An Improved TR Method for the Measurement of Permittivity of Powder and Liquid Samples with Slabline

Licun Han*[1], Zhijun Xiang[2], Bingjie Tao[1], Minhui Zeng[1], Yu Zhang[3] and En Li[1].

1. University of Electronic Science and Technology of China, Chengdu, 611731, P. R. China
2. Southwest Institute of Electronic Equipment of China (SWIEE), Chengdu, 610054, P. R. China
3. Shandong Non-Metallic Material Institute, Jinan, 250031, P. R. China

E-mail:han88606@163.com

***Abstract*-An improved TR (transmission/reflection) method for measuring the complex permittivity of powder and liquid samples with slabline is provided in this paper. The method can afford quite high accurate measurement results without singularities, and broaden the operating frequency band to 2-18GHz. Some experiments are carried out to verify the feasibility of the improved TR method for permittivity measurement. The proposed method is validated by the measurement of the permittivity of Teflon from 2GHz to 18 GHz. Some useful conclusions are obtained for the development of measurement methods.**

I. INTRODUCTION

It is of high practical value in modern medical research field that applying the biological electromagnetic effects of microwave radiation in clinical application, such as, physical therapy and cancer hyperthermia. The study [1]-[3] found, the best curative is closely related with microwave frequency and radiation, and different biological tissue has different electromagnetic properties. In order to select the best frequency and the amount of radiation, it is necessary to comprehensively understand the electromagnetic properties of biological tissue or the microwave equivalent phantom model of simulated biological tissues. Therefore, measuring the complex permittivity of the powder and liquid materials is of great significance for the development of bio-pharmaceutical.

Both at home and abroad, researchers adopt the scattering parameter method for measuring the complex permittivity of solid matter, which can't measure the paste-like substance. In order to broaden the measurement bandwidth, TR method with one sample in coaxial line [4] is proposed which covers 4-8GHz. But, there are several other issues to resolve, such as difficulty of manufacturing the sample under test, and the air gap which has great effect on the measuring accuracy. Actually, the TR method with one sample in rectangular waveguide can not only broaden the measurement bandwidth, but also reduce degree of difficulty of processing of the sample. Nonetheless, the measurement system is very difficult to clean up. To sum up, we proposed an improved TR method with one sample in slabline.

In this paper, we introduced an improved TR method by using famous SOLT calibration method in section II. The improved TR method using equivalent techniques can eliminate the errors coming from mismatches between connectors, the affection of Teflon blocks which is used to fasten the powder and liquid samples being test on the measure system, and the instabilities of the calibration kit. To sum up, the proposed method can accurately measure the relative permittivity of microwave materials.

II. THE IMPROVED TR METHOD

A. Slabline measurement system

The slabline is a transmission line where a thin wire replaces a printed trace for an inductor. In order to obtain small return loss in the measurement system, the slabline fixture is optimized for getting the characteristic impedance 50 Ohm in the whole operating frequency band (2-18GHz). The real fixture of slabline is shown in Fig.1. From the picture, it can be seen that the slabline fixture connected with VNA (vector network analyzer) by APC-7 converter. Furthermore, it is necessary to design a transition between slabline and cable. In this paper, we adopted impedance linear transformation in this transition.

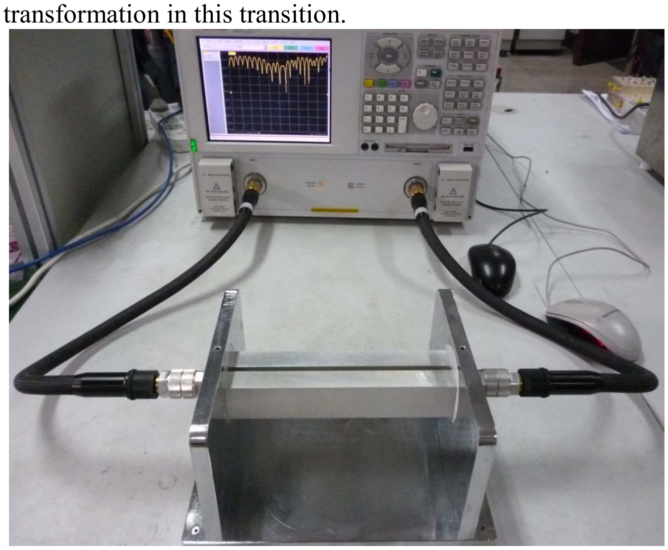


Figure 1. The real measurement system.

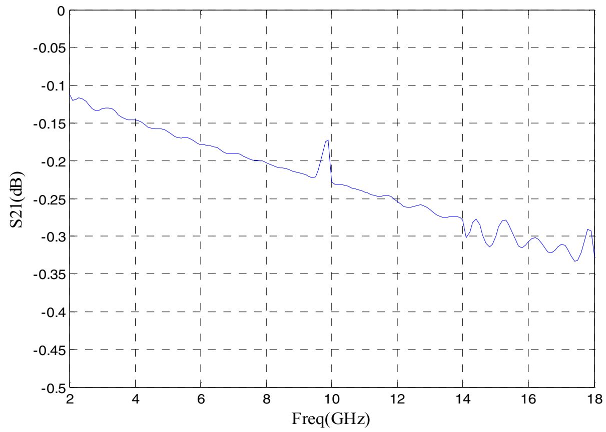


Figure 2. S21 of the structure.

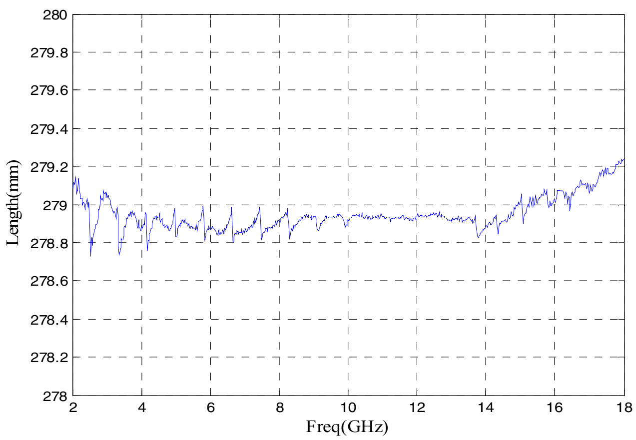


Figure 3. Equivalent length of the structure.

It is also assumed that only the dominant mode (TEM) is presented in the slabline, the metallic material of slabline is ideal conductor, and the measurement frequency (2-18GHz) is limited so that the higher-order modes cannot propagate. According to the definition of S-parameters, the S_{21} of a part of slabline can be written as [5]:

$$S_{21} = \exp(-j\theta) \quad (1)$$

$$\theta = 2\pi l / \lambda \quad (2)$$

where l and λ are, respectively, the length of a slabline and operating wavelength. If there is a lossless network which is operating on its dominant mode (TEM), it is feasible to consider this network as a transmission line.

In this paper, the slabline structure is assumed lossless, and it is easy to find that the dominant mode operating in this slabline structure is TEM. Hence, we apply this equivalent length theory to the calculation of the equivalent length of the slabline fixture. The measurement results of S21 and the equivalent length of slabline fixture are, respectively, shown in Fig.2 and Fig.3. The value of S21 is not equal to zero in the operating frequency band. And the return loss in the fixture is from the unideal conductor. The fluctuation in the line of Fig.3 is due to the unperfected match between slabline and coaxial line. In the following calculation, the average value 279mm of measurement data is chosen as the equivalent length.

To sum up, the permittivity of powder and liquid sample can be calculated from a new fixture which is quite similar to the proposed system. The system is added two Teflon blocks which is fixed the powder and liquid samples. Furthermore, we can calibrate the affection of Teflon blocks by using the equivalent theory.

B. The TR method

In this paper, it is assumed that the dielectric sample under test is isotropic, symmetric, and homogeneous. It is also assumed that only the dominant mode (TEM) is presented in the slabline structure and there is no air gap between the sample and the measurement cell. For an isotropic and symmetric sample region, the reflection coefficient at the port and the transmission coefficient of the network [6] can be expressed as the following equations:

$$\Gamma = \frac{\eta_r - 1}{\eta_r + 1} \quad (3)$$

$$T = \exp(-jkd) \quad (4)$$

$$k = k_0\sqrt{\mu_r \varepsilon_r} \quad (5)$$

$$\eta_r = \sqrt{\frac{\mu_r}{\varepsilon_r}} \quad (6)$$

where ε_r and μ_r are, respectively, the relative complex permittivity and the relative complex permeability of the dielectric sample under test, and d is the thickness of sample, η_r is the wave impedance in the dielectric region, k is the propagation constant of electromagnetic wave in the sample region, k_0 is the propagation constant of electromagnetic wave in vacuum .

According to the relationship between scattering parameters and transmission and reflection coefficients, the scattering parameters of the measurement cell can be written as:

$$S_{21s} = \frac{(1-\Gamma^2)T}{1-T^2\cdot\Gamma^2} \quad (7)$$

$$S_{11s} = \frac{(1-T^2)\Gamma}{1-T^2\cdot\Gamma^2} \quad (8)$$

where S_{11s} and S_{21s} are the measured value of the sample end. It is important that the S_{11s} and S_{21s} must be the data which has calibrated conductor loss of the entire slabline fixture [7] as shown in Fig.2. It can be calculated from the real measured data, S_{11} and S_{21}, which are the value of the whole slabline structure. The calculating formula can be written as the following equations, where l and d are, respectively, the equivalent length of the slabline fixture and the sample thickness.

$$S_{11S} = S_{11}\cdot\exp[jk_0(l-d)] \quad (9)$$

$$S_{21S} = S_{21}\cdot\exp[-jk_0(l-d)] \quad (10)$$

From (7) and (8), we can get T and Γ. And then, from (3) and (4), k and η_r can be obtained. The formula of k can be written as the following Equation (11), and where θ is the phase angle of T.

$$k = \theta / d + j \ln|T| / d \tag{11}$$

In conclusion, ε_r and μ_r of the dielectric sample under test can be given.

$$\varepsilon_r = \frac{k(1-\Gamma)}{k_0(1+\Gamma)} \tag{12}$$

$$\mu_r = \frac{k(1+\Gamma)}{k_0(1-\Gamma)} \tag{13}$$

III. MEASUREMENT RESULTS

In order to verify the feasibility of the improved TR method for permittivity measurement, a number of experiments were carried out. In the experiments, the VNA E8363B (Agilent) and a slabline fixture shown in Fig.1 are used for measurements. The dielectric sample under test in this system is Teflon placed in the center of the slabline fixture. Based on the principle [6] that the performance of Teflon is quite stable, Teflon is chosen as the standard sample to test the accuracy of the measurement system by considering the cost of the test, as shown in Fig.5. Fig.6 shows the calculated permittivity of air with certain thickness (10mm).

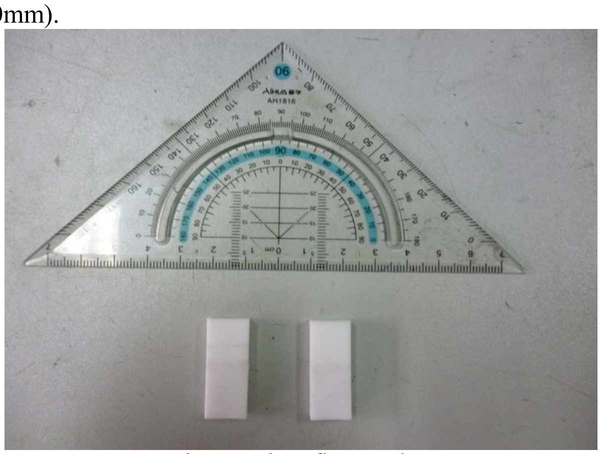
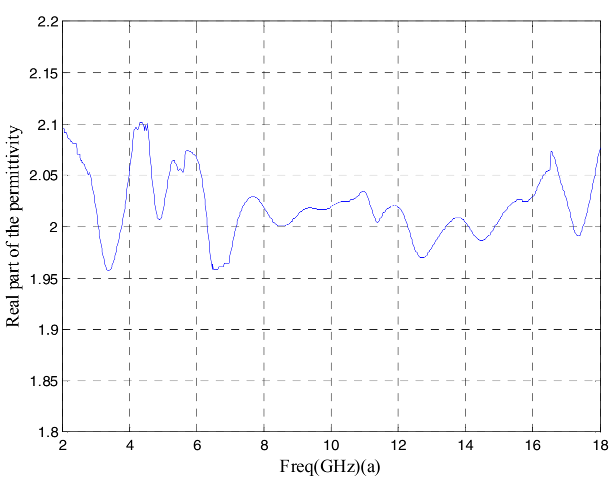


Figure 5. The Teflon samples.



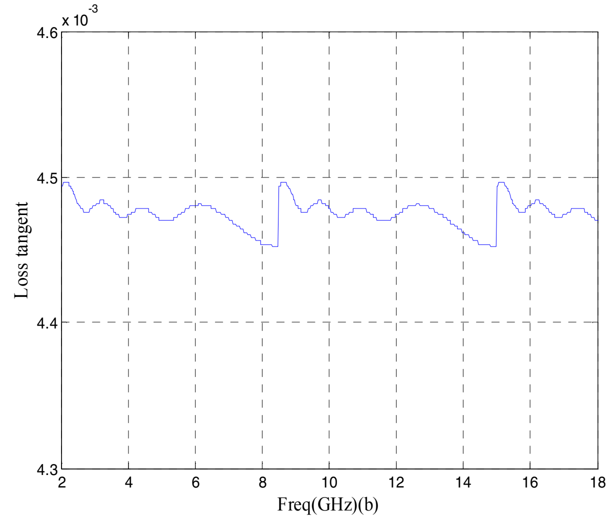


Figure 6. The permittivity of Teflon sample.

The real part of permittivity of Teflon (Fig.6) ranges from 1.96 to 2.11, and the loss tangent of Teflon is range from 0.0043 to 0.0046. The relative complex permittivity of the Teflon is 2.02-j0.0001 [7] in the operating frequency band 2-18GHz. As we know, the error of TR method is larger than any other methods. Furthermore, the error of the real part of complex permittivity is 0.01 [8] in TR method, the proposed TR method for measuring the permittivity is quite effective and acceptable, as well as high accurate.

IV. CONCLUSION

We have shown the improved TR method suited to measure the dielectric material with low loss. The experiments of air and Teflon are proved that the proposed method can be used in the test system effectively and quite simply. From the measured data, there are errors in TR method, which come from mismatch at the connections between slabline fixture and the joint of VNA, imperfection of the metallic material of slabline, imperfection of Teflon sample processing, inaccuracy of the thickness measurement of the sample, etc. With the manufacture process of composite sample [4] and the application of logarithm principle of Lichtenecker [9], the proposed TR method can be used to measure the permittivity of powder and solid samples. The application of TR method for permittivity measurement in biological pharmacy is of practical significance in environmental protection and universal health.

ACKNOWLEDGMENT

This work is supported by The Fundamental Research Funds for the Central Universities No. 2672011ZYGXJ017.

REFERENCES

[1] Yang S H, Xing D, Lao Y Q, eta1, Noninvasive monitoring of traumatic brain injury and post traumatic rehabilitation with laser induced photoacoustic imaging, Appl Phys Lett, 2007, 90(24): 243902.

[2] Leuschner C, Kumar CS, Hansel W, et al. "LHRH-conjugated magnetic iron oxide nanoparticles for detection of breast cancer metastases", Breast Cancer Res Treat, 2006, 99:163-176.

[3] Wunderbaldinger P，Josephson L，Weissleder R, “Tat peptide directs enhanced clearance and hepatic permeability of magnetic nanoparticles”, Bioconjug Chem. 2002, 13(2):264—268.

[4] L. C. Han, E. Li, G. F. Guo and H. Zheng, “APPLICATION OF TRANSMISSION/REFLECTION METHOD FOR PERMITTIVITY MEASUREMENT IN COAL DESULFURIZATION”, *Progress in Electromagnetics Research Letters*, Vol. 37, pp. 177-187, February 2013.

[5] David M. Pozar, *Microwave Engineering,* 4ed ed., vol. 2. Hamilton: Printing, 2012, pp.150-156.

[6] L. F. Chen, C. K. Ong, C. P. Neo, V. V. Varadan and V. K. Varadan, *Microwave electronics-Measurement and material characterization*, John Wiley & Sons Ltd, 2004.

[7] Michael D. Janezic, Jeffrey A. Jargon, “Complex Permittivity Determination from Propagation Constant Measurements,” Proc. IEEE, vol. 9, no. 2, Feb, 1999.

[8] Jing Shenhui, Ding Ding, Jiang Quanxing, “Measurement of electromagnetic properties of materials using transmission /reflection method in coaxial line,” Proc. IEEE, pp. 590-595, Nov, 2003.

[9] Ray Simpkin, “Derivation of Lichtenecker’s Logarithmic Mixture Formula From Maxwell's Equations,” Proc. IEEE, vol. 58, no. 3, pp. 545 - 550, Mar. 2010.