A Multiline Multi-material Calibration Method for Liquid Characterization

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Abstract—A multiline and multi-material calibration method is proposed, which is aimed at replacing state-of-the-art two-tier microwave calibration techniques in liquid characterization process. The technique combines a general “line-line” trace method and an equivalent impedance algorithm, which enables to use unknown materials loaded on various lengths of transmission lines in the calibration standards. The validation measurements are performed on coplanar waveguide (CPW) structures due to the convenient fabrication and easy integration with polymers. Measurement comparison with the previous calibration approach verifies its capability in high frequency applications.

Index Terms—calibration, coplanar waveguide, microwave measurements, nonlinear least squares.

I. INTRODUCTION

Dielectric spectroscopy measurements can provide valuable information of various liquids and solutions for researches and studies in the biological and chemical fields. However, broadband quantitative characterization relies on accurate calibration of the vector network analyzer (VNA) and the test fixture of a device under test (DUT). Differing in equipment by three or four samplers, a VNA can be calibrated with a twelve-term error model and an eight-term error model, respectively. With an addition of switch terms [1], the twelve-term problem can be solved with the eight-term algorithm, e.g. TRL (“through-reflect-line”) [2] and LRM (“line-reflect-match”) [3]. Practically, only seven parameters are required to solve the eight-term problem [1], [4].

Though there are many accurate VNA calibration approaches [1]–[3], [5], they could not remove the unwanted effects of test fixtures where the DUT is embedded. To de-embed errors caused by the test fixture, a second-tier calibration, or called “de-embedding” [6], is usually required. For instance, a reference liquid calibration method that allows any combination of fully or partially defined liquid standards has been used in water characterization [4], [7]. However, it still relies on accurate first-tier calibration.

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Fig. 1. Schematic of the measurement configuration, where S^X and S^Y are the two error boxes considered, γ_k, C_k, G_k , and l_k are related to the k th standard, and S^{km} is the measured S-parameters of the k th standard.

In this study, instead of the two-step procedure, we develop a transmission line based multiline multi-material calibration method that can directly move the reference planes from VNA ports to the DUT. The transmission lines are required to be either clearly distinct in lengths or loaded with notably different dielectric materials. This paper is organized as follows: section II describes the proposed multiline multi-material calibration procedure; Section III introduces the on-wafer measurement setup and devices, presents the validation procedure, and also discusses the results; conclusions are drawn in the final section.

II. METHOD DESCRIPTION

Fig. 1 shows the configuration of a typical on-wafer measurement procedure [6]. X' and Y' represent the two error boxes caused by the connections and cables between VNA ports and probe-tips. X'' and Y'' are errors due to the test fixture from probe-tips to the DUT. X' and Y' are often removed with a first-tier calibration, followed by a second-tier calibration to remove X'' and Y'' . In this study, the two-tier calibration process is replaced with a one-tier calibration, with the scattering (S-)parameters S^X resulting from X' and X'' , and S^Y resulting from Y' and Y'' , respectively. To characterize S^X and S^Y , seven parameters, i.e., $S_{12}^X S_{12}^X, S_{11}^X, S_{22}^X, S_{21}^X S_{12}^Y, S_{12}^Y S_{12}^Y, S_{11}^Y$, and S_{22}^Y , are required [1], [4].

The DUTs we use are identical coplanar waveguide (CPW) transmission lines fabricated on a low loss substrate and being of the same cross-sectional dimensions, on top of which various dielectric materials can be loaded. One line is loaded with a reference material of known permittivity, and another line is covered with an unknown dielectric material. The

reference material line is l_r long, and its propagation constant, distributed per unit length (p.u.l) capacitance, and p.u.l conductance [8] are denoted as γ_r , C_r , and G_r , respectively. The corresponding parameters of the line with an unknown material are l_t , γ_t , C_t , and G_t , respectively. As the p.u.l resistance R and inductance L are determined only by the electrodes' geometries and properties, they present the same values for all of the CPW lines covered with different materials [9]. Therefore, according to the equivalent impedance technique [10], the following relationship is achieved

$$\frac{\gamma_t}{\gamma_r} = \sqrt{\frac{G_t + j\omega C_t}{G_r + j\omega C_r}} \quad (1)$$

which directly relates to the measurement values through the following "line-line" equation [11]

$$\begin{aligned} Tr[M_t \cdot M_r^{-1}] &= 2 \cosh(\gamma_r \cdot l_r) \cdot \cosh(\gamma_t \cdot l_t) \\ &- \left(\frac{\gamma_r}{\gamma_t} + \frac{\gamma_t}{\gamma_r} \right) \cdot \sinh(\gamma_r \cdot l_r) \cdot \sinh(\gamma_t \cdot l_t), \end{aligned} \quad (2)$$

where $Tr[X]$ denotes the trace operation of matrix X . The cascaded matrices M_r and M_t are transformed from the measured S-parameters of the two CPW lines [8].

If we utilize a bare CPW line as the reference line (i.e., air works as the reference material), its G_r is negligible due to the low loss property of the employed substrate, and its C_r is available with a two-dimensional (2D) simulation on the cross-section of the bare line [9]. Besides, the bare line's propagation constant γ_r is readily calculated with (2) by measuring two bare CPW lines that are of clearly distinct lengths [2]. Next, with known l_k , the propagation constant γ_k of the k th DUT in Fig. 1 can be determined by using an optimization algorithm on (2), which is followed by the calculation of parameters C_k and G_k according to (1). Mathematically, when the k th DUT is embedded in the test fixture, with its four parameters and the seven unknown parameters of S^X and S^Y [1], [4], we can calculate the S-parameters between the two ports of the VNA using the following formula [6]

$$\begin{aligned} S^{kc} &= F(S_{12}^X S_{12}^X, S_{11}^X, S_{22}^X, S_{21}^X S_{12}^Y, \\ &S_{12}^Y S_{12}^Y, S_{11}^Y, S_{22}^Y, C_k, G_k, \gamma_k, l_k), \end{aligned} \quad (3)$$

where parameters C_k , G_k , γ_k , and l_k are used to calculate the ABCD matrix first with the following equation [8]. The calculated ABCD matrix is subsequently transformed to S-parameters S^k , as shown in Fig. 1.

$$\begin{bmatrix} A & B \\ C & D \end{bmatrix}^k = \begin{bmatrix} \cosh(\gamma_k l_k) & \frac{\gamma_k \cdot \sinh(\gamma_k l_k)}{G_k + j\omega C_k} \\ \frac{(G_k + j\omega C_k) \cdot \sinh(\gamma_k l_k)}{\gamma_k} & \cosh(\gamma_k l_k) \end{bmatrix} \quad (4)$$

If S^{km} is defined as the measured S-parameters of the test fixture with the k th standard embedded, as shown in Fig. 1, residuals between S^{km} and the calculated S^{kc} of all n standards can be defined as

$$|S_{err}| = \sqrt{\sum_{k=1}^n \sum_{i,j=1}^2 |S_{ij}^{km} - S_{ij}^{kc}|^2} \quad (5)$$

Fig. 2. The measurement setup and devices for multiline multi-material calibration technique, with the inset presenting the schematics of two bare lines ("Line 1" and "Line 2"), an SU-8 line ("Line 3"), and a microfluidic line ("Line 4"), where l_1 , l_2 , l_3 , and l_4 indicate the lengths of interest.

Starting with appropriate initial values, the seven parameters of the two error boxes S^X and S^Y can be determined by minimizing this equation at every frequency point with a nonlinear least squares method [4], [6].

III. MEASUREMENT RESULTS AND DISCUSSION

Validation measurements were performed on a probe-station connecting an Agilent E8361A VNA, as shown in Fig. 2. Four CPW lines that are patterned on a low loss glass substrate are used, with the cross-section geometry of these lines being 20 μ m-100 μ m-150 μ m (gap-signal-ground). Specifically, "Line 1" and "Line 2" are two bare CPW lines whose lengths, i.e., l_1 and l_2 , are 20.53 mm and 1 mm, respectively. "Line 3" is an SU-8 loaded line and "Line 4" is a microfluidic calibration fixture, where the SU-8 length l_3 and channel length l_4 are 1.5 mm and 3 mm, respectively.

Several steps were taken for validating the multiline multi-material calibration technique. First, S-parameters of "Line 1" and "Line 2" were recorded, from which the propagation constant γ_{air} and p.u.l capacitance C_{air} of an empty CPW line were obtained. Second, S-parameters of the SU-8 line-"Line 3" and the microfluidic line-"Line 4" before and after loading deionized (DI) water were recorded, representing three calibration standards. Third, by the combination of (2) and (1), we are able to extract the parameters γ_{SU8} , C_{SU8} , and G_{SU8} of an SU-8 loaded CPW line and γ_{water} , C_{water} , and

Fig. 3. Measured complex permittivities of DI water and SU-8 at 19.6°C. As a reference, literature values of water are also shown [12].

Fig. 4. Measured DI water permittivities at 19.6°C, which are extracted from S-parameters that are calibrated with previous two-tier calibration procedure and the proposed calibration technique, respectively.

G_{water} of a water loaded CPW line. With the capacitances and conductances, complex permittivities of SU-8 and DI water were calculated [9], which are reported in Fig. 3. Finally, with all of the parameters of bare line, SU-8 line, and water line, the two error boxes S^X and S^Y can be accurately determined with the algorithm described in previous section.

Another line with similar structure to “Line 4” yet of 1.5mm microfluidic channel length was used to verify the proposed multiline multi-material calibration method. We first extracted the complex permittivity of DI water from the S-parameters that were calibrated with the multiline multi-material method, as presented in Fig. 4. As a comparison, Fig. 4 also presents the permittivity results obtained from the S-parameters that were calibrated with the regularly used two-tier calibration method [9]. In the two-tier method, a typical first-tier multiline TRL calibration [5] was first performed, whereas the de-embedding error boxes were directly calculated with the distributed p.u.l R , L , C , and G of the bare line and SU-8 line [9]. Next, we compared the proposed calibration technique and the previous two-tier calibration method with the comparison algorithm [13]. The comparison result of the two calibration procedures is presented in Fig. 5.

According to the permittivity results shown in Fig. 4, at low frequencies, the proposed calibration technique is worse than the previous method. This is related to the trace algorithm of the “line-line” technique, which is preferably applicable at high frequencies [11]. Notably, at high frequencies, e.g., at frequencies between 20 GHz and 50 GHz, the permittivity re-

Fig. 5. The comparison between the proposed multiline multi-material calibration technique and the previous two-tier calibration method.

sults extracted with the proposed procedure are rather smooth, whereas the permittivities with previous two-tier technique show obvious ripples. The slight comparison difference of the two approaches at frequencies between 20 GHz and 50 GHz in Fig. 5 partly relates to probe placements, probe contacts, device fabrication tolerance, etc., which are often ignored in previous two-tier calibration process. As a result, the proposed multiline multi-material method can provide reliable calibration, especially at high frequencies. It will be of great advantages in applications where complicated CPW line based devices are employed, e.g., interdigital capacitors.

IV. CONCLUSION

A multiline multi-material calibration method based on nonlinear least squares algorithm is developed. The combination of a general “line-line” trace theory and an equivalent impedance method forms the foundation of this method. Validation measurements on DI water and the comparison with a previous calibration method have shown its feasibility of accurate calibration at high frequencies. It will be especially useful in applications where more complicated passive devices than transmission lines are used.

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