Investigation of Ring-Resonators on Multilayer LTCC

Reinhard Kulke*, Winfried Simon*, Andreas Lauer*, Matthias Rittweger*, Peter Waldow*,
Sara Stringfellow+, Royston Powell+, Martin Harrison+, Jean-Pierre Bertinet#

*IMST GmbH, Carl-Friedrich-Gauss-Str. 2, D-47475 Kamp-Lintfort, Germany, kulke@imst.de
+Marconi Caswell Ltd., Caswell, Towcester, Northamptonshire NN12 8EQ, GB
#Sorep Erulec, Bellevue , F35221 Châteaubourg Cedex, France

Abstract — **Multilayer LTCC is an interesting technology for microwave applications. Originally, the material systems have been developed for digital or low frequency modules, but the price and the 3D circuit design capabilities have driven the effort to enhance the materials and to investigate the LTCC systems in the GHz-range. This paper documents some basic tests, which have been performed at a ring resonator up to 40GHz. As a result, the quality factor Q, the effective permittiviy and the losses of a microstrip line could be determined. The paper also treats the problem of co-fired conductors, which diffuse into the substrate's surface and influence the line parameters.**

I. INTRODUCTION

At the beginning of the European research project RAMP[1] the consortium has to find an LTCC system, that promised to be suitable for their demands: low losses for applications up to 30GHz, availability on the market and in focus of further product developments. After a discussion about the capable LTCC systems the consortium decided to limit the basic investigations on two LTCC lines from Ferro and DuPont: the A6-M and the Tape 951 with different conductor pastes (Au and mixed metal: Au and Ag). The design of the first test vehicles had to be as close as possible to the later used substrate and waveguide configurations. Thus, the project partners decided to build up a 4 layer substrate with microstrip conductors on the top and an inner ground mesh under the first layer. Each test tile had three ring resonators for a two port characterization, a set of lines for TRL calibration and meander lines with different line width for DC measurements. Fig. 1 shows a photo of the 4 substrates, two made of DuPont and two of Ferro LTCC, one of each with gold and one with silver top conductors. Several tests have been performed: the quality of handling and the characteristics of the materials during the process steps (this is not subject of this report), the accuracy and reproducibility of the geometric dimensions after firing and shrinking and the DC and RF characterization. The effective permittivity, the overall losses and the conductivity of the pastes could be derived from the electrical measurements. These results have been compared with simulations of the ring resonator in the circuit design tool *Libra* from *Agilent*. An increasing deviation of the characteristic resonance peaks from measurement and simulation becomes evident. It could be found out, that the co-fired top conductors have been diffused into the surface of the substrate during the fabrication process. Depending of the depth of the diffusion a deviation of 8% in the line impedance and the effective permittivity can occur. This has been proved with the full wave design tool *EMPIRE*, which utilizes the FDTD method. From the electro-magnetic field simulation *corrected* line parameters have been derived. With a change of the microstrip substrate height and the dielectric constant an excellent simulation result of the ring resonator could be achieved. Finally, the losses of that specific microstrip line could be extracted form the ring resonator measurements. They agree very well with the loss models from the *Agilent* software. Thus, a separation of the loss factors *conductivity*, *dielectric losses* and *surface roughness* can be given in this report.

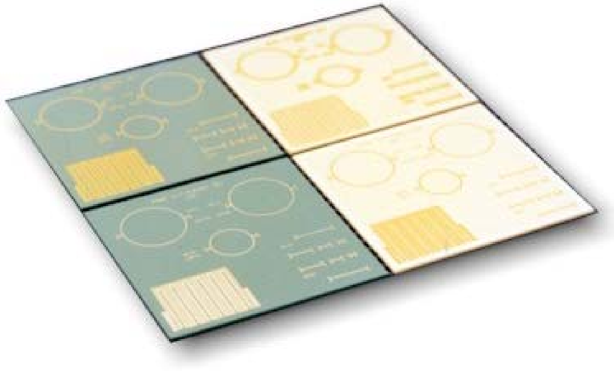

Fig. 1. Photo of the 4 test tiles with ring resonators, calibration and meander lines in gold and silver top conductor on 4-layer LTCC from Ferro (A6M: white) and DuPont (951 AX: blue)

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[1] RAMP: „Rapid Manufacture of Microwave and Power Modules", BE-97-4883

II. RING RESONATOR TEST TILES

Four different test tiles have been designed. All substrates were build up with 4 LTCC layers. Standard tapes from Ferro and DuPont have been used. The Ferro tape is named A6-M (M for Microwave applications) and has a fired thickness of 185µm. The DuPont tape is AX 951 with a fired thickness of 200µm. At the time of evaluation reliable materials of the low loss tape 943 from DuPont were not yet available. Each LTCC system has been processed with silver and *mixed metal* conductors. Mixed metal means, that the top conductor was printed with a gold paste and the inner ground and via conductors were made of silver. Such a combination of gold and silver can be critical due to a diffusion of silver particles into the gold conductor. The project partners decided to process a four layer substrate for the following reasons: the lamination properties could be tested, the test configuration should be close to the final application and the influence of the ground grid could be estimated. The overlap factor of the ground mesh was about 50%. A "shadow line" with two times of the microstrip line width is used in the ground plane. The following list summarizes the properties of the four test tiles:

1. Ferro A6M, Au FX30-025:
   mixed metal, t = 10 – 12µm
   fired thickness = 185µm (substrate),
   measured thickness = 184 –190µm,
   roughness: Ra = 0.4µm
2. Ferro A6M, Ag FX33-229:
   silver, t = 14 – 16µm, t_{GND} = 8 – 10µm
   fired thickness = 185µm (substrate),
   measured thickness = 184 –190µm,
   roughness: Ra = 0.4µm
3. DuPont 951 AX, Ag 6145:
   silver, t = 22 – 24µm, t_{GND} = 14 – 16µm
   fired thickness = 200µm (substrate),
   measured thickness = 190 –195µm,
   roughness: Ra = 0.4µm, Rq = 0.6µm
4. DuPont 951 AX, Au 5743 post fired:
   mixed metal, t = 10 – 12µm
   fired thickness = 200µm (substrate),
   measured thickness = 175 –180µm,
   roughness: Ra = 0.4µm, Rq = 0.6µm

Three different ring resonators with a variation of the microstrip line width, the diameter of the ring and the size of the gap between the ring and the connected lines have been designed. Table 1 lists the dimensions of the ring resonators and the DC resistivity of the meander lines. The name of a ring resonator indicates the designed line width and the spacing between the connection line and ring, e.g.: W260G100 ⇒ w = 260µm, g = 100µm. The figures in the table are the averages of measured dimensions. In some cases the deviation between designed and measured value is high. However, the consortium gained experience for the next fabrication process. The following considerations have been made with the real dimensions. After measuring the geometry and resistivity the RF characterization has been performed by utilizing an on-waver measurement with the probes "40A-GSG-450-DP" from Picoprobe GGB Industry. An TRL calibration with the microstrip waveguides on the Ferro Au test tile has been made, because these lines showed the best performance. Fig. 2 depicts the measured insertion losses of the ring resonators on the Ferro Au tile. The S-parameters have been measured from 500MHz to 40GHz.

TABLE I
SUMMARY OF TEST VEHICLE PROPERTIES

Ferro A6M, Au FX30-025			
Resonators	W260G100	W260G50	W275G75
gap / µm	125	67	96
width$_{ring}$/ µm	238	237	253
d$_{inner}$ / µm	15169	15193	9989
Meander	7.0 mΩ/square		

Ferro A6M, Ag FX33-229			
Resonators	W260 G100	W260 G50	W275 G75
gap / µm	105	51	75
width$_{ring}$/ µm	237	236	253
d$_{inner}$ / µm	15199	15233	10020
Meander	5.0 mΩ/square		

DuPont 951 AX, Ag 6145			
Resonators	W215 G100	W215 G50	W230 G75
gap / µm	124	58	94
width$_{ring}$/ µm	193	204	204
d$_{inner}$ / µm	15287	15276	10075
Meander	3.0 mΩ/square		

DuPont 951 AX, Au 5743 post fired			
Resonators	W215 G100	W215 G50	W230 G75
gap / µm	153	85	117
width$_{ring}$/ µm	162	179	190
d$_{inner}$ / µm	15341	15325	10108
Meander	8.0 mΩ/square		

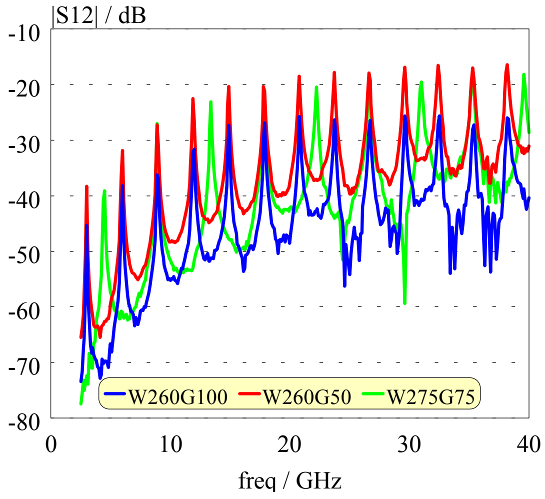

Fig. 2. Ferro A6-M, Au: measured insertion losses of the ring resonators

Some important parameters can be determined from the attenuation [1], which is defined by:

$$a_{21}(f) = -20 \log|S_{21}(f)| \qquad (1)$$

These parameters are the resonance frequencies f_n at the attenuation minima n, the 3dB-bandwidth, the loaded quality factor Q_L, the effective permittivity and the overall losses α per unit length (with c_0 = speed of light in vacuum, d = ring diameter):

$$2\Delta f_n = f_n(l) - f_n(u) \qquad (2)$$

$$Q_L(f_n) = f_n / (2\Delta f_n) \qquad (3)$$

$$Q(f_n) = Q_L(f_n) / [1-|S_{21}(f_n)|] \qquad (4)$$

$$\varepsilon_{eff} = (c_0\, n)^2 / (\pi\, d\, f_n)^2 \qquad (5)$$

$$\alpha = (27.288\, f_n \sqrt{\varepsilon_{eff}}) / (c_0\, Q)\ [\mathrm{dB/m}] \qquad (6)$$

The equations (1) to (6) have been used to determine the losses for the four different test systems. To validate the results a comparison between measured and modeled data has been performed. The authors executed the simulation tool *Linecalc* from *Agilent*, which includes the loss factors of the conductivity, the dielectric losses and the surface roughness of the microstrip line. Fig. 3 summarizes the losses in dB/cm. The simulation of a microstrip line with parameters of the DuPont material shows an excellent agreement with the measured data. A separation of the modeled loss factors results into the figures (@ 20GHz in dB/cm): $\alpha_\rho = 0.232$, $\alpha_{RGH} = 0.09$ and $\alpha_{diel} = 0.195$. This proves, that the dielectric losses have an important impact on microwave applications.

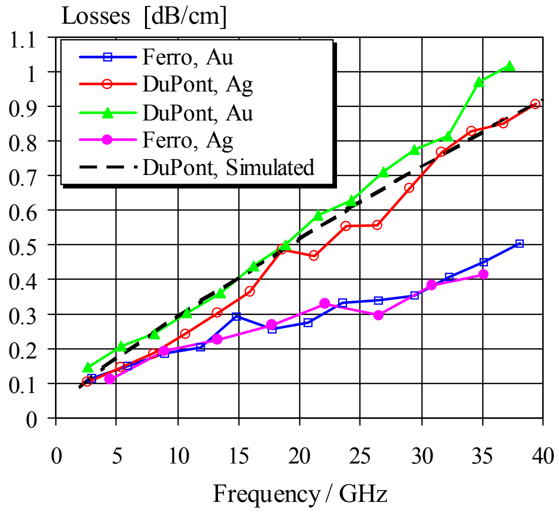

Fig. 3. From ring resonator measurement extracted losses in comparison with simulations of a MS line with DuPont parameters. Simulation: εr=7.8, h=180µm, w=180µm, t=10µm, ρ/ρ_{Au}=1.6, RGH=0.5µm, tanδ=5x10^{-3}

III. CORRECTED MICROSTRIP LINE PARAMETERS

An unexpected problem occurred, when the permittivity has been compared with simulations. The authors found out, that the measured effective permittivity of the microstrip lines was about 8% higher than expected. An investigation showed, that due to the co-firing process the top conductor diffuses into the surface of the LTCC substrate. In case of the DuPont Au test circuits, where a post-fired gold conductor has been processed, these problems did not occur. The authors tried to find a simple solution for circuit designers, who wish to correct their microstrip models with less expense. In a first step a full wave analysis with a diffused microstrip line has been performed with the IMST software *EMPIRE*. Fig. 4 shows the distribution of the electrical field in both configurations. It becomes evident, that the field concentration will be pushed into the substrate, when the conductors diffuses into the surface. This results in an increasing of the effective permittivity and a decreasing of the characteristic line impedance Z_L. The line parameters C' and L' have been extracted from the electro-magnetic modeling. The following equations show the relation between C', L' and Z_L, ε_{eff}:

$$Z_L = \sqrt{(L'/C')}, \qquad (7)$$

$$\varepsilon_{eff} = C'/C_0' \text{ and } L' = \mu_0\varepsilon_0/C_0'. \qquad (8)$$

In Fig. 5 the measured and simulated curves of ε_{eff} with and without diffused conductors are presented for the Dupont Ag and the Ferro Au systems. The modeled parameters of the microstrip line with diffused conductors have been taken to estimate a correction for a standard MS model, where the metal is assumed to be on the top of the substrate. This could be achieved by increasing the dielectric constant and by reducing the substrate height. The line width remained unchanged. To demonstrate the accuracy of this method, the ring resonator has been simulated with the circuit design tool *Libra* including the coupling gap to the connected lines. The correction has to be made only in the dielectric constant "ER" and substrate height "H" parameters of the data item "MSUB" for the whole circuit. The parameters of the microstrip elements remained the same. This way a correction for an existing and complex circuit is right easy. The results of the ring resonator simulation are outstanding. An excellent agreement between the simulated and measured data could be achieved.

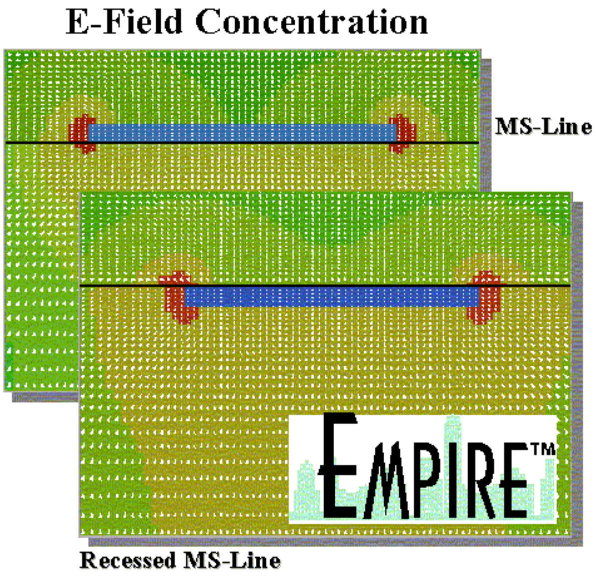

Fig. 4. Electrical field concentration calculated by a full wave analysis of a microstrip line on top of the ceramic and diffused into the substrate surface

IV. CONCLUSION

Microstrip ring resonators have been investigated to characterize the microwave properties of two LTCC systems: the DuPont tape 951 and the Ferro tape A6-M. Both have been tested with gold and silver pastes. The quality factor Q, the effective permittivity and the overall line losses could be determined from the circuits. The tests exposed, that the top conductors diffused into the surface of the substrate, which results in a change of the line parameters up to 10%. A simple method has been described to correct a standard MS model in a design tool.

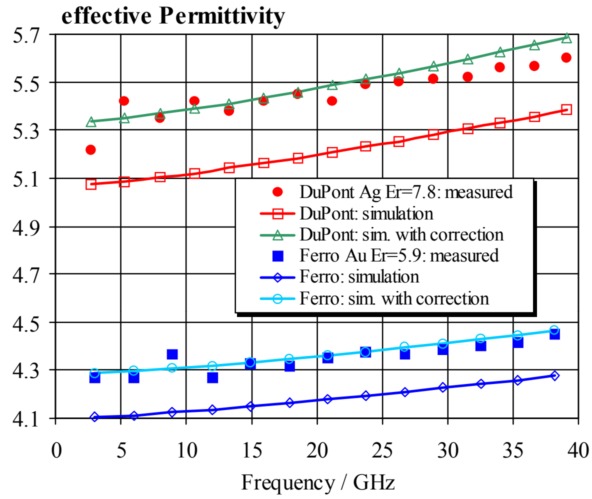

Fig. 5. Comparison of measured and simulated effective permittivity for a Ferro and a DuPont line with and without correction

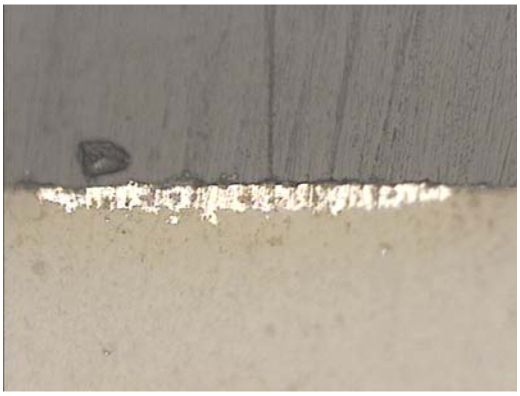

Fig. 6. Cross section photo of A6-M tape / Ag Fx33-229

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REFERENCES

[1] R. K. Hoffmann, *Intergrierte Mikrowellenschaltungen*, Springer Verlag 1983.