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# APPLICATION OF TRANSMISSION/REFLECTION METHOD FOR PERMITTIVITY MEASUREMENT IN COAL DESULFURIZATION

**Licun Han*, En Li, Gaofeng Guo, and Hu Zheng**

University of Electronic Science and Technology of China, Chengdu 611731, China

**Abstract**—In recent years, the transmission/reflection (TR) method has been successfully employed to determine the complex permittivity of dielectric material. Based on the principle that different coals have different abilities to absorb microwave energy at different frequencies, it is essential to analyze the electromagnetic property of coal to realize microwave desulfurization. Samples composed of a known dielectric and coal are manufactured in order to obtain the accurate permittivity of coal. In the article, we propose an improved TR method which is insensitive to the position of the sample in its cell. Additionally, we get the suitable mass ratio of the known dielectric and sample under test in the composite sample, and the suitable thickness of the composite sample in the permittivity measurements.

## 1. INTRODUCTION

China is rich in coal storage, which accounts for 75% of primary energy. However, $SO_2$, the emission after coal combustion is harmful to people's health, and it also leads to acid rain and environmental pollution. It is important to strictly control the emission of $SO_2$. At present, there are several coal desulfurization methods such as [1]: physical desulfurization, chemical desulfurization and microbiological desulfurization. Compared with other methods, the method of physical desulfurization is simple and economical, and it can remove the inorganic sulfur and does not cause characteristic variation at the same time. In recent decades, the physical method has been successfully employed in coal desulfurization. Based on the principle, the interaction of microwave energy and coal sample can be written

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* Corresponding author: Licun Han (han88606@163.com).

as [2]:

$$P = 56.62 \times 10^{-12} f E^2 \varepsilon_r'' \tag{1}$$

where $P$ is the absorbed energy of the coal media (W), $f$ the operating frequency (Hz), $E$ the intensity of the electric-field (V/m), and $\varepsilon_r''$ the imaginary part of relative complex permittivity.

Since the relative complex permittivity of the coal sample varies with different frequencies, the sample will have different heating and chemical reactions under microwave radiation at different frequencies [2]. Therefore, it is very important to obtain the complex permittivity of coal for analysis of coal desulfurization.

There are various techniques applied to determine the complex permittivity of coal samples in recent years. The most widely used techniques in the microwave region are: cavity resonator [3], free space [4], open-ended coaxial probe [5], and transmission-line [6–9]. However, each method has its advantages and disadvantages. Among these measurement techniques, TR method is relatively simple, as well as high accuracy in wideband frequencies. Thus, TR technique is used for the measurements of the complex permittivities of coal samples in this paper.

For the transmission/reflection method, the measurement cell is made up of a section of coaxial line or rectangular wave guide filled with the sample. The complex permittivity of the sample can be calculated from the scattering parameters obtained from a vector network analyzer.

In this paper, we introduced an improved TR method by using famous SOLT calibration method in Section 2. The improved method can remove the errors coming from the mismatches between the connectors, the metallic loss of the holder, and the instabilities of the calibration kit. Above all, the proposed method is insensitive to the position of the sample in its cell. In a certain external environment, the stability of a fixed density, the relative dielectric constant of quartz is of stability [10–12]. In order to verify the accuracy of the TR techniques for the measurements of the complex permittivities of low loss powder samples, I choose quartz samples as accuracy verification method. Samples made of the paraffin and quartz at different mass ratios are measured in Section 3.

## 2. IMPROVED TR METHOD

ABCD matrix is used here for convenience. As shown in Figure 1, these two ports are connected with a vector network analyzer, and the ABCD matrix $X$, $A$ and $Y$ are, respectively, expressed for the air region at the left part of the sample, the sample region, and the air

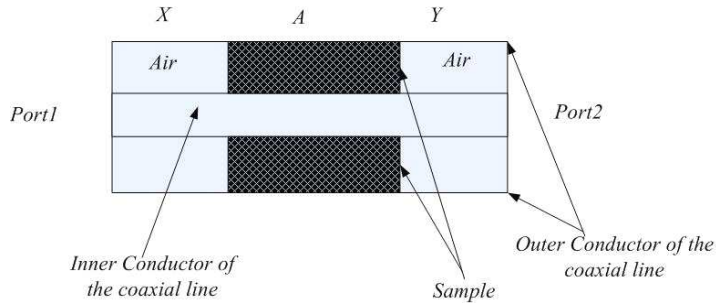


**Figure 1.** Coaxial cell loaded with a dielectric sample.

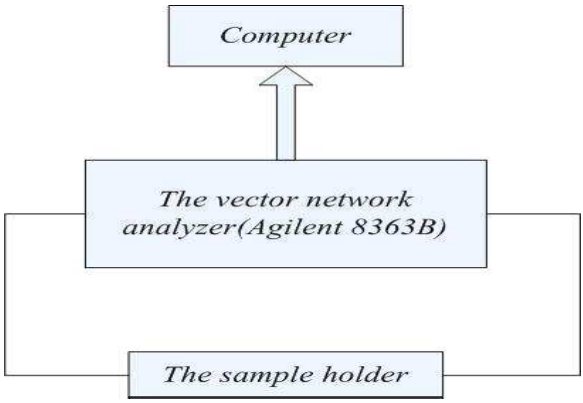


**Figure 2.** The test system.

region at the right part of the sample. The matrixes $X$ and $Y$ contain the effects of the air part of the coaxial line, and the connections effects between the holder and cables of VNA, and VNA IF mixer conversion factor, etc.. In order to eliminate these instabilities, it is essential to use SOLT calibration technique before measurement. The test system shown in Figure 2 is composed of a vector network analyzer Agilent E 8363B, computer and sample holder. SOLT calibration method is used for calibration of the system.

The thickness of sample shown in Figure 1 is $l$. The sample under test is assumed as isotropic, symmetric, and homogeneous. It is also assumed that only the dominant mode (TEM) is present in the coaxial cell, the metallic material of coaxial line is ideal conductor, and the measurement frequency is limited so that the higher-order modes cannot propagate.

In this article, we measured the coaxial cell from two directions to obtain the value of matrix $A$. The measurement cell is shown in Figure 1. After calibration, the two ports ABCD matrixes for two direction measurements can be written as:

$$M = X_A \cdot A \cdot Y_A \tag{2}$$

$$M_O = Y_A \cdot A \cdot X_A \tag{3}$$

where $X_A$ and $Y_A$ are, respectively, indicated the matrixes $X$ and $Y$ after using calibration; $X_A^T$ and $Y_A^T$ are, respectively expressed for the transposed matrix of $X_A$ and $Y_A$. For an isotropic and nonreflecting line, both $X_A$ and $Y_A$ meet reciprocal theory. Therefore, the matrixes $X_A$ and $Y_A$ are, respectively, equal to $X_A^T$ and $Y_A^T$. Based on the above assumption, the ABCD matrix for the sample of the length $l$ becomes

$$A = \begin{bmatrix} ch(\gamma l) & Zsh(\gamma l) \\ Z^{-1}sh(\gamma l) & ch(\gamma l) \end{bmatrix} \tag{4}$$

In (4), $Z$ and $\gamma$ are the characteristic impedance and propagation constant in the sample filled region. $Z$ and $\gamma$ are related to permittivity and permeability of the dielectric sample. As we assumed, the permeability of sample is nonmagnetic and equal to air in order to simply calculate.

From (2) and (3), we can get an expression as the following:

$$M_O^T = (X_A)^T \cdot A^T \cdot (Y_A)^T = X_A \cdot A^T \cdot Y_A \tag{5}$$

$$M_O^T \cdot M^{-1} = X_A \cdot A \cdot \left(A^T\right)^{-1} \cdot (X_A)^{-1} \tag{6}$$

$$Tr\left(M_O^T \cdot M^{-1}\right) = Tr\left(A \cdot \left(A^T\right)^{-1}\right) \tag{7}$$

The effect of $Y_A$ is already removed on the measurement. It is simple to find that $M^T \cdot M^{-1}$ and $A \cdot (A^T)^{-1}$ are similar matrixes, which have the same trace. Hence, it can be derived from (4) and (6) the trace of the square matrix $M_o^T \cdot M^{-1}$. Now, in the Equation (7), where $Tr(*)$ takes the trace of a square matrix $*$, the effect of $X_A$ is also eliminated.

There are many papers [13–16] introducing the calculation of permittivity of sample through measuring the $S$-parameters of coaxial line with the tested sample over years, so we can make full use of them to get electromagnetic properties of the sample under test.

In order to obtain electromagnetic property of the powder sample, it is necessary to manufacture composite sample which is made up of two dielectrics, and one of them is a known sample. Based on the assumption that the composite sample is uniform mixed and the mixed dielectrics are isotropic, symmetric, and homogeneous,

logarithm principle of Lichtenecker [17] can be expressed as:

$$\ln \varepsilon = \sum_i v_i \ln \varepsilon_i \tag{8}$$

$$\sum_i v_i = 1 \tag{9}$$

In (8), $\varepsilon_i$ is the relative dielectric constant of the $i$ part sample, $v_i$ the volume fraction of the $i$ part sample, and $\varepsilon$ the permittivity of the composite sample. In the article, the composite sample is made up of paraffin and the dielectric under test. The permittivity of the sample under test can be written as:

$$\ln \varepsilon = \ln \varepsilon_2 + (\ln \varepsilon_1 - \ln \varepsilon_2) v_1 \tag{10}$$

$$v_1 = w \times (1 + r)/p/V \tag{11}$$

$$V = \frac{\pi}{4} \left(b^2 - a^2\right) l \tag{12}$$

Therefore, in (10), $\varepsilon$ is the permittivity of the composite sample, $\varepsilon_1$ the permittivity of paraffin, $\varepsilon_2$ the permittivity of the dielectric under test, and $v_1$ the volume fraction of paraffin. In (11), $w$ is the weight of composite sample, $r$ the mass ratio of the sample under test and paraffin in the composite sample, and the definition of mass ratio is applied to the whole article. $p$ ($0.87\,\mathrm{g/cm^3}$) is the density of paraffin when being heated into molten state, and $a$ (3 mm), $b$ (7 mm) are, respectively, indicated the outer diameter of inner conductor and internal diameter of outer conductor of the coaxial cell. $l$ is the thickness of the composite sample and $V$ the volume of composite sample. In the following measurements, the cable of VNA E8363B (Agilent) has 3 mm outer diameter of inner conductor and 7 mm internal diameter of outer conductor. Therefore, there is no need of converter between cable and the sample holder.

## 3. MEASUREMENT RESULTS AND DISCUSSIONS

In order to verify the feasibility of TR method for permittivity measurement, a number of experiments were carried out. In the experiments, the VNA E8363B (Agilent) and a coaxial fixture made of brass with chromium plating were used for measurements. The air part of Figure 1 is the model of coaxial fixture, and the sample part denoted for tested dielectric. The sample of paraffin was tested for calibrated $S$-parameters measurements from 4 to 8 GHz. Figure 3 shows the calculated permittivity of sample with certain thickness (2 mm) and the exact value of permittivity. In Figure 3, the black dotted lines in (a) and (b) respectively stand for the real part of exact

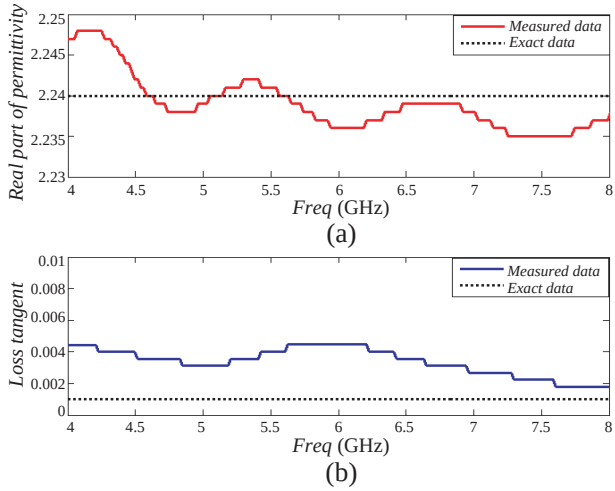


**Figure 3.** Permittivity of the paraffin sample with decided length.

value of paraffin's permittivity and loss tangent of paraffin. Figure 3 shows that the TR method has the ability to accurately measure permittivity of the sample. From the calculation, the average of real part is 2.2386, and the average of loss tangent is 0.0032. As we all known, the relative permittivity of paraffin is $2.24 - j0.0001$ in the C band, and the standard derivation of the real and imaginary parts are 0.0032 and 0.0023, respectively. The error of the measured data results from the imperfection of paraffin and unsatisfactory of workmanship of coaxial fixture and the imperfection of material quality of brass.

To obtain suitable mass ratio of paraffin and the tested sample in composite sample and appropriate sample thickness in the permittivity measurement of coal dielectric, a large amount of measurements were carried out. Three certain thickness 2.02 mm samples $S_1$, $S_2$, $S_3$ of composites dielectric were shown in Figure 4, with mass ratio 1 : 1, 1 : 2, 2 : 1, respectively, and three certain mass ratio 2 : 1 samples $S_4$, $S_5$, $S_6$, with thickness, 2.01 mm, 3.83 mm, 8.56 mm, respectively, were tested for calibrated $S$-parameters measurements from 4 to 8 GHz. As shown in Figure 5, the coaxial line is consisted of inner conductor B6 and outer conductor B4 in above 2 mm length, and B1 is the cable which is connector between VNA and measurement cell. B2 assists device for measuring the composite sample with 2.0 mm length, and in the experiment we should put the component B3 with sample in B2 flatly and then connect the two cables through B2. The internal diameter of B2 is the same with the external diameter of the whole device of B3.

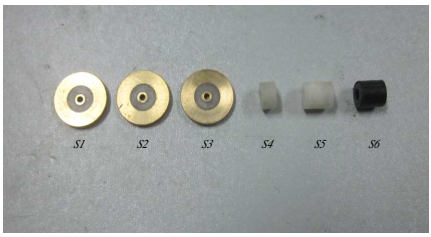


**Figure 4.** The produced samples.

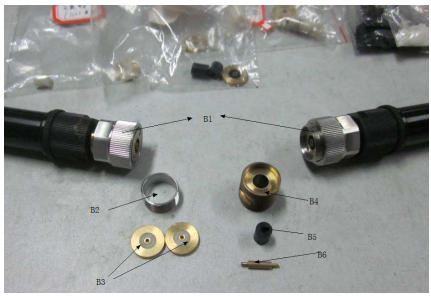


**Figure 5.** Photo of coaxial line and the tested samples.

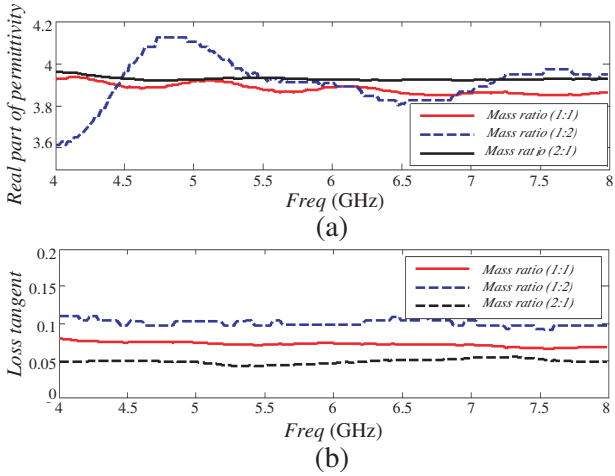


**Figure 6.** Permittivity of quartz with different mass ratio in the sample. (a) Real part of the permittivity. (b) Loss tangent of quartz.

After measuring the $S$-parameters and processing a large amount of data, Figure 6 shows the permittivity of quartz sample through TR method for electromagnetic property of composite sample with certain thickness (2 mm) made of quartz and paraffin in different mass ratios. From this figure, it is obvious to find that the relative accuracy of permittivity of quartz would be received if we choose the certain mass ratio (2 : 1) of quartz and paraffin. Figure 7 shows the electromagnetic property of quartz with different length of the composite sample. It is well known that the length of sample has great influence on the

accurate measurement of imaginary part of permittivity. The relative permittivity of the Engineering Quartz is about $3.9-j0.0001$ [18] in the C band, so the proposed method for measuring the permittivity under the condition that the composite sample $S_6$ as showed in Figure 4 with mass ratio 2 : 1 and thickness is 8.56 mm is of very high accuracy. The measurement error is obtained by the following formula:

$$\Delta = \frac{1}{N}(\varepsilon_{mi} - \varepsilon) \tag{13}$$

where $\varepsilon_{mi}$ is the measured permittivity at the $i$-th frequency points, $\varepsilon$ the average value of the measured permittivity, and $N$ the number of frequency point. From the calculated data, the standard derivations of the real and imaginary parts are 0.019 and 0.0458, respectively, and the errors of the real and imaginary parts are 0.0062 and 0.0055, respectively.

With the actual processing accuracy and experiment condition, we manufactured the composite sample with thickness 8.54 mm and mass ratio 2 : 1 in the experiment for measuring the permittivity of coal powder. Figure 5 shows the permittivity of one engineering coal sample. From the calculated data, it is convenient and efficient to capture the frequency in which loss tangent of coal sample is largest within the C band, which has great significance in coal desulfurization. In practice, we found that the connections of the measurement fixture and the precision of processing sample can hardly provide changeless

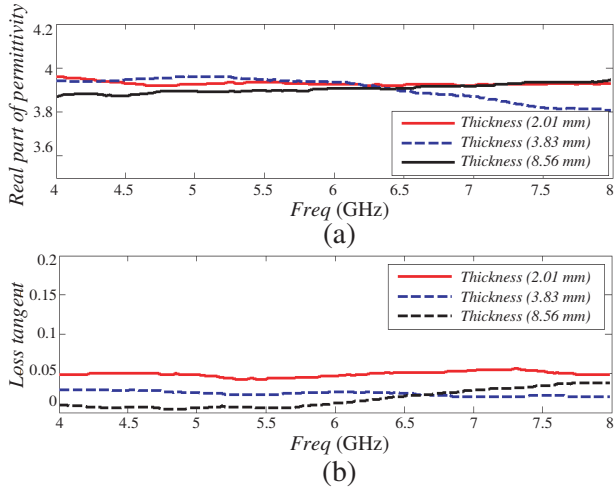


**Figure 7.** Permittivity of quartz with different thickness in the sample. (a) Real part of the permittivity. (b) Loss tangent of quartz.

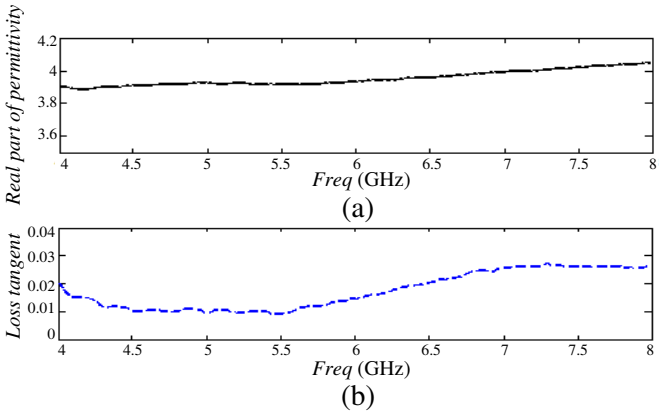


**Figure 8.** The permittivity of coal sample. (a) Real part of the permittivity. (b) Loss tangent of coal sample.

influence in different measurements. Consequently, this method should be improved with high workmanship in every process.

## 4. CONCLUSIONS

We have shown that the mass ratio 2 : 1 and thickness 8.5 mm of composite in the TR method for permittivity measurement samples are suited to get precise calculated data. The experiments for getting suitable mass ratio and length are of great value to coal desulfurization. From the measured data, there are errors in TR method, which are from mismatching at the connections between coaxial fixture and the joint of VNA, imperfection of the metallic material of coaxial line, and imperfection of composite sample processing, and inaccuracy of the thickness measurement of the sample, etc.. With the development of workmanship, TR method can provide relatively accurate electromagnetic property of coal sample. The research of application of TR method for permittivity measurement in coal desulfurization is of practical significance in environmental protection and universal health.

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