Numerical simulation study of free space method for measuring sample permittivity

Yao Qin 12*, Shuo Liu1, Bin Wei1, Mingxing Li12, Chengxin Cai 12, and Tiangang Hou1

1College of Information Science and Engineering, Henan University of Technology, Zhengzhou, 450001, China
2Key Laboratory of Grain Information Processing and Control, Henan University of Technology, Ministry of Education, Zhengzhou, 450001, China
*Corresponding author’s e-mail: qinyao@haut.edu.cn

Abstract. The composition and performance of the material can be expressed by the permittivity. The paper introduces the measurement principle of free space method and TRL calibration principle, the calculation formula of the sample permittivity is theoretically analysed, a horn lens antenna is designed to simulate the emission of plane waves, and numerical simulation software is used for simulation and optimization. In the working frequency range, the voltage standing wave ratio of the antenna is less than 1.49, and the maximum gain is 21.8dB. A free space measurement system is established in the software to measure the sample permittivity with different thicknesses, and compare the calculated value with the actual value. The results show that the root mean square error of the real part is less than 5.3%, and the root mean square error of the imaginary part is less than 1.3%. The correctness and applicability of the formula for calculating the permittivity are also proved.

1. Introduction
Permittivity can describe the composition and properties of a sample. In the industrial field, the permittivity of the radar radome is measured to give full play to its performance. In agricultural applications, electromagnetic methods are used to measure grain permittivity to sense the moisture content in grains [1]. Therefore, measuring the permittivity of sample is the basis for the study of performance and has important practical significance.

The network parameter method has become the mainstream method for measuring the permittivity of samples. This method mainly includes multi-state method [2], open coaxial probe method [3], transmission/reflection method [4] and free space method [5]. The multi-state method is suitable for single-port measurement, and the cost is lower, but the measurement accuracy is lower. The open coaxial probe method can perform high-precision non-destructive testing, but it is not suitable for measuring liquids and powdery substances. The transmission/reflection method is simple to operate and has high measurement accuracy, but it needs to destroy the shape of the solid sample and needs special ease. The free space method is a non-destructive test [6]. It only requires the sample to be flat and parallel on both sides. The material container is easy to manufacture and is suitable for measuring solids and liquids. However, the size of the sample to be measured must be large enough to reduce the influence of diffraction from the edge of the sample.
The article introduces the numerical simulation study of free space method to measure sample permittivity. First, the measurement principle of the free space method and the TRL calibration principle are explained, and the calculation formula of sample permittivity is deduced from the theoretical analysis. A horn lens antenna and a permittivity measurement system are designed in the software, which can measure the permittivity when the sample thickness is 4cm, 6cm and 11.3cm, and compare the calculated value with the actual value. The results show that the root mean square error of the real part is less than 5.3%, and the root mean square error of the imaginary part is less than 1.3%, which verifies the effectiveness of the correction method. The correctness and applicability of the formula for calculating sample permittivity are also proved.

2. Basics and principles

2.1. Free space method measurement principle.

The principle of free space measurement is that a vector network analyzer (VNA) radiates plane waves into free space through a transmitting antenna, and the microwaves generate reflected and transmitted signals at the sample. These signals are returned to VNA through the receiving antenna to obtain the scattering parameters, and use the scattering parameters to calculate the permittivity of the sample in the computer. The measurement system diagram is shown in Figure 1.

Assuming that the incident voltage $V_{inc}$ is 1, $V_r$ and $V_t$ represents the reflected voltage and transmission voltage. $\Gamma$ and $-\Gamma$ are the reflection coefficients at port 1 and port 2, the transmission coefficient in the sample is $T$. The propagation of electromagnetic waves at the sample is shown in Figure 2. The reflection and transmission parameters can be expressed as [7]

\[
S_{11} = \frac{V_r}{V_{inc}} = \frac{(1-T^2)\Gamma}{1-\Gamma^2T^2} \\
S_{21} = \frac{V_t}{V_{inc}} = \frac{T(1-\Gamma^2)}{1-\Gamma^2T^2} \\
T = X \pm \sqrt{X^2-1}
\]

$|T| \leq 1$ can be used as the principle of choosing sign. The transmission parameter and propagation constant of the sample can be expressed as

\[
T = e^{-yd}
\]
\[
\gamma = j \frac{2\pi}{\lambda_0} \left[ \mu_r \varepsilon_r - \left( \frac{\lambda_0}{\lambda_c} \right)^2 \right]^{1/2}
\]

(5)

where \( \gamma \) is the propagation constant of the sample, the wavelength in free space \( \lambda_0 = c/f \). When measuring low-loss materials \( \mu' = 1, \lambda_c = \infty \). From equation (5), the formula for calculating sample permittivity can be written as

\[
\varepsilon_r = -\gamma^2 \cdot \left( \frac{\lambda_0}{2\pi} \right)^2
\]

(6)

2.2. Through-reflect-line (TRL) calibration principle.
In order to obtain the scattering parameters at the sample, the TRL calibration method [8] can be used to eliminate measurement errors. Perform 4 measurements according to the connection method in figure 3. \([S_T],[S_R],[S_L]\) and \([S_{Dut}]\) represent the scattering parameters measured under 4 connections.

![Figure 3. Schematic diagram of four connection methods. (a) Through connection. (b) Reflect connection. (c) Line connection. (d) Connect after adding sample.](image)

where \( l_1 \) is the distance between the measurement plane and the two ports, \( l = c/4f \) is the distance of the extension line. Save the measured scattering parameters as an s2p file, then use the TRL calibration wizard in ANSYS Electronics Desktop (Tools->Calibration Wizard) to obtain the scattering parameters from of the \( l_1 \) segment and generate the s2p file [9]. Finally, the measurement system model is set in Advanced Design System, and the s2p files are sequentially imported into the model for de-embedding. Figure 4 shows a schematic diagram of de-embedding. Run the model to get the true scattering parameters.
3. Numerical simulation results and analysis

In this paper, a horn lens antenna is designed to radiate plane waves into free space. The standard rectangular waveguide WR130 is selected for feeding. The material of the dielectric lens is PTFE with a relative permittivity of 2.1. Table 1 shows the physical dimensions of the antenna model.

Table 1. Physical dimensions and variable definitions of antennas.

| Variable name | Variable (Unit: mm) | Structure name          |
|---------------|---------------------|-------------------------|
| a             | 34.849              | Waveguide width         |
| b             | 15.799              | Waveguide height        |
| wlength       | 25                  | Waveguide length        |
| a_1           | 85                  | Horn caliber width      |
| b_1           | 71                  | Horn caliber height     |
| hlength       | 250                 | Horn length             |
| F             | 150                 | Focal length of lens    |
| t             | 77                  | Thickness of the lens    |
| D             | 260                 | Diameter of the lens     |

3.1. Simulation of horn lens antenna

The structure of the horn lens antenna is shown in figure 5. Figure 6 shows the electric field diagram of the horn lens antenna at 6GHz.

The electromagnetic wave radiated from the horn antenna into the free space is a spherical wave, after the action of the lens, the waveform becomes a plane wave [10]. Since the electromagnetic wave propagates without loss in the air, there is no obvious attenuation of the electric field strength, which is consistent with the theoretical analysis. The voltage standing wave ratio (VSWR) and gain diagrams of the antenna are shown in Figure 7 and Figure 8.
The VSWR in 5.5GHz-6.5GHz is less than 1.4968. At 6GHz, the maximum gain of the antenna E and H planes are both 21.8596dB, indicating that the designed antenna meets the experimental requirements.

3.2. Simulation model of free space measurement system
According to the principle of free space measurement, a free space measurement system is constructed in the simulation software, the electric field diagram is shown in figure 9.

Figure 9. Electric field diagram of free space measurement system

Define the sample thickness as 6cm in the software, the real part of the permittivity is 4.4, and the imaginary part is 0.08. It can be seen from figure 9 that the field strength in the air is greater than that in the sample, indicating that microwaves will produce reflection and transmission signals in the sample. Figure 10 and figure 11 show the relationship between the permittivity and frequency of FR4 samples.

Figure 10. the relationship between the permittivity and frequency of FR4. (a) Not calibrated. (b) After calibration.

It can be seen from figure 10 that the calculated value obtained after calibration is very close to the true value, due to the error in the measuring instrument is eliminated. The root mean square error of the real part is 4.5%, and the root mean square error of the imaginary part is 0.92%, both are within the acceptable range, which proves the validity of the TRL calibration method. Set the thickness of the sample to 4cm and 11.3cm, and the other conditions remain unchanged. Figure 11 shows the relationship between the permittivity and the frequency.
Figure 11. The relationship between permittivity and frequency. (a) The thickness is 4cm. (b) The thickness is 11.3cm.

It can be seen from Figure 11 that in 5.5GHz-6.5GHz, the calculated value of the permittivity is very close to the real value. In Figure 11(a), the root mean square error of the real part is 5.3%, and the root mean square error of the imaginary part is 1.3%. In Figure 11(b), the root mean square error of the real part is 3.6%, and the root mean square error of the imaginary part is 1.19%. From the above analysis, it can be proved that using equation (1) ~ equation (7) can calculate the permittivity of the sample with different thicknesses.

4. Conclusion

Based on the preliminary results of this paper, the following summary and conclusions can be drawn:

1. The free space measurement principle and TRL calibration principle are explained in detail, and the calculation formula of the permittivity of the material to be measured is theoretically analysed.

2. The horn lens antenna designed by numerical simulation software, within 5.5GHz-6.5GHz, the voltage standing wave ratio of the antenna is less than 1.49, and the maximum gain of the antenna is 21.8dB, indicating that the designed antenna can meet the experimental requirements.

3. A permittivity measurement system is constructed in the simulation software, and the calculated value of permittivity is compared with the real value. The root mean square error of the real part is all less than 5.3% and the root mean square error of the imaginary part is less than 1.3%, which verifies the correctness and applicability of permittivity calculation formula.

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