RF Characterisation of No-clean Solder Flux Residues

Maeve Duffy+, Liam Floyd, Paul McCloskey+, Cian Ó Mathúna, NMRC, Ireland
Karen Tellefsen, Mike Liberatore, A. Sreeram, Alpha Metals, Central Research Laboratory, USA

+PEI Technologies,
National Microelectronic Research Centre,
Lee Maltings, Prospect Row,
Cork, IRELAND
Tel : +353 21 4904241•Fax : +353 21 4270271•email : mduffy@nmrc.ie

Abstract

The effects of solder flux residues on the electrical functionality of RF circuit boards are investigated in this paper. The electrical characteristics of the residues are tested in terms of the change in response of microstrip resonator structures caused by their presence. In this way, the corresponding change in effective dielectric constant of microstrip boards is measured, and can be used to predict residue effects on RF circuit performance. Residues deposited from five no-clean solder pastes are tested and compared, using microstrip resonator structures designed for operation over the frequency range from 0.5 – 10 GHz.

Keywords : no-clean solder, flux residue, RF characterisation, dielectric characterisation

I. Introduction :

The need for no-clean solder pastes emerged in response to legislation against the use of ozone depleting chemicals, and the desire to remove costly flux cleaning operations in the manufacture of PCB's. In terms of the performance of these pastes, a Surface Insulation Resistance (SIR) test is available for measuring the reliability of boards with flux residue remaining after soldering [1], [2]. Additional impedance spectroscopy methods have also been used to supplement SIR measurements [1], [3]. However, little information exists about the effects of flux residues on electrical circuit functionality. With requirements for increased circuit speeds and higher operating frequencies, there is particular concern about the magnitude of such effects on radio frequency (RF) circuits. To this end, the effects of flux residues are measured in terms of their effective dielectric properties on microstrip structures in this work. In this way, the change in microstrip circuit performance caused by the presence of flux residues may be deduced.

The effects of flux residues on RF circuit performance has been investigated previously by measuring the change in response of coupled microstrip lines due to the presence of a localised amount of flux residue between them. Results were given in terms of components of stray capacitance between the lines [4]. In this work, microstrip resonator structures are used to measure the change in effective dielectric constant of the substrate due to the presence of flux residue. Since effective dielectric constant is a characteristic value of microstrip circuits, resulting values may be applied to predict the effects of flux residues on the RF performance of other circuit elements.

The other main method used for characterising the electrical performance of RF circuit boards is time domain reflectometry (TDR) [5], [6]. However, the use of TDR for characterising material effects depends on the accuracy of the circuit model used to describe them. By measuring the frequency response of resonator structures in this work, basic microstrip properties are deduced that can be used in impedance models. The response of structures due to different waveforms defined in the time domain can then be predicted by transformation between frequency and time domains [7].

A brief overview of the application of microstrip resonators for measuring effective dielectric constant of microstrip structures is given in section II. Test structures for comparing the performance of no-clean solders over the frequency range from 0.5 – 10 GHz are designed in section III. Initially, the sensitivity of the structures to the presence of different quantities of flux residues was tested on boards printed with a conformal layer of solder flux. Fluxes from five solder pastes were tested in this manner, and results are presented in section IV. After verification of the procedure, a second set of measurements was carried out for boards onto which the solder pastes themselves were printed directly along conducting tracks. In this way, the effects of typical quantities of residues produced using PCB soldering processes were investigated. The procedure is described in section V, and results are analysed in terms of their effects on RF circuitry.

II. Dielectric Material Characterisation at RF :

Microstrip resonator structures are widely used for determining the dielectric constant of substrate materials at high frequency [8], [9], and results are applied to the design of controlled impedance lines and other RF circuit elements. In the same way, by measuring the response of resonators which have been printed with no-clean solder, the change in effective dielectric constant caused by the presence of resulting residues can be deduced and incorporated in design. In this way, the effects of dielectric properties of the flux residue materials is measured on typical structures used in RF circuitry. Other structures used for measuring the dielectric constant of materials include parallel plate capacitors and lengths of stripline [5]. However, the form and topology of residue samples required in these cases are not representative of residues deposited on RF circuit boards.

Typical microstrip structures used for dielectric characterisation include ring, line and T-resonators. For the purposes of this work, T-resonators were chosen, because the deposition of residue in the gaps of ring and line resonators causes increased coupling in the structures in addition to changing effective dielectric properties, thereby complicating the effects of the residues. There is no gap in the path between input and output ports in a T-resonator as shown in Fig. 1.

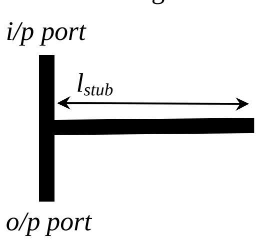

Fig. 1 : Structure of microstrip T-resonator

The frequency response of a typical T-resonator consists of a series of resonant dips as shown in Fig. 2, the first of which occurs when the stub length, l_{stub}, equals $\lambda/4$; i.e. when the impedance of the stub tends towards zero.

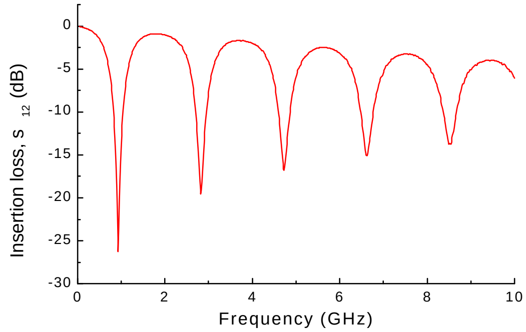

Fig. 2 : Typical T-resonator response

For the same reason, subsequent resonant positions occur at odd integer multiples of the first, while at frequencies other than resonance, the stub length is open circuit and the input signal is transmitted to the output through the microstrip length connecting between them. Clearly, the resonant frequencies of the structure depend on the length of the microstrip stub, as given by :

$$l_{stub} = \frac{(2n-1)\, l_{res_n}}{4}, \quad f_{res_n} = \frac{c}{\sqrt{e_{eff}}\, l_{res_n}} \qquad (1)$$

where c is the speed of electromagnetic waves in a vacuum, and e_{eff} is the effective dielectric constant of microstrip materials; i.e. it accounts for the dielectric constant of the substrate material, e_{sub}, below the signal conductor, and air, e_o, above it as shown in Fig. 3(a).

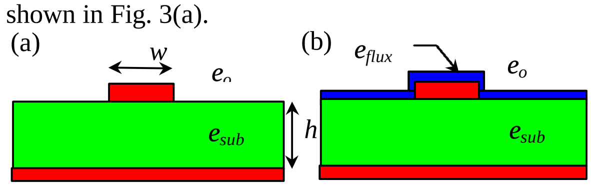

Fig. 3 : (a) Microstrip structure, (b) with flux residue

Therefore, the response of resonators may be used to characterise the high frequency performance of microstrip structures in terms of values of e_{eff}. Equally, values of dielectric constant for the substrate material, e_{sub}, may be deduced from analytic equations or by numerical solutions to the capacitance of the structure [10].

If the flux residue has dielectric properties, e_{flux}, and is deposited around the microstrip signal conductor as shown in Fig. 3(b), it also contributes to the effective dielectric constant of the structure. This is illustrated in the results of Fig. 4 for different values of thickness and dielectric constant of flux residue layers. Clearly, the presence of dielectric residue increases values of e_{eff}, and the effect is greater for larger thickness' and dielectric constant of the residue layer.

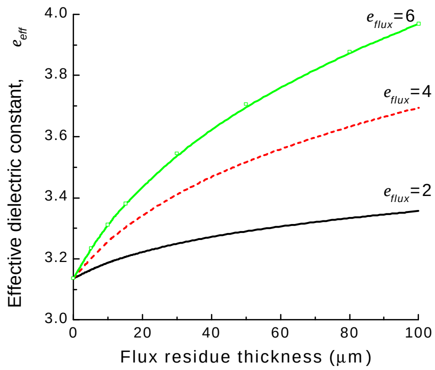

Fig. 4: Effective dielectric constant vs. residue layer

The corresponding effect on the response of microstrip resonators will be seen as a reduction in resonant frequency, as given by (1). Therefore, the change in resonator response due to the addition of flux residue provides a measure of the dielectric properties of the residues at RF. Results were produced by FEA simulation in this case.

III. Test Resonator Structures :

RF effects of flux residues from five different solder pastes were tested and compared in this work. The design of microstrip resonators for measuring the dielectric constant of the materials at frequencies up to 10 GHz is described in this section. FR4 was chosen as the test substrate material, as this is the most widely used substrate for electronics applications. Analysis of the sensitivity of microstrip impedance to the presence of surface dielectric layers in FEA indicated that the greatest sensitivity is observed for thinner substrates. Therefore, test resonator designs were based on a substrate with thickness, h = 0.2 mm. Using standard microstrip design equations [11] :

$$\frac{w}{h} = \frac{2}{p}\left(B-1-\ln(2B-1)\right)+\frac{(e_{sub}-1)}{pe_{sub}}\left(\ln(B-1)+0.293-\frac{0.517}{e_{sub}}\right)$$

$$\text{where} \quad B=\frac{59.95p^2}{Z_o\sqrt{e_{sub}}} \qquad (2)$$

and assuming e_{sub} = 4.7 for FR4, the width of signal conductors required for 50 Ω characteristic impedance, Z_o, was calculated as w = 0.36 mm.

Two T-resonators, T1 and T2, were designed with initial resonant frequencies at 0.9 GHz and 0.833 GHz respectively, so that a number of measurement points of dielectric constant was provided over the frequency range from 0.5 – 10 GHz. For the substrate properties described, corresponding T-stub lengths were calculated as 44.8 mm and 48.4 mm respectively, using (1) with e_{eff} given by [11] :

$$e_{eff} = \frac{e_{sub}+1}{2}+\frac{(e_{sub}-1)}{2}\left(1+\frac{10h}{w}\right)^{-0.555} \qquad (3)$$

Contacts were defined on each structure for probing with 400 µm pitch probes from Cascade Microtech. Approximately 50 test boards were produced to provide sufficient samples for testing each of the fluxes and solders.

Before applying flux materials, the test boards were numbered and the response of each T-resonator was measured on bare copper conductors. Measurements were carried out using a HP8722D Vector Network Analyser – the equipment was calibrated to the tips of the probes over the frequency range from 0.5 – 10 GHz. Measurements were controlled from a PC using Labview, so that results could be downloaded and stored for comparison with measurements on the same boards after the test materials were applied. In this way, the effect of variation in device structure from board to board was eliminated from the measurements, and differences in the response of resonators could be attributed solely to the presence of flux residues.

For example, the response in Fig. 2 was measured on a T1 resonator. Corresponding values of e_{eff} (without flux residue) and e_{sub} were deduced at each of the resonant frequencies using (1) and (3) respectively, and are presented in Fig. 5.

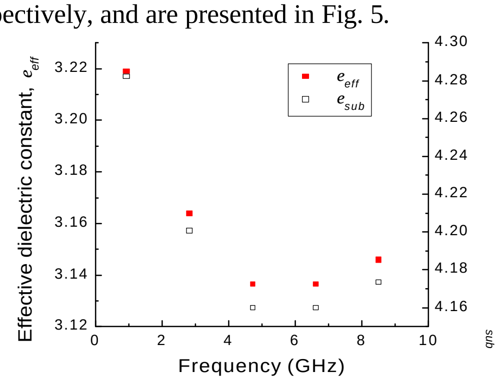

Fig. 5 : Effective dielectric constant, e_{eff} and substrate dielectric constant, e_{sub}, vs. frequency for FR4

As shown, the value of e_{sub} measured is smaller than assumed in design, and corresponding resonant frequencies are larger as a result. Similar values were deduced from measurements on the other test boards, and all results were stored for comparison with measurements on the same boards after applying the flux residues.

IV. Residues Produced from Solder Fluxes :

The use of microstrip resonators for determining RF effects of flux residues was first verified by measuring the change in resonator response caused by residues produced when a complete layer of flux (i.e. separate from solder paste) was printed over the test structures. Solder fluxes were provided in paste form for this work, and a stainless steel stencil was produced for printing the materials in a repeatable fashion; i.e. so that similar amounts of the different fluxes could be deposited. Three stencil patterns were defined for applying three different quantities of the fluxes - the patterns consisted of arrays of 1×1 cm^2 apertures spaced at different distances apart. For each flux, one board was printed through each pattern, so that three boards, each with a different quantity of flux, were printed for each flux. After printing, the boards were reflowed using a typical solder profile to produce flux residues over the surface of the boards.

The frequency response of the printed resonators was measured using the same equipment described in section III. In all cases, two clean control boards were measured under the same conditions as the contaminated boards. This was to ensure that differences in measurements performed on different days were not caused by variations in contact or calibration. To illustrate the magnitude of the effects observed, the response of a bare copper board is compared with the response of the same board printed (and reflowed) with flux in Fig. 6.

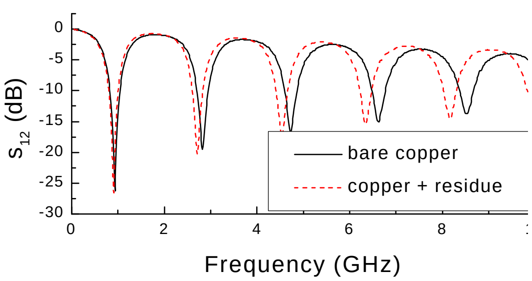

Fig. 6 : T resonator response for bare copper boards and boards printed with flux

Clearly, the flux residue has significant effects in this case. Resonant frequencies are reduced at each resonant point over the frequency range from 0.5 – 10 GHz, and this may be explained by an increase in e_{eff} caused by the addition of the flux residue; i.e. the residue appears to have dielectric properties and causes a change in resonator response. Results measured on control boards under corresponding calibration conditions showed no such reduction.

Similar effects were measured on all boards printed with different fluxes. In order to correlate the results with the amount of flux residue deposited, the average residue thickness was measured on each board using a laser profilometer. Typical thickness values measured for the different fluxes are given for illustration in Table 1.

Table 1 : Thickness of flux residues deposited from layers of flux (μm)

Flux	T1			T2		
Pattern	**#1**	**#2**	**#3**	**#1**	**#2**	**#3**
Flux 1	200	230	35	<5	5	7
Flux 2	26	20	15	10	7	5
Flux 3	10	75	50	5	7	10
Flux 4	15	60	80	5	5	<5
Flux 5	15	10	20	5	5	10

As shown, the residue thickness is larger on T1 resonators than on T2 devices. This is explained by the larger amounts of flux printed on T1 boards. However, after reflow, it was found that the amount of residue remaining on the boards was much larger than practical. Furthermore, the form and quantity of residues produced varied considerably from flux to flux, and also depending on whether the flux was deposited on copper or on FR4. Since it was required to compare the materials for similar quantities of flux residues, smaller amounts of the fluxes were printed onto the T2 resonator boards.

Results for the different fluxes are compared in Fig. 7, in terms of the change in values of e_{eff} caused by the deposition of the fluxes.

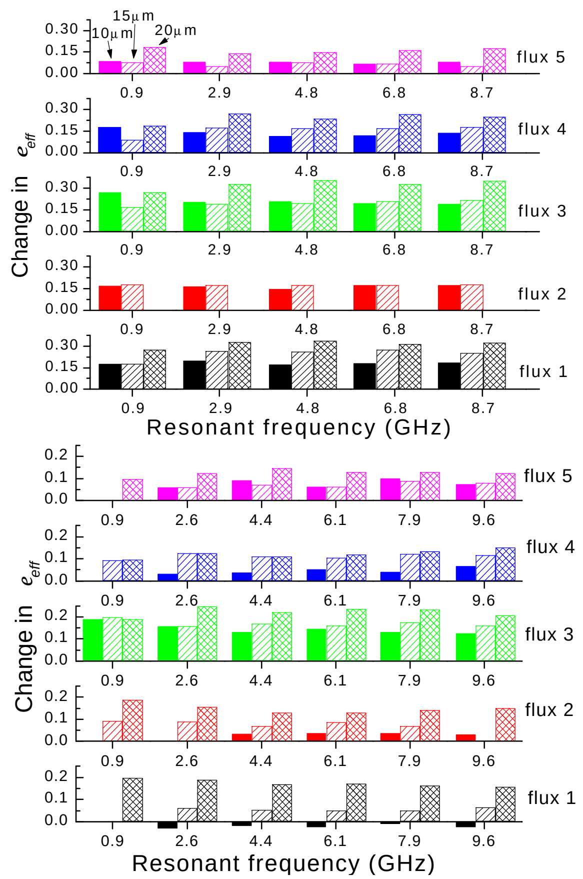

Fig. 7 : Comparison of change in e_{eff} caused by fluxes measured on (a) T1 and (b) T2 resonators

Results were deduced from the response of T1 and T2 resonators. Resonant frequencies were extracted using peak analysis, and corresponding values of e_{eff} were calculated using (1). The increase in e_{eff} caused by the deposition of the residues was calculated at each resonant frequency and results are presented in order of increasing residue thickness (as shown for flux 5). In most cases, a correlation can be drawn between the change observed and the thickness of residue applied.

Due to the larger amounts of flux printed on T1 resonators, changes in e_{eff} presented in Fig. 7(a) are larger than in Fig. 7(b). In both cases, fluxes 1, 3 and 4 have the largest effects, with smaller effects measured for fluxes 2 and 5. For example, e_{eff} is increased by up to 11.4 % due to the application of flux 3, while a maximum increase of 5.7 % is measured for flux 5. In all cases, the effects are approximately constant over frequency, indicating that the dielectric properties of the residues are approximately constant with frequency.

The purpose of this work was to verify the procedure applied and to measure the relative effects of the test fluxes. Initially, it was intended to compare the materials for similar quantities of deposited flux residues, but due to differences in print and reflow properties of the fluxes, the thickness of resulting residues was not easy to control. The results in Fig. 7 therefore provide a comparison of the fluxes for similar amounts of applied flux. The next step was to compare the materials in terms of residues produced from no-clean solder pastes containing the fluxes. In this way, the materials are compared for quantities of flux residues produced in standard PCB soldering operations.

V. Residues Produced from Solder Pastes :

In this case, the aim was to investigate the effects of residues produced from no-clean solder pastes. The test resonators were printed with solder paste directly onto the copper tracks. Two different thickness of solder pastes were printed, using 5 mil and 7 mil stencils patterned with the T-resonator structures. Three boards were printed for each thickness, giving 6 samples for each solder paste. The boards were reflowed to produce flux residues and the resonator responses were measured as before. Results included the combined effects of flux residues and increased conductor thickness due to the solders at this stage. In order to isolate the effects of the residues, results measured on boards having solder but no residue were required. Therefore, the residues were cleaned off and the measurements repeated. Control boards were measured with the contaminated boards in all cases for verification of calibration as before. The response of a T1 resonator measured on a board after printing and on the same board after removing the residue is compared in Fig. 8 to illustrate the magnitude of effects observed.

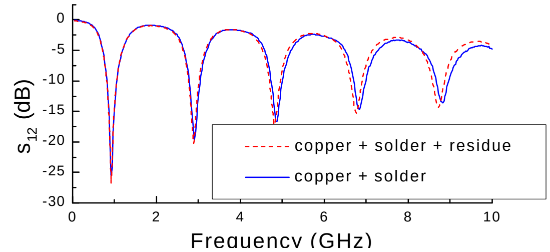

Fig. 8 : T resonator response illustrating effects due to flux residue

When compared with results in Fig. 6, it is clear that the effects of residues produced from the solder pastes are much smaller than those measured due to layers of the fluxes previously. It is interesting to note that the same level of effects was measured due to the combined effects of solder and flux residue, thereby indicating that the increased conductor thickness (of the solder) had little or no effect on the frequency response. Similar orders of effects were observed for the other solder pastes, and corresponding results of change in e_{eff} are compared in Fig. 9.

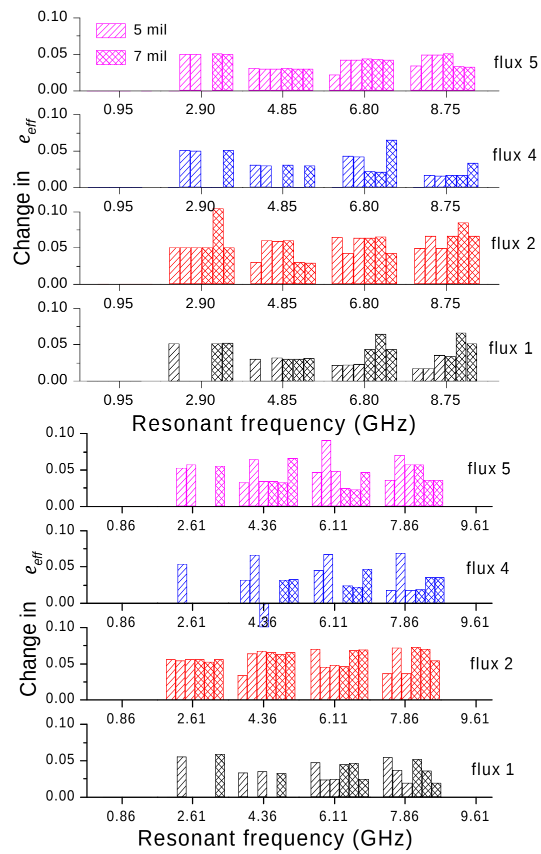

Fig. 9 : Comparison of change in e_{eff} caused by solder pastes measured on (a) T1 and (b) T2 resonators

The change in e_{eff} was calculated using values of resonant frequencies extracted from measurements on boards after printing, and on boards with residue cleaned off for each board. Due to the fact that the residue produced by flux 3 could not be cleaned off, the corresponding solder paste was not tested in this case.

As discussed above, the effects are smaller than measured for residues produced from the solder fluxes previously. This is explained by the smaller amounts of flux residue deposited; i.e. residues were localised along the sides of the conductors in this case and did not extend over the conductors as before. Typical residue thickness ranged from 20-40 μm in this case, and the same thickness range was measured on boards printed with 5 mil and 7 mil solder paste. This is seen in terms of the same order of effects measured on boards printed through the two stencils in Fig. 9.

In this case, residues produced from solder pastes 2 and 5 contributed the largest effects, with corresponding changes in e_{eff} of 3.5% & 3.2% respectively. For comparison, maximum changes caused by fluxes 1 and 4 are 2.3% & 2.4% respectively, so that the difference in effects caused by the different solder pastes is not so significant. The residues were produced using standard PCB soldering processes in this section, so that the order of effects predicted are representative of residues produced on typical RF circuit boards. Corresponding effects on circuit performance may be calculated in terms of the variation in microstrip characteristic impedance, Z_o where :

$$Z_o = \frac{120p}{\sqrt{e_{eff}}\left[\frac{w}{h} + 1.393 + 0.667\ln\left(\frac{w}{h} + 1.444\right)\right]} \quad (4)$$

For the largest effects measured in Fig. 7, corresponding levels of decrease in Z_o (50 Ω) are given in Table 2.

Table 2 : Comparison of fluxes in terms of Z_o

	flux 1	flux2	flux 4	Flux 5
ΔZ_o %	1.13	1.71	1.20	2.78

As shown, the effects of the residues on microstrip impedance are not very large. However, it should be noted that there are increasing demands for tolerance levels of less than 5% on controlled impedance boards. Furthermore, the results in this case were measured for residues deposited on FR4 substrates with e_{sub} = 4.3, so that larger effects may be seen for materials with smaller dielectric constant.

VI. Conclusions :

A method for measuring the effects of flux residues on RF circuit boards in terms of microstrip resonator response was described. Up to 11% increase in effective dielectric constant of microstrip boards was measured due to residues produced from printed layers of solder fluxes (separate from solder pastes). Smaller changes were measured for boards onto which residues were produced during reflow of no-clean solder pastes (containing the same fluxes), resulting in a maximum change in line characteristic impedance of 2.8%. Effects were compared for five different solder fluxes. Results were produced for microstrips formed on FR4 substrates in this case, but the same procedure may be applied for other substrate materials. Work is ongoing to investigate the application of such resonators for determining the change in dielectric losses caused by flux residues.

References :

[1.] L. J. Turbini, '*Comparison of methods for characterising soldering fluxes and their interactions with substrates and metallisation*', Circuit World, Vol. 23, No. 1, 1996, pp. 20-24.

[2.] D. Rocak, K. Bukat et al., '*Comparison of new no-clean fluxes on PCBs and thick film hybrid circuits*', Microelectronics Journal, Vol. 30, No. 9, Sept. 1999, pp. 887-893.

[3.] J. Guy, M. Frederickson, '*Analyzing residues using AC impedance techniques*', NEPCON – Proc. of Tech. Program (West and East), 3, 1997, pp.1270-1279.

[4.] M. S. Heutmaker, L. M. Fletcher, J. E. Sohn; '*Measurement of stray capacitance due to solder flux residue on radio frequency circuit boards*', Proceedings of MTT-S 1995, International Topical Symposium, pp. 105-109.

[5.] '*Electrical test methods*', IPC TM-650, Test Methods Manual, Section 2.5

[6.] L. Guan, A. Christou, D. F. Barbe; '*The effect of corrosion on the performance of high speed multi-chip module interconnects*', International Journal of Microelectronic Packaging, 1998, Vol. 1,pp.131-137.

[7.] R. J. Wenzel, D. C. Keezer, '*Impact of MCM technology on high speed transient waveforms*', Proc. 1997 International Symposium on Advanced Packaging Materials, pp. 148-151.

[8.] N. Jain, B. Brown, '*Dispersion characteristics of microstrip transmission line on glass microwave IC's*', IEEE Microwave and Guided Wave Letters, Vol. 7, No. 10, October 1997, pp. 344-346.

[9.] D. A. Rudy; '*Measurement of RF dielectric properties with series resonant microstrip elements*', Microwave Journal, March 1998, pp. 22-41.

[10.] P. Pieters, S. Brebels, et al., '*On the dielectric material properties for thin film integrated RF and microwave applications*', Advancing Micro-electronics, Sept/Oct 1999, pp. 19-23.

[11.] T. Edwards, '*Foundations for microstrip circuit design*', Wiley, 1991.