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BRIEF PAPER

Dielectric Measurement for Liquids Using a Coaxial-Feed Type Large-Bore Cut-Off Circular Waveguide with Good Repeatability

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SUMMARY This paper proposes a jig structure for a large-diameter coaxial-feed type stepped cut-off circular waveguide to enable accurate measurement of permittivity for liquids with good repeatability in the MHz band. The jig combines an N connector and a metal sample holder with an inner diameter slightly larger than that of the connector flange's outer conductor. The accuracy of S_{11} evaluation under short termination conditions was improved by this construction. To verify the validity of the proposed structure, several jig sets and short metal rods for S_{11} calibration were made. S_{11} was measured multiple times using the VNA when the jig tip was short, open, and with a reference material inserted (here, pure water), with methanol and ethanol as unknown liquids. The permittivity of each liquid was estimated by substituting the measured S_{11} value above into a formula involving comparison with SOM termination (short/open conditions and a known material). The liquid estimation results obtained were compared with those evaluated based on an inverse problem via MMT (mode-matching technique), with results showing good agreement, simple and stable evaluation with little variation over multiple dielectric evaluations at low frequency.

***key words:** complex permittivity, input impedance, calibration*

1. Introduction

Various methods have been proposed for evaluation of the permittivity of liquids [1]. Coaxial probing, which allows dielectric evaluation over a wide range of frequencies, is commonly used for this purpose [2] – [5]. Another approach has also been proposed for dielectric evaluation from S_{11} when a liquid is put into an open-ended coaxial line [6] – [8]. Moreover, a method for permittivity evaluation with a cut-off circular waveguide fed by a coaxial line was proposed by Bianco in 1979 [9]. The author proposed a valid method for evaluation using above structure via rigorous evaluation based on electromagnetic analysis using mode-matching technique (MMT) for an analytical jig model [10]. Various jig calibration methods have also been presented [11] – [14]. However, in previous jig, the outer-conductor inner diameter for the coaxial waveguide of the connector is the same as that of the inner-conductor outer diameter of the sample holder. As a result, when S_{11} with a metal cylinder in the jig as a short condition is evaluated, the contact state between the flange surface of the connector and the metal cylinder varies with each measurement. The author proposed novel jig structure for improvement of electrical contact [15]. This problem with variations in the values of permittivity across multiple measurements should also be improved especially at low frequencies.

In this study, a jig structure with a large-bore coaxial-feed type stepped cut-off circular waveguide with an N connector was proposed for dielectric measurement of liquids at low frequency. Repeatability in evaluation for the dielectric constant of liquids in the low-frequency MHz range using cut-off circular waveguide reflection method was significantly enhanced with this structure. The structure consists of an N connector and a metal sample holder with a slightly larger inner diameter than the outer diameter of its flange's outer conductor. This improves accuracy in S_{11} measurements under short termination. Jigs for the aforementioned structure and metal short rods for S_{11} calibration were created in multiple combinations. S_{11} was measured multiple times using a vector network analyzer (VNA) for each termination conditions. Moreover, a dielectric estimation method that does not require S_{11} calibration at the front of the sample involving comparison with SOM (short/ open conditions and a known material) termination was also proposed. The variability of the estimated values was examined for the multiple jigs created. The estimation results of permittivity for liquids from this procedure were compared with estimated values based on the inverse problem of mode-matching technique (MMT) [15] using the calibrated S_{11} at the sample front with SOM termination. The results showed good agreement between the two methods, simple and stable evaluation method with low variability even for multiple dielectric evaluations especially at low frequency.

2. Jig structure and permittivity measurement

The instability of electrical contact between the ground surface during shorting and the jig (Fig. 1 (a)) is resolved in evaluation of the dielectric constant of liquids using the cut-off circular waveguide reflection method. For this purpose, a jig structure with high repeatability (Figure 1 (b)) is proposed for accurate calibration and evaluation of S_{11}, especially in the low-frequency band. The conventional jig consists of an N connector with an inner conductor outer diameter of 2b = 3.10 mm and an outer conductor inner diameter of 2a = 9.80 mm, along with a metallic sample holder for the sample (Fig. 1 (a)). In the

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improved jig (Fig. 1 (b)), the inner diameter of the sample insertion portion is slightly larger (10.2 mm) than the outer conductor inner diameter (9.80 mm; inner conductor outer diameter: 3.10 mm). The stability of S_{11} measurement value is greatly improved by ensuring electrical contact with the center conductor and with the flange surface of the connector with a short metal rod (10.0mm) inserted. The S_{11} value for the coaxial line tip of the VNA was calibrated using a commercially available SOL (short, open and matched-load) calibration kit, and the jig shown in Figs. 1 (b) and 2 (a) was then attached. S_{11} with the tip of the coaxial line of the jig terminated featuring short and open conditions and a single reference material (pure water) and an unknown material were put into the jig and measured using the VNA. Methanol and ethanol were used for dielectric evaluation. The specific procedure is as follows:

1. The S_{11} value at the coaxial tip (Ref. 1) of the instrument before jig connection is calibrated with SOL termination using a standard N connector kit.

2. The measurement jig of the coaxial-feed-type stepped cut-off circular waveguide (Fig. 2 (a)) fed by an N connector is mounted at the coaxial line tip of the VNA.

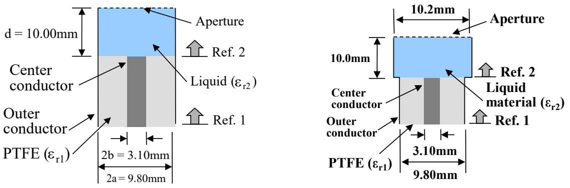
3. The S_{11} value for the SOL calibration plane (Ref. 1) is measured when the coaxial line front of the jig is shorted (Fig. 2 (b)) when open (Fig. 2 (a)) and with a reference material and an unknown material inserted.

4. S_{11} for Ref. 1 as measured with each of the above termination conditions is substituted into Equation (1) without moving the reference plane to the sample front (Ref. 2) and also without calibrating at Ref. 2 for permittivity estimation of the unknown liquid [11], [14].

The above procedure allows the omission of S_{11} calibration at the sample front (Ref. 2). The measurement procedure is thus dramatically simplified. To determine the permittivity of the target material, the following equation was used with S_{11} measurement for each termination condition substituted [11], [14]:

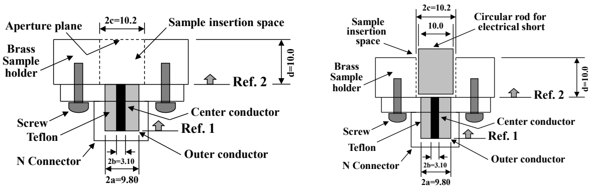
$$\dot{\varepsilon}_{rm} = \frac{\dot{\varepsilon}_{ra}\left(\dot{S}_{11m}-\dot{S}_{11o}\right)\left(\dot{S}_{11s}-\dot{S}_{11a}\right)+\left(\dot{S}_{11m}-\dot{S}_{11a}\right)\left(\dot{S}_{11o}-\dot{S}_{11s}\right)}{\left(\dot{S}_{11m}-\dot{S}_{11s}\right)\left(\dot{S}_{11o}-\dot{S}_{11a}\right)} \quad (1)$$

S_{11s} and S_{11o} represent S_{11} measured with the reference plane of the jig shortened and open-ended, respectively. ε_{ra} and S_{11a} are the dielectric properties of the reference material for comparison with the target materials and S_{11} with the reference material, respectively. S_{11m} represents S_{11} measured with the test material.



(a) Conventional structure (b) Proposed structure

Fig 1. Internal structure of coaxial-feed-type open-ended cut-off circular waveguide with an N connector

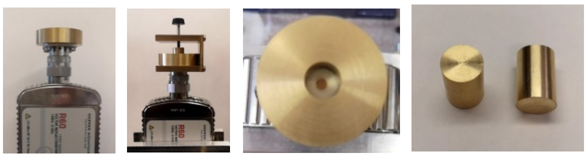


(a) open (b) short

Fig 2. S_{11} calibration for a coaxial-feed-type open-ended stepped cut-off circular waveguide with an N connector

3. Measurement of jig input impedance

Jig input impedance was measured using a Copper Mountain Technologies R60 single-port VNA with a frequency range of 10 – 1,000 MHz, 199 evaluation points, an IF bandwidth of 100 Hz, an output power of 0 dBm, and an averaging factor of 10. Input impedance at the tip of the N connector of the VNA before jig attachment was first calibrated using a commercially available SOL kit in line with the above procedure. The jig was attached to the coaxial line tip of the VNA. Input impedance was then measured with the front surface of the jig coaxial waveguide short, open and with each liquid inserted. S_{11} measurement using the VNA with the jig attached is shown in Fig. 3. The complex permittivity of the unknown material was then estimated by substituting the resulting values into Equation (1) [11].



(a) Open-ended (b) Short-ended (c) Top view (d) Short circular rods

Fig 3. Copper mountain R60 VNA for impedance data acquisition

During S_{11} measurement for the short condition, the screw was tightened using an auxiliary jig (Fig. 3 (b)). Pressure applied from above with the short brass rod (Fig. 2 (b)) ensured firm contact with the N connector flange. Contact between the outer conductor and the center conductor at the short end of the coaxial line was thus ensured. Input impedance for the SOL calibration plane (Ref. 1) with short/open conditions and liquids inserted at an air temperature of 25°C was first measured using the jig (Fig .2) after SOL calibration of the VNA with the N connector kit before jig attachment. The results at each frequency are shown in Table 1. Among these measurements, Table 1(a) shows the values obtained using the conventional jig. Meanwhile, Tables 1(b) to (d) show the values obtained using the newly proposed jig. The frequency characteristics of input impedance at 10 – 1,000 MHz are shown in Figures 4 – 6. Each termination condition was measured 10 times using different jigs and short rods on different dates and with different individuals. This showed the variability of the results. Meanwhile, when the input impedance of the short using the conventional jig was measured 10 times shown in Table 1(a), the average value was about 2 to 2.4 greater in the real part compared to the theoretical value of Z_{in} = 0.0 -j0.0. Moreover, the imaginary part showed a difference of up to approximately 0.9 at maximum. Significant variability in the measurement values was also observed. Meanwhile, in case of newly proposed jig, deviation increased with higher frequency for short conditions (Table 1 (b)). For open termination (Table 1(c)), deviation increased as frequency decreased. For pure water (Table 1 (d)), deviation decreased as frequency increased. Good repeatability was thus observed, particularly with short termination. Improved measurement accuracy for complex permittivity can be expected with the proposed jig.

Table 1. Averages of 10 input impedance evaluations for the SOL calibration plane (Ref. 1) for each termination condition (25°C) [Ω]

(a) Short (Previous jig)

Frequency [MHz]	Real		Imaginary	
	Mean	Deviation	Mean	Deviation
10	1.9511	9.9590	+0.0994	0.4354
100	2.3591	9.5487	+0.1170	1.2413
500	2.2579	8.5027	-0.5851	3.0147
1,000	1.8777	6.3842	-0.8777	4.6018

(b) Short (Newly proposed jig)

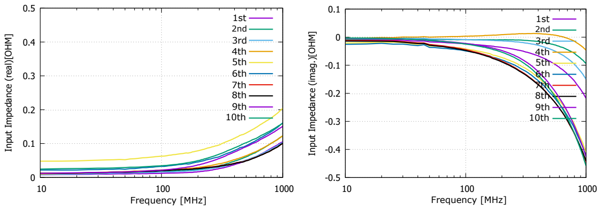
Frequency [MHz]	Real		Imaginary	
	Mean	Deviation	Mean	Deviation
10	0.0166	0.0313	-0.0107	0.0148
100	0.0259	0.0369	-0.0268	0.0303
500	0.0743	0.0570	-0.1299	0.1396
1,000	0.1332	0.0708	-0.3112	0.2652

(c) Open (Newly proposed jig)

Frequency [MHz]	Real		Imaginary	
	Mean	Deviation	Mean	Deviation
10	147650	367246	-148256	292348
100	292.269	202.495	-11660.4	1328.90
500	26.8029	1.8802	-2170.32	134.923
1,000	17.1849	2.2960	-1072.74	71.4497

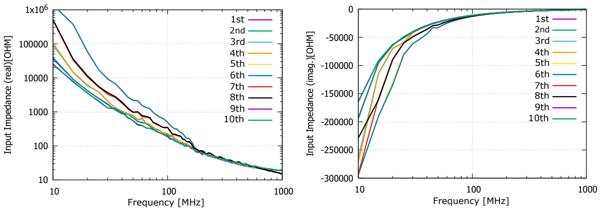
(d) Water (Newly proposed jig)

Frequency [MHz]	Real		Imaginary	
	Mean	Deviation	Mean	Deviation
10	41.4262	15.3240	-3103.21	72.9953
100	2.8585	0.0844	-301.486	7.2990
500	2.5855	0.0928	-59.5440	1.3447
1,000	2.5585	0.0817	-28.8126	0.5410



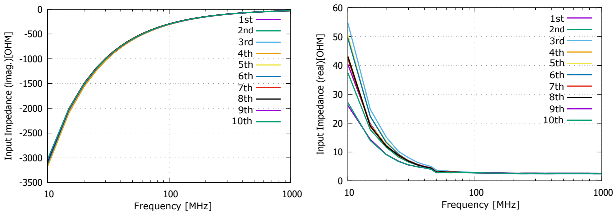
(a) Real (b) Imaginary

Figure 4. Variability of input impedance with the jig in a short condition (Newly proposed jig)



(a) Real (b) Imaginary

Figure 5. Variability of input impedance with the jig in an open condition (Newly proposed jig)



(a) Real (b) Imaginary

Figure 6. Variability of input impedance with pure water in the jig (Newly proposed jig)

4. Evaluation of dielectric constants for liquids

Next, measured input impedance for each termination condition at a room temperature of 25°C was substituted into Eq. (1) for estimation of the permittivity of methanol and ethanol. In this study, the permittivity of each liquid was also estimated using impedance for Ref. 2 after SOM calibration as an inverse problem based on mode-matching technique (MMT) [15] to compare estimated value with the above method based on Eq. (1). For this purpose, input impedance for Ref. 2 after calibration was calculated using the average of multiple measurements for short, open and various liquid termination conditions. The permittivity for each liquid using the different evaluation methods are shown in Table 2. The difference between the estimated values based on Eq. (1) and those using mode-matching method with methanol (Table 2 (a)) was within 0.16 for the real part and within 0.14 for the imaginary part from 10 to 500MHz. However, the difference was larger with a discrepancy of 0.93 for the real part and 0.21 for the imaginary part at 1,000 MHz, as opposed to the lower frequencies. This is attributed to deviation from the permittivity of the reference material associated with estimation using Eq. (1). Deviation of estimated permittivity based on Eq. (1) was within 0.69 for the real part and 0.38 for the imaginary part at all frequencies. These results demonstrate that variability remains within this range for the 10 evaluations of impedance at each termination condition. The estimated values of permittivity for ethanol also exhibited discrepancies and deviations similar to those of methanol at each frequency (Table 2 (b)). The results indicate improved repeatability of permittivity particularly from low frequencies using the proposed jig structure via quantitative analysis.

Table 2. Differences in permittivity estimation by evaluation principle with various liquids with newly proposed jig (air temperature: 25°C)

(a) **Methanol**

Freq. [MHz]	**Real**				**Imaginary**			
	Eq.(1)	Deviation	Mode-matching	Difference	**Eq.(1)**	Deviation	Mode-matching	Difference
10	33.00	0.69	33.16	-0.16	0.73	0.24	0.87	-0.14
100	33.69	0.35	33.61	+0.08	0.94	0.07	0.95	-0.01
200	33.64	0.37	33.58	+0.06	1.78	0.11	1.79	+0.01
500	32.88	0.65	33.02	-0.14	4.30	0.25	4.33	-0.03
1,000	30.41	0.37	31.34	-0.93	7.88	0.38	8.09	-0.21

(b) **Ethanol**

Freq. [MHz]	**Real**				**Imaginary**			
	Eq.(1)	Deviation	Mode-matching	Difference	**Eq.(1)**	Deviation	Mode-matching	Difference
10	24.62	0.61	24.78	-0.16	0.25	0.30	0.43	-0.18
100	25.19	0.23	25.09	+0.10	1.95	0.14	1.96	-0.01
200	24.69	0.19	24.61	+0.08	3.77	0.26	3.79	-0.02
500	21.52	0.44	21.60	-0.08	7.92	0.40	8.00	-0.08
1000	15.18	0.66	15.72	-0.54	9.96	0.12	10.39	-0.43

Meanwhile, the deviation of values obtained using the conventional jig when estimating the permittivity of each liquid using Eq. (1), and the difference compared to estimated results using the newly proposed jig are shown in Table 3. The result showed that the real part of the complex permittivity of methanol measured using the conventional jig was found to be smaller particularly at higher frequencies, compared to that estimated using the newly proposed jig. Meanwhile, the imaginary part of the permittivity estimated using the conventional jig was found to be larger, particularly at higher frequencies, compared to that estimated using the newly proposed jig. Moreover, the deviation using the conventional jig increased for both the real and imaginary parts at all frequencies compared to the deviation using the jig proposed in this paper. At the lowest frequency of 10 MHz, particularly large deviations were also observed when using the conventional jig. Accordingly, it was quantitatively demonstrated that using the newly proposed jig allows for a more accurate evaluation of complex permittivity with smaller deviations across all frequencies from 10 to 1000MHz.

Table 3. The difference in the complex permittivity estimated using Equation (1) between the proposed jig and the conventional jig.

(a) **Methanol**

Freq. [MHz]	**Real**				**Imaginary**			
	Proposed	Previous	Deviation	Difference	Proposed	Previous	Deviation	Difference
10	33.00	33.15	0.95	+0.15	0.73	0.95	0.74	+0.22
100	33.69	33.55	0.39	-0.14	0.94	1.72	0.17	+0.78
200	33.64	33.33	0.35	-0.31	1.78	3.31	0.28	+1.53
500	32.88	31.54	0.50	-1.34	4.30	7.88	0.67	+3.58
1,000	30.41	25.85	0.84	-4.56	7.88	13.62	1.28	+5.74

(a) **Ethanol**

Freq. [MHz]	**Real**				**Imaginary**			
	Proposed	Previous	Deviation	Difference	Proposed	Previous	Deviation	Difference
10	24.62	24.76	0.75	+0.14	0.25	0.30	0.31	+0.05
100	25.19	25.04	0.31	-0.15	1.95	2.57	0.18	+0.62
200	24.69	24.35	0.22	-0.34	3.77	4.99	0.33	+1.22
500	21.52	19.94	0.53	-1.58	7.92	10.59	0.54	+2.67
1,000	15.18	10.66	0.89	-4.52	9.96	12.62	0.74	+2.66

The average and deviation of the estimated complex permittivity from measurements conducted on different dates, using the mean of two types of terminations and accounting for variability in measurements from the third type of termination, are shown in Table 4. The results indicated that the variability in the estimated permittivity due to fluctuations in the measurement values of the short termination using the newly proposed jig was particularly low in the low-frequency range.

Table 4. The mean value and deviation of the complex permittivity estimated using Equation (1) with the proposed jig

(a) When the S_{11} measurement values at the open and water conditions are averaged, and the measurement values at the short condition vary.

Freq. [MHz]	**Methanol**				**Ethanol**			
	Real	Deviation	**Imag.**	Deviation	**Real**	Deviation	**Imag.**	Deviation
10	33.05	1.80	0.81	0.37	24.57	1.83	0.33	0.36
100	34.15	0.70	0.97	0.10	25.48	0.33	1.99	0.21
200	34.11	0.75	1.84	0.16	24.99	0.31	3.85	0.35
500	33.31	1.13	4.44	0.39	21.74	0.23	8.10	0.57
1,000	30.68	0.58	8.12	0.65	15.23	0.60	10.16	0.37

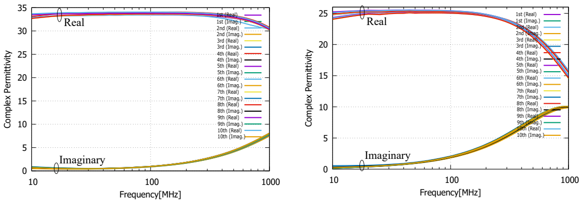
(b) When the S_{11} measurement values at the short and water conditions are averaged, and the measurement values at the open condition vary.

Freq. [MHz]	**Methanol**				**Ethanol**			
	Real	Deviation	**Imag.**	Deviation	**Real**	Deviation	**Imag.**	Deviation
10	33.24	2.78	0.76	0.57	24.79	2.87	0.27	0.58
100	34.23	0.79	0.97	0.11	25.59	0.46	1.99	0.21
200	34.19	0.82	1.83	0.16	25.09	0.41	3.85	0.35
500	33.39	1.18	4.43	0.37	21.85	0.30	8.09	0.59
1,000	30.85	0.59	8.11	0.63	15.38	0.65	10.18	0.35

(c) When the S_{11} measurement values at the short and open conditions are averaged, and the measurement values at the water condition vary.

Freq. [MHz]	Methanol				Ethanol			
	Real	**Deviation**	**Imag.**	**Deviation**	**Real**	**Deviation**	**Imag.**	**Deviation**
10	32.80	2.41	0.77	0.48	24.38	2.20	0.31	0.46
100	33.62	1.38	0.94	0.13	25.10	0.86	1.95	0.24
200	33.57	1.43	1.78	0.21	24.61	0.82	3.78	0.43
500	32.83	1.72	4.30	0.48	21.44	0.60	7.93	0.75
1,000	30.40	0.98	7.89	0.79	15.12	0.74	10.00	0.52

Figure 7 shows frequency response of complex permittivity estimated at 199 points from 10 to 1,000 MHz for each liquid at an air temperature of 25°C using the jig in Fig. 1 (b) and the formula involving SOM comparison. Complex permittivity was evaluated 10 times using different jigs and short rods on different dates and with different individuals. The real part of permittivity for methanol (Fig. 7(a)) ranged from 33.00 to 30.41, while the imaginary part ranged from 0.73 to 7.88. That for ethanol (Fig. 7(b)) ranged from 24.62 to 15.18, while the imaginary part ranged from 0.25 to 9.96. This process highlighted the variability of repeated evaluation for input impedance. The results indicate that the proposed jig structure improves repeatability, particularly in the low-frequency range. Accordingly, the study results show that the proposed jig structure and evaluation technique enable simple and high-precision evaluation for complex permittivity of small amounts of liquid with excellent repeatability based on the cut-off circular waveguide reflection method, particularly in the low-frequency MHz band.



(a) methanol (b) ethanol

Figure 7. Frequency characteristics of complex permittivity

5. Conclusions

A jig structure with a large-bore coaxial-feed type stepped cut-off circular waveguide with an N connector was proposed for dielectric measurement of liquids at low frequency. The results showed stable evaluation with little variation over multiple dielectric evaluations. Accordingly, evaluation of the dielectric constant of liquids from the MHz band with good repeatability using cut-off circular waveguide reflection method in combination with the proposed jig and technique is considered valid. In future work, evaluation for the permittivity of electrolyte solutions with high conductivity in the low-frequency range using this method will be necessary.

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