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The Effects of Radiation Losses on the Measurement of Loss Tangent Using Microstrip Ring Resonators

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Abstract— **Measurement of dielectric properties of copper clad printed circuit boards using microstrip ring resonators is a well-studied problem widely in use. The problem addressed here is different from this as the sample under test is difficult to copper clad. The sample is placed on a ring resonator fabricated on a printed circuit board of known dielectric properties and the properties of the test sample are obtained from the measurement of the resulting multilayer stack. Although the measurement of dielectric constant does not pose problems, the calculation of the loss tangent needs the radiation and conduction losses. Out of the two losses, estimation of radiation loss is a difficult task, firstly because the problem is multi-layer and, secondly because the dielectric properties of one of the layers (test sample) are unknown. As a result it is usually assumed that the radiation losses are negligible. This paper examines the effects of this assumption using accurate electromagnetic simulations.**

Keywords—ring resonator; microstrip; loss tangent; dielectric constant; measurements;

I. INTRODUCTION

Dielectric characterization is a robust method of qualification of materials for a wide range of applications. Extensive research has been performed to measure dielectric parameters and consequently introduce novel functional materials [1].

Microstrip ring resonators, proposed by Troughton to measure the dispersion of microstrip transmission lines [11], has been an attractive means for the measurement of the electrical properties of dielectrics. This technique, utilizes the resonance frequency and the Q factor of the ring resonator to compute the permittivity and the loss tangent of the substrate and is unique owing to its simplicity and accuracy due to the high Q factor and the absence of end-effects. However, this technique requires dielectric samples in the form of metal cladded substrates. This paper addresses the dielectric measurement of samples that are difficult to copper clad. [5]

The calculation of dielectric constant does not introduce any issues, however the method of determination of the loss tangent is somewhat questionable, as it requires the measurements of the conduction and radiation losses. While most literature deem these losses to be negligible, closed form formulae are available for the calculation of the conductive loss. The estimation of the radiation loss is a challenging task, since the design involves a multilayer stack and the dielectric properties of the dielectric layers (test sample) are unknown. As a result it is typically assumed to be negligible. This paper examines the effects of this assumption using accurate electromagnetic simulations.

The analysis presented in this paper is particularly attractive since it examines the effect of the radiation loss in addition to the conductive and dielectric losses. The loss tangent is then calculated from both the measurements and the simulations with and without considerations of the radiation loss, and the error percentage of the calculations against the actual value is used to determine the validity of the assumption.

The paper as such is organized as follows. In Section II, the relevant theory is described. The simulation setup is described in Section III and Section IV summarizes the Results.

II. MEASURMENT THEORY

A. Effective Dielectric constant and effective permittivity

The analysis of the problem is based on the classic work by Schneider [1]. The effective dielectric constant, $\tan(\delta_{eff})$, of a structure comprising two dielectric layers is given by [1]:

$$tan(\delta_{eff}) = \frac{1}{\varepsilon_{reff}} \sum_{i=1}^{2} p_i \tan(\delta_i) \quad (1)$$

where ε_{r1} and ε_{r2} are the relative permittivity of the PCB substrate and the test sample respectively (see Figure 1). The ε_{reff} in (1) is the effective relative dielectric permittivity defined as:

$$\varepsilon_{reff} = \left(\frac{\lambda_0}{\lambda_g}\right)^2 \quad (2)$$

where λ_0 is the free space wavelength and λ_g is the guide wavelength [1]. Moreover, p_i is defined as [1],

$$p_i = \varepsilon_{ri} \frac{\partial \varepsilon_{reff}}{\partial \varepsilon_{ri}}. \quad (3)$$

Transmission lines with multiple layers has been analysed using conformal mappings [2], Green's functions [3], and variational calculus [4]. In this work, we use the formulations in [2] where the effective relative permittivity for the $w/h_1 > 1$ case is given as:

$$\epsilon_{eff} = \varepsilon_{r1} q_1 + \varepsilon_{r2} \cdot \frac{(1-q_1)^2}{\varepsilon_{r2}(1-q_1-q_2)+q_2} \quad (4)$$

where q_1 and q_2 are filling factors which depend on the line width (w) and the substrate thickness (h_1). The expressions for q_1 and q_2 can be found in [2] and we omit them to keep the content short. At a resonant frequency, f_r, a ring structure satisfies the condition,

$$f_r = \frac{nC}{2\pi r\sqrt{\varepsilon_{reff}}} \quad (5)$$

where C is the speed of light and r is the mean radius of the ring. In (5), n is an integer and different values of n leads to multiple resonant points. As the resonant frequency, f_r can be measured, the permittivity of the test sample, ε_{r2}, can be calculated using equation (4).

However, the emphasis of this paper is the loss tangent of the test sample, $tan(\delta_2)$. An expression for $tan(\delta_{eff})$ can be obtained by evaluating the partial derivatives given by (3). Differentiation of ε_{reff} with respect to ϵ_{r1} and ε_{r2} gives [5]

$$p_1 = \epsilon_{r1} q_1 \quad (6)$$

and

$$p_2 = \epsilon_{r2} \frac{q_2(1-q_1)^2}{[\varepsilon_{r2}(1-q_1-q_2)+q_2]^2} \quad . \quad (7)$$

B. Loss tangents and quality factors

The loss tangent of the test sample, $tan(\delta_2)$ can be calculated from (1) if $tan(\delta_{eff})$ is known. This is because the values of p_1 and p_2 cab be calculated from (6) and (7). The effective loss tangent, $tan(\delta_{eff})$ can be obtained, if the unloaded Q-factor, Q_u, of the resonator is known. Q_u can be calculated by measuring the 3 dB bandwidth, B_{3dB} at the resonant frequency, f_r.

$$Q_u = \frac{f_r}{B_{3dB}} \frac{1}{1-|s_{21}(f_r)|} \quad . \quad (9)$$

Q_u includes loss components due to dielectric, conductor, and radiation losses. Thus, Q_u can be expressed in terms of unloaded quality factors due to these losses as in (10) [5], [7].

$$\frac{1}{Q_u} = \frac{1}{Q_c} + \frac{1}{Q_d} + \frac{1}{Q_r} \quad . \quad (10)$$

Since Q_u can be calculated from measurements, the unloaded quality factor due to dielectric loss, Q_d can be obtained if $Q_c$and Q_r are known. The unloaded quality factor due to dielectric loss, Q_d is related to $tan(\delta_{eff})$ by (11) [1].

$$tan(\delta_{eff}) = \frac{1}{Q_d}. \quad (11)$$

The loss tangent of the test sample, $tan(\delta_2)$ can be found by substituting (11) in (1). Note that p_1 and p_2 required for the calculation can be obtained from (6) and (7).

C. Unloaded quality factors due to radiation and conductor losses.

Calculation of radiation losses in the multi-layer structures is complicated and as a result often neglected [7], [9], [10]. The problem addressed in this paper is even more difficult as the properties of one of the layers (test sample) are unknown. However, the objective of this paper is assessing the impact of neglecting the radiation losses. This is done by modelling the problem accurately using a finite element method (FEM) based electromagnetic simulator and then obtaining the losses. As the problem is completely solved numerically, all field components are available for the calculation of losses or quality factors.

Fundamentally, the quality factor, Q is defined as [8],

$$Q = \omega . \frac{W_m + W_e}{P_l} \quad (12)$$

where W_m and W_e are the average stored energies due to magnetic and electric fields respectively. P_l is the energy loss per second. For instance, if we use the power loss due to radiation as P_l, we get P_r from (12). Similarly, using the conduction loss in (12), Q_c can be obtained. In Section IV we obtain radiation and conduction loss components using an FEM simulator.

III. SIMULATION SETUP

We model the problem using HFSS V10.1 by Ansoft Inc. In the model, a blank (without any copper cladding) FR4 board is used as the test sample because the dielectric properties of FR4 are well known. Using a known sample makes the verification process straight forward. The ring is fabricated on a Neltec NX9320 substrate. This substrate has a relative permittivity of 3.2 and a loss tangent of 0.0024. The important dimensions of the structure we simulated are shown in Figure2.

As we calculate radiation losses, the radiation boundaries were set to be at least $\lambda_g/4$ distant from the resonant structure. The radiation boundary was seeded to limit the maximum size of a meshed element to $\lambda_g/10$ to improve the accuracy.

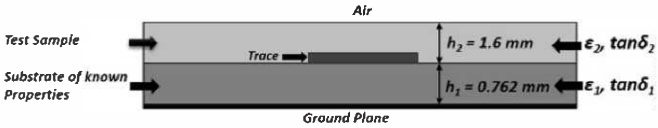

Figure 1: Multi-layer stackup.

IV. Results

Figure 3 is a plot of Simulated and measured S21, which demonstrates the accuracy of the simulation. The Dielectric Loss, Conductive Loss, Radiation Loss and the Stored Energy

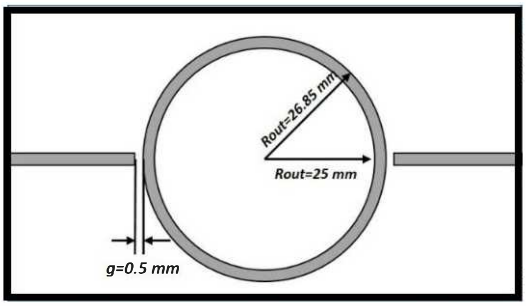

Figure 2: Geometry of the ring resonator.

were calculated and the results are as tabulated in Table I. All losses were calculated using the Field Calculator provided in HFSS. The radiated power was obtained by setting up a far field analysis setup in HFSS. The losses and stored energy in the table are for an input power of 1 W, which is a default in Ansoft HFSS.

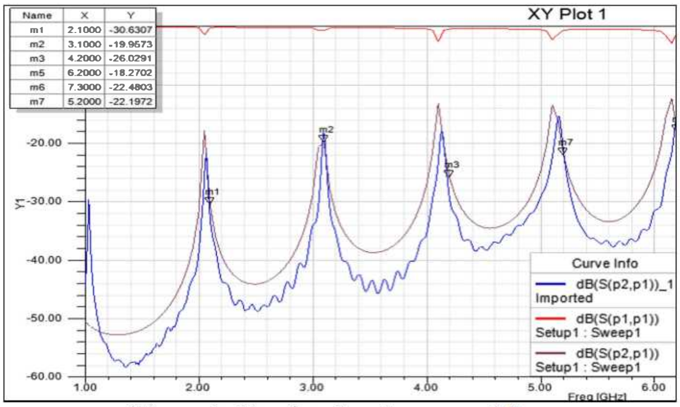

Figure 3: Simulated and measured S_{21}.

Table 2 shows the parameters calculated using simulation results. We calculated the unloaded Q using two methods, namely from an Eigen solution with HFSS and from the definition of Q_u in (12). The two values show close agreement to within 1.2%. Also, note that at resonance, the stored magnetic and electric energies should also be equal and the results in Table 1 demonstrates that there is a close match.

With the accuracy of simulations established, we now proceed to verify the significance of radiation loss. The results in Table 1 shows that the radiation, dielectric, and conductor losses amount to 3.9%, 81.6%, and 14.5% of the total loss respectively. This result clearly demonstrates that radiation losses must be accounted for accurate measurement of loss tangent. The loss tangent of the test sample are calculated with and without radiation losses and the results are given in Table 2. These results show that the loss tangent if the radiation losses are ignored (0.04) is 33.3% off from the correct value (0.03).

Discussion

The results we obtained with an accurate FEM analysis of the problem provides a good insight to the accuracies involved in the calculation of loss tangent. However, note that the actual values of ε_{r2} and $\tan(\delta_2)$ are 4.4 and 0.02 respectively and are different from the values calculated with radiation loss included (see Table 2). The accuracy limitations of the formulas developed in [2] has been reported in the literature [12] and we believe that this disparity is due to these limitations.

Resonant frequency	4.037 GHz
3 dB Bandwidth at resonance	20 MHz
S_{21} at resonance	-23.96 dB
Conduction loss	8.5 mW
Dielectric Loss	178.48 mW
Radiation Loss	31.76 mW
Stored magnetic energy	5.19×10^{-7} mW
Stored electrical engergy	4.87×10^{-7} mW

Table 1: HFSS Simulation results.

Q_u from an eign solution with HFSS	115.2
Q_u from stored energy and loss (12) .	116.6
Effective permittivity from (5)	3.33
Relative permittivity of the test sample	5.18
Loss tangent of the test sample with radiation accounted.	0.03
Loss tangent of the test sample with radaition ignoned.	0.04

Table 2: Calculated values based on the simulation.

Conclusions

In this study, we have clearly demonstrated that radiation losses are significant for the accurate calculation of the loss tangent. Dielectric characterization based on microstrip lines often neglect the radiation losses mainly due to the difficulties in measuring radiation losses. The fact that radiation losses cannot be neglected is stated in [13] based on theoretical calculations. We have complemented the same observation using accurate electromagnetic simulations.

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