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DOI:
10.1049/cp.2018.0650

Document status and date:
Published: 10/12/2018

Document Version:
Accepted manuscript including changes made at the peer-review stage

Planar Sensors for Dielectric and Magnetic Materials Measurement: A Quantitative Sensitivity Comparison

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***Abstract*—Planar transmission lines are frequently used to characterize the RF properties of materials. However, the question arises which geometry should be chosen for optimal measurement sensitivity to the material under test. Thus far, this question appears to go unanswered. In this paper, the suitability of the three most popular planar geometries is compared for material characterization. To this end, the impact of a material under test on the apparent properties (i.e. the equivalent homogeneous cross-sections) is examined. This is done for the complex permittivity and the complex permeability, using conformal mapping methods, full-wave simulations and measurements. It is shown that the coplanar waveguide (without conductor backing) is the most suitable structure of the three, since it is the most sensitive to changes in the properties of the material under test.**

***Index Terms*—Coplanar Waveguides, Coplanar Waveguides with Ground, Material Characterization, Microstrip Lines.**

I. Introduction

Within the field of material characterization, the transmission/reflection technique is often applied to obtain the broadband behavior of a material, especially when considering the measurement of both complex permittivity and complex permeability [1]. For this purpose, various types of transmission lines have been applied: rectangular waveguides, coaxial airlines, free-space techniques (using horn antennas) and planar structures. One key advantage of the latter is that it is very flexible with respect to the dimensions of the material under test. Microstrip, coplanar waveguide (CPW), and coplanar waveguide with conductor backing (GCPW) are the most often applied here, since other geometries require a 'sandwich' with the material under test (MUT) or are difficult to design for 50 Ω.

The question arises which of these geometries is the most suitable for the characterization of dielectric and/or magnetic materials. All three allow for measurements at low frequencies, since they can support even DC signals. In addition, all three work up to high frequencies, if properly designed (and depending on the MUT). Thus, the choice of geometry for this application comes down to their sensitivity to the MUT. Such a comparison would allow for an optimal choice of geometry, which has not been found documented yet. Especially challenging is the application to magnetic materials, as transmission lines are usually only modeled for and applied to dielectric materials.

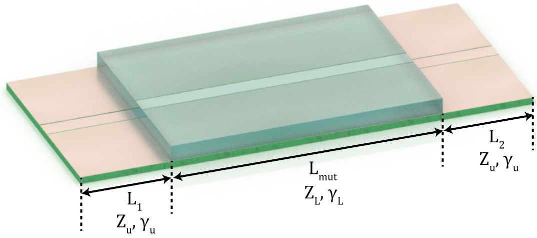


Fig. 1: 3-Dimensional view of the transmission-reflection method using a CPW.

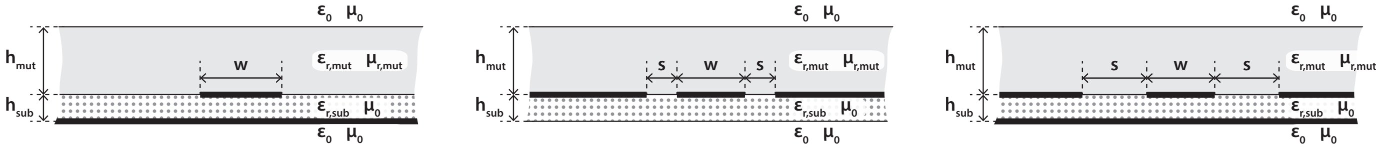
In this paper these three structures are compared with respect to their sensitivity to the MUT, as a function of MUT permittivity and permeability. Although the methods to do this are well established techniques, namely conformal mapping (CM) and full-wave simulations, their application to this problem provides valuable new insight into the structure's sensitivity to the MUT. Moreover, the optimal case is verified with measurements. The CM method's validity for these geometries and extension to magnetic materials is also discussed.

The remainder of this paper is structured as follows. In Section II the method and assumptions of the comparison are explained. Next, the range of validity of the CM for this application is discussed in Section III, followed by the results and a discussion thereof in Section IV. The work is concluded in Section V.

II. Approach and Method of Comparison

The transmission/reflection method for material characterization is based on a transmission line, with the goal to calculate the complex permittivity ($\varepsilon_r = \varepsilon_r' - \mathrm{j}\varepsilon_r''$) and permeability ($\mu_r = \mu_r' - \mathrm{j}\mu_r''$) from measured S-parameters. A 3-dimensional view of a CPW used for the transmission/reflection method is given in Fig. 1. Together, the reflection from the unloaded (Z_u, γ_u) to the loaded (Z_L, γ_L) sections and the transmission through the loaded section provide sufficient information to calculate the complex permittivity and permeability. To this end, the Nicholson-Ross-Weir (NRW [2], [3]) method is most commonly applied, mainly due to its relative simplicity.

In the case of transmission lines with a homogeneously filled (with the MUT) cross-sections (e.g. a coaxial air-line us-



(a) (b) (c)

Fig. 2: Cross-sections of the microstrip (a) CPW (b) and GCPW (c) tranmission-line configurations including a MUT.

ing a toroidal sample) the NRW delivers the MUT's parameters directly. For geometries with non-homogeneous cross-sections, an additional step is required. Assuming that the mode of propagation is Quasi-TEM, the results from the NRW algorithm correspond to the commonly used 'effective' parameters, a weighted average of the parameters of the materials that constitute the transmission line cross-section. Therefore, once this relation between the effective parameters ($\varepsilon_{\mathrm{r,eff}}$ and $\mu_{\mathrm{r,eff}}$) and the MUT parameters ($\varepsilon_{\mathrm{r,mut}}$ and $\mu_{\mathrm{r,mut}}$) is known, the MUT parameters can be calculated from the parameters produced by the NRW algoritm. The weighted contribution of $\varepsilon_{\mathrm{r,eff}}$ and $\mu_{\mathrm{r,eff}}$ depend on the detailed cross-section of the transmission line. As a result, the sensitivity of the measurement with respect to the MUT parameters using these geometries is less than in the case of a homogeneous cross-section. If the transmission and reflection coefficients are largely affected by placing the MUT instead of air, this will be visible by a large difference between the effective parameter with air and the effective parameter with the MUT. Thus, this relationship can be used to compare different geometries for their suitability for material characterization. In this paper, three common geometries are compared in this way: microstrip, CPW and GCPW. In order to derive expressions for the permittivity, a CM method is used. Their permeability counterparts are determined using the duality principle as discussed in [4].

The CM results are compared with full-wave simulations, which are performed in CST microwave studio using the time-domain solver. The mesh is refined until convergence is achieved. In addition, the results are compared with measurements for the geometry that is most suitable for material characterization. For ease of comparison, a loss-free MUT is assumed for the calculations and simulations. Furthermore, since the relation for $\varepsilon_{\mathrm{r,eff}}$ is independent of the relation for $\mu_{\mathrm{r,eff}}$, $\mu_{\mathrm{r,mut}} = 1$ is assumed when simulating for the permittivity and vice versa.

The cross-sections of the three transmission line configurations are shown in Fig. 2. The dimensions of the transmission lines that are used are indicated in Table I. Since, in practice, they will be connected to a VNA, all transmission lines are designed for a 50 Ω impedance when no MUT is present, minimizing the reflection on the VNA-transmission line interface and thereby maximizing the dynamic range of the measurement. The substrate (RT5880, $\varepsilon_{\mathrm{r,sub}} = 2.20 - \mathrm{j}0.002$ [5]) is the same in all three cases to enable a fair comparison. Further dimensions, when free to choose, are chosen based on manufacturing criteria and the need to avoid undesired (not Quasi-TEM) modes propagating on the unloaded line in the 1-16 GHz frequency range.

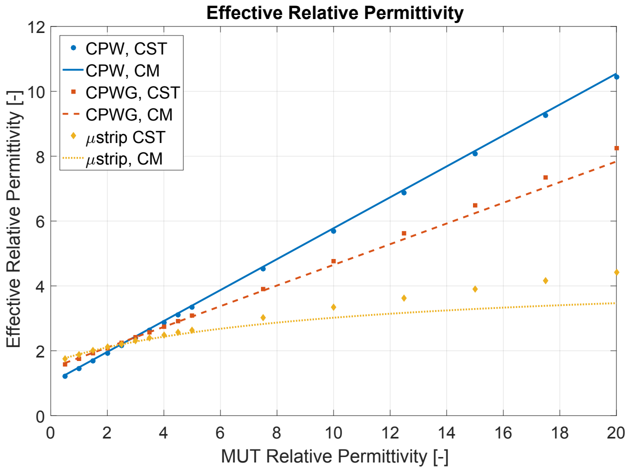
TABLE I: Dimensions of the cross-sections, as indicated in Fig. 2.

Geometry	w	s	h_{sub}	h_{mut}
microstrip (Fig. 2a)	2.42 mm	-	787 μm	2 mm
CPW (Fig. 2b)	2.00 mm	89.0 μm	787 μm	2 mm
GCPW (Fig. 2c)	2.00 mm	401 μm	787 μm	2 mm

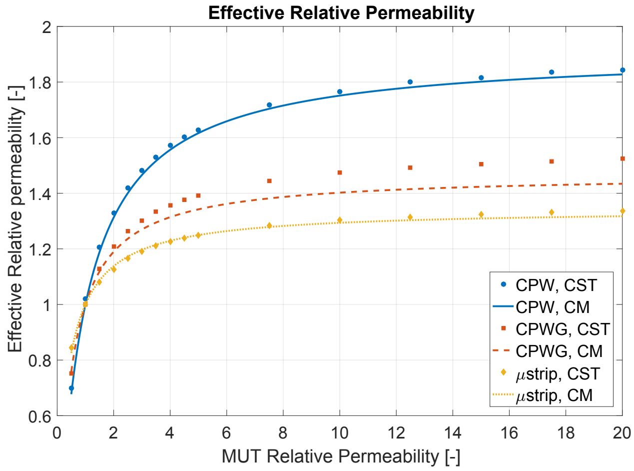
III. Validity of Conformal Mapping Methods

Before the CM method is applied to the configurations shown in Fig. 2, its validity needs to be assessed for these geometries. Conformal mapping is a useful mathematical tool to transform a finite polygon to an infinitely wide parallel plate problem, which is significantly easier to solve analytically. However, to correctly apply this transformation, the problem description should satisfy Laplace's Equation [6]. This means that only Quasi-TEM modes should exist. To enforce this, the boundaries between dielectric media are assumed to be perfect magnetic conductors (PMCs). For each configuration in Fig. 2, different conformal maps have been proposed [7]–[9], but all rely on these assumptions.

For configurations without a MUT (i.e. the commonly used transmission lines, $\varepsilon_{\mathrm{r,mut}} = 1$), the fields are mostly confined to the substrate. Therefore, it is valid to assume a Quasi-TEM mode exists and thus to use the conformal map to calculate the effective parameters. Once a MUT is introduced, as shown in Figs. 1 and 2, with a larger permittivity or permeability than the substrate, the fields are drawn more into the MUT. Since the CPW has all its conductors in one plane, adding a MUT will not change the fundamental behavior of the transmission line: one could view this as a case in which the MUT has become the substrate. With the MUT present for the other two cases, however, increasing the permittivity or permeability causes larger tangential components of the magnetic field at the boundaries between the dielectrics (including the boundary containing the conductors). These tangential components in the magnetic field at the boundaries violate the PMC boundary assumption and thus degrade the accuracy of the solution. Therefore, it can be expected that the accuracy of the calculated effective parameters decreases for increasing $\varepsilon_{\mathrm{r,mut}}$ and/or $\mu_{\mathrm{r,mut}}$ for the GCPW and microstrip.



(a)



(b)

Fig. 3: Effective permittivity as a function of MUT permittivity (a) and effective permeability as a function of MUT permeability.

IV. Results and Discussion

The results from the simulations and calculations are shown in Fig. 3. Figure 3a shows an increasing mismatch between CM and CST results for the microstrip and the GCPW for increasing $\varepsilon_{\text{r,mut}}$. As explained in Section III, this is due to the increasingly severe violation of the PMC boundary assumption. The permeability in Fig. 3b also displays a mismatch between the CM method and the CST simulations. However, this mismatch is less pronounced due to the reciprocal nature of the duality that was applied.

It can be observed that for the CPW and GCPW, there is a linear relation between $\varepsilon_{\text{r,mut}}$ and $\varepsilon_{\text{r,eff}}$ (Fig. 3a) while the relation between $\mu_{\text{r,mut}}$ and $\mu_{\text{r,eff}}$ saturates for large $\mu_{\text{r,eff}}$ (Fig. 3b). In contrast, the microstrip configuration also exhibits a saturation behavior for the permittivity, which is most pronounced in the CST simulation results. To maximize the sensitivity to the permittivity and permeability of the MUT, it is desired to have a steep slope in both figures. The geometry which performs best in this respect is the CPW.

To quantify the sensitivity the derivatives of the conformal mapping relations of permittivity and permeability are calculated numerically and are shown in Fig. 4. There it can be observed that the derivative of the relations for the CPW is indeed highest for both permittivity and permeability, followed by the CPWG and finally the microstrip line. In addition, it can be seen that both coplanar lines have a constant sensitivity to the permittivity of the MUT, while the sensitivity of the microstrip decreases for increasing MUT permittivity. Furthermore, the decrease of the sensitivity for permeability is stronger for the geometries which employ a conductor backing (CPWG and microstrip) than the CPW.

The results above indicate that the CPW is the best choice and has therefore been fabricated, using the same geometry and substrate as the simulations and calculations, enabling measurements in the 1-16 GHz range.

The procedure described in [10] is used to determine the $\varepsilon_{\text{r,eff}}$ and $\mu_{\text{r,eff}}$, but without applying a gap calibration. A TRL calibration is performed to de-embed the connectors to a 50 mm long CPW section, on which the MUT is placed as shown in Fig. 1. The unloaded sections (L_1 and L_2) are then de-embedded using the measured propagation constant of the unloaded line, and the effective parameters of the loaded section are extracted using the NRW algorithm, where the relative permeability is fixed to unity for dielectric materials to improve the accuracy of the measurement.

The MUT parameters are assumed to be exactly known for this comparison. The absolute values of the parameters are used, since the imaginary parts have a significant contribution for lossy materials such as FGM-125. Due to the high dispersion of this material, one measurement provides several points by analyzing the result at different frequencies. For the other materials the frequency is chosen to avoid the not Quasi-TEM modes and half-wavelength resonances within the loaded transmission line section. The measurement of the unloaded transmission line (corresponding to MUT is air) shows nearly no frequency dependence.

The measurement results, as well as their relative error with respect to the CM method, are given in Table II. When comparing these to Fig. 3, it can be observed that the measured $|\varepsilon_{\text{r,eff}}|$ values for high-permittivity MUTs are lower than the simulated and calculated effective permittivity values. This can be attributed to and modeled as an air gap between the metallization and the MUT [10]. Nevertheless, the approximations are accurate for low-permittivity materials, even without applying a gap correction, since the effect of an air gap becomes more prominent for increasing permittivity of the MUT. The measured $|\mu_{\text{r,eff}}|$ on the other hand is very close to the simulated and calculated $|\mu_{\text{r,eff}}|$, which further validates the calculated and simulated results.

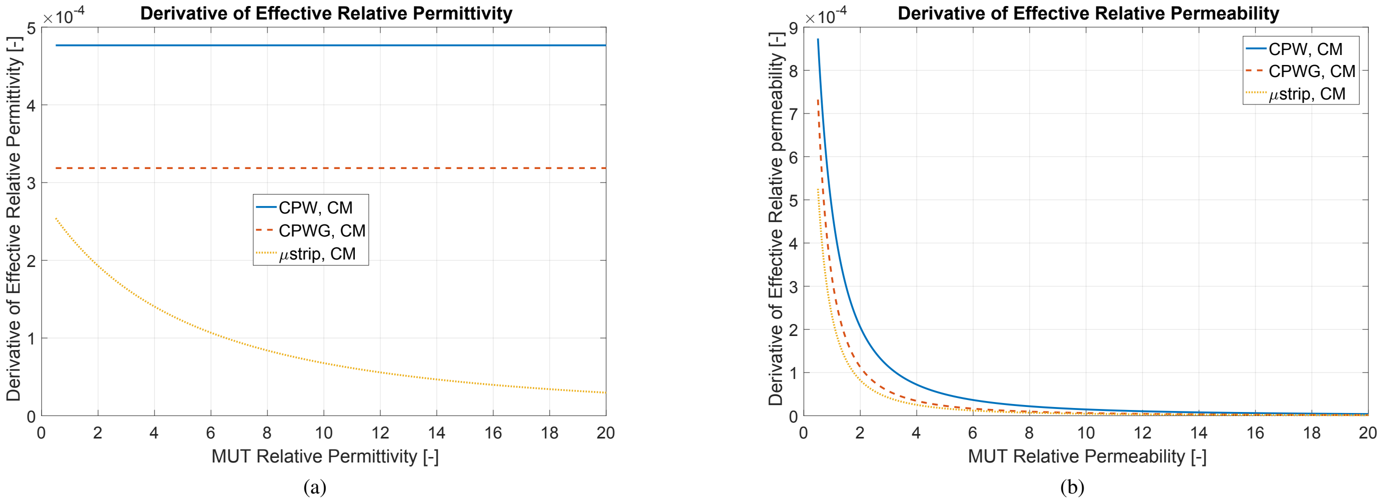


Fig. 4: Derivative of effective permittivity as a function of MUT permittivity (a) and derivative of effective permeability as a function of MUT permeability.

TABLE II: Measurement results of the CPW with various MUT's compared to CM.

MUT	$\lvert\varepsilon_{\mathrm{r,mut}}\rvert$	$\lvert\varepsilon_{\mathrm{r,eff}}\rvert$ *CM*	*Measured*	*Relative error*	$\lvert\mu_{\mathrm{r,mut}}\rvert$	$\lvert\mu_{\mathrm{r,eff}}\rvert$ *CM*	*Measured*	*Relative error*
Air	1	1.49	1.56	4.4%	1	1	-	-
[11], 2 GHz	2.75	2.32	1.97	4.8%	1	1	-	-
[12], 1.5 GHz	9.8	5.68	4.80	15.6%	1	1	-	-
[13], 1 GHz	7	4.35	3.96	8.9%	4.03	1.56	1.61	3.5%
[13], 2 GHz	7	4.35	3.95	9.2%	2.97	1.46	1.53	4.8%
[13], 3 GHz	7	4.35	3.96	8.9%	2.34	1.38	1.46	5.9%
[13], 4 GHz	7	4.35	3.96	8.9%	1.92	1.30	1.40	7.6%

V. Conclusion

In this paper three planar transmission line structures are compared with respect to their applicability to material characterization of dielectric and magnetic materials: microstrip, coplanar waveguide and conductor-backed coplanar waveguide. This is achieved by comparing CM methods, full-wave simulations and measurements. The validity of CM for this application is discussed. It is shown that the coplanar waveguide (without conductor backing) is the most suitable structure of the three: it can be modeled accurately using analytic expressions, and it is the most sensitive to changes in the properties of the material under test.

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