Method of printed circuits and semiconductor substrates material parameters extraction using wideband reflection measurements

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Abstract. This paper is dedicated to a new method of high frequency circuits material properties extraction based on the reflection measurements of a line shorted two or more times along its length. The line should be fabricated on the material under test. To achieve more precise calculation results, the proposed method uses processing in the time domain. The experimental results section shows obtained assessments for relative permittivity and dielectric loss tangent of the RO4350B hydrocarbon ceramic laminate. Measurements have been conducted over the frequency range up to 20 GHz.

1. Introduction

Dielectric materials interacting with electromagnetic field inside radio-electronic devices at telecommunication, control, radiolocation, navigation, remote sensing and others systems, to a large degree define the extreme achievable characteristics of the devices (attenuation, sensitivity, Q-factor of oscillatory system, frequency stability) and systems. Because of it, there is a demand in materials’ dielectric parameters data in a wide frequency range from infra-low up to microwave frequencies\cite{1}.

High precision measurements of the electric circuits’ scattering parameters in a wide frequency range can be performed with a vector network analyzer (VNA). Commonly, in order to define material properties as an integral part of scattering parameters measurements and processing, sample under test is put between ports of calibrated VNA. A brief description of known material measurement technologies is given in\cite{2}. The outlined extraction methods are based on processing the measured reflection coefficients (RC) and transmission coefficients (TC) of a material under test within the specified frequency range. In some cases, these measured parameters are treated in the time domain. For example, the system calibration method described in\cite{3} uses the GRL algorithm (Gated Reflect Line) based on the TRL technique (Thru-Reflect-Line) with supplementary time domain analysis and filtering. Abilities of the TRL and, in particular, the multiline TRL (mTRL)\cite{4}, are not limited by that. When performing these calibrations, the propagation constant is being estimated, so one can assess material’s dielectric properties. The propagation constant is defined due to treatment of measurements of transmission lines with different length, which are connected between test ports of VNA according with the above-mentioned calibration algorithms.

The main drawback of the transmission measurements is the fact that the transmission path is not...
homogeneous media, thus one should take into account areas where there is no material. The paper
 describes a new method based on the reflection measurements of a shorted line that is fabricated on
high frequency circuits material. In order to implement the method with high accuracy and fidelity, it
is enough to use 1-port VNA, for example such as a cable and antenna analyzer, with a time domain
analysis option integrated. To verify the proposed method versus similar measurements after mTRL
calibration, the authors used a 2-port VNA together with a 2-port printed circuit board fixture.

2. Proposed method

Usually the fixture consists of two connectors and board with leading transmission line between them,
for example fixture, which provides shunt-through measurement algorithm. The line is needed to set
the components in the right way, to lead RF energy toward measurement reference planes, as well as it
allows performing the separation of signals reflected from these connectors in the time domain.
Required calibration and correction methods of measurement setup for this case are described in [5].
In order to shift reference planes to component contact pins it’s convenient to use the transmission line
model that is described by a number of parameters, including material properties.

The investigated method of the material parameters extraction is based on the reflection
measurements of the shorted leading line, as if a sliding short standard would be used. Let us note that
the line should be fabricated on a board or substrate, material parameters of which you are going to
validate. The short standard is placed along the transmission line and can be made in form of a simple
metal plate shorting the signal and ground conductors of the line.

Let us consider the offered method in more detail. As mentioned previously, this method treats the
measured reflection coefficient of specified fixture at two positions of the short standard. For
explanation and calculation, let us use a fixture with a microstrip line. The microstrip line is one of the
most popular types of planar transmission lines primarily because it can be fabricated by
photolithographic processes and is easily miniaturized and integrated with both passive and active
microwave devices [6]. Figure 1 shows positions at \( l_1 \) and \( l_2 \) away from connector 1. The measured
reflection coefficient is the sum of three signals localized at the time axis: direct reflection from
connector 1, reflection from the short standard, and reflection from connector 1 at reverse signal
propagation (multiple reflections) as well. The line length and distances \( l_1, l_2 \) should be ones that
provide enough resolution for performing time domain gating and filtering (it depends on operating
frequency range of VNA used).

In figure 1, a part of the line illustrated as \( \Delta l = l_2 - l_1 \) will be considered a reciprocal structure with
transmission coefficient equal to \( \exp(-\gamma \Delta l) \), where \( \gamma = \alpha + j\beta \) is propagation constant.
After processing the measured reflection coefficient in time domain applied, one can get formulas
below at two positions of the short standard:

\[
\hat{\Gamma}_1 = S_{21} S_{12} \cdot \exp(-\gamma 2l_1) \cdot \Gamma_s ; \tag{1}
\]

\[
\hat{\Gamma}_2 = S_{21} S_{12} \cdot \exp(-\gamma 2l_2) \cdot \Gamma_s , \tag{2}
\]

![Figure 1. Two positions of the short standard.](image-url)
where $S_{21}$ and $S_{12}$ – forward and reverse transmission coefficients of connector; $\Gamma_S$ – reflection coefficient of the short standard. Signals in time domain can be separated and filtered by using traditional windowing functions or more accurate algorithm of joint assessment described in [7]. In order to separate signals, the joint assessment algorithm uses a special distance-frequency system model, and treats all signals together by least mean square technique.

One can notice that after dividing (2) by (1), influence of the unknown reflection and transmission coefficients is being excluded:

$$\frac{\hat{\Gamma}_2}{\hat{\Gamma}_1} = \exp(-2\gamma2\Delta l). \quad (3)$$

Therefore, the following assessments of real and imaginary parts of propagation constant can be found:

$$\hat{\alpha} = \text{Re} \left[ \frac{-\ln(\hat{\Gamma}_2 / \hat{\Gamma}_1)}{2\Delta l} \right] ; \quad \hat{\beta} = \text{Im} \left[ \frac{-\ln(\hat{\Gamma}_2 / \hat{\Gamma}_1)}{2\Delta l} \right]. \quad (4)$$

Assessment of effective relative permittivity [4]:

$$\hat{\varepsilon}_{re} = \left( \hat{\alpha} + j\hat{\beta} \right) \frac{\gamma^2}{2\pi f / c}. \quad (5)$$

For calculation relative permittivity $\varepsilon_r$, an appropriate microstrip line model equation can be taken [8]:

$$\varepsilon_{re} = \frac{\varepsilon_r + 1}{2} + \frac{\varepsilon_r - 1}{2} \left( 1 + \frac{10h}{W} \right)^{-1/2}, \quad (6)$$

where $W$ – conductor width, $h$ – dielectric substrate thickness.

It should be noted that for investigated fixture, the dielectric substrate thickness is less than a gap between signal conductor and ground surfaces on the top layer. Therefore, using such microstrip line model is allowed here. When working with semiconductor substrates, as rule, developers of RF devices use coplanar waveguide. So one just needs to consider other line model equation, for example as listed in [9]. Max relative calculation error according to (6) is less than 2 %. If necessary, one can find and apply more accurate models of the transmission lines in dependence on measurement task requirements.

The equation for relative permittivity can be easily obtained in the analytical form by solving (6):

$$\varepsilon_r = \frac{2\varepsilon_{re} - 1 + (1 + 10h/W)^{-1/2}}{1 + (1 + 10h/W)^{-1/2}}. \quad (7)$$

Let us note that $\varepsilon_r = \varepsilon'_r - j\varepsilon''_r$, and dielectric loss tangent:

$$\tan \delta = \frac{\varepsilon''_r}{\varepsilon'_r}. \quad (8)$$

3. Experimental results

This experiment was performed using a test fixture made of the RO4350B high frequency circuit material [10]. In Figure 2 there is measurement setup consisting of two-port VNA and the fixture connected to test ports of the VNA by couple of magnitude and phase stable RF cable assemblies. The fixture included a 50 Ohm precision line, and Beatty standard (line with 25 Ohm segment) as well. Both lines of 130 mm length were microstrip lines. During testing, short standard was set to 50 Ohm line only. Key parameters of the line: $W=0.52$ mm, $h=0.254$ mm. Width $W$ was preliminarily measured by the Mahr MarVision MM 320 microscope with approximately 1 µm level accuracy.
The required reflection measurements with short standard were carried out with the Cobalt C1220 VNA [11] in frequency range from 100 kHz to 20 GHz (output power level -5 dBm, IF filter bandwidth 1 kHz). The first short standard position was 60 mm from the beginning of the line, while the second position was shifted by $\Delta l=30$ mm toward connector 1.

Figure 2. Test fixture used (top) and measurement setup (bottom).

Calculation results of the relative permittivity (7) and dielectric loss tangent (8) are demonstrated in Figure 3 by thick solid curves. Thin solid lines show results by using (4) and then (5) – (8) with changing $\Delta l$ by $\pm 100$ µm. For comparison analysis, in Figure 3 there are results obtained after 2-port mTRL calibration in a form of dash lines. For conducting of the mTRL calibration, special test fixture with several lines having different length was used. The extraction results according to the mTRL algorithm show the averaged material parameters along the fixture.

![Figure 3](image3.png)

Figure 3. Relative permittivity (left) and dielectric loss tangent (right) for the RO4350B material.

In the RF devices design and development process, the manufacturer of the RO4350B high frequency circuit material recommends using real relative permittivity $\varepsilon_r=3.66$, whereas measurement results show the value close to 3.48. Also in the data sheet [10] there is $\tan\delta=0.0031$ (2.5 GHz) and $\tan\delta=0.0037$ (10 GHz). According to offered measurement and calculation technique, results for $\varepsilon_r$ are
almost the same, but for \( \tan \delta \) it is approximately 4 - 5 times larger. Position error \( \Delta l \) influences \( \varepsilon_r \) only. So, for example, the position error of 100 \( \mu m \) provides error of \( \varepsilon_r \) less than 1 % over the frequency band up to 20 GHz. Behavior of the obtained characteristics at low frequencies depends on the material parameters dispersion and is due to peculiarities of the time domain processing as well.

4. Conclusion
In the paper there is new method of printed circuits and semiconductor substrates material parameters extraction. This method is simple and cost effective algorithm in purpose of determination of relative permittivity and dielectric loss tangent assessments.

To achieve high accuracy during on-wafer measurements with substrates at frequencies up to 110 GHz and above, it is necessary to provide correct positioning and mechanical repeatability for short standard contact. The standard can be created using wafer RF probe with a special type of configuration in a form of shorted conductors. Usually, in on-wafer measurement systems there are optical microscopes and different strain sensors, which can provide a positioning accuracy not larger than 1 \( \mu m \) along with acceptable contact repeatability. Using the method offered in the paper, one can implement reference on-wafer calibration algorithm.

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