Design of Embedded High Q-Inductors In MCM-L Technology

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Abstract — **Although discrete surface mount passive components (resistors, capacitors and inductors) have been popular in mixed signal designs, the development of integrated passive components suitable for integration with printed wiring boards is relatively recent. This integration is imperative since in some mixed signal designs, off-chip passive components take up more real estate on the boards than the analog and digital signal processing units. This paper shows the possibility of fabricating a large number of MCM's with high wiring density and integrated passives using standard PWB technology. However, the presence of inherent lossy materials in standard PWB technology reduces the Q factor of embedded passives in the more traditional components such as spiral inductors. In this paper, the embedded passives were modeled using coupled line parameters obtained using quasi-TEM approximations. This modeling approach provides advantages and more insight over the more traditional methods for modeling embedded passives. Based on this modeling approach a systematic method to improve the quality (Q) factors of the integrated inductors is also presented based on a layout optimization scheme. By departing from the traditional spiral inductors, a max Q-factor of 103 was obtained for an 11nH inductor at 2.2 GHz with a resonant frequency of 3.6 GHz. Several other inductors have been obtained with Q-factors ranging from 23-38 for inductors ranging from 28nH to 20nH respectively. The authors believe that this is the first paper showing such high Q-factors for embedded passives in organic technology.**

I. Introduction

The trend in portable wireless electronics is to combine digital and radio frequency (RF) circuits into compact mixed signal modules. Embedded passive components represent an exciting emerging technology that has the potential of increasing reliability and integration and at the same time reducing cost and shrinking sizes of devices. However, it is imperative to model the behavior of passive components, which are constituents in critical components such as filters, couplers, phase locked loops, etc., extremely accurately and in a reasonable CPU time. The trade off of speed vs. accuracy is one that has always plagued designers and it is the goal of the design community to come up with solutions that are fast and accurate for modeling embedded components. Besides the difficulty in modeling embedded passives, the presence of severe parasitic effects in silicon-based RF IC's makes the design of high Q reactive components difficult [2,3]. Low temperature cofired ceramic (LTCC) MCM's for RF and wireless systems [4,5] have provided a solution to the above problem. However, LTCC is an extremely expensive process to implement for consumer applications.

This paper demonstrates the design of high Q inductors and other embedded components on an MCM-L type process implemented at the Packaging Research Center, Georgia Tech. The substrate was processed as an effort to developing novel technologies for low-cost, integrated substrates involving multi-layer thin films using sequential build-up (SBU) technology on organic laminates [1]. By moving away from the traditional spiral inductors to inductors with cascaded loops, a max Q-factor of 103 was obtained for an 11nH inductor at 2.2 GHz with a resonant frequency of 3.6 GHz. The size and inductor performance compare well with the inductors characterized in [4,5], which were fabricated using LTCC. Several other inductors have been obtained with Q-factors ranging from 23-38 for inductors ranging from 28nH to 20nH respectively. These results prove the possibilities of using ordinary PWB technology, with inherently lossy substrates, as a possible candidate for embedding high Q components in a low cost process. The design, fabrication and characterization have been discussed in Section II.

The accurate modeling of embedded passive components is as imperative as measurement in order to characterize their behavior. Embedded passives have been modeled using several approaches. One approach is to use commercial full-wave EM solvers, based on Finite Element Theory (FEM) or Method of Moments (MOM), but these simulations are long and optimization is non-trivial. Although empirical models are currently available in RF design systems such as Libra and Advanced Design System (ADS by Agilent), models need to be developed for new processes. An empirically based predictive modeling method is presented in [7] using equivalent circuits. In [8], a method is presented to synthesize lumped-element circuits of embedded RF components directly from rational functions. Another approach is to use lumped component approximations for the transmission lines and discontinuities. However, this approach induces artificial ringing in the simulated response.

In this paper, a method is presented to simulate n-port embedded RF components using coupled line parameters obtained using quasi-TEM approximations. The coupled line approach uses a distributed model, which is discussed in section III. The discontinuities in the circuit, such as the bends, vias and steps in width, can be modeled using scalable models [8], which is also discussed in section III. The system response for the complete passive structure is obtained using the theory of segmentation, which is also discussed, in section III [9]. This modeling approach is useful for new processes where models are currently unavailable and predictive modeling can get very tedious. It also provides independence from full wave simulators and circuit simulators, which are expensive and tedious to use. The modeling of embedded passive component responses using coupled line parameters, known well to digital and analog designers, will be extremely beneficial for mixed signal designs and applications with embedded components.

This modeling technique also provides a better understanding of the parasitic effects of discontinuities, multi-coupled line proximity effects, and skin effect losses and eddy current losses. This understanding is required to reduce parasitic effects in low-cost, however lossy substrate technology, such as the MCM-L technology discussed in [1]. The use of spiral inductors reduces the required area for required nominal inductance but has low Q-factors. By cascading the loops of the spiral inductors in series as discussed in section II, significantly higher Q-factors were obtained. The authors believe that is the first paper demonstrating such high Q-factors for embedded passives in organic technology.

II. HIGH Q-INDUCTORS IN MCM-L TECHNOLOGY

The current generation of processing available at the Packaging Research Center, Georgia Tech involves high density wiring layers and integral passive components. The cross section of the test vehicle fabricated is shown in Fig. 1. The shaded areas represents the conductor layers with 9 um Copper electroplated on to them. The details of the processing and its advantages over other higher cost processes have been discussed in [1].

Fig. 1. Cross-section of MCM-L layout

The substrate, as mentioned, was lossy. FR4 has a tanδ=0.01 and ε_r=3.7 at 1GHz. Dupont Vialux has a tanδ=0.015 and ε_r=3.4 at 1GHz. Several embedded passives were designed on this substrate to characterize its performance. Some of the few that have been measured and analyzed are discussed here. Fig. 2 shows the top-view of the cascaded loop microstrip inductors. These were fabricated on the top metal layer (Metal 3A) with Metal (1B) as the ground reference. This provided a ground plane separation of approximately 42 mils, which is well suited for planar microstrip inductors. The solid lines are 2 mil copper traces on Metal 3A and the solid gray lines represent the crossovers and underfils on Metal 2A. The shaded gray block is the reference ground plane connected to bottom ground plane, Metal 1B, using through-hole vias.

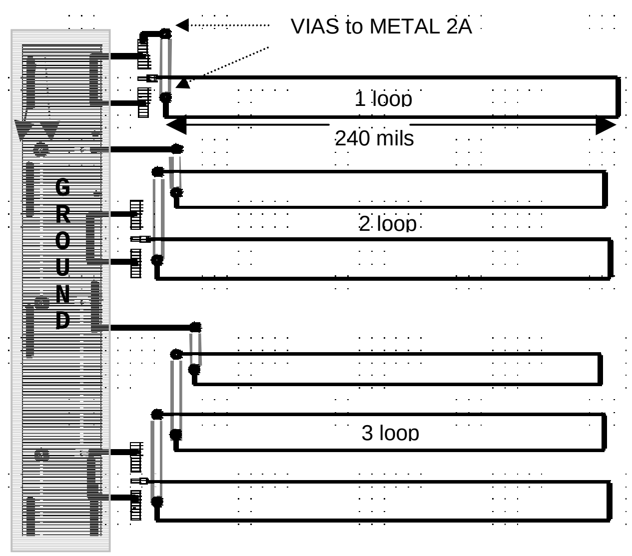

Fig. 2. Top view of cascaded loop inductors

Table I, shows the tabulated data for the inductors shown in Fig. 2. A max Q-factor of 103 was obtained for the one loop inductor using 1-port network analyzer measurements. The VNA was first calibrated using standard SOLT (short-open-load-thru) calibration. Max Q-factors of 38 and 23 were obtained for the 2-loop and 3-loop microstrip inductors respectively.

Type	Qmax	L(nH)	Area (mils^2)	SRF (GHz)
1 loop microstrip	103 at 2.2 GHz	11nH at 2.2GHz	240 * 21	3.6
2 loop microstrip	38 at 1.2 GHz	20.5nH at 1.2GHz	240 * 60	2.2
3 loop microstrip	23 at 0.65 GHz	29nH at 0.65 GHz	240 * 86	1.6

Table. 1. Tabulated data for Microstrip Loop Inductors

Fig. 3 show the normalized reactance vs. frequency and Fig. 4 shows the measured Q-factors vs. frequency for the inductors shown in Fig. 2.

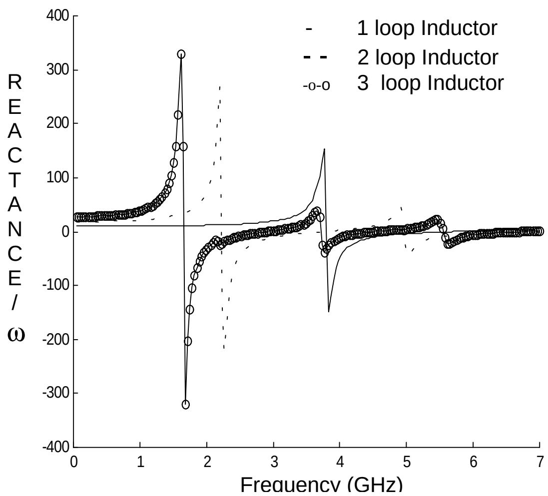

Fig. 3. Reactance vs. Frequency for loop inductors

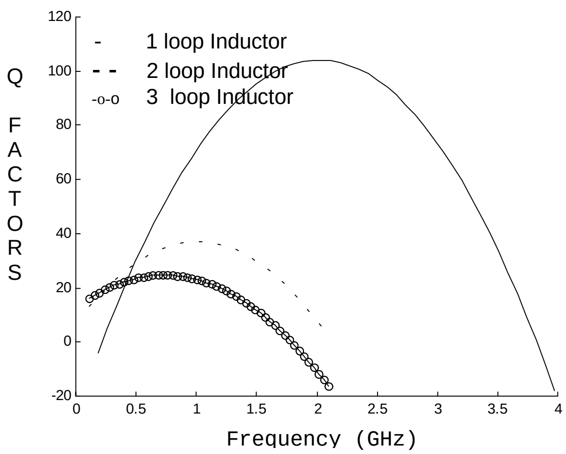

Fig. 4. Q-Factor vs. Frequency for loop inductors

Several embedded microstrip inductors were also fabricated and measured but did not provide high Q-factors because of the reduced separation from the ground plane. These inductors were characterized easily using the modeling technique discussed ahead.

III. Modeling Of Embedded Passives

A set of 'n' coupled lines can support 'n' independent modes of propagation (called normal modes). This section explains the methodology to capture the responses of coupled lines using the quasi-TEM modes of propagation. The accuracy of this assumption improves as the ratio of the wavelength to the thickness of the dielectric increases. A 2D electromagnetic solver such as ANSOFT 2D provides characteristic mode impedances and propagation constants for lossy and lossless lines. The mode impedances and propagation constants can be used to create a distributed model for the multi-line coupled line section. The advantage of using a distributed model is that it prevents artificial ringing induced by lumped circuit equivalents of the same structure. A Z-matrix for a set of 2 symmetric lossless coupled lines of length, L, can be obtained from the even-mode impedance (Z_{oe}), odd-mode impedance (Z_{oo}), even-mode propagation constant (β_e) and odd-mode propagation constant (β_o) as follows [6]:

$$Z_{11}=Z_{22}=Z_{33}=Z_{44}=Z_{oe}.\cot(\beta_e L) + Z_{oo}.\cot(\beta_o L)$$
$$Z_{12}=Z_{21}=Z_{34}=Z_{43}=Z_{oe}.\cot(\beta_e L) - Z_{oo}.\cot(\beta_o L)$$
$$Z_{13}=Z_{24}=Z_{31}=Z_{42}=Z_{oe}.\csc(\beta_e L) + Z_{oo}.\csc(\beta_o L)$$
$$Z_{14}=Z_{23}=Z_{32}=Z_{41}=Z_{oe}.\csc(\beta_e L) - Z_{oo}.\csc(\beta_o L)$$

The analysis can be extended to asymmetric multi-line lossy-coupled line sections using the analysis in [6]. The capability to analyze asymmetric coupled lines in segments of the embedded passives also enables the designer to optimize the performance of RF passives on varying parameters such as different widths for different coupled line sections in the passive. An example of such an optimization would be in the case of spiral inductors where wider outer turns and narrower inner turns help reduce ohmic losses in the outer and eddy current losses in the inner turn respectively [3]. Another optimization technique is to reduce eddy current losses and coupling losses by cascading thin microstrip loops, (Section II), instead of using spirals. The discontinuities in the circuit were modeled using the concept of scalable models, which is an extension of the work done in [9]. These models were then cascaded using segmentation discussed ahead.

Consider two multi-port segments, A and B with $n+q$ and $r+m$ ports respectively with q ports from the first segment connected to r ports from the second segment.

The Z-matrices of the segments A and B can be written together as

$$\begin{bmatrix} \mathbf{Vp} \\ \mathbf{Vq} \\ \mathbf{Vr} \end{bmatrix} = \begin{bmatrix} Zpp & Zpq & Zpr \\ Zqp & Zqq & Zqr \\ Zrp & Zrq & Zrr \end{bmatrix} \begin{bmatrix} \mathbf{Ip} \\ \mathbf{Iq} \\ \mathbf{Ir} \end{bmatrix} \qquad (1)$$

Where,

$$Vp = \begin{bmatrix} Vn \\ Vm \end{bmatrix}, \quad Ip = \begin{bmatrix} In \\ Im \end{bmatrix}$$

And

$$Vq = Vr \text{ and } Iq + Ir = 0 \qquad (2)$$

Substituting the above equation (2) into (1) the Z-matrix for the overall network is given as

$$Zp = Zpp + (Zpq - Zpr).Zrq.(Zrp - Zqp)$$

$$Zrq = (Zqq - Zqr - Zrq + Zrr)^{-1} \quad [9]$$

Fig. 5 shows a 2-turn microstrip inductor simulated in SONNET, which simulates microwave planar structures using the Method of Moments (MOM) technique. The technique has also been verified for 1-, 2 ¼-, 2 ½- and 3 turn inductors. The segmentation of 2-turn inductor structure is shown in Fig. 3 as a cascade of varying lengths of coupled line sections and coupled and single bend discontinuities (shown as the dotted line boxes).

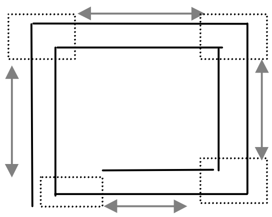

Fig. 5. Segmentation of 2-turn inductor

The response for the 2-turn inductor using the segmentation theory is compared to the simulation in SONNET in Fig. 6. The simulations show excellent correlation.

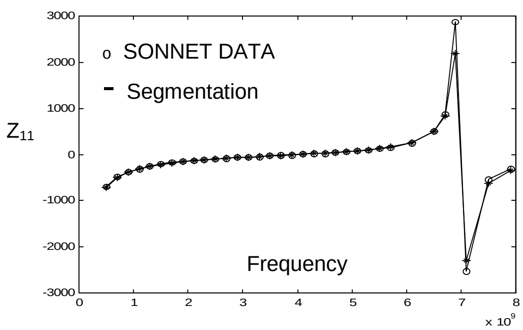

Fig. 6. SONNET vs. Segmentation Theory for 2-turn inductor

This modeling approach is useful for new processes where models are currently unavailable and predictive modeling or modeling based on experience can get very tedious, especially if optimization is desired.

V. COMPARISON WITH LTCC

LTCC processing capabilities have made it the most suitable process for mixed signal designs, high-density wiring and embedded passive integration. Although, it is an expensive process to implement, it provides an excellent benchmark for any alternative processes towards integrated MCM's. [4] Presents RF/Microwave characterization of 20-layer ceramic (LTCC) based technology. A relatively high Q of 52 at 1.3 GHz was obtained with an effective inductance of 6.7 nH. The 2D planar inductor was approximately 1.2*1.2mm^2. In [5], a higher Q of 83 was recorded for an inductor of 6 nH. However, the area of the inductor (3.5*3.5*1.6 mm^3) is rather large for a mixed signal design application. The inductors in MCM-L technology were measured against these benchmarks. By moving away from the traditional spiral inductors, a max Q-factor of 103 was obtained for an 11nH planar 2D inductor at 2.2 GHz with a resonant frequency of 3.6 GHz as discussed in Section II. The area of this inductor was 6*0.5mm^2, which compares well to the inductors fabricated using LTCC [4,5]. These results clearly indicate the inexpensive organic laminate technology as an alternative to LTCC.

VI. CONCLUSION

The paper demonstrates the feasibility of using ordinary MCM-L based on organic substrate as a extremely cost effective, high density RF/microwave packaging solution with embedded passives. A more practical modeling technique provides insight into optimizing the performances of embedded passive and inter-connect structures using the fundamental concepts of coupled line and segmentation theories. The high Q inductor measurements and modeling technique together show the possibility of using inexpensive organic technology to integrate mixed signal designs in the future as an alternate to expensive processes such as LTCC and also as an alternative to the inherently lossy processes such as on chip components (SOC) technology.

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