Determination of Dielectric Constant and Dissipation Factor of a Printed Circuit Board Material Using a Microstrip Ring Resonator Structure

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***Abstract* - A microstrip ring resonator structure is used for determination of dielectric constant and dissipation factor of FR-4 type printed circuit board material. This article contains essential information of the microstrip ring resonator measurement method, characteristic of the microstrip line losses, dielectric constant and dissipation factor calculation techniques. Basing on presented information, dielectric properties of high loss printed circuit board materials can be determined at wide frequency band. Methods of this paper have been used in both FR-4 EPSILON-R Modeling and Halogen-free material projects.**

I. Introduction

A ring resonator structure is applied in many different microwave and radio frequency circuits. Troughton [1] presented the first ring resonator application for determination of phase velocity and dispersive characteristics of a microstrip line in 1969. Since then, ring resonator structures have been used to determine effective permittivity, dielectric constant, dissipation factor and losses in function of the frequency.

Dielectric constant and dissipation factor of printed circuit board can be measured accurately at wide frequency range with a single microstrip ring resonator structure. Benefits of the ring resonator structure at the dielectric properties measurement are:

1) The ring resonator structures can be manufactured in normal industrial etching process.
2) Minor radiation losses from the resonator structure. There is no need for calculation or measurement of the radiation losses.
3) Accurate resonance frequency and harmonics over a wide frequency band.

Dielectric constant and dissipation factor can be determined with the two-port ring resonator structure, which includes feed lines, a closed transmission line loop and coupling gaps. Resonance frequencies of a two-port microstrip ring resonator can be calculated with the equation:

$$2\pi r = n\lambda_g\ , \qquad (1)$$

where r is the mean radius of the ring, n is the number of harmonic and λ_g is the guided wavelength. (For more information, refer [1], [2].) A microstrip ring resonator structure implemented to FR-4 type printed circuit board material is presented in Fig. 1.

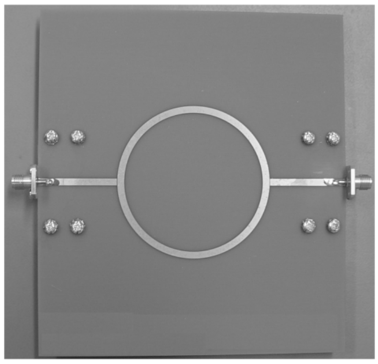

Fig. 1. The microstrip resonator structure implemented to FR-4 type printed circuit board material.

II. Use of The Microstrip Ring Resonator Structure on Dielectric Properties Measurement

Usually in dielectric properties measurements frequency response of the two-port ring resonator structure is measured with a network analyzer. The unwanted effects of connector interfaces of the ring resonator structure have to be eliminated for example by a thru-reflect-line (TRL) calibration. Basing on the measured frequency response and equation (1), values of effective permittivity can be calculated in function of frequency. The dielectric constant can be calculated basing on the frequency dependent value of the effective permittivity. Losses of material can also be calculated basing on the measured frequency response of the ring resonator. In order to get reliable measurement results, the effects of coupling gaps have to be known or eliminated. In addition, the mean radius of the ring and characteristic impedance of the ring resonator, have to be chosen to be suitable to eliminate curvature effect and higher order modes [3].

A. Effects of The Coupling Gaps

(1)

The effects of the coupling gaps are not taken into account in the equation (1). The coupling gaps have an influence to the resonance frequencies of the ring resonator structure. Normally coupling between the feed lines and the ring resonator are implemented as a loose coupling. The loose coupling produces negligible effects to the resonance frequencies [2, page 63]. Suitable length for the coupling gaps has to be chosen by using prototypes or modern electromagnetic simulation tools. The effects of the coupling gaps are minor to the determined values of dielectric constant and dissipation factor, if the coupling is implemented as loose one.

III. Calculation Values of Dielectric Constant and Dissipation Factor

The basic idea behind the determination of the dielectric constant is design the microstrip ring resonator to the certain main resonance frequency. The design is based on the estimated value of the dielectric constant. The main resonance frequency and harmonic resonance frequencies will be deviated depending amount of the difference between the estimated and the actual value of the dielectric constant of the material.

An accurate way to calculate values of the dielectric constant at each resonance frequency can be carried out with an iteration method. The recommend iteration method is based on the Kirschning's and Jansen's [4] accurate model for effective dielectric constant of microstrip. The closed-form empirical relation for effective permittivity as follows [4]:

$$\varepsilon_{\mathrm{eff}}(f) = \varepsilon_{\mathrm{r}} - \frac{\varepsilon_{\mathrm{r}} - \varepsilon_{\mathrm{e}}}{1 + P(f)} \qquad (2)$$

$$P(f) = P_1 P_2 \left[(0.1844 + P_3 P_4) \cdot 10 fh\right]^{1.5763} \qquad (3)$$

$$P_1 = 0.27488 + \left[0.6315 + \frac{0.525}{(1 + 0.157 fh)^{20}}\right] \cdot \frac{w}{h} - 0.065683 e^{-8.7513 w/h} \qquad (4)$$

$$P_2 = 0.33622 \cdot \left[1 - e^{-0.03442 \varepsilon_{\mathrm{r}}}\right] \qquad (5)$$

$$P_3 = (0.0363 e^{-4.6 w/h}) \cdot \left[1 - e^{-(fh/4.87)^{4.97}}\right] \qquad (6)$$

$$P_4 = 1 + 2.751 \cdot \left[1 - e^{-(\varepsilon_{\mathrm{r}}/15.916)^{8}}\right] \qquad (7)$$

where w width of the conductor strip
h thickness of the laminate material
ε_{r} dielectric constant
$\varepsilon_{\mathrm{eff}}$ effective permittivity
ε_{e} static value of effective permittivity.

The iteration is carried out with equations (2) – (7). The measured resonance frequencies, the estimated value of dielectric constant, dimensions of the microstrip line and calculated values of the frequency dependent effective permittivity are initial data for the iteration.

A. Calculation of The Dissipation Factor

Determination of dissipation factor in function of frequency, is based on measuring a loaded quality factor Q_{L} of the microstrip ring resonator structure at each resonance frequency. The loaded quality factor includes losses, which are due to external load and the microstrip ring resonator itself. In these measurements, source of the external load are the feed lines, connector interfaces and measurement cables. The loaded quality factor Q_{L} can be obtained from –3dB bandwidth of a resonance peak [2]:

$$Q_L = \frac{f_0}{BW_{-3db}}, \qquad (8)$$

where f_0 is resonance frequency and $BW_{-3\mathrm{dB}}$ is the -3dB bandwith. The unloaded quality factor Q_0, which includes the total losses of the microstrip ring resonator can be calculated from the measured value of the loaded quality factor [2]:

$$Q_0 = \frac{Q_{\mathrm{L}}}{(1 - 10^{-L/20})}. \qquad (9)$$

For the calculation of the unloaded quality factor is value of the insertion loss L [dB] needed at each resonance frequency. The total quality factor of the microstrip line includes quality factors of the conductor losses, the dielectric losses and the radiation losses [5]:

$$\frac{1}{Q_0} = \frac{1}{Q_C} + \frac{1}{Q_D} + \frac{1}{Q_R}. \qquad (10)$$

(12) The radiation losses of the microstrip ring resonator structure are negligible, because there are no open ends in the microstrip ring resonator structure [6]. The total losses of the microstrip ring resonator structure are due to the dielectric losses and the conductor losses. Thus, the attenuation constant of the microstrip line ring resonator can be calculated as follow:

$$\alpha = \alpha_{\mathrm{c}} + \alpha_{\mathrm{d}}, \qquad (11)$$

where α_{c} is attenuation constant of conductor and α_{d} attenuation constant of dielectric. The quality factors of the conductor and the dielectric losses can be calculated basing on attenuation constants.

$$Q_c = \frac{8.686\pi}{\alpha_{\mathrm{c}} \lambda_{\mathrm{g}}} \qquad (12)$$

$$Q_d = \frac{8.686\pi}{\alpha_d \lambda_g} \qquad (13)$$

where λ_g guided wavelength.

The attenuation constant of the dielectric can be calculated basing on subtract of the total losses of the microstrip line ring resonator structure and the conductor losses.

$$\alpha_d = \alpha - \alpha_c = \frac{8.686\pi}{Q_0 \cdot \lambda_g} - \alpha_c \qquad (14)$$

The attenuation constant of the conductor can be obtained by calculating, simulating or measuring. Accurate numerical experimental equations for conductor losses have been presented by Pucel et al.[7] and Schneider [8]. The surface roughness of conductors increases the conductor losses. Use of the Morgan [9] experimental expression with conjunction of the equation of Pucel et al. and Schneider to take account the effects of surface roughness, has been recommend by Hammerstad [10]. Conductor losses calculated using either of the equations in conjunction with Morgan expression are almost similar.

The conductor losses of the microstrip ring resonator structure have been calculated in FR4 EPSILON-R Modeling project and in Halogen-free material project with equations of Schneider [8] and Morgan [9]. More information about differences of the conductor loss calculation methods is presented on this report on the paragraphs of the experimental research. Following equations are used for calculation of the conductor losses:

$$\alpha_c h[\mathrm{dB}] = \begin{cases} \dfrac{10}{\pi \ln(10)} \dfrac{R_S}{Z} \dfrac{32-(w/h)^2}{32+(w/h)^2}\left[1+\dfrac{h}{w}\left(1+\dfrac{\partial w}{\partial t}\right)\right], \dfrac{w}{h} \le 1 \\ \dfrac{20}{\ln(10)} \dfrac{\varepsilon_e Z R_S}{\eta_0^2}\left\{\dfrac{w}{h}+\dfrac{6h}{w}\left[\left(1-\dfrac{h}{w}\right)^5+0.08\right]\right\} \cdot \\ \left\{1+\dfrac{h}{w}\left(1+\dfrac{\partial w}{\partial t}\right)\right\}, \dfrac{w}{h} \ge 1 \end{cases}, \qquad (15)$$

when

$$\frac{\partial w}{\partial t} = \frac{1}{\pi}\ln\left(\frac{2x}{t}\right)$$

$$x = \begin{cases} h, \dfrac{w}{h} \ge 2\pi \\ 2\pi w, \dfrac{w}{h} \le 2\pi \end{cases}$$

α_c conductor losses of microstrip line [dB]
ε_e effective permittivity
η_0 Free space wave impedance
h thickness of the laminate material
R_S surface resistivity of the conductor strip
t thickness of the conductor strip
Z characteristics impedance of microstrip with ε_r=1
w width of the conductor strip.

Effects of the surface roughness of the conductor strips were taken into account with Morgan's equation [9], which is presented in more straight form in [10]:

$$\alpha_{c,tot} = \alpha_c\left[1+\frac{2}{\pi}\arctan\left(1.4\left(\frac{\Delta}{\delta}\right)^2\right)\right], \qquad (16)$$

where Δ RMS value of the surface roughness
δ skin depth of electromagnetic wave.

Dissipation factor tanδ of the material can be calculated from the definition of the dielectric losses. Schneider [11] has been presented experimental definition for the dielectric losses:

$$\alpha_d = 27.3 \cdot \frac{\varepsilon_e - 1}{\varepsilon_r - 1} \cdot \frac{\varepsilon_r}{\varepsilon_e} \cdot \frac{\tan\delta}{\lambda} \text{ [dB/lenght unit]} \qquad (17)$$

where λ wavelength
δ skin depth of electromagnetic wave
ε_r dielectric constant
ε_e static value of effective permittivity.

IV. EXPERIMENTAL RESEARCH

Experimental research of dielectric properties of FR-4 type material was realized with the microstrip ring resonator structures. In addition, the effects of the calculation equations of the conductor losses to results of the measurement method were investigated. A measured frequency response of single microstrip ring resonator structure implemented on FR-4 type material is presented in fig 2.

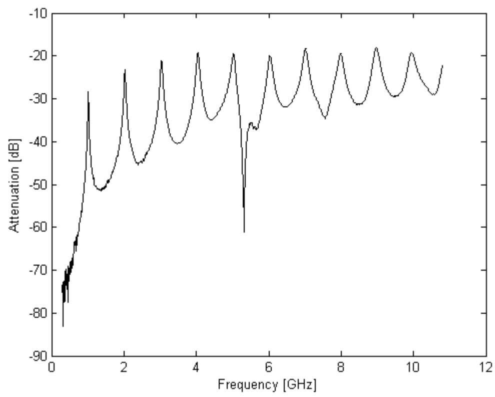

Fig. 2. The frequency response of single microstrip ring resonator structure implemented on FR-4 type material (RC 45%).

Values of dielectric constant and dissipation factor were calculated basing on the measured frequency response. Iterated values of dielectric constant in function of frequency at 23ºC temperature are presented in fig. 3. The values of dielectric constant have been iterated only at resonance points.

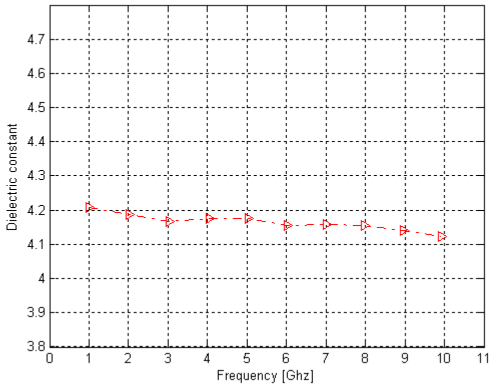

Fig. 3. Values of dielectric constant iterated at each resonance frequency. (FR-4 type material, RC 45%)

Values of dissipation factor in function of frequency at 23ºC temperature are presented in fig. 4.

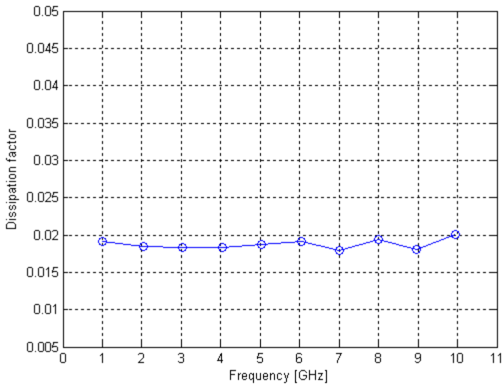

Fig. 4. Values of dissipation factor calculated at each resonance frequency. (FR-4 type material, RC 45%)

The conductor losses of the microstrip ring resonator structure were calculated with equations of Pucel et al. [7] and equations of Schneider [8]. The expression of Morgan [9] was used to take effects of surface roughness of the conductor into account. The calculated conductor losses were compared to results gained by ADS/Linecalc program. All those methods are based on Wheeler's incremental inductance rule. Dimensions of the used microstrip line conductor are presented in table I.

TABLE I. DIMENSIONS OF THE MICROSTRIP LINE CONDUCTOR

width of the conductor strip	2237 um
thickness of the laminate	1258 um
thickness of the conductor strip	69 um
RMS surface roughness of conductor	0.6 um

Differences between the results of the different conductor losses calculation methods are presented in fig. 5. Effects of the different conductor losses calculation methods to the determined values of dissipation factor are presented in fig. 6.

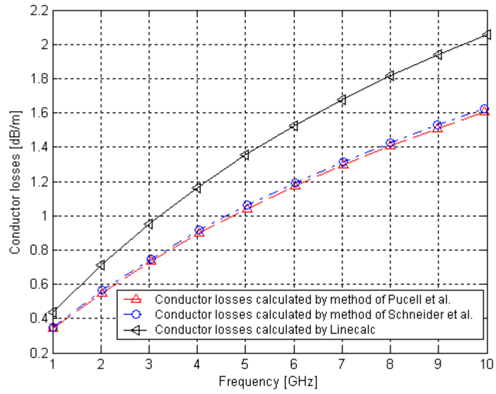

Fig. 5. Values of conductor losses calculated by different conductor losses calculation methods.

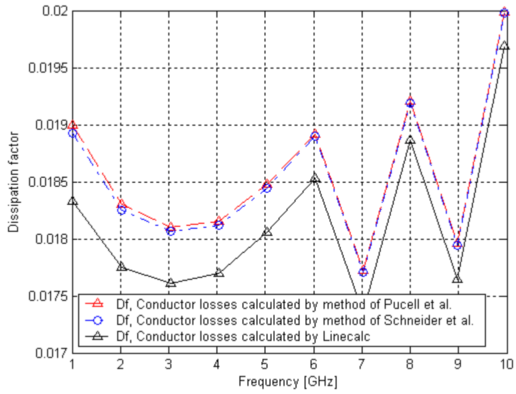

Fig. 6. Effects of the different calculation methods to the values of dissipation factor. (FR-4 type material, RC 45%)

The difference between values of the conductor losses calculated by the different equations have only minor effects to calculated values of dissipation factor. Reasons for minor effects of the conductor losses are high dielectric losses of FR-4 type material compared to the conductor losses. With low loss microwave material, conductor losses may be dominating losses and determination of conductor losses has to be done as accurate as possible.

V. CONCLUSIONS

The microstrip ring resonator structure can be used to accurate determination of dielectric constant and dissipation factor of printed circuit board materials at wide frequency band. The experimental research with FR-4 type material has shown the method to be suitable for high loss dielectric materials. Important notes are:

1) The iteration method based on Kirschning's and Jansen's accurate model for effective dielectric constant of microstrip is an accurate method to

determinate dielectric constant of printed circuit board material.

2) The difference between the conductor losses calculation methods of Pucell and Schneider has minor effects to the determination of dissipation factor of a high loss printed circuit board material.

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