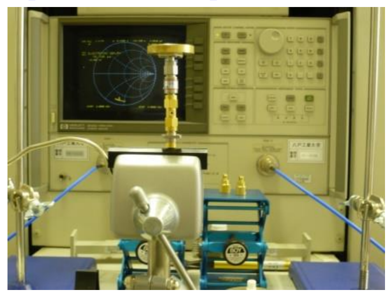


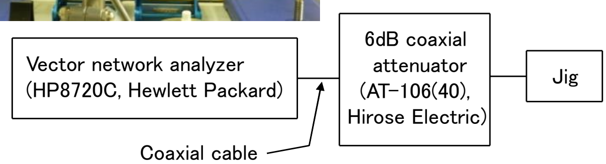


Auxiliary jig for contact of the short rod with the front of the coaxial line (left)

Structure of the cut-off circular waveguide for stable calibration with short (right)

Experimental Setup for Dielectric Measurement of Liquids





Experimental setup

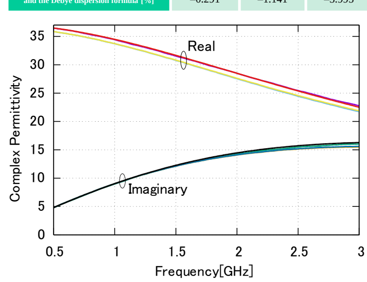
Result of Dielectric Measurement for Liquids

(a) methanol

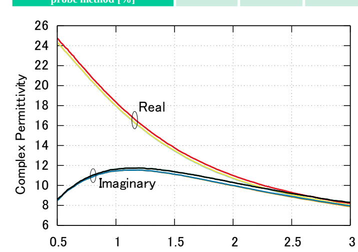
Condition		Frequency [GHz] 0.50	1.5	3.0
Inner diameter of sample insertion part [mm]	ϕ4.40 (MoM)	35.83 –j 4.800	30.82 –j 12.13	21.87 –j 15.62
	ϕ4.10 (MMT)	36.45 –j 4.827	31.52 –j 12.18	22.77 –j 16.05
Debye dispersion formula [21], [22]		36.48 –j 4.814	31.66 –j 12.27	22.51 –j 16.27
Difference between the MoM and the MMT at ϕ4.40 [%]		+0.028 +0.000	+0.130 +0.083	+0.644 +0.644
Difference between the MoM at ϕ4.40 and the MMT at ϕ4.10 [%]		–1.701 –0.559	–2.221 –0.411	–3.953 –2.679
Difference between the MoM at ϕ4.40 and the Debye dispersion formula [%]		–1.782 –0.291	–2.653 –1.141	–2.843 –3.995

(b) ethanol

Condition		Frequency [GHz] 0.50	1.5	3.0
Inner diameter of sample insertion part [mm]	ϕ4.40 (MoM)	24.36 –j 8.500	13.50 –j 11.12	8.026 –j 7.955
	ϕ4.10 (MMT)	24.76 –j 8.606	13.76 –j 11.38	8.204 –j 8.292
Coaxial probe method (Inverse problem via the MoM) [21], [27]		24.60 –j 8.163	13.07 –j 10.42	8.181 –j 6.953
Difference between the MoM and the MMT at ϕ4.40 [%]		+0.041 +0.000	+0.223 +0.090	+0.728 +0.875
Difference between the MoM at ϕ4.40 and the MMT at ϕ4.10 [%]		–1.616 –1.232	–1.890 –2.285	–2.170 –4.064
Difference between the MoM at ϕ4.40 and the coaxial probe method [%]		–0.976 +4.128	+3.290 +6.718	–1.895 +14.411



(a) methanol



(b) ethanol

Frequency characteristics of relative complex permittivity

[1] K. Shibata, "Measurement of Complex Permittivity for Liquid Materials Using the Open-ended Cut-off Waveguide Reflection Method," IEICE Trans. Electron., Vol. E93-C, No. 11, pp. 1,621 - 1,629, 2010-11

[2] K. Shibata, "S11 Calculation for a Coaxial-loaded Type Stepped Cut-off Circular Waveguide by the Moment Method," Proc. of International Symposium on Electrical and Electronics Engineering, ISEE 2021, pp. 84 - 89, Ho Chi Minh City, Vietnam, 2021-4.

[3] K. Shibata, "S11 Calibration Method for a Coaxial-loaded Cut-off Circular Waveguide Using SOM Termination," Proc. of the 2020 IEEE Sensors Applications Symposium, IEEE SAS 2020, Kuala Lumpur, Malaysia, 2020-3.