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Wireless Sensor Node using RF MEMS components

Master thesis

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Abstract

Design of sensors with limitations in areas up to a few mm^2, ultra low-power, capable of customization into a Wireless Sensor Network (WSN) for monitoring applications, represents one of the most challenging and discussed issues in electronic sensor development societies. There have been several attempts recently, in development of the common wireless sensor components. Efforts have been concentrated on area and power minimization, reliability and security. Recently, examples in development of a System on Chip (SoC) as Application Specified Integrated Circuit (ASIC) capable of measurement and transmission to a Wireless Sensor Network (WSN) has been reported.

Design of such a sensor is quite challenging; partially because of the demanding multi discipline approach involving μ/nano-Electronic, Micro Electro Mechanical System (MEMS), Radio Frequency Micro Electro Mechanical System (RFMEMS), Radio Frequency (RF) transmission dexterity. Another obstacle on the path is compatibility to a diversity of standards and regulations in different countries and satisfying various authorities and disciplines.

Unanswered paradigm question would be whether it is possible or necessary to design a general purpose Wireless Sensor Node on Chip (SNoC) covering the entire aspect of WSN interests. Probably there will never be such a sensor satisfying requirements of all demands. In this thesis one typical sensor node design as SoC will be suggested and the advantages and drawbacks discussed. More precise; RF communication and RFMEMS possibilities and limitations will be discussed. To prohibit confusion between the term Wireless Sensor Network and Wireless Sensor Node, we will consequently address SNoC as a Wireless Sensor Node in this thesis.

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Acronyms

AD	Analog to Digital
ADC	Analog to Digital Converter
ASIC	Application Specified Integrated Circuit
ASK	Amplitude Shift Keying
BPF	Band Pass Filter
BPSS	Brain Pressure Sensor System
BW	Band Width
BWSN	Biomedical Wireless Sensor Network
CAD	Computer Aided Design
CMOS	Complementary Metal-Oxide Semiconductor
CMU	Carnegie Mellon University
CPU	Central Processing Unit
DAC	Digital to Analog Converter
DRIE	Deep Reactive Ion Etching
DC	Direct Current
DSP	Digital Signal Processor
EIRP	Effective Isotropically Radiated Power
EMC	Electro Magnetic Compatibility
FCC	Federal Communications Commission
FEM	Finite Element Manufacturing
FFT	Fast Fourier Transform

GaAs	Gallium Arsenide
GeSi	Germanium Silisium
HS	Hydrocephalus Sensor
IC	Integrated Circuit
ISM	Industrial, Medical, Scientific
LNA	Low Noise Amplifier
LPF	Low Pass Filter
MES	Microelectronic Systems
MEMS	Micro Electro Mechanical System
MIMO	Multi Input Multi Output
MOSFET	Metal-Oxide-Semiconductor Field-Effect Transistor
MRI	Magnetic Resonance Imaging
NEMS	Nano Electro Mechanical System
NMOS	N-channel MOSFET
OOK	On Off Keying
OTS	Off The Shelf
PA	Power Amplifier
PCB	Printed Circuit Board
PD	Phase Detector
PDF	Probability Density Function
PFD	Phase Frequency Detector
PLL	Phase Locked Loop
PM	Primary Module
PMOS	P-channel MOSFET
PSRR	Power Supply Rejection Ratio

PSU	Power Supply Unit
PWM	Pulse-Width Modulation
RF	Radio Frequency
RFID	Radio Frequency Identification
RFMEMS	Radio Frequency Micro Electro Mechanical System
RIE	Reactive Ion Etching
RMS	Root Mean Square
S/N	Signal to Noise
SAR	Specific Absorption Rate
SISO	Single Input Single Output
SHF	Super High Frequency
SNoC	Sensor Node on Chip
SNoC-T	Sensor Node on Chip-Transmitter
SNoC-TRX	Sensor Node On Chip-Transceiver
SoC	System on Chip
SNR	Signal to Noise Ratio
TMC	Transcutaneous Magnetic Coupling
TSI	Trenched Silicon Island
UIO	University Of Oslo
UWB	Ultra Wide Band
VCO	Voltage Controlled Oscillator
VHF	Very High Frequency
UHF	Ultra High Frequency
WSN	Wireless Sensor Network

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1 introduction

Development of ultra low power sensors using MEMS technology in the last decade has made WSN a promising technology for various applications.

MEMS technology used in µ-sensors, actuators and RFMEMS components utilized in tiny RF modules are key terms in development of practical μsystems. This technology has been a major contribution to growth of many new potential deployments in instrumentation electronics. One particular application is biomedical wireless sensor nodes which require these RF modules for wireless transmission of physiological values measured in human body. Other topical applications with the same type of requirement could be mechanical surveillance and control, measurement of ambient and environment, temperature and other types of physical signals.

Availability of a cost-effective, flexible $\mu m/nm$, ultra low power mm^2SNoC will introduce this sensor a vast majority of new applications. But, the proper mm^2-sensor should be also capable of combining easy customization, energy-efficient computation and RF communication to reach a wireless application marked. Nowadays, autonomous cm^2 sensor nodes appear to be within reach. Yet, biomedical sensors seem to have wide requirement diversity. Consequently, general type of sensor encounters much more difficulties covering whole aspect of demanding limitations in different type of deployments.

Requirement specification used in this thesis is based on Hydrocephalus Sensor (HS) type of sensor specified by SINTEF as a valid example. It is advantageous to concentrate on one practical SNoC instead of a versatile general purpose sensor. Nevertheless, principles described here can be used as a practical approach in design of the general purpose wireless sensor node. Though, to achieve a practical sensor, trade-off between integration and multi module assembly will be necessary due to process complexity and substantial sacrifices in performance involved with establishing a true single-chip solution.

1.1 Goals of this thesis

The main objective for thesis will be the design procedures of a stand alone SNoC and design studies of one critical component by using monolithic RFMEMS technology. In this thesis, I will focus on design study and feasibility of the critical lumped element, necessary for proper functioning of RF module. The module should satisfy requirement specification demanded from such a complex sensor node in the WSN or Biomedical Wireless Sensor Network (BWSN) applications. Although the objective of this document is based on a short term thesis and limited in projection of subsequent suggestions, I will design the RFMEMS element and present a perspicuous conclusion as comprehensive as the time limits allows. During this thesis either the following terms will be studied or related questions answered:

- Identification of criteria and central blocks in design of a SNoC
- What modules or components are critical and necessary to design a wireless sensor?
- Study the possibility of using RFMEMS components as a substitution for discrete lumped elements
- Discussion and providing a design layout involving monolithic post-processing CMOS-MEMS technology which contributes to manufacturing of a practical wireless bio-electronic sensor

1.2 Outline of thesis

Chapter 2 gives overview of medical application (hydrocephalus), a brief introduction of a typical SNoC and criteria for using of RF transmission in short-range wireless technologies and at last relevancy of RFMEMS to SNoC. This chapter concludes by drawbacks and advantages of RFMEMS technology versus discrete and traditional electronic.

Chapter 3 starts with a short background information about SNoC as an electronic sensor component. Introduction of different modules in a typical sensor like power supply, RF-module and oscillator is continued in the next section. This chapter proceeds with some types of communication protocols including duplex and simplex versions. Next sections describe some possible design suggestions of modules and blocks. At last one simple realistic design suitable for implementation as RF MEMS, post processed monolithic integrated circuits is given.

Chapter 4 will describe design consideration of SNoC as a module and some critical discrete components. To begin with, characterization of wireless power transfer adequate and vital criteria for this module is studied. Characterization of optimum inductor implementation for power and RF transmission is the next issue discussed here. In next sections planar inductor modeling, topologies, calculation theories, advantages and drawbacks on compensating methods are studied in this chapter. At last to case studies based on the design criteria selected for the suggested SNoC application is given to be realized by the implementation as RFMEMS lumped element.

Chapter 5 starts with a brief introduction on post-process RFMEMS implementation technology. In the following sections some examples of how the components estimated through this thesis are designed based using this technology. At last ASIC designed and transferred for production is shown.

In chapter 6 some aspects studied in this thesis and a brief overview of what was achieved is presented.

Chapter 7 is conclusion of the thesis. At last some potential to be done activities are listed due to road map of a functioning wireless sensor node, suitable for use as a stand alone node in a BWSN.

2 Concept and experiences

2.1 Background - Medical application (hydrocephalus) using pressure sensor

There have been some serious efforts in development of a hydrocephalus sensor, both as a MEMS sensor element [2] and electronic system [3, 4] at SINTEF in last few years. The requirement specifications used in this thesis are generally based on HS meant for persons which have undergone an operation for the condition hydrocephalus. Therefore a brief introduction to hydrocephalus and treatment is given below based on [2, pages (11, 12)].

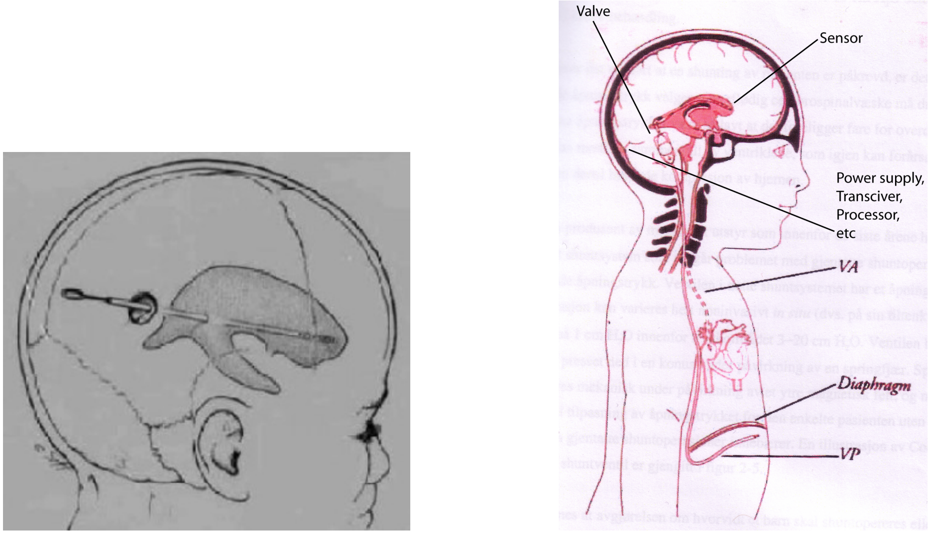
The human brain produces about 500 ml brain fluid per day. Most brain fluid is produced by the choroid plexus, a network of blood vessels covered by a tissue membrane. Choroid plexus is found in water-filled cavities within the brain, called ventricles. The brain is floating in the fluid, which therefore protects the brain from crushing under its own weight and from blows. It also nourishes, cleans and acts as a volume buffer. Ordinarily, the brain fluid is produced and drained at a constant rate so that its volume of 150 ml is replaced every 8 hours. However, if something obstructs the circulation between the production and drainage sites, an abnormal accumulation of brain fluid may occur. This is the condition called hydrocephalus, or more familiar water on the brain. In newborns, the resulting increased brain pressure causes the head to enlarge since the skull bones are not yet fully developed. Macrohead in earlier days often was seen as a symptom of untreated hydrocephalus.

In adults, hydrocephalus is more likely to result in brain damage. Hydrocephalus occurs in one out of 500 births [5] and may furthermore be acquired later in life due to tumor, hemorrhage, meningitis etc. Hydrocephalus is treated by surgical insertion of a ventricle shunt that drains off the excess fluid. A valve opens when the pressure exceeds a preset limit, and the fluid is guided into for instance the abdomen or to other areas of the body where it can be absorbed by the circulation system.

After all, it is important to mention that hydrocephalus is a condition and not a disease. This is important because it means that the individuals, after first having a surgery, can live a quite normal life. This has to be taken into account when designing the measurement system. After successful shunt operation, however, maintenance problems may often occur.

A survey at the Rikshospitalet University Hospital, disclosed that maintenance problems are mainly related to occlusion of the ventricle catheter [6]. Increased brain pressure will again be the result and repeated surgery will be necessary.

To cope with this problem, a pressure sensor should be permanently mounted into the brain to monitor if some malfunctions occur in the shunt ventricle catheter. A processor can then open a security valve preventing hazardous symptoms in brain. The catheter mounting and shunt are shown in figure 2.1:



(a) Installation of a catheter inside the brain

(b) Shunt catheter inside the body

Figure 2.1: Overview of catheter and shunt valve inside the body

Due to limited space inside the brain for mounting the sensor, this device should be as small as possible. In this thesis, the sensor element and noise sensible signal conversion circuits are suggested to be installed inside the brain and the rest of electronics included power supply, processor and communication modules outside the skull but underneath the head skin.

As mentioned before, there is extremely small room for installation of this sensor system. As specified by requirement specification ([2]), the inner diameter of the ventricular rubber catheter is 1.5 mm, as shown in figure 2.2. Hence, there is an essential minimization requirement in this application. There is no doubt compared to other technologies that a MEMS pressure sensor is the unique alternative for measurement of HS pressure satisfying this demand.

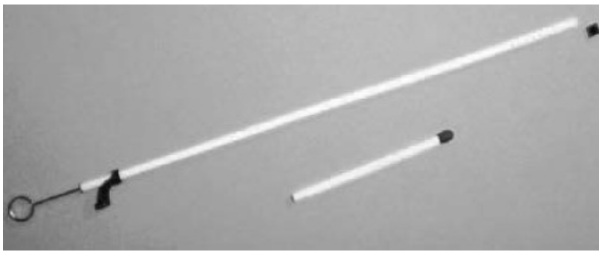


Figure 2.2: Size of Catheter

Even though, the space on the tip of the catheter is extremely small, but sensor should be mounted inside ventricles for two reasons:

1. measurement can be deteriorated by other phenomenon in the head if the sensor is mounted far away from ventricles

2. if sensor is mounted underneath skin or skull for convenience, some impediment inside the catheter may cause false measurements and a risk that the valve does not receive malfunction indication

Another module which I have suggested during this thesis to be preferably inserted in the tip of catheter would be Analog to Digital Converter (ADC). Both in the earlier experiments and reports ([2, 3, 4], noise has been characterized as one of the critical terms to be taken into serious consideration for proper functioning.

Signals produced by measurement in the HS is typically bellow mV [2], and a nominal distance of ca 10 cm between sensor and the rest of the system underneath skull or skin will obviously add a lot of noise made by internal cable resistance, cross talk between adjacent signal wires and power conductors, permittivity of the tissues around flexi-cable and not to forget the antenna effect of a relatively long cable.

In the next section the concept SNoC will be presented.

2.2 Is technology mature for a SNoC?

Reduction in sizes of electronic and electro mechanical components in combination with decreasing power consumption demands makes design of practical sensors possible. Transistor density in electronic integrated circuits was predicted to be doubling every couple of years by founder of Intel Corporation, Gordon E. Moore, known as

“Moore’s law” already in 1965. Moore’s original statement can be found in his publication [7]:

> *“...The complexity for minimum component costs has increased at a rate of roughly a factor of two per year ...*
> *...Certainly over the short term this rate can be expected to continue, if not to increase. Over the longer term, the rate of increase is a bit more uncertain, although there is no reason to believe it will not remain nearly constant for at least 10 years.*
> *...That means by 1975, the number of components per integrated circuit for minimum cost will be 65,000.*
> ***I believe that such a large circuit can be built on a single wafer.....***”.

This theorem has been evaluated since then and the established practical results have been shown in figure (4.1) with astonishing precision.

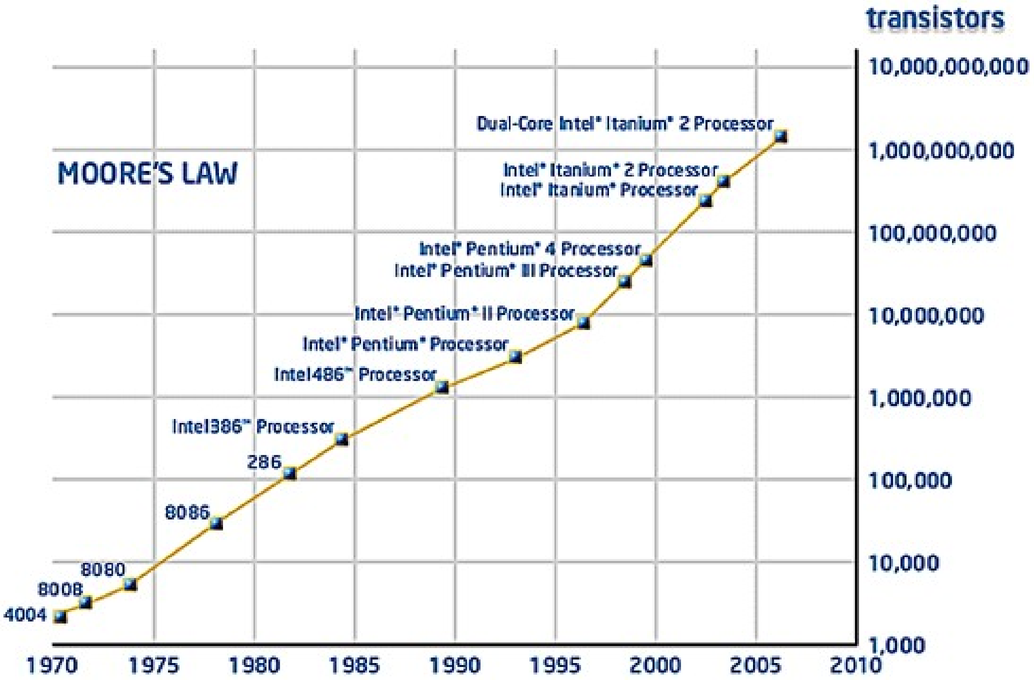


Figure 2.3: Moor’s law measured since 70’s

Development and access to ASIC and MEMS devices in the last two decades, has contributed to new generation of health and industrial sensors. Component sizes and power consumption were some of major practical barriers against popularization of these types of consumer products, just for some years ago. Lack of proper technology and components affected human health, industry and environment.

Today, it is normal to see how our health and security as consumers are dependent on access to reliable electronic instruments and equipment. People in both communication industry and health sector were suffering due to lack of the proper technology. In health sector for instant, dialysis instruments were (some still are) power demanding and heavy; Patients had to carry those by a trolley side by side. Generally, patients are dependent on hospital facilities measuring vital values by sensors essential for diagnosis. For example, there is still no reliable total remotely readable and controllable HS sensor network.

Now after four decades, Moore's law still manifests itself. Electronic industry has already access to 60nm technology and some are experimenting with 35 nm. Smaller physical semiconductor dimensions ares required to achieve more data, lower power consumption and higher frequencies. These obstacles challenge designers and scientists to develop new technologies overcoming physical limitations. Research and development in several fields suggest on a promising future maintaining Moore's law; Multi gate transistors, multi level logic, strained silicon materials, high factor dielectric materials, monolithic and pre-post processed MEMS and RFMEMS components are some of many approaches important to be mentioned here.

Consequently, SNoC seems not only to be possible but also achievable at present stage considering the vital conditions for survival of any electronic component: size, component cost, power consumption, manufacturability, reliability, standardization ability.

2.2.1 RF signal transmission in Short-range Wireless Technologies

Mediums for wireless communication are either free ambience like air, vacuum, space or through compact obstacles for example constructions, water or human body. Wireless sensor nodes should be designed to function properly in the intended operating medium.

The human body medium demands transmission of signals through materials consisting of flesh, bones, liquid,etc. Therefore, signals should be capable of propagating not only into free space with an adequate Signal to Noise (S/N) margin relative to distance specified from the receiver, but also have enough effect to penetrate the encountering obstacles on its path to receiver with the S/N ratio adequate for perception.

However, propagation of RF signals in free space deteriorates quadratic relative to distance from transmitter source. Nevertheless, propagation through free space is much more efficient than a leading liquid medium. Friis [8] presented already in 1946 that expected loss in propagated signal through free space is quadratic proportional to the distance from transmitter and inversely related to the wavelength of the signal. In other words, the higher frequency (shorter wavelength) and longer distance the more signal loss:

$$Loss_{path} = (\frac{4\pi\, d}{\lambda})^2 \tag{2.1}$$

This formula is based on the simple famous basic formula of relation between the transmitted and received power at two distinct antenna positions:

$$\frac{P_r}{P_t} = \frac{A_r A_t}{d^2 \lambda^2} \tag{2.2}$$

where in this equation:

P_t = Power fed into the transmitting antenna at its input terminals,
P_r = Power available at the output terminals of the receiving antenna,
A_r = Effective area of the receiving antenna,
A_t = Effective area of the transmitting antenna,
d = Eistance between antennas,
λ = wavelength

Based on [8], electric waves are absorbed by leading materials. This phenomenon seriously degrades penetrating capability directly proportional to the frequency of propagated wave, electric conduction capability and dimensions of the antenna (thickness or area).

Short-range Wireless Technologies

Modern Wireless Technologies which stands for communication methods supplying a vast majority of systems characterized as Single Input Single Output (SISO) to Multi Input Multi Output (MIMO) systems spreads from low frequency, low power and single channel one way systems to pico-cellular systems.

Although, there is a diversity of communication protocols which can be used in short range wireless networks. In this thesis I have focused on ASK modulation due to the simplicity and relatively low power requirement. This type of modulation in the simplest mode can be implemented just by a single transistor functioning as both oscillator and power amplifier at the output port.

Even though, the nano-electronics will not have the major influence in the size of a sensor module. Most probably the lumped elements, crystals (if any), power supply transformer and antenna elements constitute the most space demanding parts in this type of equipment.

Fortunately, by using RFMEMS many of these components will be substituted by much smaller elements in μmdimension area. Good news is that the MEMS technology has kept the pace with nano-electronics. The technology Nano Electro Mechanical System (NEMS) is still young but has a promising future to contribute to even smaller modules by providing lumped elements in nano-meter scale.

2.3 Is MEMS or RFMEMS relevant to SNoC?

During the last three decades, electronic technology has revolutionized our life in many ways or vice versa, as some believes.

Constant increase in number of components per area unit has resulted consequently in inclination of computational functionality in the 90's and new millennium. This massive device compression has conduced μ-Electronics, lately n-Electronics and wireless communication part of daily, or rather inevitable part of consumer's life.

Sometimes it seems to be a never ending exponential increase in component density per area unit. This trend with a direct proportionality leads to a reduction in size and power consumption of devices. This coincidence may have been the major contribution to several improvement tasks in electronic industry like for example:

- escalating number of wireless devices,
- rapid growth of network nodes,
- diminishing device sizes in wireless communication and instrumentation,
- enhanced of battery life,
- brisk reduction in sensor sizes,
- continual cost reduction

The convergence between these trends is expected to result in *"ubiquitous"* electronic computation power in any aspect of life. But nano-Electronics device compression curves have already suffered by nonlinearity shown within this trend and encountered some severe limitations. Especially, this regards the balance between heat generation by increased component density necessary to perform augmented functions and simultaneously inadequacy of heat dissipation through reduced area available on these devices.

Comparing to a decade ago, slopes of Electronic Integrated Circuit (IC) density curves have become somewhat flat and non-linear. Consequently, some other solutions than traditional CMOS technologies have been requested by developers as alternative solution against just shrinking transistor dimensions. To maintain the constant compression rate and coping with this already overloaded curves, continuously searching for alternative solutions and exploiting compensating technologies are essential. Until lately, a huge area demanding part of electronic devices was (or still is) the passive lumped elements included antennas which are inevitable in RF-communication.

In general, some of the main obstacles in achievement of sub-cm RF-modules design and implementation of IC, ASIC or SoC have been power dissipation and size of discrete lumped elements. Many engineers and developers are struggling with these challenges on a daily basis. MEMS and RFMEMS technology have contributed to minimization and customization of SoC's, especially in case of space sensitive RF-communication modules.

RFMEMS technology is maybe the most conspicuous factor in efficiency improvement of lumped elements, but has on the other hand a major reduction potential in component size and consequently power dissipation. Scientific development and implementation papers frequently report that many researchers and institutions are interested in and working on development of new methods and materials to implement lumped elements using MEMS technology. This is good news for some engineers, producers and consumers which commonly may have considered power and space demanding RF-lumped elements as *"necessary evil"*.

RFMEMS relevancy to SoC may no longer be a matter of curiosity, but rather an inevitable reality. Especially when continuously maturing post, pre and monolithic processes make implementation of CMOS compatible and MEMS fabrication more and more available.

2.4 Why RFMEMS?

One relevant question may still be: While μelectronic technologies are established within mass production commercial markets, why should RFMEMS be a topic theme now?

Obviously, μ-electronic has been a major contributor to the realization and population of μ-wireless sensor nodes by increasing the amount of functionality and on the other hand by reducing circuit area, volume and consequently power consumption or by enhancing levels of circuit integration with mixed-signal design. However, this development trend has not followed the same pattern or slope of minimization regarding some important fields, for example: lumped elements which are inevitable in realization of high frequency communication and instrumentation devices.

Consumer and market requirements on minimization of sensors, wireless sensor nodes and power consumption have lately contributed to accelerate RFMEMS component development and methods. This includes implementation of these components in conjunction (Pre or Post process) or even in the same process (monolithic process) as established CMOS technology and fabrication methods.

Development of RFMEMS elements have recently been a major activity in many electronic development and scientific environments. Many of recognized universities have educational programs aiming for this type of elements as a serious alternative for discrete RF elements. Several organizations have already approved development of RFMEMS elements in their annual program.

Some aspects which resulted in focusing on RFMEMS development in the last decade can be mentioned here:

- Size reduction of lumped elements has not followed the same intensity and curve slope as μ-Electronics. Therefore there is still a huge potential in minimizing component, module and device sizes and improvement of total efficiency

- Matching networks containing discrete lumped elements increasing sizes of SoC modules, has been one of the obstacles in design of sub-cm RF-module . Minimizing components makes distances between different modules and ports shorter. Since sizes of RFMEMS components are usually much smaller than comprehensive operation frequency, thus matching networks between different modules using these components are negligible. The positive effect of small sizes of RFMEMS in eliminating need for matching networks will be described in more details in chapter 5.

- Stray and parasitic components are directly proportioned to component dimensions, packages and distances between these. Hence, minimizing components has huge impact on performance of the device and results in better noise characteristics reducing the effect of stray capacitances and inductors

- Power requirements improve as a result of pure lumped components and less dissipation in stray or parasitic components. Resistance in lumped components is directly proportional to the length of the conductors. Also, dimension reduction reduces resistive dissipation, simultaneously increases quality factor of component which is inversely related to the serial resistance
- Lower power dissipation leads to reduction in power requirements, hence minor power supply unit or battery dimension, reduction in charging capacitor values and minor dimensions
- Marked requirements for stand alone μW powered modules accelerate development of μm-scaled lumped elements

RFMEMS technology is enabling the development of relatively inexpensive passive lumped elements available for integration with autonomous devices and wireless sensor nodes in volumes ranges from mm^2 to several cubic cm.

By implementation of lumped elements through RFMEMS technology and producing relatively inexpensive, Wireless Sensors used in simple or massive distributed networks, Wireless Communication network or actuator nodes can be rapidly deployed. Conclusively, RFMEMS technology is allowing a dramatic reduction in the size, power consumption in electronic components, particularly; sensors, actuators, communication components, and power supply units, RF-modules, SoC.

In the following sections, some relevant components applicable as MEMS devices for small, efficient and µ power communication, actuating or sensing will be reviewed. In addition, CMOS post-process μ machining will be discussed as a method of achieving low cost and high integration.

3 SNoC

3.1 From transistors to Sensor Node On Chip?

Sensors have been used in one way or another since the beginning of 19's century. In 1834, invented the ingenious British Charles Babbage a speedometer sensor for locomotives, he decided to construct an "analysis engine" capable of calculating algebraic equations. Even though he spent 40 years on his project, results became nothing more than some drawings and a "different engine" known as a primitive calculator. Technology was not mature then.

In spite of unfinished final product, we admit that some of Babbage's ideas have inspired modern electronic industry, e.g. how to continue development in decades without delivering a product.

However, early sensors were not comparable to the present sensors regarding reliability, sensitivity, price, complexity of installation, data accessibility and resistance in noisy environment. Those days, without access to processors sensors were "just" sensors. Electronic industrial revolution after the 2'nd world war and semiconductor development became a springboard in almost all aspects of human life and industry. Availability of mass produced cheap and low power electronic components has consequently made new opportunities in consumer electronics, health care, maritime, space and so on.

3.2 Wireless Sensor Node - A Novel Sensor Node On Chip

In this thesis we introduce SNoC as an autonomous device sensing some physical value capable of transferring measured values somehow to a predefined perception point for further treatment.

Accordingly, SNoC is a very comprehensive term and will not be considered as an unambiguous unit covering all aspect required by different applications from such a device. Nevertheless, majority of requirements addressed to SNoC in a WSN system can categorize sensors into two main types:

- simplex low power SNoC
- duplex SNoC

3.2.1 Simplex low power SNoC

Sensors in some systems, are simply supposed to transmit measured raw values to a receiver asynchronously and independent of the signal state or receiver state. This is relevant, especially if the sensor is dedicated to a peer to peer surveillance single sensor measurement.

Hence, a simplex type of communication or rather, information node, will be adequate to simply transfer some measured value through a pre-dedicated channel to a predefined particularly receiver.

However, this sensor needs to be programmed to transfer data in constant predefined time intervals. Otherwise, this sensor should be trigged before transmission. Usually, the circuit which is transferring power into this type of sensor will serve as both power supply and triggering system.

3.2.2 Duplex SNoC

Simplex SNoC will be the optimum choice in some applications, but these sensors will be inadequate for most applications and wireless sensor networks. For instant, in multi sensor node systems or in noisy environment, there should be some type of node identification or synchronization. This selectivity is necessary not only due to activating of single nodes but also management of reliable reception of information transmitted by nodes, avoiding signal jam.

In addition, configuration ability of nodes in most wireless sensor systems is an essential requirement regarding addressing, programming, calibration, communication protocols or transmission band selection. Usually, duplex sensors demand more power availability compared to equivalent simplex devices.

Although, any of these to categories are strongly subject to requirements of specific applications, there will be some common essential blocks in each of sensor nodes as presented in figure 3.1:

1. power and power management
2. sensor element; on chip, discrete
3. data converter; ADC, Processor
4. radio; transceiver, transmitter

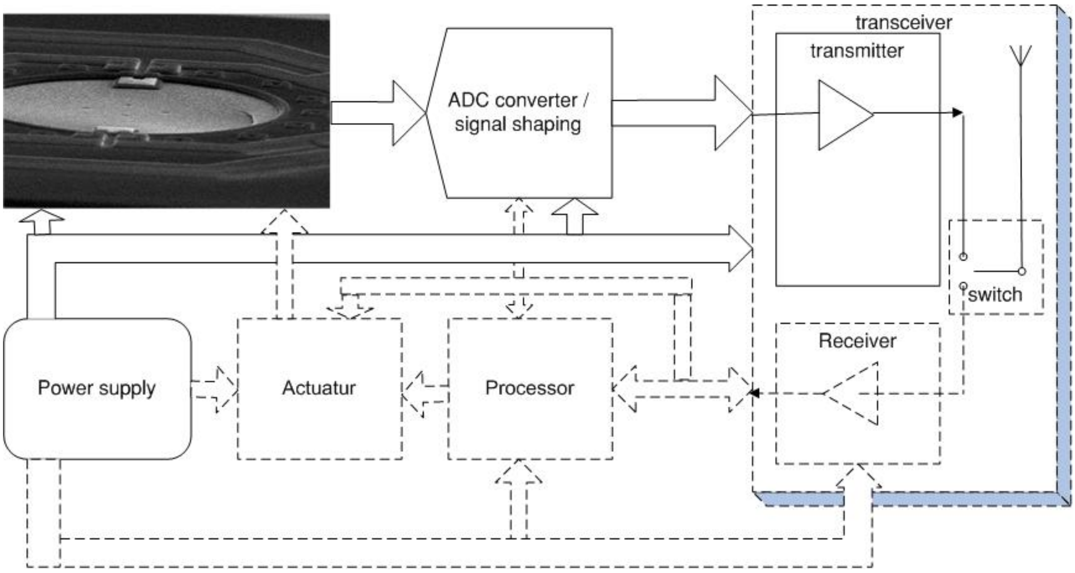


Figure 3.1: A typical sensor node simplex and duplex(dashed lines)

As presented in the figure 3.1, the sensor element, power supply, signal conversion and transmission including RF antenna will be the essential minimum part of any sensor node.

In more complex and rugged wireless sensor systems, if the sensor is supposed to pre-process measured signals, Digital Signal Processor (DSP) or some type of µ-processor and sometimes typical actuators should be included in the device. These processors empower sensor devices to measure, pre-process and prepare signals for best performance concerning the transmission medium or power consumption. Simultaneously, with these powerful processors integrated in the node, sensor device will become a more complete component capable of more accurate measurement, signal and noise analysis, optimum transmission power and reception of commands and configurations.

In next section we will suggest and describe two possible typical sensor nodes, simplex and duplex, and how these can be build up.

3.3 A typical sample of SNoC

As mentioned in the last section, contents and technology of each block in a typical sensor is depending on application, requirements, propagation and field of utilization, power accessible, bit rate, space available and perhaps an even longer list than what mentioned here. But to converge ideas into the most applicable sensor, this thesis is focusing on two types of sensors. These principal ideas may be usable as a basis for further research and development.

3.3.1 Simplex SNoC

The following block diagram shown in figure 3.2, consists of a minimum amount of blocks or modules absolute necessary for a sensor transmitting some particulary measured physical values to a receiver.

I designate this node as SNoC-T to distinguish this simplex transmitter from a duplex transceiver which will be called SNoC-TRX capable of transmitting and receiving measured data and/or control signals through the link.

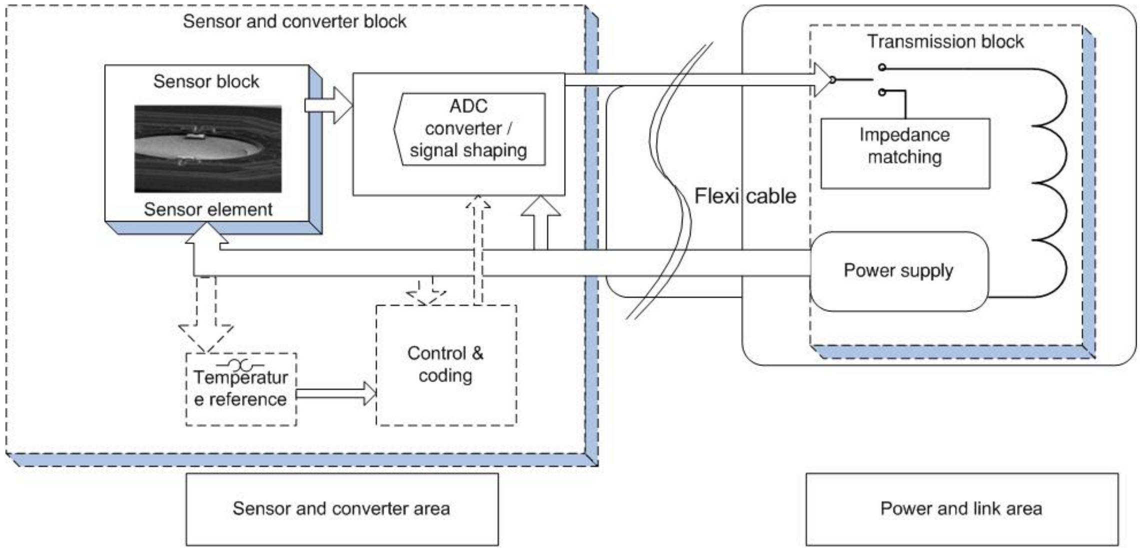


Figure 3.2: A typical Sensor node with combinational power and data transmission inductor

Generally, the same coil has been used in most WSN for transmission of power and data. This method is preferred in some biomedical applications [9, 3, 4] due to the advantage of space savings and circuit complexity using the same inductor for transmission of data simultaneously as receiving power and control data. But no advantage would be without some drawbacks.

Disadvantages of combined inductor principle

Mainly, the reason to use a combined inductor as supply source and data communication port, seems to be minimization. In most cases complexity minimization is intended to save space or cost. But to achieve this simplicity, there has to be some compromises, usually not to the best for electronic signal quality.

In sensors using single power and data inductor, compromises between power consumption and critically low S/N is inevitable.

1. One of the drawbacks in this procedure is poor signal strength and low signal to noise values. This relatively poor S/N has been reported as one of many obstacles, for example in [3] and [4].

2. The second drawback will be noise floor. Combination of RF signal and power will cause inclination in noise floor (1/f) in the same feedback loop and mixing of digital and analogue signals in the same circuit.

3. The third disadvantage of common inductor apparently is a more complex matching process of impedances between primary and secondary. Hence, non optimal matching at resonance frequency in the secondary coil.

3.3.2 Suggestions to improve SNoC-T

In the last section some disadvantages were mentioned using common data and power coil sensors. The following suggestions will improve the quality of SNoC-T operation and will be basis of the design further in this thesis:

- **Isolation of RF-data signal path from RF-power transformer path.** This is obviously the solution to match inductors exactly to the corresponding resonance frequency. This action will result in better S/N ratio since better matching to the resonance module increases signal value, both in the transmission or power transfer port. Therefore, in this thesis antennas for transmission of data is separated from energy absorbing coil, as illustrated in figure3.3.

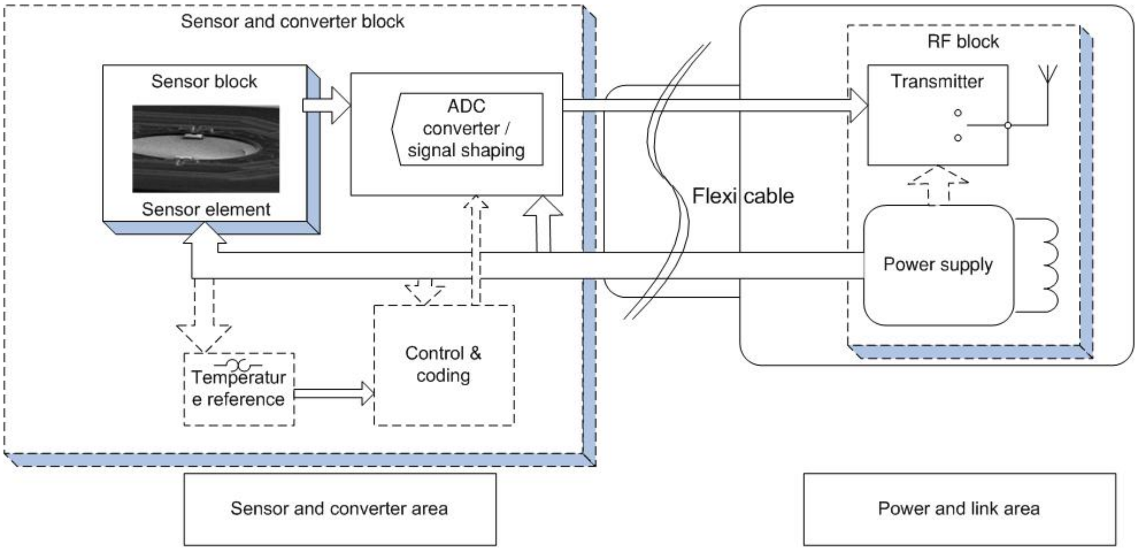


Figure 3.3: SNoC with RF transmission

- **Separation of RF and power block substrate from low signal circuits.** RF transmitter and power supply circuits are mounted on the same substrate. Interconnection between these two modules and converter or sensor circuit via a flexi-cable is suggested, as illustrated in figure 3.4. As described in the last chapter, it would be exceptional if there is enough space around the measurement point. Even so, there is usually a relatively long path to the skin or receiver antennas. Power transmission by inductors implanted far from primary results in a high amount of energy loss in tissues through the signal path.

- **Increasing S/N** is achieved by either lowering the noise or increasing difference between signal and noise. One of the solutions to gain higher S/N values is for example by escalating number of bits in ADC or by inclining reference voltage. Anyway, by providing a data conversion with high value of dynamic range, better signal quality i gained. But conversion steps in analogue to digital converter demand more power consumption pr resolution bit. Usually,because of the low power amount available in this kind of μ-Sensor, a compromise between signal quality and power available is inevitable.

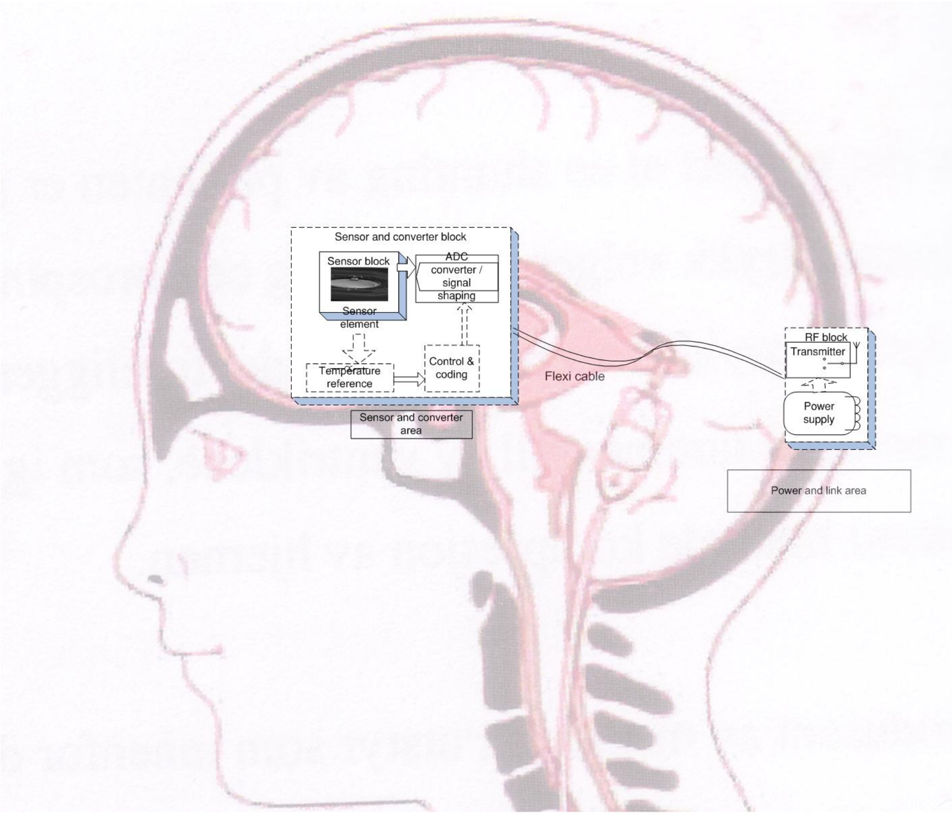


Figure 3.4: SNoC with RF and power under the skin- rest in the head

3.3.3 Implementation of SNoC

On the other hand, conductivity σ influences the signal loss directly in different tissues and parts of the body. This factor is not a constant value and differs from person to person and tissue to tissue by decades. The best way to achieve some stable power and reliable data transfer is to place antennas as close as possible to the receiver or transmitter and in bio-medical environment directly underneath the skin. Antennas and inductors are not the sole parts to be mounted on a substrate under the skin.

Rectifiers and RF-transmitter should be mounted on the same substrate due to randomly stray capacitances between the signal transfer cable and tissues or cross-talk between signal or power wires. In addition, space limitation makes using of shielded coaxial cable very difficult. For example, the diameter of catheter tube or pipe in case of measurement of hydrocephalus is not more that 0.5 mm. This tube has to transfer water without any obstacles in the path.

Also, unshielded flexible µmwires seems to be the unique practical base band signal or power transfer medium inside or in conjunction of tissues. Thus, to avoid RF signal loss through cable or addition of noise to signal, I suggest keeping RF and power transmission circuits as close as possible to the external circuitry. The most practical proposed solution seems to be implantation of the RF Part in the space between scull and right underneath of the skin.

3.4 Typical Power Supply for SNoC

To consider a proper Power Supply for SNoC we need to distinguish between two essential types of sensors; sensors permitting battery or power supplies consisting of rechargeable batteries, and sensors unable to accept active batteries and are dependent of external power source through RF inductive coupling (e.g. implanted devices). These second sort of sensors are typically designed to be used in human body or extremely small compartments (e.g. smart cards) or hazardous areas dangerous for batteries. A combination of these two alternatives will be interesting for some applications.

Batteries will cause a major risk to human body because of leakage possibility, time limited operation time, relatively big sizes, replacement requirements, etc. Sensors supposed to be mounted in human body should preferably be designed admitting power somehow other than battery power. In modern bio-electronics, it is less accepted to connect a human body to a cable braid degrading the quality of life, risk of accidentally cut, undetermined disconnecting or dependence to specialized hospital facilities.

Power requirements for sensors implanted or used in the body should for all preferences be transferred unwired. Inductive power transmission is the most convenient and usual method for this type of sensors. Adequate reliable and easily accessible power, is vital for proper functionality to bio-sensors. Next section presents considering points in design of inductive power transmission.

3.4.1 Battery supply versus inductive power

Ever since explorations of mini size practical batteries, these components have been the inseparable parts of portable consumer electronics. In 60's, while the first pacemakers began to be available in practical sizes, portable batteries compatible to human body containing enough power, have been the scarce product. As pointed in previous section, there are several limitations prohibiting μ-bio sensors utilizing power supply containing implantable batteries. Some obstacles in using batteries are explained as following:

Disadvantages of Battery as active power supply

1. Batteries may leak hazardous liquids inside the human body, even with sealed capsule

2. Available space for implantation of a battery around or close to measuring point, is sometimes much less than the volume required by components proper for sensor functionality

3. Batteries are time and power limited supplies. Replacement of malfunctioned or destroyed batteries is unavoidable and demands surgical operation. Durability maybe lengthened by rechargeable circuitry or other electronic applications designed for the purpose. But even so, present applicable technology is unable to provide everlasting rechargeable batteries

4. Bio-electronics components placed in the human body should be preferably implanted as close as possible underneath the skin, making replacement of empty or malfunctioned parts easier. These bulky under-skin implants complicate and deteriorate life quality of patients in most cases.

5. Metal or conductor packaging cans, chemical mixtures filling up batteries, electrodes or cases will be a possible element absorbing radiated electromagnetic waves resulting in heat generation.

The last point will mostly happens when patients are treated by radiology or Magnetic Resonance Imaging (MRI) instruments. Because of these disadvantages, avoiding batteries as power supply sources in bio-electronic sensors will be essential. In spite of these mentioned disadvantages, in industry version of these type of sensors or control nodes, rechargeable or battery driven nodes are preferred. Simply, regarding much less complexity in replacement, installation or support and services. But additional disadvantages leads to serious consideration of alternative power sources in wireless network systems and particularly BWSN.

Wireless nodes are usually low cost components and can not tolerate expensive batteries as an option in most cases. Support, logistic, installation and maintenance costs will conclude that battery driven nodes are unpractical and inconvenient for many industrial applications as well. (e.g. it is unpractical and expensive to replace millions of queue-free bricks utilized as RFID nodes in vehicle industry after few years functioning).

Although, passive power supplies are much less efficient than battery power supplies, those are more convenient and especially preferred for bio-electronic sensors meant for implantation. Passive RF-powering is the unique alternative for long term power consumption in implanted bio-electronic sensors. One reasonable method to empower these sensors is by Transcutaneous Magnetic Coupling (TMC) method which is near field magnetic induction applied directly to the skin; this method seems to be appropriate for powering implanted μ-bio sensors requiring a few mW s of power.

Among advantages of TMC is wireless powering. Simultaneously as transmission of data bi-directionally through the same inductor is possible. Avoiding percutaneous plugs, wires and conduits are some of the other advantages of inductive TMC powering method.

3.4.2 Inductive Power Transmission methods -TMC

An RF powering system is basically a transformer. Primary and secondary inductors are physically separated by space, obstacles or in the human body by tissue and liquids. Requirements of power conversion from ac to dc and voltage regulation increase proportionally with complexity of electronic system in the node (implanted sensor) or power dissipation.
To obtain efficient and adequate power, some of the most important factors would be access to high-Q, low-loss inductors with optimized coupling efficiency. Power transmission is possible using an inductor as primary coil of a transformer inducing electromagnetic field into secondary. This secondary inductor, should be capable of producing enough energy at the resonance frequency for activating and properly functioning of SNoC.

Usually, the external power source will consist of an oscillator and a matched Power Amplifier (PA). This thesis will not discuss design and criteria for such power supply module in details, and mainly concentrate on the design parameters for RFMEMS components.

One of the obstacles to be considered will be the strongly restricted size of the secondary coil in transformer. This part will obviously be relatively small sized because of limited available space. On the other hand, inductor should have an adequate size to accumulate enough energy and withstand deterioration caused by body tissue, absorbing electromagnetic fields between the primary and secondary inductor.

Detailed inductor calculations and power transformer component considerations will be way off aspects of this document, but some of the most important issues will be presented in next paragraphs.

3.4.3 Modules in a typical Power supply

In figure 3.3, the block diagram of a SNoC-T was presented. Energy required by digital, analogue and RF circuits will be supplied by the power block. Detailed modules in this block are shown in figure 3.5.

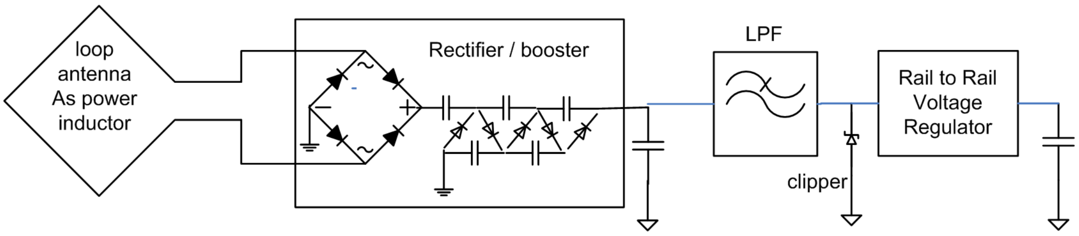


Figure 3.5: Simple regulated Rail to Rail Power Supply unit for SNoC

This block diagram represents a typical power supply. Anyhow, the importance of high quality regulation should be emphasized. A high quality sensor power supply, in addition to provide low drop Rail to Rail voltage and providing enough current, should be temperature compensated, reliable and deliver high efficiency ($> 93\%$). Several design suggestions are reported using switched-capacitor or voltage boosted regulators. These type of high efficiency and low drop out regulators should be implemented providing stable and adquate power for this type of sensors. Nevertheless, optimum performances is dependent on some other important factors like adequate Power Supply Rejection Ratio (PSRR).

By the way, designing sensor node limited just to few mm^2 available space, may be achievable by utilizing RFMEMS components in RF and power supply modules. Later in this thesis, RFMEMS alternative elements substituting RF discrete lumped components are suggested in detail.

3.4.4 Power supply inductor

To absorb maximum power available from primary inductor, a matched secondary inductor at resonance frequency is compulsory. Design should be made such as that inductor is matched to resonate at the excitation frequency by using a parallel capacitor. To achieve highest impedance at the excitement frequency, parallel matching network even just by a single lumped element should be adapted for this inductor. By using matching network or element, the tank is capable of delivering maximum energy to the load at resonance frequency. There have been some research and efforts to design optimum planar inductors providing maximum energy required by implanted sensors e.g. [4, 3, 9]. Thus, some results and examples of these designs are used to estimate the values needed for typical sensor.

Power supply inductor design criteria are depending on requirement specification of the application, sensor and the system. Designs already experimented at University Of Oslo (UIO), has suggested a power consumption ≥ 5 mW adequate for such sensor [4, 3, 2]. This amount of power available has been experimented to be enough for measurement, conversion, processing and transmission of data [4, 3]. Anyhow, energy transformation is highly influenced by inductor shape and topology.

3.5 RF block

In case of a implanted bio-medical SNoC underneath the skin, frequency modulated RF transmitter or some type of time domain transmitter Like Ultra Wide Bandwidth can be used. In both cases, absorption of energy would be a factor to be considered regarding power loss and consequently reduction in propagation range. However, reliability of the sensor measurements is directly proportional to the power propagated, at least up to some adequate level. As we mentioned earlier, human body acts like a resistor due to the conducting liquid inside the tissues parallel with a non-ideal capacitor with some dielectric value measured for different type of human tissues [10]pages 206,207.

As it was shown in 2.1, propagation losses are directly proportional to the frequency. For higher frequencies, the more loss and absorption of signal by tissues will occur. I proposed optimum frequency for power transmission needed by the current module to be 10MHz. From basic RF theories it is given that optimally matched length for antenna for effective transmission should be $\lambda/4$. But for low frequencies like this, the length of the antenna will be extremely long. λ for 10MHz wave is $\approx$30m and obviously, matching length of 7.5m required for best propagation condition is unpractical for implantation in the human body. The length has not much effect on the transformer inductor since this is not intended for propagation. Besides the fact that, primary and secondary are supposed to be as close as possible to each other.

Although we have chosen a low frequency for power transmission, if we choose a much higher frequency for communication purposes (Very High Frequency (VHF) or Ultra High Frequency (UHF)) standardized by authorities, we will gain the benefit of using some already developed Off The Shelf (OTS) components to realize the receiver part during test and improvements or even in production phase.

Also, it will be convenient to utilize already approved frequencies in Industrial, Medical, Scientific (ISM) band like: $433 \cdot 92$ MHz, 868-870 MHz, 902-928 MHz, or $2 \cdot 4$-$2 \cdot 4835$ GHz. For SNoC-T discussed in this thesis the I suppose 915MHz transmitter frequency for a prototype phase. By selection and using this license free frequency, test and approvals of the prototypes will be much easier since there are several component providers supplying regulated receivers adjusted to this ISM frequency.

Power requirement in transmitter for this frequency is specified by desired range of propagation. By all means, 0dBm would be adequate for 10-20 mtransmission in free space even with tissue attenuation of signal or not optimally matched antenna for reception by a typical receiver in a normal room. However, the propagation distance is dependent on several factors like power transmitted, receiver sensitivity, area of both transmitter and receiver and medium 4.3. There are several available commercial products, capable of communicating up to hundred meters at these ISM frequencies with 0dBm transmission power. Hence, this module should have no problem in transmitting adequate perceptible power to an indoors network area by transmission at this frequency and power.

3.5.1 Modulation - Frequency Modulated Mode

In this section we briefly focus on modulating the measured and converted analogue signal with RF carrier for propagation to the receiver. Among the most important design criteria for SNoC-T and especially the RF-Block we can mention; power consumption pr bit, channel occupation and linearity.

However, we should notice that most of these conditions are described and regulated by authorities. Therefore, we may leave terms linearity and channel occupation as intrinsic regulated requirements and for the moment concentrate on power consumption as the dominating factor for modulation type selection criteria.

A modulation method which is simpler, power efficient and asynchronous seems to be more proper for our purpose than power thirsty linear synchronous modulation principles. Logically because the suggested sensor will just transmit measured values at intervals decided by the external energy provider. In addition, it should be mentioned that continuously synchronized data stream for measurement of such physical values occasionally is needed. ASK or sometimes known as OOK (Figure 3.6) modulation method is simple to implement, consumes power just in transmission duration of logical one(or zero), and does not require a lot of complex and power thirsty circuitry to be designed. This kind of modulation is used in many commercial application and will be a proper choice for sensor node modules, due to simplicity and power efficiency.

Actually it is possible to design the ASK transmitter just by a transistor. This transistor can be designed as oscillator with enough power to transfer the required power to the antenna. Oscillator can simply be turned on by logical one's. Otherwise it can stay turned off, therefore term “On Off Keying”. This topology requires a fast oscillator which does not need many pulses before stabilization in the oscillation is achieved. To compensate for settling time, it is possible to startup the oscillator in

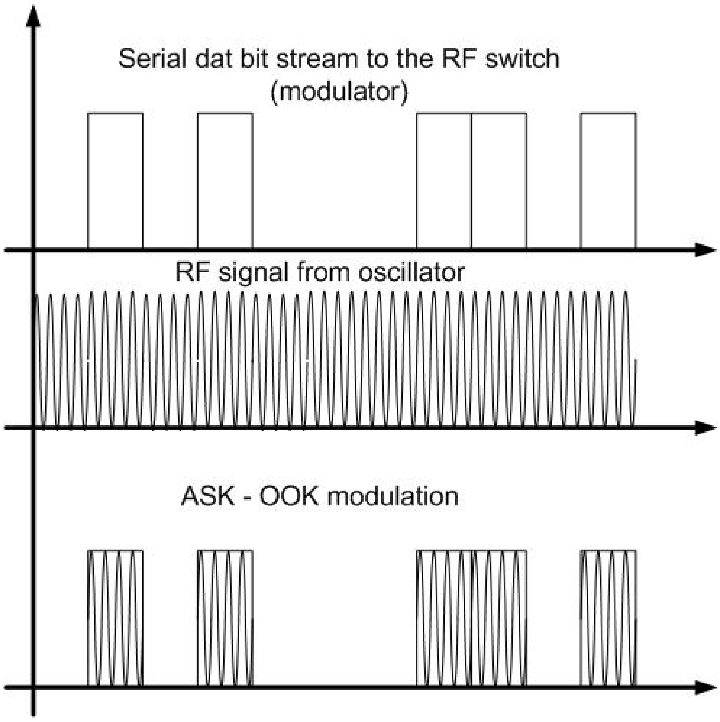


Figure 3.6: Principle of the ASK or OOK modulation

advance before bit transmission has started. But in most cases it would not be a point to be considered, since data rate is much lower than transmission frequency. For instant, if bit rate is 50 kbps, the bit cycle duration would be 20μ sec. If frequency of the carrier is selected to be 900 MHz, then the duty cycle is $1.2nano$ sec. It means that even a stabilization time of 100 cycles is needed by oscillator, the disposed delay on the bit is not more than $120nano$ sec which correspond to 0.006 of the bit time and is obviously negligible. Usually, baud rates much lower than 50 kbps are adequate for measurement of Brain Pressure Sensor System (BPSS) type of condition alterations. Measurements of up to 50 samples pr second is adequate and therefore neither samplings rates nor transmission baud rate, would be critical terms. On the other hand, accuracy and power consumption should be considered as main critical challenges in design of SNoC.

Next section is a description in functionality principles and important design consideration of oscillators, proper for utilizing in a SNoC.

3.5.2 VCO or synthesizer?

Generally, to transfer data wireless we need an oscillator to modulate the data bits on the RF frequency with some type of frequency or phase modulation principle. In most applications a VCO will be inevitable to provide stable frequency to modulator, but in next step synthesizer (PLL) will be considered as an alternative. Indeed this type of oscillator provides higher stability factor, more operation flexibility in different frequency bands and possibility of selectable channel bandwidths, if required. Although these advantages are necessary in some applications, two input signals are necessary for proper functionality of synthesizers(PLL). Usually, one is reference frequency and the other variable frequency source (generally VCO). There are different design topologies and technologies applicable for optimum design approaches to VCO's or synthesizers. Anyway, power limited SNoC-T requires a low power, fast, stable and accurate oscillator after activation by the power supply.

PLL could be called the heart of a synthesizer and therefore a brief functionality overview of this module is given here to determine critical elements in proper functioning of this oscillator. The principle of a typical PLL (and synthesizer) is illustrated in the bottom block of figure 3.7. Usually, there is a variable frequency source (F_{CF_VCO}) in the PLL, capable of oscillating in the whole bandwidth of operation. Frequency difference between this oscillator and a reference oscillator ($F_{CBW-VCO}$) will be detected by a comparator (Phase Frequency Detector (PFD)). The output of the comparator (PFD) which corresponds to the difference in frequencies, will then be integrated to an average Direct Current (DC) signal by a filter (CORR-LPF). This correction signal will control the output frequency of the variable oscillator (F_{CF_VCO}) and the whole circuit provides a loop called for PLL. In case of SNoC-T, this frequency (F_{CF_VCO}) is transmission frequency which will be modulated by measured signals converted to bits in the RF switch. Naturally, the functionality of a PLL (or synthesizer) is critical to the quality of the output frequency.

A common and state of the art alternative to realize a stable and fast PLL is using a sequential phase/frequency detector (PFD) in conjunction with charge pumping of the succeeding integrator (CORR-LPF). The output of the (PFD) has a major impact on the phase locking speed of a PLL. Therefore a current boosting circuit called "charge pumping" is added to charge the integrator (CORR-LPF) to provide a much faster average DC signal. This DC value will then control the frequency of the F_{CF_VCO} upward or downward, corresponding to the declining or inclining DC value as correction signal. The charge pump circuit is simply utilized by two transistors, shown in the figure. The utilization of PFD has several desirable features. Among those we can point out:

- high margins against false lock (not using XOR as Phase Detector (PD))
- In-phase input and oscillator signal condition when in lock
- attaining quick lock

As mentioned, charge pump circuit is simply included due to boosting the time of charge or discharge of capacitors in the CORR-LPF, directly proportional to the phase or frequency differences provided by detector.

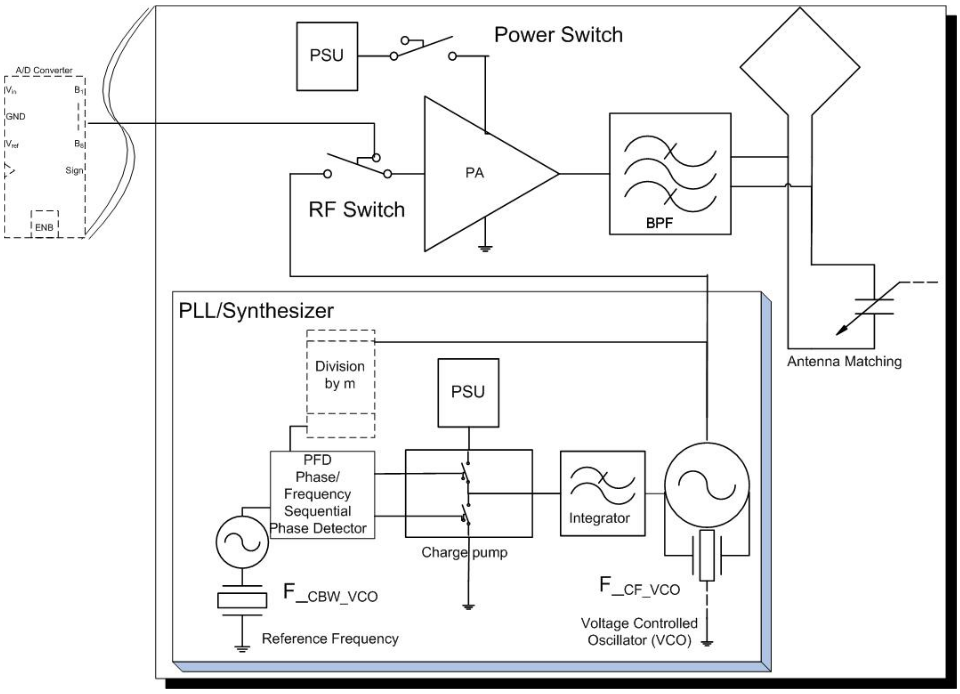


Figure 3.7: RF block with ASK modulator unit for SNoC with channel selection alternative

Frequency division block is compulsory to provide different carrier frequencies and hence, functioning as multi channel module. It is possible to construct even more fractional frequencies by employing more complex division methods. In this type of synthesizer (PLL), $F_{CF_{V}CO}$ oscillates at m times higher frequency than reference frequency. For instant, if the operation frequency $F_{CF_{V}CO}$ supposed to be 915 MHz, reference oscillator ($F_{CBW-VCO}$) with free running frequency of 15 MHzand 8 bit channel control counter providing a divide by 61, will force $F_{CF_{V}CO}$ to oscillate at the mentioned frequency.

Whereas, several nodes in the same wireless network are desirable, frequencies or shorter channel band width are needed and synthesizer design will be able to provide these frequencies. Thus, several channel selection steps will be achievable by increasing counter bits and lowering reference frequency. Channel steps simply are equal to this reference frequency. Fractional division enables synthesizer to operate in even more detailed frequency range, but will not be discussed here. ISM will allow operation in the range of 902-928 MHzand will theoretically be able to place 26 nodes operating in 1 MHzchannel Band Width (BW) in the same network area or simply, doubling number of networked sensors by using 500 kHzreference frequency (F_{CBW_OSC}), hence channel bandwidth.

While in some applications capability of channel selection is a mandatory requirements specification, in some others like sensor discussed in this thesis, a simplex SNoC-T is adequate. In such case, synthesizer (PLL) can be omitted in favor of simple but accurate, low power and low phase noise VCO. Of course, to achieve high efficiency and accuracy in wireless data transmission, we need high Q inductors. High Q inductors are essential in design of low-noise VCO as well, since the phase noise of oscillators is proportional to $1/Q_{Tot}^2$ (Q_{Tot} is total quality factor of the tank components of VCO).

Sometimes out-of-plane inductors are aligned in large angles with respect to the substrate to reach high Q values [11, 12]. Anyway, to achieve optimum accuracy in VCO, temperature instable poly resistive materials or crystals which demand much more complex process production line should be prohibited and preferably RFMEMS inductor and capacitor implemented in metal layers should be used to realize tank elements [ref: chapter 4 and 5 in this thesis].

The simple SNoC-T can be concluded as followed in the figure 3.8.

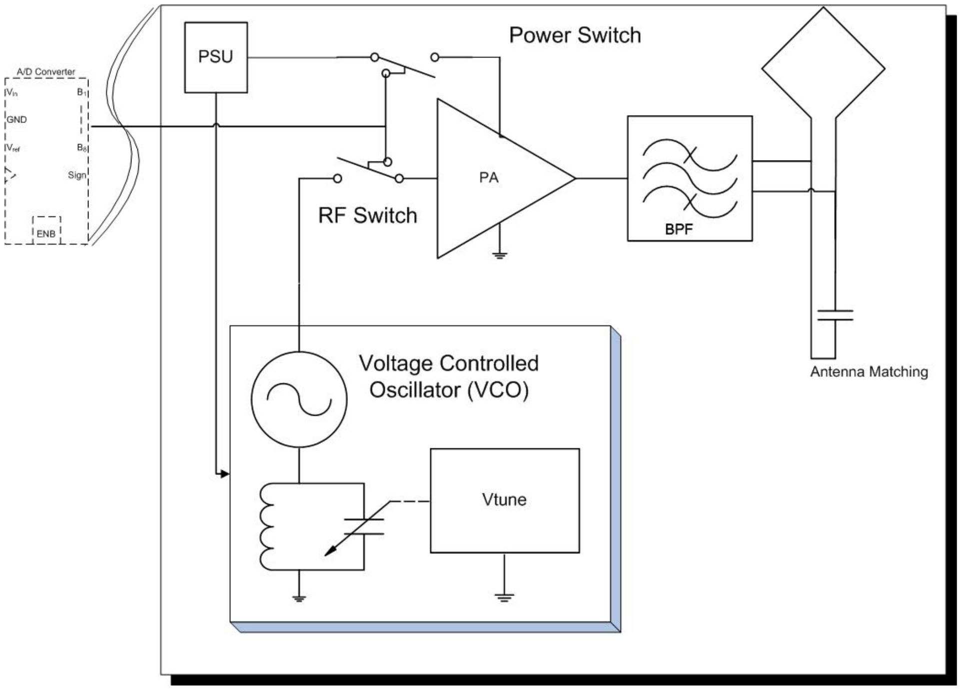


Figure 3.8: Simplex VCO based SNoC-T

In the last sections some critical components for proper function of a SNoC has been discussed and some examples of practical possible solutions were given. Next section will provide some different examples of modules and contents in a typical sensor node .

3.5.3 An example of PLL based frequency selectable duplex SNoC-TRX

The following example presents a multi channel duplex transceiver enabled for RF and channel bandwidth frequency selection. It should be mentioned here that if the SNoC is supposed to designed in respect to different rules and regulations, the synthesizer should be programmable.

Synthesizer block

Obviously, using this topology is not free of tears and wears. This device will need at least two oscillators; one as main carrier F_{CF-VCO}, and the other as channel Band width selection oscillator $F_{CBW-VCO}$, which usually have much lower frequency than the main oscillator. This aforementioned oscillator is necessary in case of multi channel operation. Figure 3.5.3 is an illustration over a multi channel, selectable channel band width SNoC-TRX. In this block diagram, the $F_{CBW-VCO}$ has a bank of selectable RFMEMS tanks. Hence, by selection of different tanks, $F_{CBW-VCO}$ oscillates at corresponding resonance frequencies of the tank selected. This would be useful if SNoC-TRX is supposed to operate at different channel band widths or separation guard band widths from adjacent channels. But, channel separation will be defined in advance for most ISM applications. Thus, the tank bank would be unnecessary and can be omitted for majority of sensors.

To select different channels or frequencies, a control section will simply command a division of carrier frequency F_{CF-VCO} by a factor m. This will easily be achieved by a using a division by m counter circuit. Output frequency should be equal to the reference frequency, $F_{CBW-VCO}$. Any difference between these two frequencies, will be detected at phase/frequency detector circuit PFD and be charged pumped to the CORR-LPF and force the F_{CF-VCO} back to the supposed oscillation frequency. This relationship can be shown roughly as follows:

$$F_{CF-VCO} = K_f * \int \left[\frac{F_{CF-VCO}}{m} \otimes F_{CBW-VCO} \right] \odot (F_{CBW-VCO}) \tag{3.1}$$

In this equation frequency of carrier (F_{CF-VCO}) is defined by the phase difference between reference frequency $(F_{CBW-VCO})$ and division of carrier frequency by a factor of m. Transfer function of the system K_f, will directly define not only the frequency but also phase noise margins of this oscillator. Therefore, design of a VCO with relatively low phase noise, would be essential in proper functionality of this sensor node.

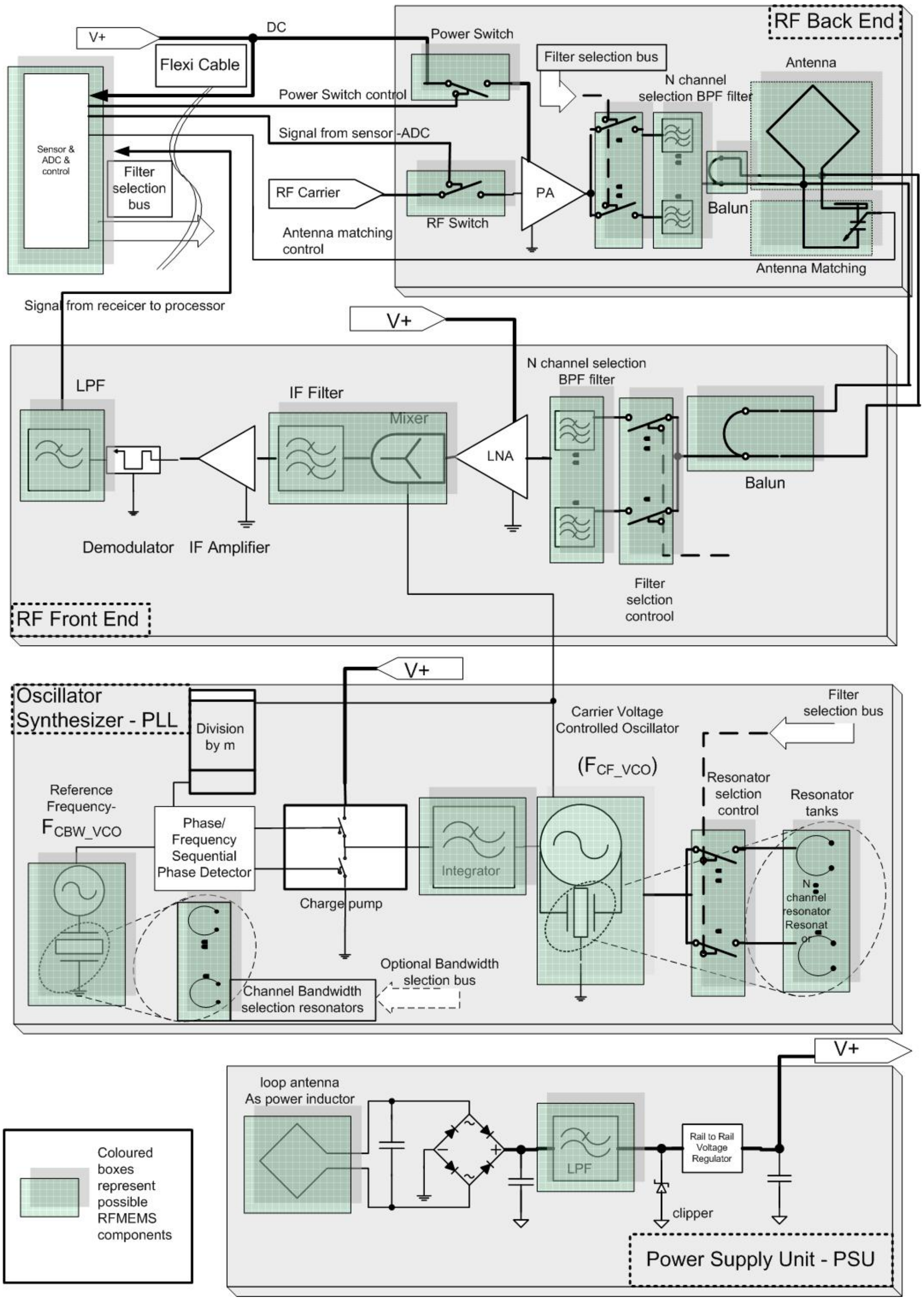


Figure 3.9: blocks suitable for using of MEMS and RFMEMS components in a Full duplex Transceiver for SNoC

Another important block in figure3.5.3, is resonator selection block and resonator tanks for the RF variable oscillator F_{CF-VCO}. These tanks are compulsory for multi band functionality of the SNoC-TRX. Indeed, ISM band has different criteria in different countries. In some continents and countries, for example the band at 900 MHz for most countries in Europe is 862-870 MHz. Whereas the same band is valid for 950-956 MHz in Japan, while in USA the same band is valid for 902-928 MHz. But in South America and Oceania the same band is just allowed around 915-927 MHz. Thus, to be cover for different demands, the synthesizer should not only have flexible $(F_{CBW-VCO})$ but also variable band selection capability for (F_{CF-VCO}). Therefore the tanks and band selection switches has been added to the design in the synthesizer block. Though the crystals are placed in the figure as the alternative resonator element, it should be mentioned that crystals are usually place demanding components and sre unpractical in case of the multi channel or the multi band operation. In those opportunities there is just one practical alternative solution to the tasks mentioned above, RFMEMS. Therefore, in design procedure of multi channel and band width the selection control circuits should be implemented. I the figure these circuits have not been shown, but only the "resonance tank selection bus".

The resonance tank selector switches are placed to connect the proper tank to the oscillator. These switches can be applied by just some transistors in a monolithic process approach. Likewise, the equivalent selection mechanism could be applied on the reference oscillator $(F_{CBW-VCO})$, if different channel bandwidths are supposed to be selected.

At last it should mentioned that channel selection or carrier frequency can be fractioned by another division of n, so a much more detailed frequency will be achievable, but this type of design is not discussed in this thesis.

receiver

Receiver block is shown as RF Front End block in figure 3.5.3. In this figure a "balun" (balanced to unbalanced) is placed after the receiver antenna. Common mode antennas should have balun avoiding jamming the signal path from antenna to LNA or channel or matching filters. Common mode antennas should have balun avoiding jamming the signal path from antenna to LNA or channel or matching filters. This element can be omitted if differential mode type of antenne with ground at one end is used.

As mentioned in previous section, if the module is supposed to function as multi channel system, selectable filter should be implemented. These selectable filters are implantable as RFMEMS matching elements. LNA is amplifying the received and filtered signal to the mixer. Local oscillator frequency to this mixer in receiver modus is provided by the synthesizer module. This frequency should be higher (or lower) than received frequency equal to IF frequency. In some occasions IF could be omitted dependent of the application.

Transmitter

This module contains simply a switch which modulates measured signals with RF frequency from synthesizer (or VCO). Measured signal is converted by ADC as a series of bits which turns the RF switch on and off based on the value of the bits. Thus, the RF signal is modulated as series of bits with high frequency, amplified and propagated via antenna. By the way, to reduce power consumption of PA as well as reduction in noise during stand by periode, another switch power PA by equivalent bit rate. Output of the PA is connected via selectable matching or Band Pass Filter (BPF) filters to the antenna. Like the receiver, signal should rather be connected to the antenna via balun if the common mode antenna is applied. The matching filters on RF back end are also preferred if multi channel operation is required. RFMEMS filters like, as explained in front end section, can be utilized here.

In this section a typical transceiver with some key components and modules was described. Green blocks represent potentially substitutable components by equivalent RFMEMS elements. Implementation of these RFMEMS components will save a lot of space in this type of module. However, some of the blocks illustrated in this example can be omitted if applications is not required to function as reciprocal communication node. An example of a transmitter version of SNoC is described in next section.

3.5.4 A typical simplex SNoC-T

As noticed in last example, duplex transceiver is capable of transmitting and receiving information and commands, but on the cost of power, space and complexity.

In some occasions like for example single measurement node, simple sensors are more preferred instead of power hungry complex sensors. Figure 3.10 shows an example of a sensor without RF receiver.

Obviously, the Front End section in this sensor is missing due to redundancy. This simple sensor does not need oscillation bank and tanks since there is no receiver to select different frequencies. Likewise if it is supposed to be used at a predefined constant frequency, necessity of filter bank at RF Back End will be omitted, as well.

To conclude, when there is no selectable filter or tank, selection mechanism will be unnecessary and therefore even less communication cables and wires to the sensor element are needed. This will reduce complexity of connectors as well. Another module which will be omitted is the detector as are the wires to the processor.

Even though by eliminating many modules and simplifying the whole system, there will still be some power consuming and space demanding components in this block diagram. Fortunately, there are some potential improvement possibilities in this module. For example, this module will become much smaller and consume less power by replacing crystals with RFMEMS lumped elements, and by combining the RFMEMS elements with oscillator transistors in monolithic processes. These potential replaceable components are illustrated in the figure 3.10 as colored blocks and dashed lines.

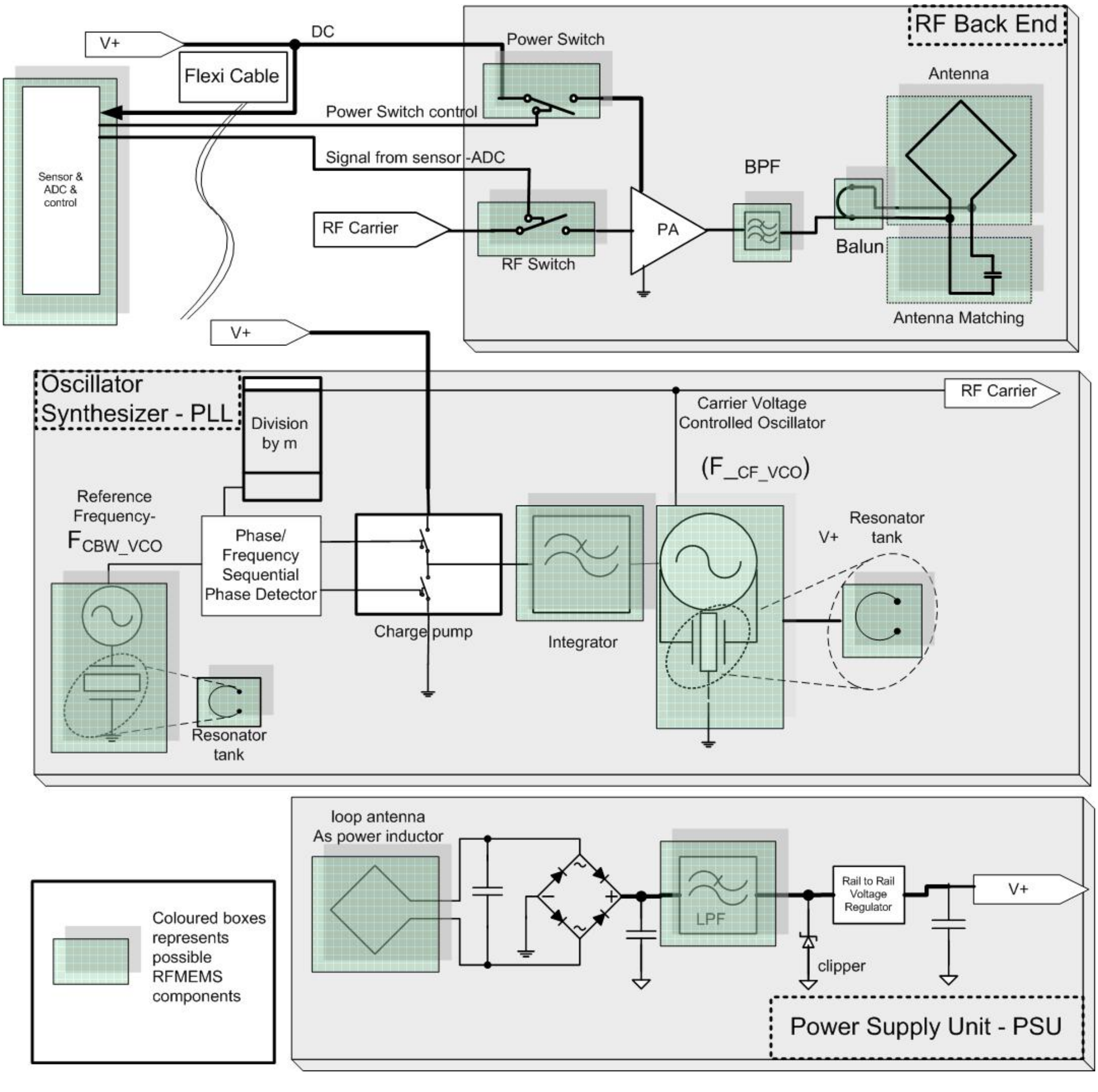


Figure 3.10: blocks suitable for using of MEMS and RFMEMS components in a Simplex Transmitter for SNoC

How simple can a SNoC-T be designed suitable for use as Bio-sensor in the human body?

Though the last version of SNoC-T was relatively simple and compact, but there will still be some possibilities to be exploited for reducing the sensor volume to the absolute minimum regarding space. Figure 3.11 illustrates which modules may potentially be realized as RFMEMS component candidates. The block diagram in figure 3.11 represents a simplex VCO based transmitter sensor node block diagram. It is noticeable that in this design PLL has been omitted.

Carrier frequency in this simple sensor is based on a VCO and not PLL. Hence, one accurate oscillator to function properly in the environment requirement is essential. Functionality of this sensor is limited to applications requiring a single sensor. This sensor should be capable of transferring measured data into a limited distance (of few meters) to a receiver.

Requested energy can be absorbed transcutaneous by injection from a handhold transmitter matched to a receiving inductor in the power supply module, inside the human body. Voltage rectified in the bridge is then regulated and delivered to the measurement and transmission modules. Since the primary power source is outside the body, transferred flux can relatively be arbitrary adjusted dependent on application.

The critical point in this sensor would be the design of low noise low power VCO. The oscillator tank has crucial impact on frequency stability and phase noise of the oscillator. Therefore, the quality factor of lumped elements in the oscillation tank should be as high as possible.

As explained later in 4.11, all relevant quality factors are dependent on the energy conservation of reactive lumped elements, L and C. Since the L is the dominant value in a tank equation 4.9 and 4.6, the most important part of a quality factor ($\omega_c L_e q / R_e q$) in a LC tank is influence of L. Thus, when tank is the most critical part in oscillator behavior, special focus should be concentrated on design of inductor in a parallel tank of oscillator.

Figure 3.11 is an illustration of the absolute minimum modules in a VCO based transmitter without use of PLL. Finally, details in some different blocks of the figure 3.11 has been shown in figure 3.12. In this more detailed figure, possible RFMEMS components in conjunction with CMOS realizable parts and circuits has been illustrated as green boxes. Yellow boxes as well represent some components which can be omitted if the application permit that.

In the Oscillator block, a possible design sketch has been drawn by dashed lines.

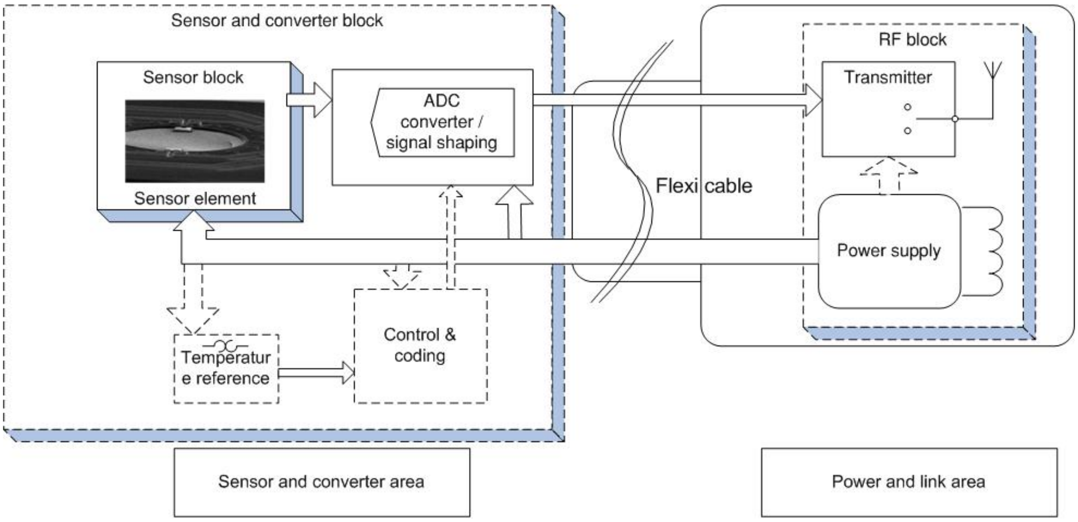


Figure 3.11: blocks suitable for using of MEMS and RFMEMS components in a very simple Transmitter for SNoC

In this chapter some ideas about design and consisting parts in low power SNoC-T was presented. Next chapter gives some more detailed aspects of design consideration and characterization of essential elements in this device. Important realization estimations and approximation methods to achieve optimum results in design of critical components of a SNoC will be presented in next chapter.

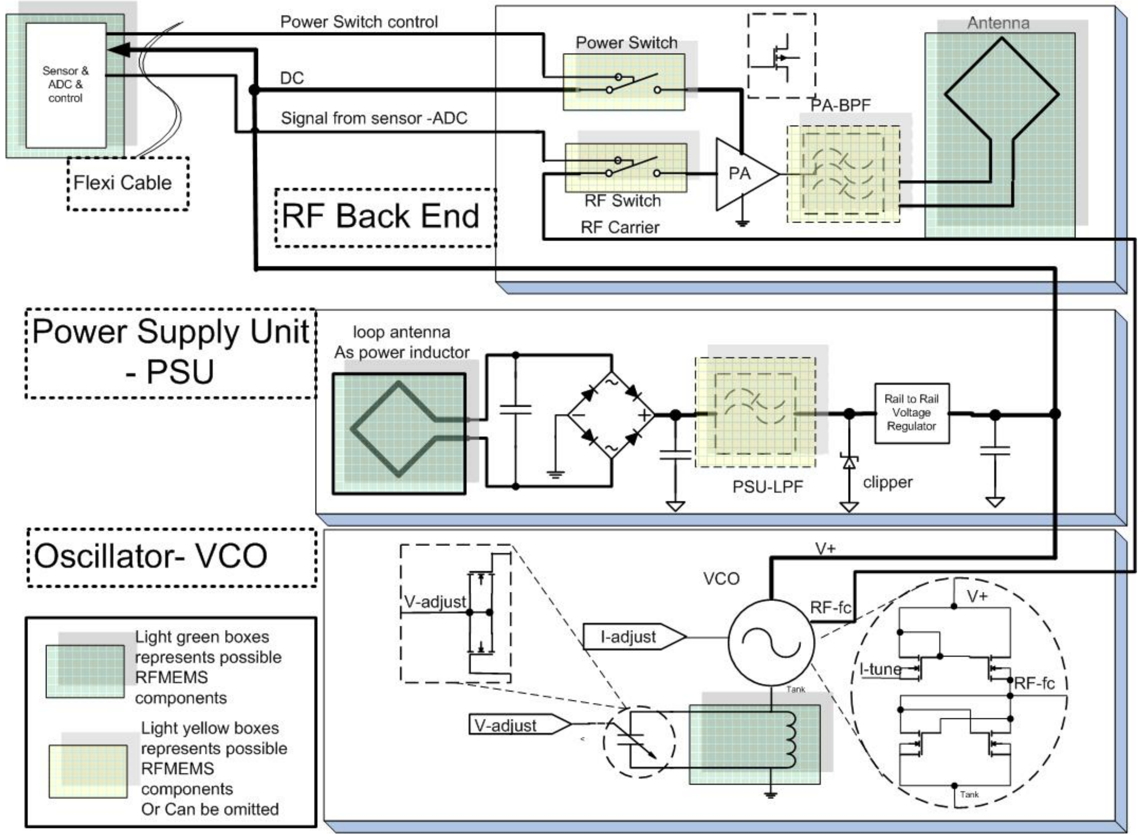


Figure 3.12: blocks suitable for using of MEMS and RFMEMS components in a very simple Transmitter for SNoC

4 SNoC - Design consideration

In this chapter some component requirements are described in more details covering power requirements and methods, frequency of power transmission or data communication, lumped element design criteria and characteristics.

4.1 Power Transfer and considerations

Power required to be transferred from Primary Module (PM) (for convenience we will use this term in this thesis representing the external module transferring power and/or data link to the sensor module) is an ambiguous term and dependent on the sensor node type and design. This requirement in a sensor node is dependent of many factors among those;

- range of transmission,
- data measurement and link rate,
- activity period,
- type of processing

Anyhow, total required power by a typical SNoC is determined by the following factors:

$$P_{2tot} = P_{rect} + P_{an} + P_{dig} + P_{RF} \tag{4.1}$$

Here P_{2tot} represents the total power required at the secondary inductor to supply wireless sensor node with enough energy adequate for correct measurement and transmission. On the right side of equation P stands for power required by the following:

P_{RF}: *Required power by RF transmitter dependent of transmission range, medium(s), Rate required for data transfer, type of modulation,*
P_{dig}: *Digital circuit and power required for data processing,*
P_{an}: *Dissipated power by analogue converters, sensor, passive components,*
P_{rect}: *Power dissipated in rectifier, lumped elements,*

Power required at primary to satisfy requirements of the sensor will then be:

$$P_{1tot} = P_2tot + A_l + Ti_l \tag{4.2}$$

P_1tot: *Power transferred from primary coil of transformer,*
A_l: *Ambient losses,*
Ti_l: *Tissue losses*

Power required for transmission from the PM depends on the frequency and waveform which can be sinusoidal or square wave. Simultaneously, if transformer supposed to be used as RF data link, spectrum consideration will be inevitable due to satisfaction of Electro Magnetic Compatibility (EMC) rules and regulations.

However, safety standards in terms if power penetration density for whole body exposure limit recommended by IEEE for frequency ranges 3-30 MHz is $9/f^2$ kW$/m^2$ or $\frac{900}{f^2_{MHz}}$ mW/cm^2.

It should be mentioned that in cases of closely coupled RF fields, the field is concentrated between two coils and most of the body is basically unaffected. Nevertheless, Specific Absorption Rate (SAR) for whole body could be as low as 1% of the recommended limit, even if SAR in the vicinity of the coils could exceed ten times this limit.

In other words, power required for SNoC and transmission via RF are compatible with standards and regulations as long as power dissipation requirements remains within few mW *c*riteria. In case of human body transposed for higher power rates, calculation should be done to determine if RF transferred through the skin exceeds SAR, which will not be covered by this thesis.

4.1.1 Selection of Proper factors for optimum Power Transformation

Equation 4.3 presented as follows, shows that received effect is mainly subjects to two factors when distance and transmitted power are constant:

$$P_r = P_t \cdot A_e \frac{\lambda^2}{d^2} \tag{4.3}$$

A_e: *Effective area at receiver antenna,*
P_t: *Transmitted power,*
λ: *Wavelength of the carrier,*
d: *Effective distance between transmitter and receiver*

As we described in previous section, power density requires for closed area transmission and bio-electronic sensor are within the margins of safety recommendations. Hence, assuming constant adequate power achieving best performance and efficiency from a transformer has two dependence factors; optimum frequency, antenna area and form-factors.

4.1.2 Selection of optimum frequency for power transmission

Frequency of power transmission is a critical factor affecting both power loss, quality of operation and design criteria. Especially regarding bio-medical sensors low frequency links are recommended due to limited accessible power since complicated wiring or batteries are in some cases inconvenient and mostly unpractical.

Body tissues are composed of cells filled largely with conductive fluids and encapsulated by thin membranes. The intracellular fluid consist of various salt ions, polar protein and polar water molecules. Electromagnetic fields make free ions to oscillate which increases conduction current associated with conduction losses. On the other hand, rotation of dipole molecules affects the displacement current which is associated with dielectric losses.

The conduction current is directly proportional to conductivity factor; likewise, displacement current is directly related to permittivity of the material. Both conductivity and permittivity coefficients of human tissues increase with frequency. Based on the typical values of these parameters measured among a variety of individuals, it is suggested that the frequency for power transmission to the RF couple of an implantable electronic system should not exceed 10MHZ [13], so that the dissipation of absorbed power by tissues remains less than 2% of the transmitted power.

At this frequency, losses are predominantly eddy current losses and depth of field penetration is much larger than depth of implanted sensor, consequently, the effect of the power dissipation volume can be neglected [14].

Characteristic impedance of the antenna for best matching and efficiency, is not only dependent of the antenna area, but also frequency. Higher frequency and hence, shorter wavelength will result in reducing antenna-size for the same inductor reactance. Consequently, to keep the length, area as short as possible for the same impedance or power susceptibility, not to change the matching point, we have to choose as high frequency as possible in the recommended bandwidth.

For instant, if we choose 1 MHz frequency as carrier frequency for power transmission, the wavelength will be 300 m in free space. It means that in practical conditions the transmitting and receiving antennas are much shorter than wavelength.

To find the optimum frequency we need to have an idea about how far our proposed frequency is capable to penetrate tissues of human body. As a general estimation rule [10], we present depth of penetration in human body which will be opposite of damping constant for an average body as shown in equation 4.4:

$$\alpha = \omega\sqrt{\mu_0\epsilon_0\epsilon_r}\sqrt{\frac{1}{2}\left(\sqrt{1+\left(\frac{\sigma}{\omega\epsilon_0\epsilon_r}\right)^2}-1\right)} \tag{4.4}$$

In this equation:

α *Damping constant for the body,*
σ: *Typical tissue conductivity,*
ϵ_r : *Relative dielectric factor of a typical body* (≈ 75),
ϵ_0 : *Dielectric factor of free space* $(8.85 \bullet 10^{-12})$,
μ_0: *Permeability of free space* $(4\pi \bullet 10^7)$,
σ: $\approx 1,5(S\ /m)$

To illustrate how deep electromagnetic waves of 1 MHz carrier frequency will penetrate inside the tissues, we define δ as propagation depth by the following equation 4.5 :

$$\delta = \frac{1}{\alpha} \tag{4.5}$$

$Penetration depth factor$

In equation 4.5 δ is penetration of electromagnetic waves in tissues of human body versus frequency shown in Figure 4.1.

Obviously, this length declines drastically between 1MHz to 10MHz , from 43cm to 13cm But up to 100 MHz $t$here is not noticeably steepness in decreasing directly proportional to penetration depth. This effect will qualify selecting of 10MHz to give adequate penetration depth and simultaneously small and practical antenna dimensions because of the relatively high frequency.

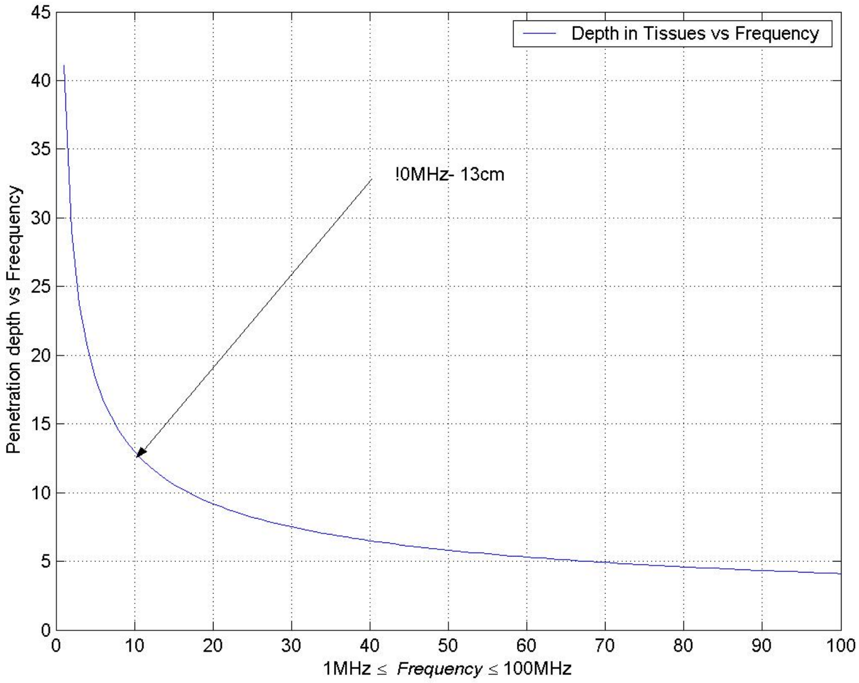


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Figure 4.1: *Penetration of electromagnetic waves in human tissues versus Frequency(MHz)*

4.2 Characterization of optimum inductor implementation for power and RF transmission

Selection of layout, length and technology in design of inductor as the main carrier of energy and/or data, has an essential influence on performance of the sensor node. Therefore, we survey some critical parameters and compare different designs to give an idea about advantages and drawbacks for various types.

Once more, we have to distinguish between biomedical electronic sensors limited in available space, and general purpose sensor nodes with totally different power and volume requirements. Biomedical sensors are not only subject to much limited space, but also have to withstand deterioration phenomenon in the human body. To resist this destructive process, sealing and packaging protection technologies in addition with robust design maintaining long-life performance of the sensor, is vital for successful result. In most cases biomedical sensor requirements describe a 10 years minimum life-time for biomedical sensors while in industry, 15 years is an often used common popular term.

Inductors for this type of application can be made in three ways:

1. Discrete encapsulated lumped inductors
2. Printed Circuit Board (PCB) electroplated planar wires formed as spirals
3. Coils and spirals made by MEMS technology

	Coil type		
property	Discrete	PCB(inc.flexi card)	MEMS
price	medium	cheap	expensive
Q	high	low	medium
volume	medium($\approx< cm$)	big($\approx> cm$)	small ($\approx> mm$)
area	medium($\approx< cm$)	big($\approx> cm$)	small ($\approx> mm$)
complexity	high(bulky)	medium(planar)	high(pre/post-process)
internal R	low($sub\Omega$)	medium(Ω)	low ($sub\Omega$)
substrate-loss(ϵ)	low	high	medium

Table 4.1: comparison of inductor implementation techniques

Apparently, each of the choices has some drawbacks and advantages. In next section we will concentrate on planar inductors calculated for flexi-board or PCB to show some characteristics and then compare the results with equivalent circuit made by other technologies.

4.2.1 Planar inductor layouts and characteristics

Lumped elements made in different shapes as conductive spirals, have been used in vast majority of consumer electronics during the last two decades. Perhaps a non-complex and cheap way of realization has been some of the major factors in planar inductor popularity. Nevertheless, compromises have been done in design by engineers due to the low quality of planar inductor characteristics, but the simplicity has counted in advantage for this type of coil in spite of weaknesses mentioned in the table of technology comparison.

Majority of planar inductors are made as quadratic or rectangular form. Most Computer Aided Design (CAD) programs do not support circular spirals layout until recently some Finite Element Manufacturing (FEM) or MEMS design software has made it possible to take circular planar spirals in calculation. But even with access to these expensive tools there are some lack of exact models and different fabrication characteristics which make arbitrary type of design inconvenient to most designers.

Therefore, most developers have related their design to some " rules of thumbs" or manual estimation. In next section I will mention some practical ways to estimate one of the most critical and demanding elements in design of electronics, MEMS or RFMEMS; the inductor.

Disadvantage of planar approach will be the small inductor value and consequently low achievable Q. Generally Q of an inductor will be defined as equation 4.6:

$$Q_{eq} = \omega L / R_{eq} \tag{4.6}$$

Where Q is equivalent quality factor of the inductor, L is inductance, $\omega = 2\pi f$, f is frequency and R_{eq} is equivalent of resistance in wires of inductor. This resistance is naturally serial resistance in the conductor but in most cases it would be much more practical to have a corresponding parallel value for this which is illustrated in figure 4.2, and can easily be derived from 4.6 and impedance calculation to be as 4.7:

$$R_{par} = \frac{L}{C \cdot R_{ser}} \tag{4.7}$$

Though R_{par} is a useful value in calculation, it does not exist as a real value and is based on the value of R_{ser} and quality factor of the tank. By using 4.6 and 4.7, we find:

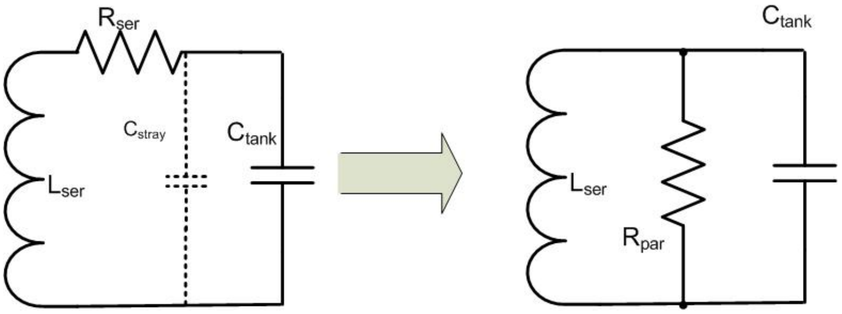


Figure 4.2: parallel resistance tank

$$R_{par} = Q^2 \cdot R_{ser} \tag{4.8}$$

By some simple calculation we find equivalent value Q at resonance frequency as:

$$Q_{eq} = \frac{1}{R}\sqrt{\frac{L}{C}} \tag{4.9}$$

Conclusively, ratio of L/C has a direct impact on quality factor of a LC tank. The higher L and the lower C are the higher Q in a parallel tank.

In general, the maximum energy stored in an inductor is dependent on inductance value L and alternate current produced in the inductor by the induced flux. This energy can be presented in equation 4.10:

$$E_{Leq} = LI_{max}^2/2 \tag{4.10}$$

But to absorb maximum energy at a predefined frequency of power transmission, a matching component or network is required to match the secondary impedance to primary inductor. This network will at the resonance frequency have the highest value of impedance in a parallel topology or minimum in serial version.

Practically, we use a matching capacitor parallel to the inductor to minimize effect of stray capacitances between wire loops of inductor as well and controlling the resonance frequency through this capacitance at the same time. Figure 4.3.

Following is explanation of matching model components presented in the figure 4.3:

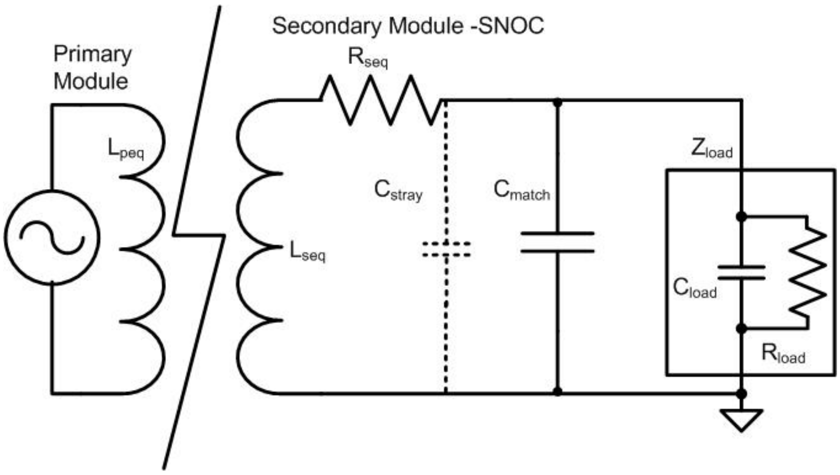


Figure 4.3: matching capacitor of PSU inductor

L_{peq} : *Primary equivalent Inductance,*
L_{seq} : *Secondary equivalent Inductor used to absorb energy from primary,*
C_{stray} : *Capacitance equivalent with coupling capacitance between wires or substrate,*
C_{match} : *Secondary matching Capacitance,*
R_{seq} : *Equivalent internal series resistor of inductor,*
Z_{load} : *Equivalent impedance of power consumption module*

At the resonance frequency electromagnetic energy will be absorbed and saved as current in inductor. This energy flows to the capacitor and stored as voltage. By other means the energy accumulated in a reactive lumped element would be generally as presented in equation 4.11,

$$E_{L_{seq}} = L_{seq} I_{max}^2/2 = C_{tot} V_{max}^2/2 \tag{4.11}$$

L_{seq} : *Secondary equivalent Inductor used to absorb energy from primary,*
C_{tot} : $C_{stray} + C_{match}$

As seen from 4.11, to increase the energy absorbed by inductor in a power supply, either we have to increase the inductance value L which in our case is limited naturally by available adequate space, or by increasing current. This could be realized in practice by reduction of internal serial resistance in inductor. (reducing the current consumption in electronic circuits or sensor element is another way to increase efficiency of the inductor and power supply).

Basically, to maximize available energy by increasing inductance factor L, we have to increase number of spiral turns in a planar inductor (L α n^2) until enough energy is achieved. Consequently the area of the inductor and resistance (R α n) will increase declining the inductor quality by choosing this solution. Another approach could in some cases be increasing permeability of the inductor by using transformer core. Unfortunately, this solution can not be used for HS since ferromagnetic materials should not be used in BPSS because of hazardous risk caused by extremely high energy imposed by Magnetic Resonance Imaging instruments.

Internal serial lossy resistance in inductance results in power dissipation, equal to following eq. 4.12:

$$P_{res} = R_{seq} I_{max}^2 / 2 \tag{4.12}$$

As a general definition quality factor [15] in a resonance tank is :

$$Q_{tank} = \frac{\omega_{resonance} E_{stored}}{P_{dissipated}} \tag{4.13}$$

This corresponds to the general definition of lumped element tank analogy:

$$Q_{tank} = \frac{reactive\ impedance}{dissipative\ impedance} = \frac{reactance}{real\ impedance} \tag{4.14}$$

By using equations 4.12 and 4.11, equivalent quality factor in a resonance tank would be introduced as equation 4.15:

$$Q_{tank} = \frac{\omega_{resonance} L_{seq}}{R_{seq}} \tag{4.15}$$

The resonance frequency in a LC tank is defined by:

$$\sqrt{1/LC} \tag{4.16}$$

Thus, using 4.16 quality factor can be defined as following equation 4.17,

$$Q_{tank} = (\frac{1}{R_{seq}}) \sqrt{\frac{L_{seq}}{C_{tot}}} \tag{4.17}$$

It should be mentioned here that quality factor is representing not only energy but also band width and phase stability of the tank. The equations 4.15 and 4.17 show how essential serial resistance value of an inductor is in quality and functionality of a resonance tank.

Therefore it is most important to use different methods, technologies and materials to design an inductor with as low as possible internal serial resistance and stray capacitances to adjacent wires and substrate. This would be the case both for high frequency oscillators as well as low frequency energy supply tanks.

4.3 Planar inductor modeling and topologies

Planar inductors are identified as inductors made on the basis of two dimensional layout on X-Y directions. This topology enables design of surface based inductors to be an integrated part of PCB or IC. Some possible geometries are classified as strip inductors or spiral inductors. As mentioned before, simulation tools used in design of silicon IC technology or PCB, has some limitation due to lack of circular design of inductors. Hence, there are some difficulties in the dimensional simulation and exact design process for these types.
Success in implementation of inductor with satisfactory performance, depends on accurate models of lumped elements. Several detailed models derivations for lumped elements are available through publications [16]. A limited version of modeling principles is given in this report. Figure 4.4 Illustrates a square planar inductor modeled by discrete elements including various parasitic components influencing the behavior of the inductor.

Another issue to be considered in design of inductor regardless of topology, is connection ports. Input and output ports of an implemented inductor will be asymmetrical if input port connects to the inner part of the inductor and the output port to the outer part of inductor, as shown in figure 4.4. Obviously, the outer part has a longer wire than the inner part of the inductor. This results in resistance and stray capacitances distributed asymmetrically for inner and outer wires to the connected ports.

Besides the width, thickness and shape, substrate affects the quality factor at high frequencies. At these frequencies, flux interferences from inductor wires will be absorbed by low resistive substrate. Equivalent circuit and model of a typical RFMEMS based inductor at high frequency and with two arbitrary layers of substrates have been illustrated in figure 4.4; The top layer represents an insulator layer and bottom layer the substrate .

Following is an explanation of typical inductor model components presented in figure 4.4:

L_{seq} : *Serial equivalent Inductance made by electromagnetic flux,*
R_{seq} : *Serial equivalent conductor resistance,*
C_{leq} : *Capacitance equivalent with coupling capacitance between wires,*
C_{ox} : *Capacitance between conductor area and substrate,*
T_{ox} : *Thickness of the oxide layer,*
C_{sub} : *Stray capacitance in substrate, usually neglected due to high, conductivity in silicon (below* $6\Omega cm$*),*
R_{sub} : *Equivalent resistor of substrate,*
T_{tot} : *Thickness of die,*
T_{met} : *Thickness of conductor,*
W_{met} : *Width of metal conductor wires*

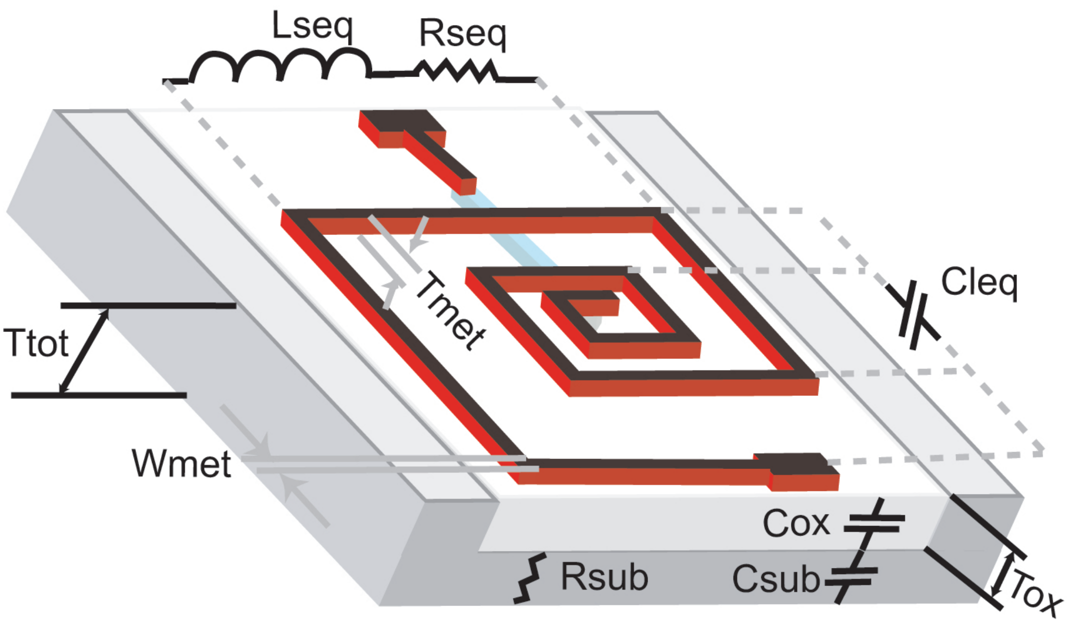


Figure 4.4: General modeling of RFMEMS inductor

As shown in the figure 4.4, a model based on two-port element has been presented and is defined as a $\pi - model$, since both input and output ports encounter some stray capacitance to insulator layer and substrate. A schematic representing this model is shown in figure 4.5.

The inductor implanted on the substrate shown here , has a total quality factor which would be the sum of unloaded parallel quality factors of substrate and the conductor [1]. The quality factor equation is presented as 4.18 :

$$\frac{1}{Q_{tot}} = \frac{1}{Q_{sub}} + \frac{1}{Q_{con}} \tag{4.18}$$

Equivalent quality factor of inductor implanted on a non ideal substrate

Equation 4.18 emphasizes that quality factor of inductor is affected by substrate and should be implemented on a material with high quality factor or high resistivity. This is in contrast to the fact that in monolithic manufacturing, CMOS transistors require low resistive substrate and RFMEMS demands high resistivity to avoid eddy current. It means that there should be some compromise to achieve high quality inductors which will be discussed in the next sections.

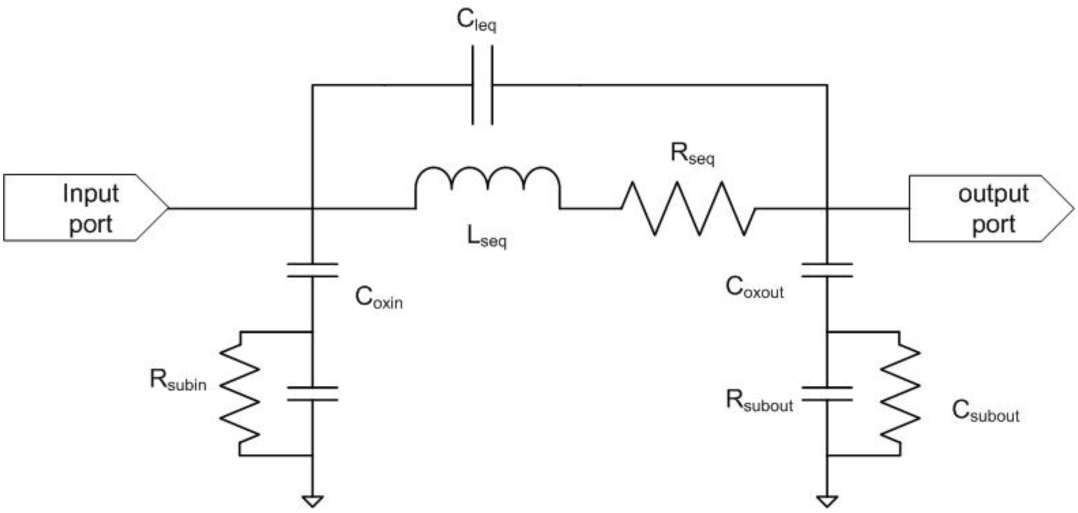


Figure 4.5: π model of inductor implemented on complex substrate

The schematic presented in figure 4.5 represents a theoretical model of an ideal inductor implemented on the substrate without effect of the increasing length of the windings. But practically, input port is usually connected to the inner winding of the spiral avoiding the big stray capacitors. Hence, at the second winding the length of the inductor is already much longer and much higher capacitance between adjacent conductor lines occurs. This trend escalates when windings distances are increasing from the inner winding for each extra turn.

Increasing capacitance is just one of many obstacles in this topology. The other phenomenon is increasing resistance and inductance. Both of these values are directly proportioned to the length of the conductor. Thus, the outer winding which is connected to the output port, has totally different and asymmetric impedance compared to the input port. Following schematic shown in figure 4.6 is a modified and more correct version of the simple version illustrated in the last figure.

Calculation for the total capacitance in this spiral is given by equation 4.19, just to show how much C_{ind} (combination of sidewall and fringing capacitances between each section) affects asymmetric behavior of the traditional spiral inductor.

$$Cpn_{leq} = \frac{(L_{n+1}+L_n)}{2}\left(\frac{\epsilon_{gap}t}{p-w} + \frac{\epsilon_{gap}}{2\pi}Ln\left(\left(\frac{w}{p-w}+1\right)\right)^2 - 1\right)\left(1 + 2\left(\frac{p-w}{w}\right)^{\left(1+\left(\frac{w}{(p-w)}\right)\right)}\right) \tag{4.19}$$

(Equivalent fringing and sidewall capacitances between each section of spiral)

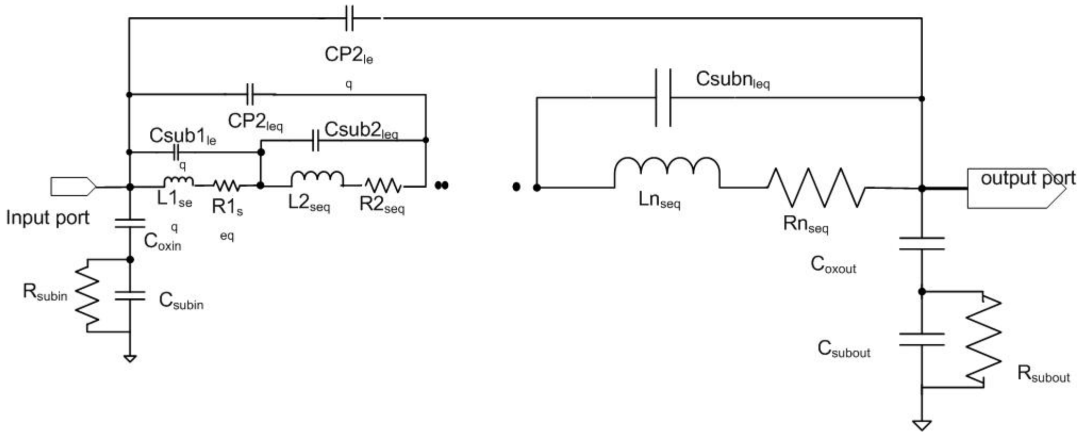


Figure 4.6: exact model of inductor implemented on complex substrate

Here P is distance between adjacent sections, and Cpn_{leq} is capacitance between each section. In the schematic 4.6, $Csubn_{leq}$ is the capacitance to the substrate or conducting layer above the inductor. All other terms are as explained in 4.4.

As seen in figure 4.6, the effect of the capacitances, inductances and resistors for each section of the spiral is increasing the further the section is from the center. In next section an example of eliminating asymmetric input and output is discussed.

4.3.1 Elimination of asymmetric planar inductors

In the last section, asymmetric parasitic elements showed the necessity of spreading impedances symmetrically through the length of the planar spiral inductors. Symmetrically distributed impedances will be provided by designing planar inductors based on the cross-over layout topology. This approach is similar to the methods been used in electrical power distribution, compensating against asymmetrical reactive energy loss through stray capacitances to adjacent wires. The solution is simply crossing over(or under) windings periodically. In the traditional spiral form, the the length and diameters of the outer and the inner windings are inverse proportional to each other. By other means, the port connected to the outermost winding encounters longest wires, thus larger stray capacitances than the port connected to the inner winding with the least stray values.

In cross over method on the contrary, dimensions for windings are equally distributed between the input turns and the output windings. Since the dimensions are is shrinking equally toward center of the spiral by each turn for the output and the input path, the capacitances are distributed equally between these two ports. Actually, the inner port or the outer port terms have no meaning anymore, since both ports are reciprocally equal to each other. Thus, the input or the output encounters the same length and stray parasitic values along the whole spiral, from the outermost to the inner circle or vise versa. Hence, to design symmetrically planar inductors this topology should be utilized due to excellent symmetric distribution of stray capacitances, resistances and inductances between the input and output ports.

As shown in figure 4.7, impedances seen by the input and output ports of indicator will be symmetrically matched due to cross-over topology. Obviously, manufacturing the cross over inductors demands at least two available conductor layers.

It should be mentioned here that since stray elements are equally distributed between the input and the output ports, these ports encounter half of the oxide or substrate capacitances (serial) and resistances each, as these are parallel with each other. Another mentioned advantage of the cross over spiral topology is the effect of the increasing inductance pr area unit due to increased coupling factor. Schematic model for this topology will simply be as shown in figure 4.8.

Although, cross over inductors solve the asymmetrical distributed stray obstacles, there are still some other deteriorating phenomenon affecting the quality factor of spiral planar inductors which are discussed in the next section.

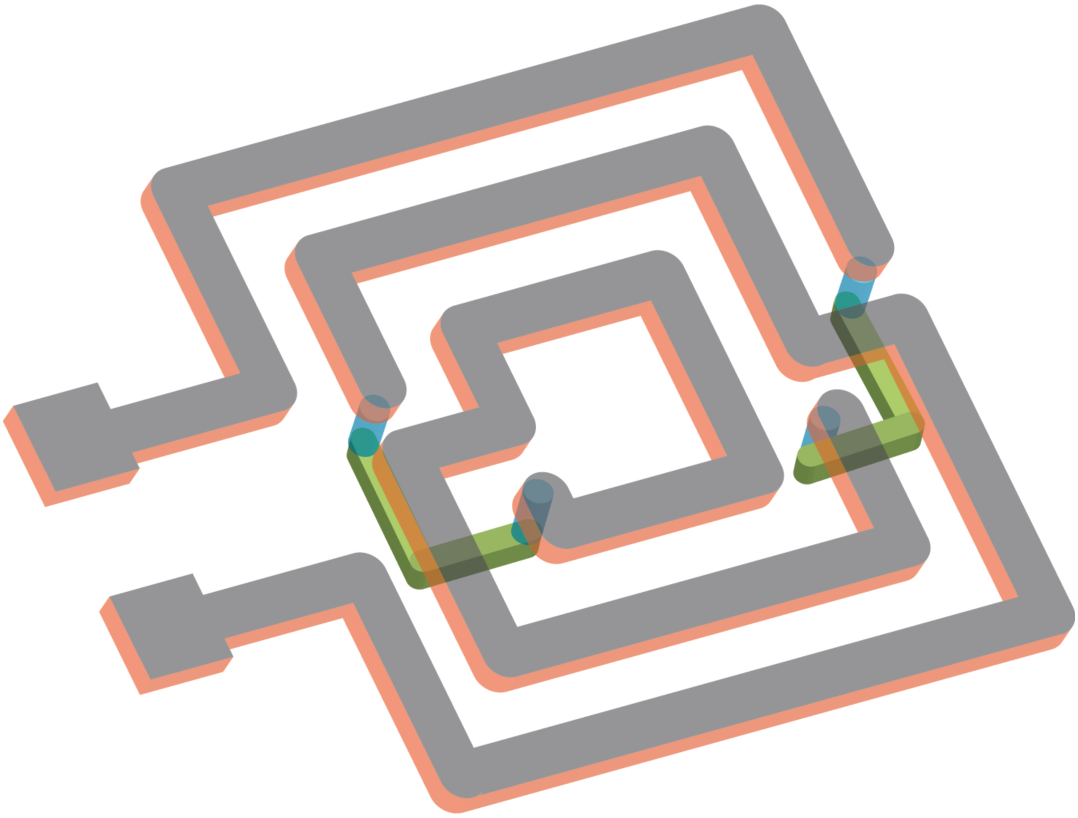


Figure 4.7: Cross-over MEMS inductor - compensating mismatching

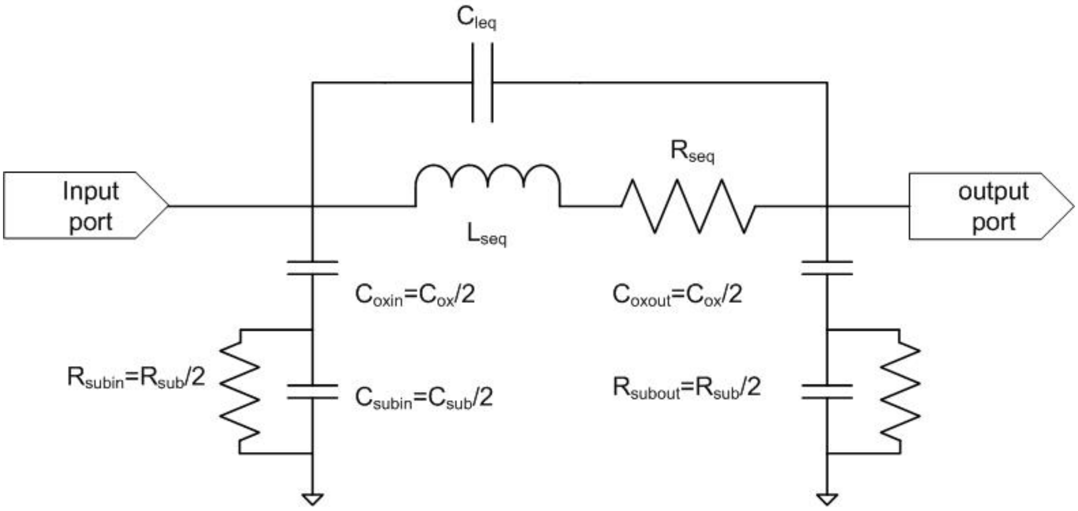


Figure 4.8: π model of symmetric inductor implemented on complex substrate

4.3.2 Effect of non-ideal substrate on quality factor

There is another obstacle to cope with in planar inductor implantation. Induced electromagnetic fields from each winding of the spiral will penetrate into conducting material of substrate (in case of CMOS technology) resulting in electric field. Based on the Faraday's law, this fields will produce electric current in substrate. This current behave as a dissipative loss for the inductor in the substrate. This current is known as Eddy current and 4.9 shows an illustration of how this current is provided by the electromagnetic flux interference in the substrate.

At RF frequencies, induced currents in the conducting substrate limit Q_{sub} by converting the electromagnetic fluxes into resistive dissipation. Equations 4.20 and 4.21 illustrate the detailed elements in the induced current to the substrate at the presence of electromagnetic fields [17].

$$\nabla \cdot H = j\omega\epsilon^{''} E + \left(\omega\epsilon^{'} tan\delta + \sigma\right) E \tag{4.20}$$

$$\nabla \cdot E = -j\omega\mu H, J = \sigma E \tag{4.21}$$

H :	*Magnetic field density,*
E :	*Electric Field,*
ω :	*Angular frequency,*
$\epsilon^{'}$:	*Substrate permittivity (real),*
$\epsilon^{''}$:	*Substrate permittivity (imaginary),*
μ	*Permeability of substrate,*
σ :	*Conductivity in substrate,*
$tan\delta$:	*Loss tangent in substrate*

Usually, the electric induced fields dominates over the magnetic loss for low resistive values. Highly doped low resistive CMOS is mostly used as the substrate in monolithic post processing RFMEMS technology. In high resistive substrate materials on the other hand, magnetic losses will be the dominating part of this equation.

However, aforementioned equations show that low resistive material will increase eddy current produced by magnetic induction to the substrate at frequencies which results in low Q_{sub}. Thus, the total Q deteriorates as explained in equation 4.18.

Following figure 4.9, is an illustration over how magnetic fields interfere the substrate and cause Eddy current.

Although, cross-over inductor implementation will solve asymmetrically parasitic phenomenon, but this topology still represents some disadvantages comparing to the

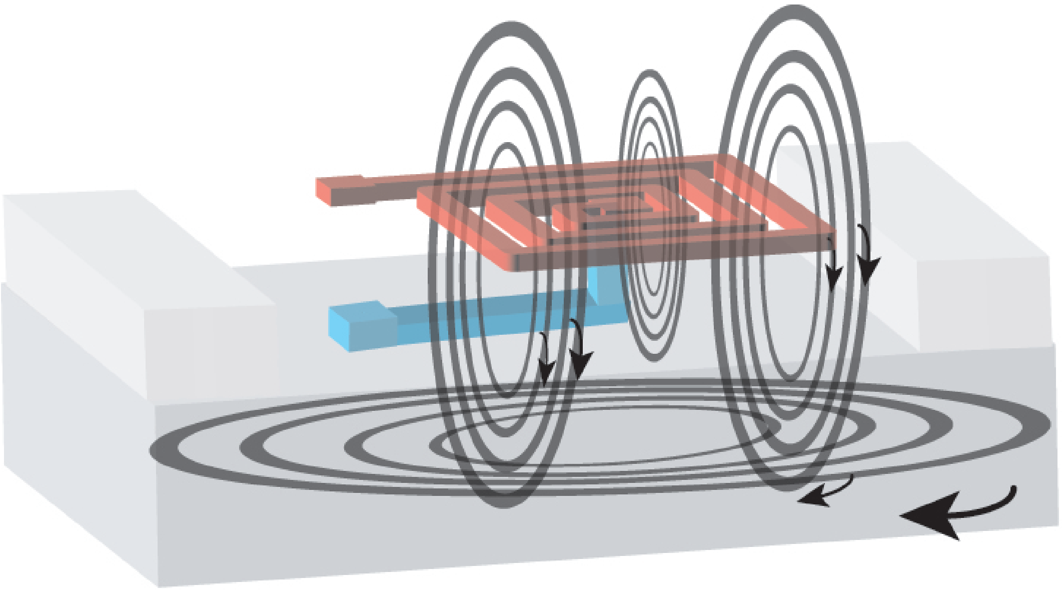


Figure 4.9: Eddy current in the substrate

simple square planar topology.

Some of the most important drawbacks of cross-over inductor topology are:

- modeling and layout become more complex,
- at least two metal layers are needed to connect cross over wire elements to each other,
- more expensive process due to the use of several vias and metal layers, thus several process steps

There are still several obstacles to be solved in achieving high-Q inductors. Some other compensation methods to reduce the effect of the lossy substrate will be discussed in RFMEMS chapter. Next section describes a solution to another obstacle; internal serial resistance of the conductor.

4.3.3 Resistive conductor materials in inductor and compensation methods

As we saw in previous sections, one of the most important parameters in quality factor of an inductor is serial internal resistance 4.6. This resistance is directly proportional to the resistivity factor of the material, length and cross section area of the conductor, as described in the figure 4.10 and by equation 4.22:

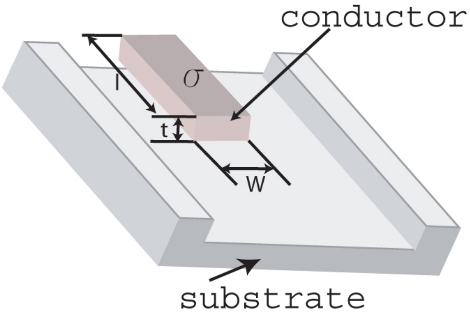


Figure 4.10: A slice of the conductor in the planar spiral inductor

$$R = \frac{l_{tot}}{\sigma \cdot w \cdot t} \tag{4.22}$$

l_{tot} : *Total length of the conductor,*
w : *Width of the conductor,*
t : *Thickness of the conductor,*
σ : *Conductivity of the conductor,*

Hence, to reduce resistor value and simultaneously keeping the length fixed due to maintaining inductance value, we have to increase; width, thickness or conductivity.

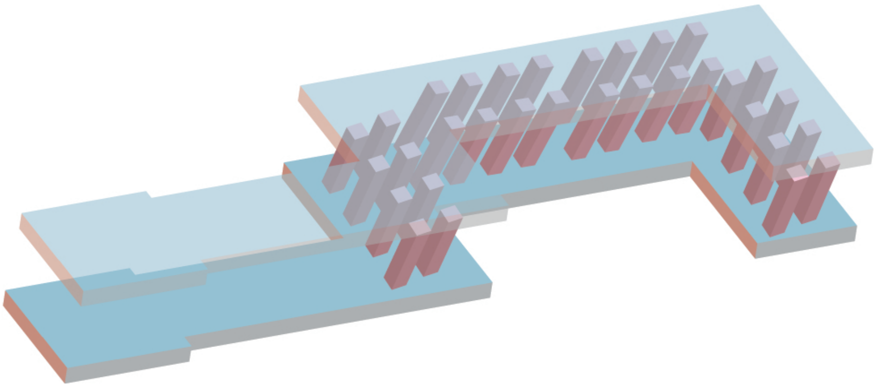
- **Width:** Increasing the width can result in lower resistance, but will simultaneously increase the capacitance value between each wire and substrate, as described in 4.19. This parasitic capacitance is inaccurate and usually affected by process tolerances which contributes to unreliable stray values.

- **Thickness:** Most fabrication precesses provide several metal layers, hence realization of planar inductors as geometrical structures in CMOS or MEMS technology is available. Some suppliers offer from 4 to 9 metal layers intended for circuit wiring, which enables designers to take the advantage of these layers and use them to realize inductors. By taking a advantage of this opportunity, engineers control the conductor thickness, resistance and quality factor.

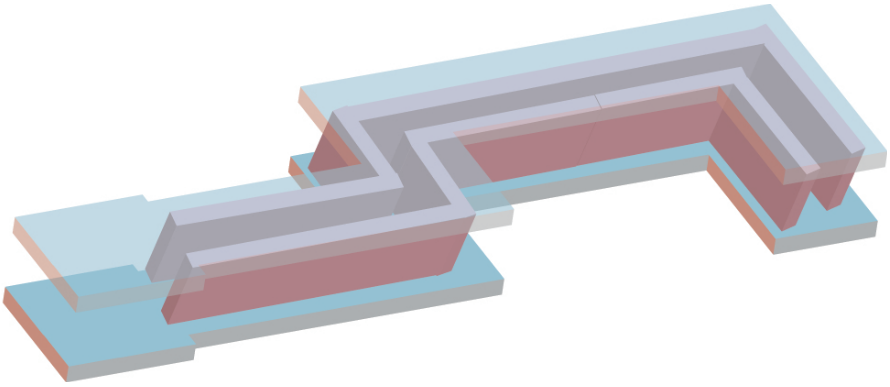
  Usually, metal layers are implemented in modern processes by using copper with conductivity of $\sigma \approx 57.14\mathrm{S/m}$ or aluminum with $\sigma \approx 37.7\mathrm{S}/meter$. These metal layers normally reside on top of the substrate and are often embedded in silicon dioxide SiO2 with a relative permittivity of $\epsilon_S iO2 \approx 4$. Conductivity factor of silicon substrate is dependent on several factors like doping but is mostly determined by the factories as $\epsilon_{SiSub} \approx 20$. Thus, the relative conductivity of substrate combined for silicon dioxide and si will be $\epsilon_{Sub} \approx 12$.

  Some other materials like polysilicon have been used as conductor in CMOS technology, but metal layers have a better conductivity than polysilicon materials (for salicided polysilicon typical $5 - 7\Omega/sq$ are given by manufacturers which usually are used as conductive material in CMOS technology). Although metal layers have good conductivity, they are not perfect conductors. Therefore two or more metal layers shall be shunt connected for a reduction of the intrinsic metal resistance. To make some examples, I have used two shunting metal layers as conductor material in this thesis. Shunt metal layers have been reported by different fabricating approaches. Utilizing vias connections shunting metal layers (interconnection between two or more layers using metal) is one of the most common technologies.

  Traditionally, tungsten was commonly used as metal for realization of VIA connection in IC technology. Recently, copper or aluminum as connection material are commonly been used by MEMS or IC-fabrications. By realization of copper or aluminum as VIA connection material, it is possible to use metal bars as a vertical implanted metal wall instead of separated vias. Figure 4.3.3 illustrates both technologies. This approach uses intermetallic stripes along the inductor windings to reduce the internal resistance of metal by $30 - 60\%$.



(a) connection between two metal layers by matrix of vias



(b) connection between two metal layers by wall made as via bars

Figure 4.11: Different via connection principlefs between two metal layers

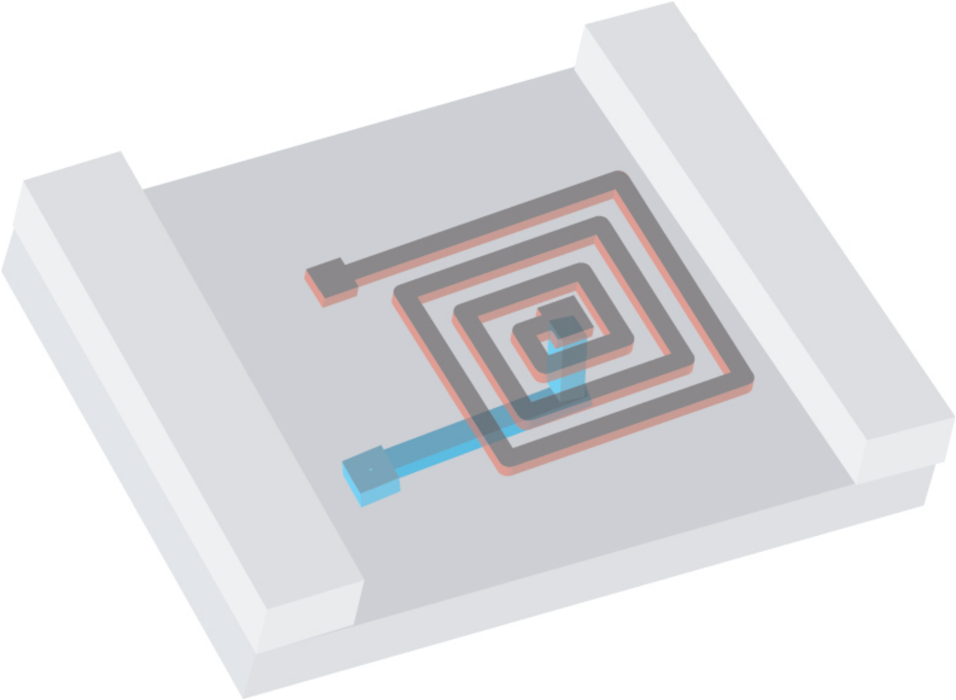


Figure 4.12: Traditional MEMS quadratic spiral inductor

- **Inductor with escalating width:** Anyway, for both of the simple spiral or the cross over versions of planar inductor topologies, there is still a last issue to be considered; asymmetrical distribution of the winding resistances. Each turn of the overall spiral or wiring loops in inductor, are getting longer and longer the further loops are located from the center of the loop. This is simply caused by the fact that the circumferences grow toward the outer limit of the planar spiral inductors.

  Consequently, the resistance which is directly proportional to the length of the conductor, increases for each turn the further the conductor loop is located from the center. To reduce this disadvantage resistances should be maintained fixed for alle winding turns independent of distance from the senter. Thus, since the thickness is fixed for the total length, compensating for increasing resistance can be utilized by increasing width proportional to the length. This will be simply done by increasing the conductor's width for each corresponding turn of the spiral toward the outer loop. This method is called for "Escalating conductor width" in this thesis. Hence, the resistance in the escalating conductor width will be held relatively fixed along the spiral, because of the increasing width.

- **Escalating spacing:** Although escalating conductor width will solve asymmetrical distribution of resistances along the spiral, this solution will result in increased fringing capacitances between adjacent windings as well. As mentioned in previous point, the farther windings are located from the center loop, the wider are the conductors and the larger surface area of the metal. Fringing capacitances are partially proportional to the adjacent conductor areas. Thus, the conductor area enlargement results in increasing fringing capacitances. To reduce the effect of escalating conductor width on the fringing capacitances, the distance between windings (spacing) should increase proportionally to the conductor width. This solution results in longer distances between adjacent conductors and is called "escalating spacing" in this thesis. This method has been shown in figure 4.13.

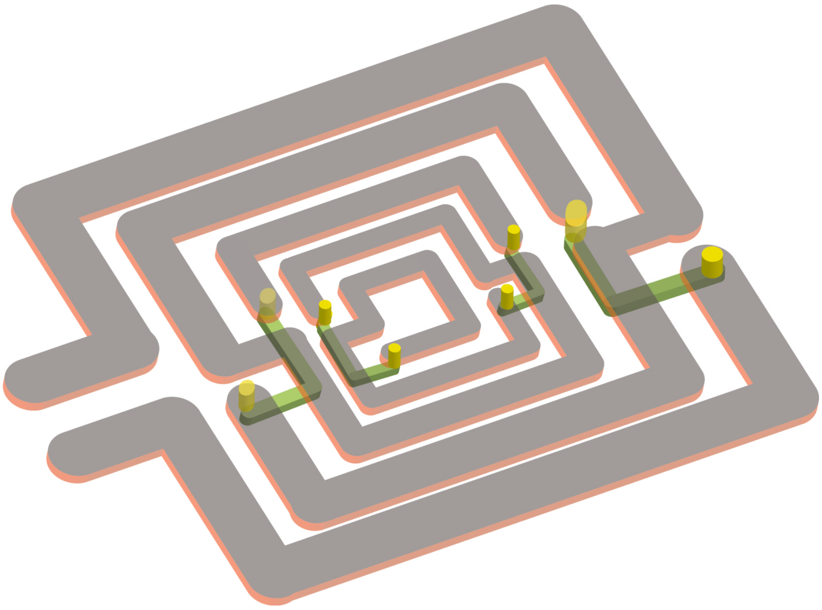


Figure 4.13: Cross-over inductor using escalating width and spacing

But even with a low resistive approach in inductor implementation, layout design or topology has a major impact on quality and behavior of planar inductor. Mostly, inductors have been conveniently implemented as square planar spirals. But, regardless of inductor shapes, quality and behavior of inductors are mostly dependent on application.

For example in case of TMC method of coreless transformer power transmission, one inductor acts as primary inductor, transferring electromagnetic waves through air or tissue of human body to the secondary inductor. It maybe preferred to use circular spiral coils rather than square spiral coils for a neuroprosthetic transcranial telemetry system [18] due to implantation convenience of circular planar implant under skin.

Most CAD layout tools enables designers to draw straight forwarded lines or in sub angles of 90° like 45°. Also, drawing inductors as semi circles can be realized by orthogonal topology which constructs a semi circle by drawing 8 equal sections connected in 45° angle. Orthogonal design topology compromises advantages between circle and square spirals. But simulation inaccuracy will still be the major challenge to be solved.

Since there are not still many reliable tools for estimation of inductor values, the next section will discuss some theorems concerning estimation and approximation of inductor value calculations.

4.3.4 Planar inductor calculation theories

Design engineers have usually used possibilities in CAD tools by using straight sections of strips in spiral path or as meanders to design simple geometry for simulation or layout of inductors. But results estimated by these simulation tools are highly unreliable and mostly do not take all of the characteristics of the manufacturing variables into consideration. Hence, manually estimated values of inductors still are a reasonable contribution to the expected results.

Inductance value calculation of planar and on-chip inductors has been described and formulated since Grocer [19] published his tables in 1946. But there have been some improvements in these estimations, especially due to the shapes and design of the conductors. Maybe the most relative value estimation formula for a planar circular spiral inductor was presented by [20] as:

$$L(\mathrm{nH}) = (o.o1)\, 2AN^2\pi \left[ln\left(\frac{8A}{C}\right) + \frac{1}{24}\left(\frac{C}{A}\right)^2 ln\left(\frac{8A}{C} + 3.583\right) - \frac{1}{2} \right] \tag{4.23}$$

(Rebeizs's estimation of inductor value)

Following is an explanation of the different terms in equation 4.3.4,

$N =$ *Number of turns*
$D_0 =$ *Outer diameter of the spiral, in mil*
$D_1 =$ *Inner diameter of the spiral, in mil*
$A = (D_0 + D_1)/4$ *In mil*
$C = (D_1 - D_0)/2$ *In mil*

But as mentioned earlier, most Manhattan geometry CAD tools do not imply with circular spirals in design layout and simulation. Layout with quadratic or rectangular spiral inductors is quite common and therefore it is most convenient to estimate calculation for this type of design as well. Thus, equation 4.3.4 has been introduced by Greenhouse [21] in 1974 and with some modifications still reliable.

This estimation gives inductor values in μH for planar square coils converted in dimensions in cm:

$$L = o.o184SN^2\left[log\left(\tfrac{0.7874S^2}{t+w}\right) - log\left(0.9504S\right)\right] + 0.008SN^2\left[0.914 + 0.2235\left(\tfrac{t+w}{S}\right)\right]$$

(Greenhouse's estimation of quadratic spiral inductor value)

(4.24)

while,

$S =$ *Maximum side dimension, in cm*

$N =$ *Number of turns*

$t =$ *Conductor thickness, in cm*

$w =$ *Conductor width, in cm*

This equation has been modified several times depending on different applications, and most of equations require a lot of computational power to give estimation of inductor characteristics.

A simpler version of inductance estimation with adequate accuracy is helpful to give us an idea of values expected for quadratic spiral planar conductors. Perhaps Bryan's estimation [22] is the most convenient and simplest equation shown in 4.3.4 to give a roughly idea of expected inductor value.

$$L = o.o241aN^{5/3}Ln\left(\frac{8a}{c}\right)$$

(Bryan's estimation of quadratic spiral inductor values)

(4.25)

while,

a =*Outside plus inside diameter divided by 4 , in cm,*

c =*Outside minus inside diameter divided by 2 , in cm,*

N =*Number of turns,*

L =*Inductance in μH,*

Although Bryan's or other estimation equations will give us some ideas about values of the planar inductors, we have to take some incorrectness into consideration. Especially, there is a major inaccuracy in case of multiple turns planar spiral. In this case, mutual inductance has a major impact on inductor values and nonlinearity in frequency spectra.

Generally, inductor values would be mutually influenced positively by currents in the same direction, i.e. M_+ and vice versa M_-. Total inductor would be as defined in equation 4.26:

$$L_{tot} = L_0 + \sum M \equiv L_0 + M_+ - M_- \tag{4.26}$$

where in 4.26, L_{tot} is the total inductance, L_0 eq:mutual-ind-1 is the sum of the self-inductances of all the straight segments divided into z elements presenting a square spiral. $\sum M$ is the sum of all the mutual inductances, both positive and negative.

$$L_0 = \sum_{x=1}^{z} L_x \tag{4.27}$$

Since mutual inductance is positive when current flow in two parallel conductors is in the same direction and negative when current flow is in opposite directions, $\sum M$ in equation 4.26 can be rewritten as 4.28:

$$\sum M = \sum M_+ - \sum M_- \tag{4.28}$$

Where, $\sum M_+$ is the sum of the positive mutual inductances and $\sum M_-$ is the sum of the negative mutual inductances. Exact estimation and calculation of quadratic planar spirals is not a main task of this thesis and is left to CAD tools for the future projects.

Next section will introduce some approaches on approximations of inductor values and how to cope with the obstacles during the proper tank design.

4.3.5 Approximation of inductor values

To estimate the value of inductors used in tanks of power supplies or oscillators, I have made some suggestions to present a practical approach on approximation of the inductance value. As we mentioned in 4.13;

$Q_{tank} = \omega_{resonance} E_{stored} / Pdissipated,$

and by some simple calculations from 4.15 we find:

$Q_{tank} = \omega_{resonance} L_{seq} / R_{seq}.$

By using this equation and knowing approximately the serial resistance in the inductor and assuming some practical capacitor, we can approximate the value required for an inductance based on the desired quality factor.

Approximation procedure:

- Decide a power consumption value based on the requirements in the application,
- Find out the proper frequency in accordance to the rules and regulations to be approved by the authorities. Simultaneously this frequency will give the optimum performance for the particular application.
- Load impedance which is simply approximated to be supply voltage divided by current required from application. This impedance should be matched with the parallel resistance of the tank.
- After finding this parallel resistance, find the corresponding serial resistance based on equation 4.8.
- Based on already calculated values of ω_{res} and R_{ser} and having Q, calculate desired value for L.
- At last by knowing characteristics of the conductor from fabrication, nominal values for cross-over unit resistance or conductivity values will result in a length of conductor to achieve calculated resistance.
- Estimate the value of inductance by the calculated length, width and thickness of the material based on Bryan, Rebeiz or other computing programs and find out the compromise between number of turns in the spiral and width, length.
- Finally select a value for capacitance to achieve resonance frequency with the calculated R_{ser} and estimated L.

4.3.6 Case study of inductor value for power supply

For instance, in case of SNoC and using some specifications given by [2, 3, 4] we assume the required current by the circuit is 2 mA and the available voltage should be 3 V. This type of circuits designed in modern nano-electronic will be adequate for most sensor application.

Currently, by using nano-electronic technology it would be more than adequate power for this type of sensor application. With this power requirement we need to have 1.5 to 2 mA available current from inductor to power the load. Hence, the impedance of the load should correspond to at least 1.5kΩ at 3 V DC avoiding overloading of the power supply.

To produce this required current at the resonance frequency (10 MHz, chapter 5.1.2) we need:

- Frequency for power transfer in this application was selected to be 10 MHz (chapter 5.1.2).
- R_{par} selects to be matched with Z_{load} (1.5 kΩ).
- R_{ser} should be lower than, $15 - 20\Omega$.
- By knowing R_{ser}, Q and the frequency and using 4.15, L is approximated to be 2.4μH.
- By using fabrication values for resistivity which for this example is 200 mΩ/sq, to achieve 15Ω we have to have a length of 730 000 μm with cross-over width 300μm and thickness 30μm.
- Using estimation methods (Bryan), to achieve an inductance of 2.4μH by these values results in an inductor with 15 turns quadratic spiral with almost 3 3cm of outer side length.
- Finally a resonance parallel capacitance for this inductor can be calculated to be ca 100pF.

This case study shows the approach from requirement specification of application to design estimation which results in an inductor with a quadratic side length of ca 3cmand by using a capacitor of ca 100pF we will achieve value of 10 for Q at 10 MHz which would be achievable by most not expensive technologies.

Simultaneously, we can conclude that SNoC with the above mentioned specification is not practically suitable for RFMEMS technology, due to the size of the inductor.

4.3.7 Case study of inductor value for oscillator

The same procedure will give the following values for resonance frequency of 900MHz. By the way, design of low noise and low current oscillator requires much higher Q factor than the power supply case. Thus, in this example we have to select a much higher Q factor. The regulation limitation in the ISM band around 900MHz allows a bandwidth of around 20MHz, giving the quality factor of 45. This quality factor is for whole system and can be adjusted by the filters in transmitter part. This value seems to be high for available *RFMEMS* technologies, and therefore we assume a practical quality factor of 20 for this inductor. Detailed design discussion around VCO is not an aspect of this document.

- Frequency for carrier in this application is selected to be 900MHz (chapter 4.5).
- In oscillator tank all current is flowing through series resistance at resonance frequency and be dissipated in this resistance. This dissipation will be:

  $$P_{res} = (R_{ser} I_{max}^2)/2 = (R_{ser} Vmax^2)/2L^2\omega_{res}^2 \tag{4.29}$$

  Equation 4.29 shows how important value of L is to keep power dissipation in an oscillator at the lowest rate. But R_{ser} is dissipating the power and has been compensated by the VCO. In next chapter, examples of topologies are shown coping with this obstacle.
- R_{par} is best selected to be as low as possible avoiding oscillator compensation for resistive dissipation in the serial resistor of the tank inductor. This is a matter of an extensive oscillator calculation, but by remembering the fact that current at resonant frequency flows through the tank resistor, and by assuming a current consumption in oscillator of about 100μA , R_{par} is supposed to be maximum (30kΩ). We choose a value much lower for R_{par}, for example, 1kΩ. This results in a much higher value for Q.
- Considering the Q to be a practical RFMEMS achievable value of 20, R_{ser} should be ca 2Ω.
- L is then approximated to be 7nH by using 4.15.
- By applying fabrication sheet resistance values, for this example is 20mΩ/sq, to achieve 2Ω we have to have a length of 1600μm with cross sectional width 2μm and thickness 8μm.
- Finally a resonance parallel capacitance for this inductor can be calculated to be ca 4pF.

Since it is much more difficult to approximate complex systems like oscillators, therefore it would be amore accurate procedure to use simulating tools to approximate for values of inductors or oscillators. Next section will present some estimations calculated based on the aforementioned approximation methods. I have used these estimations and used these values to design different layouts for the last example.

4.3.8 Inductance estimation

Finally, to estimate a dimension for inductance of tank in the VCO, several calculation and programming was necessary. Following is the result.

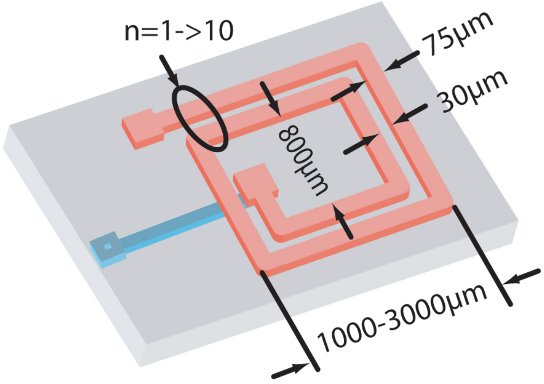
At first, to find out which one of the estimation equations is the most accurate, calculation by programming in matlab has given the following results. But to have a procedure to compare accuracy of the equations and simultaneously find the best dimension estimation, I had to test these estimations by iteration to see how different factors affect the result.

Primarily, one inductor with just one turn was calculated. To compare some results, inductor with 1, 5 and 10 windings were selected to estimate the values based on the four estimation methods. The inductor dimensions proposed in the table 4.2, are the same for all estimations. But as mentioned previously, some of these equations do not take the thickness, spacing or escalating width or a combination of all int to consideration. Obviously, results were too far from each other regarding the neglection of vital characteristic factors of the inductor. Comparison curves for winding iterations between 1 to 10 turns are plotted as curves and shown in the figure 4.14.

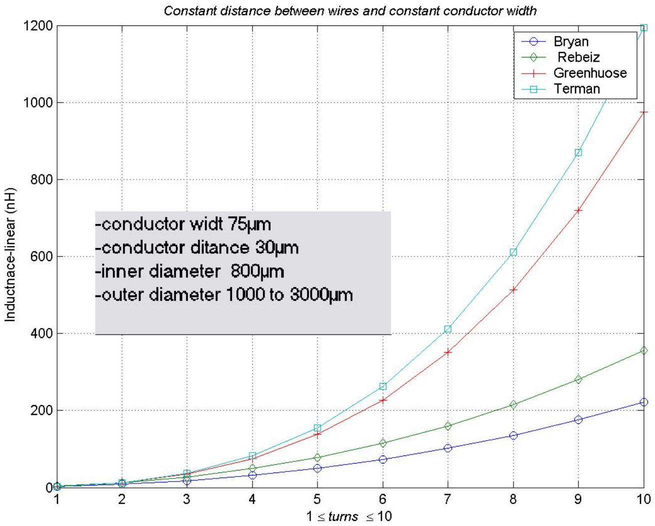
	Inductance estimation		
Condition	conductor Width 75μm	spacing 30μm	thickness 28μm
turns	1	5	10
Equation	**Inductance value in nH**		
Bryan	2.3037	49.862	222.52
Rebeiz	3.4765	78.008	356.08
Greenhouse	2.4663	137.57	975.47
Terman	2.3525	155.26	1194.5

Table 4.2: comparison of inductor estimation equation theorems

The following figure 4.14 is an illustration of the inductor estimated for the table 4.2:



(a) Spiral flat inductor with fixed width and distance



(b) Spiral flat inductor with fixed width and distance and 1 to 10 turns

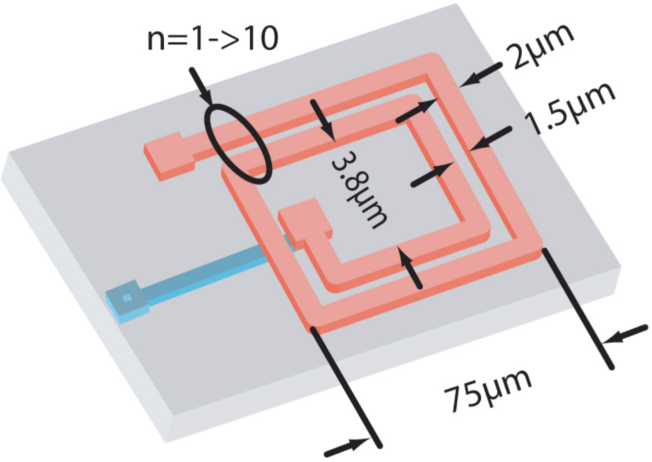
Figure 4.14: spiral quadratic inductor with fixed width/distance and 1 to 10 turns

Finally, here is the value estimation of the tank inductor, suggested for the oscillator $((F_{CF-VCO}))$ in the SNoC-T module (3.12) at carrier frequency (900 MHz) in the ISM band. By selecting a relatively small resonance capacitance (5 pF) in parallel with the inductor and by calculating the inductor at resonance frequency (4.16), we will find that the tank inductor should be around 6nH. To compare the estimation methods again fot this inductor, dimensions are approximated using the characteristics given by the monolithic manufacturer of the prototype designed in this thesis. Based on the mentioned process values and by using an average between Bryan and Rebeiz estimations, a 6 nH inductor can be achieved by 10 turns of 2 μm width and a spacing of 1.5 μm. To compare different estimation equation the inductor with the same dimensions and iteration og windings between 1-10 turns are calculated. The estimation plot and values calculated are as follows:

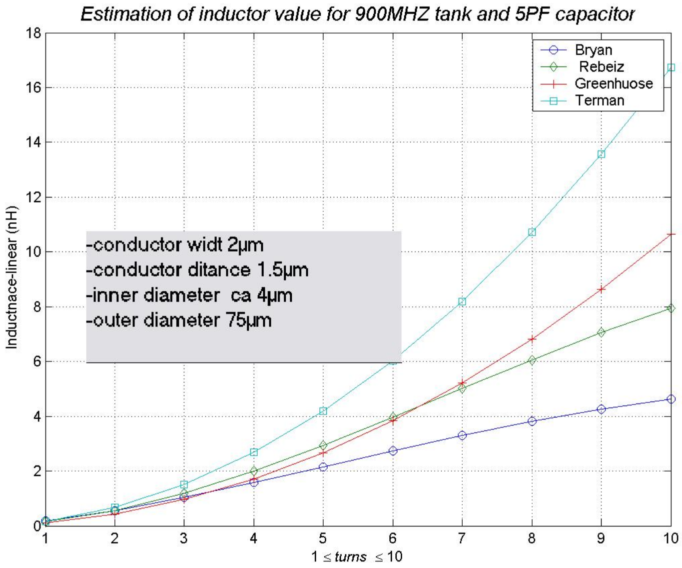
	Inductance estimation at 900 MHz		
Condition	conductor Width 2μm	spcing 1.5μm	thickness 5μm
turns	1	5	10
Equation	**Inductance value in nH**		
Bryan	0.18573	2.1574	4.6352
Rebeiz	0.14789	2.9376	7.9518
Greenhouse	0.10644	2.6609	10.644
Terman	0.16736	4.184	16.736

Table 4.3: Approximation of inductor at 900 MHZ with equation theorems

The following figure 4.15 is the illustration of the inductor estimated in the table 4.3:



(a) spiral flat inductor with fixed width and distance



(b) spiral flat inductor with fixed width and distance, outer dimension of 75 μm and 1 to 10 turns

Figure 4.15: spiral quadratic inductor with fixed width/distance and 1 to 10 turns and 75 μm

Finally, the planar quadratic spiral inductances calculated by the various methods described above, give us some ideas how inaccurate manual approaches can be. Neither were the calculations based on a cross over, escalating width, escalating spacing or a circular cross over conductors. The differences noted are particularly alarming when one considers that none of the methods used, were derived for circular spirals. Indeed, all but the Bryan's method took into consideration both the width(fixed) and the thickness of the conductor.

However, it should be mentioned here that an inductor with the dimensions given in table 4.3 has been designed as RFMEMS component for a monolithic post process, prepared by Carnegie Mellon University (CMU) and delivered for prototyping. This inductor plus some other variants are described in details in chapter 5. Testing should be done on this inductors as soon as these are delivered, to verify and compare the results against the different methods. Although no direct measurements have been made on the example inductors, measurements of corresponding inductors have shown to agree with results calculated by the expanded Bryan's [22] or Rebeiz's [20] methods within experimental error [21].

Obviously, accurate value estimation of planar inductors can be a time and computational demanding. Some commercial estimation SW is available like HFSS (ANSOFT) or Momentum (Agilent) which preferably, should be used for modeling of different inductor types before processing expensive chips.

There are some other cheap but naturally not so user friendly, shareware versions as well, but in this thesis estimation has been limited to Bryan's [22] equation, since the focus has been more on the principle of SNoC.

5 RFMEMS - Process, components and implementation

5.1 RFMEMS Components

In the previous chapters typical sensors, blocks in sensor nodes, some critical components and design consideration were discussed. Necessity and requirement of alternative technologies, empowering continuous minimization of sensor modules was also mentioned. The primary facilitators for the aforementioned trends are advances in μ-fabrication technology, both in μ/nano-Electronics and MEMS, NEMS and RFMEMS.

In this section, some practical examples made through this thesis as RFMEMS-based lumped elements, in particular inductors, are briefly reviewed and key technologies needed to extend their characteristics into frequencies at VHF and UHF ranges are discussed.

As pointed out in 4.22, series resistances in interconnections or structural materials are shown to be a common concern for virtually all MEMS components, from mechanical vibrating beams, high-Q inductors, tunable capacitors to switches and antennas.

Environmental impurities and parasitic elements such as feed through capacitance, eddy currents and molecular contaminants are identified as major performance limiters for lumped elements implemented in integrated circuits and especially regarding RFMEMS components. Elimination strategies for against these obstacles are still been researched via for example combinations of monolithic integration processes and encapsulation packaging technologies.

Discrete RF lumped elements have always been important to electronic industry, especially because these components influence sensitivity factors, demand large implementation spaces and play a significant role in quality of signals in RF modules. In applications using VHF to Super High Frequency (SHF) or higher, component sizes comparing to wavelength will be a major factor in signal quality deterioration.

Usually, signal diminutions in RF modules or components are caused by dissimilarity between evenly fractions of wavelength and a combination of component sizes or conductor lengths. These disparities have apparently negligible influence on the signal quality in μm elements made as RFMEMS components.

For example, the wavelength of a sinus signal at 1 GHz is almost 30 cm. Dimension matching to this signal will be around 7.5cm ($\lambda/4$). Components used in a module to be matched into this frequency should preferably have dimensions bellow 1/20 of this value (3mm), avoiding serious impact on signal characteristics. Depending on the design criteria, discrete lumped elements usually may have dimensions $\geq$5 mm and therefore require matching.

In general, aforementioned wavelength is much larger than element sizes of RFMEMS lumped elements. Thus, signal quality in sub GHz to few GHz frequencies stays almost unaffected by RFMEMS components. Simply because mismatching noise made by small component dimensions compared to wavelength in signal path, are negligible.

Since, the deterioration phenomenons caused by component sizes or distances are minimal, RFMEMS component design procedure can simply be focused to other obstacles like;

- the lumped element characteristics,
- stray parasitic,
- material characteristics

In the following section, details of the implemented lumped elements examples designed in this thesis will be discussed. Though, these components are not produced before the deliverance of the thesis, but the verification of theories presented in this document and real components can be done as soon as the chips are delivered from fabrication.

5.2 Selection of MEMS Processes for implementation of Inductors

To find out the optimum MEMS process suitable for manufacturing of the inductors required for SNoC-T, a review of appropriate technologies is given in this section. Planar implemented inductors designed on PCB and substrate material like FR4 (with permittivity constant of about 4) or some other ceramic substrates, have practically been the major solution in designing of electronic circuit and integrated circuits for several decades. But during the last decade, MEMS/RFMEMS technology has made μ-scaled lumped elements with relatively high Q available to μ-electronics.

In contrast to the low cost, easy to implement inductor in PCB or CMOS technology, there are some disadvantages related to implementation of lumped elements using MEMS technology. Following will be among the most important disadvantages of planar MEMS inductors:

- Silicon as substrate represents relatively high-conductivity and high permittivity, hence loss in high-frequency. High resistive silisium or other substrate materials can be available, but these are not suitable for monolithic combination to CMOS transistor technology, requiring low resistive, low noise substrate
- CMOS process exhibit poor Q (< 15) due to ohmic loss of thin metal or poly silicon layers
- most practical materials used as isolation of lumped element from leading substrate have poor dielectric coefficient and represent loss

Nevertheless, MEMS based lumped elements are getting more and more usual in design of mixed mode electronics. A comprehensive diversity of MEMS technology principles contribute to implement lumped elements, like; bulk technology, surface micro machining, and so on.

Surface RFMEMS inductors can be implemented in all of the main MEMS design and manufacturing principles. The most practical way to design an inductor in μ-electronics has been spiral planar inductor by using one or more metal layers as conductor or as practiced in some processes by using low resistive poly silisium materials.

5.2.1 Which RFMEMS inductor variant is optimum?

Inductors are mainly manufactured as RFMEMS in three categories; inductor on on substrate, inductor on insulator and suspended inductor. To select the optimum category for SNoC-T module, a brief overview of these categories are given in this section. Some examples of implemented inductors using metal or poly silicon on substrate or insulator are shown in figure 5.1. The insulators between spiral inductors on substrate in these examples, are mostly used for supporting purpose of the inductors weight and avoiding curling during process steps. But in case of conducting substrate, this layer is not just supporting construction, but also insulating layer.

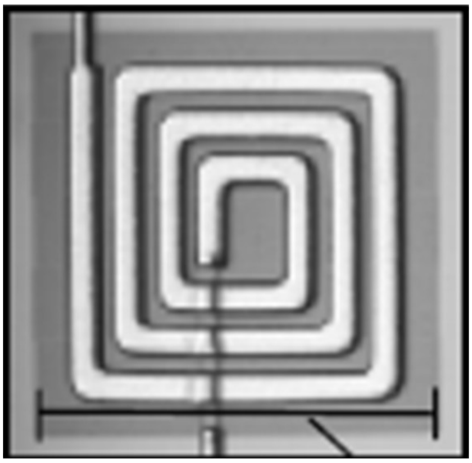


Figure 5.1: planar quadratic inductor on insulating substrate
[1]

However, designing high-quality inductors as explained in chapter 4 and 5, requires high resistivity in substrate. Nevertheless, a high-quality planar inductor is very difficult to realize, since the low-impedance in Si substrate or high permittivity of other insulator materials causes a large transmission loss and low self-resonant frequency due to its parasitic. Impurity of doping materials is another obstacle which results in major impact on substrate resistivity and limiting insulation or at least decreasing resistivity factor in Si .

To achieve higher resistivity some other substances or combination of substrate materials have been experimented and in some occasions commercialized. For instant, implementation of thick embedded oxide islands, thick PECVD SiO2, thick Avatrel polymer and GaAs substrate turns out to be very expensive and difficult. Figure 5.2 and 5.3 show a couple of examples implementing this methods and materials.

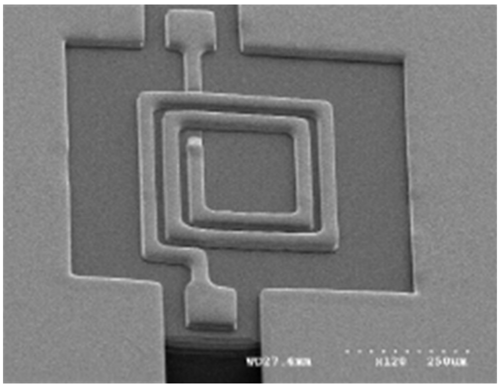


Figure 5.2: A 3.3nH Cu inductor on 20μm thick PECVD SiO2, tmetal=1.5μm,n=s=20μm, dout=400μm [1]

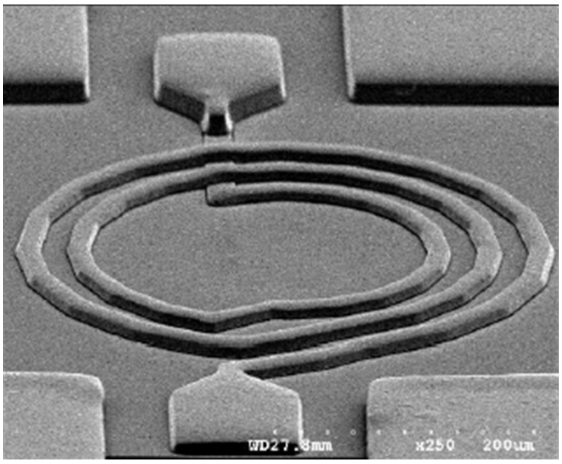


Figure 5.3: A multiple-turn inductors on 20 μm PECVD SiO2 tmetal1 = 1.5μm,tmetal2 =20μm [1]

As mentioned previously, insulation layers are mostly used as supporting layers for heavy or larger spirals. In case of minor dimensions and less weight (ng) this supporting layer can be neglected. Recently, some positive experimental results about special versions of conducting substrate constructions with much higher resistance against Eddy current have been reported [23]. To achieve this type of resistance, substrate is trenched in small and deep stripes blocking for the flux fields induced to the substrate by inductor. An illustration of how this design interrupts Eddy current path is shown in figure (fig 5.4).

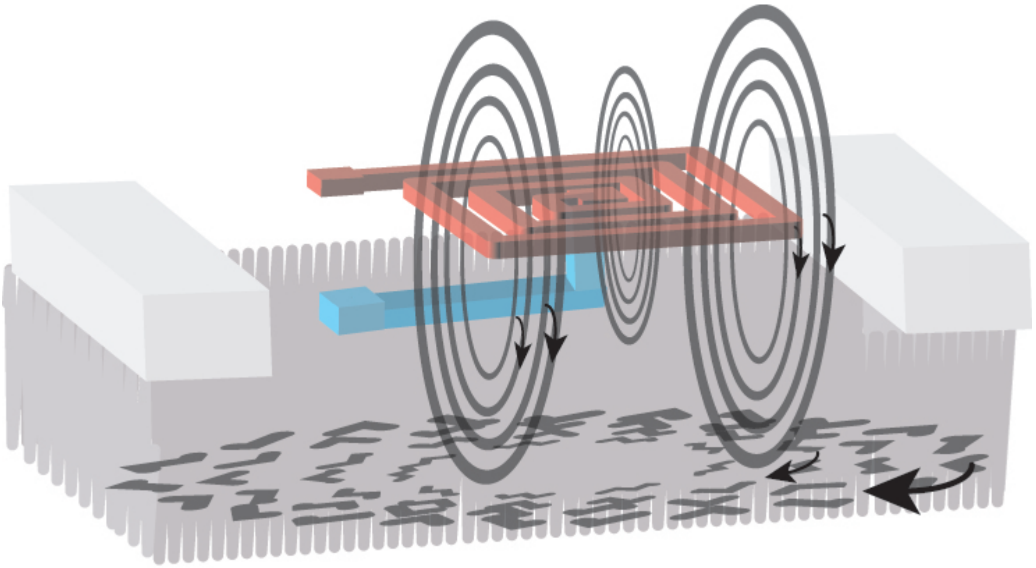
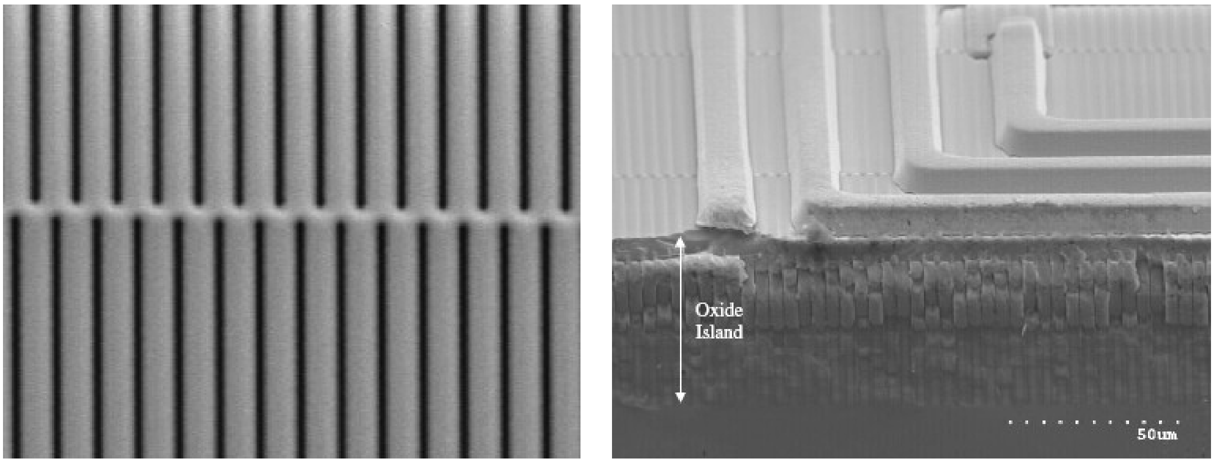


Figure 5.4: Effect of Trench Silicon Island on substrate resistance

While these current paths are interrupted by trench stripes, $Q_{substrate}$ decreases and Q_{metal} becomes the dominant part of the unloaded Q_{tot} which is parallel value of these two quality factors in high frequencies, ref. 4.18. By adapting this type of technology, high Q ($\geq$50) for Cu inductors in 1 GHz frequency is newly reported [23]. This method is called Trenched Silicon Island (TSI), and some examples are shown in 5.5.

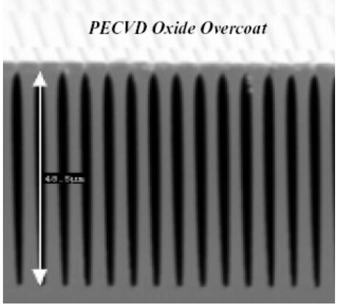
Consequently, this complex technology seems to be much more expensive than what price budget of SNoC can afford and some alternative qualitative technologies where surveyed during this thesis. For instance, inductors can be implemented on thick polymide or epoxy resin that are over 10μm thick which may be used as insulator layers. In this type of process, polymide or epoxy resin insulator can be coated onto the Si or metallic substrates, which enables the implementation of high-quality planar spiral inductors.

Although TSI reports some interesting results, this method is expensive and there are not many manufacturers yet which offer this technology. Anyway, suspended inductor was selected for implementation in this thesis.



(a) top view of a low stressed OI(oxidation temperature: 950°C)

(b) picture of Trenched Silicon Island(TSI)



(c) microscope picture of a 3 turnround edge inductor, w=15μm, dout=400μm, s=15μm, tmetal=8μm [23]

Figure 5.5: Trenched Island technology in the substrate

In the next section is given an overview of an alternative technology to achieve high-Q inductor by removing some part of the substrate and insulator, called suspension method.

5.2.2 Implementation inductor using suspension

We have already discussed the drawbacks of using a low resistive substrate and some approaches to compensate for this deteriorating factor. The solution to improve the effect of the substrate needs to be concentrated on removing or decreasing the following factors:

1. Eddy current
2. Low resistive substrate
3. Stray capacitances through insulating layer

Following is a table comparing different approaches related to these terms.

	RFMEMS inductance tecchnology			
	insulating layer	TSI	Suspension	ideal technology
Eddy current	high	low	very low	very low
R_{sub}	very low	low	very low	very low
C_{ox}	high	high	very low	very low
C_{sub}	low	very high	low	very low
Q_{ind}	medium	very high	very high	very high
inductance value	medium	medium	medium	very high
Price	medium	very high	medium	very low

Table 5.1: comparison of implementation methods

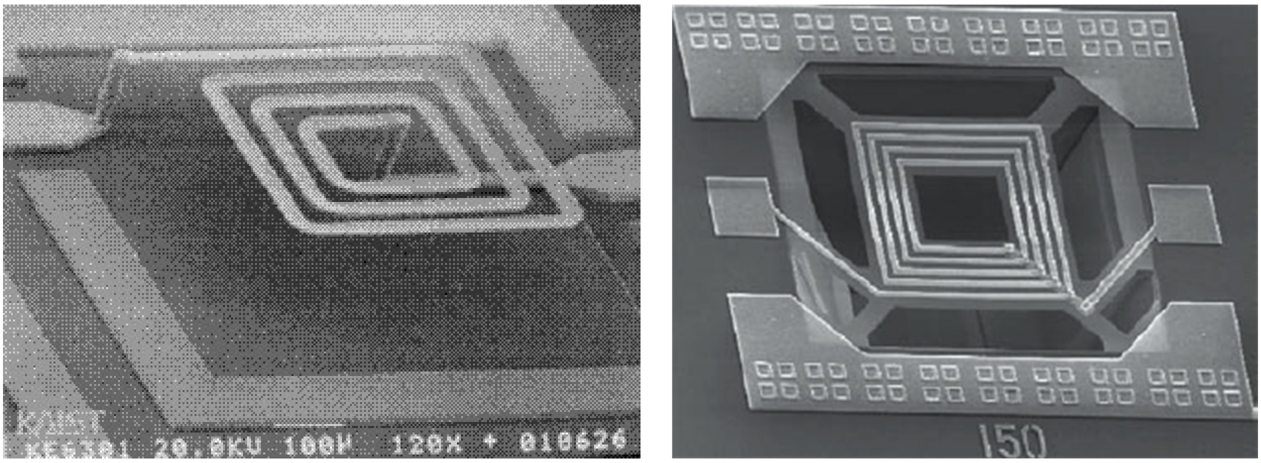
As illustrated in table 5.1 actually, suspension methods seem to qualify for the most factors ideal to a SNoC application. This approach removes the supporting layer underneath the conductor layer. Thus, dielectric factor will be high equal to air or in case of vacuum packaged component much higher than air.

Some part of the substrate is removed underneath the inductor, which results in lower stray capacitance C_{ox}. Simultaneously, distance between conductor and substrate is increased resulting in much less induction to the substrate. This technology minimizes influences of substrates with low resistivity and eliminates insulators with high permittivity.

Generally, there are two types of suspension methods presented by manufacturers;

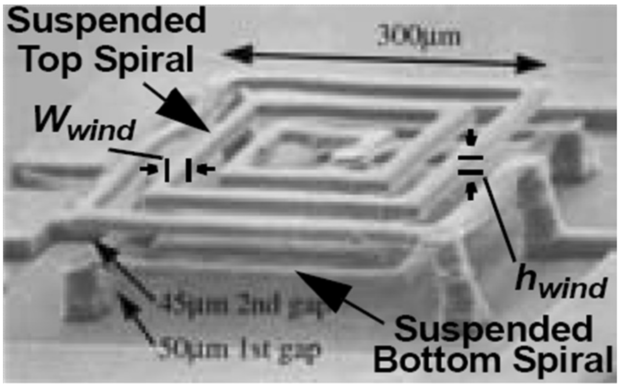
1. Inductors can be realized by lifting the conductor in a distance above the insulating or substrate
2. Insulating and/or substrate are removed by different principles like etching or RIE/DRIE

Both of these methods are used in different applications and many reports are announcing promising results in different frequency bands. Some of the most popular and practical types of MEMS inductors are shown in figure 5.6.



(a) Suspended quadratic inductor with air gap height of 100μm [24]

(b) suspended quadratic inductor double spirals with air gap on membrane [25]



(c) suspended quadratic inductor double spirals with air gap [26]

Figure 5.6: Inductors suspended a distance above the substrate

Anyhow, there are some different approaches to manufacture these types of inductors. I used suspension by removing substrate designing the prototypes of the inductors discussed in this thesis. This was simply because as mentioned in chapter 3, SNoC should be preferably manufactured as monolithic to save both space and quality. The manufacturer STμElectronics has provided a method in cooperation with Carnegie Mellon University to provide monolithic MEMS/RFMEMS procedure as post-CMOS approach.

In this process RFMEMS structures are built up by using CMOS interconnecting metal-dielectric stacks. Metal layers are in modern technologies offered as low resistive interconnect alternative instead of high resistive poly silicon. The process uses metal layers as protection mask for underneath layers. In the last step of this procedure substrate can also be removed and providing much more distance between RFMEMS structure and the underlying substrate.

The top layer in this process is copper insulated by PEVCD Sio2 from substrate. There are 4 metal layers buried in the insulator. Figure 5.7 is an illustration how this process layers are stacked up:

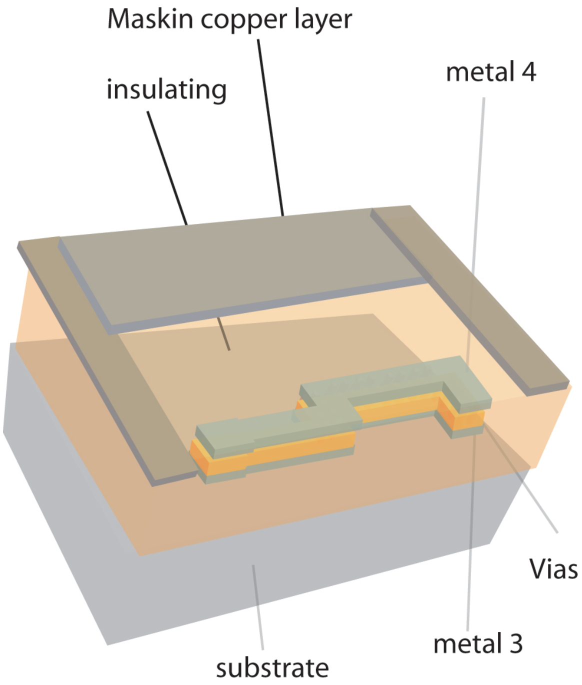


Figure 5.7: overview of insulator over substrate and two buried metal layers connected by vias

As seen, to reduce serial resistances of the conductors metal layers 4 and 3 are connected by vias. The copper layer is on the top and masks all layers underneath. This masking results in protected all layers which are masked by copper layer. This will actually protect the transistors implanted in the substrate. Thus the monolithic process is possible since the buried transistors and electronic circuits are masked by this layer. Indeed, all metal layers can be a mask layer as well by keeping in mind limitations described in design rules.

The first step in the etch process is to remove unmasked insulating material. Insulator removing will be provided by chemical stuff like $CHF_3/O2$ and RIE process. The chemical step will remove carefully the insulating not only in large areas but also tiny pitches between adjacent conductors in the spiral. Figure 5.8 presents this step.

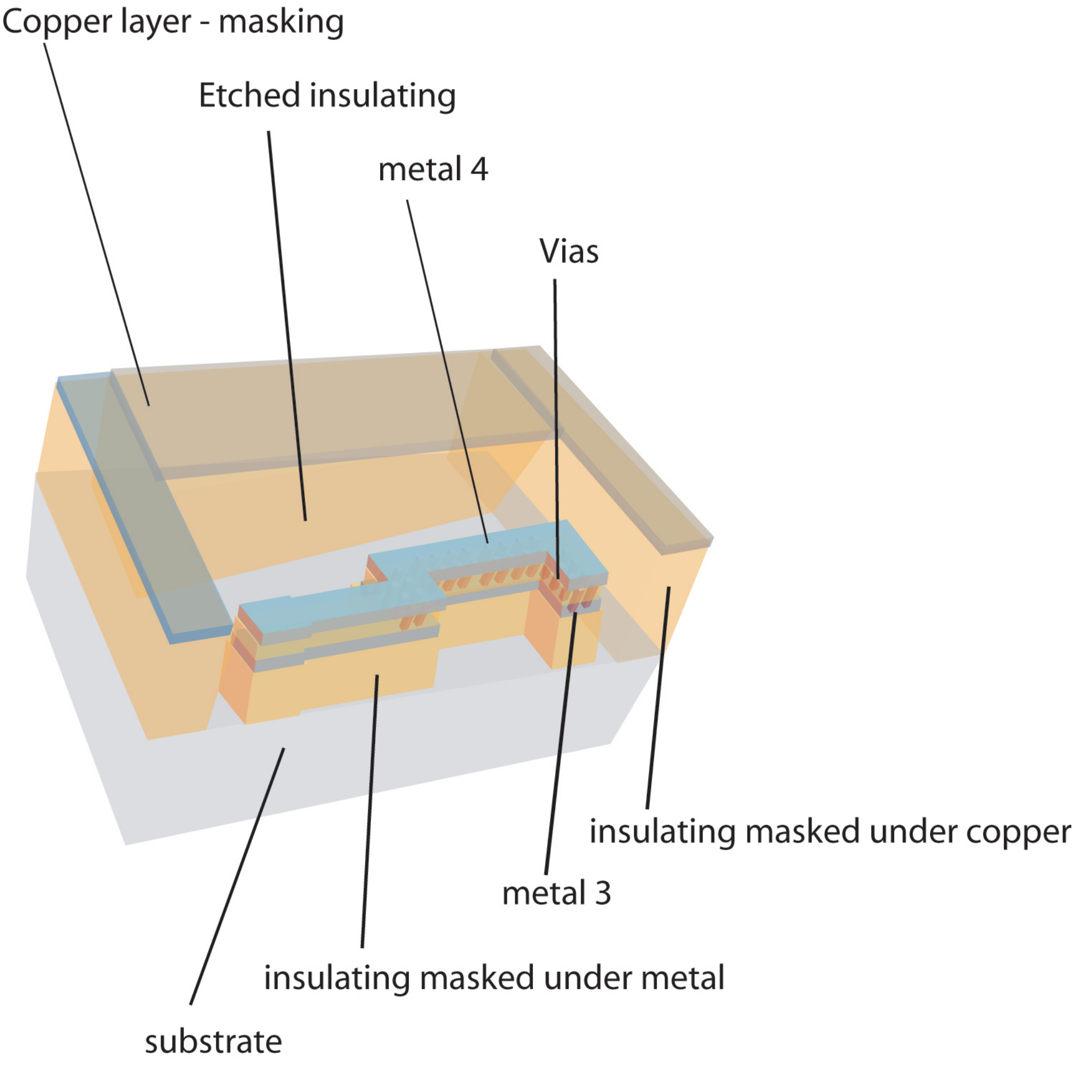


Figure 5.8: insulator removed by $CHF_3/O2$ and and RIE process

On the third step the substrate area not masked by copper and metal layers is removed by fine tuning DRIE process. This process is able to penetrate and remove almost 35μm of substrate depth. When this step is finished, all layers are supported by substrate equal to the design layout. This step is shown in figure 5.9:

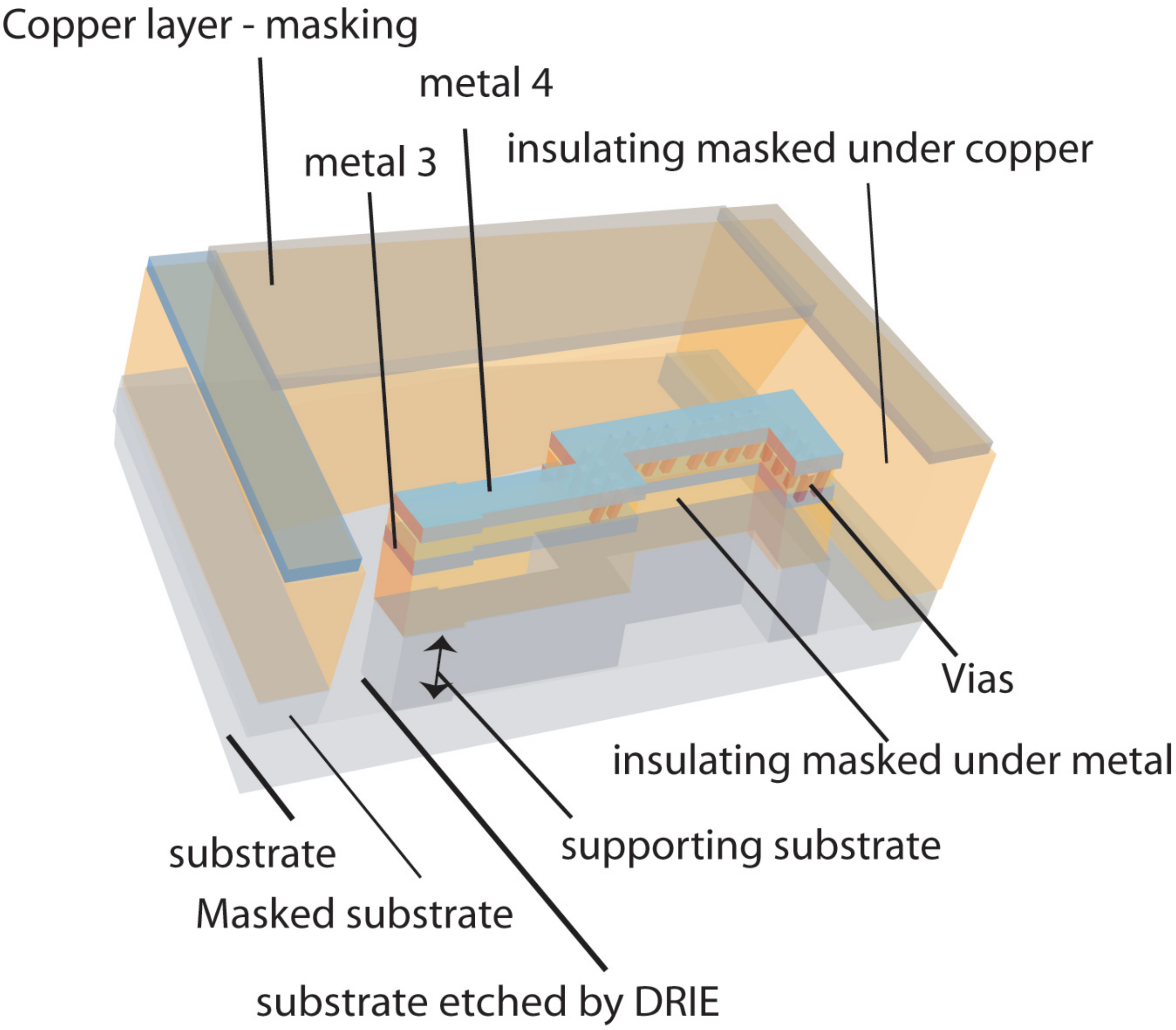


Figure 5.9: substrate removed by DRIE process

At last the remaining substrate not unmasked by copper and metal layers and below some dimension defined by the process (20μm) is removed by etching process. By the end of this process there is only structures hanging in the air suspended to the supporting anchors or metal layers intended to do the bearing. Figure 5.10 is an illustration of the last step of this monolithic process.

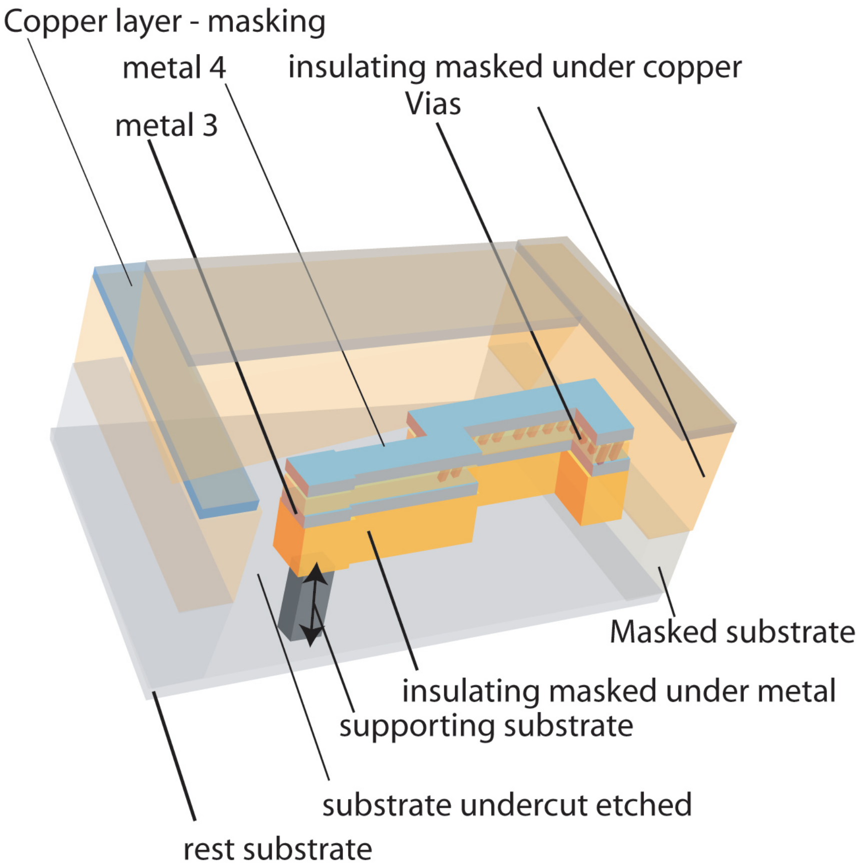


Figure 5.10: supporting substrate removed by chemical process

The procedure for removing the dielectric layer is based on the chemical etching. After etching the insulation material removing of substrate in the opening window of the metal masks is proceeded (nominal 35μm). Finally, Si substrate undercut for deep removing, first by using DRIE, then proceeding with chemical etching of the substrate supporting the struuctures. In next section some implementation using these methods will be discussed.

5.3 RFMEMS implementation of inductor

As mentioned previously, implementing the planar spiral inductors a monolithic post-CMOS process is selected. Since frequency for communication was selected to be in ISM band and for suggested SNoC 900MHz was selected, the inductor suitable for this application should have a value of almost 7nH parallel with a 5 pF capacitor as explained in 4.3.8 and estimated in table 4.3.

Keeping these values in mind an corresponding inductor was designed in cadence, based on the rules and regulations of ST-μElectronics and CMU. Layout of this inductor is shown in figure 5.11:

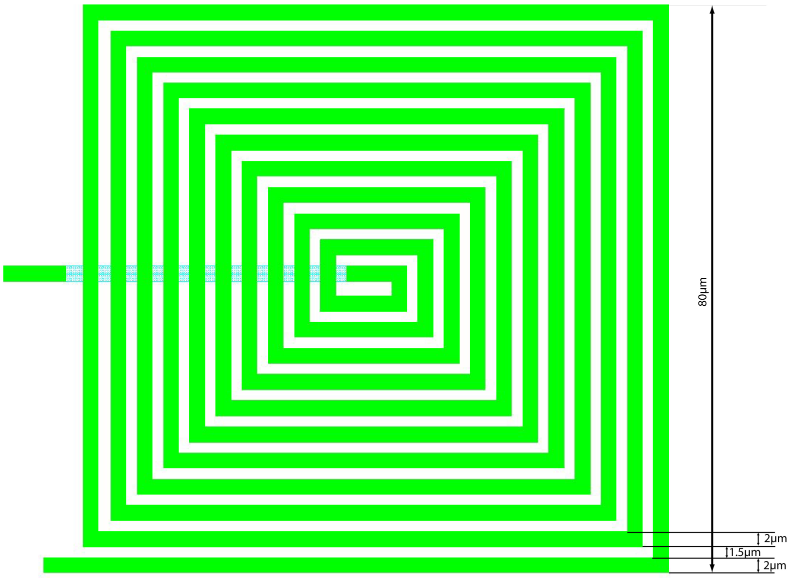


Figure 5.11: quadratic spiral inductor layout designed for monolithic process

As seen from the figure 5.11, this inductor has a traditionally quadratic spiral layout. It has 10 turns and windings are in a fixed pitch of 1.5 μm and fixed conductor width of 2 μm. Thickness is increased by shunting metal3 and metal4 layers (layers on top). This prototype could be used in verification of the values estimated by the approximation methods mentioned in chapter 4.

The value is supposed to be 7 nH with a length of almost 1600 μm with a side length of 80 μm. The sheet resistance given by ST-μElectronics is 40mΩ/sq. By using 2 μm width on 2μm thick conductor, resistance is supposed to be 16Ω which gives a quality factor of 2 to 3, much worse than what has been specified. To achieve a higher quality factor, metal layer 3 and 4 are connected to each other by vias and provided a thickness of 8-10μm. This inductor is located on the north east on the figure 5.15 and connected to pins numbered as 1 and 2 in this figure and called as inductor A (5.15).

Based on this metal thickness resistance of the inductor supposed to be ca 2Ω. This resistance will contribute to a quality factor of around 15- 20 at 900MHz. This will be verified when the RFMEMS ASIC is manufactured and delivered.

Next prototype example designed is modified inductor version of the first one based on the cross-over topology mentioned in chapter 5. This inductor is illustrated in figure 5.12.

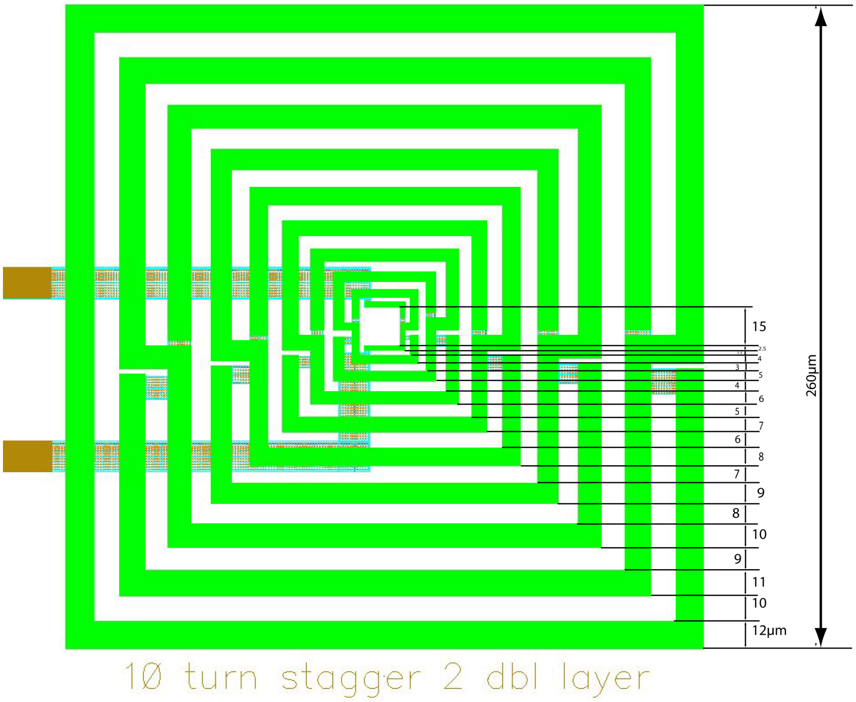


Figure 5.12: quadratic spiral inductor layout designed for monolithic process-crossover 10 turn

This inductor is not only cross-over but also staggered both in relation to the conductor width and pitch. Input and output ports are symmetrically connected to the inner winding with minimum of stray capacitance. The width of the inner conductor is selected to be 3 μm and increasing almost linearly to 12 μm for the outer winding.

The pitch is as well 2 μm for first gap between first and second winding, which ends to 10 μm for the 9'th pitch. Vias here is the same as for traditional quadratic spiral, and connected metal 3 and 4 together.

The outer winding is almost 3 times longer (1000μm) and side length of this spiral is almost 260 μm compared to the traditional quadratic spiral. Because of the staggering design the area of the design is much larger than the traditional spiral since both the width and pitch increase iteratively with number of turns.

This inductor is located on west in figure 5.15 and connected to pins 3 and 4 of the package and called for inductor B. The dark green areas between pins and the inductors with many vias which are barely visible, are meant for masking of the supporting substrate and are implemented based on the design rules.

At last to compare linearity of this inductor regarding number of turns and length of the conductor, two extra inductors were designed in addition to the mentioned inductors. Both of these are chosen to be 5 turns and staggering width and pitch.

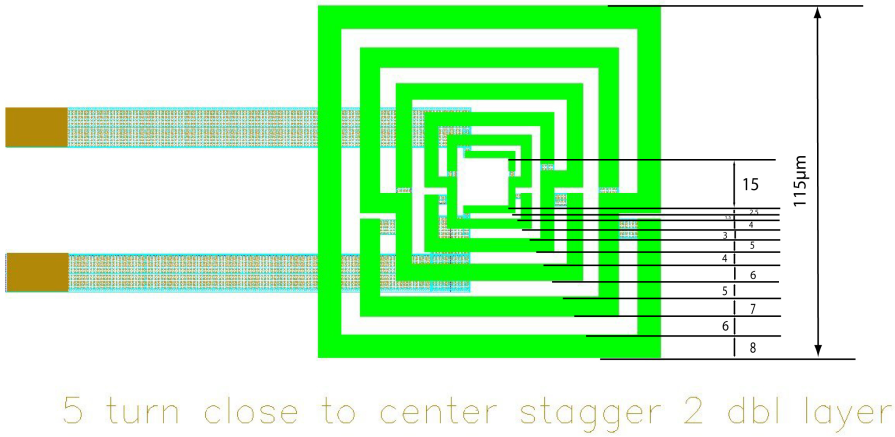
First of these shown as inductor C in figure 5.15, designed with a diameter equal to 15μm for the first winding and the second one, D, with an inner diameter of 100 μm.

By examining these inductors, relation between linearity of the inductor value and the distance from the center will be tested and verified. None of the approximation methods mentioned in this thesis has given an exact estimation for this type of topology, quadratic spiral inductors with staggering pitch and width and compensated thickness by vias or several metal layers. These two last inductors, C and D are shown in figure 5.13, 5.14 and 5.15.

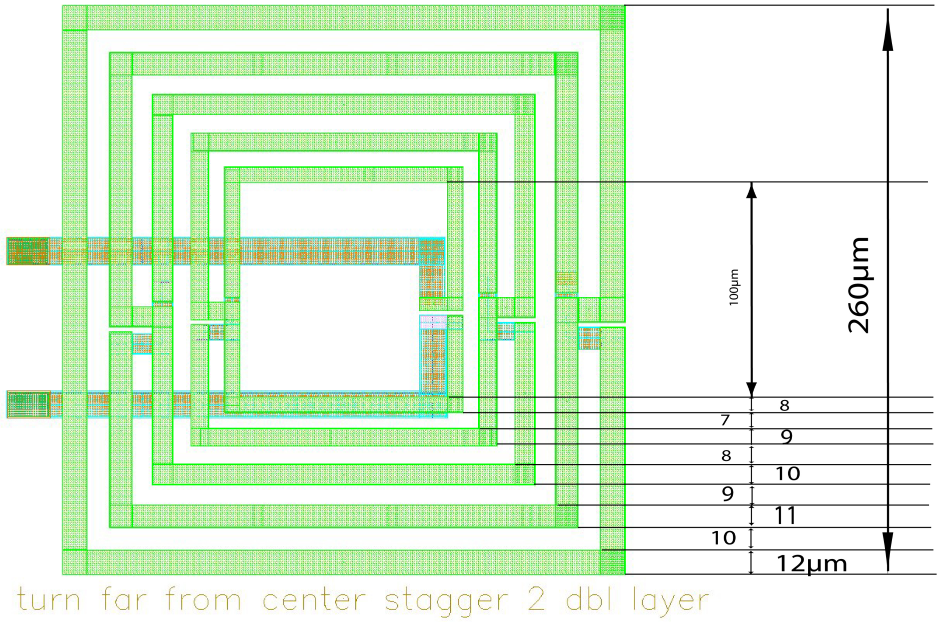
Finally, as shown in figure 5.13, there are some drawbacks related to this staggering solution due to the wider conductors. As seen in the figure 5.13 the outermost conductors is much wider than inner windings, hence much more area for the outer conductors is demanded comparing to the simple planar spirals.

Although, this solution maintains the resistance fixed to a constant value through the entire length of inductor, but increases the fringing capacitance between adjacent wires regarded the higher capacitance value pr longer segments. Thus, to reduce this fringing capacitance the distance between adjacent conductors have to be increased proportional to the width of the conductors.

Unfortunately, increasing the distance between adjacent wires requires further area from in addition to an area demanding design. At last, all of the implemented inductors and pads connected to these are shown in the total ASIC layout.



(a) Suspended quadratic inductor with air gap and 5 turns, 3μm inner circle



(b) suspended quadratic inductor with air gap and 5 turns, 70μm inner circle

Figure 5.13: quadratic spiral inductors suspended with 5 turns and staggering pitch and windings

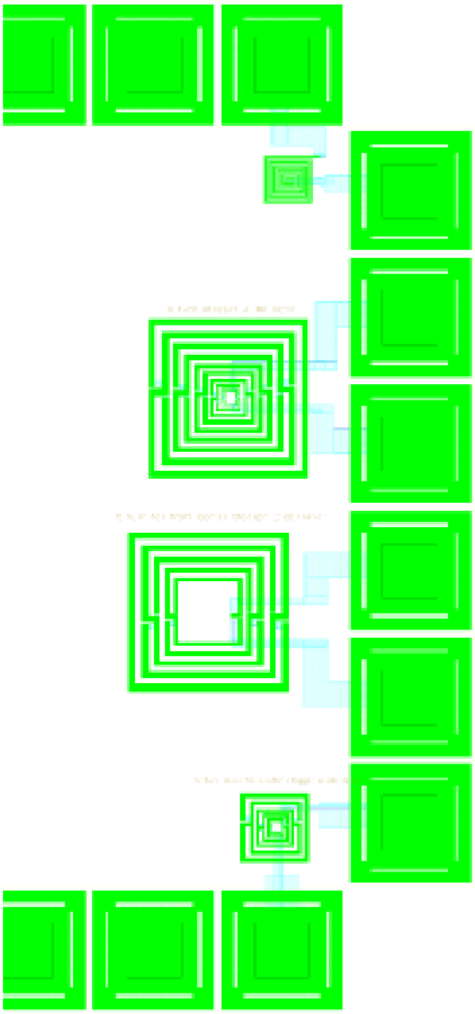


Figure 5.14: RFMEMS ASIC with quadratic spiral inductor layout designed for monolithic process-crossover

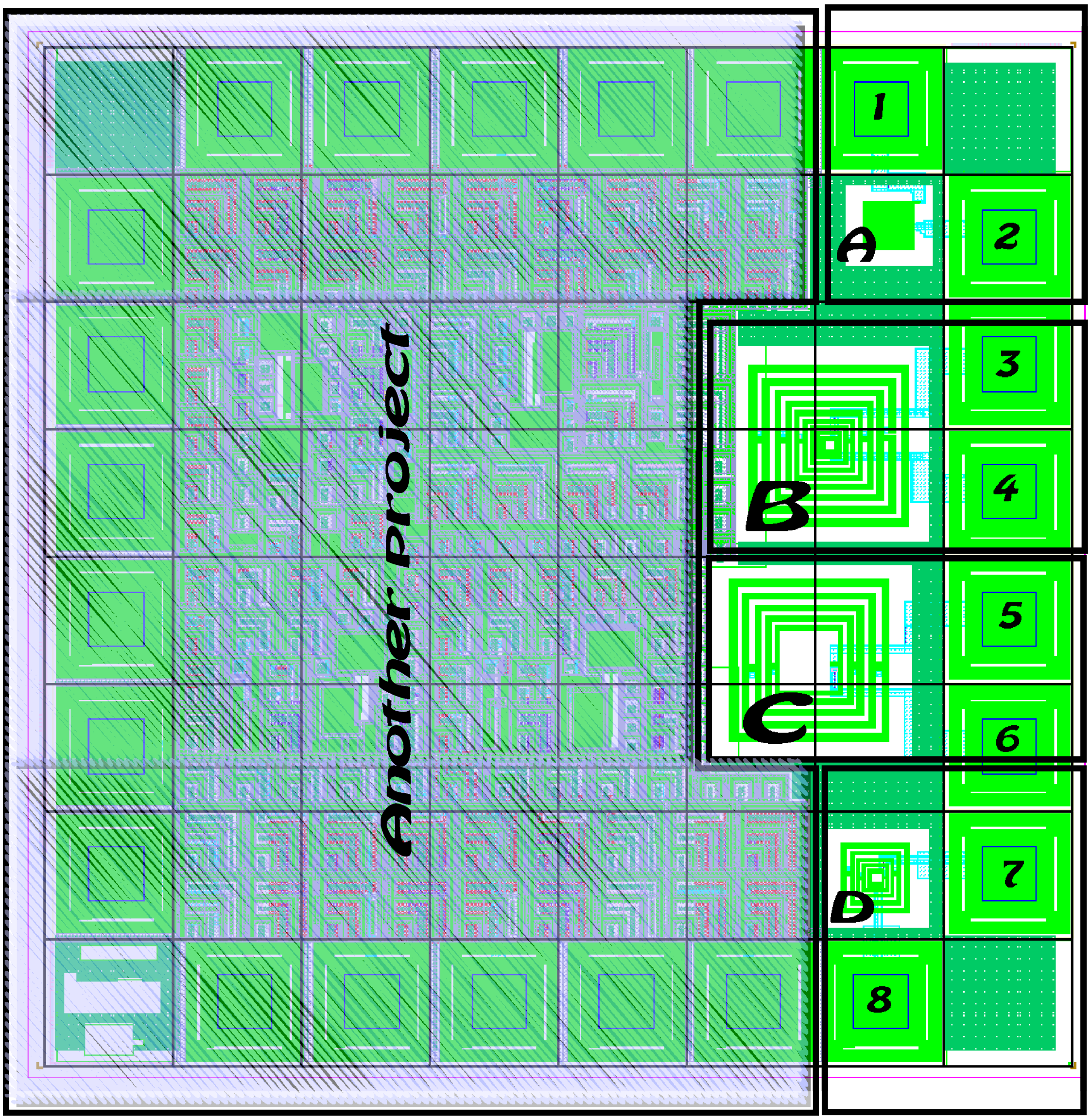


Figure 5.15: RFMEMS ASIC with quadratic spiral inductor layout designed for monolithic process-crossover

6 SNoC - discussion

In this master thesis I have presented a possible solution for design of a wireless sensor node on chip . This sensor could either be utilized as a node in a wireless sensor network system or as a stand alone sensor operating as a peer to peer node. However, the main function task is as a node in a general purpose measurement systems or in bio-electronic applications. Here, the particular condition of HS and the remotely monitoring of the sensor element measurements has been anticipated as the start point.

Naturally, one of the most important factors in proper functioning of the battery less sensor nodes is the adequate available power. Discussion around the wireless power transmission and selection of the frequency resulted in distinguishing between data and power transmission channel. In case of the power transmission, 10MHz and for data transmission, 915MHz in ISM band was selected. However, one should notice that in different countries or even situations, these frequencies and bands are subjects to be changed.

RF-communication modules are one of the compulsory critical modules in the wireless bio sensors. A low power, low noise RF module is one of the most important modules for optimum functionality in such system. Another aspect is the selection of the communication principles dependent on the main tasks of this type of application. For instance, is it necessary to have a full or semi duplex, or just a simplex communication principle is adequate for keeping the circuitry as simple as possible?

During this thesis the simplex transmitter was preferred instead of the duplex. Most sensors in the bio electronic sensor systems are supposed to measure and transfer some very simple signals without the requirements of high or complex power hungry communication protocols. Besides, there is no contradiction against combination of receivers as multi chip modules to the transmitters as a add on option.

However, studies in this thesis were focused on characteristics and design of the most important elements in the development of a simple sensor as a transmitter. By this means, some other important issues were omitted due to the time limitations. One of these issues is for example the power transmission device. This device plays a vigorous part in the proper functionality of the wireless sensor. If the power device supposed to operate as a user friendly device, it should be as small as possible simultaneously providing adequate noise free energy for the system.

Yet another task omitted in this thesis is the security of communication to a node. The measured signals should be in most cases scrambled. The security aspect of the signal measurement is vital for this type of sensors in the operation modus. This is the case both for the privacy aspects and avoiding the signal interference with other sources. But when the security mechanism and scrambling of data is implemented, there should be adequate guaranty in perception of the vital measured data. This discussion will not be an easy task and should be considered seriously before adaptation of the sensors.

Finally, the security issue should be considered at the highest level since this sensor is supposed to be implanted in the human body and has a major impact on the human life. Especially cautions should be taken regarding the sealed packaging and the effect of the different liquids on the life cycle of the device. Discussions are not finalized before there is a reasonable solution for recovering or removing a malfunctioned device.

7 SNoC - Conclusion

7.1 Overview

The aim of the thesis was to introduce some realizable solutions to design a SNoC, proper for implantation inside the body. Based on the extremely small space available, the sensor element and electronic modules should be designed to fit in an area below few mm^2. Therefore, RFMEMS lumped elements were suggested as the alternative for discrete components. RFMEMS inductors were studied especially as a substitution for crystals and antennas.

7.2 Achievements

The main goal for the thesis was to show if and how mm^2 SNoC modules are realizable. Critical and central blocks in design of a SNoC were identified and discussed. Modules or components critical and necessary to design a wireless sensor pointed out and design criteria described. Afterward through the thesis, the focus was concentrated on the most space demanding components. The obstacles in the design of these sensors found out to be dimensions, quality of the alternative components, convergence of the multi discipline technologies and power requirements. The RF elements are the most quality challenging and space requiring lumped elements in these modules.

At last, by studying the behavior and characteristics of the inductors, the solution concluded to design RFMEMS inductor elements in a monolithic 250 nano-m BiCMOS design process. To reduce the costs, area and number of processes, RFMEMS should be considered as a complementary approach to the traditional CMOS process which is mandatory in manufacturing of the μ/nano-electronic circuits. Thus, a state of the art monolithic post-processing approach was selected and implemented to cover up for the requirements. This process is still in a preliminary status and is a result of the co-operation project between ST-μ-Electronics and Carnegie Mellon University [27].

However, to implement an inductor with optimum quality factor, suspended topology in post processed monolithic approach was used. This conclusion was a result of studying the advantages and drawbacks of several implementation technologies. Finally, the suspended version of the inductor was selected as the alternative satisfying the following requirements: high-Q (≈20), small sized (<1 mm) and accurate lumped element (2μm width and 1μm thickness).

There are a couple of other promising processes as alternatives for manufacturing of a SNoC. But, studies during the thesis concluded with sovereignty of the suspended inductor, implemented in monolithic process. This conclusion was mostly based on the:

- Simplicity of the monolithic process [27] comparing to the other alternatives [11, 12, 23, 1]
- Cheaper process since commonly used etching and structuring processes are used
- Realizable and cheaper manufacturing since all process steps are implemented on the same die in this monolithic process
- Leniently post-process steps avoiding damages to the buried electronic circuits by using relatively low processing temperatures

Based on this study, development of a functioning SNoC for use as HS sensor is realizable. The first research step in this approach has already taken. One package including RFMEMS inductors has been designed and sent for implementation. This package is designed for testing and verification of the estimated values for the RFMEMS inductors studied through the thesis.

One of the most important points remarked through this thesis was the topology of the lumped elements. Several geometrics or metal layer manipulation methods were studied. The advantages and drawbacks extracted. Based on these experiences symmetrical inductors with increasing width and spacing were designed. These are designed in the same package to compare some of the theoretically calculation results in practice with the realized versions.

Although the expected goals defined for this thesis have been achieved, this report maybe the preliminary step of many steps to develop a μm sensor for proper functioning in the body. At last section some suggestion are given as a road map for the future projects and research work.

7.3 Suggestions to be done

During this thesis some key modules in a sensor node were discussed and design suggestions described. However, there are still quite a lot to be done before the sensor can be produced as a finished product. Here are a list over the most important "to be defined" tasks,

1. **Carrier oscillator:** The tank inductor in the carrier oscillator was discussed in details. however, an important part of the oscillator here is the amplifier. In the oscillator block of the figure 3.12, the differential transistors representing the oscillation amplifier were drawn in a dashed circle. This circuit or another suitable oscillator should be designed and manufactured. Simultaneously,the stability and effect of the oscillator on the loaded tank should tested and verified.

2. **CMOS varactor:** Another item to be designed and verified would be frequency control circuit. In figure 3.12, a variable active capacitor is suggested which should be capable of controlling the frequency linearly in whole operation bandwidth. This control circuit is proposed to be a CMOS varactor transistor. This circuit should be designed and verified to give an optimum frequency control function over oscillator.

3. **Tank capacitor:** In the thesis the design, characteristics and manufacturing of the inductor as one of the most space requiring elements was in focus. But the tank capacitor has a significant influence on the quality factor of the oscillator. The manufacturing and different design topologies of the capacitor should be researched, to achieve effective and accurate capacitor design procedures.

4. **RF switches:** The switches used as modulator in the RF block suggested in this thesis was not discussed. This switch can be designed by using a transistor or RFMEMS mechanical switch. This circuit should be designed to test and verify functionality and matching against power amplifier and oscillator.

5. **Power amplifier and antennas:** The back end amplifier is the last electronic component before the signals are sent to the filters or directly to the antenna. This amplifier should be designed to generate low noise. it should also be matched to the filter or antennas to operate in a wide band range if the SNoC-T is supposed to be a multi channel or a multi band node.

6. **Antenna:** Both the power supply and the transmitter antennas are critical elements in proper functionality of the node. Although the inductor design has been discussed in details in this thesis, the antenna should be designed both for low frequency power supply and high frequency power amplifier. These antennas should be adapted to the RFMEMS monolithic technologies and verified

against influence of the other lumped or active elements, utilized on the same die.

7. **Duplex communication:** In this thesis, design and characteristics of SNoC-T were discussed. This module was defined as a proper alternative for using in BWSN. But SNoC-T as a simplex communication node is not adequate for many applications. Especially when there is requirements of actuating some mechanical parts by the node. The duplex alternatives should be designed and verified for this type of communication nodes.
8. **System design:** Although sensor node is one of the main obstacles in design of wireless sensor networks, the external components and the infrastructure systems are very important for proper functionality of the entire system. This system should be defined in details and all modules specified.

Bibliography

[1] Ingelin Clausen. *An implanted micro electro mechanical system for permanent measurement of human brain pressure*. PhD thesis, University of Oslo, Department of Physics, 2005.

[2] Morten Berg. Sensor og utlesningskrets for måling av intraktanielt trykk. Master's thesis, University of Oslo, Department of Physics, 2002.

[3] Jon Due-Hansen. Systemløsning for måling av intrakranielt trykk. Master's thesis, University of Oslo, Department of Physics, 2002.

[4] University of Utah and Health-Sciences-Center. High-risk newborn - hydrocephalus. `<http://www.uuhsc.utah.edu/healthinfo/pediatric/Hrnewborn/hcp.htm>`, 2005.

[5] S. Myrvold C. Tiller and T. Lundar. Nevrokirurgisk shuntbehandling av barn med hydrocephalus. *Tidsskrift for den Norske lægeforening*, 11:1298–1302, 2000.

[6] Gordon E. Moore. Cramming more components onto integrated circuits. *Electronics*, April 19., 1965.

[7] H. T. Friis. A note on a simple transmission formula. *Proc. IRE*, pages 254–256, 1946.

[8] G.A. DeMichele P.R. Troyk. Inductively-coupled power and data link for neural prostheses using a class-e oscillator and fsk modulation. *IEEE EMBS*, September 17-21 2003.

[9] Constatine. A. Balanis. Advanced engineering electromagnetics, 1989.

[10] J. Y.-C. Chang, Asad A. Abidi, and Michael Gaitan. Large suspended inductors on silicon and their use in a 2-pm cmos rf amplifier. *IEEE Eelectron Device Letters*, 14(5), May 1993.

[11] Hasnain Lakdawala, Xu Zhu, Hao Luoand Suresh Santhanam, and L. Richard Carley. Micro machined high-q inductors in a 0.18-μm copper interconnect low-k dielectric cmos process. *IEEE Solid-state circuits*, 37(3), Marxh 2002.

[12] Ieee standard for safety levels with respect to human exposure to radio frequency electromagnetic fields 3khz to 300ghhz, 1992.

[13] C. POLK and E. Postew. Crc handbook of biological effects of electromagnetic fields, 1986.

[14] T.H. Lee A.Hajimiri. *Low noise oscillator*. Kluwer, BOSTON/Dordrecht/London, 1999.

[15] R.Thüringer. Characterization of integrated lumped inductors and transformers. Master's thesis, Institut für Nachrichten- und Hochfrequenztechnik, 2002.

[16] Mina Rais-Zadeh and Farrokh Ayazi. Characterization of high-q spiral inductors on thick insulator on silicon. *IOP electronic journals-Journal of micromechanics and microengineering*, 5(15):2105–2112, 2005.

[17] D.M.Pozar. *Microwave engineering*. John Wiley and Sons, 1998.

[18] Maulik R. Shah, Richard P. Phillips, and Richard A. Normann Member IEEE. A study of printed spiral coils for neuroprosthetic. *Transcranial Telemetry Applications*, VOL. 45, NO. 7:867, JULY 1998.

[19] Frederick W. Grover. Inductance calculations: Working formulas and tables, 1946.

[20] Chen-Yu Chi and Gabriel M. Rebeiz. Planar microwave and millimeter-wave lumped elements and coupled-line filters using micro-machining techniques. *IEEE TRANSACTIONS ON MICROWAVE THEORY AND TECHNIQUES*, APRIL, 1995.

[21] H. M. GREENHOUSE. Design of planar rectangular microelectronic inductors. *IEEE Transactions On Parts, Hybrids, and Packaging*, JUNE, 1974.

[22] H. E. Bryan. Printed inductors and capacitors. *Tele-Tech and Electronic Industries*, December, 1955.

[23] Mina Raieszadeh, Pejman Monajemi, Sang-Woong Yoon, Joy Laskar, and Farrokh Ayazi. High-q integrated inductors on trenched silicon islands. *IEEE transactions on microwave theory and techniques*, pages 7803–8732, 2005.

[24] amicom. Suspended quadratic inductor with air gap height of 100μm. <`http://www.amicom.info/OpenPlatform/index.php/Image:Inductors_3.GIF`>, 2006.

[25] Sun Y., H. Van Zeijl, L. Tauritz, and R.G. Baets. Suspended membrane inductors and capacitors for application in silicon mmics. *IEEE Microwave and Millimeter*, pages 99–102, 1996.

[26] Yoon J-B, B.K.Kim, C.H. Han, E. Yoon, and C.K. Kim. Surface micromachined solenoid on-si and on glass inductors for rf applications. *IEEE Electron Device letters*, VOL. 20:487, 1999.

[27] G.K.Fedder. St7rf mems-specific design rules, November 2006.