Microstrip Dielectric Substrate Material Characterization with Temperature Effect

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Abstract **─** This paper describes a dielectric substrate materials electromagnetic (EM) characterization method in the ultra-wideband (UWB) frequencies from DC to 5 GHz by taking into account the temperature influence. The proposed method theoretical principle is described and fundamentally built with the analytical formulation from the microstrip transmission line (TL) theory. From this basic concept, the analytical equations enabling to determine the dielectric material relative permittivity and loss tangent from the given S-parameters are established. The characterization method is validated with numerical and experimental tests. As proof of concept, a prototype of microstrip TL printed on FR4 epoxy substrate was designed, fabricated and experimented. The relative permittivity and loss tangent were extracted in the UWB frequency from DC to 5 GHz in the range of temperature varied from 40°C to 140°C. This innovative characterization method is useful for the investigation on the frequency dependent and especially by taking into account the temperature influence on the substrate materials; for example, during the microstrip circuits design phase.

Index Terms **─** Measurement method, microstrip line, relative permittivity, substrate material, temperature effect.

I. INTRODUCTION

With the tremendous trend on the electronic circuit design shirking size, the electromagnetic compatibility/ interference (EMC/EMI), the signal integrity and the temperature influence become critical effects [1-5] which must be integrated to the design and fabrication phases. These undesirable physical phenomena are more and more crucial for the deep submicron VLSI [1-2]. It was found that the thermal effects can induce particular phenomenon as the electromigration in the integrated circuits [3-4]. Moreover, the clock signal performances can be degraded due to the thermal influence on the substrate [5]. More recently, electronic research and design engineers were experimented that the temperature effect and the moisture are susceptible to degrade the printed circuit boards (PCBs) global performance [6]. Due to the constant increase of integration density, the substrate material characterization with the frequency and temperature dependence becomes a challenging subject for the microwave and integrated circuit designers and manufacturers [2,7]. Until now, very few investigations on the temperature influence to the electronic devices performance as the integrated [8] and hybrid [9] circuits are available in the literature. Despite the developed electromagnetic (EM) classical modeling, simulation and test techniques [10-11], the simultaneous influence of electrical, EM and temperature effects on the microwave circuits and devices remains an open question for the electronic research and design engineers. Furthermore, most of the existing classical EM characterization techniques dedicated to the dielectric materials are based on the consideration of S-parameters by using waveguide structures. Some of the available techniques are essentially carried out with the through, reflect, line calibration [11], coplanar lines [12-14], and split ring resonators [15]. However, those techniques present a heavy process complexity and they do not include the temperature effect and require sophistical analytical approaches. The existing measurement technique of complex permittivity which takes into account the temperature variation as proposed in [16] was set with different shapes of resonant cavity. Nevertheless, such a characterization technique is particularly limited in terms of the operating frequency. Furthermore, it cannot be used for predicting the material characteristics in the baseband and microwave frequencies, which can be regularly required for the digital and microwave or mixed signal integrity analysis [17].

To overcome such technical limits, a relevant characterization method enabling to predict the substrate

Submitted On: February 26, 2015
Accepted On: July 28, 2015

material parameters in the ultra-wideband (UWB) frequency (with baseband frequency up to some GHz) with the use of microstrip technology can be envisaged. In addition to the flexibility of microstrip line theoretical approach, it enables a particularly simple experimental process as can be found in [17].

This paper addresses the EM characterization technique of dielectric substrate material with the temperature influence based on the miscrostrip line theory. For the better understanding, the paper is principally organized in three main sections. Section 2 is focused on the methodological approach of the substrate material characterization method under study. The fundamental formulas enabling to determine the permittivity will be proposed. The experimental application of the analytical approach constitutes Section 3. A microstrip test structure printed on FR4 epoxy will be investigated. The conclusion of the paper is drawn in the last section.

II. METHODOLOGY OF THE PROPOSED DIELECTRIC MATERIAL CHARACTERIZATION

The theoretical approach of this substrate material characterization method is elaborated in the present section. The method is essentially built with the consideration of microstrip structure. After brief introduction of the structure geometrical definitions and its S-parameters, the formulas allowing the extraction of the parameters to be determined will be proposed.

A. Description of the structure for the proposed substrate material EM characterization

The most accurate experimental way to perform a substrate material EM characterization in the base band and broadband microwave frequency dependence is based on the S-parameters measurement consideration. Thanks to the design simplicity and the flexibility of the analytical approach, the transmission line (TL) and resonator structures are the most popular technology to realize this characterization technique. In fact, by considering the exploitation of S-parameters analytical definition in function of the geometrical parameters, the substrate EM parameters as the permittivity formulation can be extracted. Along the paper, the TL implemented in microsrip structure will be investigated to establish the theoretical approach.

The configuration of the structure using the dielectric substrate characteristic measurement method under study is shown in Fig. 1. It acts as a microstrip TL with physical length *d*, metallization width *w* and thickness *t* which is printed on dielectric substrate with height *h*. The substrate complex permittivity versus frequency *f* and temperature *T* will be extracted from the TL measured two-port S-parameters.

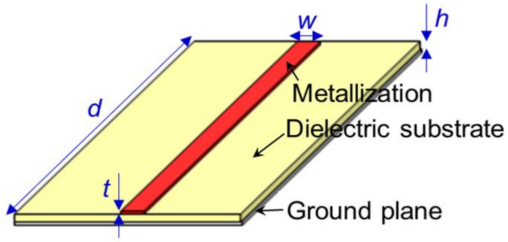


Fig. 1. Microstrip line structure and its physical parameters.

Along the paper, the reference impedance is denoted Z_0=50 Ω. The two-port system S-to-Z transform applied to the microstrip structure proposed in Fig. 1 allows to determine the access and transfer impedances. From where, the input and transmitted impedance versus the frequency *f* with respect to the S-parameters measurement versus the environment temperature *T* are defined as:

$$Z_{11}(jf,T)=\frac{\begin{array}{c}Z_0\cdot(1+S_{11}(jf,T)-S_{22}(jf,T)\\ -S_{11}(jf,T)\cdot S_{22}(jf,T)\\ +S_{12}(jf,T)\cdot S_{21}(jf,T))\end{array}}{\begin{array}{c}1-S_{11}(jf,T)-S_{22}(jf,T)\\ +S_{11}(jf,T)\cdot S_{22}(jf,T)\\ -S_{12}(jf,T)\cdot S_{21}(jf,T)\end{array}}, \quad (1)$$

$$Z_{21}(jf,T)=\frac{Z_0\cdot 2S_{21}(jf,T)}{\begin{array}{c}1+S_{11}(jf,T)+S_{22}(jf,T)\\ -S_{11}(jf,T)\cdot S_{22}(jf,T)\\ +S_{12}(jf,T)\cdot S_{21}(jf,T)\end{array}}, \quad (2)$$

with *j* is the complex number. In the one hand, these expressions permit to determine the TL matrix impedances from the measured S-parameters by using a VNA. In the other hand, by assuming that the TL is Z_0-loaded and non-dispersive, the same input and transfer impedances can be determined knowing the characteristic impedance Z_c and the propagation constant γ via the following expressions:

$$Z_{11}=Z_c\frac{\cosh(\gamma\cdot d)}{\sinh(\gamma\cdot d)}, \quad (3)$$

$$Z_{21}=\frac{Z_c}{\sinh(\gamma\cdot d)}. \quad (4)$$

The equality of these analytical formulations combined with the microstrip line properties constitutes the building block of the determination method of the substrate material parameters under study described in the next paragraphs.

B. Analytical equations of the dielectric substrate parameter extraction with frequency dependence including the temperature influence

First and foremost, the dielectric characteristics are established from the microstrip line analysis combined with the Bahl and Trivedi theory [17]. By definition, the TL propagation constant is defined in function of the per-unit loss α and the phase constant β via the basic expression $\gamma(jf,T)=\alpha(f,T)+j\beta(f,T)$. From the member to member division of Equations (3) and (4), the following expression of the propagation constant can be obtained:

$$\gamma(jf,T)=\frac{1}{d}\operatorname{arg}\cosh\left[\frac{Z_{11}(jf,T)}{Z_{21}(jf,T)}\right]. \tag{5}$$

Then, the effective relative permittivity $\varepsilon_{r_{eff}}(f,T)$ of the dielectric material constituting the microstrip TL can be established from the phase constant thanks to the relation:

$$\varepsilon_{r_{eff}}(f,T)=\left[\frac{c\cdot\partial\beta(f,T)}{2\pi\partial f}\right]^{2}, \tag{6}$$

with c is the light speed in the vacuum. From where, the substrate relative permittivity can be extracted with the expression [17]:

$$\varepsilon_r(f,T)\approx\frac{2\varepsilon_{r_{eff}}(f,T)-1+a(w/h)}{1+a(w/h)}, \tag{7}$$

where the mathematical function $a(.)$ is defined by:

$$a(x)=\begin{cases}\dfrac{1}{\sqrt{1+12/x}}+0.04(1-x)^{2} & for\ x<1\\[2ex] \dfrac{1}{\sqrt{1+12/x}} & for\ x\geq 1\end{cases}. \tag{8}$$

Finally, the loss tangent can be extracted from the equation:

$$\tan\left[\delta(f,T)\right]\approx\frac{c\cdot\alpha(f,T)}{\pi\cdot f\sqrt{\varepsilon_{r_{eff}}(f,T)}}. \tag{9}$$

During the numerical modelling, those analytical relations were implemented as Matlab program. The computed results will be discussed in the next section.

III. EXPERIMENTAL INVESTIGATION

After introduction of the experimental setup, the measurement results exploitation will be presented in this section based on the previous analytical approach.

A. Circuit under test design and experimental setup

The microstrip TL assumed as the circuit under test is photographed in Fig. 2. It can be seen that this TL presents physical parameters w=1.5 mm and d=164 mm. The circuit is printed on FR4 epoxy substrate with height h=0.8 mm and copper etched with thickness t=35 µm. The S-parameters of the circuit under test were measured with the Agilent VNA 8502C from DC to 5 GHz. Moreover, after calibration, it was placed in the furnace provided by THITEC® depicted in Fig. 3. The furnace presents the physical size 50cm×47cm×50cm or volume 117 liters. The furnace operates with a digital function allowing to program the temperature of its internal chamber. For the present study, the temperature chamber was increased from ambient T=40°C to 140°C. In order to consider the temperature influence on the circuit under test, the sampling of the measured $S(jf,T)$-parameters was recorded at least after five minutes of the temperature change.

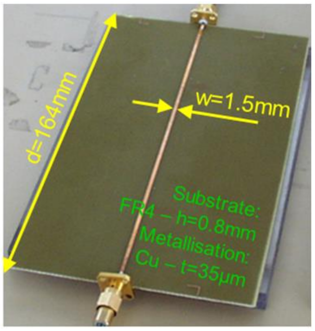


Fig. 2. Photograph of the circuit under test.

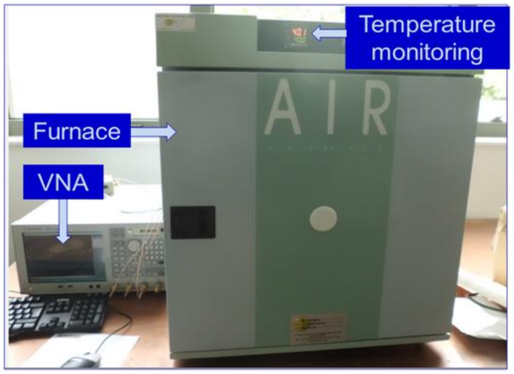


Fig. 3. Photograph of the experimental test bench including the VNA and the furnace.

To check the relevance of the proposed method, preliminary numerical tests with EM computation based on the method of moment (MoM) were performed.

B. Numerical tests with method of moment simulation

To perform the numerical tests, the inputs parameters are the physical dimensions of the tested line, the operating frequency band and the given S-parameters. Two microstrip TLs supposed with different physical lengths d_1=82 mm and d_2=164 mm printed on the dielectric substrate with relative permittivity ε_r=4.5, loss tangent tan(δ)=0.018 and h=0.8 mm etched with Cu-conductor were designed and simulated in the ADS/Momentum environment. The comparisons between the super UWB substrate characteristics extracted from the simulated S-parameters are displayed in Fig. 4.

A good correlation between the extracted dielectric characteristics is observed. However, a relative variation lower than 8% is occurred compared to the ideal parameters, mainly due to the MoM numerical inaccuracy. This preliminary result confirms the feasibility of the characterization method under study independently to the TL physical length and to operate notably in the UWB frequency.

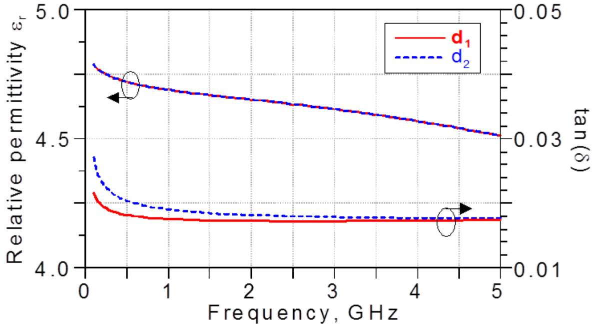


Fig. 4. Comparisons between relative permittivity and loss tangent versus frequency from MoM simulations.

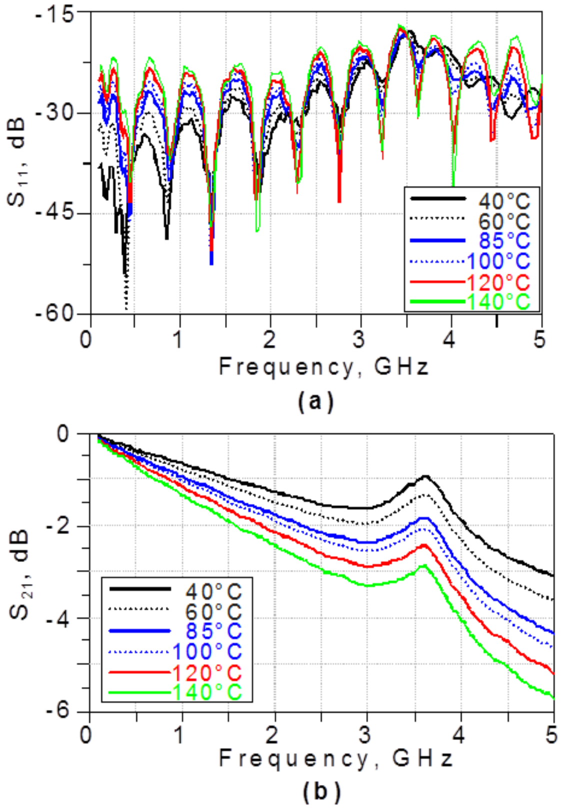
Based on the full wave approach, it can be pointed out that the present method generates numerical relative errors lower than 10%. Furthermore, comparisons between the performances of the coplanar-, cavity- and microstrip-structure based methods are addressed in Table 1.

Table 1: Comparison between the coplanar, cavity and microstrip structure based dielectric characterization methods

Methods	Coplanar	Cavity	Microstrip
Bandwidth	Not adapted to lower frequencies	Limited by resonant effect	Limited To tens GHz
Complexity	Low	High	Low
Temperature	Adapted	Difficult	Adapted

C. Extraction of dielectric material in the UWB frequency with temperature-dependent

Based on the experimental setup shown in Fig. 3, the DUT S-parameters were measured from DC to 5 GHz by increasing the temperature step by step. For the sake of simplicity and temperature influence illustration, only the measured $S_{11}(f,T)$ reflection and $S_{21}(f,T)$ transmission parameters at T={40°C, 60°C, 85°C, 100°C, 120°C, 140°C} are presented respectively in Fig. 5 (a) and in Fig. 5 (b). It is noteworthy that during the test, there is no significant difference between $S_{11}(f,T)$ and $S_{21}(f,T)$, for T varied from the ambient temperature of about 20°C to 40°C and the TL losses increase with the temperature. Then, the UWB characteristics of the FR4 constituting the DUT substrate from DC to 5 GHz can be determined from expressions (7) and (9).



(a)

(b)

Fig. 5. Measured S-parameters of the DUT of Fig. 2 for T={40°C, 60°C, 85°C, 100°C, 120°C, 140°C}.

Consequently, the measured dielectric constant $\varepsilon_r(f,T)$ is plotted in Fig. 6 (a). It can be emphasized that the obtained relative permittivity $\varepsilon_r(f,T)$ is proportionally inverse of the temperature T. Moreover, $\varepsilon_r(f,T)$ presents an absolute variation of about 0.27 when increasing the temperature from 40°C to 140°C. Furthermore, Fig. 6 (b) depicts the loss tangent in the same temperature range. The loss tangent $\tan[\delta(f,T)]$ increases with T from about 0.025 with margin of about 0.02. The loss tangent is sensitivity to the TL resonance frequencies. This temperature effect can be reduced by choosing material with less thermal coefficient of expansion and low losses. The envelop of loss tangent can be estimated by using other methods like strip line ring resonator using proper calibration method and by reducing the systematic error and instrumental error through repeated characterization. Compared to the existing characterization techniques introduced in [10-11], the proposed method is simpler and allows to operate in UWB frequency from DC to several GHz. In addition, it enables the microwave structure modelling versus temperature.

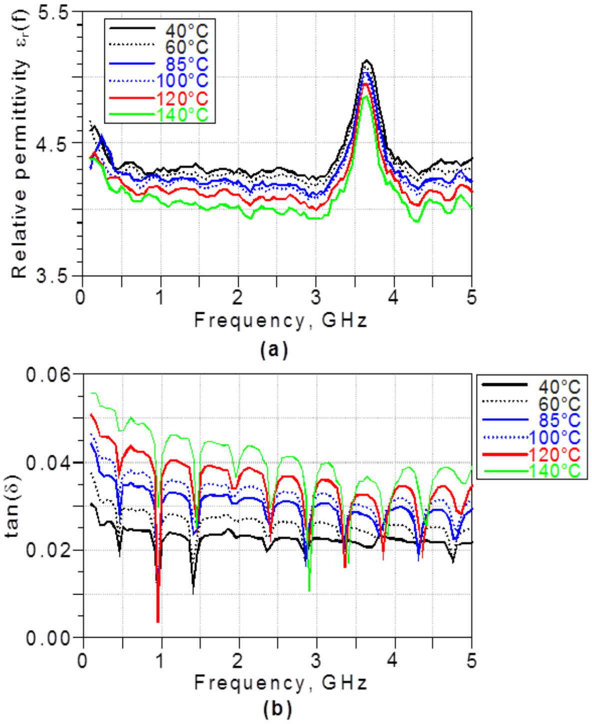


Fig. 6. (a) Measured FR4 substrate dielectric constant, and (b) loss tangent vs frequency and temperature.

D. Discussion the potential application with the extraction of the frequency dependent RLCG-model with the temperature consideration

Several applications of the proposed EM characterization method can be envisaged for the PCB design engineering as the signal and power integrity analyses. It can be emphasized that the developped method is beneficial thanks to the proposed EM characteristic with the temperarature influence. To do this, the performant TL behavioural model as the RLC-network modelling can be utilized. It can be recalled that given the characterisitc impedance $Z_c(jf,T)$ and the propagation constant $\gamma(jf,T)$, the TL RLC-model can be extracted. As suggested in [7], the per unit-length parameters R_u, L_u, C_u and G_u can be calculated with the following expressions:

$$R_u(f,T)=\frac{\Re\{\gamma(jf,T).Z_c(jf,T)\}}{d}, \tag{10}$$

$$L_u(f,T)=\frac{\Im\{\gamma(jf,T)\cdot Z_c(jf,T)\}}{2\pi f\cdot d}, \tag{11}$$

$$C_u(f,T)=\frac{\Im\left\{\dfrac{\gamma(jf,T)}{Z_c(jf,T)}\right\}}{2\pi f\cdot d}, \tag{12}$$

with $\Re[z]$ and $\Im[z]$ are respectively the real and imaginary parts of the complex number z. The TL RLC-model can be extracted based on the model presented in [17]. The feasibility of this future application can be understood with the variation of the TL per unit length RLC-parameters $R_u(T)$, $L_u(T)$ and $C_u(T)$ at 1 GHz addressed in Table 2.

Table 2: Per unit length RLC-parameters $R_u(T)$, $L_u(T)$ and $C_u(T)$

T	R_u (Ω/m)	L_u (nH/m)	C_u (pF/m)
40°	1.29	344	138
60°	1.62	353	138
85°	1.93	360	137
100°	2.12	369	135
120°	2.33	370	133
140°	3.54	370	127

The thermo-electromagnetic characterization method under study presents potential applications for:

- The EMC engineering in particular with the EM shielding effectiveness prediction [18-20] by overcoming the limitation in terms of the frequency band in addition to the temperature effects.
- The RF engineering with the use of unknown complex structure material absorption in the broadband frequency band [21].
- And facing to the open questions on the integration of the composite materials in the different areas, the present characterization method offers a possibility of the effective parameter modelling of the innovative materials as the complex composites [22].

IV. CONCLUSION

A simple and efficient characterization method of dielectric substrate constant and loss tangent is developed. The method is particular innovative with its possibility to operate in super UWB frequency with temperature influence. The proposed method is based on the use of microstrip TL properties. The analytical concept illustrating the methodology principle is presented. To illustrate the proposed method functionality, a proof of concept was designed, fabricated, simulated and experimented. The relevance of the method was verified with MoM numerical tests. Then, an application with a prototype of microstrip TL printed on FR4 epoxy substrate is presented. The dielectric constant $\varepsilon_r(f,T)$ and loss tangent tan[$\delta(f,T)$] from DC to 5 GHz was extracted by considering the temperature variation from 40°C to 140°C. Moreover, since the linear thermal coefficient of copper is 18.10^{-6}m/mK, the temperature from 40°C to 140°C, i.e., by 100°C will increase the length of microstrip line from 164 mm to 164.3 mm, i.e., by 0.18%.

The present method is limited to the prediction of the PCB substrate global characteristic. The main drawback is for the characterization of typically micrometric size materials. In addition, the method is particularly sensitive to the measurement artefacts.

The exploitation of the proposed method for the microwave PCBs reliability prediction, the EM compatibility investigation and signal integrity analysis with respect to the temperature influence is in progress.

ACKNOWLEDGMENT

Acknowledgement is made to the Upper Normandy Region for the PULSAT project support of this research work through the FEDER fund.

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