A Simplified Equivalent Model for Microwave Characteristics of Porosified LTCC

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Abstract

High frequency materials show a manifold variety of complex permittivities for different applications. Recent research results demonstrated that porosification of Low Temperature Cofired Ceramics (LTCC) represents a new manufacturing technology, which enables local selective reduction of the relative permittivity. The permittivity gradients were measured and subsequently modeled to perform electromagnetic field simulations. The results of the generated complex CAD model can be used, to create a simplified equivalent model, which is suitable for rapid RF circuit design on porosified LTCC. Since material properties vary between circuit components on dense and porous LTCC, the permittivity-dependency on the lumped elements of the transmission line model is considered. It is shown that the introduced porosification gradient can be transferred to an equivalent circuit diagram according to the transmission line model.

1. Introduction

Low Temperature Cofired Ceramics (LTCC) substrates offer numerous benefits for microwave circuits like low dielectric losses $\tan_\delta$, multilayer stack ups with integrated passive components and high relative permittivity ϵ_r. The field expansion shrinks with increasing ϵ_r, which results in smaller microwave structures that keep the required component size small and lowers interference emissions. However, an integration of patch antennas requires separate regions of lower permittivity, in order to achieve efficient radiation characteristics. For this application the state of the art offers a mixture of substrates (e.g. LTCC and polymer) with inherent disadvantages like expensive manufacturing, bond wires with parasitic inductances and different thermal coefficients of expansion that result in local strain and reduced lifetime. A wet chemical porosification process, first presented by [1] overcomes these drawbacks by locally decreasing ϵ_r directly below the surface of the LTCC tape.

This paper presents an analysis of the achieved porosification gradient after [2], which is modeled according to [3] using the time-dependent diffusion equation to emulate the etching process on the LTCC surface. In a second step, the gained simulation results are transferred to a simplified CAD model, consisting of vertically stacked layers, each filled with homogeneous ϵ_r. Afterwards, the influence due to porosification on the lumped elements of the transmission line model is shown.

2. Measurement and CAD Modeling

According to [2], the porosification gradient was measured by scanning electron microscope (SEM) imaging of porosified LTCC. Fig. 1(a) shows the cross section of the porosified substrate, exposed by focused ion beam (FIB). The derived material-air contrast image is depicted in Fig. 1(b), which has been extracted graphically from the SEM measurement results.

Fig. 2 shows the measured material-air fraction of the near-surface region at a depth between 0 µm and 17 µm. The porosification process with the materials DuPont DP951 [4] and Heraeus CT702 [5] were performed under equivalent etching parameters by chemical treatment in phosphoric acid with a purity of 85 vol.% at 130°C for 8 hours.

The application of conductors on highly porous surfaces, suitable for antenna front-ends at 77 GHz, is technically challenging, since the conductive material is not allowed to be deposited within the introduced air. In order to obtain an

(a) SEM Measurement (b) Contrast Image (c) Simulated Model

Figure 1: 2D measurement and CAD model of porosification gradient.

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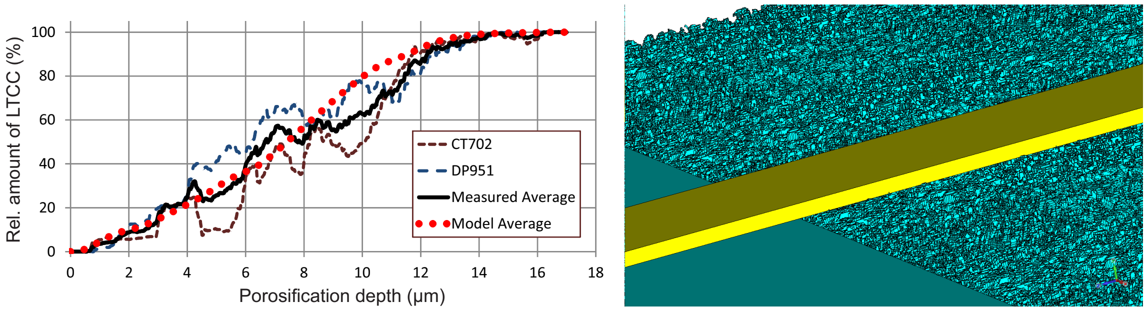


(a) Relative amount of LTCC material over porosification depth

(b) 3D CAD model of conductor on porosified DP951

Figure 2: Measured and 3D modeled porosification gradients.

estimation on the impact by a partially penetrating conductor track into the porosified surface on microwave characteristics, the porous structure was 3D modeled according to the measured porosification gradient. This was accomplished by simulating the etching process with the time-dependent diffusion equation

$$\frac{\partial c(x,t)}{\partial t} - \nabla \cdot (D(x)\nabla c(x,t)) = 0 \text{ in } \Gamma\,, \tag{1}$$

$$c(x,t) = 1 \text{ on } \partial\Gamma_D\,, \tag{2}$$

$$\frac{\partial c(x,t)}{\partial n} = 0 \text{ on } \partial\Gamma_N\,. \tag{3}$$

$c(x,t)$ is the relative liquid concentration of phosphoric acid as a function of space $x \in \mathbb{R}^3$ and time t on the cubic domain Γ. Consequently, the relative material concentration is given as $1 - c$. On one face of Γ, a Dirichlet boundary condition Γ_D is applied, simulating the source of the diffusive process. All other boundaries are Neumann type Γ_N. The initial condition $c(x,0)$ is set to zero in the whole domain, which corresponds to dense LTCC. The alumina grains within the LTCC are hardly affected by the acid and therefore modeled by a lower dissolving coefficient $D(x)$ than in the rest of the domain.

Fig. 1(c) shows a 2D cross section of the resulting simulated CAD model. Due to hardware requirements, the 3D resolution was limited to 1 µm^3 for subsequent electromagnetic field simulations with the generated structure. A comparison with the measurement shows that the achieved resolution within the CAD model is approximately lower by factor 5, but the average of the modeled porosification gradient in Fig. 2(a) is in good agreement with the measurements.

A picture of the generated CAD model is illustrated in Fig. 2(b), showing a conductor partially within porosified DP951. Electromagnetic field simulations from 0 Hz to 110 GHz with different vertical conductor positions on the porosified model were performed. The simulation results for $\epsilon_{r,eff}$ are displayed in Fig. 3(a), with the red continuous line representing the dense LTCC and the blue continuous line with the maximally reduced $\epsilon_{r,eff}$, assuming the best possible position on top of the porous surface.

The simulations show that the effectiveness due to porosification strongly decreases for each µm, the conductor penetrates into the substrate. Consequently, measures must be taken for the conductor applications in order to minimize this occurrence.

Since the computational requirements with this structure are too high for reasonable RF circuit design, a simplified model for these porosified areas on the substrate has been introduced by [2]. Fig. 3(b) shows a cross section of a simplified model, describing the porosification gradient by discretized layers. Additionally it was shown that with increasing number of homogeneously filled layers a saturation effect for the relative deviation $\Delta\epsilon_{r,eff}$ with respect to the complex model takes place. This substitute model is used in the further analysis for a network-based circuit-theory on porosified substrates.

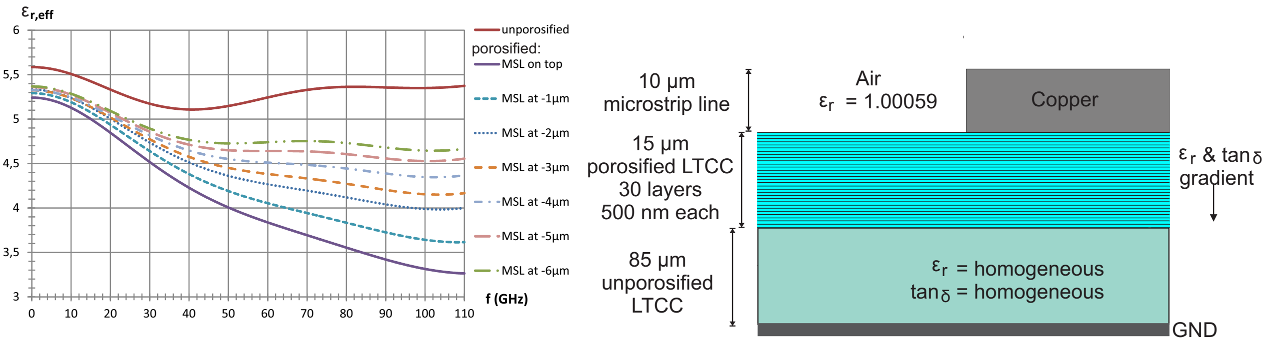
3. Network-based Description of porous LTCC

Fig. 4(a) shows a schematic representation of the elementary components of a transmission line, which are derivates with respect to the conductor length. The newly introduced adapted transmission line model on porous LTCC is depicted in Fig. 4(c), which is described in the following.

According to [7], the characteristic impedance Z_0 of a homogeneous conductor can be calculated by

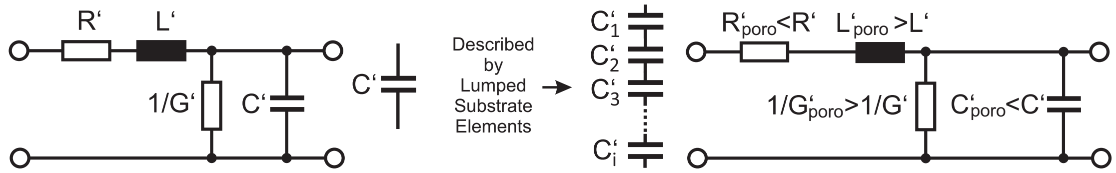
$$Z_0 = \sqrt{\frac{R' + j\omega L'}{G' + j\omega C'}}, \tag{4}$$

where $\omega = 2\pi f$ is the angular frequency. In case of a thin conductor $\frac{W}{h} >> 1$, the characteristic impedance can be approximated according to [8] by (5)



(a) Simulated $\epsilon_{r,eff}$ spectra for various vertical MSL positions (b) Cross section of simplified 3D model for embedded, discretized ϵ_r gradients

Figure 3: Simulation results and equivalent 3D model for permittivity gradient implementation of porosified LTCC.



(a) Transmission Line Model (b) Capacitance by Porous LTCC (c) Lumped Elements with Porous LTCC

Figure 4: Equivalent circuit for infinitesimal short MSL.

$$Z_0 = \frac{120\pi\,\Omega}{\sqrt{\epsilon_{eff}}\left[\frac{W}{h} + 1.393 + 0.667\ln\left(\frac{W}{h} + 1.444\right)\right]}. \tag{5}$$

Since the capacitance C' of a microstrip transmission line (MSL) depends on $\epsilon_{r,eff}$ and the vacuum capacitance C_0, a porosified area comprises a reduced value of C' by $\Delta C'_{poro}$, expressed by

$$C' = \epsilon_{r,eff} \cdot C_0, \tag{6}$$

$$\Delta C'_{poro} = (\epsilon_{r,eff} - \epsilon_{r,eff,poro}) \cdot C_0. \tag{7}$$

Since according to Fig. 3(b) the ϵ_r gradient can be discretized by i homogeneously filled layers, an extension to the capacitance description of a microstrip transmission line has to be applied. Therefore, the discretized capacitance $C'_{poro,disc}$ of an MSL can be modeled as a series of lumped element capacities C'_i, illustrated in Fig. 4(b), leading to

$$C'_{poro,disc} = \xi\left(\sum_{n=1}^{i}\frac{1}{C'_i}\right)^{-1}. \tag{8}$$

The correction factor $\xi < 1$ compensates for the increased electric field spreading in air due to the reduced $\epsilon_{r,eff}$, and therefore the increased electrical distance between the conductor and the ground plane.

A measured porosification gradient can be associated with a vertical permittivity gradient $\epsilon_r(y)$ by using the rules for nonlinear mixtures of materials, e.g., by [9], and described by a fit function. This enables an integral continuous description of $C'_{poro,cont}$ by

$$\frac{1}{C'_{poro,cont}} = \int_0^d \frac{1}{\epsilon_0\epsilon_r(y)\cdot A_{eff}}\mathrm{d}y, \tag{9}$$

depending on the distance of the capacitive coupling d and the effective area A_{eff} of the corresponding conductor. Using (8) and (9), a relative error $\Delta C'_{poro,err}$ due to limited number of discretized layers within electromagnetic simulations can be calculated by

$$\Delta C'_{poro,err} = \frac{C'_{poro,disc} - C'_{poro,cont}}{C'_{poro,cont}}. \tag{10}$$

According to [7] at low frequencies the differential resistance R' and differential conductance L' is nearly constant, which also accounts for porosified substrates. With increasing frequency, the current concentrates at the edges of the MSL, arising from the skin effect. Therefore, R' grows with frequency because of the reduced effective conductor cross section. This frequency-dependent behavior also affects L', which is proportional to Z_0 and the vacuum permeability μ_0.

Since L' is not directly influenced by changes of ϵ_{eff} due to porosification, only the altered current distributions at the transmission line edges cause a slight influence. Comparing porosified LTCC to the dense case, L' mainly depends on the line width W of the microstrip [6]. When maintaining e.g. Z_0=50 Ω on an etched area, the inductance L'_{poro} of a MSL on porosified LTCC grows due increased W by a few %, which can be calculated by (5).

Assuming that the conductor shape on a porosified area is equivalent to the dense case, R'_{poro} is expected to be slightly smaller than R', since the electric field concentration at the lower MSL edge is reduced by porosified LTCC, and therefore the effective conductor cross section will be enlarged.

The electrical conductance G' of dense LTCC is nearly zero. Porosification slightly decreases the electrical isolation of the conductors, because the introduced air lowers the effective thickness of the substrate. Since only near-surface areas are porosified, most of the isolation is preserved and G'_{poro} is marginally larger than G'. However, if LTCC is entirely porosified in its depth, G'_{poro} will rise significantly, and has therefore to be considered in the modified transmission line model for porosified LTCC.

4. Conclusion

In this paper, an electromagnetic model of a chemical etching process on LTCC is presented, which enables the technology of location selective reduction of the effective permittivity within LTCC tapes. Porosification gradients for two different substrates were measured, and reproduced as 3D CAD models using the time-dependent diffusion equation. Since the conductors are expected to penetrate into the near-surface porosified area, 3D electromagnetic field simulations were performed, which revealed the influence of the vertical conductor position on the resulting effective permittivity of the porosified tape.

A simplified layer model was used, to describe the resulting porosification gradient of the complex model. The homogeneously filled layers allow a network-based description of a conductor on a porous area, using lumped elements according to the transmission line model.

It is shown that a reproducible porosification process of LTCC can be described by modifications of lumped elements within the transmission line model, which is suitable for SPICE simulation based RF circuit design.

5. Acknowledgments

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