Parameter Retrieval of Samples on a Substrate From Reflection-Only Waveguide Measurements

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***Abstract*— A microwave method has been proposed for constitutive parameters' extraction of samples on a known substrate. The advantage of this method is that it relies on noniterative reflection-only (air- and metal-backed) scattering (S-) parameters so that it is a good candidate for the characterization of samples when only one-port measurements are available. It is validated by the X-band (8.2–12.4 GHz) waveguide S-parameter measurements. A sensitivity analysis is followed to evaluate and improve the performance of our method.**

***Index Terms*— Complex permeability, complex permittivity, known substrate, noniterative, reflection-only.**

I. INTRODUCTION

RELATIVE permittivity (ε_r) and permeability (μ_r) are intrinsic properties to a given material. There are a variety of microwave techniques, each with superior advantages and drawbacks, available in the literature [1], utilizing this intrinsic property. Transmission–reflection nonresonant methods are the widely used microwave methods for broadband material characterization [2]–[12]. While some of them retrieve ε_r and μ_r of single-layer materials [2], [3], others extract ε_r and μ_r of multilayer structures [4]–[12], and some of which are, essentially, suitable for ε_r and μ_r measurement of materials on a known substrate; e.g., thin films on a substrate [13]. While the methods [4], [5], [7]–[12] extract electromagnetic properties ε_r and/or μ_r using explicit-form of expressions, the method [6] uses constrained optimization routine for the ε_r extraction. Besides, while the method [4] uses deembeeding process, the methods [5]–[12] relies on direct or quasi-direct analysis for ε_r and/or μ_r extraction. However, all these methods require two-port measurements.

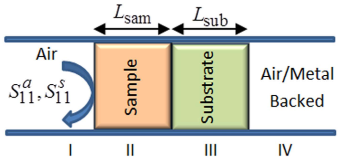

Fig. 1. Configuration for reflection-only measurements of a material with length L_{sam} on a known substrate with length L_{sub} in a waveguide section.

On the other hand, reflection-only one-port nonresonant methods can also be used for broadband material characterization [14]–[20]. These methods can remove the effect of the Fabry–Perot frequencies on extracted electromagnetic parameters of low-loss samples [18]. Besides, they are useful when only one side of the sample is accessible. While some of these methods [14], [15], [19], [20] use reflection-only measurements of one sample with and without offset from the short, others [16], [17] utilize reflection-only measurements of two identical samples without any offset from the short. However, all these methods are applicable for the electromagnetic characterization of one material. To extend these studies for ε_r and μ_r extraction of a material on a known substrate, in this letter, a microwave method is proposed using one-port measurements of air- or metal-backed configuration to be applicable for one-port vector network analyzers (VNAs), such as HP 8752C and HP 8714B.

II. THEORETICAL ANALYSIS

Fig. 1 illustrates a material with length L_{sam} on a known substrate with length L_{sub} for its constitutive parameter measurement within a waveguide structure. Assuming that the waveguide is operated at its dominant mode (TE_{10}) and enforcing the boundary conditions over the interfaces I–II, II–III, and III–IV in Fig. 1, air-backed (S_{11}^a) and metal-backed (S_{11}^s) reflection S-parameters can be determined

$$S_{11}^a = \frac{r_{12}\left(1 + r_{23}r_{34}T_3^2\right) + \left(r_{23} + r_{34}T_3^2\right)T_2^2}{\left(1 + r_{23}r_{34}T_3^2\right) + r_{12}\left(r_{23} + r_{34}T_3^2\right)T_2^2} \quad (1)$$

$$S_{11}^s = \frac{r_{12}\left(1 - r_{23}T_3^2\right) + \left(r_{23} - T_3^2\right)T_2^2}{\left(1 - r_{23}T_3^2\right) + r_{12}\left(r_{23} - T_3^2\right)T_2^2} \quad (2)$$

$$r_{12} = \frac{\mu_{\text{sam}}\sqrt{1 - f_g} - \sqrt{\mu_{\text{sam}}\varepsilon_{\text{sam}} - f_g}}{\mu_{\text{sub}}\sqrt{1 - f_g} + \sqrt{\mu_{\text{sub}}\varepsilon_{\text{sub}} - f_g}}, \quad f_g = \frac{f_c}{f} \quad (3)$$

$$r_{23} = \frac{\mu_{\text{sub}}\sqrt{\mu_{\text{sam}}\varepsilon_{\text{sam}} - f_g} - \mu_{\text{sam}}\sqrt{\mu_{\text{sub}}\varepsilon_{\text{sub}} - f_g}}{\mu_{\text{sub}}\sqrt{\mu_{\text{sam}}\varepsilon_{\text{sam}} - f_g} + \mu_{\text{sam}}\sqrt{\mu_{\text{sub}}\varepsilon_{\text{sub}} - f_g}} \quad (4)$$

$$r_{34} = \frac{\sqrt{\mu_{\text{sub}}\varepsilon_{\text{sub}} - f_g} - \mu_{\text{sub}}\sqrt{1 - f_g}}{\sqrt{\mu_{\text{sub}}\varepsilon_{\text{sub}} - f_g} + \mu_{\text{sub}}\sqrt{1 - f_g}} \quad (5)$$

$$T_2 = e^{-ik_0\sqrt{\mu_{\text{sam}}\varepsilon_{\text{sam}} - f_g}L_{\text{sam}}}, \quad T_3 = e^{-ik_0\sqrt{\mu_{\text{sub}}\varepsilon_{\text{sub}} - f_g}L_{\text{sub}}} \quad (6)$$

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where ε_{sam}, μ_{sam}, ε_{sub}, and μ_{sub} are, respectively, the relative complex permittivity and permeability of the sample and the substrate; r_{12}, r_{23}, and r_{34} are the reflection coefficients at the interfaces I–II, II–III, and III–IV, respectively; T_2 and T_3 are the propagation factors within the sample and the substrate; f_c and f are the cutoff and operating frequencies; k_0 is the free-space wavenumber; and the time reference is $\exp(+i\omega t)$.

III. PROPOSED METHOD

Our goal is to noniteratively extract ε_{sam} and μ_{sam} from S_{11}^a and S_{11}^s for known ε_{sub}, μ_{sub}, L_{sam}, and L_{sub}. Toward this end, T_2^2 is derived from (2) using $r_{23} = -(r_{12}+r_{34})/(1+r_{12}r_{34})$

$$T_2^2 = \frac{\left(r_{12}-S_{11}^s\right)\left[\left(1+r_{34}T_3^2\right)+r_{12}\left(r_{34}+T_3^2\right)\right]}{\left(1-S_{11}^s r_{12}\right)\left[r_{12}\left(1+r_{34}T_3^2\right)+\left(r_{34}+T_3^2\right)\right]}. \tag{7}$$

Substituting T_2^2 in (7) into (1), one can derive

$$r_{12} = -M \mp \sqrt{M^2-1}, \quad M = A/(2B) \tag{8}$$

$$\begin{aligned} A &= \left(1+S_{11}^a S_{11}^s\right)\left(r_{34}^2-1\right)\left(r_{34}+1\right)T_3^2 + \left(S_{11}^a - S_{11}^s\right) \\ &\quad \times \left(-r_{34}^3 T_3^4 + \left(1-2T_3^2\right)r_{34}^2 + \left(2-T_3^2\right)T_3^2 r_{34} + 1\right) \end{aligned} \tag{9}$$

$$\begin{aligned} B &= S_{11}^a\left(1-r_{34}^2T_3^2\right)\left(r_{34}+T_3^2\right) \\ &\quad - S_{11}^s r_{34}\left(1+r_{34}T_3^2\right)\left(1-T_3^2\right). \end{aligned} \tag{10}$$

The correct sign for r_{12} in (8) can be ascertained by enforcing the passivity principle for passive samples, that is, $|r_{12}| \leq 1$, where $|\star|$ denotes the magnitude of "$\star$." Then, the evaluated r_{12} can be substituted into (7) to calculate T_2^2. Finally, ε_{sam} and μ_{sam} can be determined using r_{12} in (3) and T_2 in (6) as

$$\mu_{\text{sam}} = C\frac{2\pi}{k_0\Lambda\sqrt{1-f_g}}, \quad \varepsilon_{\text{sam}} = \frac{1}{\mu_{\text{sam}}}\left[\left(\frac{2\pi}{k_0\Lambda}\right)^2 + f_g\right] \tag{11}$$

$$C = \frac{1+r_{23}}{1-r_{23}}, \quad \frac{1}{\Lambda} = \frac{i}{4\pi L_{\text{sam}}}\left(\ln\left(T_2^2\right) \mp i2\pi m\right) \tag{12}$$

where "ln" denotes the logarithm and m is the branch index whose value can be evaluated from the stepwise method [21].

IV. MEASUREMENT AND DISCUSSION

An X-band rectangular waveguide setup, as shown in Fig. 2(a), operated at its dominant mode (8.2–12.4 GHz) was chosen for validation of our method due to its ease of construction and wide availability commercially. The VNA from Keysight Technologies (N9918A) with a frequency range of 30 kHz–26.5 GHz was used for measuring S-parameters. Two phase-stable cables (1-m long) were used for establishing the connection between the VNA and the waveguide-to-coaxial adapters (X-band). Two additional X-band waveguide straights (approximately 200 mm) were utilized to eliminate the effects of higher order modes, which might be created at the intersection of these straights, and the measurement cell, which houses the sample on a known substrate. Before measurements, the setup was calibrated by the thru-reflect-line (TRL) calibration technique [22] with a 9.40-mm line standard [8], [9], [11], [12].

For the validation of our method, a polyethylene (PE) material (sample) with a length of 1.00 mm and an FR4 material (substrate) with a length of 1.50 mm, as shown in the inset of Fig. 2(a), were machined so that they precisely fit the whole guide cross section, in order to eliminate the high-order effects. While selecting these materials, we considered three points. First, the sample was thin enough to implement the possible application (thin film on a substrate) of our method (see Section I). Second, the dielectric properties of the sample and substrate were largely different to test the efficacy of our method. Third, electromagnetic properties and the length of the substrate do not introduce substantial attenuation, which is to be discussed shortly. Fig. 2(b) illustrates the average of measured $|S_{11}^a|$ and $|S_{11}^s|$ of the PE sample on FR4 substrate after carrying out eight independent measurements (positioning (removing) the sample on the substrate into line standard and bolting (unbolting) process) when the substrate coincides with the right terminal of the line standard, after cleaning thoroughly the surfaces of short circuit termination and FR4 substrate. S_{11}^s measurements were realized by the variable short circuit (Flann Microwave). Although, for our (two-port) case, there is no need to use a matched load for S_{11}^a measurements, it must be used for one-port measurements.

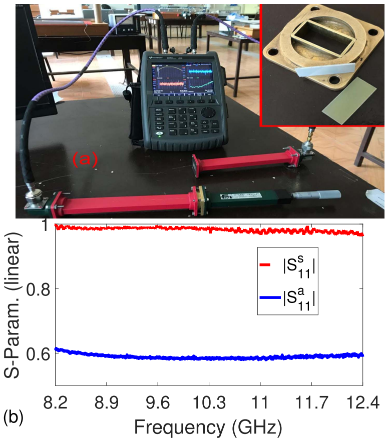

Fig. 2. (a) X-band waveguide setup used for validating the PM and (b) measured magnitudes of S_{11}^a and S_{11}^s of the PE sample on a known FR4 substrate.

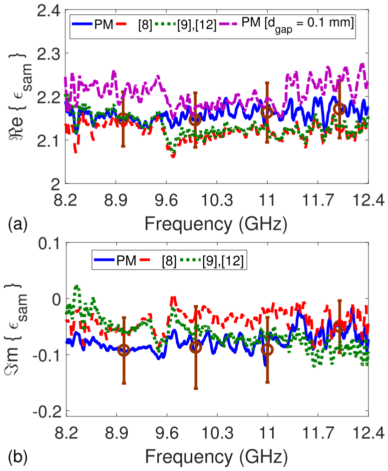

Fig. 3. Extracted (a) real and (b) imaginary parts of ε_{sam} of the PE sample on the FR4 substrate by the PM, the method in [8], and the methods [9], [12].

The reference shift corresponding to the air region of 6.9 mm between the left terminal of the line standard and the front face of the sample was taken into account

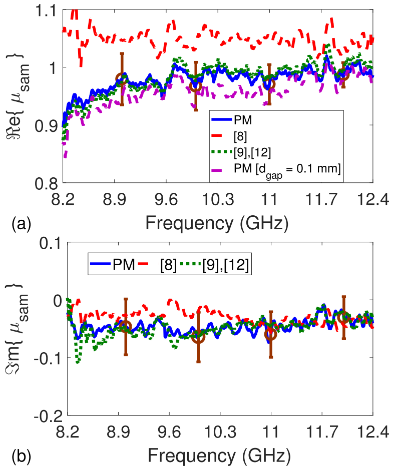

Fig. 4. Extracted (a) real and (b) imaginary parts of μ_{sam} of the PE sample on the FR4 substrate by the PM, the method in [8], and the methods [9], [12].

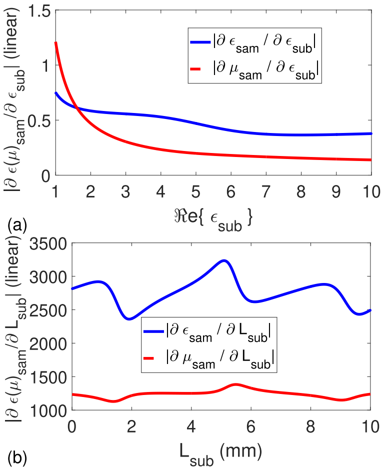

Fig. 5. Dependence of (a) $|\partial\varepsilon_{\mathrm{sam}}/\partial\varepsilon_{\mathrm{sub}}|$ and $|\partial\mu_{\mathrm{sam}}/\partial\varepsilon_{\mathrm{sub}}|$ over $\Re e\{\varepsilon_{\mathrm{sub}}\}$ and (b) $|\partial\varepsilon_{\mathrm{sam}}/\partial L_{\mathrm{sub}}|$ and $|\partial\mu_{\mathrm{sam}}/\partial L_{\mathrm{sub}}|$ over L_{sub}.

before starting to the extraction of our method. Figs. 3 and 4 show retrieved $\varepsilon_{\mathrm{sam}}$ and μ_{sam} by our method [denoted by proposed method (PM)] and the methods [8], [9], [12], after applying smoothing over approximately 60-MHz range to the average measured S-parameters. Because the methods [9], [12] produce similar results, the result of only one of them is shown in Figs. 3 and 4.

In application of our method and the methods [8], [9], [12], the stepwise method [21] was used along with $\varepsilon_{\mathrm{sub}} = 4.25(1 - i0.025)$ [11]. It is noted from Figs. 3 and 4 that extracted $\varepsilon_{\mathrm{sam}}$ and μ_{sam} by our method are in good agreement with those by the methods [8], [9], [12] and those by the dielectric resonator method [23]. In order to examine the effect of any gap d_{gap} between the substrate and the short-circuit termination, $\Re e\{\varepsilon_{\mathrm{sam}}\}$ and $\Re e\{\mu_{\mathrm{sam}}\}$ were extracted when $d_{\mathrm{gap}} = 0.1$ mm, as shown in the insets of Figs. 3(a) and 4(a). It is seen that d_{gap} can alter the accuracy of our method, meaning that special care should be paid in performing short-circuit termination measurements.

In order to evaluate the repeatability of the measurements and give some information of measurement error, standard deviation ($\sigma_{\varepsilon_{\mathrm{sam}}}$ and $\sigma_{\mu_{\mathrm{sam}}}$) values were computed at each frequency from eight independent measurements

$$\sigma_\chi = \left[\frac{1}{N_{\mathrm{meas}}}\sum_{p=1}^{N_{\mathrm{meas}}}(\chi_p - \overline{\chi})^2\right]^{1/2} \quad \overline{\chi} = \frac{1}{N_{\mathrm{meas}}}\sum_{p=1}^{N_{\mathrm{meas}}}\chi_p \tag{13}$$

where χ means $\varepsilon_{\mathrm{sam}}$ or μ_{sam}; $\overline{\chi}$ shows average values; and N_{meas} is the number of independent measurements. Calculated $\Re e\{\sigma_{\varepsilon_{\mathrm{sam}}}\}$, $\Im m\{\sigma_{\varepsilon_{\mathrm{sam}}}\}$, $\Re e\{\sigma_{\mu_{\mathrm{sam}}}\}$, and $\Im m\{\sigma_{\mu_{\mathrm{sam}}}\}$ values were, respectively, less than 0.25, 0.15, 0.15, and 0.15 over the whole band. These values are shown by brown errorbars in Figs. 3 and 4 for frequencies 9, 10, 11, and 12 GHz.

It is instructive to discuss the limit for maximum and minimum values for $\varepsilon_{\mathrm{sam}}$ and μ_{sam} that our method can accurately measure. This limit varies with many parameters, including f, $\varepsilon_{\mathrm{sub}}$, μ_{sub}, L_{sam}, L_{sub}, the accuracy of the measured S-parameters, the accuracy of calibration, guide losses, and air gaps between material surfaces and the guide and between the short termination and the substrate in complex manner. The sensitivity analysis was performed to examine $\partial\chi/\partial\varepsilon_{\mathrm{sub}}$, $\partial\chi/\partial\mu_{\mathrm{sub}}$, $\partial\chi/\partial L_{\mathrm{sam}}$, and $\partial\chi/\partial L_{\mathrm{sub}}$, where χ means $\varepsilon_{\mathrm{sam}}$ or μ_{sam} after performing partial differentiation [24] of the examined quantity χ with respect to $\varepsilon_{\mathrm{sub}}$, μ_{sub}, L_{sam}, or L_{sub}. For example, Fig. 5(a) and (b) illustrates the dependencies of $|\partial\varepsilon_{\mathrm{sam}}/\partial\varepsilon_{\mathrm{sub}}|$ and $|\partial\mu_{\mathrm{sam}}/\partial\varepsilon_{\mathrm{sub}}|$ over $\Re e\{\varepsilon_{\mathrm{sub}}\}$ with 0.01 increments [$L_{\mathrm{sub}} = 1.5$ mm] and the dependencies of $|\partial\varepsilon_{\mathrm{sam}}/\partial L_{\mathrm{sub}}|$ and $|\partial\mu_{\mathrm{sam}}/\partial L_{\mathrm{sub}}|$ over L_{sub} with 0.01-mm increments [$\varepsilon_{\mathrm{sub}} = 4.25(1 - i0.025)$] for $f = 10$ GHz, $L_{\mathrm{sam}} = 1.0$ mm, $\varepsilon_{\mathrm{sam}} = 2.25 - i0.0001$, and $\mu_{\mathrm{sam}} = 1$ (PE sample on FR4 substrate). We note from Fig. 5(a) that larger $\Re e\{\varepsilon_{\mathrm{sub}}\}$ produces smaller $|\partial\varepsilon_{\mathrm{sam}}/\partial\varepsilon_{\mathrm{sub}}|$ and $|\partial\mu_{\mathrm{sam}}/\partial\varepsilon_{\mathrm{sub}}|$. Besides, $|\partial\varepsilon_{\mathrm{sam}}/\partial L_{\mathrm{sub}}|$ and $|\partial\mu_{\mathrm{sam}}/\partial L_{\mathrm{sub}}|$ decrease at some discrete L_{sub} values, as shown in Fig. 5(b). This validates that the FR4 substrate used in our measurements seems to have an optimum thickness at 10 GHz (the mid frequency of the X-band). Finally, it is noted that $|\partial\varepsilon(\mu)_{\mathrm{sam}}/\partial L_{\mathrm{sub}}|$ is much greater than $|\partial\varepsilon(\mu)_{\mathrm{sam}}/\partial\varepsilon_{\mathrm{sub}}|$, meaning that care should be given in obtaining precise information of L_{sub} more than $\varepsilon_{\mathrm{sub}}$ in the extraction of $\varepsilon_{\mathrm{sam}}$ and μ_{sam}.

It should be mentioned that our method assumes that electric losses are the superposition of dielectric losses associated with pure dielectric losses (e.g., electronic and ionic polarization) and conductivity, and the electric and magnetic losses are independent. However, for some materials, electric and magnetic losses are interrelated by some coupling mechanism of complex media (e.g., the magnetoelectric coupling coefficient of bianisotropic materials [11], [25]). Furthermore, our method does not take into account finite conductivity of waveguide walls due to relatively smaller L_{sam} and L_{sub}.

V. CONCLUSION

A microwave method has been proposed for noniterative constitutive parameters retrieval of samples on a known substrate from measured one-port air- and metal-backed S-parameters. The waveguide measurements and sensitivity analysis were performed to validate and improve their performance. In the near future, it is decided to extend our study to the electromagnetic characterization of bianisotropic materials.

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