Tolerance Optimization of an LTCC via transition by a simple method for determining shape sensitivities of slightly shifted metallic surfaces

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***Abstract* — A perturbation approach is presented to estimate the influence of geometry variation on the performance of microwave devices. A first-order expression is given for the change of the scattering matrix due to a slight shift of a metallic surface by using the reciprocity condition between port sources and the perturbated volume element. Based on this result, the consequences of slight geometry changes can be estimated in an intuitive manner from mode field images. This is demonstrated in the practical example of a vertical microstrip-to-stripline transition at microwave frequencies for implementation in an industrial LTCC-process, where robust design is of utmost importance.**

***Index Terms* — Hybrid integrated circuit packaging, tolerance analysis, design centering, Design methodology, Coupled mode analysis**

I. INTRODUCTION

In many processes related to microelectronic production, tolerance requirements are directly related to cost. This means, that decreasing tolerance windows by two often increases production cost by a factor of two or sometimes even more. Hence there will in many cases be the design requirement of hardening a particular electromagnetic structure towards production tolerance. However, only few electromagnetic design tools support reasonable sensitivity analysis on a basis of simulated fields.

In this paper the optimization of a via transition is proposed by means of an intuitive method for calculating the shape sensitivities based on electromagnetic field data, which occurs as a by-product of many contemporary design-tools. The intuitive method is based on the perturbation theory for the scattering matrix presented below. A more rigorous proof will be published elsewhere.

II. MATHEMATICAL FORMULATION OF THE METHOD

As our unpertubed system we consider an N-terminal microwave junction. The junction is defined by metallic surfaces $Q:\vec{r}_{Q_m}(g,h),\quad m=1...M$ We now consider a perturbation consisting in a slight shift of a part of m', i. e. one of the metallic surfaces,

$$Q' = \left\{ \vec{r} = \vec{r}_{Q_{m'}}\left(g(u,v),h(u,v)\right)\right\}. \qquad (1)$$

With the corresponding surface normal vector $\vec{n}(\vec{r}), \vec{r}\in Q'$, the perturbation p is defined by the perturbation volume;

$$V_p : \left\{\vec{r}_p = \vec{r}_{Q'}(u,v) + \xi'\vec{n}(u,v), 0 \le \xi' \le \xi\right\}. \qquad (2)$$

Typical geometries created by shifted surfaces are displayed in Fig. 1, defining in each case a perturbation volume Vp.

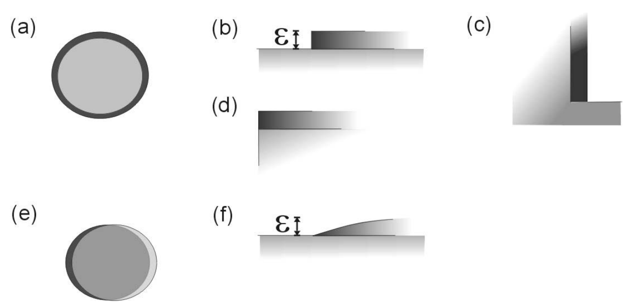

Fig. 1: Basic types of surfaces shifted by ε, the perturbation volume V_p indicated dark; (a) - (d) are cases described by (2a), (e) and (f) are cases described by (2b). The light area in (e) indicates a shift with $f<0$.

For a small shift ξ, the impact on the scattering matrix can be expressed in the following manner:

$$S_{mn}(\varepsilon) = S_{mn}(0) + W_{mn} = S_{mn}(0) + \xi w_{mn} + O(\xi^2) \qquad (2)$$

Both ports of the structure shall be modelled as homogeneous waveguides of infinite length. Sources in the form of electric and magnetic currents fitting the respective waveguide mode $J_n(u_n,v_n)$ and $K_n(u_n,v_n)$ are located in reference planes parameterized by u_n,v_n within the waveguide n and excite its dominant mode propagating into the structure. This mode is assumed to have unit power and zero phase. This mode excited at port n creates an outgoing wave at port m and a reaction between ports n and m can be calculated.

$$\begin{aligned} \langle n,m\rangle &= \iint_{u_m,v_m} E_n J_m - H_n K_m du_m dv_m = \\ &= \iint_{u_m,v_m} S_{mn}E_m J_m + S_{mn}H_m K_m du_m dv_m \qquad (3) \\ &= S_{mn}\iint_{u_m,v_m} E_m J_m + H_m K_m du_m dv_m = S_{mn} \end{aligned}$$

A geometry perturbation like in Fig. 1 can be modelled as an additional current density in the system, which has to obey particular conditions. Most important, its electromagnetic field has to compensate the original fields within the disturbed volume V_p.

Hence it is clear that at the bottom of V_p, which is the border between V_p and the unperturbed metal surface, $j_{P,n}$ obeys the condition

$$j_{P,n}(r) = -j_n(\mathrm{r}) \qquad \mathrm{r} \in \mathrm{r}_{Q'}(\mathrm{g,h}). \tag{4}$$

at the opposite side of the perturbing volume, the new current will be approximately the same as the original current on the unperturbed boundary.

$$j_{P,n}(r + \xi n_{Q'}) = j_n(\mathrm{r}) + \mathrm{O}(\xi) \qquad \mathrm{r} \in \mathrm{r}_{Q'}(\mathrm{g,h}). \tag{5}$$

On the boundary surface of the perturbed volume, which is perpendicular to the unperturbed surface, the current will mainly flow perpendicularly to the original surface. Furthermore it is assumed that the current is continuous and compensates the original *H*-Field within the volume of V_p approximately. These conditions can be fulfilled assuming the following expression for the perturbation current at any point on the surface of V_p with the unit normal vector $\vec{n}$:

$$\vec{j}_{P,n} = \vec{n} \times \underline{\vec{H}}_n . \tag{6}$$

To find the impact of the disturbed current density on a particular port m and the respective *S*-parameter S_{mn}, we realize that reaction is a linear quantity and therefore equation holds:

$$\langle n + j_{P,n}, m \rangle = \langle n, m \rangle + \langle j_{P,n}, m \rangle . \tag{7}$$

For this reason it is sufficient to calculate the reaction between the Source n with the current density $j_{P,n}$ caused by the geometry perturbation on its surface by the source m.

$$\langle j_{P,n}, m \rangle = \oiint_{\partial V_p} j_{P,n} \cdot \underline{\vec{E}}_m dA = \oiint_{\partial V_p} \vec{n} \times \underline{\vec{H}}_n \cdot \underline{\vec{E}}_m dA = \oiint_{\partial V_p} \underline{\vec{H}}_n \times \underline{\vec{E}}_m \cdot d\vec{A} \tag{8}$$

By application of Gauss' theorem we rewrite the surface integration as a volume integration:

$$\begin{aligned} \oiint_{\partial V_P} \underline{\vec{E}}_n \times \underline{\vec{H}}_m \cdot d\vec{A} &= \iiint_{V_P} div\left(\underline{\vec{E}}_n \times \underline{\vec{H}}_m\right) dV = \\ &= \iiint_{V_P} \underline{\vec{H}}_m \cdot rot\underline{\vec{E}}_n - \underline{\vec{E}}_n \cdot rot\underline{\vec{H}}_m dV \end{aligned} \tag{9}$$

Plugging in Maxwell's equations to get rid of the curl operators on the electric and magnetic fields yields the simple expression:

$$\langle j_{P,n}, m \rangle = -j\omega \iiint_{V_P} \mu \underline{\vec{H}}_m \cdot \underline{\vec{H}}_n + \varepsilon \underline{\vec{E}}_m \cdot \underline{\vec{E}}_n dV . \tag{10}$$

For the *S*-parameter set $S_{nm}(\xi)$, for small perturbations V_p, which are parameterized with ξ,eqn (2) becomes, considering eqns (3) ,(7), (8) and (10),

$$S_{nm}(V_p) = S_{nm} - j\omega \iiint_{V_P} \mu \underline{\vec{H}}_n \cdot \underline{\vec{H}}_m + \varepsilon \underline{\vec{E}}_n \cdot \underline{\vec{E}}_m dV + O(\xi^2) . \tag{11}$$

This as a start holds for perturbations, where a metal surface is translated in such a way that a volume element which previously contained electromagnetic fields afterwards is filled by metal. Cases like in Fig. 1e, where a previously metal filled volume afterwards is filled by the nearby dielectric would require suitable continuous extrapolation of the electromagnetic fields first. However, it seems also appropriate to firstly calculate a positive translation of the same size and to count this value negatively in eqn. (11) afterwards.

The above considerations imply that the sensitivity of S_{nm} with respect to geometry change is directly related to the coupling density

$$\chi_{nm} = \mu\, \vec{H}_m \vec{H}_n + \varepsilon\, \vec{E}_n \vec{E}_m . \tag{12}$$

IV. APPLICATION TO AN LTCC INTEGRATED TRANSITION

In this section the use of the method with respect to the design of microwave structures is demonstrated. In mass-production LTCC-processes one of the most important tolerance mechanisms is related to imperfections in the stacking of the readily patterned green-sheets, which lead to misalignment between the via-positions as well as the conductor pattern in adjacent layers. This misalignment is most critical in structures extending over several patterned layers of the final module.

For this reason as a practical example a microstrip-to-stripline transition for implementation in LTCC will be investigated. The microstrip conductor on top of the ceramics is guided through a hole in the associated groundplane into a stripline environment in a way that the microstrip groundplane at the same time forms the upper groundpane of the stripline environment. The electrical connection between the microstrip- and stripline conductors is established using two stacked vias. Further vias are necessary for balancing the currents on the top and bottom stripline groundplanes and for shielding and suppressing parallel plate waves. An idea of the geometry can be gained from Figure 2.

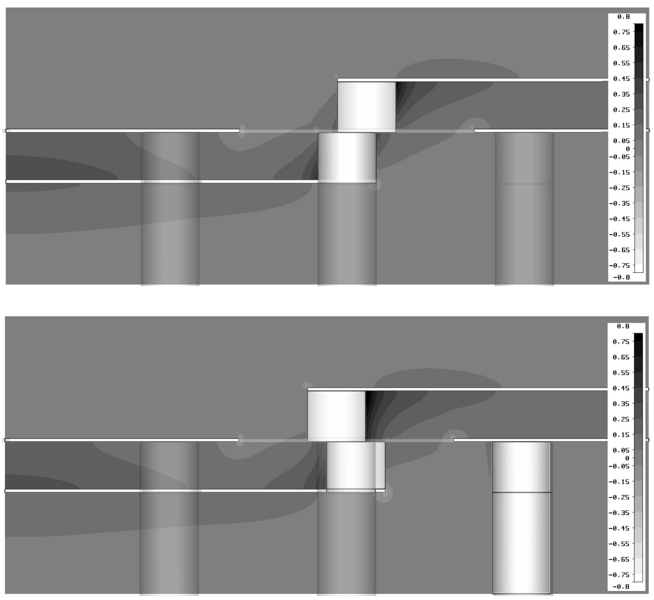

Fig. 2: Via transition with the upper via shifted forward (upper image), and backward (lower image). The coupling density between left-and right moving modes is indicated by greyscale

A rigid tolerance analysis has been carried out using monte carlo techniques but also the methodology described above and it turned out that those techniques complement each other in a very advantageous manner, since the calculus presented in this paper opens an intuitive possibility for discovering optimization potential. The coupling density (12) is shown for a configuration with vias shifted backward and forward. The coupling densities on the left and the right of vias are very different for the backward shift, and more similar for the forward shift. A further small shift of the upper via to the right would produce a positive shift on the right side and a negative shift on the left side. For the forward shift, eqn. (11) yields a much smaller value, because contributions from the left and right areas cancel by some degree. Furthermore, a smaller value from (11) for the forward shift is expected from the absolute values of the coupling density.

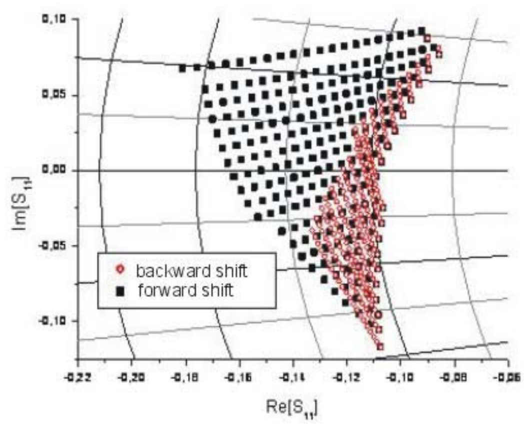

Fig. 3: Simulated values of scattering matrix element for reflection of the via transition of Fig. 3 for various values of the forward and backward shift.

To verify this prediction, a simulation has been carried out using a 2,5D EM simulation tool. Starting from the perfectly centered and aligned case, the via positions of upper and lower via have been set to relative positions of –50 micron up to +50 micron with 10 micron steps. This makes 121 configurations altogether, the input reflection of which can be seen in Fig. 3. The diagram is divided in two groups of points for easier legibility. Points marked 'forward shift' indicate via positions where the top via is positioned on the right of the bottom via. This corresponds to a field distribution similar as the one in Fig. 2 (upper image). Points marked 'backward shift' belong to via positions as indicated in Fig. 2 (lower image), where the top via was shifted to the left of the bottom via.
It can be seen that in the group named 'backward shift' the points are much closer together although the parameter step is the same for both groups. The totally covered area for the regions of forward shift and backward shift are equal for the parameter space but behave like 1:3 for the area covered in the Smith-diagram. Hence it can be stated, that a slight offset in the central via positions of the investigated transition result in a significant gain in robustness.

V. CONCLUSION

A first order scattering theory based on computed mode patterns is given for application in electromagnetic structures with one or multiple ports. It can be used to gain a quantitative as well as a qualitative understanding of tolerance impact on a given design. The quantitative aspect can be helpful when optimizing geometry parameters. But often the qualitative understanding of tolerance-impact by visualizing its density-function is even more helpful since it opens room to find structural improvements instead of just tuning parameters.

V. ACKNOWLEDGEMENT

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