De-Embedding Considerations for High Q RFIC Inductors

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***Abstract* — In this paper, considerations for accurate de-embedding technique using the "open-thru" de-embedding methodology, aimed at de-embedding of high quality factor (Q) radio frequency integrated circuit (RFIC) inductors will be presented. In addition, proper design of on wafer ground-signal-ground-signal-ground (GSGSG) probe tip padset and de-embedding structures ("open" and "through") will be discussed. It will be shown, through EM simulations that accurate characterization of properly designed de-embedding structures results in very reliable and accurate de-embedding using the previously developed "open-thru" de-embedding method.**

***Index Terms* — De-embedding, inductor characterization, open-thru method, padset.**

I. INTRODUCTION

The accurate modeling and characterization of on-chip passive devices such as inductors, transmission line interconnects, baluns, transformers and others are critical for a first-pass design success. To develop accurate passive device models, measured test site S-parameter data (with subtracted padset parasitics) needs to be available. This would then allow major passive device electrical parameters such as quality factor (Q), resistance (R), inductance (L), capacitance and characteristic impedance (Z) to be extracted and compared with a device model or preliminary electromagnetic (EM) simulation results.

A number of simple and accurate de-embedding techniques have been developed in the past for on-wafer active and passive device characterization [1-4]. They allow for probe padset parasitics to be subtracted from the "device with attached padset" measurement data thus giving the S-parameters of a device itself.

Among the various on-wafer de-embedding techniques, the "open-short" method [1] is very well known. The problem with this technique is that it is always difficult to properly design an ideal "short" device, in particular in more advanced multi-layer metal processes that require stacked vias for connection to lower level metals that are typically connected to ground, as pointed out in [4,5]. The open-thru de-embedding technique [4] doesn't require "short" device measurements and is therefore used in this work.

The open-thru de-embedding method models the measurement probe padset as a series impedance and shunt admittance. The technique uses measured "open" and "through" devices to generate S-parameter blocks which correspond to a realistic "short" structure. When a realistic "short" device is constructed, the standard "open-short" method [1] is employed to complete the de-embedding procedure. In the original work [4] it wasn't verified if the accuracy of the proposed "open-thru" method is affected by a padset design. The proposed method in [4] also uses a low frequency resistance value of a "through" device bridge as a part of a construction of a realistic "short" de-embedding device process. That approach works fine when a "through" device bridge is short enough that it has negligible parasitics. In the case of longer bridges low frequency resistance cannot be used safely over a wide frequency bandwidth and the bridge inductance can't be neglected as well.

This paper shows how a GSGSG probe padset design can be modified to improve the overall de-embedding accuracy when using the technique described in [4]. Paper also presents some modifications done to the original "open-thru" method formulation which are necessary to achieve an accurate de-embedding when a "through" device bridge is too long so it can't be modeled just by its low frequency resistance value. We will use a high Q differential inductor design (which has small self RL values) as a test vehicle to verify the newly proposed GSGSG probe padset design and "open-thru" de-embedding technique modifications.

II. DE-EMBEDDING OF HIGH Q RFIC INDUCTORS

This study was conducted on structures designed in a 0.18um RFCMOS process technology. A high Q differential inductor was designed using a six metal layer stack. Suitable open and through de-embedding structures were designed for an open-thru de-embedding procedure. The study began with the investigation of whether the simulation of the intrinsic device (inductor without pads) would match the characteristics of a de-embedded inductor. To obtain the characteristics of the intrinsic device accurately, EMX[6], a full-wave simulator was used. The intrinsic inductor, the inductor with attached padset as well as the de-embedding open and through structures were all characterized in the simulation environment. Figs.1a – 1c show the layouts of the inductor and the de-embedding structures. The inductor is designed using the topmost metal layers 6 and 5 and has a poly shield. The padset for RF contact has a low resistivity metal 1 layer under the signal pads that shorts the ground pads together and also shields the signal pads from the substrate. The open-thru de-embedding technique was then applied to the simulated data and the resulting de-embedded characteristics of the inductor were compared with the characteristics of the simulated intrinsic inductor. In applying the open-thru de-embedding technique, two approaches were used – a) the open-thru case where the characteristics of the bridge of the through de-embedding structure is assumed to be static with frequency and b) the open-thru-stub case where the bridge is simulated accurately to include the frequency effects.

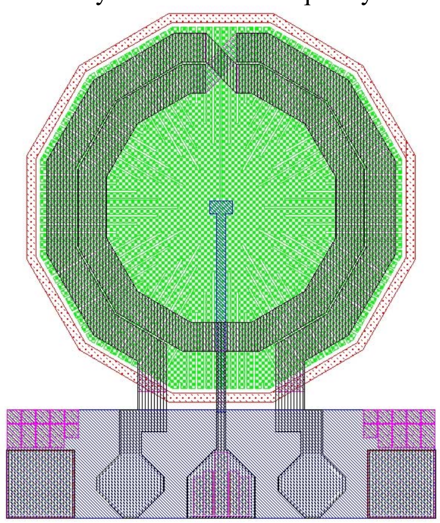

Fig1a. Inductor with padset

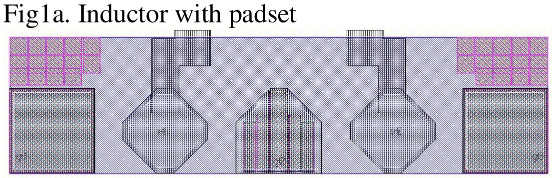

Fig1b. Open de-embedding padset

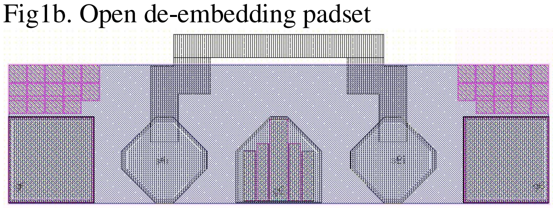

Fig1c. Through de-embedding padset

Figs. 2a – 2c show the comparison of the inductor characteristics of the intrinsic device (no Pads) and the device after open-thru and open-thru-stub de-embedding. From these it is seen that there is a noticeable difference between the deembedded inductor characteristics and the characteristics of the intrinsic inductor.

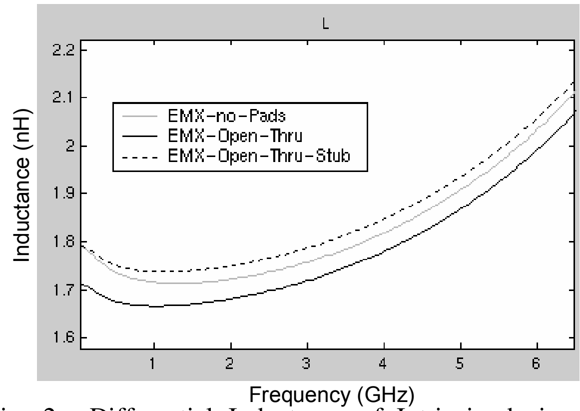

Fig. 2a. Differential Inductance of Intrinsic device Vs open-thru and open-thru-stub de-embedded data

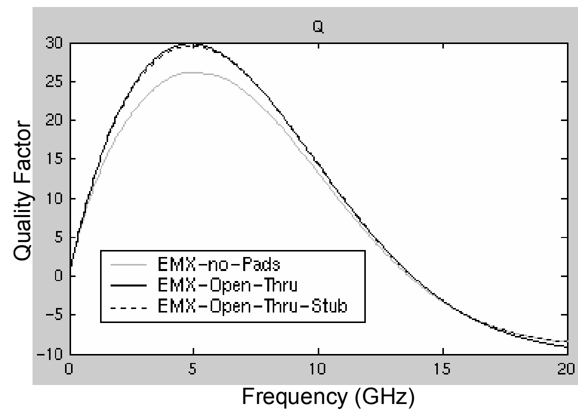

Fig. 2b. Differential Quality factor of Intrinsic device Vs open-thru and open-thru-stub de-embedded data

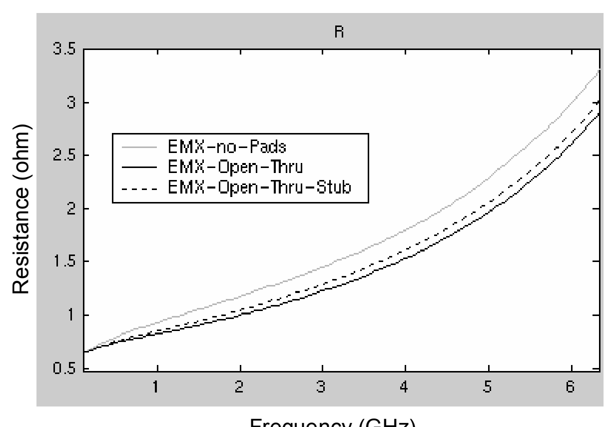

Fig. 2c. Differential Resistance of Intrinsic device Vs open-thru and open-thru-stub de-embedded data

III. IMPROVING DE-EMBEDDING ACCURACY

Figs. 2a-2c indicate inherent inaccuracies in the de-embedding methodology using the padsets shown in Figs. 1a – 1c. To investigate the reasons for the inaccuracies, the de-embedding structures were investigated thoroughly and several experiments were conducted to investigate the factors that influence the de-embedded data. After several EM simulation experiments, it was identified that the problem could be linked to the layout of the de-embedding structures which had a rectangular block of M1 layer under the entire pad/de-embedding structures. This low resistivity M1 layer under the probe pads seemed to be causing undesired coupling effects between the input and output signals of the GSGSG padset which is not properly accounted for in the de-embedding technique. To verify that the discrepancies between the intrinsic device simulation data and the de-embedded data can be distinctly attributed to the M1 layer under the probe pads, the simulation experiment was repeated on the original layouts with the M1 block under the padsets removed. Figs. 3a – 3c show the inductor characteristics and comparisons of the intrinsic and de-embedded inductor.

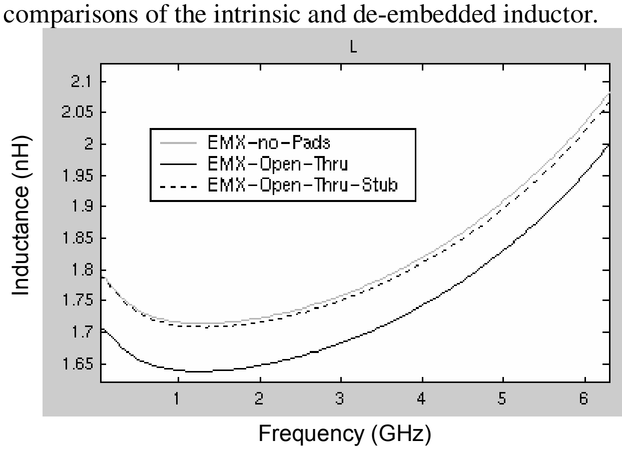

Fig. 3a No M1 shield under padset: Inductance of Intrinsic device Vs open-thru & open-thru-stub deembedding

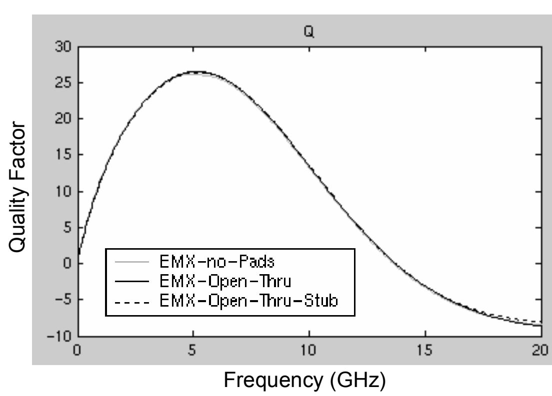

Fig. 3b. No M1 shield under padset: Q of Intrinsic device Vs open-thru & open-thru-stub de-embedding

From the figures it can be seen that when the M1 block under the padsets is removed, there is excellent correlation between the de-embedded and intrinsic inductor data. It can also be seen that using the frequency dependent model for the through bridge (labeled as open-thru-stub case in the figures) as opposed to a fixed resistance (labeled as open-thru case) to account for the through bridge makes a significant impact on the accuracy of the open-thru de-embedding technique. The experiment of removing M1 block under the padsets demonstrated that the de-embedding inaccuracies using the open-thru methodology were linked to the M1 shield under the pads. However, the purpose of M1 shield under the pads is to provide shorting of ground pads and shielding from substrate effects.

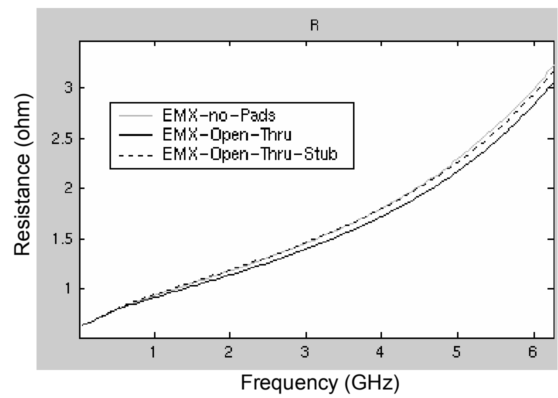

Fig. 3c No M1 shield under padset: Resistance of Intrinsic device Vs open-thru & open-thru-stub de-embedding

Therefore completely eliminating the M1 shield was not desirable. Careful consideration of the factors that contribute to the de-embedding inaccuracies when the M1 block is present under the pads lead to the following conclusions: a) The M1 block under the pads was coupling to the bridge of the de-embedding- through padset which is not accounted for in the de-embedding algorithm; b) The signal pads of the de-embedding GSGSG padsets were coupling to each other through the low resistivity M1 underneath. To conclusively prove that the M1 to bridge coupling was a strong factor in the de-embedding inaccuracies, the simulations were repeated for layouts where the M1 block under the padsets was made much narrower such that the M1 edge was significantly far from the through bridge. This showed significant improvement in the de-embedding accuracy. Following this, the layout was further modified to cut out slots in the modified (narrow) M1 block between the signal pads of the GSGSG padsets to isolate the input and output signals. Figs. 4a shows the layouts of the modified through de-embedding padset reflecting the narrow M1 block with slots under the

GSGSG padsets. The open as well as inductor with pads are designed with the same modifications in M1.

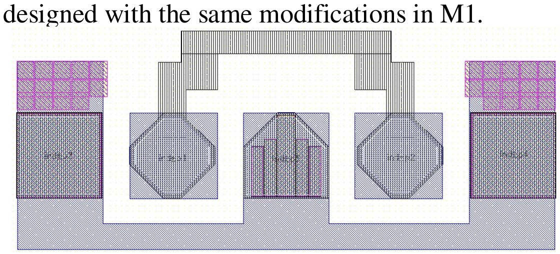

Fig4a. Modified Through Padset (Narrow M1 with Slots)

The simulations were repeated for the modified layouts and it was seen that this resulted in very accurate de-embedding. Figs. 5a-5c show the comparisons of the intrinsic inductor characteristics with those of the de-embedded inductor. The figures show the inductor characteristics for the case where a static resistance is used for the bridge as well as for the case where a frequency dependent simulation result is used for the through bridge. From the figures it can be seen that the modified layouts with the narrow M1 with slots to isolate M1 from the through bridge and to minimize signal-signal cross talk leads to very accurate de-embedding. As mentioned earlier, it is also seen that for accurate de-embedding using the open-thru technique, it is best to use a frequency dependent model for the bridge of the through padset.

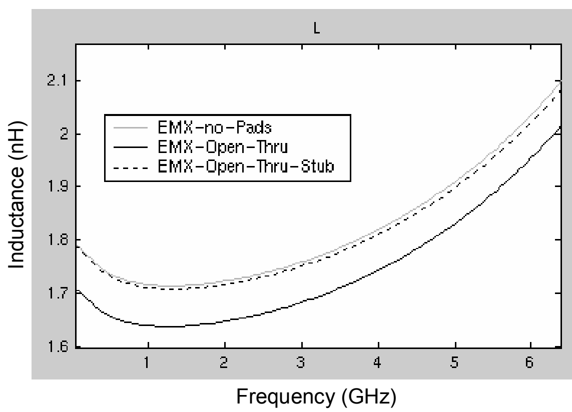

Fig. 5a. Narrow M1 with slots: Inductance of Intrinsic device Vs open-thru and open-thru-stub de-embedded data

IV. CONCLUSION

It was shown that for a differential inductor, particularly with a long gap between the inductor inputs, the de-embedding through device will have a long bridge and it is necessary to describe the bridge with frequency dependent characteristics when constructing a realistic 'short' device for open-thru de-embedding. It was also shown that accurate EM simulations can be used to design proper padsets which can provide accurate de-embedding. The results in this paper also show that with proper design of pads, the open-thru de-embedding technique results in very accurate de-embedded data.

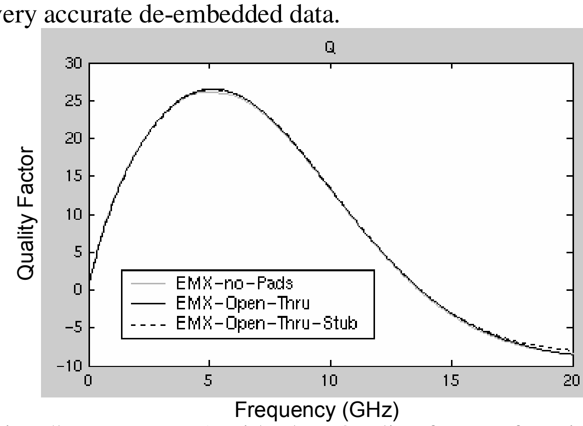

Fig. 5b. Narrow M1 with slot: Quality factor of Intrinsic device Vs open-thru and open-thru-stub de-embedded data

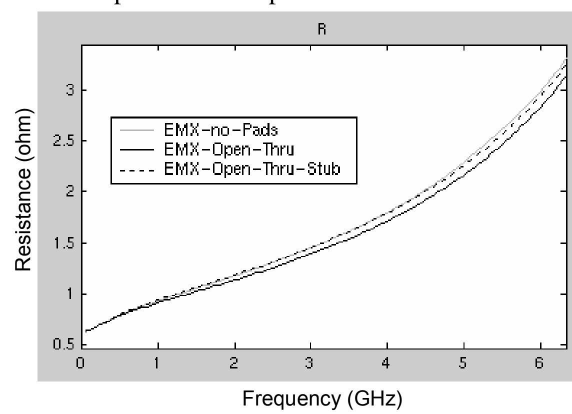

Fig. 5c. Narrow M1 with slots: Resistance of Intrinsic device Vs open-thru and open-thru-stub de-embedded data

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