Very high-Q inductors using RF-MEMS technology for System-On-Package wireless communication integrated module

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Abstract: **We present the fabrication and the characterization of very high-Q suspended RF-MEMS inductors for RF applications in C-band, X-band and Ku-band. The fabrication technique relies on conventional MEMS micro-machining on a low cost ceramic RF substrate. This low temperature, low cost manufacturing technique is therefore compatible with the fabrication of a complete S-O-P wireless integrated module. A physical based model of the inductors is presented. It takes into account the influence of substrate losses and radiation losses. The fabricated devices exhibit very high performances such as Q above 100 and self-resonance frequency as high as 50 GHz.**

I. INTRODUCTION

The integration of RF front-end modules has emerged as a key driving force for the development of next generation of wireless data communication systems. For these portable and low-powered applications, high level of integration, high performances components and low cost manufacturing techniques are required. However, quality factor and frequency limitations still limit RF front-end circuitry to a large number of discrete passive components and make RF front-end module integration very critical. High-quality factor (Q) inductor design and fabrication remain a challenge for applications that depend on passive components performance (i.e. low phase-noise voltage-controlled oscillator (VCO), power amplifier (PA), low noise amplifier (LNA) and double-balanced Gilbert-cell mixers. On-chip inductors suffer from low Q-factor and high parasitic effects due to substrate losses. Active circuitry simulating inductors show high power consumption and noise injection. Therefore, innovative designs, fabrication technologies and suitable materials are needed in order to improve inductors performances (high Q, high peak-Q frequency). Examples of implementations on both ceramic and organic multi-layer interconnection substrates for System-On-Package (SOP) solution have been reported [1]. This emerges as the most effective approach to achieve cost and size reduction while satisfying the performances and specifications required by the new wireless communication systems. Additionally, a large body of literature reports on MEMS based manufacturing technologies that allow fabricating suspended microstructures i.e: suspended micro-inductors. Such a configuration enhances the performances of the device by reducing the influence of substrate losses. However, RF-MEMS inductors reported to date do not exhibit quality factors exceeding 80 and the self-resonance frequency (SRF) is limited to 10 to 20 GHz [2,3].

In this paper, we present the fabrication and the characterization of very high Q and SRF suspended inductors. The fabrication technique relies on a conventional MEMS micro-machining, i.e. micromolding and electroplating of thick / high aspect ratio micro-structures and removal of sacrificial layers. This low temperature, low cost manufacturing technique is therefore compatible with the fabrication of a complete S-O-P wireless integrated module. The typical air gap between the conductor line and the substrate is 100 µm. Different designs have been implemented for applications in C-band, X-band and Ku-band. A physical modeling and RF characterization is carried out. The devices exhibit very high RF performances such as Q above 100 and self-resonance frequency as high as 50 GHz.

II. DEVICE CONCEPT & FABRICATION.

A. *Device presentation*

We investigated suspended inductor performances on a low cost ceramic board using MEMS type fabrication in order to develop very high Q passives for System-On-Package integrated wireless module. A conceptual view of suspended high Q inductor included in a S-O-P wireless module is described in Fig.1. We chose a co-planar inductor topology for its easier technological implementation, large design flexibility and low number of verticals via which leads to less parasitics. Three metal layers are needed to build these devices. The first metal layer forms the ground-plane, the underpass of the inductor and the interconnection with the rest of the module. The second metal layer is used for the vertical via connected to the underpass. The third metal layer completes the inductance which is suspended 100 µm above the surface of the substrate.

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B. *Device fabrication*

The substrate is a ceramic-filled, woven fiberglass reinforced PTFE. It exhibits dielectric constant of 2.94 @10 GHz and loss tangent of 0.0025 @10 GHz and is commonly used as core substrate for MCM-L type multi-layer substrate.

The fabrication sequence is based on a micro-molding and electroplating technique [4]. This fabrication approach uses ultra-thick negative-tone photosensitive SU-8 epoxy to create a micro-mold. The mold is subsequently filled with electroplated copper (resistivity: 2.10^{-8} Ω.m), completing one metal layer (Fig.2.a). The process is repeated in order to complete the second (Fig.2.b) and third metal layers (Fig.2.c). Once the third metal layer is complete, the epoxy mold is selectively removed using plasma etching.

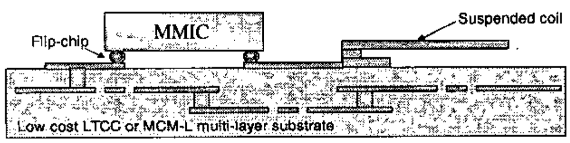


Fig.1. Concept view (not to scale) of RF-MEMS suspended inductor included in a S-O-P wireless integrated module

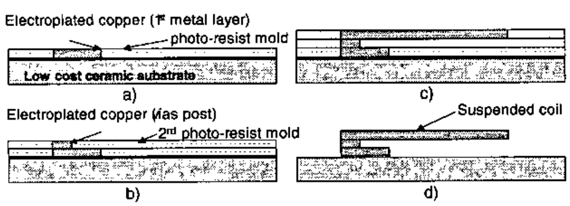
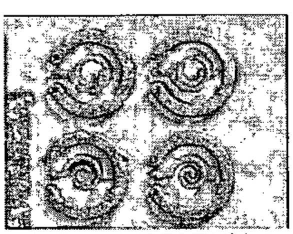


Fig.2. Process flow for suspended RF-MEMS inductor.

Fig.3, 4 and Fig.5 show photographs of 1.5 and 1 turn fabricated RF-MEMS inductors. Each Cu layer is 50 μm thick. The third layer is suspended 100μm above the substrate.



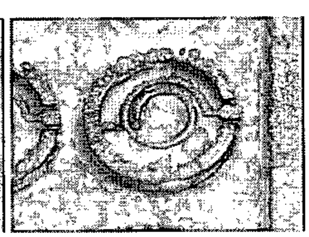


Fig.3. Suspended RF-MEMS inductor library.
Fig.4. Suspended RF-MEMS inductor (1.5 turns).

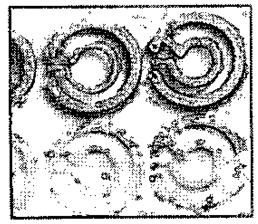


Fig.5. Suspended and on-board RF-MEMS inductors (1 turn).

III. RF-MEMS INDUCTOR PHYSICAL MODEL

The optimization of RF inductor performances requires the identification of the relevant parasitics and their effects. hysical modeling leads to in-depth understanding of the devices [5]. The physical based hybrid model for a typical suspended co-planar inductor is shown in Fig.6

The inductance and the resistance directly associated to the inductive coil are modeled respectively by L_s and R_s. The coupling between turns and the overlap between the coil and the underpass generate direct capacitive coupling between the input and the output port. These parasitic coupling effects are modeled by the series capacitance C_s. C_{air}, C_{sub}, R_{sub} are related to the air gap capacitance, the substrate capacitance and the substrate resistance respectively.

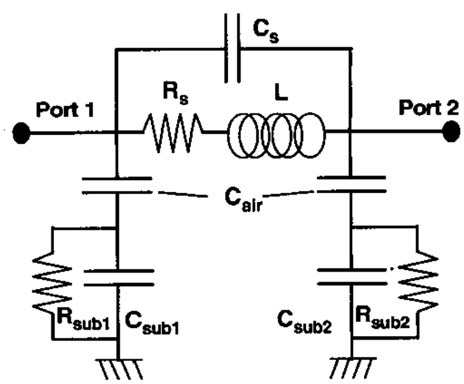


Fig.6. Physical based hybrid model for suspended spiral inductor.

We carried out self-inductance calculations using formulas based on the partial element equivalent circuit (PEEC) analysis method proposed by Ruehli *et al*[6]. We used also full wave simulations and measurement data to adjust empirical coefficients to take into account the mutual inductance effect. Because of the current distribution across the cross- section of the conductor, skin depth effect, metal roughness and crowding current effect, the evaluation of the series resistance is challenging. PEEC formulas [7] were used as well as measurement data to adjust empirical coefficients. At very high frequencies all conductors are subject to radiation losses. Polynomial frequency dependency was added to the expression of the series resistance to take into account those effects. Air gap capacitance, series capacitance have been directly calculated from the structure's topology. Substrate capacitance and resistance have been extracted from measurement results. The complete modeling procedure will be detailed in submitted extended publication [8].

The physical model described in Fig.6 can be simplified in the one-port case as described in Fig.7.

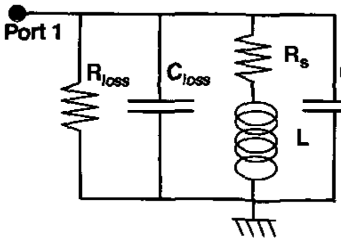


Fig.7. Equivalent hybrid model for 1 port suspended spiral inductor.

With

$$R_{loss} = \frac{1}{\omega^2 C_{air}^2 R_{sub}} + \frac{R_{sub}.(C_{air}+C_{sub})^2}{C_{air}^2} \quad (1)$$

$$C_{loss} = C_{air}.\frac{1+\omega^2.(C_{air}+C_{sub}).C_{sub}.R_{sub}^2}{1+\omega^2.(C_{air}+C_{sub})^2.R_{sub}^2} \quad (2)$$

The most fundamental definition for the inductor quality factor is given by:

$$Q = 2\pi.\frac{\text{peak magnetic energy} - \text{peak electric energy}}{\text{energy lost in one oscillation cycle}} \quad (3)$$

In the one port case, this can be expressed as follows:

$$Q = \frac{\omega L}{R_s}.\text{substrate loss factor}.\text{self-resonance factor} \quad (4)$$

With

$$\text{substrate loss factor} = \frac{R_{sub}}{R_{sub} + [(\omega L/R_s)^2 + 1]R_s} \quad (5)$$

$$\text{self-resonnace factor} = 1 - \frac{R_s^2(C_{sub}+C_s)}{L} - \omega^2 L.(C_{sub}+C_s) \quad (6)$$

A high performance substrate, suspended topology and proper spacing between turns greatly reduce parasitic capacitances. This leads to enhanced quality factor and very high frequency of operation.

IV. RF MEASUREMENT & CHARACTERIZATION

A. *Inductance and Self-resonance frequency*

We designed and fabricated a complete library of inductors with one end grounded. We performed S-parameters measurements with HP8510C Network Analyzer, Cascade coplanar ground-signal-ground probes in a temperature, humidity and pressure($1.5*10^{-2}$mBars.) controlled environment. Particular care was given to perform very accurate LRRM calibration for the high Q measurements. The ceramic substrate was put in direct contact with the testing chuck. Substrate capacitance was extracted directly from the measurement without any de-embedding method to remove probes pad parasitic. It is noteworthy to mention that, the measurements reflect the performances of the overall structure including the effects of the lateral ground plane. Fig.8 shows agreement between the measurements and the physical based model for 1 turn inductor (350 µm diameter), and for 1.5 turns inductors 350, 550 and 850 µm diameter respectively. Conductor width and spacing between turns are 40 µm.

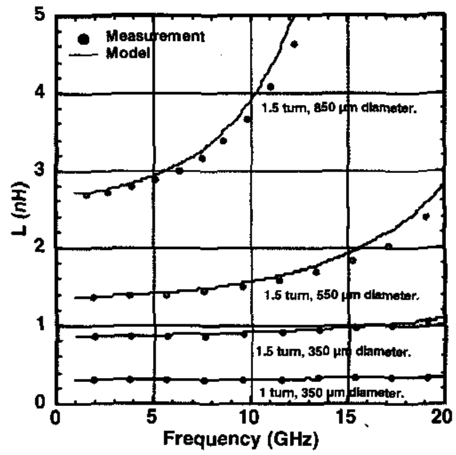


Fig.8. Inductor measurements results compared with the physical model.

The fabricated inductors exhibit inductance values ranging from 0.3nH up to 2.7nH and self-resonance frequency from 50 GHz to 18 GHz. The results are detailed in Table 1.

B. *Quality factor*

Fig.9 shows measured performances and physical based model for 1.5 turns and 350µm diameter inductor. The physical based model initially developed did not model the degradation of the quality factor due to radiation losses. A polynomial frequency dependency was added to the expression of the series resistance in order to model radiation losses and lead to better agreement with the measurements. The resulting Q factor is over 100 @12Ghz (Fig.9).

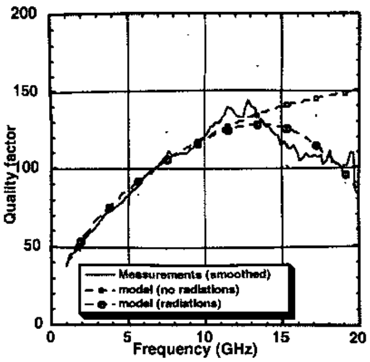


Fig.9. Measured performances and physical based model for 1.5 turns and 350μm diameter suspended inductor.

To investigate the substrate effect on the RF performances, we fabricated and measured one-turn inductors suspended in air and one-turn inductors built directly on the substrate. The suspended structures exhibit a quality factor of 150 in X-band, while quality factor of inductors directly built on the board are slightly above 100@12GHz (Fig.10)

One-turn inductors are very challenging to accurately measure and model because very high Q inductor measurements are limited by the accuracy of low resistance and phase noise of the network analyzer. In our case, quality factor results above 150 are not meaningful for these devices with this measurement method due to the phase noise of the network analyzer. However, Fig.10 shows the beneficial impact of the air gap.

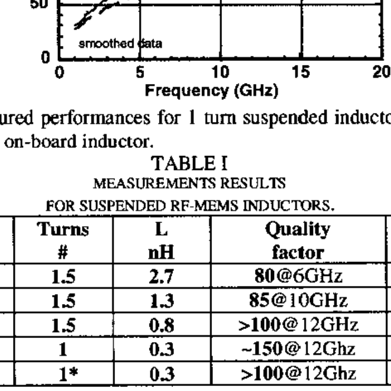


Fig.10. Measured performances for 1 turn suspended inductor compared with one turn on-board inductor.

TABLE I
MEASUREMENTS RESULTS
FOR SUSPENDED RF-MEMS INDUCTORS.

Diameter μm	Turns #	L nH	Quality factor	SRF GHz
850	1.5	2.7	80@6GHz	18
550	1.5	1.3	85@10GHz	25
350	1.5	0.8	>100@12GHz	50
350	1	0.3	~150@12Ghz	> 50
350	1*	0.3	>100@12Ghz	>50

*on board.

V. Conclusion

In this paper we presented the concept and the fabrication of very high-Q suspended RF-MEMS inductors built on a low cost ceramic substrate. RF characterization and a physical based model have been carried out. The impact of eddy current, substrate losses and radiation losses on the quality factor has been modeled by means of frequency dependent series resistance expression. Measured devices show very high performances such as Q above 100 and self-resonance frequency as high as 50 GHz. As far as the knowledge of the authors these results are the highest results reported to date for a MEMS based inductor.

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