S-Parameter Broadband Measurements On-Coplanar and Fast Extraction of the Substrate Intrinsic Properties

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***Abstract*—A broadband technique for determining the electromagnetic properties of isotropic thin-film materials, which uses a coplanar line, is presented. Complex permittivity and permeability are computed from S-parameter measurements of a coplanar cell propagating the dominant mode. Measured ε_r and μ_r data for several materials are presented between 0.05 GHz and 40 GHz. This technique shows a good agreement between measured and predicted data.**

***Index Terms*—Broadband measurement, coplanar, permeability, permittivity, propagation, S-parameters.**

I. Introduction

In numerous applications, for a large variety of thin-film materials and in a Broadband of frequencies, the permittivity and permeability measurements are required. Contrary to the box-shaped broadband cells (coaxial, rectangular waveguide or stripline device) [1]–[3], the coplanar and microstrip lines used as sample-cells do not present air gaps between the sample and the conductors, since they are produced onto the sample to be characterized. Moreover, they allow thin-film materials to be characterized and the characteristic impedance to be changed by modifying the conductive strip width. Thus, it is possible to optimize their shape in order to propagate the dominant mode (quasi-TEM) and to perform accurate S-parameter measurements with the same cell in a broadband of frequencies. In the case of dominant mode and contrary to the microstrip, the coplanar characteristic impedance (Fig. 1) is quasiconstant in the dc to 40 GHz frequency range for a large variety of substrates and a cell structure such as $h > W+2S$. It was computed from the spectral domain approach (SDA) [4]. The cell configuration was optimized in order to have about a 50 Ω characteristic impedance at low frequencies. The coplanar quasi-TEM mode dispersion being low, it is possible to compute its propagation constant and characteristic impedance from approximate equations derived from conformal imaging [5] instead of a rigorous numerical analysis as for example the SDA numerical method, which decreases considerably the computation time.

In this letter, an easy and fast processing method of the S-parameters measured from coplanar cells for determining the complex permittivity and also the complex permeability of the substrates is proposed. It is based on the quasi-TEM mode propagation and approximate equations. The S-parameter measurement bench employs a vector network analyzer and a high-quality test fixture on-coplanar covering 0.05–40 GHz.

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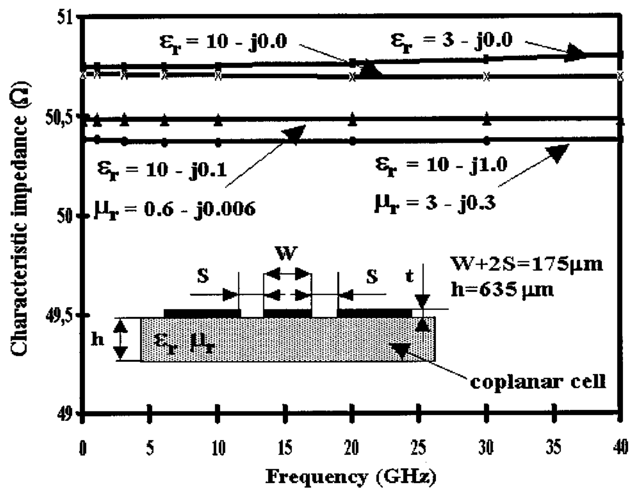


Fig. 1. Magnitude of calculated coplanar characteristic impedance against frequency and various substrates: —■—■—■— Characteristic of the substrate: $\varepsilon_r = 3 - j0.0, \mu_r = 1 - j0.0$. —×—×—×— Characteristic of the substrate: $\varepsilon_r = 10 - j0.0, \mu_r = 1 - j0.0$. —▲—▲—▲— Characteristic of the substrate: $\varepsilon_r = 10 - j0.1, \mu_r = 0.6 - j0.006$. —●—●—●— Characteristic of the substrate: $\varepsilon_r = 10 - j1.0, \mu_r = 3 - j0.3$.

II. Processing Method

The processing method is based on the S-parameter measurements at the coplanar access planes. It requires the propagation to be the quasi-TEM dominant mode and its dispersion to be low ($h > W + 2S$). In this case, it is possible to write simple formulas for the characteristic impedance (Z_c), propagation constant (γ), and total loss tangent ($tg\delta$) for coplanar on a substrate exhibiting both dielectric and magnetic properties [6]:

$$Z_c = Z_0' \sqrt{\frac{\mu_{\text{reff}}}{\varepsilon_{\text{reff}}}} \tag{1}$$

$$\gamma = \omega\sqrt{\varepsilon_0\mu_0}\sqrt{\varepsilon_{\text{reff}}\mu_{\text{reff}}} \tag{2}$$

$$tg\delta = q'_{tg\delta d} \cdot tg\delta_{\text{deff}} + q'_{tg\delta m} \cdot tg\delta_{\text{meff}} \tag{3}$$

where

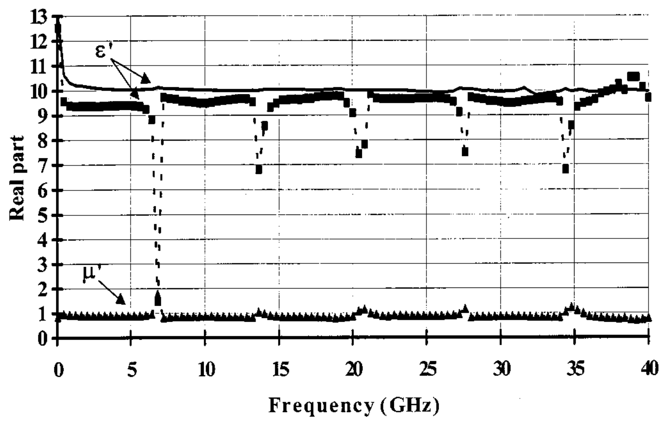
$tg\delta_{\text{deff}} = \varepsilon''_{\text{reff}}/\varepsilon'_{\text{reff}}$;

$tg\delta_{\text{meff}} = \mu''_{\text{reff}}/\mu'_{\text{reff}}$;

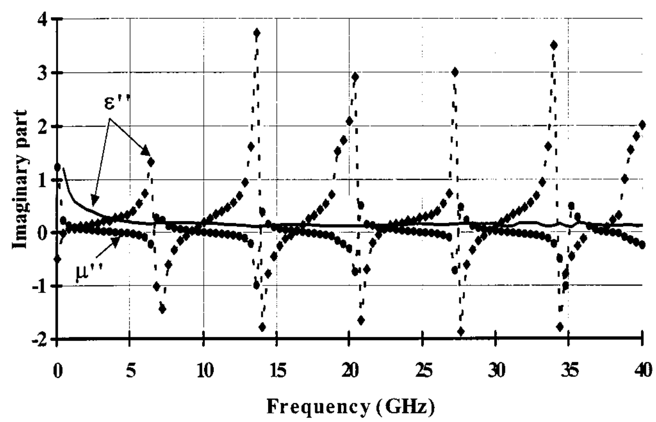
$q'_{tg\delta d} = 1 - (\varepsilon'_r)^{-1}/1 - (\varepsilon'_{\text{reff}})^{-1}$;

$q'_{tg\delta m} = 1 - \mu'_r/1 - \mu'_{\text{reff}}$.

Z_0' characteristic impedance when $\varepsilon_r = \mu_r = 1$, which is computed from an approximate equation [5].



(a)



(b)

Fig. 2. Measured ε_r and μ_r data for alumina (cell dimension: $W = 50\ \mu$m, $W+2S = 175\ \mu$m, $h = 635\ \mu$m, $t = 5\ \mu$m, length $d = 1$ cm): (a)——— ε_r' value ($\mu_r = 1 - j0$ fixed in the processing method), -■-■-■- ε_r' value, -▲-▲-▲- μ_r' value; (b)——— ε_r'' value ($\mu_r = 1 - j0$ fixed in the processing method), -◆-◆-◆- ε_r'' value, -●-●-●- μ_r'' value.

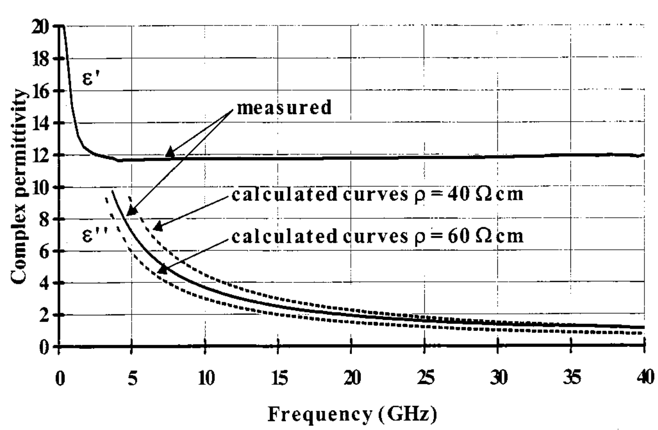


Fig. 3. Measured ε_r data for doped silicon (cell dimension: $W = 70\ \mu$m, $W + 2S = 175\ \mu$m, $h = 230\ \mu$m, $t = 3\ \mu$m, length $d = 1$ cm); ——— measured ε_r' and ε_r'' values, — — — — — calculated ε_r'' values.

The reflection/transmission method [1], [2] allows to get the first reflection (Γ) at the input of the coplanar cell and the first transmission (T) along the coplanar cell of length "d". The resolution of the equations leads to the terms of complex effective permittivity and permeability:

$$\varepsilon_{\text{reff}} = \varepsilon_{\text{reff}}' - j\varepsilon_{\text{reff}}'' = j\frac{1}{\omega d\sqrt{\varepsilon_0\mu_0}}\left(\frac{1-\Gamma}{1+\Gamma}\right)\left(\frac{Z_0'}{Z_0}\right)\ln(T) \quad (4)$$

$$\mu_{\text{reff}} = \mu_{\text{reff}}' - j\mu_{\text{reff}}'' = -j\frac{1}{\omega d\sqrt{\varepsilon_0\mu_0}}\left(\frac{1+\Gamma}{1-\Gamma}\right)\left(\frac{Z_0}{Z_0'}\right)\ln(T) \quad (5)$$

where Z_0 is the characteristic impedance of the test device (50 Ω).

The exchange between complex effective permittivity and permeability, and the sample desired relative characteristics (ε_r, μ_r) is obtained from approximate equations [5]. In the case of magnetic materials, the exchange approximate equation is acquired by a duality relationship. The duality consists to realize the conversions $\varepsilon_r \rightarrow 1/\mu_r$ and $\varepsilon_{\text{reff}} \rightarrow 1/\mu_{\text{reff}}$ in the approximate equation for the dielectric case [6].

III. Measurements and Results

The coplanar measurements were realized with the HP85107 network analyzer and the test fixture Cascade Microtech covering 0.05–40 GHz. This test fixture has two coaxial to coplanar transitions of 50 Ω characteristic impedance used as probes. It allows different sizes of coplanar, measurements easy to implement, repeatable and accurate, thanks to the calibration procedure using a line-reflect-match (LRM) and a calibration kit of 50 Ω characteristic impedance. The two achieved measurement reference planes are at the two probe outputs. Return losses, insertion losses and repeatability were better than -20 dB, -2 dB and ± 0.1 dB, respectively, over the entire 0.05 GHz to 40 GHz frequency range.

Both probes are put at the coplanar access planes in order to get the S-parameters and to use the above processing method. To illustrate this characterization method, coplanar cells were made from thin-film technology [5] on alumina ($\varepsilon_r' = 9.85$, $\varepsilon_r'' < 0.001$ at 10 GHz, $\mu_r = 1$) and doped silicon ($\varepsilon_r' = 11.7$, $\rho = 40$–$60\ \Omega$ cm, $\mu_r = 1$) samples with well-known dielectric properties. The measurements performed on each of these materials were obtained at room temperature and they are represented in Figs. 2 and 3. The measured ε_r' and μ_r' values for alumina [Fig. 2(a)] correspond to those anticipated (except the peaks). In order to avoid inaccurate peaks due to the periodic behavior of the sample-cell with the frequency (specially when substrate is loss less) and to obtain accurate results on the complex permittivity values of nonmagnetic materials, we fixed $\mu_r = 1 - j0$ in the processing method as in [7]. Thus, the ε_r' values for both samples (solid lines) have an error better than 3% compared with the manufacturer values. In the alumina case [Fig. 2(a)], the resulting ε_r' is approximately 0.5 higher (closer to the known value at 10 GHz) than when the computed μ_r is used. In the processing method with $\mu_r = 1$ fixed, we took into account a length d less than 10 mm due to the position error of the probes. In the case of losses, large errors are also shown for alumina [Fig. 2(b), solid line] with $\mu_r = 1$ fixed. These errors are mainly due to the network analyzer, the test fixture performance, and the whole coplanar cell (dielectric, metallic and radiation) losses. The measurement of low-loss samples is difficult with this technique. To obtain reasonable accuracy, ε_r'' must be greater than 0.2 as in the case of measured doped silicon, where the values are in good agreement with the manufacturer.

IV. Conclusion

A characterization broadband technique of isotropic thin-film materials has been developed. It uses a coplanar line as cell, which does not present air gaps. Moreover, its characteristic impedance can be optimized in order to propagate the dominant mode and to realize accurate measurements. The complex properties (ε_r, μ_r) are easily computed from a fast processing method of the S-parameters using approximate equations. The S-parameters are measured at the coplanar access planes with a network analyzer and test fixture on-coplanar. The experimental results have demonstrated the technique validity. This technique can be conveniently applied to the study of materials in the 0.05 GHz to 40 GHz frequency range.

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