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A NEW DEEMBEDDING METHOD IN PERMITTIVITY MEASUREMENT OF FERROELECTRIC THIN FILM MATERIAL

X. He, Z. Tang, B. Zhang, and Y. Wu

School of Electronic Engineering
University of Electronic Science and Technology of China
China

Abstract—A new deembedding method in permittivity measurement of ferroelectric thin film material is proposed in this paper. By measuring the two scattering matrixes of the two samples with different length, the propagation constant of the actual network under test (ANUT) can be obtained. Further more, the permittivity would be extracted. The results show that though the proposed deembedding method, the error induced by embedding can be eliminated successfully and the propagation constant of the ANUT can be extracted accurately.

1. INTRODUCTION

Ferroelectric materials are of great interest for the development of electrically tunable microwave devices components including tunable resonators, filters, and phase shifters [1–6]. All these devices are designed and made on ferroelectric thin films, deposited on dielectric substrates, which produce internal electric polarization changes with an externally applied electric field. A number of techniques have been developed which have the potential to be applied in the microwave parameters measurement of materials [7–10]. Because of the small thickness of the thin-film, it is difficult to measure the electromagnetic parameters accurately.

The coplanar waveguide (CPW) structure is widely used to measure the electromagnetic parameters of the ferroelectric thin film materials. Since the width of the central conductor strip in CPW structure is always small, it is hard to make the characteristic impedance of the CPW matched with the characteristic impedance of the coaxial line which is always $50\,\Omega$. Thus, the CPW is made with the transitions to eliminate this discontinuity, and then there comes an embedding question.

In this paper, a new method is proposed to solve the embedding problem. Simulation software is used to simulate the two samples of CPW structures with transitions. By getting the scattering matrixes of two samples, the propagation constant of the CPW structure without transitions is extracted. And for ferroelectric thin film material, the dielectric constant can be extracted from the propagation constant. The results show that great accuracy is achieved.

2. THEORY

The samples of CPW structure with transitions are shown in Figures 1(a) and (b). There are two parts in the Figure 1(a) — Part one and Part two. Assuming that the ABCD matrix of the network from terminal face T-T to terminal face J-J is $A1$, the ABCD matrix of the network from terminal face J-J to terminal face T'-T' is $A2$, the ABCD matrix of the network from terminal face T-T to terminal face T'-T' is $A3$, and the characteristic impedances connected to terminal face T-T and terminal face T'-T' are both z_0.

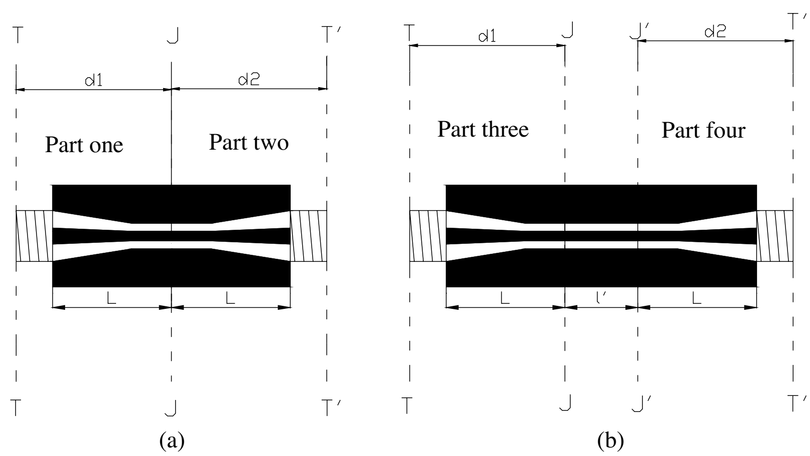

Figure 1. Two samples of CPW structure with transition.

$A1$ is denoted as follows:

$$A1 = \begin{bmatrix} a & b \\ c & d \end{bmatrix} \tag{1}$$

As there is an antisymmetric relationship between Part one and Part two and the whole network from terminal face T-T to terminal face T'-T' is symmetrical and reciprocal, such results could be got as follows:

$$A2 = \begin{bmatrix} d & b \\ c & a \end{bmatrix} \tag{2}$$

$$ad - bc = 1 \tag{3}$$

$$A3 = A1 \times A2 = \begin{bmatrix} a & b \\ c & d \end{bmatrix} \times \begin{bmatrix} d & b \\ c & a \end{bmatrix} = \begin{bmatrix} ad+bc & 2ab \\ 2cd & ad+bc \end{bmatrix} \tag{4}$$

According to the theory of network, the relationships between the ABCD matrix $A3$ and the scattering matrix S of the network from terminal face T-T to terminal face T'-T' in Figure 1(a) are expressed as follows:

$$ad + bc = \frac{1}{2} \cdot \left[\frac{1 - s_{11}^2}{s_{21}} + s_{21} \right] \tag{5}$$

$$2ab = \frac{1}{2} \cdot \left[\frac{(1 + s_{11})^2}{s_{21}} - s_{21} \right] \cdot z_0 \tag{6}$$

$$2cd = \frac{1}{2} \cdot \left[\frac{(1 - s_{11})^2}{s_{21}} - s_{21} \right] / z_0 \tag{7}$$

From the Equations (3), (5)∼(7), one can get that:

$$ad = \frac{(1 + s_{21})^2 - s_{11}^2}{4s_{21}} \tag{8}$$

$$bc = \frac{(1 - s_{21})^2 - s_{11}^2}{4s_{21}} \tag{9}$$

$$ab = \frac{z_0}{4} \cdot \frac{(1 + s_{11})^2 - s_{21}^2}{s_{21}} \tag{10}$$

$$cd = \frac{1}{4z_0} \cdot \frac{(1 - s_{11})^2 - s_{21}^2}{s_{21}} \tag{11}$$

To simplify the Equations (8)∼(11), we define:

$$\begin{cases} \dfrac{(1 + s_{21})^2 - s_{11}^2}{4s_{21}} = x_1 \\ \dfrac{(1 - s_{21})^2 - s_{11}^2}{4s_{21}} = x_2 \\ \dfrac{1}{4z_0} \cdot \dfrac{(1 - s_{11})^2 - s_{21}^2}{s_{21}} = x_3 \end{cases} \tag{12}$$

From Equations (8)∼(12), one can get that:

$$\begin{cases} a = \dfrac{x_1}{x_3} \cdot c \\ b = x_2 \cdot \dfrac{1}{c} \\ d = x_3 \cdot \dfrac{1}{c} \end{cases} \tag{13}$$

Sample (b) is shown in Figure 1(b), which is only longer than sample (a). Part three and Part four in Figure 1(b) are exactly the same as Part one and Part two in Figure 1(a) respectively. So the ABCD matrix of the network from terminal face T-T to terminal face J-J in Figure 1(b) is equal to the ABCD matrix $A1$ and the ABCD matrix of the network from terminal face J'-J' to terminal face T'-T' in Figure 1(b) is exactly the same with the ABCD matrix $A2$. Besides, the characteristic impedances connected to terminal face T-T and terminal face T'-T' in Figure 1(b) are both z_0.

The network from terminal face J-J to terminal face J'-J' is the actual network under test (ANUT). We assume that the ABCD matrix of the ANUT is A, the characteristic impedance of the ANUT is z_c, the propagation constant of the ANUT is γ, the length of the ANUT is l' and the ABCD matrix of the network from terminal face T-T to terminal face T'-T' in Figure 1(b) is $A4$, the scattering matrix of the network from terminal face T-T to terminal face T'-T' in Figure 1(b) is S'. As the ANUT is symmetry and reciprocal, such results could be got as follows:

$$A = \begin{bmatrix} ch\gamma l' & z_c sh\gamma l' \\ \dfrac{sh\gamma l'}{z_c} & ch\gamma l' \end{bmatrix} \tag{14}$$

$$\begin{aligned} A4 = A1 \cdot A \cdot A2 &= \begin{bmatrix} \dfrac{x_1}{x_3} \cdot c & x_2 \cdot \dfrac{1}{c} \\ c & x_3 \cdot \dfrac{1}{c} \end{bmatrix} \cdot \begin{bmatrix} ch\gamma l' & z_c sh\gamma l' \\ \dfrac{sh\gamma l'}{z_c} & ch\gamma l' \end{bmatrix} \\ &\quad \cdot \begin{bmatrix} x_3 \cdot \dfrac{1}{c} & x_2 \cdot \dfrac{1}{c} \\ c & \dfrac{x_1}{x_3} \cdot c \end{bmatrix} \end{aligned} \tag{15}$$

According to the theory of network, those results we can get:

$$\begin{aligned}&(x_1+x_2)\,ch\gamma l'+x_2\cdot x_3\cdot\frac{1}{c^2}\frac{sh\gamma l'}{z_c}+\frac{x_1}{x_3}\cdot c^2 z_c sh\gamma l'\\ =\;&\frac{1}{2}\cdot\left[\frac{(1-s'_{11})(1+s'_{11})}{s'_{21}}+s'_{21}\right]\end{aligned}\tag{16}$$

$$\begin{aligned}&2\cdot\frac{x_1\cdot x_2}{x_3}ch\gamma l'+x_2\cdot x_2\cdot\frac{1}{c^2}\frac{sh\gamma l'}{z_c}+\frac{x_1\cdot x_1}{x_3\cdot x_3}\cdot c^2 z_c sh\gamma l'\\ =\;&\frac{1}{2}\cdot\left[\frac{(1+s'_{11})^2}{s'_{21}}-s'_{21}\right]\cdot z_0\end{aligned}\tag{17}$$

$$\begin{aligned}&2\cdot x_3\cdot ch\gamma l'+x_3\cdot x_3\cdot\frac{1}{c^2}\frac{sh\gamma l'}{z_c}+c^2\cdot z_c sh\gamma l'\\ =\;&\frac{1}{2}\cdot\left[\frac{(1-s'_{11})^2}{s'_{21}}-s'_{21}\right]/z_0\end{aligned}\tag{18}$$

Some simplified equations are as follows:

$$\begin{aligned}\frac{1}{2}\cdot\left[\frac{(1+s'_{11})\,(1-s'_{11})}{s'_{21}}+s'_{21}\right]&=x_4\\ \frac{1}{2}\cdot\left[\frac{(1+s'_{11})^2}{s'_{21}}-s'_{21}\right]\cdot z_0&=x_5\\ \frac{1}{2}\cdot\left[\frac{(1-s'_{11})^2}{s'_{21}}-s'_{21}\right]/z_0&=x_6\end{aligned}\tag{19}$$

From Equations (16)~(19), the propagation constant γ of the ANUT could be got by:

$$ch\gamma l'=x_1\cdot x_4+x_2\cdot x_4-x_3\cdot x_5-x_1\cdot x_2\cdot x_6/x_3\tag{20}$$

$$\begin{aligned}\gamma=\frac{1}{l'}\cdot\ln\Big[&x_1\cdot x_4+x_2\cdot x_4-x_3\cdot x_5-x_1\cdot x_2\cdot x_6/x_3\\ &\pm\sqrt{(x_1\cdot x_4+x_2\cdot x_4-x_3\cdot x_5-x_1\cdot x_2\cdot x_6/x_3)^2-1}\,\Big]\end{aligned}\tag{21}$$

As the values of the S_{11}, S_{21}, S'_{11} and S'_{21} can be got from the vector network analysis machine, the value of l' can be measured, and the value of z_0 is known as $50\,\Omega$, the γ can be calculated from formulation (21) and the value of γ with the positive imaging part is chosen. For the dielectric medium, the relative permeability is 1; the permittivity can be calculated from the γ.

3. RESULTS

A certain CPW structure which is shown in Figure 2 is used to verify the new method proposed in this paper. It is assumed that the permittivity of the ferroelectric thin-film material is 500-5j, the permittivity of Al_2O_3 is 9.5-0.00095j, the width of central conductor (W) is 0.25 mm, the slot (s) is 0.1 mm, the ferroelectric material thickness h_2 is 800 nm and the thickness of Al_2O_3 is 0.5 mm, the length of the CPW is 4 mm, the width of the CPW d is 3mm.

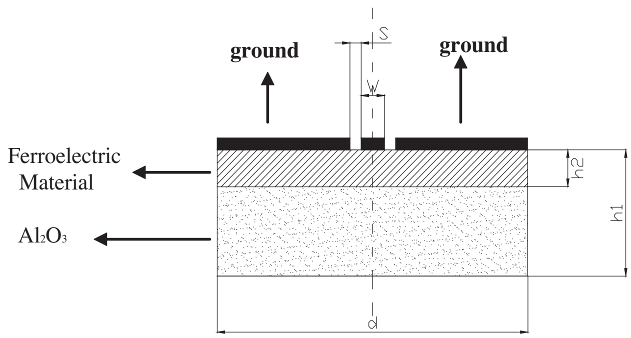

Figure 2. The CPW structure.

Table 1. The propagation constants of the same network calculated by two different methods.

frequency (GHz)	γ' reference value	γ with deembedding method
1	0.54245+57.921i	0.55891+57.881i
2	0.86428+115.55i	0.99791+115.6i
3	1.1012+173.16i	1.1257+172.98i
4	1.3347+230.75i	1.3302+230.52i
5	1.5358+288.35i	1.4981+287.97i
6	1.7592+345.97i	1.6701+345.52i

The simulation software is used to simulate in two steps. The first step is simulating the CPW structure without transitions shown in Figure 2, the scattering matrix of the CPW structure is got from the simulation software, using the transmission/reflection method [11] the propagation constant γ' of the CPW structure is calculated as a reference value. The second step is simulating the two samples in Figure 1(a) and Figure 1(b) which the ANUT is exactly the same with the CPW structure in the first step, the scattering matrixes S and S' mentioned in Section 2 are got from the simulation software, propagation constant γ of the ANUT is calculated using the deembedding method proposed in this paper.

From Table 1, one can see that the propagation constants calculated by the deembedding method precisely agrees with the reference value from 1 GHz to 6 GHz. The relative error of the imaginary part of the propagation constant is less than 0.2%. It is indicated that the deembedding method proposed in this paper has high degree of accuracy.

4. CONCLUSION

In this paper, a new deembedding method in permittivity measurement of ferroelectric thin film material is proposed. By comparing the propagation constant calculated by the deembedding method with the actual propagation constant calculated by transmission/reflection method, one can see that by using the proposed new deembedding method, great accuracy is achieved. And this method can not only be used in the CPW structure, but also be used in other transimission line structures, such as microstrip line structures, so it is very applied in ferroelectric thin film material measurement field.

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