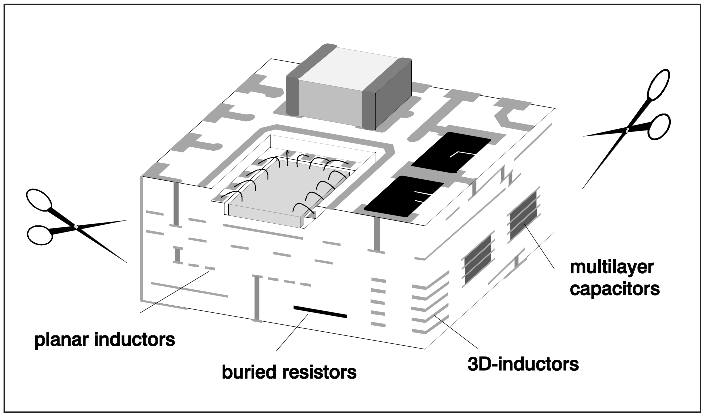
RF Models of Passive LTCC Components in the Lower Gigahertz-Range

Karl-Heinz Drüe and Heiko Thust, Technical University of Ilmenau
Jens Müller, Micro Systems Engineering GmbH & Co.

Printed thick-film elements are well appreciated for high-frequency applications. Line structures are applied up to >10 GHz, and passive elements like resistors, inductors and capacitors work in the lower Gigahertz-range as well.

Low Temperature Cofired Ceramics (LTCC) offers a wide range of possibilities to realize multilayer circuits with an almost unlimited number of signal layers and low conductor losses. However, its key advantage compared to the high-temperature multilayer is the ability to integrate passive components like resistors, capacitors and inductors into the circuit carrier. Denser circuits with an increased scale of integration are obtained by removing these elements from the substrate surface.



■ **Figure 1. Cross section of a ceramic multilayer circuit with embedded passive components.**

With its uniform dielectric sheet thickness, the parallel processing and its outstanding electrical parameters (low permittivity, low loss), LTCC is predestined for highly-integrated, cost-effective wide band applications. A further argument is given by the fact that the range of inductor and capacitor values which can be realized is useful for high-frequency applications.

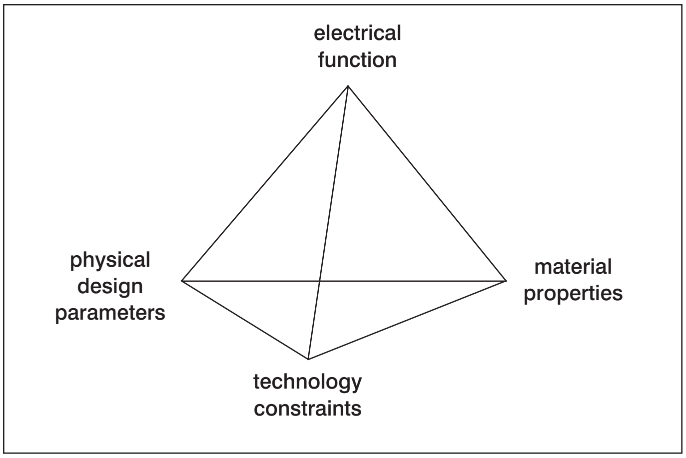
This article focuses on the behavior of passive RF components which are embedded in the multilayer. It summarizes previous papers presented at different conferences [3, 8, 9].

Background

One of the key pace-setters of the microelectronics industry is the demand for smaller and denser circuitry to increase the systems performance and to save costs. With telecommunications sector applications requiring increasing frequency bandwidths, technology related properties will mark the boundary of possibilities. Problems relating to unwanted parasitic elements, e.g. high load capacitances, have to be considered in the physical layout design. Multilayer ceramic circuits based on Low Temperature Cofired Ceramics (LTCC) offer a wide range of opportunities to realize both interconnection structures and passive components in a dense package.

Glass-ceramics are also well known as stable dielectrics with excellent properties even at microwave frequencies.

The passives may be placed on top of the substrate — but to gain a better scale of integration it is desired to bury them between internal layers. Included in this concept of “Passive Integration” are resistors, capacitors and inductors. The number of additionally required passive elements can be decreased and thus, the overall reliability is improved. Figure 1 shows a cross-section of a multilayer demonstrating the opportunities of LTCC-design.



■ **Figure 2. Influencing parameters in electrical component design.**

The desired electrical function or element is influenced by material properties (related to the chosen tape-system), technology constraints (e.g. conductor or via resolution) and physical design topics such as line lengths or distances to adjacent ground planes (Figure 2). The required circuit element will almost always be accompanied by unwanted parasitics.

One way to optimize the design cycle is to find geometrical and material dependent models. Once their behavior is known, they can be modified by changing the design conditions (paste, tape material, sheet thickness, etc.).

Measurement methods

Characterization of passive components is possible by either time domain or frequency domain techniques [1]. In the frequency domain the elements are measured with a network analyzer to obtain S-parameters. The scattering matrix can serve as an input for a high-frequency CAD tool or as a data base to extract the parasitics for a model generation. Both the impulse response and the S-parameters reveal the basic electrical character of the component — in other words, whether its "electrical length" can be regarded as short compared to the signal wave length. In the first case, the component will be considered as lumped or concentrated. If the components dimensions are not negligible they show distributed or transmission line characteristics. Capacitors and resistors are usually very small and can be described as lumped elements. Inductors are more complex elements which are very sensitive to adjacent ground planes. This results in a mix of lumped and distributed characteristics.

Furthermore, in most cases it is not sufficient to model a lumped element as a single impedance. Additional parasitic inductances or capacitances are always necessary for a wide band description.

These parasitic effects are different according to the component's relationship to the ground plane, and some effects may be caused by multiple influences. Therefore, a series of test vehicles must be examined in all possible arrangements (e.g. with and without ground plane) in order to find correlations between component geometry and their behavior.

For a first simple description it is often suitable to apply a Π-model (Figure 3). The extraction of z, y_1 and y_2 from the S-matrix of a series element is shown in Equations 2 to 4. First, the S-parameters are transformed to the *ABCD*-matrix (chain-parameter). After some simple operations the model elements are derived.

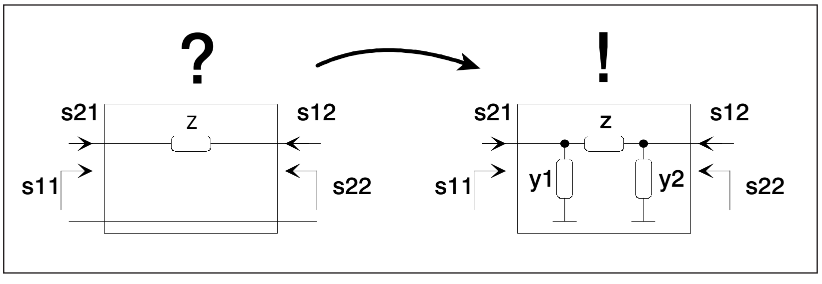
$$\begin{bmatrix} A & B \\ C & D \end{bmatrix} = \begin{bmatrix} \frac{1+s_{11}-s_{22}-(s_{11}s_{22}-s_{12}s_{21})}{2s_{21}} & \frac{1+s_{11}+s_{22}+(s_{11}s_{22}-s_{12}s_{21})}{2s_{21}} \\ \frac{1-s_{11}-s_{22}+(s_{11}s_{22}-s_{12}s_{21})}{2s_{21}} & \frac{1-s_{11}+s_{22}-(s_{11}s_{22}-s_{12}s_{21})}{2s_{21}} \end{bmatrix} \tag{1}$$

$$z = B \tag{2}$$

$$y_1 = \frac{D-1}{B} \tag{3}$$

$$y_2 = \frac{A-1}{B} \tag{4}$$

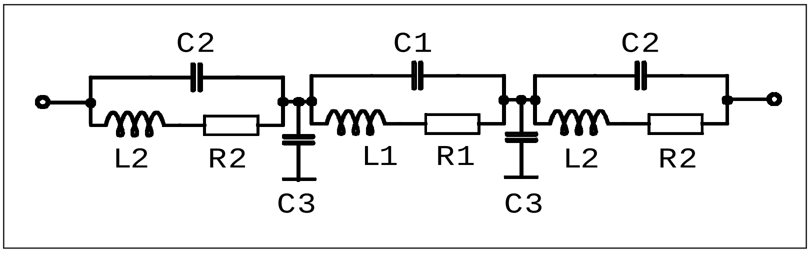
The more stringent the requirements for the simulation model, the more elements need to be added to it. Both experience and alternating simulation/comparison will help to obtain useful models for a wide frequency range. Once a valid model is established you can run computer based curve fitting programs to achieve the model elements. In the next step, the correlation between physical component parameters (length, width, etc.) and model elements should be derived. As a result of this, it will be posssible to predict the frequency behavior during the design process of arbitrary components. The effort in the model extraction will be paid off by very fast simulations compared to field solvers.



■ **Figure 3. Model for S-Parameter Interpretation**

Properties of passive elements

Resistors — Two methods were used to determine the properties of resistors in our department. The first method is based on



■ **Figure 4. Universal equivalent circuit for resistors in microstrip environment.**

between the inner and the outer conductor. This form of the test substrates minimizes the reflections at the transition. The lengths of all resistors had to be 2 mm (diameter of the inner pad 3 mm, inner diameter of the outer ring 7 mm). In order to vary the *l*/*w* ratio, different widths had to be chosen (0.3-2 mm, *l*/*w* 1-6). Single and shunted resistors (up to 4 resistors in parallel) were realized. The air-filled coaxial line allowed reflection measurements for the conventional substrates (one-port devices) and both reflection and transmission measurements on LTCC substrates because the coaxial pattern was on the top and the bottom of these substrates. So it was possible to locate the LTCC-DUTs between two coaxial lines for the S-parameter measurements.

resistors located inside a 50 ohm microstrip structure [4] with different length/width (*l*/*w*) ratios.

The widths of the resistors were chosen to 0.6 mm which is also the width of the line to reduce reflections at the border between resistor and line. The influence of the connecting microstrip lines was eliminated by a de-embedding procedure after measurement. All scattering parameters were measured and used to determine the properties of the resistors. Model elements were calculated using MDS [11].

The disadvantage of the microstrip arrangement is the ground plane under the resistors. This method was used for standard resistors on conventional alumina substrates. The resistors on these test substrates had length to width ratios of 1, 2, 3 ... to 10.

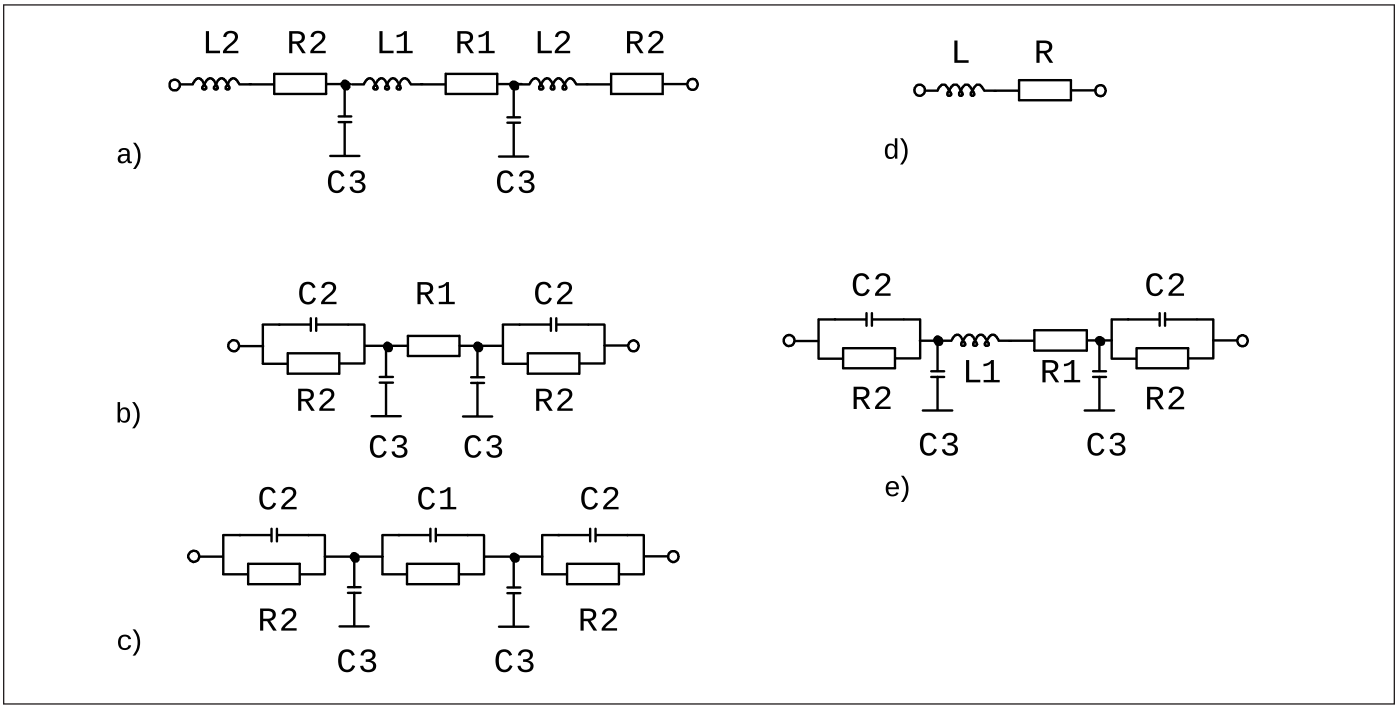
To avoid the disadvantages of the above method, a second one was developed [3]. The DUTs were glued by epoxy at the end of a 50 ohm air filled coaxial line. This connection was not hardened, so it was easy to change the DUTs. For the tests with the air filled line, the pads had a concentric form and the resistors were located between the inner and the outer conductor.

The complex impedance of one-port devices was calculated from the reflection factor $\rho(f)$ by applying equation (5):

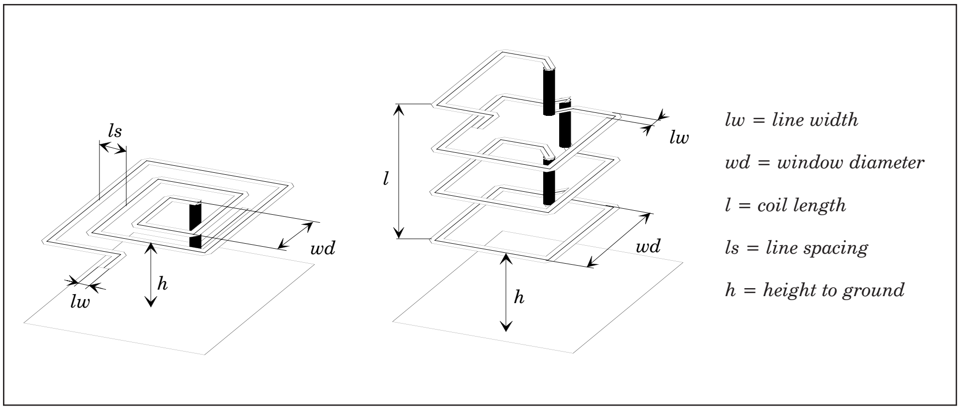
$$\underline{Z}(f) = \frac{1+\rho(f)}{1-\rho(f)} \cdot 50\Omega \qquad (5)$$

The S-parameters of the DUTs evaluated as two-port devices were again transformed to *ABCD*-parameters to determine the model elements.

In [10] a common equivalent circuit for resistors in microstrip environments was given. After the measurements in microstrip environments, this model was slightly modified (Figure 4) [4]. This equivalent circuit had to be adapted for different materials and *l*/*w* ratios.



■ **Figure 5. Adjusted equivalent circuits for resistors with different sheet resistances. a: Rp < 100 W, b: Rp = 1 kW; c: Rp > 10 kW (ground planes under the resistors). d: Rp < 100 W standard technology, LTCC on top, Rp < 25 W buried resistors in LTCC. e: all others with higher Rp (d, e: resistors without ground planes)**



■ **Figure 6. Inductor shapes in LTCC.**

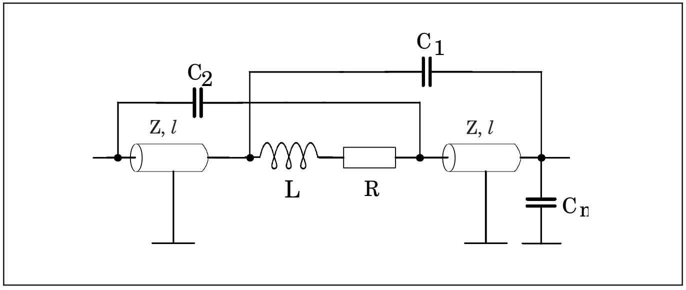
In most cases the models for a special material are much simpler. Without a ground plane under the resistors we will get another simplification. It is useful to separate the models of the resistive layers and the terminal configuration, which always shows a capacitive behavior. In order to do this the admittance of an empty termination was subtracted from the measured admittance.

The MDS software was able to find values for the equivalent circuits with a very good agreement between models and measurements. Figure 5 shows the models found by MDS.

Some rules could be found during simulation. The central resistor R_1 should be chosen to 69 percent of the DC resistance R_0 for all l/w ratios. For the model according to Figure 5a the proportion $L_2/L_1 = 0.5$ gives the best results. The proportion C_2/C_1 is about 1 for 10 kΩ inks and decreases for higher values of R_p.

As predicted, the measurements without a ground plane under the resistors gave simpler models. Figure 5d and 5e show these models for different sheet resistances.

The measurements at LTCC substrates gave similar results and models. A significant difference is the much higher square resistance of buried resistors in LTCC compared with resistors on the top of a substrate. Resistors with low sheet resistance (100 ohms and less for standard and 25 ohms for buried LTCC) have an inductive part of the impedance and may be modelled by a very simple equivalent circuit (Figure 5d). The origin of this inductance could be the conductive paths inside the resistors. Only the buried resistors with the lowest values showed this inductive behavior.



■ **Figure 7. General model of a 3D-inductor.**

Resistors with higher values of R_p show a capacitive behavior. This could be caused by an increased number of insulating particles inside the resistive layer.

Inductors — Two major shapes are used for coils — the planar square or circular spiral inductor and the 3D-helical inductor (Figure 6). The latter requires several layers, one for each its turns. In terms of quality the flat coil has disadvantages. Each additional turn causes a non-linear growth of resistance due to the increasing winding diameter.

In general, the RF resistance reflects the skin and proximity effect. Another important aspect is the neighborhood to ground/power planes or to other metal planes. The mutual inductance of mirror currents in metal plates reduces the overall inductance of the coil. Design rules which do not include this parameter will not give satisfactory results.

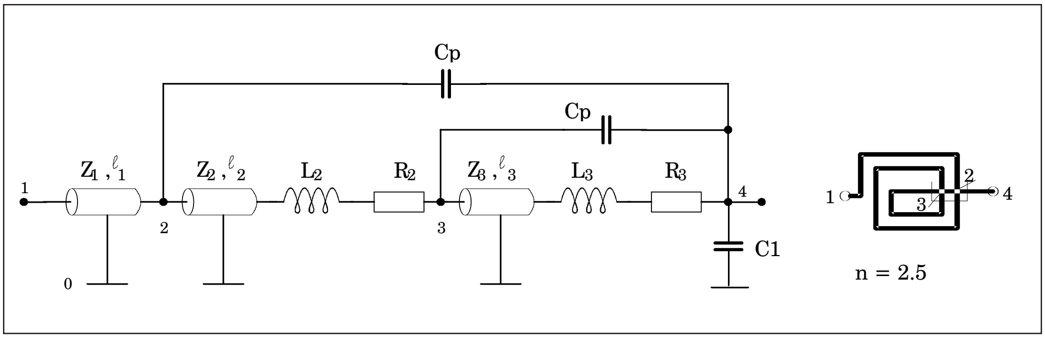
Some coils with close ground relations reveal distributed character and behave more like a transmission line. This behavior can be modeled with lumped elements only in a limited range. However, the coupling capacitor becomes negative [2]. The better interpretation in this case is the transmission line model whose wave impedance is obtained from Equation 1 as:

$$Z_w = \sqrt{\frac{B}{C}} \tag{6}$$

A typical structure for the 3D-inductor-model developed for curve fitting is shown in Figure 7. It consists of two line elements which contribute to the series inductance and distributed shunt capacitances to ground. Its impedance is a function of the ratio line width to ground distance and the number of turns. The electrical length is also determined by the inductor length.

The inductance L represents the lumped part of the total inductance of the coil. R contains the frequency-dependent conductor losses. For most simulations it is sufficient to compute R at the highest frequency point used and to use this value for the whole frequency range. It is also possible to put all losses into a lossy transmission line model, if available. C_1 and C_2 describe the capacitive coupling between windings. It turned out that these capacitors are only sensitive to line width, coil diameter and turn to turn distance (not to the number of windings). C_2 is responsible for the first self resonance. Therefore, line widths and material permittivity should be kept as small as possible. The large capacitive coupling of the deepest winding to ground is achieved by C_m. This model is valid for both series and shunt connection.

The flat spiral inductor model applied is quite simple: each winding consists of a part of a concentrated induc-



■ **Figure 8. Model of a 2.5-turn planar inductor.**

tance $L_{1..n}$ with conductive losses $R_{1..n}$ and a transmission line segment. The connection of the coil center to outer pad crosses every winding (except the first half turn) and causes several equal coupling capacitances $C_{1..n}$. Similar to the 3D-coil we find an additional small capacitance at the far end of the inductor. With every turn added the model becomes larger but the coupling capacitor parallel to almost the whole circuit mainly determines the behavior. The influence of that element vanishes with relatively thick low-k LTCC tapes.

Capacitors — Capacitors are usually made of two or more plate electrodes with dielectric layer(s) between them. The capacitance is a function of dielectric thickness, material permittivity and electrode area. The capacitance density for LTCC-capacitors is therefore limited by the minimum tape thickness (handling problem) and the tape permittivity which is usually low for microwave applications to get a high phase velocity.

In order to improve the capacitance density, another dielectric material is required. High-k dielectrics are widely known for capacitor pastes. They are mainly based on $BaTiO_3$ or related materials [5]. Several methods to include the high-k material have been introduced. One approach uses the capacitor ink to print the dielectrics directly on the electrode on the green sheet [6]. The top electrode is on the back of the adjacent tape. High-k-dielectrics may also be cast to a high-k-tape. If the shrinkage during firing is matched between low- and high-k tape the high-k tape can be inserted as a separate layer. This results in the problem of possible moisture penetration into the high-k layer at the edges of the substrate. Unmatched tapes can be combined by using the tape insert array method [7], which increases the expenses for mechanical work. Depending on the applied high-k material a capacitance density of about 1 to 3 nF/mm² is possible, but the permittivity is not stable over a wide frequency range [8].

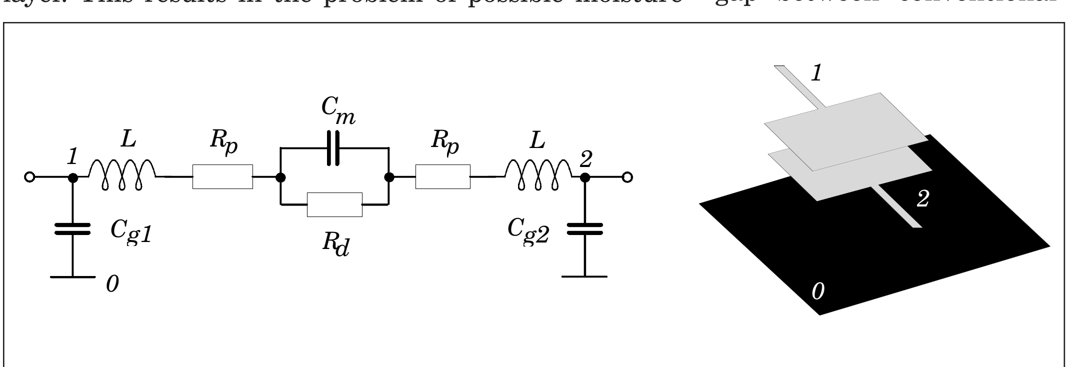
Capacitors in multilayer circuits are represented by a Π-model made by capacitances to ground and inductors in series to the main capacitor C_m. The resistors describe the losses caused by the loss factor of the dielectrics and the conductor. Each plate electrode as well as the steps in the line width at the transition line/plate incorporate inductances.

Investigations carried out on simple configurations showed that the longer the electrodes are the higher the inductive influence will be. That means short wide plate electrodes should be preferred. Another problem is again caused by ground planes. They may be arranged with a distance to the capacitor plates of only one layer. The capacitance C_{g2} of the closest plate to ground is then even higher than the desired main capacitance C_m. A cut-out in the ground plane reduces C_{g2}. On the other hand the inductance of the plates will grow as well, lowering the self-resonance frequency.

Conclusions

Passive components integrated in a dense LTCC-multilayer can be used to reduce the circuit sizes. The variety of designs (layout, material) allows optimized arrangements of elements for high-frequency applications which would not work with discrete components.

The full exploitation of all opportunities offered by the LTCC-technology requires one to consider material, processing and design aspects. LTCC-based circuits or multi-component devices may help to fill the frequency gap between conventional circuit engineering with "ideal" elements far below their parasitic influence and pure microwave applications with transmission line elements. ■



■ **Figure 9. Model and shape of a plate capacitor.**

References

1. A. Elshabini-Riad, N. Moorthy Muthukrishnan, "An Overview of Wide-band Characterization and Modeling of Thick Film Materials and Components," *Proceed-*

ings ISHM '89 Conference, Baltimore, MD, 1989

2. Y.C. Shih, C.K. Pao, T. Itoh, "A Broadband Parameter Extraction Technique For The Equivalent Circuit Of Planar Inductors," *Intl. Microwave Symposium Digest*, June 1-5, 1992, Albuquerque, NM.

3. K.-H. Drüe, H. Thust, "RF-Behavior of Printed Resistors in the Frequency Range up to 6 GHz," *Proceedings ISHM '96 Conference*, Minneapolis, MN, 1996.

4. A. Royla, "HF-Verhalten von gedruckten Widerständen," diploma work, Technical University of Ilmenau, 1996.

5. R. Wahlers, et al., "Low Firing Temperature Capacitor Tape Material," *Proceedings of the International Symposium on Microelectronics*, Dallas, TX, Oct. 1993.

6. Y. Baba, H. Ochi, S. Segawa, "High Reliability Internal Capacitor of LTCC," *IEEE Transactions on Components, Packaging, and Manufacturing Technology* — Part A, Vol. 18, No. 1, March 1995.

7. L. Drozdyk, "Capacitors Buried in Green Tape," *Proceedings of the International Symposium on Microelectronics*, Dallas, TX, Nov. 1993.

8. J. Müller, H. Thust, "3D-Integration of Passive RF-Components in LTCC," *Proc. of the Second Pan Pacific Conference*, Maui, HI, Jan. 1997.

9. J. Müller, H. Riecke, T. Tuschick, "Synthesis of 3D Inductors with Optimized RF Performance," *Proc. of the First Pan Pacific Conference*, Honolulu, HI, Feb. 1996.

10. F. Grandjean, G. Angenieux, B. Flechet, "Extraction of Equivalent Circuits of Hybrid Microstrip Resistor by Harmonic Measurements," *Proceedings of the International Symposium on Microelectronics*, San Francisco, CA. 1992.

11. *Designer's Task Reference*, HP Microwave and RF Design Systems Release 5.0, Hewlett Packard, Edition 2, 1992.

Author information

Dr. Heiko Thust is Dean of the Faculty of Electrical Engineering and Information Technique, the Technical University of Ilmenau, Germany. He holds a Dr.-Ing. and Ph.D. degrees and has done research in microwave techniques and wave propagation as well as hybrid microelectronics. He is a member of NTP subcommittee of IMAPS.

Dr. Karl-Heinz Drüe is a scientific assistant in the Microperipheric group at the Technical University of Ilmenau. He is a member of ISHM. He has a Dr.-Ing. degree and has worked on advanced testing techniques.

Dr. Jens Müller is a development engineer at Micro Systems Engineering GmbH & Co. in the substrate division. He has a Dr.-Ing. degree and has studied thick-film inductors and complex LTCC structures like those described in this article. He is a member of ISHM Germany and IMAPS USA.