MEMS Based Inductor Implementation for RF Front End of Mobile Terminal

Vidyadhar Vibhute, Sanjib Chatterjee, Vikas Kyatsandra, Jugdutt Singh, Aladin Zayegh, Aleksandar Stojcevski
Centre of Telecommunication and Microelectronics, Victoria University, P.O.Box 14428, Melbourne City MC 8001, Victoria, Australia

ABSTRACT

There has been significant growth in the wireless market where new applications are accompanied with strict design goals such as low cost, low power dissipation and small form factor. Large capacity and range for new applications are the driving force for development of new standard such as third generation mobile system (3G). Recent research results show that the development that was not possible with current IC technology is made possible with MicroElectroMechanical Systems (MEMS) technology. Significant amount of research is taking place to replace the off-chip components with on-chip components to design a high performance receiver front end. The passive components such as switches, capacitors and inductors are integral part of RF front end. High quality (Q) inductors are used to design RF front-end components such as voltage-controlled oscillator (VCO) and low noise amplifier (LNA). However, they are the bottleneck in achieving the on-chip optimum components, because of Q factor dependence on parasitic effects, limiting the performance. In recent research publications different on-chip inductor structures such as coil, polygon, rectangular and stacked configurations have been suggested and used to implement high value of inductance. In this paper design and implementation issues of MEMS inductor are presented. The paper is divided in two sections, the first section presents the role of MEMS based passive components and second section presents design issues, implementation and analysis of different MEMS based inductors.

Keywords: MEMS components, MEMS inductor, High Q, Power

1. INTRODUCTION

The fast growing demand of wireless communications for voice and data has driven recent efforts to dramatically increase the levels of integration in RF transceivers. To achieve a single chip solution as well as power efficient and capability to support multifunction and multi standard different technologies have been explored. MicroElectroMechanical Systems (MEMS) based radio frequency (RF) systems shows to play a significant role in designing new products by reducing area, power and providing an efficient wireless solution. Passive components such as inductor play important role in designing front end components such as VCO and LNA. Designing an optimum on-chip inductor is a major bottleneck because of poor Q value due to parasitic effects and substrate losses. MEMS based passive components and circuitry opens up new integration options for wireless systems.

This paper describes the design and implementation issues of different MEMS inductors for a direct conversion receiver. The paper is organised as follows. Section 2 discusses the direct conversion receiver architecture and possible MEMS components in this architecture. In section 3 design issues of MEMS inductors are discussed. Section 4 presents implementation and analysis of different MEMS based inductor from various aspects such as geometry, material conductivity and stacked configurations. Section 6 concludes with summary of the design and implementation issues.

2. DIRECT CONVERSION RECEIVER (DCR)

The increasing demand for wireless communication applications, such as cellular telephony, wireless data networks, global positioning system, etc., motivates a growing interest in building miniature wireless receiver with efficient RF-front end. Architecture selection is one of the key steps in receiver front-end design flow and recent researches [1-4] indicate the choice of direct conversion architecture as the most suitable architecture for a low power, low cost and efficient wireless application. The main advantage of DCR is the highest level of integration that can be achieved, permitting a single chip solution with minimum on-chip and off-chip components [3]. As shown in Figure 1, the
incoming weak signal is down converted to base band eliminating the need for an intermediate frequency filter (IF) [2]. The first band pass filter (BPF) selects the RF band. The low noise amplifier (LNA) provides amplification of the signal with minimum noise added to it; a quadrature mixer down converts the amplified signal in I and Q channel signals (which are out of phase with each other) using reference frequency from local oscillator (LO). The low pass filter (LPF) removes most of the high frequency unwanted signals.

![Figure 1: Direct Conversion receiver [2]](image)

Some of the advantages of direct conversion receiver (DCR) architecture as compared to other architectures are [3,7]:

- Reduced number of components and lowest cost
- Reduced die area and power consumption
- Image frequency problem does not exist so image filter is not required
- Monolithic implementation is possible
- Direct conversion of RF signals allows channel filtering to be done at baseband where implementation of power-efficient on-chip filtering is feasible.
- Excellent candidate for extension of single receiver architecture to multi function / band / mode system.

Because of the advantages the DCR architecture is considered to be optimal for wireless receivers. However, DCR architecture has several design issues such as time varying DC offset, LO leakage, flicker noise and Phase and Gain Mismatch of IQ Paths. The DC offset problem can be corrected using digital signal processor or auto zeroing technique. Gain and phase mismatch between the I and Q channel filters and amplifiers with large cascaded gain can cause asymmetry and rotation in the signal constellation resulting in error vector magnitude (EVM) degradation. Feasibility of on-chip VCOs at double or quadruple of receive frequencies makes it possible to use digital dividers to generate accurate phase quadrature at RF [3, 5].

Market forces and growth of data transfer in wireless communication is putting new challenges for receiver design such as single chip for RF, mixed signal and DSP, performance improvement for better quality of service, power efficiency for longer battery life, selectivity and multi standard compatibility. These issues can be addressed by either removing or miniaturizing off-chip components or by taking benefits of MEMS technology.

MEMS is an enabling technology and can replace most of the components in a receiver [3,4] but presently this solution is not viable because of being a new technology, limited tool support and fabrication process. Hence, certain passive components which contribute most towards performance can be implemented instead of all MEMS solutions for RF front end. As a result of this, benefits of both technologies will lead to new design and applications. Three most discussed MEMS components for RF front end for wireless communication are switches, variable capacitors and inductors [7]. Among these three components, this paper deals with MEMS inductors and its design and implementation issues because a) high Q inductor is required for efficient operation of LNA and VCO, b) integrated capacitors with relatively high Q (>40) are available [10,11] but due to substrate loss Q of integrated inductor is usually very low (<10) [8,9].
3. DESIGN AND IMPLEMENTATION OF MEMS INDUCTOR

An inductor is a circuit component which is capable of producing voltage across its terminals in response to a changing current flowing through it. The time-varying magnetic field due to current in an inductor induces electromotive force. Inductors are usually coils of wires, circular or spiral in shape, in which windings are necessary to enhance the flux linkage and hence a large inductance in small area.

A few possible geometries of planar inductive elements for RF applications are shown in figure 2. These can be generally classified as strip inductors or spiral inductors. Straight sections of the inductors are used for low inductance values typically less than 10nH while spiral (circular or rectangular) have higher Qs and can provide higher inductance values. The presence of a ground plane affects the inductance. The inductance decreases when the ground plane is brought nearer to the conducting line. Planar inductors are made with a single metallisation scheme, in which a conducting layer is etched on a dielectric substrate. The finite conductivity of metal layer and the loss in the dielectric substrate can introduce losses in the inductor. A metal layer of thickness 3 to 4 times the skin depth can reduce the conductive losses.

![Figure 2: Planar Inductor Geometries](image)

This inevitable area limitation of monolithic integrated circuits prevents further improvements in $Q$ because the $Q$ of the inductor is roughly proportional to its physical area. Magnetic components operating at high frequencies rapidly increase eddy current and hysteresis loss in the magnetic cores as the operating frequency increases. The micro machining techniques provide several approaches for the miniaturisation of inductors operating at high frequencies. Magnetic cores and conductor with desired thickness and width with good dimensional control could be realised using MEMS technology.

3.1 Design Issues

The key parameters for the design of inductor layout such as outer dimensions, width and spacing of the metal tracks, thickness of the metal, number of turns and the substrate material can be summarized in the following points:

- **Effect of line spacing:** When the line spacing decreases, it is observed that the inductance of the spiral coil increases whereas that of the meander coils decreases. This is because of spiral coil has positive mutual inductance and the meander coil has negative mutual inductance. Thus it is advisable to achieve less line spacing between conducting metal strips to increase positive mutual inductance [7].

- **Effect of line width:** the series resistance of the planar coil is related to the sheet resistance of the metal strip, which is inversely proportional to the width of the strip. The series resistance of the coil also affects the magnetically induced losses, which depends on the time derivative of the magnetic flux through the metal strip since the magnetic flux is related to the flow of the current. This loss usually increases with increase in frequency as well as the strip width. Hence there will be an optimum strip width, which minimises the series resistance and maximise the $Q$ factor [7].

- **Effect of number of turns and Quality Factor:** there exists a trade off between the inductance and quality factor when increasing the number of turns of a spiral inductor. When the numbers of turns increase, the inductance...
increases while Q decreases. As the area of the inductor increases due to the increase in the number of turns, the capacitance between the numbers of turns also increases; thus reducing the Q. Hence we should strive to select the optimum number of turns, line width, and spacing along with the proper selection of the substrate.

A typical planar inductor description used in the paper is shown in figure 3 below. It can correspond on a rectangular spiral conductors, placed on an insulate substrate, or a magnetic substrate. The inductance value $L_T$ is determined by summing elementary inductance of each straight segment, taking but also mutual inductances. In our case, only mutual inductances linked to straight parallel conductor segments exist [16]. So,

$$L_T = L_0 + \sum M$$

Where $L_0$ is the sum of self-inductances of all straight segments and $\sum M$, the sum of all mutual inductances.

![Figure 3: Model of Planar Inductor](image)

In case of classical electronic circuits, negative mutual inductances are usually so small in magnitude compared to the global inductance that it can be neglected. However, in microelectronic field, its neglect can induce errors until 30 % in inductance values. Hence, it becomes necessary to adopt a method to evaluate more precisely the micro machined inductance value. There exist several mathematical methods to evaluate inductances [14, 16]. To accurately design and simulate an inductor using CAD tools (e.g. Coventorware) Expanded Grover Method has been used for inductance calculation [15].

4. SIMULATION AND RESULTS

The implementation of MEMS high-Q inductors has been designed using Coventorware™. The inductor has been analysed for the

- Effect of material conductivity on inductance and Q
- Effect of Number of Turns on Inductance and Q
- Effects of geometry on inductance and Q
- Effect of stacked configuration on inductance and Q

4.1. Effect of Material Conductivity on Inductance and Q

The results of the implemented MEMS inductor are proposed in this section. The layout the rectangular inductor is presented in Figure 4(a) and 4(b).

![Figure 4: (a) layout of inductor and; (b) 3D model of the inductor on substrate](image)
Table 1 summarises the characteristics of the implemented MEMS inductor. As shown in figure it is a 3.5 Turn inductor with supports in the middle and the corners and shows the basic conductor with the return path to ground.

The inductor is placed upon a substrate 100um thick with 1um thick oxide layer and a Silicon Nitride passivation layer. The inductance and resistance as generated by the solver is in the order of 18-20nH over a frequency variation of 1-10GHz. Figure 5(a) and 5(b) shows the inductance and resistance plots generated by the CAD tool. The results portray the inductance and resistance values simulated. The simulated Q is approximately >30 at 2GHz.

<table>
<thead>
<tr>
<th>Width of conductor lines (w)</th>
<th>40um</th>
</tr>
</thead>
<tbody>
<tr>
<td>Spacing between conductors (s)</td>
<td>40um</td>
</tr>
<tr>
<td>Thickness of conductors (t)</td>
<td>9um</td>
</tr>
<tr>
<td>Area</td>
<td>1240x1240</td>
</tr>
</tbody>
</table>

Material analysis conducted on 3 basic materials Copper, Gold and Aluminium. The variation of materials has been fully analysed, as illustrated in Figure 6.

As observed in Figure 6(a), the inductance value of the designed MEMS inductor increases with frequency while its resistance value decreases with frequency, as shown in Figure 6(b). However, copper is the optimum choice of material for the MEMS inductor implementation.
Figure 7 illustrates the variation of Q factor with respect to frequency for the three materials. It can be seen that copper provides the highest Q value as compared to its counter parts.

![Figure 7: Frequency v/s Q with respect to material change](image)

4.2 Effect of Number of Turns on Inductance and Q

Varying the number of turns by keeping area of the inductor fixed can provide different value of inductances. For the inductor parameters of table 1 inductance linearly varies with increase in number of turns. The inductance increases approximately at 1nH per turn but at the cost of eddy losses with increasing number of turns. The number of turns of the inductor has been varied from 1.5 to 6.5 turns and the effect on inductance and Q are plotted as figure 8.

![Figure 8: Variation of number of turns on Inductance and Q](image)

4.3 Effect of geometry on Inductance and Q

The effect of varying the geometry has been fully analysed to study the effect of geometry on inductance and Q factor. Identical inductor dimensions are presented. Table I has been used to create square, octagonal and circular spiral geometries (figure 9(a),(b) and (c) respectively) and similar analysis have been performed to indicate the variation of Q.
with increased curves. It is noticed that Q increased with increase in contours. Figure 10 shows that circular spiral exhibits maximum Q as compared to octagonal and square spiral geometries.

(a) (b) (c)

Figure 9 (a) Square Geometry; (b) Octagonal Geometry; (c) Circular Geometry

![Effect of Geometry on Q](image)

Figure 10: Variation of Q with varying geometry.

**4.4 Effect of Stacked configuration on Inductance and Q**

Stacked spirals give larger inductance values. Inductances as high as 30nH are simulated and plotted as shown in Figure 11. Special care needs to be taken in the construction of the stacked spiral so that the current flow direction of the overlying spirals are not mutually opposite as compared to the underlying spiral. If the spirals are constructed such that the current flow are in opposite directions, it leads to increase in negative mutual inductance and decrease in inductance.

**5. CONCLUSION**

The DCR architecture and MEMS technology for wireless communication are presented. MEMS inductor design issues have been discussed. Different aspects of implementations such as effect of number of turns, geometry and effect stacked structures have been studied successfully with supported analysed data. Inductance value of more than 18nH is obtained with Q value of >30 at 2GHz for a 3.5 turn rectangular spiral inductor. It is also observed that with increase of
number of turns inductance value increases at the rate of 1nH per turn. Moreover, analyses of different geometries prove that with increased number of contours Q factor increases significantly. Also, high value of inductance can be obtained by increasing the number of stacks. With a three layered stacked configuration inductance value as high as 30nH is obtained. The key parameters for the design and implementation of inductor includes proper choice of structure, width and spacing of metal tracks, thickness of metal, number of turns and substrate material. The inductance as well as its quality factor can be fine tuned by the proper selection of above mentioned parameters.

![Figure 11 (a) single stacked and (b) Double stacked square planar spiral inductor](image)

![Figure 12: Inductance rising linearly with respect to layers stacked.](image)

6. REFERENCES


