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Coils on PCB

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Abstract:

General

In order to increase the integration level of the TV-tuner, it is necessary to replace the existing air-coil by coils on the Printed Circuit Board (PCB). The simulations of coils on PCB are done with the Fasterix simulation tool. Fasterix is developed by the Electronic Design & Tools (ED&T) Philips department, and makes it possible to simulate the coil behavior. Possible simulations of the coil parameters such as inductance value and quality factor, as well as measurements are done.

Problem definition

Is it possible to reach the needed quality factor and inductance value by using the coils on PCB?

How accurate are the Fasterix simulations with regard to the inductance value and quality factor?

Tasks

Learn to work with simulation tools and designing coils on PCB in a simulation tools. Determine the quality factor and inductance value of different coil shapes on different kind of PCB material. Create a design for correct measurements, in order to confirm the simulated results with measurement results.

Making of coils on PCB (for measurements). Measure the designed coils and give feedback for these designs. Report the taken steps in order to make the used method reproducible.

Written and oral representation to a principal.

Objective

The objective is to design different kind of coils on PCB with the help of simulation tools.

A comparison of simulation with measurement results will be done. Designing of coils for a possible integration in the TV-tuner circuit.

Results

Influence of the coil shape and PCB material on inductance value is defined by Fasterix simulations and measurements. The needed inductance value is reached and by changing PCB coil dimensions other values can be created. Simulation results of Fasterix correspond with measurement results. Quality factor of a single coil is rather high (Q > 100).

Implementation of the two coils in the tracking filter is done. The conditions of the tracking filter are almost feasible.

Conclusions:

Conclusions

By changing the coil shape/size the needed inductance value can be reached. Simulations confirm this as well as the measurements. Deviation between simulated and measured inductance value is negligible. For a single coil the quality factor is high, but implementing a coil in a circuit results in a lower quality factor. Because the quality factor is easily influenced by the skin effect and other losses the simulation results are not corresponding for high frequencies (f > 600MHz) with the measurement results. Still Fasterix simulation tool provides an approximation of the quality factor behaviour.

It is possible to implement the coils on PCB in the trackingfilter. The suppression of image frequency with –50dB is feasible. The dimensions of the layout are satisfying. By fine tuning the coils and the layout it is possible to realise the frequency range of 400MHz to 800MHz and a relation of wanted and image frequency of 5/3RF.

Recommendations

In order to higher the quality factor several ideas are existing. Main idea is to optimise the PCB design, meaning that the parasitic capacitance is as low as possible. Also by removing the groundplane underneath the coil can result in higher quality factor. Possibility of two parallel coils on PCB and its influence on the quality factor has to be examined. For all these possibilices the Fasterix simulation tool can be used, whereby the full frequency range (all losses included) is necessary for a realistic approximation of quality factor.

Contents

1 Introduction

In the Integrated Transceivers department (*reference [I1])* of Philips Research a new TV-tuner concept has been defined. A TV-tuner adjusts the received signal (coming from air or antenna) for further demodulation. Today's TV-tuners contain about thirty air-coils, which are mostly used for an analog filter-circuit. These air-coils are mostly manually aligned, which leads to an expensive TV-tuner. Within the project group a new concept of receiving the TV-signal has been developed, which makes it possible to reduce the size of a TV-tuner or even integrate it and make it adjustment-free.
Figure 1-1 shows one of the first TV-tuners *(at the back),* followed by the current versions *(front left and right)* and the possible future version of the TV-tuner in chip-form *(front middle).*

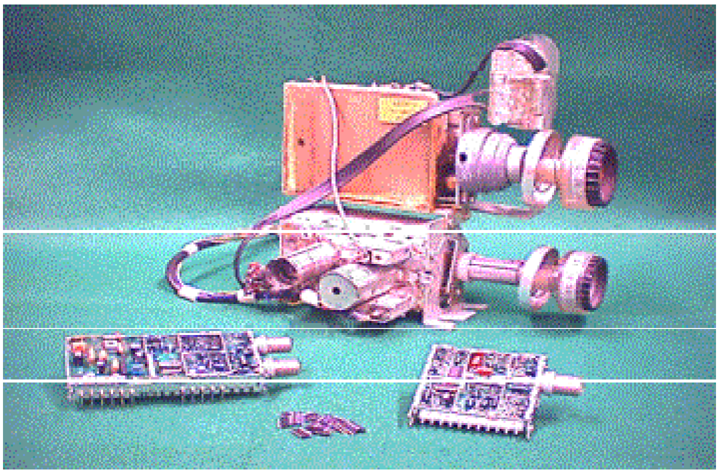


Figure 1-1 *Past, present days and possible future TV-tuners.*

1.1 Problem

One of the problems of the new TV-tuner concept is that the integrated TV-tuner still contains air-coils.
To replace the air-coils by planar coils, several parameters must be studied. For example, to see whether a high quality factor (20 or more), of the coil on PCB can be achieved. A coil has non-idealities like resistor and parasitic capacitance that disturb the coil behavior in a certain frequency range. To make sure that the coils behave inductive, the limitations must be investigated and reported.

1.2 Idea

Study whether it is possible that the simulation tools can simulate the inductance value and quality factor of a coil on PCB.Design and simulate the behavior of coils on PCB with the simulation tool Fastrix *(figure 1-2)*. Fasterix is developed by ED&T (*reference [I2]*) , for IC-design as well as PCB design for analog and mixed applications. Fasterix will help to comprehend the coil behavior and find out the advantages and disadvantages of coils on the PCB. Both the quality factor and the inductance value will be simulated. The accuracy of the simulation can be evaluated by the measurements.

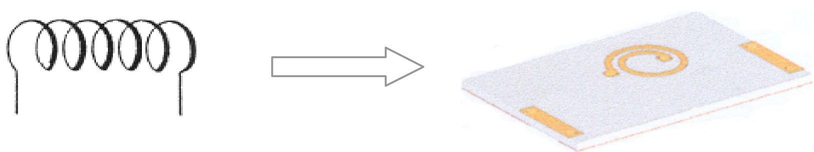


Figure 1-2 *Air-coil and PCB coil.*

1.3 Tasks

Research
Study of the existing documentation about coils on PCB as well as study of the basic coil theory their behavior. Study of different simulation tools (Fasterix, Momentum, ADS-Schematics and Pstar).
The measurement environment and the possibility of making a PCB-layout have to be inquired.

Simulation
Calculation and simulation of the PCB coils behavior can be done with the EM simulation program Fasterix. Fasterix calculates the electromagnetic field of a designed coil by solving the Maxwell equations. This makes it possible to simulate the inductance value and the quality factor of a coil. Simulation results, simulation methods and the considerations that have been made must be critically evaluated.

Measurement
The accuracy of the simulation results will be confirmed by measurements of the designed PCB coils.
The measurement environment is used as a reference for the simulation, to make sure that the results are compatible.

Evaluation & Report
The procedure and recommendations will be clearly documented. The simulation tools have to be evaluated. Simulation and measurement results must be compared and the possible difference reported. Positive results about the quality factor and behavior of the coil will lead to an integration of the designed coils into a TV-tuner circuit. One of the important tasks is writing the report. The report will contain a short representation of the steps that have been done during the accomplishing of the assignment.

1.4 Aim

Study the influences of different coils-shapes (on PCB) on the inductance value and quality factor by simulations with Fasterix and ADS-Schematics. Study the possibility of achieving the wanted inductance value and quality factor using simulation tools as well as confirming the simulation results by measurement. Implementation of designed coils into the TV-tuner circuit.

1.5 Method of research

The method of research is similar to a BOTTOM-UP method as shown in *figure 1-3.* Studying the coil behavior starts from the basics. This includes getting familiar with the simulation tools, deriving possible equations for the inductance value and build other theoretical knowledge.
The simulation and measurement results will be compared and reported. The evaluation of the interface between simulation tools, Fasterix and ADS, is also necessary.

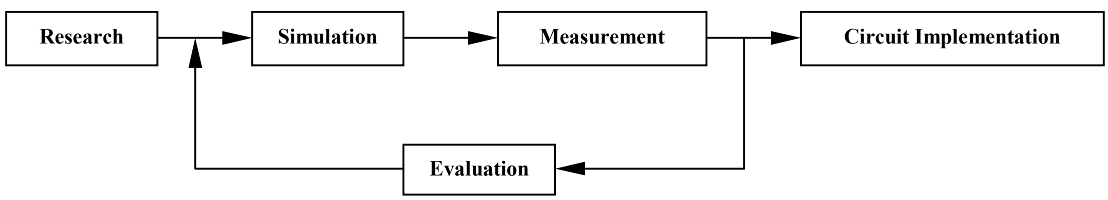


Figure 1-3 *BOTTOM-UP research method.*

At the end of the assignment, the necessary conclusions and recommendations will be reported. Possibility of integration of designed coils into the TV-tuner circuits will also be investigated and possible implementation of the coils into a TV-circuit will be done.

2 Theoretical background

Coils are used in a number of different applications and like capacitors *(Appendix A.3)* and resistors are passive components. Different kind of coils exists for different applications. In energy techniques coils are used as transformers and current limited elements. RF coils are used in filters, resonance and tunable circuits. Air-coils in a TV-tuner circuit are mainly used in filter or tuner circuits. The several coil parameters have a great influence on the quality factor and inductance value. To understand the behavior of a PCB coil, first the general basics of coils are studied. The behavior of the tracking filter with coils on PCB must be the same as with air-coils in order to replace the air-coils with coils on PCB. Therefore the behavior of the tracking filter is studied. The properties of a microstrip are also studied, because they are needed when measuring the coils. Different simulation tools such as ADS, Momentum and Fasterix are used to simulate the coils on PCB.

2.1 Coil basics

To understand the behavior of coils in general, documentation has been studied *(reference [B7])*. In this section the basic coil theory will be represented, as following:

- *DC-behavior*
- *AC-behavior*
- *Non-ideal coil*
- *Quality Factor*
- *Skin effect*

2.1.1 DC-behavior

In *figure 2-1* the coil is connected to a DC-source. At the moment that switch *'S'* is closed, the current 'I_L' and the voltage 'U_L' will behave as given in *formula [2-1]*.

When the current reaches the maximum value, $I_{L,\max} = \frac{U_b}{R}$, the voltage 'U_L' reduces to zero and the coil functions as short-circuit.

$$I_L = \frac{U_b}{R} \cdot \left(1 - e^{\frac{-R\,t}{L}}\right) \qquad\qquad U_L = U_b \cdot \left(e^{\frac{-R\,t}{L}}\right) \qquad \textbf{[2-1]}$$

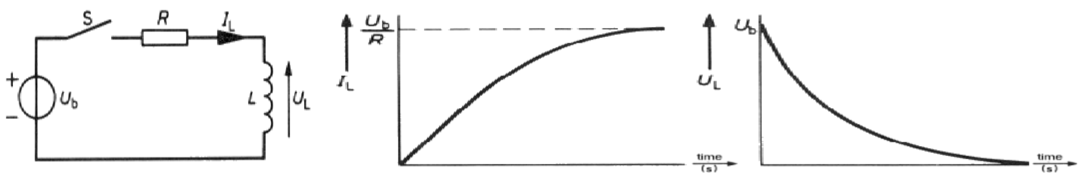


Figure 2-1 *DC-behavior of the current and voltage across a coil.*

2.1.2 AC-behavior

In *figure 2-2* the coil is connected to an AC-source. If the AC-source provides a sine-shaped signal then it appears that 'i_L' and 'u_L' are also sinus signals with a phase difference of 90 degrees.
The impedance and the AC-voltage of a coil are given by *formula [2-2].*

$$Z = j\omega \; L \qquad u_L = L \; \frac{di_L}{dt} \qquad \textbf{[2-2]}$$

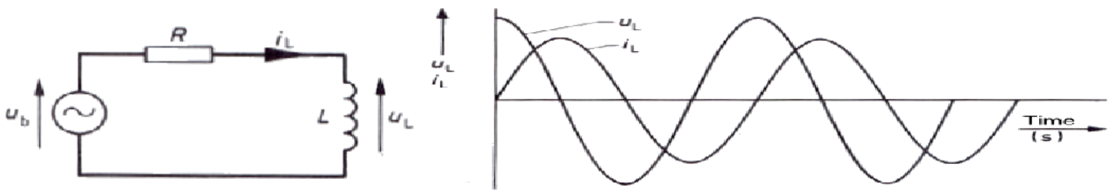


Figure 2-2 *AC-behavior of the current and voltage across a coil.*

2.1.3 Non-ideal coil

An ideal coil consists of a conductor without any losses, thus only self-inductance is generated.
In practice, a coil always has an unwanted behavior caused by the parasitic capacitance's and the internal resistance. To understand the coil behavior, an approximation-circuit that represents the non-ideal coil is derived, where L, C, and R are considered constant as shown in *figure 2-3.* For this approximation-circuit a transfer function H(jω) *(reference [B8])* can be derived as shown in *formula [2-3]* and thus the magnitude, real and imaginary functions can be derived and plotted by using *formulas [2-4], [2-5] & [2-6].*

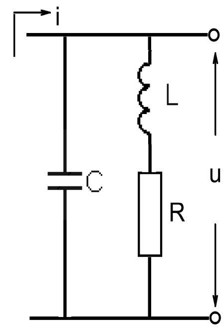


Figure 2-3 *Non-ideal coil.*

$$Z = \frac{u}{i} = H(j\omega) = \frac{j\omega L + R}{(j\omega)^2 LC + j\omega CR + 1} \qquad \textbf{[2-3]}$$

$$|H(j\omega)| = \left| \frac{j\omega L + R}{(j\omega)^2 LC + j\omega CR + 1} \right| = \frac{\sqrt{L^2 \;\omega^2 + R^2}}{\sqrt{C^2 \;\omega^2 \;(L^2 \;\omega^2 + R^2) - 2 \;C \;L \;\omega^2 + 1}} \qquad \textbf{[2-4]}$$

$$\Im m(H(j\omega)) = \Im m\left(\frac{j\omega L + R}{(j\omega)^2 LC + j\omega CR + 1} \right) = \frac{\omega \;(L - C \;(L^2 \;\omega^2 + R^2))}{C^2 \;\omega^2 \;(L^2 \;\omega^2 + R^2) - 2 \;C \;L \;\omega^2 + 1} \qquad \textbf{[2-5]}$$

$$\Re e(H(j\omega)) = \Re e\left(\frac{j\omega L + R}{(j\omega)^2 LC + j\omega CR + 1} \right) = \frac{R}{C^2 \;\omega^2 \;(L^2 \;\omega^2 + R^2) - 2 \;C \;L \;\omega^2 + 1} \qquad \textbf{[2-6]}$$

In *figure 2-4* the values L, C, and R-values have been chosen as indicated and the transfer function of this coil is analysed. When the frequency increases the values of parasitic capacitance and impedance losses increases too. This means that at a certain point the impedance of the inductance is equal to the impedance of the parasitic capacitance. This is called the resonance frequency f_0 ($\omega_0 = 2\ \pi\ f_0$). At higher frequencies then the resonance frequency the will not behave as an inductance but as a capacitance.
At lower frequencies the resonance frequency can be approached using *formula [2-7]*. At much higher frequencies the internal resistor increases because of the skin effect, and thus the created approximation-circuit, do not provide an accurate representation of coil behavior.

$$f_0 \approx \frac{1}{2\ \pi\ \sqrt{L\ C}} \qquad \textbf{[2-7]}$$

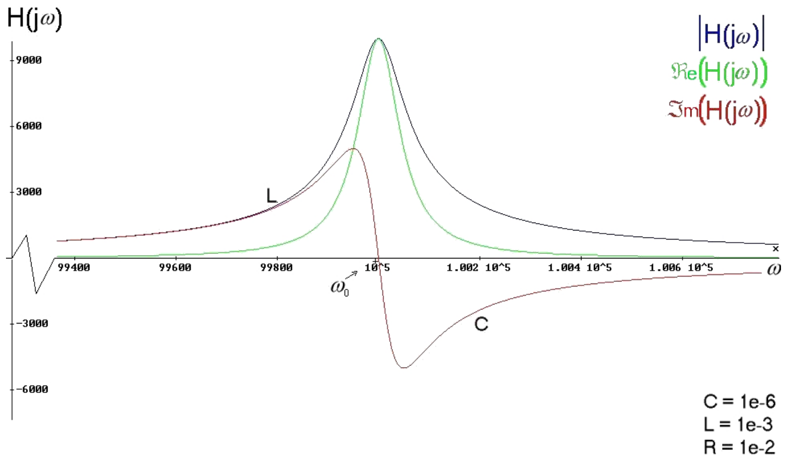


Figure 2-4 *Transfer function example.*

2.1.4 Quality factor

The quality factor *(reference [B10], [B11])* of an inductor is an important coil parameter if coils are used in low loss circuits and narrow-band tuned circuits. The quality factor is generally represented by *formula 2-8 (Q_{gen})*.

$$Q_{gen} = \frac{2\ \pi\ \textit{energy stored}}{\textit{energy loss in one oscillation cycle}}$$

[2-8]

$$Q_{complex} = \cot \delta = \frac{\mathrm{Im}(U_L)}{\mathrm{Re}(U_R)}$$

A complex vectorial presentation of the quality factor is shown in *figure 2-5*. Using the complex representation of coil model, it is much easier to calculate the quality factor value (*formula 2-8* $Q_{complex}$). For an air-coil a high quality factor (Q > 200) can be reached. A high quality factor means that the internal resistance is very low, and therefor the losses are low.

The quality-factor is related to:
- Bandwidth
- Inductor outside diameter
- inductance and resistance of coil
- Conductor width to spacing ratio
- Selectivity

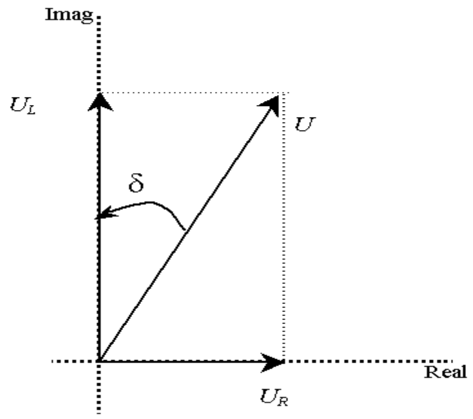


Figure 2-5 *Vectorial voltage representation of a coil.*

2.1.5 Skin effect

The skin effect *(reference [B7])* is caused by the alternating magnetic field, which pushes the current to the outside of the conductor. The current density in the centre becomes smaller than at the outside of the conductor. When the frequency increases the skin effect increases. At very high frequencies the current only flows through a thin layer at the surface of the conductor. This results in an increase of the resistance and a decrease of the quality factor. The current distribution through a conductor can be calculated, but in most cases it is only possible with difficult mathematical formulas. The current density in the surface of a conductor decreases with a certain depth. The depth where the current density decreases to 37% of the original current density at the surface, is called skin depth *(formula 2-9).* If the skin depth is known, a prediction of the current distribution can be made. In case the trackwidth is many times the skin depth, the current will be concentrated near the outer edges of the conductor.

$$\delta = \sqrt{\frac{\rho \ 10^6}{\pi \ f \ \mu}} \qquad \textbf{[2-9]}$$

where: $\delta = skin\ depth \quad (mm)$

$\rho = resistivity \quad (ohm \ \ m)$

$f = frequency \quad (Hz)$

$\mu = permeabilty = \mu_0 \ \ \mu_r$

2.2 Coils on PCB

James Clerk Maxwell (1831-1879) is responsible for the theoretical prediction of the EM-fields behavior *(reference [B1] & [B2] & [B3])*. The approximation of the inductance value of a coil on PCB coil can be calculated by the Maxwell laws. For a manual approximation of the DC inductance value, Maxwell's equation is far too complex, that's why the calculation is done by much simpler formula, such as Wheelers and Current Sheet expressions, more formulas are mentioned in *appendix A*2.
Modified Wheelers (1927) *formula [2-10]* provides a rather accurate (2%) approximation of inductance values and can be used for calculating the DC inductance value of different shapes of PCB coils, as shown in *figure 2-6*. The coefficients K1 and K2 are layout dependent and are shown in *table 2-1.*
Also, the Current Sheet *formula [2-11]* provides a rather accurate (2%) approximation of DC inductance values. The coefficients c_1, c_2, c_3 and c_4 are layout dependent and are shown in *table 2-2*.

Modified Wheeler expression:

$$L = K_1 \; \mu_0 \; \frac{n^2 \; d_{avg}}{1 + K_2 \; \rho} \quad (H) \qquad \textbf{[2-10]}$$

Current Sheet expression:

$$L_{gmd} = \frac{\mu_0 \; n^2 \; d_{avg} \; c_1}{2}\left(\ln(c_2/\rho) + c_3\rho + c_4\rho^2\right) \quad (H) \qquad \textbf{[2-11]}$$

Where: $\mu_0 = 4 \; \pi \; 10^{-7}$
n = number of turns
d_{out} = outer diameter [m]
d_{in} = inner diameter [m]
$d_{avg} = \frac{1}{2}(d_{out} + d_{in})$ [m]
$\rho = \frac{d_{out} - d_{in}}{d_{out} + d_{in}}$ [m]

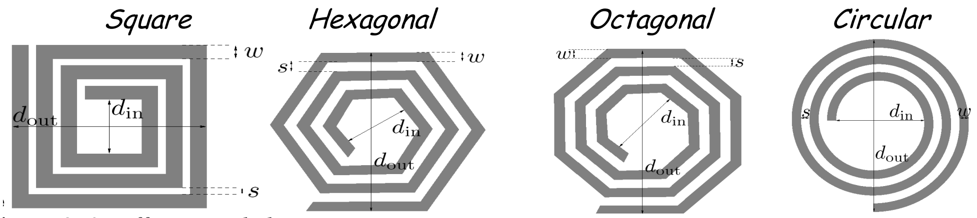


Figure 2-6 *Different coil shapes.*

Layout	K_1	K_2
Square	2.34	2.75
Hexagonal	2.33	3.82
Octagonal	2.25	3.55
Circular	2.09	3.33

Table 2-1 *Coefficients for Modified Wheeler Expression.*

Layout	c_1	c_2	c_3	c_4
Square	1.27	2.07	0.18	0.13
Hexagonal	1.09	2.23	0.00	0.17
Octagonal	1.07	2.29	0.00	0.19
Circular	1.00	2.46	0.00	0.20

Table 2-2 *Coefficients for Current Sheet Expression.*

Different inductance values are needed for the TV-tuner circuit. To determine the most suitable shape for the coils, modified Wheeler and Current sheet expressions are used as a start up. For the AC-behavior of a coil model Fasterix simulations are used.

2.3 Tracking filter

The tracking filter *(reference [B12],)*is a part of a TV-tuner circuit and is used for pre-selection of the wanted channel and suppression of the image channel. Both wanted (R_F-frequency) and image channel are down-converted in a R_F-mixer with a local oscillator frequency (LO*) (figure 2-7)* that results in a frequency spectrum shown in *figure 2-8.* The RF- and image frequency fold on the same frequency, which eventually results in a distortion of the TV-image.

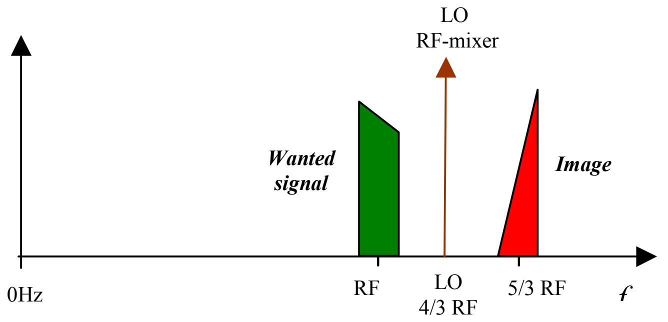


Figure 2-7 *Mixing RF- and image frequencies with a LO frequency in the RF-mixer.*

Figure 2-8 *RF-mixer output.*

The tracking filter is used to reduce the distortion of the TV-image. This is done by suppressing the image frequency as shown in *figure 2-9 & 2-10.*

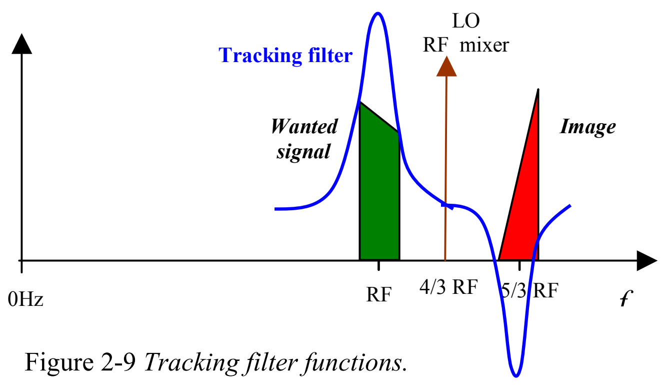


Figure 2-9 *Tracking filter functions.*

Figure 2-*10 RF-mixer output with the use of a tracking filter. Image is suppressed.*

The tracking filter consist of a tuneable LC resonance section *(A in figure 2-11)* with an input coupling inductor *(B in figure 2-11)*. The tuneable LC section consists of a coil and varicap. A varicap is a diode, in which the depletion layer can be varied by a voltage. This results in a capacitance which can be adjusted by varying this voltage. In the application used capacitance can vary from 2pF ($V_{tune} = 30V$) to 18pF ($V_{tune} = 0V$). The tunable LC section consists of a serial and parallel LC-filter where the resonance frequency is calculated: $f_0 = \frac{1}{2\pi\sqrt{LC}}$.

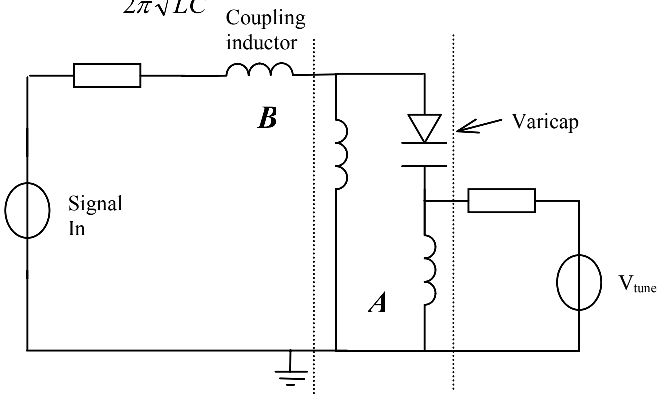


Figure 2-11 *Schematic tracking filter.*

The parallel LC-filter is a bandpass filter *(figure 2-12)* and the serial LC-filter is a bandstop filter *(figure 2-13)*. These two filters are used to select the wanted frequency and to suppress the image frequency. The resonance frequency of the bandstop filter is 5/3 RF and of the bandpass filter 3/3 RF. The behavior of these two filters used together is shown in *figure 2-14*. If the capacitance of the varicap increases, the resonance frequency of the filters decreases. By using this concept the wanted frequency can be selected. The curve shown in *figure 2-14* will move to the right or to the left.

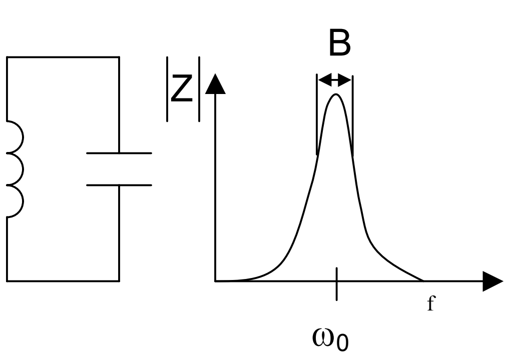


Figure 2-14 *Bandpass filter.*

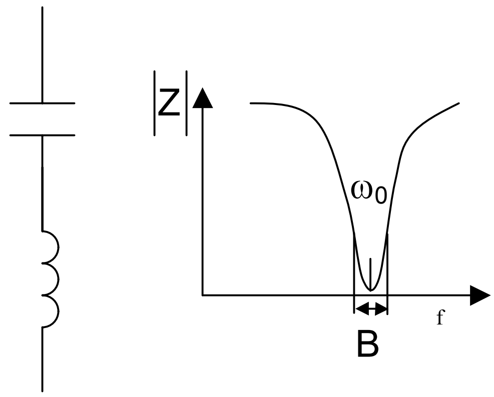


Figure 2-12 *Bandstop filter.*

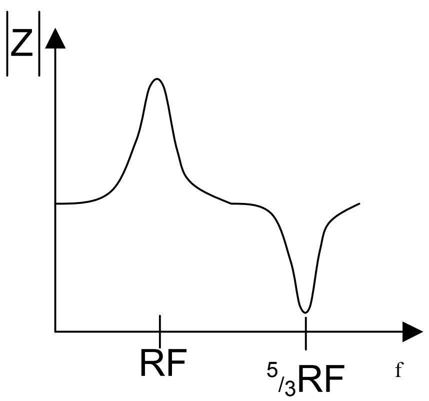


Figure 2-13 *Behavior a tuneable LC resonance section.*

2.4 Microstrip

Reflections occur when the characteristic impedance of the track and/or the load are not equal to the characteristic impedance of the source. Tracks that have a fixed characteristic impedance are called 'micro-strips'. The characteristic impedance of track should be equal to the characteristic impedance of the source and can be manipulated by:

- Adjustment of the height (t) or the width (w) of the track
- Distance between tracks and the distance between the track and the groundplane (w)
- Choice of PCB material (ε_r)

A microstrip is made of a groundplane, metal strip with a special width *(W),* a thickness *(t)* and a substrate with a certain thickness *(h)*, as shown in *figure 2-15.*

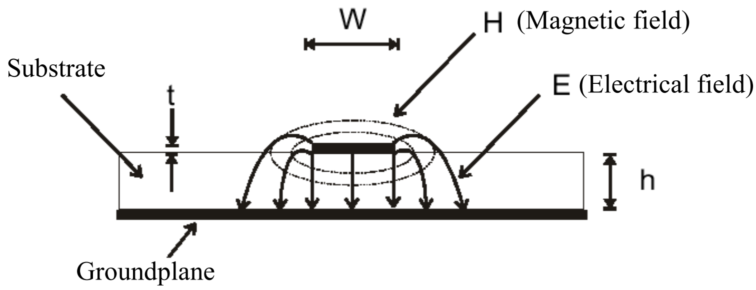


Figure 2-15 *Cross-section of a microstrip.*

Because the electrical field (E) of a microstrip flows through the dielectric media's of the PCB material (ε_r) and air (ε_0), a new parameter ε_{eff} is introduced where: $\varepsilon_0 < \varepsilon_{eff} < \varepsilon_r$

The effective dielectric constant (ε_{eff}) of a microstrip can be calculated with *formulas [2-12] to [2-15].*
For more information see *reference [I6] & [I7] & [B4].*

$$\varepsilon_{eff} = \frac{\varepsilon_r + 1}{2} + \frac{\varepsilon_r - 1}{2} F\left(\frac{W}{h}\right) - C \quad \textbf{[2-12]}$$

where:

$$F\left(\frac{W}{h}\right) = \left(1 + 12\frac{h}{W}\right)^{-\frac{1}{2}} + 0.04\left(1 - \frac{W}{h}\right)^2 \quad \text{for W/h < 1} \quad \textbf{[2-13]}$$

$$F\left(\frac{W}{h}\right) = \left(1 + 12\frac{h}{W}\right)^{-\frac{1}{2}} \quad \text{for W/h > 1} \quad \textbf{[2-14]}$$

$$C = \frac{\varepsilon_r - 1}{4.6} \frac{\frac{t}{h}}{\sqrt{\frac{W}{h}}} \quad \textbf{2-15]}$$

The microstrip that is needed for the measurement must have a characteristic impedance of 50ohm, because the LCR-meter has an impedance of 50ohm. When these two are not equal reflections are introduced, which have a negative influence on the measurements. The characteristic impedance (Z_0) of a microstip, with known dimensions and PCB material, can be calculated by *formula [2-16], (reference [I6] & [I7])*

$$Z_0 = \begin{cases} \frac{60\cdot\pi}{\sqrt{\varepsilon_{eff}}} \ln\frac{8h}{W} + \frac{W}{4h} & \text{for } W/h \le 1 \\ \frac{120\cdot\pi}{\sqrt{\varepsilon_{eff}}} \cdot \frac{1}{W/h + 1.393 + 0.667\cdot\ln\cdot(W/h + 1.44)} & \text{for } W/h \ge 1 \end{cases} \quad \textbf{[2-16]}$$

The width of the microstrip used for the measurements is calculated with Appcad 2.0. This is a Agilent program that calculates the characteristic impedance of a microstrip with known dimensions, as shown in the Appcad user interface in *figure 2-16.*

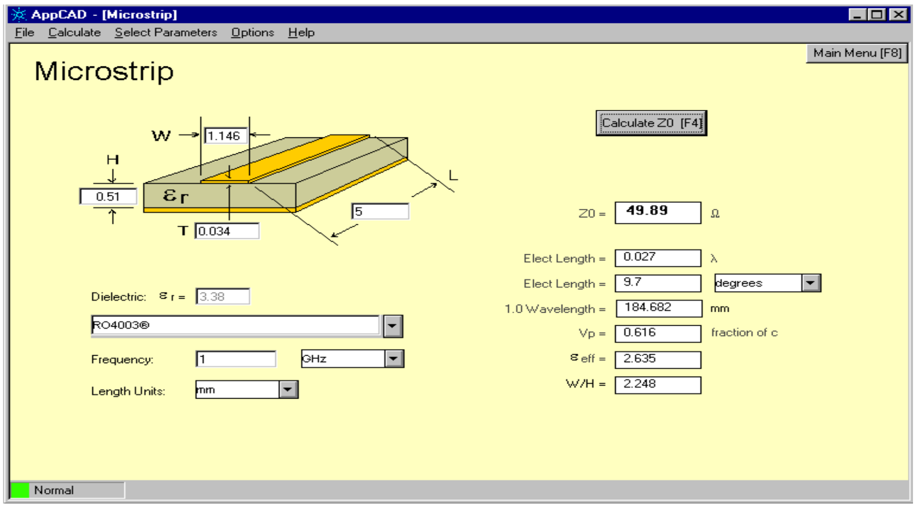


Figure 2-16 *Appcad user interface microstrip calculation.*

2.5 Simulation tools

Circuit design has a great history. In the past circuits were first designed on paper and the component values were calculated by hand. After a long designing period the circuit was implemented as a breadboard and components were connected by wires. Often, unexpected behavior of the circuit occurred and by implementing the circuit on PCB it was possible to realise the reduction of unexpected effects. Transfer from breadboard to PCB was also done by hand, which led to numerous of design mistakes. Today, electronic design is done using computer aided design (CAD) packages, which makes it possible to simulate the behavior of circuits at higher frequencies.

To create a coil on PCB, simulation tools are used, which makes it possible to calculate the EM-fields and examine the behavior in the frequency domain. The following simulation tools are used during the fulfilment of the assignment:
- Advanced Design System (ADS)
- Fasterix
- Momentum
- Pstar

To simulate PCB design behavior, the following substrate and metallization parameters has to be specified:

Substrate parameters:
- Thickness
- Permittivity ε_r
- Loss tangent

Metallization parameters:
- Thickness
- Conductivity
- Loss tangent

For the calculation of the component bahavior it is necessary that the named parameters are defined.
Substrate layers define the dielectric media, ground planes, air and other layered material. Metallization layers are the conductive layers between different substrate layers and are used in conjunction with the layout layers. By mapping the layout layers, on which the circuit is drawn, to the metallization layers, it can be positioned on the substrate.
Mapping can be done in two ways as a strip or as a slot. When using a strip, the objects on the layout layer are conductive, and the rest of the layer is not conductive. A slot is an inverse of a strip.
The simulated and measured coils are constructed on a PCB, which consists of one dielectric media with on both sides the metallization layer as shown in *figure 2-17*. The two layout layers can be connected to each other through the substrate with a so called via.

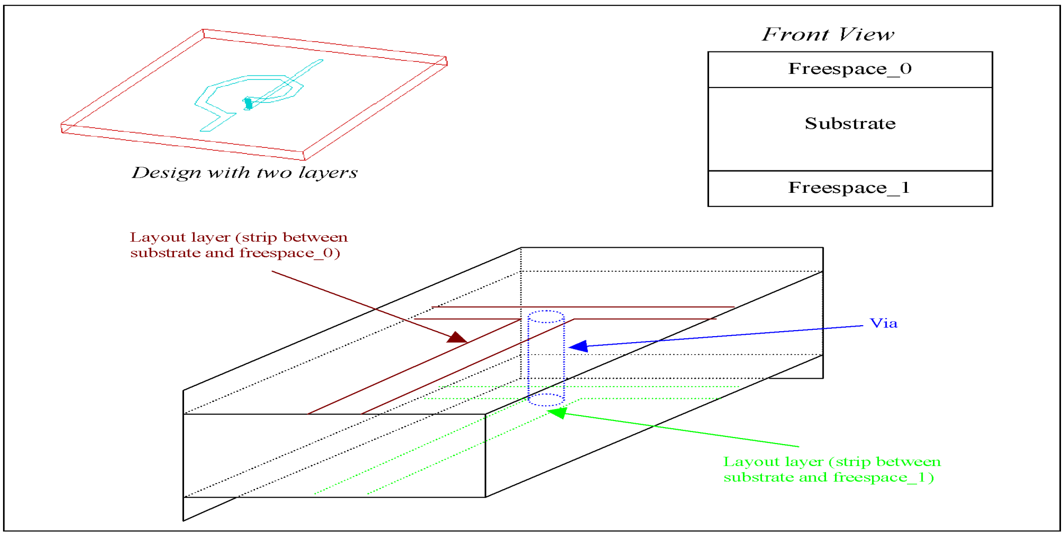


Figure 2-17 *Angle and front view of substrate and layers.*

2.5.1 Advanced Design System

Advanced Design System (ADS) is a powerful electronic design automation software system from Agilent. It offers designers complete design integration of products such as cellular and portable phones, pagers, wireless networks, radar and satellite communications systems.
Advanced Design System runs on PC as well as on workstation, with complete file compatibility between platforms and across networks.ADS features the following design possibilities:

- *RF (Radio Frequency) Board Designer:* Designing the circuits and subsystems with PCB technology. Simulations are done with Momentum or with the recently implemented Fasterix interface.
- *RFIC Designer:* RFIC Designer enables RFIC design engineers to improve RFIC designs through the use of leading-edge simulation and optimization technologies.
- *Microwave Circuit Designer:* Linear and nonlinear microwave circuit design.
- *Digital Signal Process (DSP) Designer:* System-level DSP design.
- *Communication Systems Designer:* Top level DSP and high-frequency system design.

2.5.2 Fasterix

Fasterix is one of the simulation tools, which makes it possible to simulate digital and analog system behavior at higher frequencies (up to a few GHz), on PCB or on chip.
Figure 2-18 gives an overview of the steps which are performed in a simulation using Fasterix.
Vias and air bridges connect topologies between layers, allowing users to simulate multi-layer PCBs.

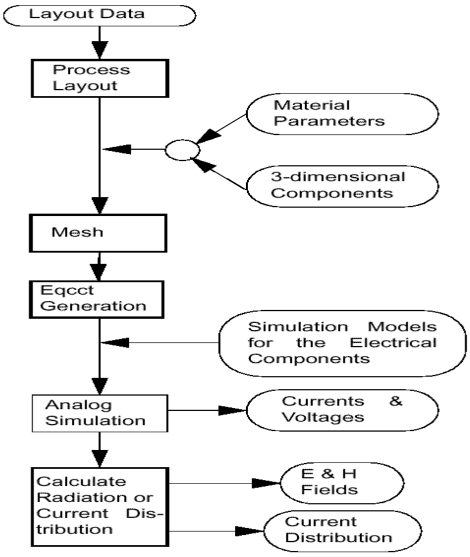


Figure 2-18 *Overview of the Fasterix program flow***.**

Layout processor
During the first steps of the 'layout processor', the layout data is checked and converted to a suitable format for further simulation.
At this moment the layout can be prepared in the following ways:

- *In the Agilent Advanced Design System (ADS), figure 2-19 :* This interface between Fasterix and ADS is recently made by the group ED&T at Philips Research and is used for the assignment.

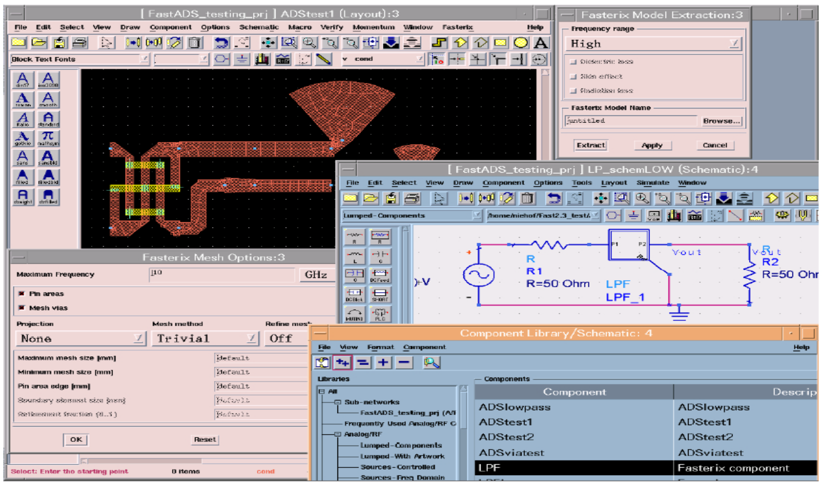


Figure 2-19 *Fasterix in ADS.*

- *Using Mentor Graphics Board Station Version 7 or 8*
- *Importing from a GDSII file*
- *Using the mechanical layout package ME10*
- *Manual preparation of the Layout*

If the layout process is completed successfully, the data of the following parameters are provided:
- Material (dielectric constants, conductivity)
- Dimensional component (screen, wires and cables)

Mesh Generator
The mesh generator divides the layout into a number of elements (as shown in chapter 3.4). The number of elements determines the accuracy of the calculated parasitic (R, L, C) parameters of the layout. The number of elements is determined by defined maximum frequency for which the generated equivalent circuit model of the layout must be valid.

Equivalent circuit generator
The equivalent circuit generator' calculates the values of the parasitic components R, L, C between parts of the layout. The results of this operation are an equivalent circuit model as shown in *figure 2-20*. In the ADS-Schematic window it is now possible to connect the defined pins to a source.

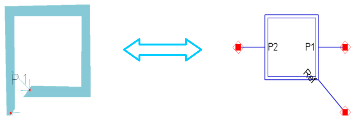


Figure 2-20 *Equivalent circuit component.*

Analog simulation
The analog simulation can be done in the ADS schematic environment as well as in Pstar. Using the equivalent circuit model made by Fasterix, the usual procedure of simulating a circuit can be done in the ADS-Schematic window. For more information about Fasterix see the references site *I3*, *I4* and *I5*.

2.5.3 Momentum

Momentum is a software tool from Agilent that helps with the performance prediction of high-frequency circuit boards, antennas, and ICs without extensive fabrication cost. As well as Fasterix, Momentum runs directly from the layout environment of the Agilent ADS.
Based on Method of Moments analysis, Momentum computes S-parameters of general planar circuits. Vias and air bridges connect topologies between layers, allowing users to simulate multilayer RF/micro wave printed circuit boards, hybrids, multichip modules, and integrated circuits.

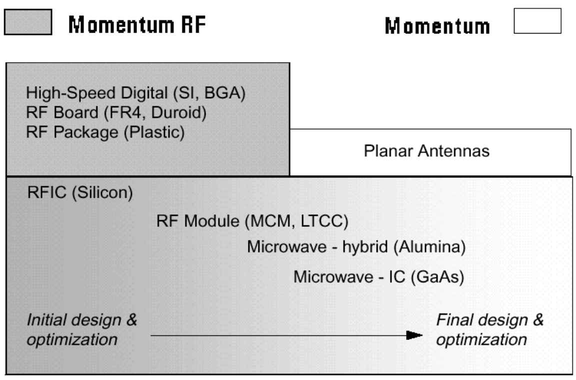


Figure 2-21 *Momentum modes for different applications.*

The following Momentum modes are existing depending on the design application as shown in *figure 2-21*.
- Momentum Micro wave provides an accurate approach for solving geometry's that are large in comparison to the wavelength of the highest simulation frequency.
- Momentum RF is used for structures under a half wavelength, utilising the RF mode of Momentum that makes it possible to ignore effects such as space and substrate radiation.
  This option is used for the simulation comparison between Fasterix and Momentum simulation results.

Layout processor
The layout data is prepared in the Agilent ADS or is imported from another design tool. ADS can import files in a variety of formats.

Mesh Generator
Same function as Fasterix mesh, only the different algorithm for generation of mesh is used and thus the difference in the simulation time is introduced.

Output format
Output chart formats include *Cartesian* and *Smith charts*, tabular listings that differ from the Fasterix 'equivalent circuit' output file.

Analog simulation
Analog simulation can be done in the ADS-Schematics environment. Using the two-port component out of the ADS-Schematics window, it is possible to refer the generated Momentum output file to a two-port model as shown in *figure 2-22*. Now the two-port model can be used in the ADS-Schematics window and the analog simulation of the circuit can be done.

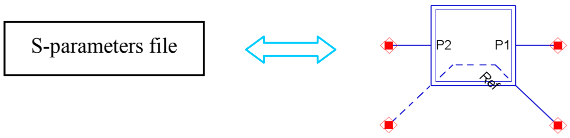


Figure 2-22 *Output file as a ADS two-port component.*

3 PCB-coil Simulation

3.1 Analog simulation

Using the ADS-schematics window, it is possible to simulate the behavior of PCB coils and thus make the inductance value and quality factor value visible. A coil-model generated by Fasterix is imported in an ADS-schematic window. The circuit as shown in *figure 3-1* is built, where at the input of a coil-model, the AC voltage source is connected and the resistance of 50ohm is attached. An AC-small signal simulation is done to compute the values of 'U' and 'I'. Where 'U' is the voltage at the input of the coil and 'I' the current through the source. In the ADS-Schematic window the possibility exists to define the equations. For example the quality factor in *figure 3-1* is defined by:

Q = imag(Z) / real(Z) = imag(U/I) / real(U/I) = imag (out/SRC1.i) / real(out/SRC1.i).

After simulation in ADS-schematic the quality factor can be selected and viewed in the Data-Display window. In the ADS-schematic the current direction is defined from positive to negative node of the source and thus must be included in defined equations.

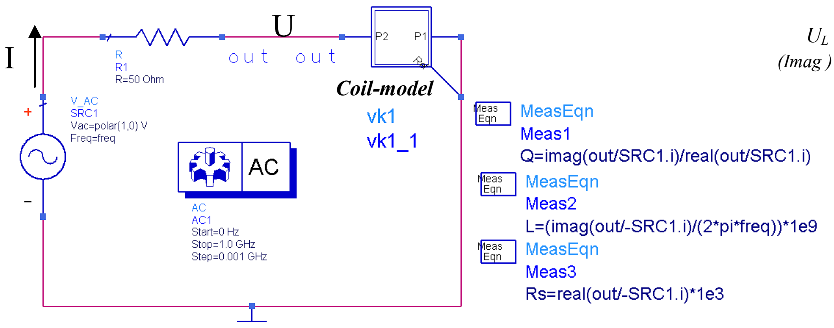


Figure 3-1 *ADS simulation circuit with component-model.*

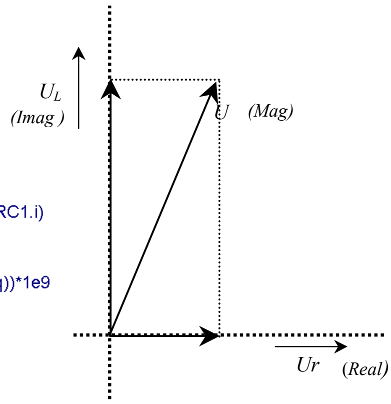


Figure 3-2 *Vectorial voltage representation of coil-model.*

Inductance value

A not ideal coil consists of an imaginary part (*imag*) and a part (*real*). The magnitude (*mag*) of a coil is the vectorial addition of imaginary and real part a shown in *figure 3-2*. The real part consists of resistance of a coil and can be calculated as shown in *formula [3-1]*. The imaginary part is the reactance 'X_L' of a coil and can be calculated as shown in *formula [3-2]*. The impedance '*Z*' of a coil can be calculated as shown in *formula [3-3]* & *[3-4]*.

$$real[Z] = real\left[\frac{U}{I}\right] \neq \frac{real[U]}{real[I]} \quad \textbf{[3-1]}$$

$$imag[Z] = X_L = j\omega L = imag\left[\frac{U}{I}\right] \neq \frac{imag[U]}{imag[I]} \quad \textbf{[3-2]}$$

$$Z = R + X_L \quad \textbf{[3-3]}$$

$$mag[Z] = mag\left[\frac{U}{I}\right] \quad \textbf{[3-4]}$$

The imaginary part of a coil-model represents the inductance value and is defined as shown in *formula [3-5]*.

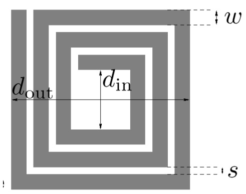
$$L = imag\left[\frac{U}{I}\right] \Big/ (2\ \pi\ f) \qquad \textbf{[3-5]}$$

The quality factor
The quality factor of the Fasterix coil-model can be calculated by dividing the imaginary and real part of the coil-model, according to *formula 3-6.*

$$Q = X_L \big/ R \quad = \quad imag[Z] \,/\, real[Z] \quad = \quad imag\left[\frac{U}{I}\right] \Big/ real\left[\frac{U}{I}\right] \qquad \textbf{[3-6]}$$

3.2 Layout processor

Layout data of the coils on a PCB can be prepared in the ADS-Layout window. The ADS-Layout window contains no useful tools for drawing the complex PCB coil shapes like octagonal, hexagonal and circular shapes. Because of this disadvantage other possibilities were searched. An existing FORTRAN-program is used. This program makes possible to create the Layout data for any desired coil shape. Several parameters must be provided, as shown in *figure 3-3*, in order to create the Layout data. For a coil shape 'Pointsperrev m' must be defined. For example if m = 4 the coil shape is square. *Appendix A.4* showns how 'Trackwidth' and 'Trackspacing' must be calculated, as well as how to import FORTRAN layout data in the ADS-Layout window.



baseradius = $\frac{1}{2} \cdot d_{in}$
trackwidth = w
trackspacing = s
pointsperrev = m (m > 0 , integer)
numberofwindings = n (n > 0 , real)

Figure 3-3 *Parameters needed for FORTRAN-program.*

3.3 Equivalent circuit generation

Based on the mesh elements and the material parameters, the equivalent circuit module generates the equivalent circuit for the layout, which is valid up to the specified maximum frequency. Generated equivalent circuit file is suitable for an ADS analog simulator. In this paragraph general simulation results are shown for High/Full frequency ranges and their influence on the coil parameters are determined.

3.3.1 High frequency range

The generated model is only valid from flow up to the specified maximum frequency, where flow is the frequency at which the inductive effects dominate the resistive effects in the designed coil. This frequency depends on the geometry and the material parameters of the coil. This option requires less CPU time than the Full model and gives less accurate results in the low frequency range.

This means that the Z_0 calculation is not accurate enough and therefore the quality factor is inaccurate and unrealistic. *Figure 3-4* shows a coil simulation example that proves the unrealistic (Q ≈ 3500) high frequency range simulation results of a quality factor.

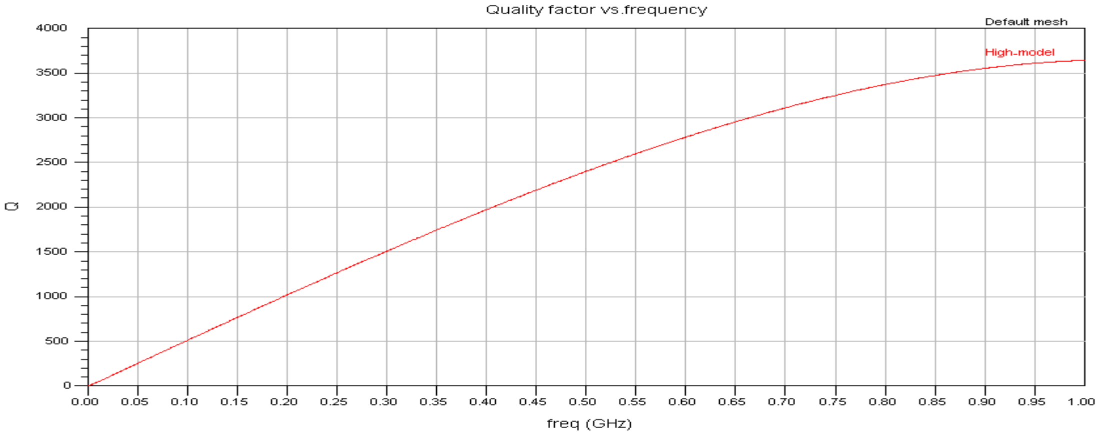


Figure 3-4 *Simulated quality factor of high model coil.*

3.3.2 Full frequency range

The generated model is valid from 0Hz up to the specified maximum frequency. It also allows skin effect, dielectric losses and radiation to be included. These options will have an enormous influence on the quality factor of the designed coil as proved in *figure 3-5.* Full frequency range option requires more CPU time than the High option. It includes the losses and thus the quality factor of a coil on PCB is far more realistic (Q ≈ 130). Still, the quality factor of 130 is unexpected high and will be explained in more detail in this chapter.

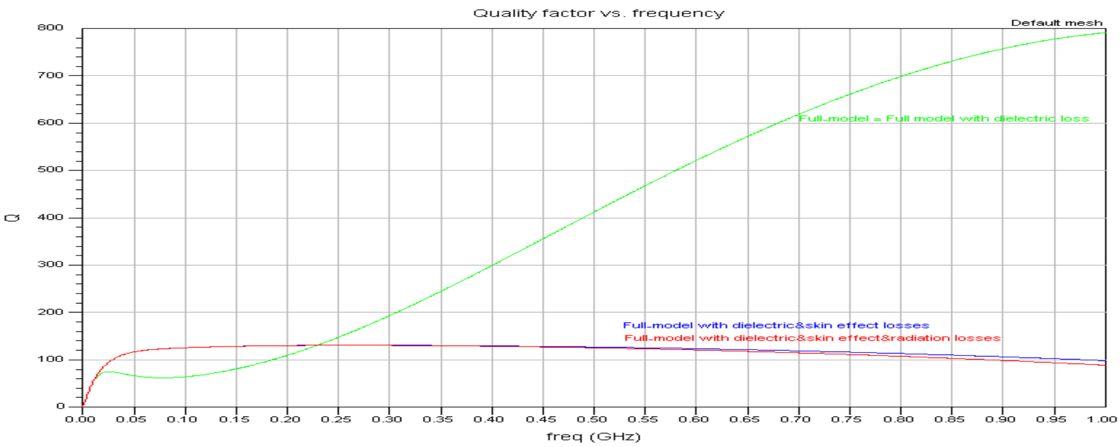


Figure 3-5 *Simulated quality factor of full model coil for different loss options.*

3.3.3 *Low frequency range*

This model is only valid for low frequencies, which cannot be used for an accurate simulation in frequency domain. This option is not suitable for the use of assignment because of the inaccurate results.

3.3.4 *DC frequency range*

The generated model is only valid for zero frequencies and only contains the parasitic resistor. This option is not suitable for the use of assignment because of the inaccurate results.

3.4 Mesh generation

Fasterix as well as Momentum generates the mesh for a certain coil shape. An example of the mesh generated by Fasterix is shown in *figure 3-6.* Before the generation starts several mesh parameters have to be defined, dependably of wanted application and the accuracy of a simulations results for designed coil. In *figure 3-7* the 'Fasterix Mesh Options' window is shown.
For example, if the coil is used in the frequency range 100MHz < f < 1GHz, the *maximum frequency* of ≥ 1GHZ must be defined. *Maximum* and *minimum mesh size* has a certain default value, which is determined by the used simulation tool dependably on the coil shape, sort substrate and the defined maximum frequency. For an accurate calculation of the quality factor, with Fasterix, it is necessary to manually define the *Boundary element size*. Quality factor is strongly dependent of the track resistance, which is influenced by the skin effect. By defining the boundary element size the skin depth is defined and more accurate results are provided.

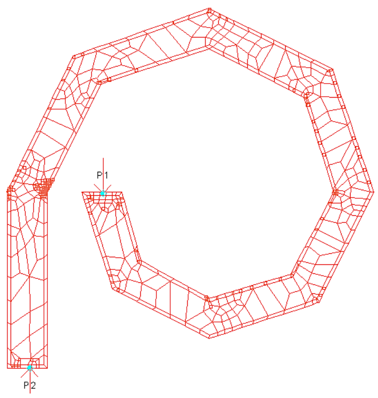


Figure 3-6 *Mesh generated by Fasterix.*

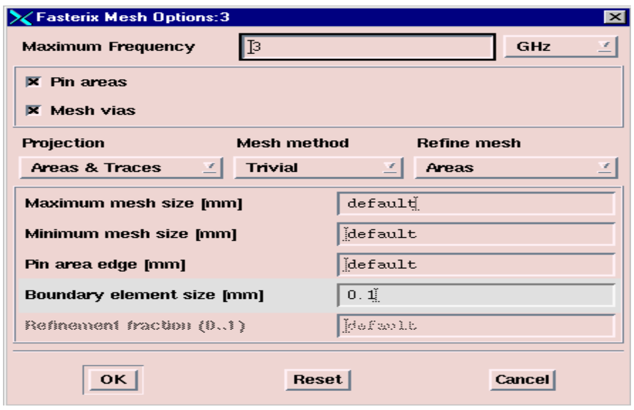


Figure 3-7 *ADS Mesh window menu.*

3.4.1 *Fasterix versus Momentum*

Several coil shapes were simulated by Fasterix and sometimes the result seemed strange and inaccurate. The possibilities of simulating the designed coils with other simulation tools were available, such as Momentum RF. The comparison is made in:

- Mesh generation
- Simulation time
- Inductance and Quality factor value

Mesh generation
In *figure 3-8* the generated mesh by Fasterix and Momentum is shown. The mesh algorithm causes difference between these meshes. Momentum mesh algorithm divides the conductor surface by a regular method. This is opposite to the Fasterix mesh algorithm. Fasterix is mesh algorithm creates an irregular form, which is sometimes a cause of inaccurate simulation results.

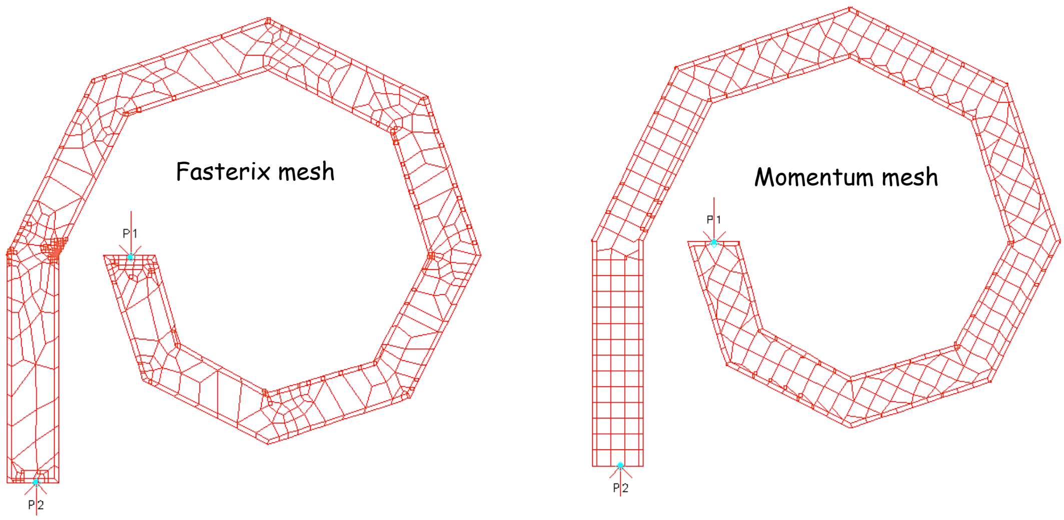


Figure 3-8 *Fasterix and Momentum mesh.*

Simulation time
The simulation time of both Fasterix and Momentum must be compared. Because of difference in algorithm between Fasterix and Momentum the simulation time also differs. The mesh generation, frequency and layout shape influence the accuracy and the duration of the simulations. This argument is used for the simulation time comparison between Fasterix and Momentum. Actually, the number of mesh elements by Fasterix is equated to a number of mesh elements generated by Momentum. This is shown in *figure 3-9*, where Fasterix 'The number of elements' is equated to sum of Momentum's 'Rectangular cells' and 'Triangular cells'. Frequency and layout shape is also equated to each other.

Inductance and quality factor value
The comparison result for inductance value are satisfying a negligible difference is noticed. For the quality factor this is not a case, as explained in c*hapter 3.5.3*.

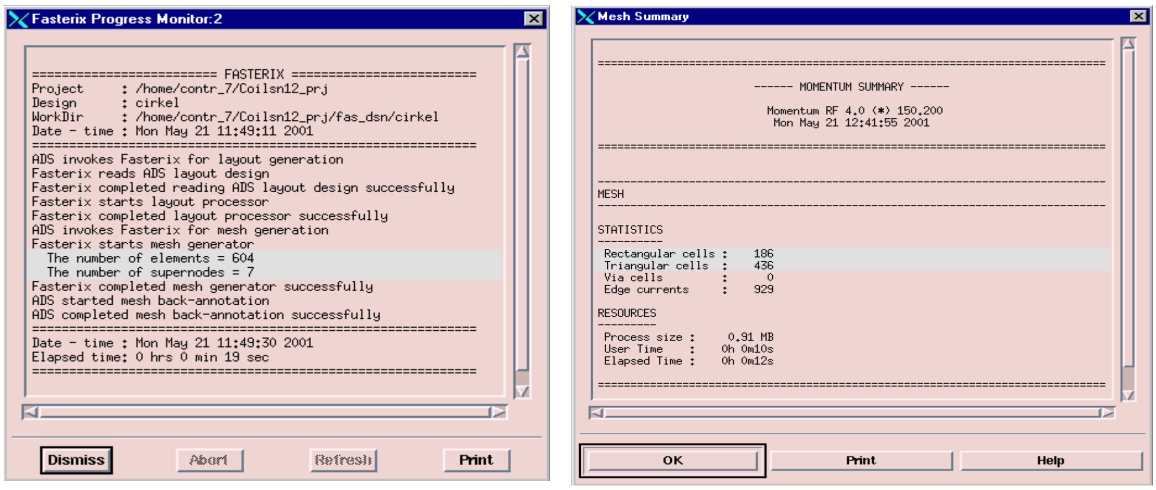


Figure 3-9 *Fasterix vs. Momentum.*

3.5 Simulation remarks

This paragraph provides several remarks on the simulation tools and coil dimensions. Remarks are mainly made on the inductance and quality factor simulation values. Influences of changing the simulation parameters and the coil dimensions on these values are examined. Especially the mesh 'Boundary element size' causes the difficulties for an accurate Fasterix simulation of quality factor.

The following parameters/simulation tools have been changed:
- *Coil dimensions*
  - *Number of turns*
  - *Variation in baseradius, trackwidth and trackspacing*
  - *Dielectric media*
  - *Vias*
- *Mesh variation*
- *Fasterix versus Momentum*

3.5.1 Coil dimensions

In this paragraph the influence of coil shape parameters on the inductance and quality factors are shown and explained by means of examples and graphics. Hexagonal, octagonal, square and circular coil shapes are used.

Number of turns
The influence of the varying dimension parameters (of the coil on PCB) on the inductance and quality factor are simulated. Hexagonal, octagonal, square and circular coil shapes are used.
The trackwidth and trackspacing are equal to 1mm. The base radius is equal to 2.5mm. The number of turn 'n' is changed from n = 1 to n = 2.

Figure 3-10 represents the inductance value of the coil-model, which is inductive in this frequency range. This is not a case if the number of turns increases to n = 2, as shown in *figure 3-11* (same frequency range). This coil model behaves inductive till the resonance frequency. The parasitic capacitance increases and thus the resonance frequency shifts to a lower frequencies (*in figure 3-11* $f_0 \approx$ 730MHz). After resonance frequency coil-model behaves as a capacitor. In both figures y-axis is represented by the inductance because of assignments objective. Naturally the y-axis represents an imaginary value divided by (2·π·f).

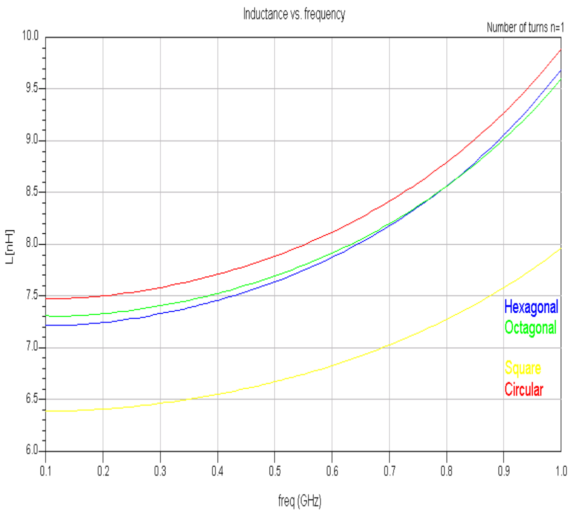


Figure 3-10 *Inductance value for n = 1.*

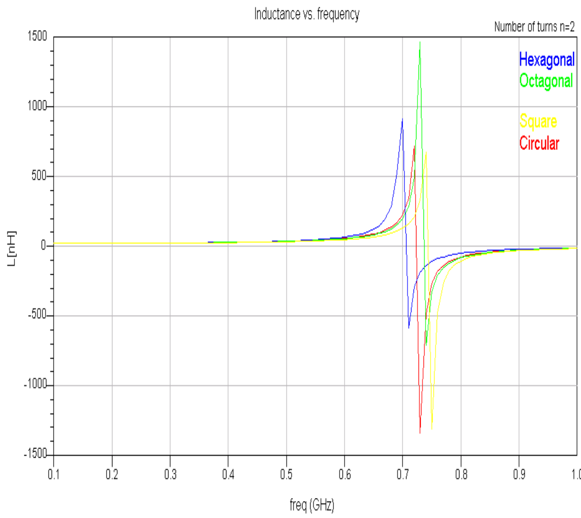


Figure 3-11 *Inductance value for n = 2.*

The quality factor in the frequency as well as the influence of the coil shape on quality factor are represented in *figure 3-12*. If the number of turns increases to n = 2, as shown in *figure 3-13 the* coil model behaves inductive until the resonance frequency. In this frequency range the quality factor is positive. After resonance frequency, the coil-model behaves as a capacitor and the quality factor becomes negative. In both figures, y-axis is represented by the quality factor of a coil because of assignments objective. Naturally y-axis represents an imaginary value divided by the real value of the coil model. Regarding the quality factor magnitude, it can be concluded that Q > 100 is rather high and must/will be confirmed with measurements. By defining the 'boundary element size' this quality factor magnitude lowers.

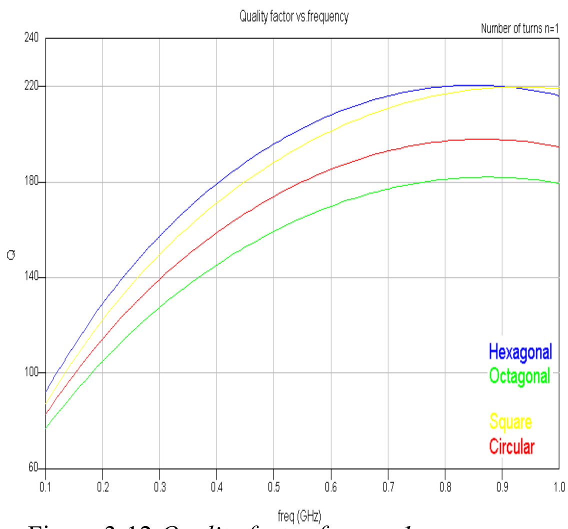


Figure 3-12 *Quality factor for n = 1.*

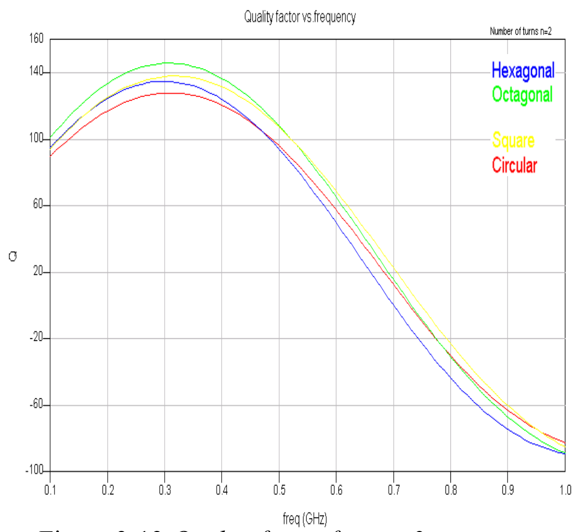


Figure 3-13 *Quality factor for n = 2.*

Variation in baseradius, trackwidth and trackspacing
The coil shape used for this simulation is octagonal and the FORTRAN-program is used to generate the Layout data of the coils. The changed dimensions are number of turns, baseradius. trackwidth and trackspacing. The values used are cording to the ones in *table 3-1.*

Name	Baseradius [mm]	Trackwidth [mm]	Trakspacing [mm]
Bas1	1	1	1
Bas2	2	1	1
Bas3	3	1	1
Trackwd2	2	2	1
Trackwd3	2	3	1
Tracksp2	2	1	2
Tracksp3	2	1	3

Table 3-1 *Used dimensions for simulation.*

Each time a simulation is done, one of the parameters is changed. The simulation is done with an octagonal coil shape on a PCB (type RO4003) and are done with an ideal groundplane.
Simulation provides general information about the quality factor and inductance value. Results of these varied parameters can be find in *Appendix A.11*.

Dielectric media
To understand the influence of the dielectric media several simulations are also done. The height and permittivity of the dielectric media are changed. The values used for height are 0.51mm and 1.8mm, for real permittivity the values are 3.38 and 4.46. Results of dielectric media on the quality factor and inductance value can be find in *Appendix A.12*.

Vias
In the application used, the coils on PCB are integrated in a circuit that consists of vias. To study the influence of these vias on the inductance value and quality factor simulations are done.
The layout used in this simulation is shown in *figure 3.14*. The coil on PCB is surrounded by other tracks, which are connected to the groundplane with vias.

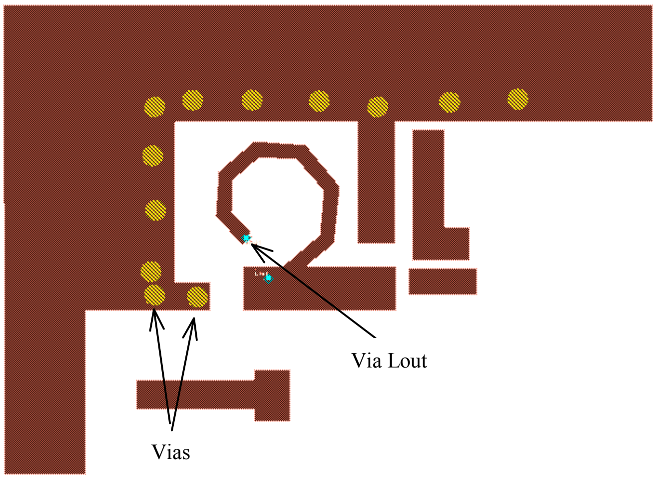


Figure 3-14 *Used layout for simulation vias.*

The simulations are done to predict the influence of vias on the inductance and quality factor of the designed PCB coil.
Three kind of simulations are done:
- No vias *(Layout without vias)*
- No via at end of coil *(Layout without 'Via Lout'*)
- With vias *(Layout with vias)*

Expectation are that the quality factor will decrease because of the extra introduced losses by the soundings tracks. The vias has no influence of the inductance value. Results confirm the expectation and they are shown in *Appendix A.13*.

3.5.2 Mesh influence

Mesh influence on the inductance value is examined for the same circular coil. It seems that Fasterix determination of the default 'boundary element size' ('b.e.s.') is not always successful. The default 'b.e.s.' value can be viewed in the '*filename.fasout'* file, which is generated by Fasterix. In *figure 3-15* an example is shown where the 'b.e.s.' is changed from default value of 0.27mm to 0.1mm. The variation in the inductance value is negligible and it is not necessary to change the default 'boundary element size' value, as shown in *figure 3-15*.

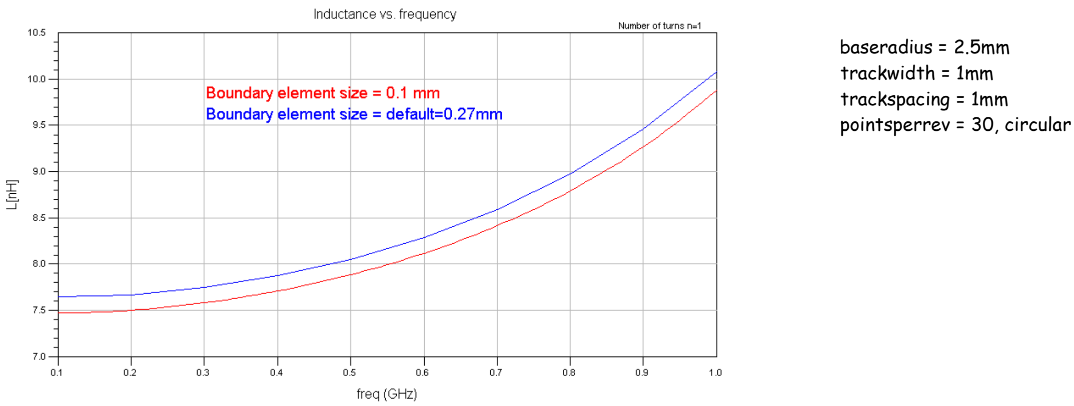


Figure 3-15 *'B.e.s.' influence on the inductance value.*

Mesh influence on the quality factor is examined for the circular coil. 'Boundary element size' has to be manually defined , because the quality factor is strongly dependant of the skin effect (and skin depth) and because the default value does not always represents a realistic b.e.s. In the '*filename.fasout'* file the default 'boundary element size' can be viewed.
In *figure 3-16* an example is shown where the b.e.s. is changed from default value of 0.27mm to 0.1mm. Enormous variation in the quality factor is noticed, as shown in *figure 3-16*.

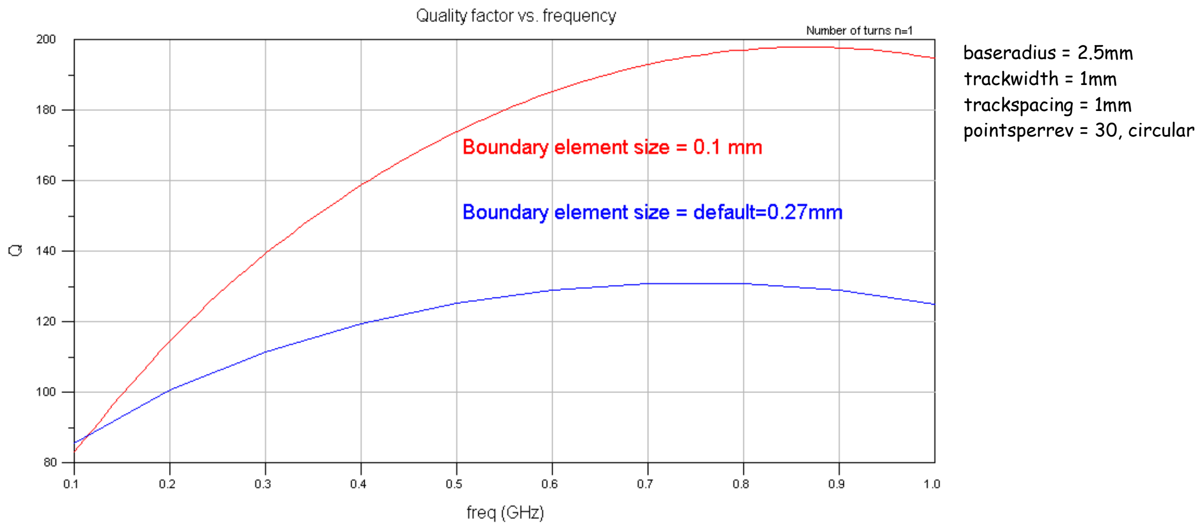


Figure 3-16 *B.e.s. influence on the quality factor.*

3.5.3 *Fasterix versus Momentum*

The number of mesh elements of Fasterix and Momentum is equated in order to make a simulation result comparison. In *figure 3-17* an example is shown whereby the Fasterix and Momentum inductance value is plotted. Deviation in the inductance value is negligible. Fasterix and Momentum give almost same simulation results.

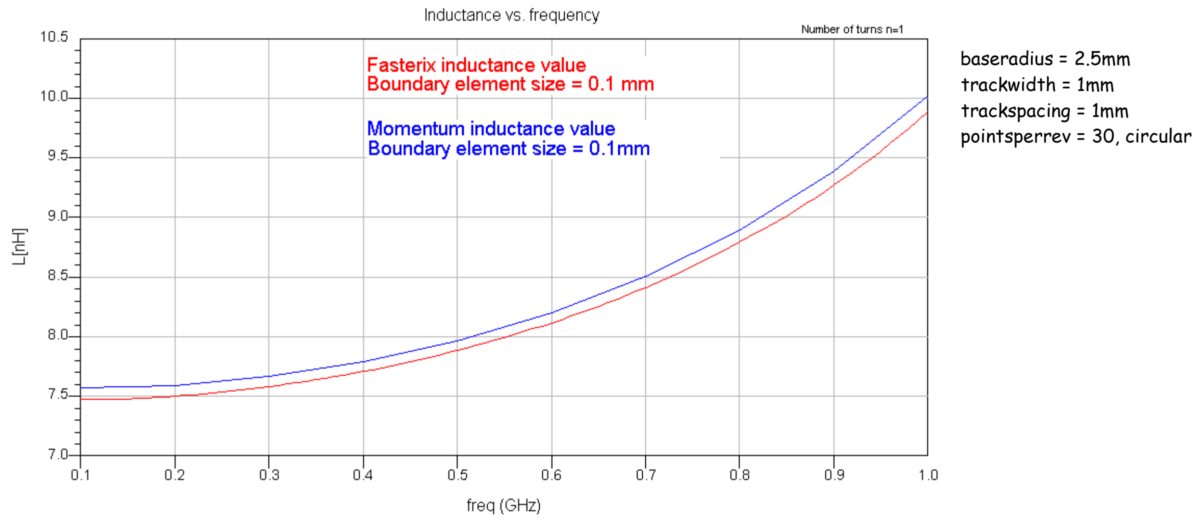


Figure 3-17 *Inductance value by Fasterix and Momentum.*

In *figure 3-18* an example is shown whereby the Fasterix and Momentum quality factor is plotted. An enormous difference in the quality factor between Fasterix and Momentum is noticed. These results will/are be confirmed with measurements.

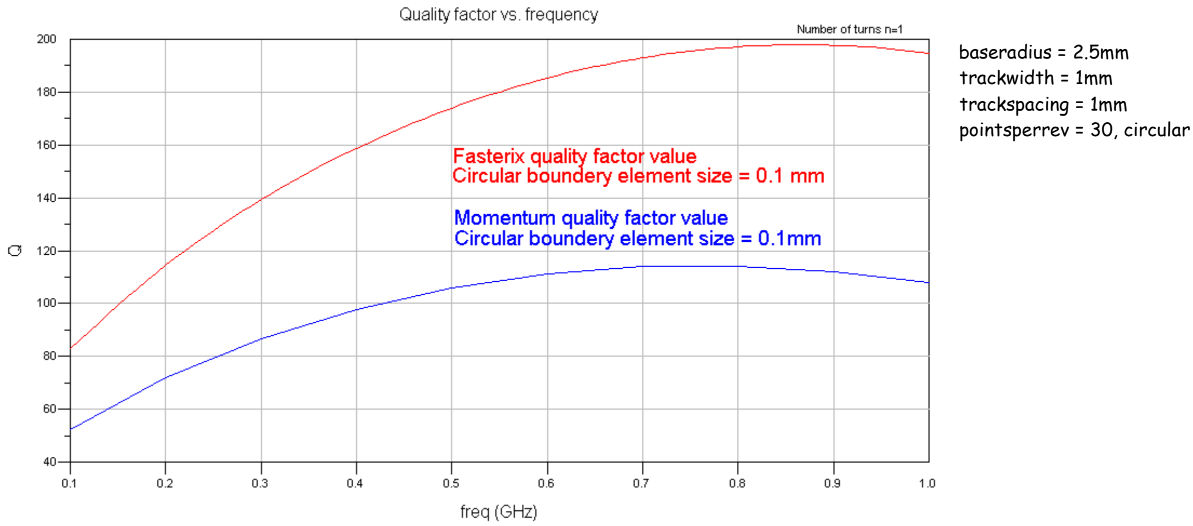


Figure 3-18 *Quality factor by Fasterix and Momentum.*

3.5.4 Simulation remarks conclusion

Simulations

The influence of changed simulation parameters/setups is examined for as well the quality factor as inductance value. Fasterix mesh size, notably ‘boundary elements size’ has a influence on the accuracy of the simulation results. Also the default value of ‘boundary elements size’ is not always realistic and must be manually defined. Full frequency range model (with all losses included) must be used for calculation of the quality factor. This is necessary because the skin effect, dielectric and radiation losses at higher frequencies had a great influence on the quality factor.

Inductance value

Inductance value can easily be manipulated by changing the coil dimensions. However for the TV-tuner application it is important that the resonance frequency is after 1GHz ($f_0 \geq$ 1GHz). The resonance frequency can be influenced by changing number of turns, track width, track spacing and by changing the dielectric media, as follows:

- Baseradius increment results in increase of the inductance value.
- Trackwidth increment results in influences the self-resonance frequency. At higher frequencies the inductance value increases faster.
- Trackspacing increment results in inductance value increases.

Influences of dielectric media:

- Permittivity increment: Influences the self-resonance frequency. At higher frequencies the inductance value increases faster.
- Height increment: Inductance value increases too.

Fasterix simulation results are compared with the Momentum simulation results. The both simulations tools provide the same inductance value behavior with a little deviation which is negligible.

Quality factor
First simulations of the quality factor provided an unrealistic values (Q>3000) beacause the High frequency range model is used. Full model makes posible to include losses and the more realistic values are simulated (Q>100). The influences of changed coil dimentions on the quality factor are also examined and are as follow:
- Baseradius increment results in more curved line and a little changes in value.
- Trackwidth results in a little influence on the quality factor.
- Trackspacing increment results in qualtity factor decrease, at higher frequencies .

Influences of dielectric media:
- Permittivity increment results in quality factor decrease.
- Height increment results in quality factor decrease.

Influence of vias:
- Decrease of quality factor when vias are used
- ‘Via Lout’ has no influence

Fasterix simulation results are compared with the Momentum simulation results. The results are not corresponding which is probably caused by difference in the mesh algorithm. However a curve behaviors are similar to each other and an approximation of the quality factor behavior is achieved.

4 Designed coils

One of the tasks is to measure coils and compare the measurement results with the simulations results. The simulation and measurement layouts are the same. This is done to have the same environment for simulation as well as measurements.

Measurements of the inductance value and quality factor are done with an LCR-meter. The coil cannot be fitted directly to the LCR-meter, therefore a connector and a microstrip are needed for an accurate measurements. The measurements are layout dependent, it is important that the influence of the design on the measurements should be reduced to a minimum.
Problems expected with a layout:

- Influence of microstrip on inductance value of a coil
- Current distortion at transition connector and microstrip
- Current distortion at transition microstrip and coil
- Influence of groundplane on quality factor and inductance
- Determine electrical length of microstrip

First simulations and measurements are done using 'Layout design One' *(figure 4-1).* These measurements and simulations are done to understand the influence of shape, trackwidth and groundplane around a coil, on the inductance value.
At first it did not seem possible to simulate the realistic quality factor. That is why the quality factor was only measured. Later on it was possible to simulate the quality factor, but 'Layout design One' influence the measurements and therefore it wasn't simulated afterwards because of the reasons mentioned in *chapter 3.4*.
Because the simulated and measured inductance value had a non-acceptable deviation, two steps were taken to find out what the cause could be:

- Another simulation program (Momentum) was used to simulate the inductance value
- Another layout was made to reduce the influence of the layout on the measurement

To reduce the influence of the layout on measurements another layout was made. With this design, 'Layout design Two' *(figure 4-2),* the influence of the number of turns on inductance value and quality factor was examined.

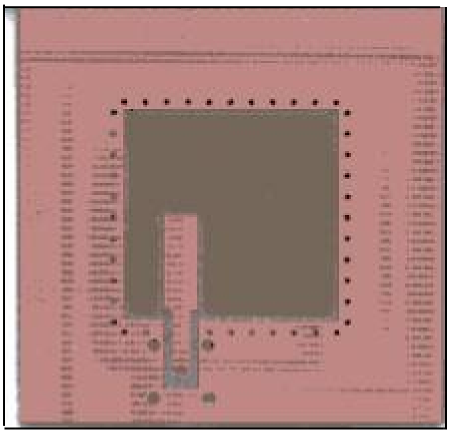


Figure 4-1 *Layout design One*

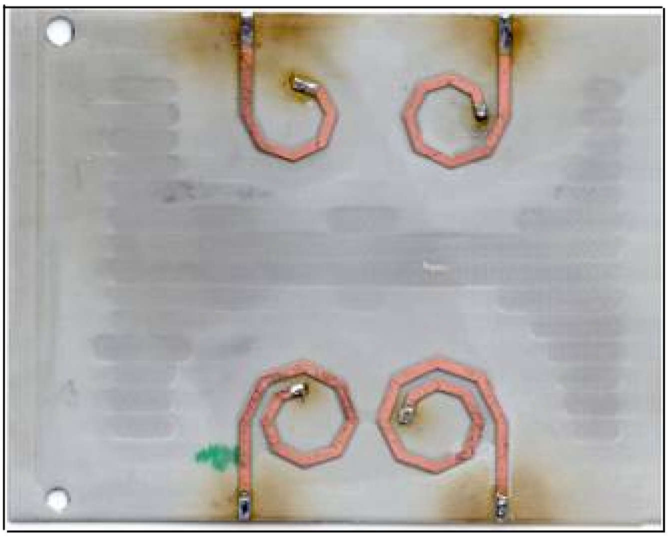


Figure 4-2 *Layout design Two*

4.1 LCR-meter measurement

The RF LCR-meter 4287A *(reference [B6])* from Agilent *(figure 4-3)* is used to measure the serial inductance, quality factor and serial resistor. Before measurements, it is necessary to calibrate and compensate the LCR-meter in order to make the measurements more accurate *(figure 4-4)*.
Calibration is done with the use of an open/ short /load. It removes the error factors between the measuring instruments and the calibration reference plane. To reduce the measurement error of high Q (low dissipation factor) the option 'Low loss capacitor' is used.
To measure the coil only, the connector and the microstrip to the coil are compensated. This removes error factors between the calibration reference plane and the compensation plane.

Figure 4-3 *LCR-meter.*

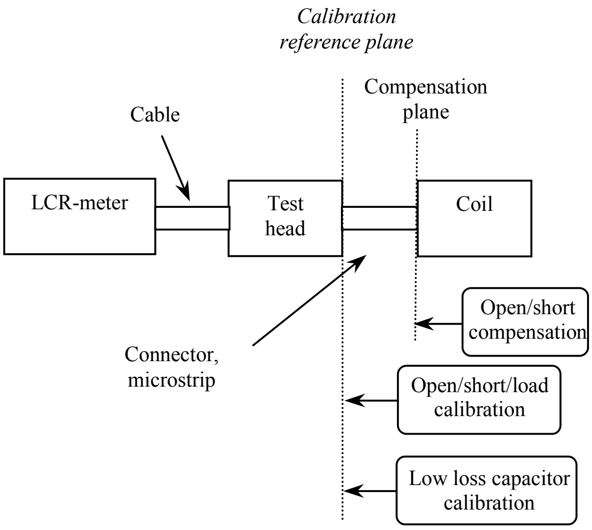


Figure 4-4 *Calibration and compensation.*

Before compensation, the electrical length of the connector and microstrip must be determined.
By connecting the short compensation track to the LCR-meter it is possible to check if the compensation is done correctly. Resistor (Rs) and capacitance (Cp) of the short track must be in the range of pico to femto.
To measure with the LCR-meter, the frequency range, power and average points are setup.

The setups are:
- Power = -13dBm
- Frequency range from 100MHz to 1GHz with an interval of 100MHz
- Average points of 32

Operation note 'Agilent Technologies 16195B Calibration Kit' describes how to calibrate and Compensate the LCR-meter *(reference [B6])*.

4.2 Layout design One

The design of 'Layout design One' *(figure 4-5)* is made to implement different kind of coils on the same layout. Some assumptions were made for this layout:

- Properties of the PCB:
  - Material: FR4
  - Metallization height: 34µm
  - Substrate thickness: 1.8mm
  - Permitivity: real 4.46
  - Loss tangent: 0.0027
  - Conductivity: $5.8e^{7}\ {}^{siemens}/_{m}$
- The PCB layout makes it possible to place different kind of coils up to an outer diameter of 10mm
- The groundplane around the coil is square with a width of 10mm
- The topside groundplane is connected with the groundplane at the bottom
- The PCB has a diameter of 40mm
- The microstrip width is calculated with Appcad 2.0 and is 3.5mm

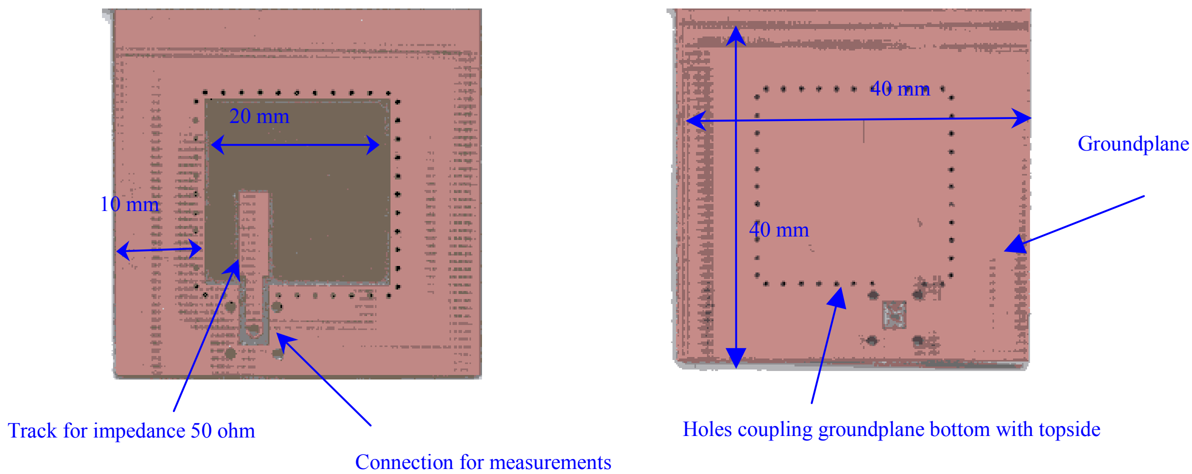


Figure 4-5 *PCB measurement layout design One.*

The inductance value of four types of coils *(table 4-1)* are examined with this layout. Sample 1 and 2 differ in shape, sample 3 in dimensions and sample 4 in groundplane.

Name	Shape coil	Remarks	L [nH]	Base radius (mm)	Trackwidth (mm)	Track spacing (mm)	Number of turns
Sample 1	Rectangular	Drawn without Fortan program	6	0	1	0.4	1
Sample 2	Octagonal		6	1	0.6	0.5	0.92
Sample 3	Octagonal		5	2	1	1	.5
Sample 4	Octagonal	No groundplane around coil	5	2	1	1	.5

Table 4-1 *Used samples with their dimensions.* * *See chapter 2.3.*

4.2.1 Results 'Layout design One'

The simulation and measurement results are compared and some differences in inductance values are noticed *(figure 4-6 and 4-7):*

- The measured inductance value is more stable than the simulated one
- An non-acceptable deviation between measurements and simulation
- The shape of a coil (octagonal, circular, hexagonal or rectangular) has almost no influence on the inductance value
- If a coil is not surrounded with a groundplane the measured value is more stable

The differences between measurement and simulation results were not acceptable and can be caused by:

- Measurements
- Chosen layout
- Simulation program

To find out the reason of the deviation, two steps are taken:

- Compare the simulation results from Fasterix with another simulation program
- Make a new layout which reduces the influence of the layout

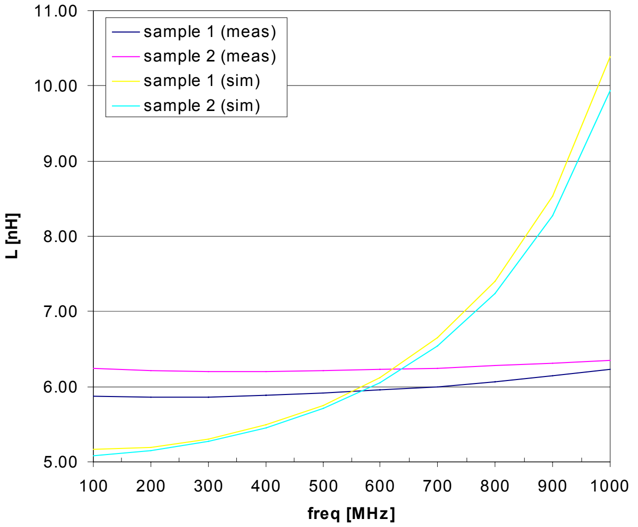


Figure 4-6 *Measurement, simulation results sample 1 & 2.*

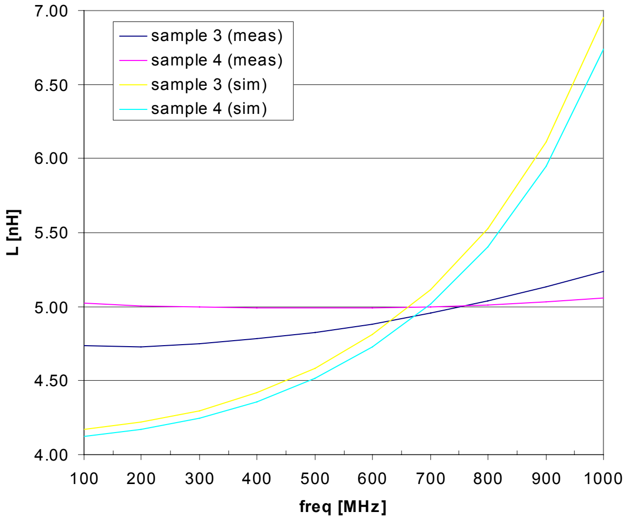


Figure 4-7 *Measurement, simulation results sample 3 & 4.*

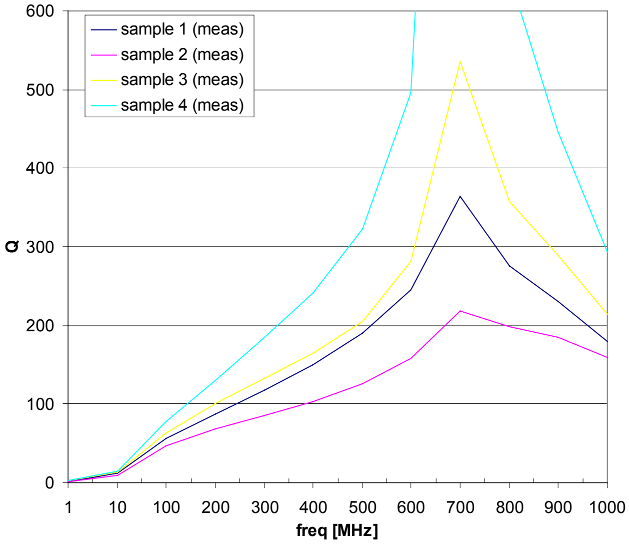


Figure 4-8 *Measurement results of quality factor.*

4.2.2 *Fasterix and Momentum comparison*

Momentum is another simulation tool used to set up and perform electromagnetic simulations on passive, planar circuits. Because the deviation between measurement and Fasterix simulation results of 'Layout design One' was not acceptable, a simulation comparison between Momentum and Fasterix is done. The results of inductance values in Momentum complied with those from Fasterix *(figure 4-9*).

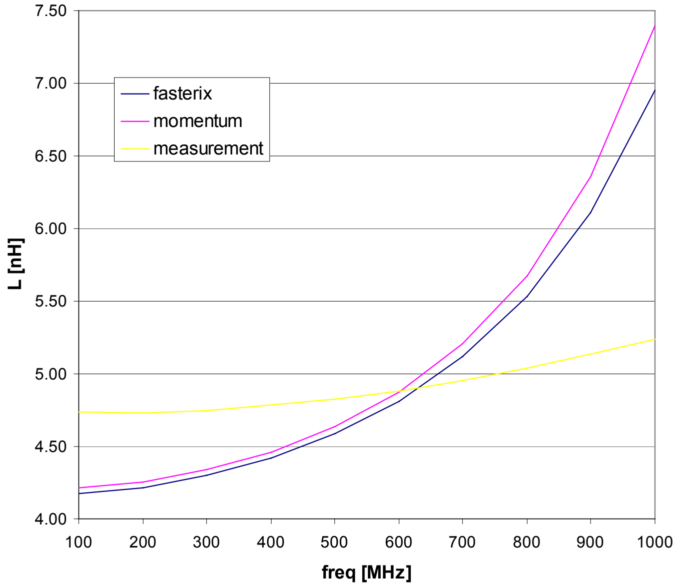


Figure 4-9 *Simulation results Fasterix and Momentum sample 3.*

With this knowledge, it can be concluded Fasterix does not cause the difference between measurement and simulation.

4.3 Layout design Two

To overcome the measurement problems with 'Layout design One' a new layout is made. It will reduce the distortions produced by the layout as well as solve the difficulties with the LCR-meter.

Some new assumptions for this design were made:
- The PCB-layout makes it possible to place different kind of coils
- PCB is thinner (0.51mm) than the used PCB in the 'Layout design One' (1.8mm)
- Properties of the PCB:
  - Material: RO4003
  - Metallization height: 34µm
  - Substrate thickness: 0.51mm
  - Permitivity: real 3.38
  - Loss tangent: 0.0027
  - Conductivity: $5.8e^{7}\ ^{siemens}/_{m}$
- Microstrip width is calculated with appcad 2.0 and is equal to 1.1463mm.
- The coil has a trackwidth similar to the microstrip width.
- The PCB only has a groundplane at the bottom.

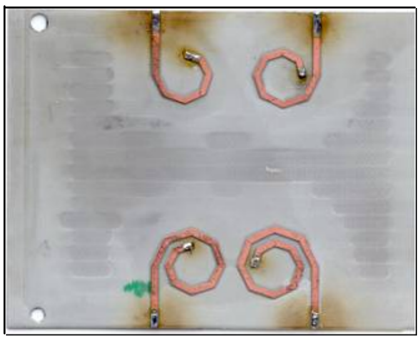


Figure 4-10 *PCB measurement layout design Two.*

4.3.1 Results 'Layout design Two'

The coils used in this measurement differ in number of turns. *Figure 4-11* shows that when the number of turns increases the inductance value also increases. At a certain point, when the number of turns increases the coil behaves like a capacitance. Also, when the number of turn increases, the inductance value increases much faster. The measured and simulated quality factor decreases if the amount of turns increases, as shown in *figure 4-12*, more results in *appendix A6-A10.*

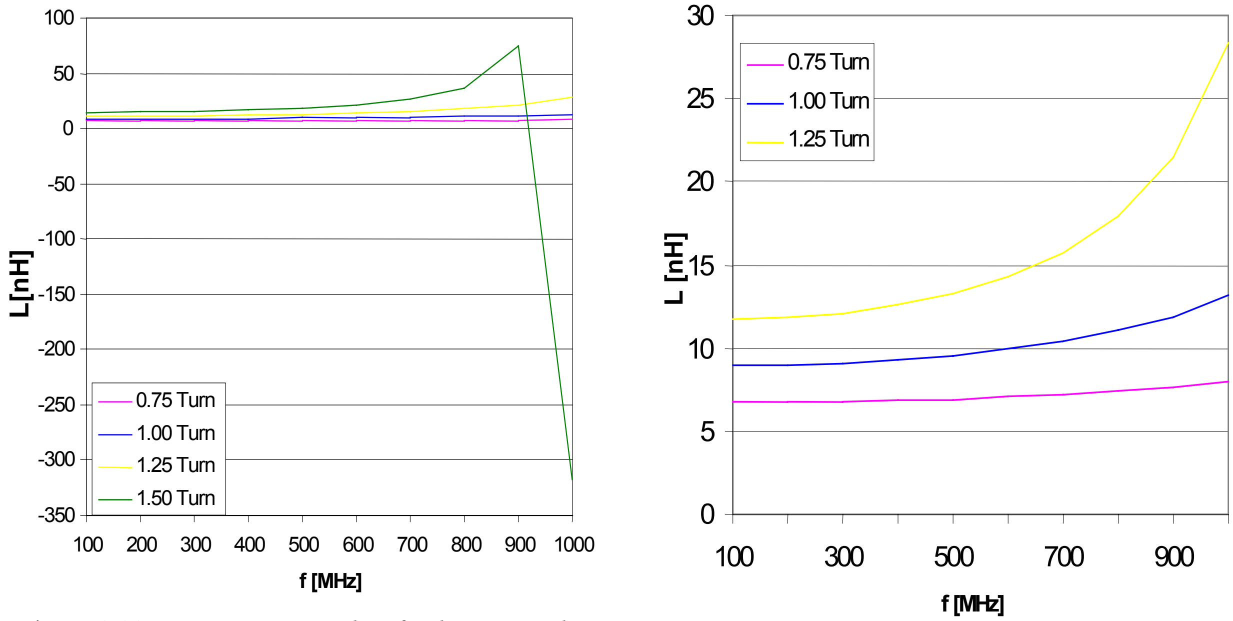


Figure 4-11 *Measurement results of inductance value.*

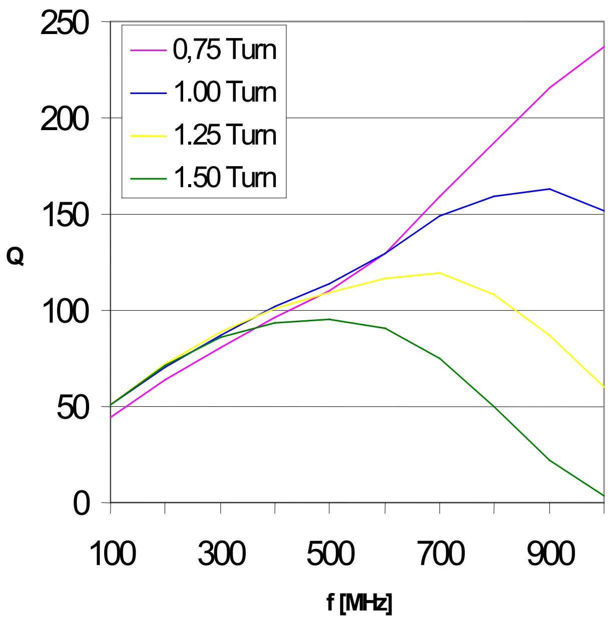


Figure 4-12 *Measurement results of quality factor.*

When a comparison is done between measurement and simulation results, it is noticed that the inductance value is almost the same *(figure 4-13),* unlike the measurements of 'Layout design One'. Rs and the quality factor *(figure 4-14 and 4-15)* notice a little deviation. This is caused because the compensation of the microstrip with LCR-meter is not done well and/ or the simulation is not quite right.
Probably it is both, because exact compensation is very difficult to do and simulation of quality factor and Rs is not accurate. Because the results are satisfactory, no new measurements are necessarily.

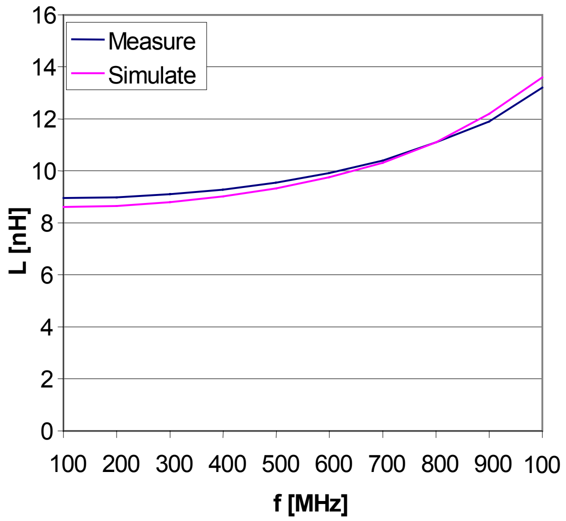


Figure 4-13 *Measurement and simulation results inductance value of coil with one turn.*

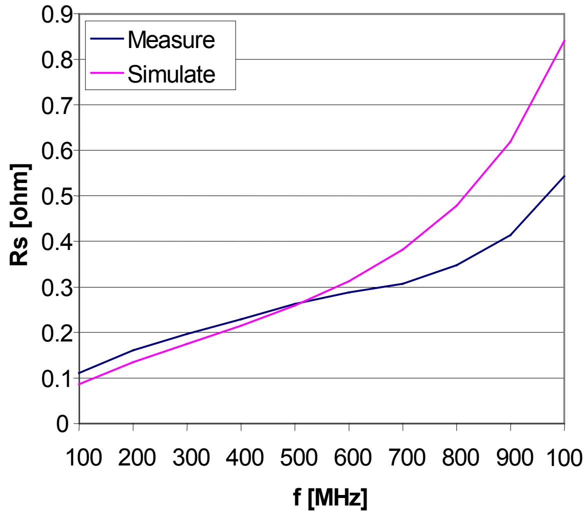


Figure 4-14 *Measurement and simulation results of resistor of coil with one turn.*

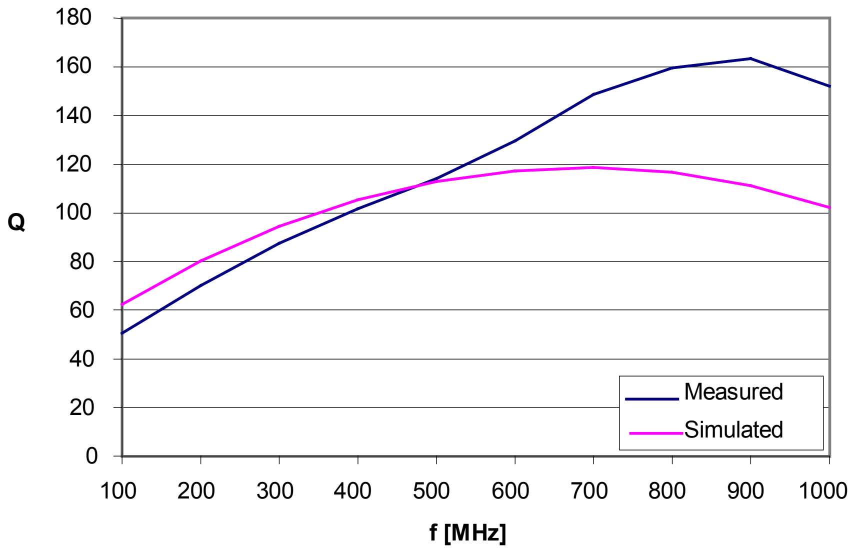


Figure 4-15 *Measurement and simulation results of quality factor of coil with one turn.*

4.4 Designed coils conclusion

If a coil is measured, it is important to use a layout that has almost no influence on the measurements. ‘Layout design One’ has an influence on the measurements.
This is caused by:

- Current distortion at end of microstrip because microstrip width is wider than coilwidth
- Microstrip is near coil. This can influence the induction of the coil.
- Connection of LCR-meter is vertical on PCB. This give reflection on the transition

These problems are solved when using ‘Layout design Two’. Measurements and simulations results has an acceptable deviation.
If the number of turns increases, the inductance value increases too. At a certain point the coil behaves like a capacitance. This is due to the self-resonance frequency of the coil, which is a unwanted behavior. When designing coils, take the frequency range used for the coil into consideration.

The spiral shape has almost no influence on the inductance value. The groundplane surrounding the coil on both top- and bottomside has almost no influence on the inductance value, but it will influence the quality factor of a coil. This is because a groundplane or other tracks nearby the coil will create a parasitic capacitance, which has a negative effect on the quality factor.

The simulation tool Fasterix can be used to simulate coils, it gives a good representation of the behavior of a PCB coil.

5 Circuit implementation

The simulation and measurements of single coil did correspond. This conclusion is necessary for the further simulations with Fasterix. The air-coils that are used in the tracking filter circuit have to be replaced with coils on PCB. Implementing a coil in a circuit will have a great influence on the quality factor. The quality factor will lower because of the extra introduced losses. This is caused by other layer material situated nearby the coil, which increase the parasitic capacitance of the inductor.

The tracking filter as shown in *figure 5-1* consist of three air-coils. In the beginning only one air-coil will be replaced by the PCB coil in order to get a good overview of the behavior of an implemented PCB coil. This is shown in *figure 5-2*. If the behavior of the tracking filter *(chapter 2.3)* complied with the conditions, the other two air-coils will be replaced by PCB coils.

Recommancations:

- The frequency range of the selectable frequency is 400MHz to 800 MHz
- Suppressing image frequency with a minimum of –40dB
- The image frequency is 5/3 * wanted frequency

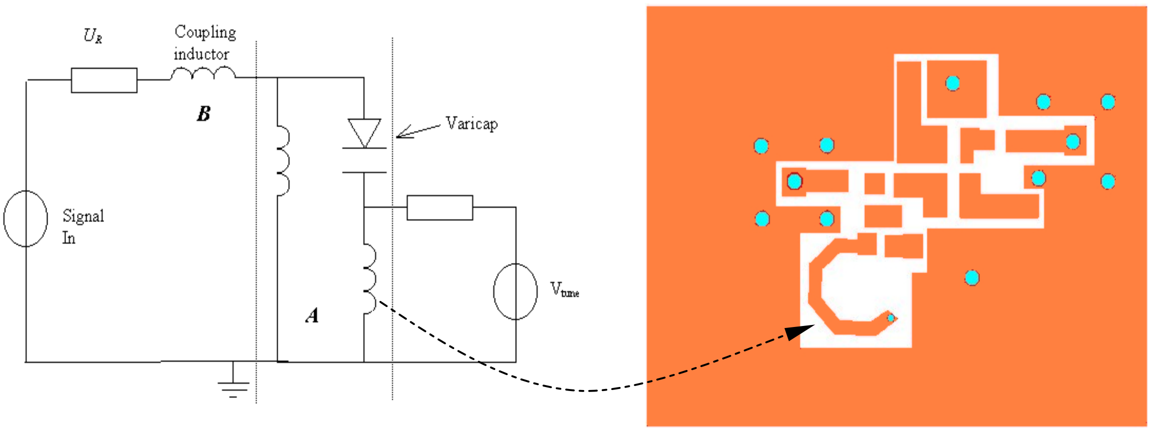


Figure 5-2 *Tracking filter with a coil on PCB.*

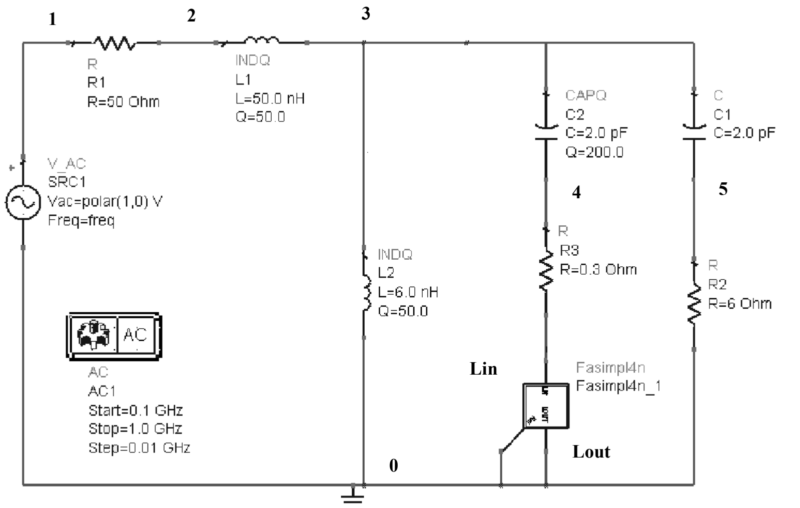
Figure 5-1 *PCB design of tracking filter.*

5.1 Simulation

Simulations of the PCB design, shown in *figure 5-2*, are done with Fasterix and Momentum.
First, simulation have been done with the PCB design (with a unideal groundplane). The generation of the coil model was a time costing event. Fasterix generation lasted about 35 minutes and Momentum needed 3hour and 30minutes. This result motivates to use the Fasterix simulation tool.

The generated Fasterix coil model is now used in ADS-schematics and a circuit is build. Analog simulation in ADS turned out to be a very time costing event. After a whole work day of simulating the simulation was still not finished. This is caused because the ADS reading algorithm of the Fasterix coil model is not optimal. This big disadvantage of ADS simulation tools is only for large Fasterix files (>30Mb). By using the Pstar simulator, which reads large Fasterix files in much shorter time the analog simulations can be done.

For the generation of pstar-file the circuit has to be defined, by writing the analysis-file. The Fasterix coil model is connected to other tracking filter components, as shown in *figure 5-3,* according the schematics as well as with analysis-file. Fasterix is now able to generate the pstar-file. Pstar simulation can be started, out of Fasterix or directly in Pstar.




```
circuit;

E_1  (1,0) sw(1,0);
R_1  (1,2) 50;
L_1  (2,3) 50n;
L_2  (3,0) 6n;
C_1  (3,4) 2p;
R_3  (4,"Lin") 0.3;
S_1  ("Lout",0);
C_2  (3,5) 2p;
R_4  (5,0) 6;
end;

ac;
  f = as(0.1g, 1g, 0.1g);
  transfer=db(vn(3));
  file: transfer;
end;
run;
```

Figure 5-*3 Schematics of tracking filter circuit and the matching analysis-file.*

5.2 Measurements

Even though the simulations are still not done properly, the tracking filter layout (with the PCB coil) is made. For measurements of the layout a network analyzer is used. The tracking filter should behave according *figure 5-4* and the named condition must be achieved. The measurement results are shown in *figure 5-5*. The results are not completely corresponding with the expected/needed conditions.

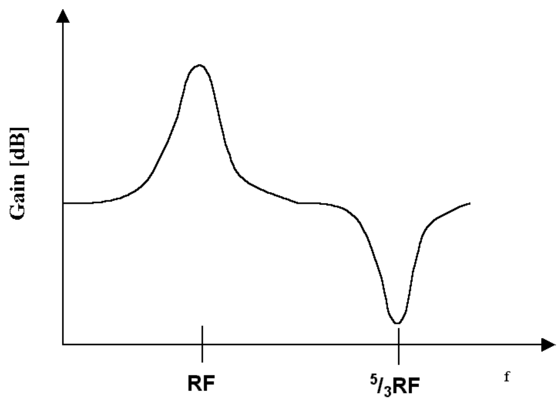


Figure 5-4 *Wanted tracking filter behavior.*

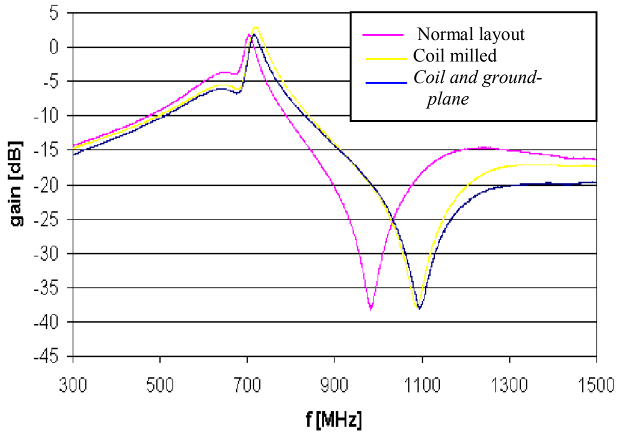


Figure 5-5 *Measured tracking filter behavior.*

Almost a suppression of the image frequency of –40dB is feasible. The measured behavior of the tracking filter correspond with the theoretical behavior of the tracking filter. The relation between wanted frequency and image frequency was not corresponding to the conditions.

Because only one PCB coil is used in this layout, a new measurement is done with a layout '*Two*' *(figure 5-6)* with two implemented coils. The air-coils of 6nH and 4nH are replaced
The results of the measurement *(figure 5-7)* of this layout '*Two*' where very satisfing. A suppression of almost –50dB was feasible. Layout '*Two*' was still to large.

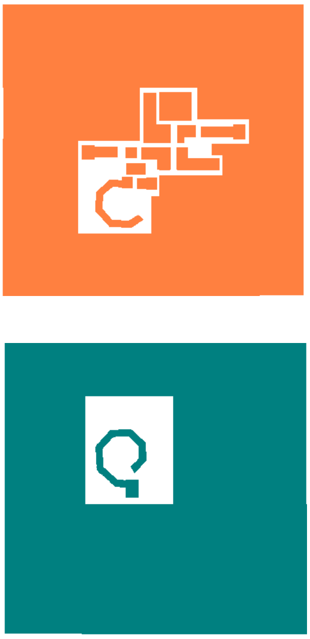


Figure 5-7 *Layout 'Two' of measurement with two coils. Top- and bottomlayer (real scale).*

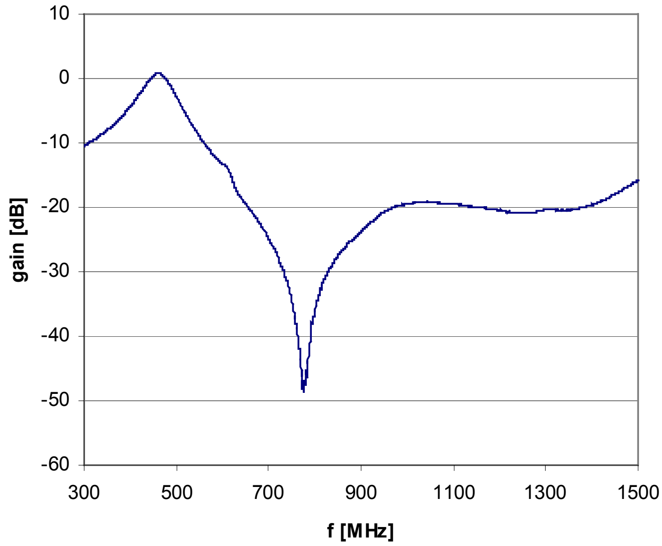


Figure 5-6 *Measurements result of layout 'Two'*

To decrease the layout, layout '*Three*' (figure 5-8) was made. A suppression of –50dB with a tuning voltage of 5V was feasible *(figure 5-9)*. The relation between the wanted and image frequency, and frequency range was still not according the requirements.

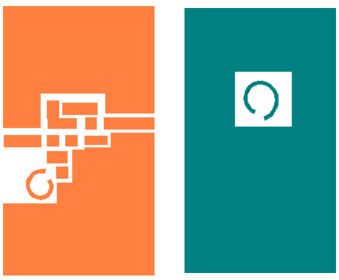


Figure 5-8 *Layout 'Three' of measurement with two coils. Top- and bottomlayer (real scale)*

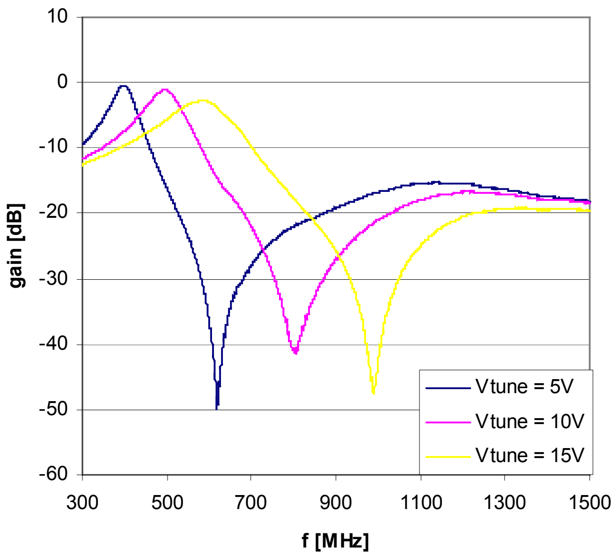


Figure 5-9 *Measurements result of layout 'Three'.*

Realising the relation between wanted and image frequency, and frequency range layout '*Four'* was made. The values of the PCB coils decrease to 5nH and 2.5nH. No measurements where done at the moment this report was published.

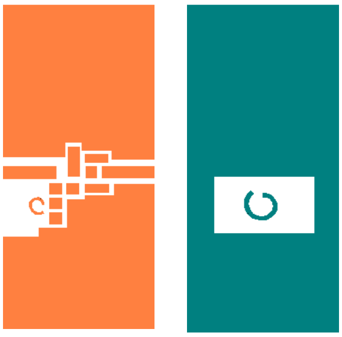


Figure 5-10 *Layout 'Four' of measurement with two coils. Top- and bottom-layer (real scale)*

5.3 Circuit implementation conclusion

Simulation

For the simulation of PCB coil, in the tracking filter circuit, the generation coil model should be done by Fasterix. This in order to prevent a time costing simulation with Momentum.

For the analog simulation it is necessary to observe the size of the Fasterix coil model file. If this file becomes rather large (>30MB) the analog simulation should not be done in ADS but in Pstar. ADS algorithm of reading the Fasterix coil model file is not optimal and thus is time costing.

For the Pstar simulations the analysis-file must be defined (filename.analysis). Fasterix uses this file for the generation of the pstar-file (filename.pstar). Generated pstar-file includes now the Fasterix coil model and the analog simulation can be done.

Measurements

Tracking filter PCB-layout is made and measured. One air-coil is replaced by the PCB coil and the tracking filter behavior is measured. The measurements are done with the network analyzer, but are not completely corresponding with the expected/needed results. The suppression of the image frequency of –40dB or more is feasible. By fine tuning the circuit and PCB coils it conceivable to achieve the recommandations of the tracking filter.

6 Conclusions and recommendations

6.1 Conclusions

Simulation

Simulation and measurements of coils on PCB are done in order to find out if it is possible to reach the needed quality factor and inductance value. Simulations are mainly done by recently implemented Fasterix-ADS interface. Fasterix-ADS interface added more positive advantages to Fasterix user interface. This regarding the visual possibility of creating and drawing a layout. The Momentum simulations are also done, which confirmed the Fasterix results of inductance value, but gave rather big deviation in the quality factor value. This deviation is caused by difference in the mesh algorithm. Mesh has a great influence on the accuracy of the simulation results. Fasterix mesh size, notably 'boundary elements size' must be manually defined because the determination of default value, for planar kind of PCB coils causes the difficulties for Fasterix mesh generator. Full frequency range model with all losses included must be used for calculation of the quality factor. This is necessary because the skin effect, dielectric and radiation losses at higher frequencies had a great influence on the quality factor.

Measurements

Measurement layouts of simulated single coils are made. Two layouts are made, 'Layout design one' and 'Layout design two'. 'Layout design one' did not corresponded with the simulation results, because the negative influences of current distortion at end of microstrip, connection of LCR-meter and electrical length of microstrip. In 'Layout design two' these negative influences are reduced, which resulted in a negligible deviation between simulation and measurements results.

Implementation

Finally designed coils are implemented in the PCB layout of a tracking filter. Simulation of this PCB layout is a very time costing event. Measurements of tracking filter (with the implemented coil) are done, which resulted in a attenuation of –40dB are even more is feasible. The tracking filter with implemented coils function like a tracking filter. By fine tuning the circuit and PCB coils it is conceivable to achieve the recommandations of the tracking filter.

. This is not enough and is caused due to the low quality factor. The study of the coil implementation is in an early stage and by continuing the research it will probably result in a satisfying function of the PCB coil. The research of implemented coil in a circuit is still in progress.

Inductance value

In order to reach the needed inductance value (in range from 1nH to 50nH) several simulations are done. 'Layout design two' confirmed the simulation results and thus the correctness of Fasterix and Momentum simulations. By changing the dimensions of coil on PCB the inductance value can be influenced and changed. Also the influence of changing the simulation parameters, such as the mesh size, maximal frequency and frequency models (High, Full) are studied. These parameters had a negligible influence on the inductance value. All steps are reported and can be used as manual for continuing the PCB coil design.

Quality factor

In order to reach the needed quality factor (Q>20) several simulations are done. For the simulation of the quality factor it is necessary that the right simulation parameters are defined. This regarding the mesh size, frequency model (High, Full), substrate loss tangent, surroundings etc. Full frequency model has to be used because the losses such as skin effect, dielectric and radiation have a direct influence on the quality factor. Also the mesh size (Boundary elements size) has to be defined for an accurate calculation of the skin effect. For a single coil a rather high quality factor is reached (Q>100), which is confirmed with the simulations as well as with measurements. However the implementation of the coil into a tracking filter circuit results in enormous decrement of the quality factor. This is confirmed by the measurements as well as with the simulations. Further research the quality factor of implemented PCB coil must be done.

6.2 Recommendations

Simulation

Simulation of PCB coil can be time costing if the setups are not done properly. This documents represents all necessary setups that will lead to accurate Fasterix simulation results.

Preparation of the layout data in the ADS-Layout window is limited considering the spiral coils shapes. This is a reason that for a design of the layout data the Fortran program must be used. This program allows the user to crate a complex coil shape in short time.

Considering the simulations of designed coil it is important that the Full frequency range model is used because of the possibility of including the losses. Also an important simulation parameters is the mesh. Fasterix mesh algorithm is not always optimal for irregular coil shapes and if not observed can lead to system crash. Thus the number of mesh elements must be observed and if it exceeds the expected value the coil layout has to be redrawn or rotated. Determination of default value of 'boundary elements size' must be manually defined. 'Boundary elements size' defines the skin depth and thus the accuracy of the quality factor value. However if this value is equated to the skin depth it will possibly lead to system crash. 'Boundary element size' should have the value of one tenth of the track width which will prevent the unwanted Fasterix behavior or possible system crash. Changes in the Fasterix mesh algorithm will probably solve this problem.

Momentum simulation tool can be useful for the comparison of the Fasterix simulation results. However if the layout size increases Momentum needs more simulation time then Fasterix. In case of implementation of PCB coil in tracking filter layout Fasterix generated a large files (filesize > 30Mb). Because of non optimal ADS-Schematic algorithm for reading the Fasterix file, it costs to much time to simulate the analog behavior of the coil model. In this cases the analog simulation of the Fasterix coil model should be done in Pstar.

Measurements

For the corresponding simulation and measurements results the correct layout design is necessary. The width of the impedance track should be equal to the width of the coil track. This will prevent unwanted current distortion. Also the correct calibration of the LCR-meter is necessary.

Implementation

Layout design should be as optimal as possible. This regarding the parasitic capacitance and other losses. This can be achieved by solid connection to the groundplane and small distance between component/tracks and the groundplane.

Inductance value

Inductance value can easily be realized. This document provides the insight into the inductance value behavior versus the changing of coil dimensions.

Quality factor

Implemented coil results in a lower quality factor. Main idea is to optimise the PCD design, meaning that the parasitic capacitance is as low as possible. In order to increase quality factor the other possibilities must be studied. For example, removing the groundplane underneath the coil can result in higher quality factor. Possibility of two parallel coils on PCB and its influence on the quality factor has to be examined. For all these possibility the Fasterix simulation tool can be used, whereby the Full frequency range (all losses included) is necessary for a realistic approximation of quality factor.

References

[I] = Internet Sites

[I1] *http://pww.natlab.research.philips.com:25138*, Integrated Transceivers

[I2] *http://pww.natlab.research.philips.com:25138,* ED&T organization/information

[I3] *http://pww.natlab.research.philips.com:25138/AnalogueSimulation/index.html,* Informative documents about Fastrix simulation tool

[I4] *http://pww.natlab.research.philips.com:25138/AnalogueSimulation/index.html,* Fastrix User Manual

[I5] *http://pww.natlab.research.philips.com:25138/AnalogueSimulation/index.html,* Fastrix Tutorial

[I6] *http://www.dct.com/~mulitplx/wireless/rf_design/strip.cgi,* Calculation microstrip

[I7] *http://www.emclab.umr.edu/pcbtlc/microstrip.html,* Calculation microstrip

[B] = Books/Documentation

[B1] *Elektrostatica en Magnetisme*

[B2] *Improved designs for thin film inductor*, Douglas C. Giancolliz, 1993, ISBN 90 395 0395 8

[B3] *On-chip Spiral Inductors with Patterned Ground Shilds for Si-Based Rf IC's*, Frank S. Brukett

[B4] *Basic properties of RF circuits,* C. Patrick Yue, G. Dolmans

[B5] *Karakterisering van 10GHz en 17GHz radiokanalen met behulp van microstrip antennes,* G. Verstraeten, Operation Manual , *Agilent 4287A RF LCR Meter*

[B6] *Elektrotechnische Materialen voor HTO,*A.A.P.C. Kockx, O.G.M. Baars, C.J. van Oosterwijk, A. Reitsma, 1994, First Edition, ISBN 90-236-0748-1

[B7] *Elektrische Netwerken,* Ir. P. Holmes, 1992-1994, Second Edition, ISBN 90-6789-359-5

[B8] *Characterization of Spiral Inductors on Silicon and Glass,* L.F. Tiemeijer and R.J. Havens, Nat.lab. Technical Note 135/97

[B9] *High-Q On-Wafer Spiral Inductors Measurements,* Federico Bruccoleri, Nat.lab. Technical Note 75/99

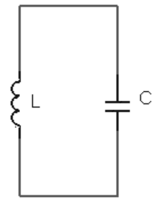
[B10] *On-chip high-Q passive devices,* G. Dolmans, Nat.lab. Technical Note 74/99

[B11] *Hoogfrequentversterker* ROC westerschelde, EEC6140M.INF

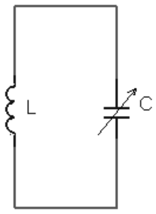
A Appendix

A.1 Short formulas

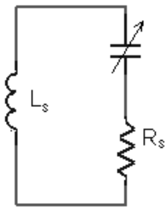
This appendix includes some derived formulas that can be used for a fast calculation of quality factor, bandwidth, resonance frequency and shunt/serial transformation parameters.



$$\omega_0 \approx \frac{1}{\sqrt{L\ C}} \qquad f_0 \approx \frac{1}{2\ \pi\ \sqrt{L\ C}} \qquad B \approx \frac{\omega_0}{Q_0}$$



$$\omega_0 \therefore \frac{1}{\sqrt{C}} \qquad C \therefore \frac{1}{{\omega_0}^2}$$

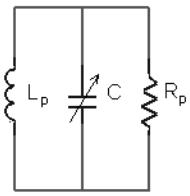


R_s=constant

$$Q_0 \approx \frac{\omega_0\ L_s}{R_s} \qquad Q_0 \therefore \omega_0$$

$$B \approx \frac{\omega_0}{Q_0}$$

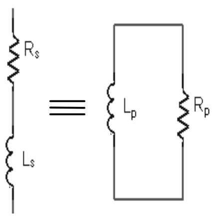
B = constant



R_p = constant

$$Q_0 \approx \frac{R_p}{\omega_0\ L_p} \qquad Q_0 \therefore \frac{1}{\omega_0}$$

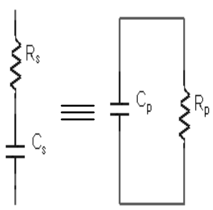
$$B \approx \frac{\omega_0}{Q_0} \qquad B \therefore {\omega_0}^2$$



Q >>1

$$Q_0{}^2 \approx \frac{R_p}{R_s} \qquad R_p = \frac{\omega^2\ L_s{}^2}{R_s{}^2} R_s \qquad R_p \therefore \omega^2$$

$$L_s \approx L_p$$



$$C_s \approx C_p$$

$$Q_0{}^2 \approx \frac{R_p}{R_s} \qquad R_p = \frac{R_s}{\omega^2\ C_s{}^2\ R_s{}^2} \qquad R_p \therefore \frac{1}{\omega^2}$$

A.2 Inductance formulas

Modified Wheeler expression (only for circular coils):

$$L = \frac{0.8 \cdot a^2 \cdot n^2}{6 \cdot a + 10 \cdot \left(\frac{d_{out} - d_{in}}{2} \right)} \quad (nH) \qquad \textbf{[A2-1]}$$

where: n = number of turns
d_{out} = Outer diameter [mils]
d_{in} = inner diameter [mils]
$a = \frac{1}{4}\,(d_{out} + d_{in})$ [mils]

Modified Wheeler expression:

$$L = K_1 \;\mu_0\; \frac{n^2 \; d_{avg}}{1 + K_2 \;\rho} \quad (H) \qquad \textbf{[A2-2]}$$

where: $\mu_0 = 4 \;\pi\; 10^{-7}$
n = number of turns
d_{out} = outer diameter [m]
d_{in} = inner diameter [m]
$d_{avg} = \frac{1}{2}(d_{out} + d_{in})$ [m]
$\rho = \frac{d_{out} - d_{in}}{d_{out} + d_{in}}$ [m]

Layout	K_1	K_2
Square	2.34	2.75
Hexagonal	2.33	3.82
Octagonal	2.25	3.55

Table A2-1 *Coefficients for Modified Wheeler Expression*

Geometric mean distance (GMD):

$$L_{gmd} = \frac{\mu \;n^2 \;d_{avg} \;c_1}{2}\left(\ln(c_2 / \rho) + c_3\rho + c_4\rho^2\right) \quad (H) \qquad \textbf{[A2-3]}$$

where: $\mu_0 = 4 \;\pi\; 10^{-7}$
n = number of turns
d_{out} = outer diameter [m]
d_{in} = inner diameter [m]
$d_{avg} = \frac{1}{2}(d_{out} + d_{in})$ [m]
$\rho = \frac{d_{out} - d_{in}}{d_{out} + d_{in}}$ [m]

Layout	c_1	c_2	c_3	c_4
Square	1.27	2.07	0.18	0.13
Hexagonal	1.09	2.23	0.00	0.17
Octagonal	1.07	2.29	0.00	0.19
Circle	1.00	2.46	0.00	0.20

Table A2-2 *Coefficients for Current Sheet Expression*

Data fitted Monomial Expression:

$$L_{mon} = \beta \; d_{out}^{\alpha_1} \; \omega^{\alpha_2} \; d_{avg}^{\alpha_3} \; n^{\alpha_4} \; s^{\alpha_5}$$

where: n = number of turns
d_{out} = outer diameter [m]
d_{in} = inner diameter [m]
ω = trackwidth [m]
s = trackspacing [m]
$d_{avg} = \frac{1}{2}(d_{out} + d_{in})$ [m]

Layout	β	α_1 (d_{out})	α_2 (ω)	α_3 (d_{avg})	α_4 (n)	α_5 (s)
Square	$1.62 \,.\, 10^{-3}$	-1.21	-0.147	2.40	1.78	-0.030
Hexagonal	$1.28 \,.\, 10^{-3}$	-1.24	-0.174	2.47	1.77	-0.049
Octagonal	$1.33 \,.\, 10^{-3}$	-1.21	-0.163	2.43	1.75	-0.049

Table A2-3 *Coefficients for Data Fitted Monomial Expression.*

Some inaccurate equations:
15 - 20%

Voorman: $$L_{voo} = 10^{-3} \; n^2 \; d_{avg}$$ **[A2-5]**

Dill: $$L_{dil} = 8.5 \; 10^{-4} \; n^{5/3} \; d_{avg}$$ **[A2-6]**

Bryan: $$L_{bry} = 2.41 \cdot 10^{-3} \cdot n^{5/3} \cdot d_{avg} \cdot \log\left(4/\rho \right)$$ **[A2-7]**

Ronkanien: $$L_{ron} = 1.5 \; \mu_0 \; n^2 \; e^{-3.7(n-1)(\omega+s)/d_{out}}$$ **[A2-8]**

Crols: $$L_{cro} = 1.3 \cdot 10^{-4} \cdot \left(d_{out}^3 / \omega^2 \right) \; \eta_a^{5/3} \; \eta_\omega^{1/4}$$ **[A2-9]**

$$L_{sp} = 1.98 \cdot a \cdot n^{2.13} \left(\frac{a}{b_s} \right)^{0.16} \cdot \left(0.903 + \log \frac{a}{b_s} \right) \qquad (nH)$$ **[A2-10]**

$a=(d_{out}-d_{in})/4$
b_s width of the coil turns $b_s = (d_{out}-d_{in})/2$

strip conductor free space:

$$L \approx 0.2 \left(\ln \frac{l}{w+s} + 1.19 + 0.22 \frac{w+s}{l} \right) \qquad (\mu H / m)$$ **[A2-11]**

above groundplane

$L \approx k \;\; L_{freespace}$ k=0.57-0.135ln(w/h)

There are two kind of modified Wheeler formulas [A2-1] and [A2-2]. The idea is to get one modified Wheeler expression because formula [2] uses ‘K1 and K2’, formula [1] is converted into formula [2]. Formula [1] is only for circular coils with the diameter in mils and expressed in nH. Formula [2] is for hexagonal, octagonal and square shaped coils with the diameter in meters and expressed in H.

Formula 1	Formula 2
$L = \frac{0.8 \cdot a^2 \cdot n^2}{6 \cdot a + 10 \cdot \left(\frac{d_{out} - d_{in}}{2} \right)} \quad (nH)$	$L = K_1 \ \mu_0 \ \frac{n^2 \ d_{avg}}{1 + K_2 \ \rho} \quad (H)$

So:

$d_{avg} = \frac{1}{2} \ (d_{out} + d_{in})$

$a = \frac{1}{4} \ (d_{out} + d_{in})$

$a = \frac{1}{2} \ d_{avg}$

$$L = \frac{0.8 \cdot \left(\frac{1}{2} \cdot d_{avg}\right)^2 \cdot n^2}{6 \cdot \frac{1}{2} \cdot d_{avg} + 10 \cdot \left(\frac{d_{out} - d_{in}}{2} \right)} \qquad \left(: \frac{1}{2} \right)$$

$$L = \frac{0.4 \ d_{avg}{}^2 \ n^2}{6 \ d_{avg} + 10 \ d_{out} - d_{in}} \qquad (: d_{avg})$$

$$L = \frac{0.4 \ d_{avg} \ n^2}{6 + 10 \ 2 \ \frac{d_{out} - d_{in}}{d_{out} + d_{in}}} \qquad \left(\rho = \frac{d_{out} - d_{in}}{d_{out} + d_{in}} \right)$$

$$L = \frac{0.4 \ d_{avg} \ n^2}{6 + 20 \ \rho} \qquad (: 6)$$

$$L = \frac{\frac{1}{15} \ d_{avg} \ n^2}{1 + 3\frac{1}{3} \ \rho}$$

Now formula [1] is almost converted into formula [2].

Because: $K_1 \ \mu_0 \ factor_m \ (m) = \frac{1}{15} \ 10^{-9} \ (mils)$ $factor_m$ is necessary to convert mils into meters. This $factor_m = 2.54 \ 10^{-5}$

$K_1 = 2.09 \quad and \quad K_2 = 3\frac{1}{3}$

A.3 Something about capacitors

A.3.1 DC-behavior

In the schematics below is the capacitor connected to a DC-source. At the moment that the switch S is closed the current I_C and the voltage U_C behave as given in *formula [A5-1]*.

At the moment when current reaches the maximum value $I_{C,\max} = \frac{U_b}{R}$ the voltage U_L drops down to a zero and the coil functions as a shortcut as shown in *figure3-1*.

$$U_C = U_b \cdot \left(1 - e^{\frac{-t}{RC}}\right) \qquad I_C = \frac{U_b}{R} \cdot \left(e^{\frac{-t}{RC}}\right) \qquad \textbf{[A3-1]}$$

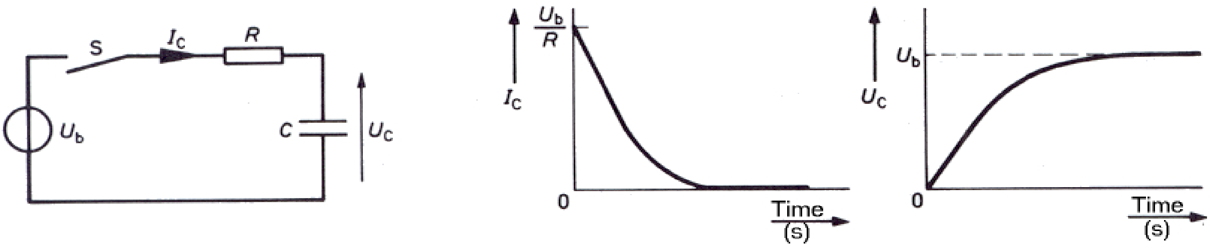


Figure A3-1 *DC-behavior of the currant and voltage across a capacitor.*

A.3.2 AC-behavior

In the schematics below is the capacitor connected to a AC-source. If the AC-source a sinus is then it appears that the i_C and u_C are also sinus signals with the phase difference of 90 degrees *(see figure A3-2).*

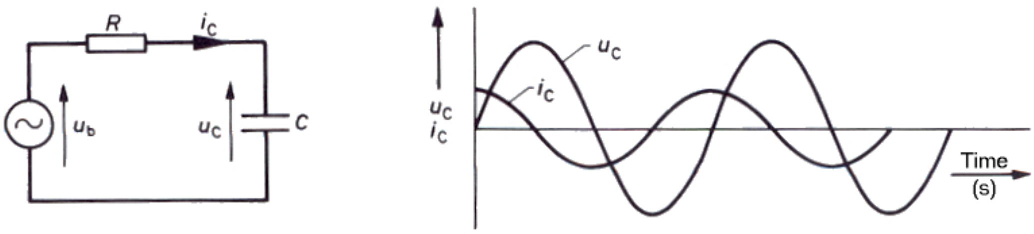


Figure A5-2 *AC-behavior of the current and voltage across a capacitor.*

$$Z = \frac{1}{\omega \; C} \qquad i_C = C \; \frac{du_C}{dt} \qquad \textbf{[A3-2]}$$

A.3.3 Not an ideal capacitance

An ideal capacitor consists of two conductors without any losses and a dielectric media with infinite impedance, thus the ideal capacitance.
In practice a capacitor always has a not wanted behavior which is caused by the parasitic inductance and the internal resistance of the dread, as shown in *figure A3-3*.

Those values are mostly very small and thus negligible and the resonance frequency can be approached by

$$f_0 \approx \frac{1}{2\ \pi\ \sqrt{L\ C}}$$

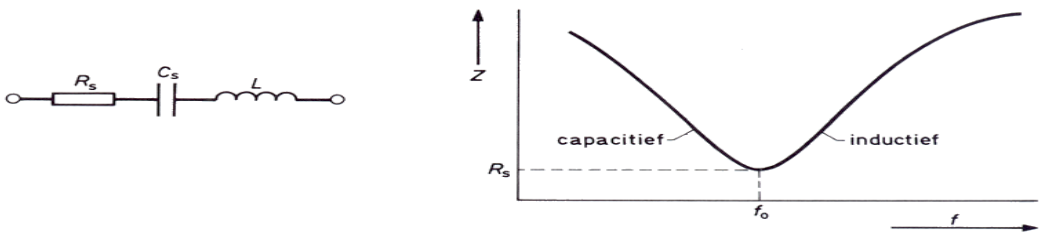


Figure A3-3 *Behavior of not ideal capacitor.*

A.4 Needed Fasterix setups for designing of a coil

The EM-field simulations are done with a Fasterix-tool. In order to create a certain coil-shape in Fasterix it’s necessary to give the coordinates, this is one of the reasons that a interface between ADS and Fasterix is made. Within ADS it is now possible to create visually different coil-shapes and in a Fasterix-window the necessary parameters can be adjust. Also after simulation a model-component is made which makes possible in ADS-schematic environment to build a circuit which is most similar to a measurement-environment.
This chapter lead the user through the necessary simulation steps in order to get a accurate simulation results.

A.4.1 Drawing the Coils in ADS

In an ADS-environment it is possible to draw the coil manually. This is rather difficult and time costing event especially if the coil shape isn’t rectangular.
This is one of the reasons that a program is written which makes it possible to enter the coil-dimensions. This program calculate the lines from corner to corner of the coil and write it to a file which can be imported in ADS.
The program is a FORTRAN program *(appendix A*5) and can be edited in “Unix-environment” by typing :

Command line: ‘nedit spirads.f’

In *figure A6-1* is a part of the program given which has to be changed due to different kind of coil-shape. In this program the baseradius, linethickness, linespacing, pointsperrev (shape of coil), number of turns can be entered. It is possible to make almost every shape, with different kind of dimensions.
Now the program has to be executed in “Unix-environment” by typing :

Command line:’f77 spirads.f’
Command line: ‘a.out’
An ADS file is made in the example case; ‘cirbr5nH_a’, which can be directly imported in ADS-layout window.

```
c File for import in ADS
      OPEN(2,file='cirbr5nH_a')
      pi=DATAN(1.d0)*4.d0


c     *****************************
c     Input unit (mm) and form Coil
c     *****************************

      filename='cirbr5nh'
      baseradius=1
      linethickness=1d0
      linespacing=0.5d0
      pointsperrev=30
      numberofwindings=0.89
```

Figure A4-1 *A part of the program*

When the program spirads.f is used to drawn a coil, take into account that the linethickness/ spacing is not accurate. Because the program use the value for linethickness/ spacing the oblique side *(s),* which is not the actual width. Therefore this value must be manual calculated. The value *(a)* is the actual linethickness/ spacing (called trackwidth and trackspacing).
The angle (α) is calculated with $\alpha = 180 / pointsperrev$ determine the shape of the coil. It are the number of corners. In case the shape is octagonal the number of pointsperrev are 8.

The linethickness (s) is calculated with $s = a / \cos\alpha$

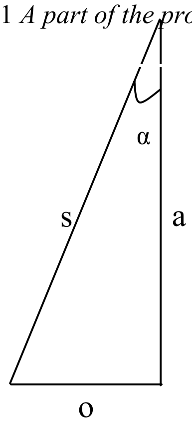


Figure A4-2 Calculation linethickness/ spacing

A.4.2 Import file in ADS

To import a file in ADS an EGS Archive Format and the desired Import File Name must be selected *(figure A4-3*). The format of the "Import File Name (Source)" must be filename'_a' in our case "cirbr5nH_a". When this is done click on OK and the layout is opened.

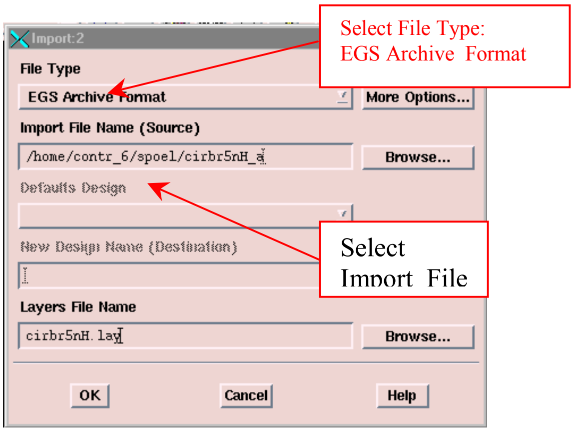


Figure A4-3 *Import file setups ADS.*

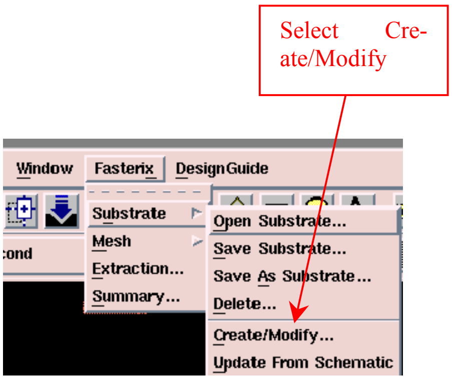


Figure A4-4 *Fasterix menu.*

A.4.3 Fasterix setup

Before start the simulation some setup have to be done.
First the substrate/ layer setups. Select Create/ modify *(figure A4-4)* and a new window is opened to setup a substrate properties *(figure A4-5)* such as thickness, permittivity and permeablity of a substrate. In our case the thickness of the substrate is 0.51mm with a real permittivity of 3.38.
By clicking on the "metallization layers" the properties of different layers can be defined.
Defining the properties of a different layer can be done by selecting the desired layout layer *(figure A4-5)*. In our case a 'definition (cond)' of 'Sigma(Re,thickness)' is selected with a conductivity of $5.8e^{+7}$ and a thickness of 35µm for a top/ bottom layer and 0.51mm for a via.
To make a layout as describes in chapter layers and substrate some strips and vias are created.
This is done by mapping the desired layout layer as a strip, slot or via. A strip is the objects on the layout layer are conductive, an the rest of the layer is not, a slot is an inverse of a strip. A via is connection between two strips through the substrate.

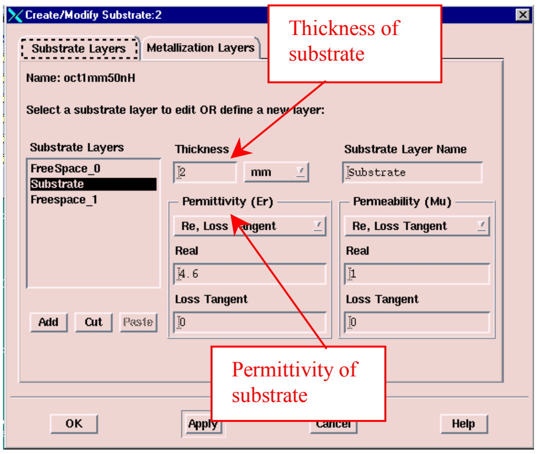


Figure A4-5 *The substrate layers.*

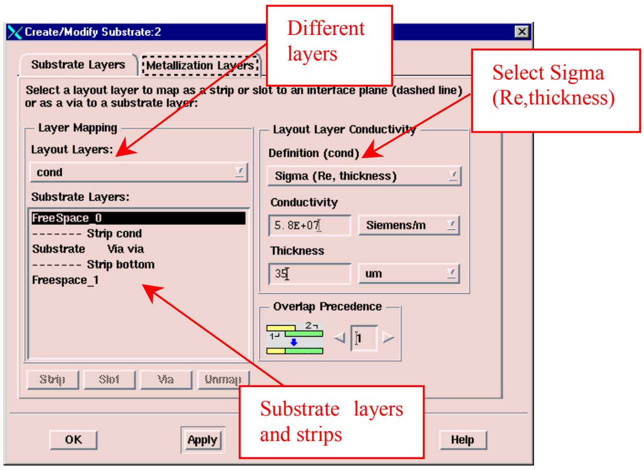


Figure A4-6 *The metallization layers.*

A.4.4 Making a coil on PCB

To make a PCB of an ADS coil-layout an export file in ADS must be created. Select export in the menu and a window *(figure A4-7*) is opened. Select Type File “Gerber” and a file destination and click on OK. A new dialog window is opened also click on OK. Dialog window *(figure A4-8)* is opened which allows to setup the Gerber export options.

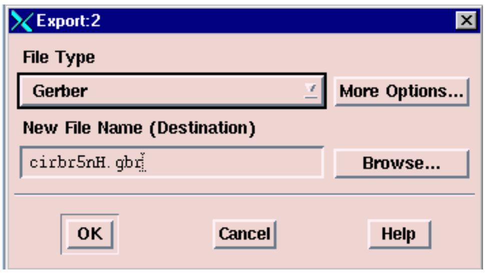


Figure A4-7 *Export window.*

Click on translation settings and a new window *(figure A4-9)* is opened. Select Outline/Fill ‘Fill’ and Gerber Output Format ‘RS274X’ and click on Ok. The right setups are done to convert the ADS layout into a Gerber file. Select Translate and a Gerber file is made, the dialog window can be closed.
The Gerber file is saved as “cond.gbr” can be imported in Boardmaster.

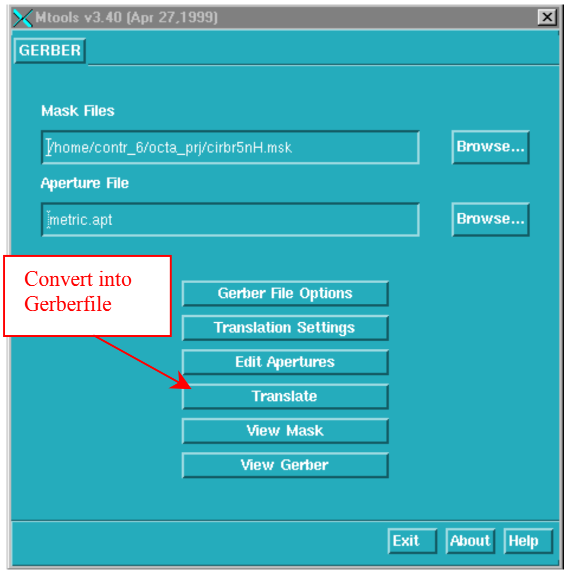


Figure A4-8 Gerber convert window.

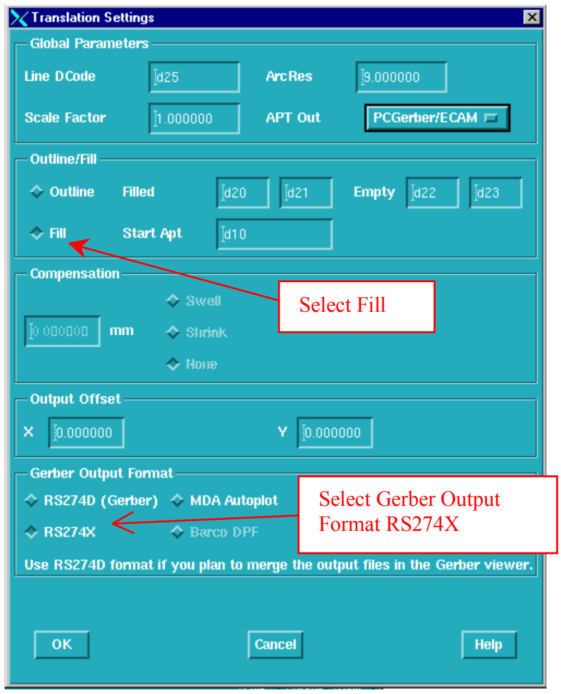


Figure A4-9 Translation settings window.

A.5 Program for making an ADS-file

```
program coilads
     IMPLICIT NONE

     DOUBLE PRECISION linespacing,linethickness,baseradius,
    &           dphi,dr,pi,r,Ri(1:300),x(1:300),y(1:300),
    &           phii(1:300),phi,fr,fphi,pin1x,pin1y,
    &           pin2x,pin2y,leadwidth,leadangle,viax,viay,
    &           leadlength,pintopinl,alpha,xl(1:5),yl(1:5),
    &           numberofwindings,xro(1:5),yro(1:5)
     INTEGER       pointsperrev,
    &           orientation,totalpoints,i,xr(1:300),yr(1:300),
    &           xlr(1:4),ylr(1:4)
      CHARACTER *8 filename

c File voor import in ADS
     OPEN(2,file='octa150_a')
     pi=DATAN(1.d0)*4.d0

c    ***************************************************************
c    Input unit (mm) and form Coil
c    ***************************************************************
     filename='octa150'
     baseradius=2.5
     linethickness=1.15d0
     linespacing=1d0
     pointsperrev=8
     numberofwindings=1.50
     orientation=1
     viax=0.d0
     viay=0.d0

     dr=(linespacing+linethickness)/pointsperrev
     dphi=2.d0*pi/pointsperrev

c    ***************************************************************
c    Generate centerpoint
c    ***************************************************************
     x(1)=viax+baseradius+linethickness
c    x(1)=viax+0.d0
     y(1)=viay+0.d0

c    ***************************************************************
c    turns
c    ***************************************************************
     phi=0.d0
     r=baseradius+linethickness
     totalpoints=int(numberofwindings*pointsperrev)
     DO 10 i=1,totalpoints
     Ri(i)=r+i*dr
     phii(i)=phi+orientation*i*dphi
     x(i+1)=viax+Ri(i)*DCOS(phii(i))
     y(i+1)=viay+Ri(i)*DSIN(phii(i))
10   CONTINUE
```

```
c     ****************************************************************
c     Calculate endpoints of coil, fr=finalr
c     ****************************************************************
      fr=r+numberofwindings*(linespacing+linethickness)
      fphi=orientation*(numberofwindings-int(numberofwindings))*2.d0*pi
      x(totalpoints+2)=viax+fr*dcos(fphi)
      y(totalpoints+2)=viay+fr*dsin(fphi)
      fr=fr-linethickness
      x(totalpoints+3)=viax+fr*dcos(fphi)
      y(totalpoints+3)=viay+fr*dsin(fphi)
      fr=fr+0.5d0*linethickness
      pin2x=viax+fr*dcos(fphi)
      pin2y=viay+fr*dsin(fphi)

c     *****************************************************************
c     Calculate the point back towards the center
c     *****************************************************************
      r=baseradius
      DO 40 i=totalpoints,0,-1
      Ri(i+1)=r+i*dr
      phii(i+1)=phi+orientation*i*dphi
      x(2*totalpoints+4-i)=viax+Ri(i+1)*DCOS(phii(i+1))
      y(2*totalpoints+4-i)=viay+Ri(i+1)*DSIN(phii(i+1))
40    CONTINUE

c     *****************************************************************
c     close loop
c     *****************************************************************
      x(2*totalpoints+5)=x(1)
      y(2*totalpoints+5)=y(1)

c     ****************************************************************
c     Generate the leadwire
c     ****************************************************************
      leadwidth=linethickness
c     alpha=DATAN(baseradius/fr)
c     leadangle=fphi+orientation*alpha
      leadangle=pi/4.d0
      pintopinl=DSQRT(baseradius+fr*fr)
      leadlength=pintopinl+leadwidth
      xl(1)=-0.5d0*leadwidth
      yl(1)=-0.5d0*leadwidth
      xl(2)=-0.5d0*leadwidth
      yl(2)=0.5d0*leadwidth
      xl(3)=-0.5d0*leadwidth+leadlength
      yl(3)=0.5d0*leadwidth
      xl(4)=-0.5d0*leadwidth+leadlength
      yl(4)=-0.5d0*leadwidth
      xl(5)=pintopinl
      yl(5)=0.d0
```

```
c     ****************************************************************
c     Rotate
c     ****************************************************************
      xro(1)=dcos(leadangle)*xl(1)-dsin(leadangle)*yl(1)
     &  +baseradius+0.5d0*linethickness
      yro(1)=dsin(leadangle)*xl(1)+dcos(leadangle)*yl(1)
      xro(2)=dcos(leadangle)*xl(2)-dsin(leadangle)*yl(2)+baseradius
     &     +0.5d0*linethickness
      yro(2)=dsin(leadangle)*xl(2)+dcos(leadangle)*yl(2)
      xro(3)=dcos(leadangle)*xl(3)-dsin(leadangle)*yl(3)
     &       +baseradius+0.5d0*linethickness
      yro(3)=dsin(leadangle)*xl(3)+dcos(leadangle)*yl(3)
      xro(4)=dcos(leadangle)*xl(4)-dsin(leadangle)*yl(4)+baseradius
     &      +0.5d0*linethickness
      yro(4)=dsin(leadangle)*xl(4)+dcos(leadangle)*yl(4)
      xro(5)=dcos(leadangle)*xl(5)-dsin(leadangle)*yl(5)+baseradius
     &      +0.5d0*linethickness
      yro(5)=dsin(leadangle)*xl(5)+dcos(leadangle)*yl(5)

      write(2,*) '$$ filename',' = ',filename
      write(2,*) '$$ baseradius',' = ',baseradius
      write(2,*) '$$ linethickness',' = ',linethickness
      write(2,*) '$$ linespacing',' = ',linespacing
      write(2,*) '$$ pointsperrev',' = ',pointsperrev
      write(2,*) '$$ numberofwindings',' = ',numberofwindings
      write(2,*)
      write(2,*)
      write(2,*) 'UNITS UM,10000;'
      write(2,*) 'GRID 0.1000,2 0.0000,0.0000;'
      write(2,*) 'LOCK 0.0000;'
      write(2,*) 'TSLANT 0.0000;'
      write(2,*) 'RESOLUTION 0.0000;'
      write(2,*) '$$'
      write(2,*) '$$        layer  line'
      write(2,*) '$$  label  type   type   color   pen  layer'
      write(2,*) '$$'
      write(2,*)
      write(2,*) 'EQU ','cond',' :D',' :L1',' :C15',' :P1',' 1;'
      write(2,*) 'EXIT;'
      write(2,*)
c    aanpassen van filenaam
      write(2,*) '$FILES ',filename,'$;'
      write(2,*)
      write(2,*) 'EDIT;'
      write(2,*) 'EDIT;'
      write(2,*)
      write(2,*) 'EDIT ',filename,';'
      write(2,*) 'GRID 0.0001,1 0.0000,0.0000;'
      write(2,*) 'ADD P1 :W0.0000'

      DO 30 i=1,2*totalpoints+5
      IF ((x(i)).GE.0.d0) THEN
      xr(i)=INT(1000.d0*x(i)+0.5d0)
      ELSE
      xr(i)=INT(1000.d0*x(i)-0.5d0)
      ENDIF
      IF ((y(i)).GE.0.d0) THEN
```

```
      yr(i)=INT(1000.d0*y(i)+0.5d0)
      ELSE
      yr(i)=INT(1000.d0*y(i)-0.5d0)
      ENDIF
      write(2,*)  xr(i),', ',yr(i)

30    CONTINUE
      write(2,*)
c     write(2,*) 'ARE ',' "NET_0" ',' "signal_2" ',' SOLID ',
c    &      '4'


      DO 50 i=1,4
      IF ((xro(i)).GE.0.d0) THEN
      xlr(i)=INT(1000.d0*xro(i)+0.5d0)
      ELSE
      xlr(i)=INT(1000.d0*xro(i)-0.5d0)
      ENDIF
      IF ((yro(i)).GE.0.d0) THEN
      ylr(i)=INT(1000.d0*yro(i)+0.5d0)
      ELSE
      ylr(i)=INT(1000.d0*yro(i)-0.5d0)
      ENDIF
c     write(2,*)  ' ',xlr(i),',',
c    &           ylr(i)
50    CONTINUE
      write(2,*) ';'
      write(2,*) 'Grid 0.1000,1 0.0000,0.0000;'
      write(2,*) 'SAVE;'
      write(6,*) 'Pin 1: ',xro(5),',',yro(5)
      write(6,*) 'Pin 2: ', pin2x,',',pin2y
      write(6,*) 'viax ',viax+baseradius+0.5d0*linethickness
      write(6,*) 'viay ',viay
      CLOSE(2)
      END
```

A.6 Results Design layout Two with 0.75 turns

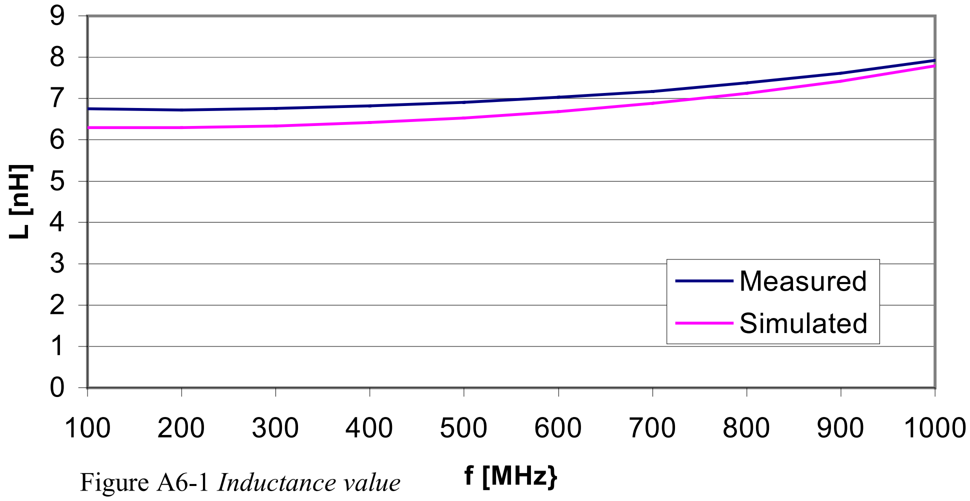


Figure A6-1 *Inductance value*

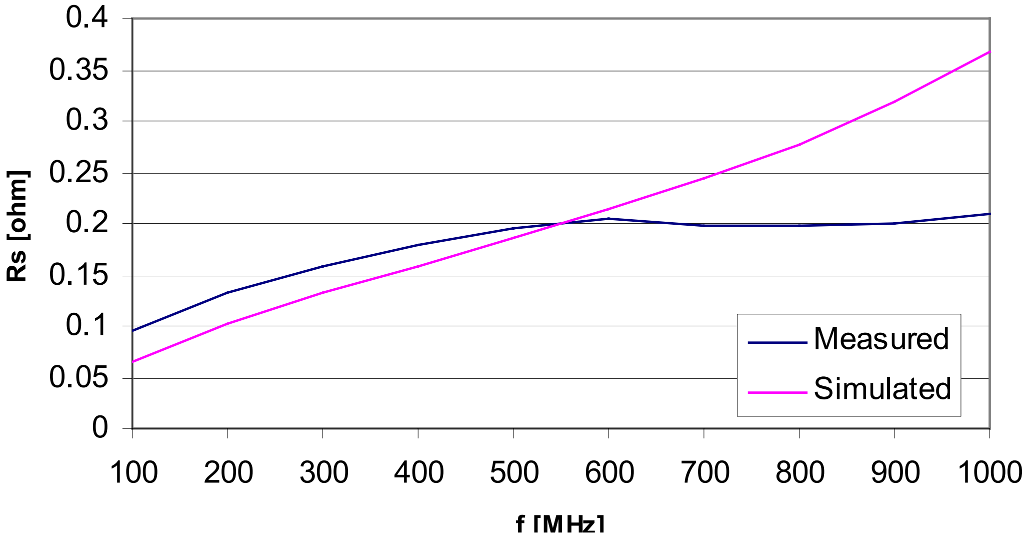


Figure A6-2 *Serial resistance*

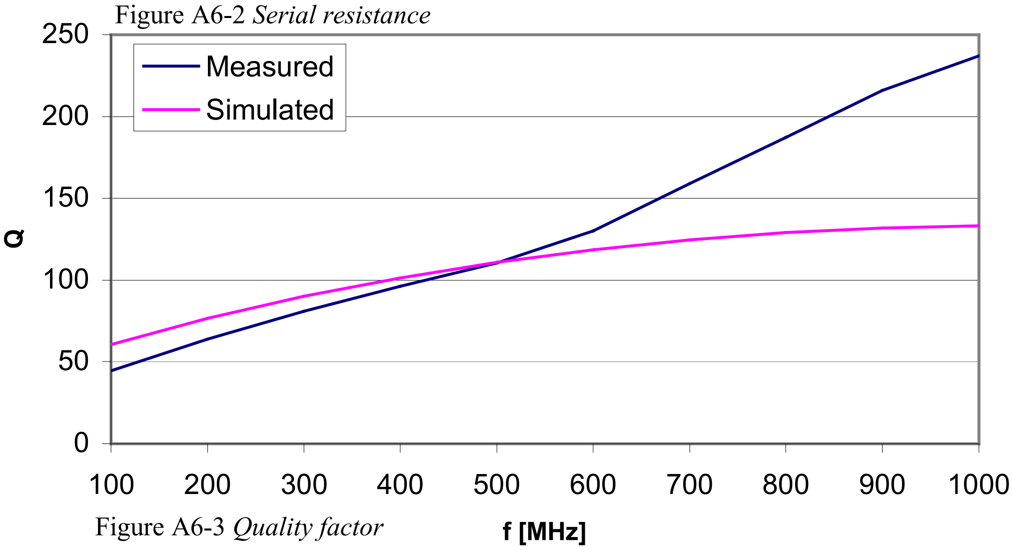


Figure A6-3 *Quality factor*

A.7 Results Design layout Two with one turn

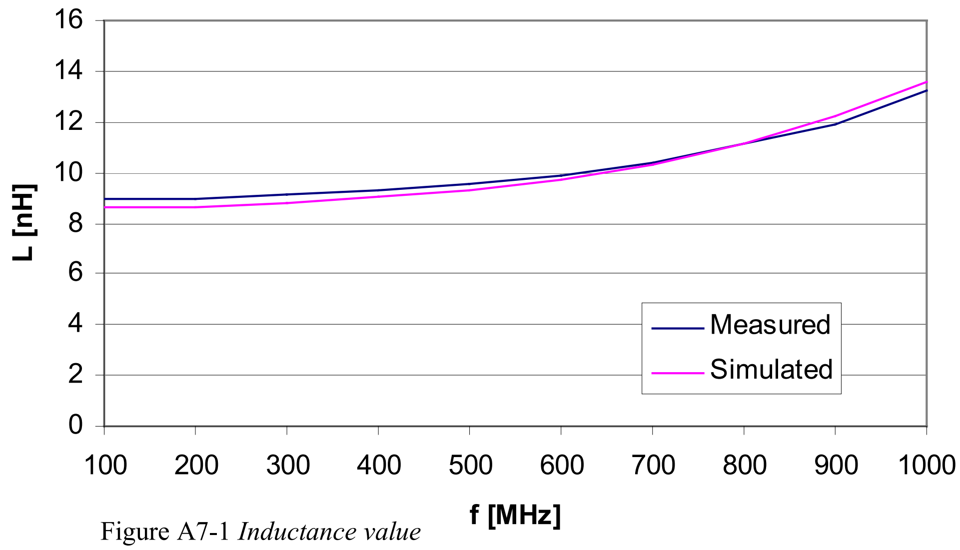


Figure A7-1 *Inductance value*

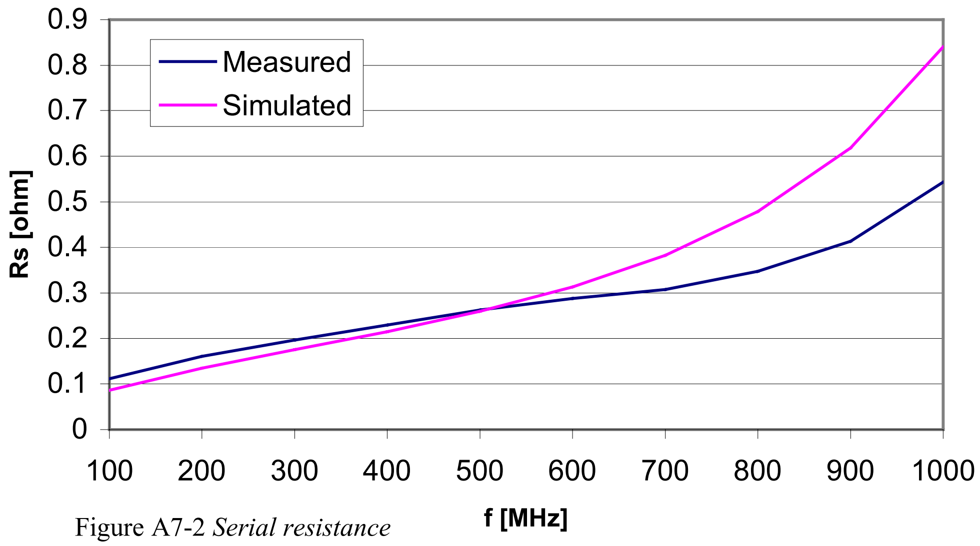


Figure A7-2 *Serial resistance*

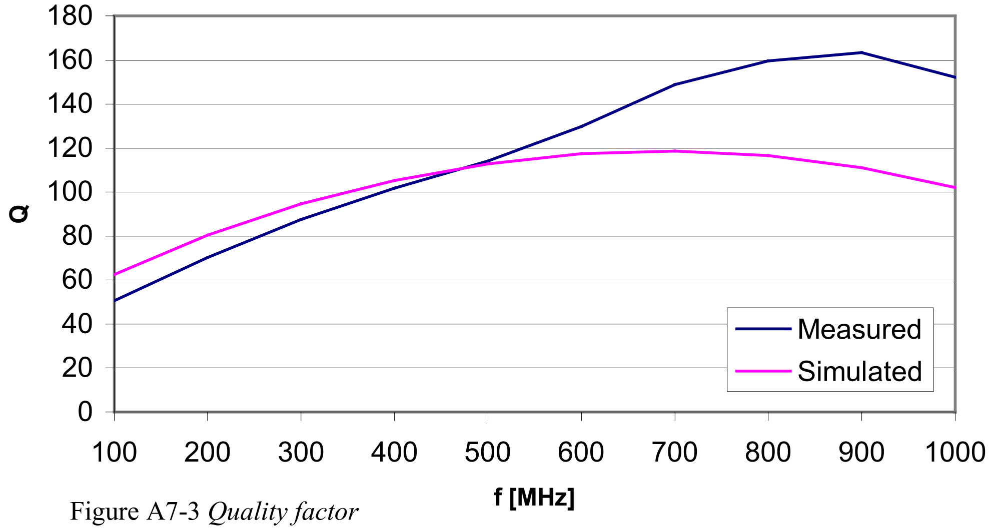


Figure A7-3 *Quality factor*

A.8 Results Design layout Two with 1.25 turn

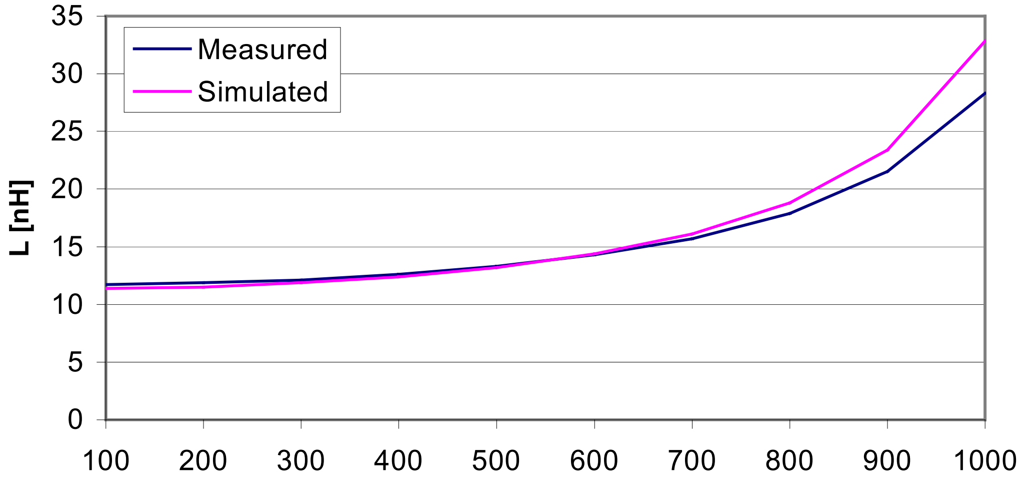


Figure A 8-1 *Inductance value*

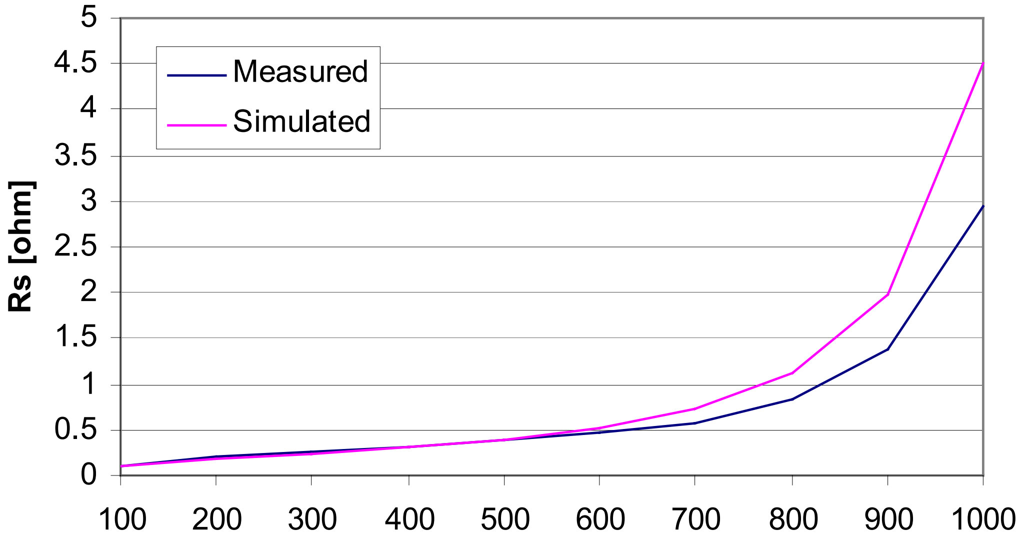


Figure A8-2 *Serial resistance*

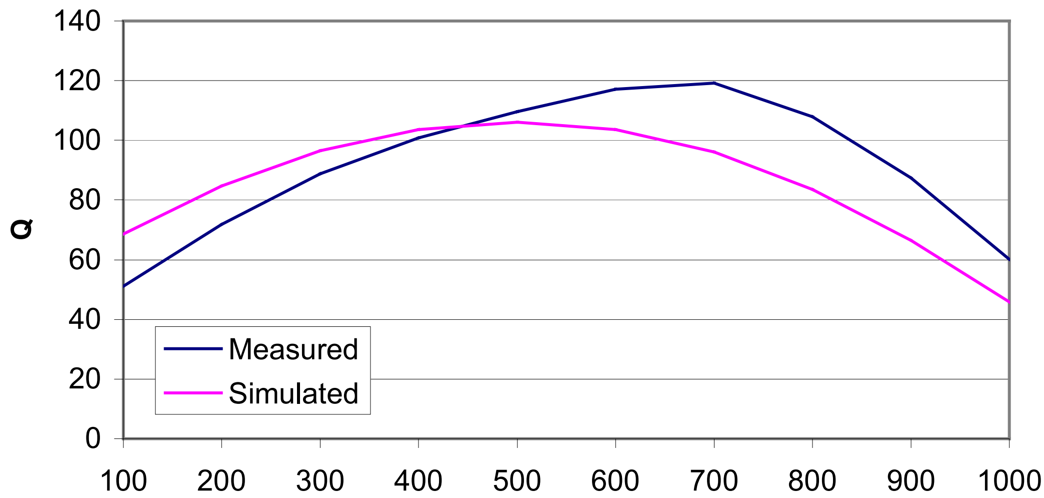


Figure A8-3 *Quality factor*

A.9 Results Design layout Two with 1.50 turn

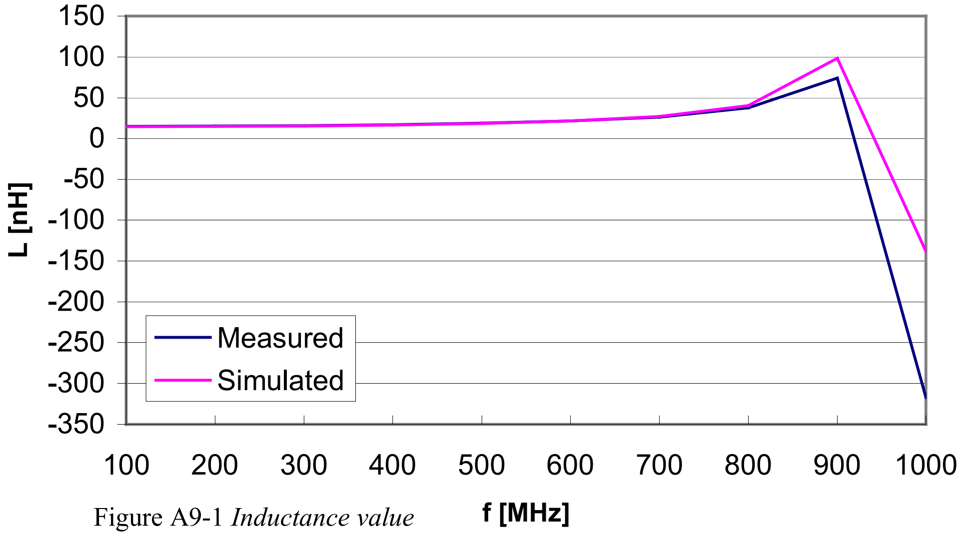


Figure A9-1 *Inductance value*

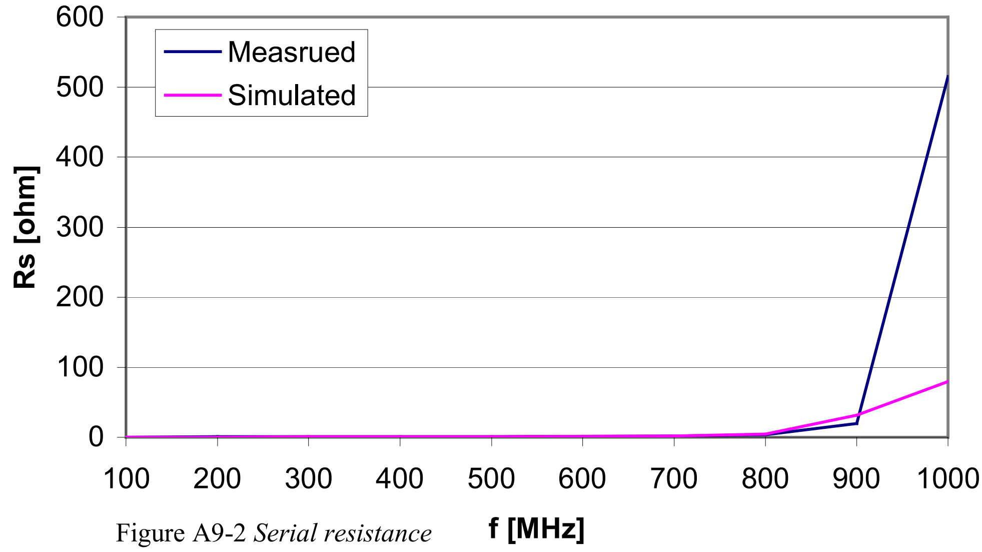


Figure A9-2 *Serial resistance*

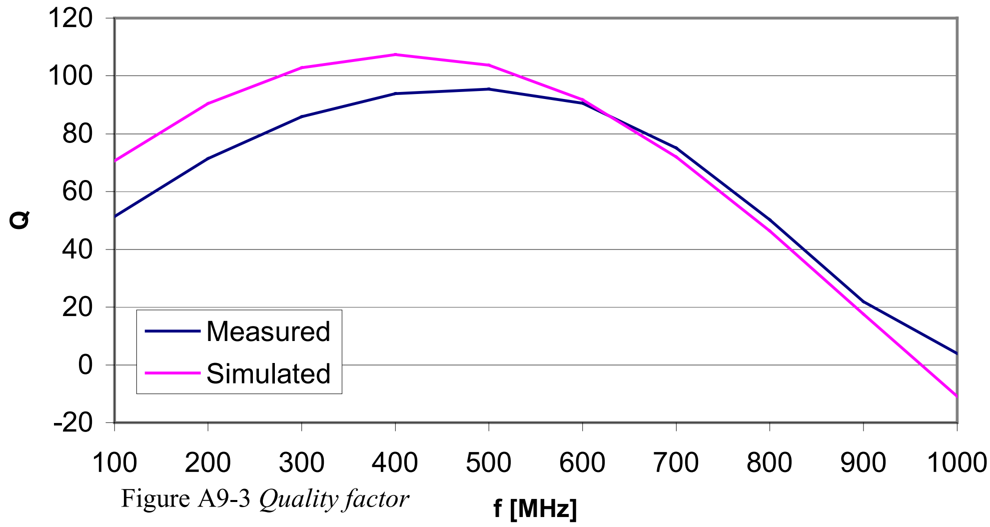


Figure A9-3 *Quality factor*

A.10 Comparison quality factor with different turns

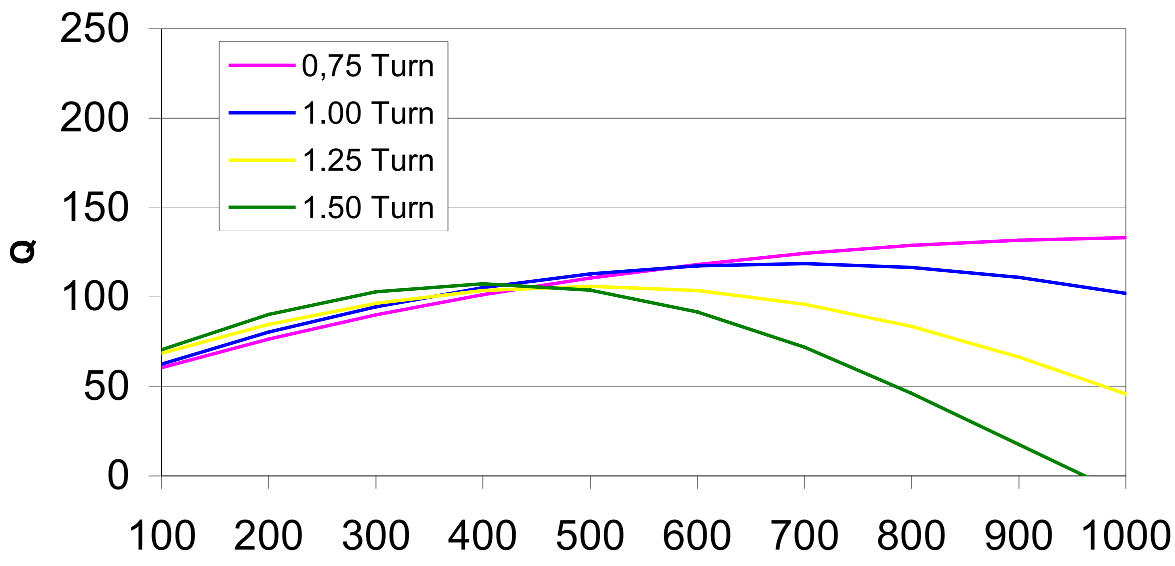


Figure A10-1 *Simulated quality factor.*

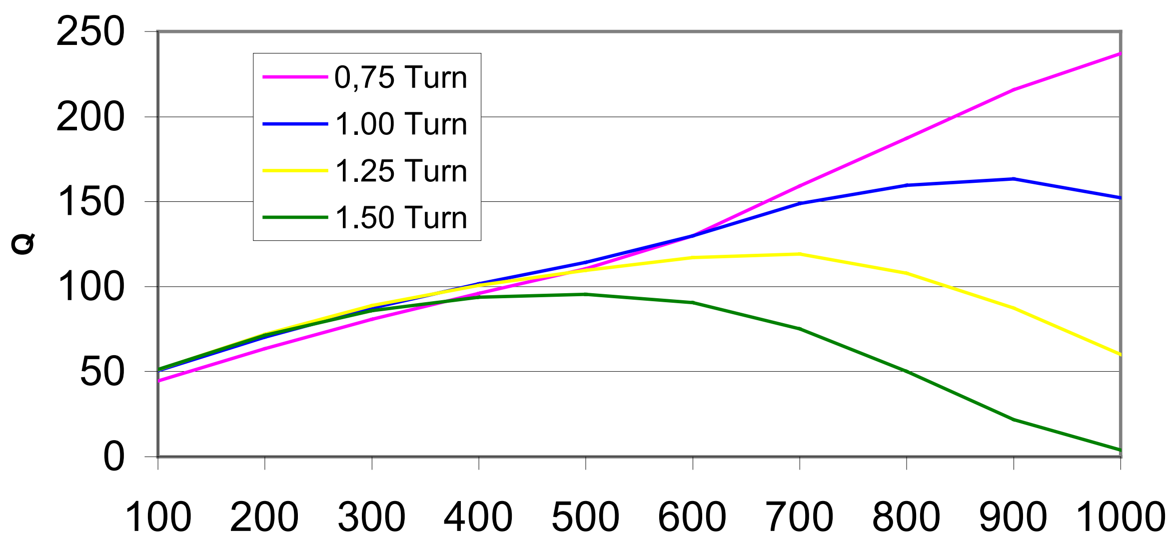


Figure A10-2 *Measured quality factor.*

A.11 Simulation results changing dimensions

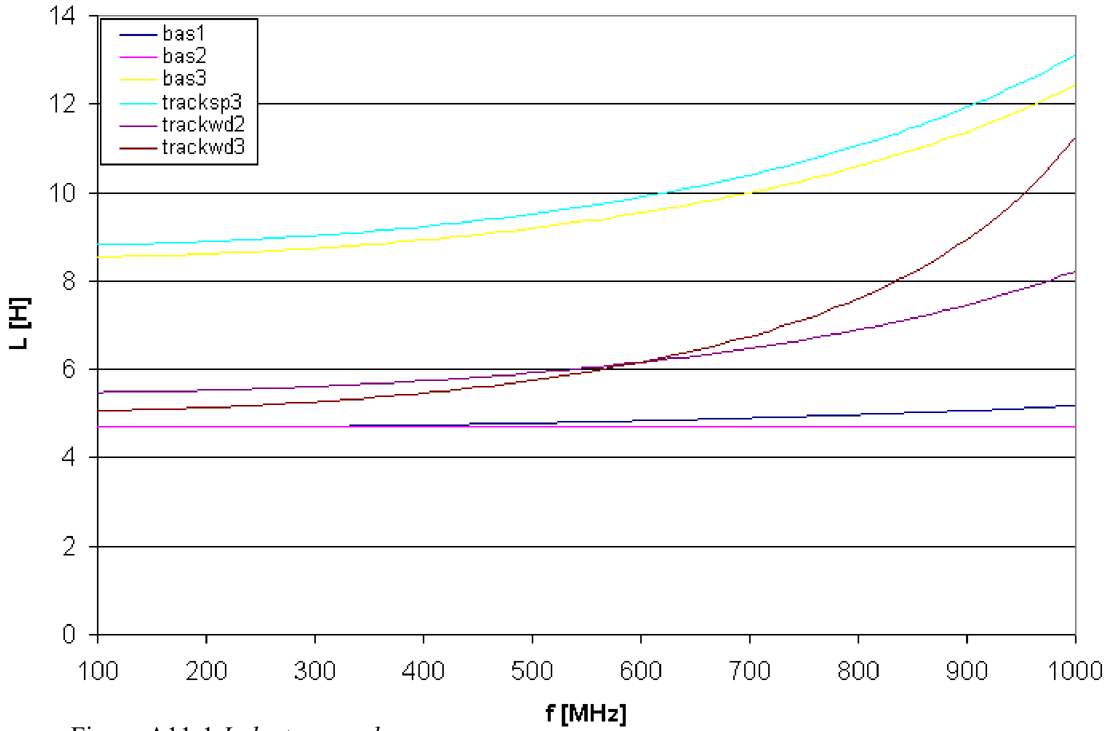


Figure A11-1 *Inductance value.*

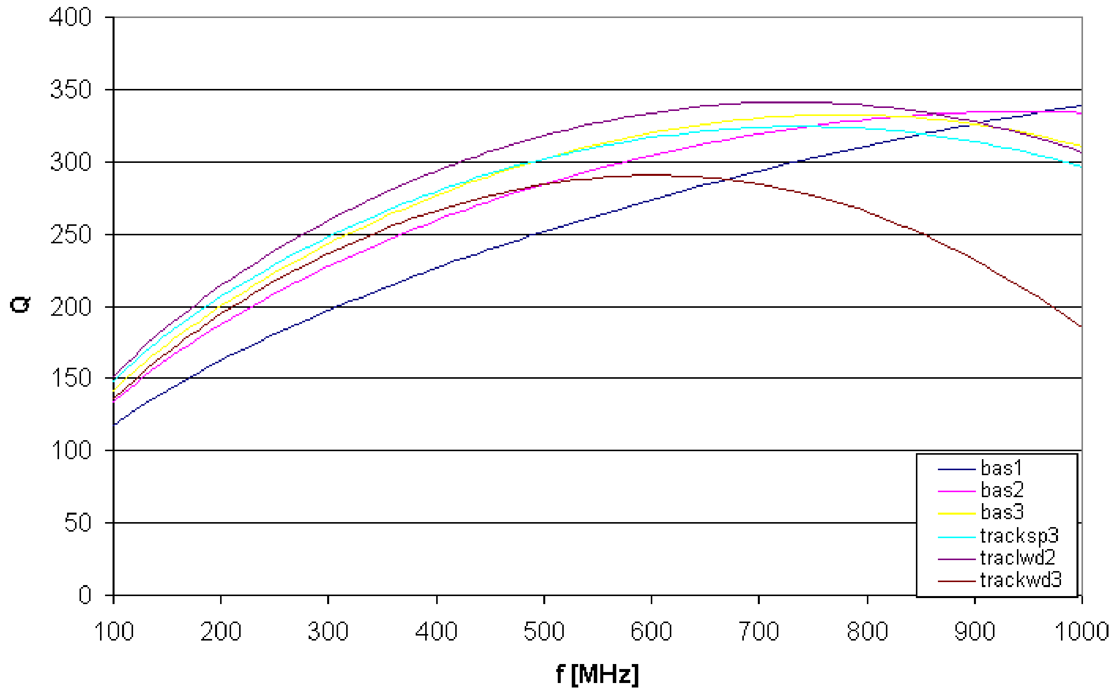


Figure A11-2 *Quality factor.*

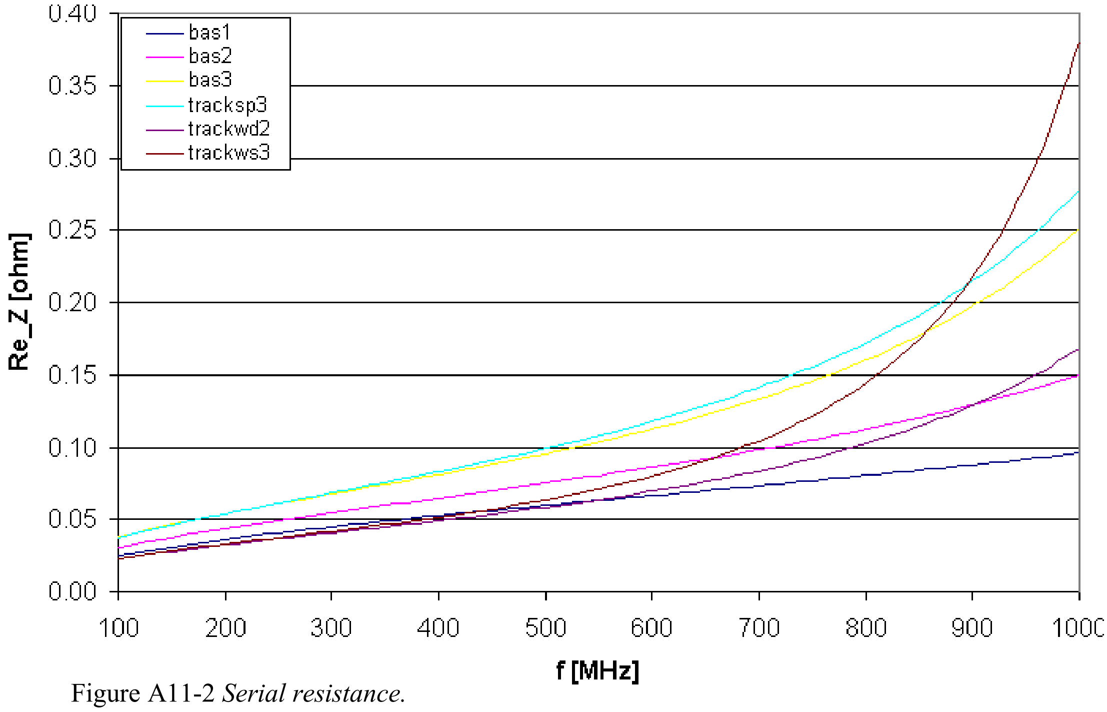


Figure A11-2 *Serial resistance.*

A.12 Simulation results dielectric media

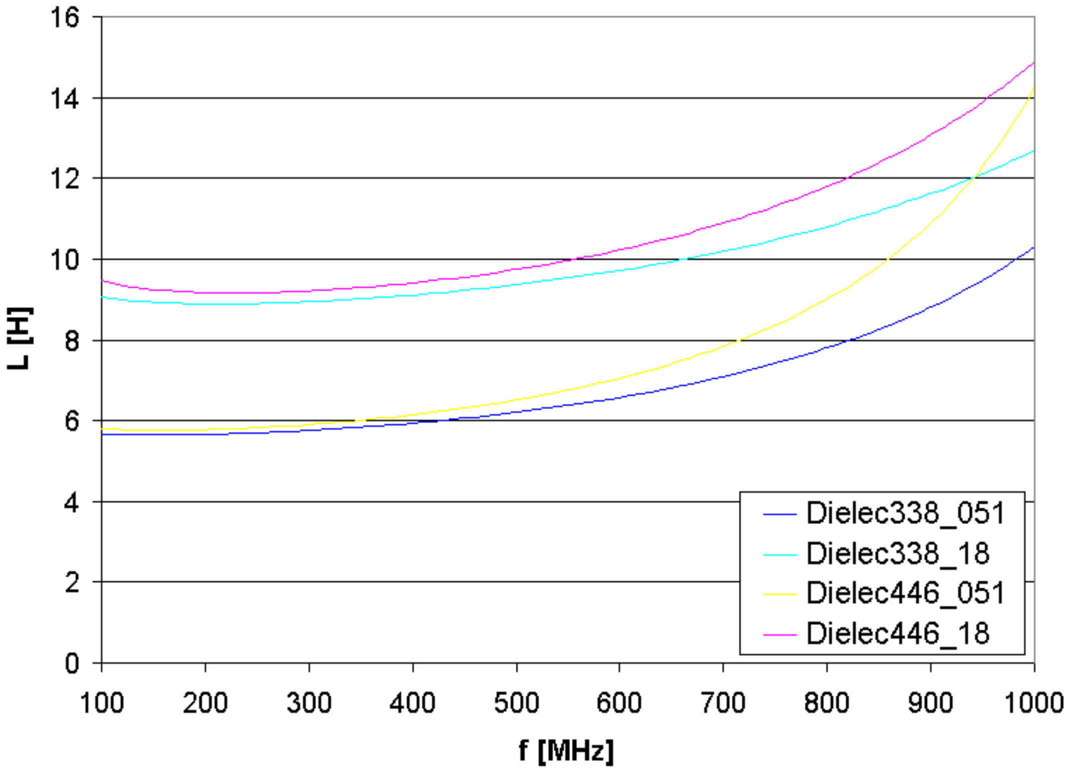


Figure A12-1 *Inductance value.*

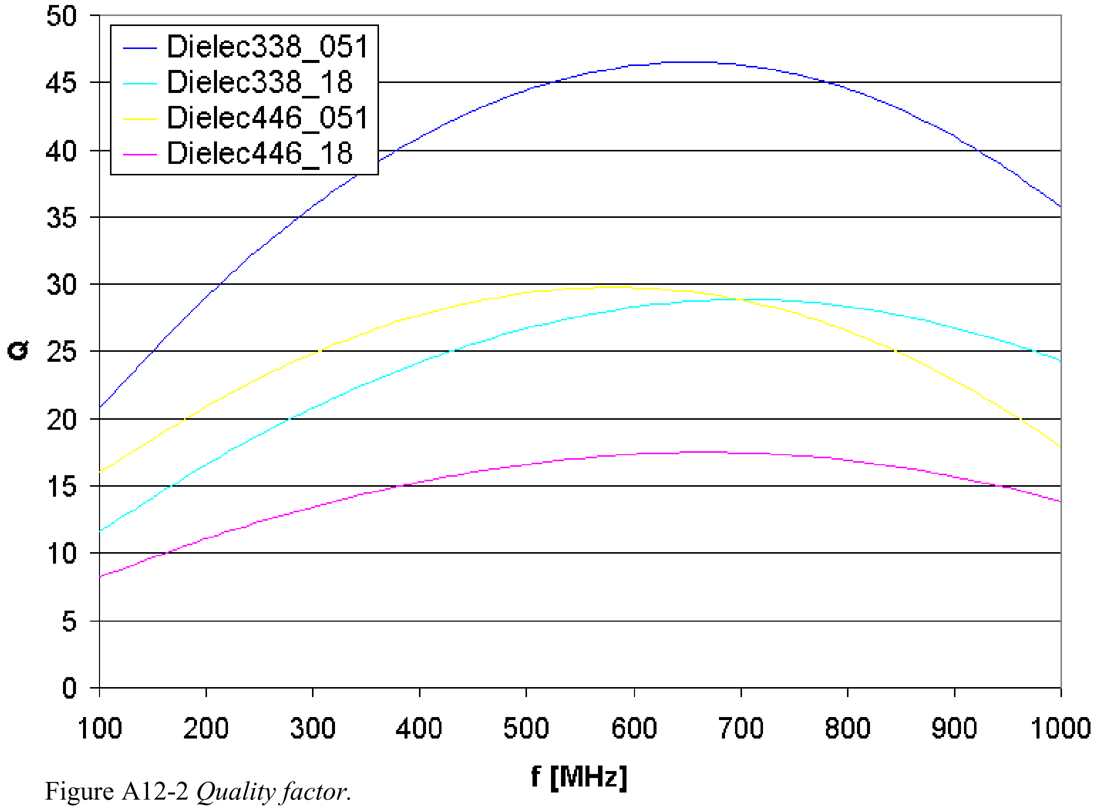


Figure A12-2 *Quality factor.*

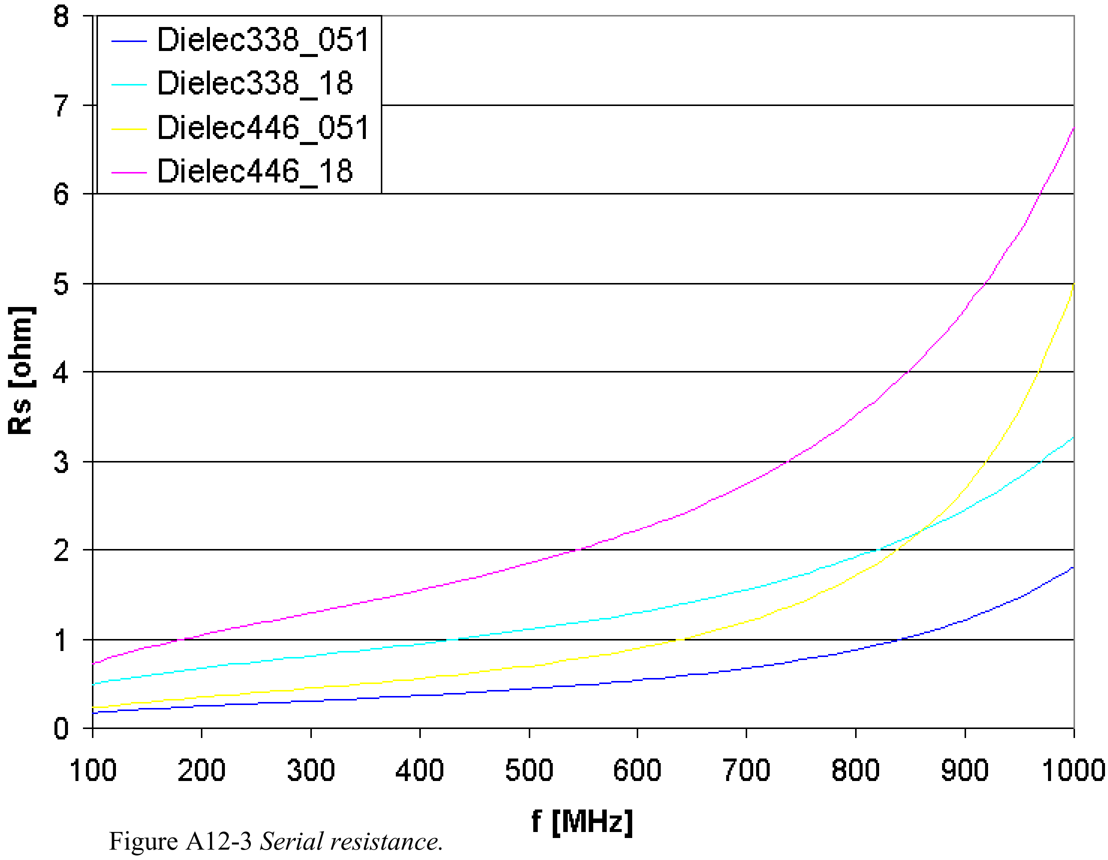


Figure A12-3 *Serial resistance.*

A.13 Simulation results influence of vias

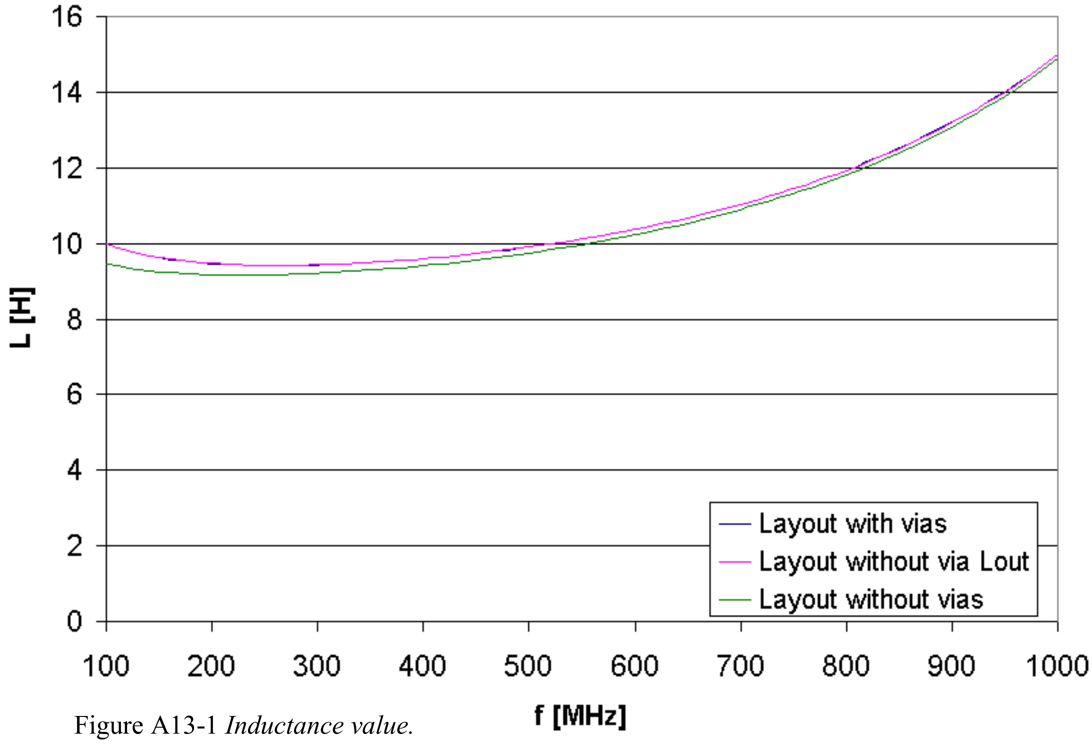


Figure A13-1 *Inductance value.*

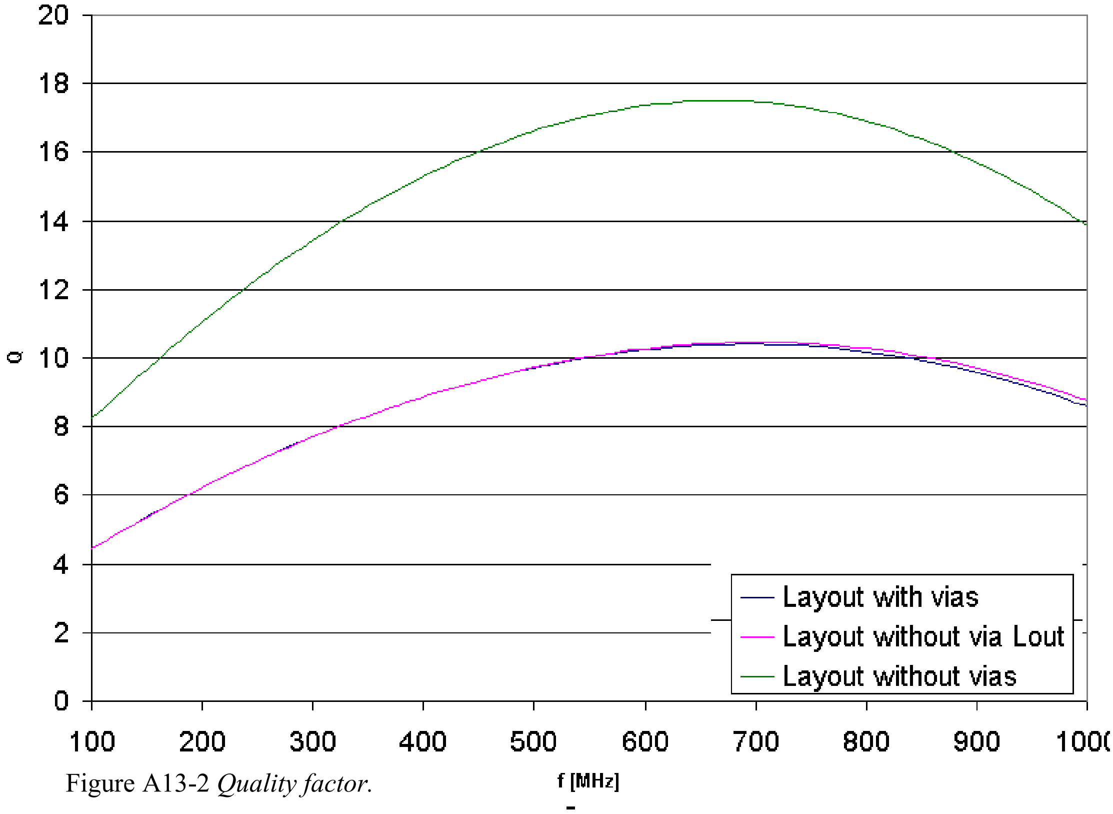


Figure A13-2 *Quality factor.*

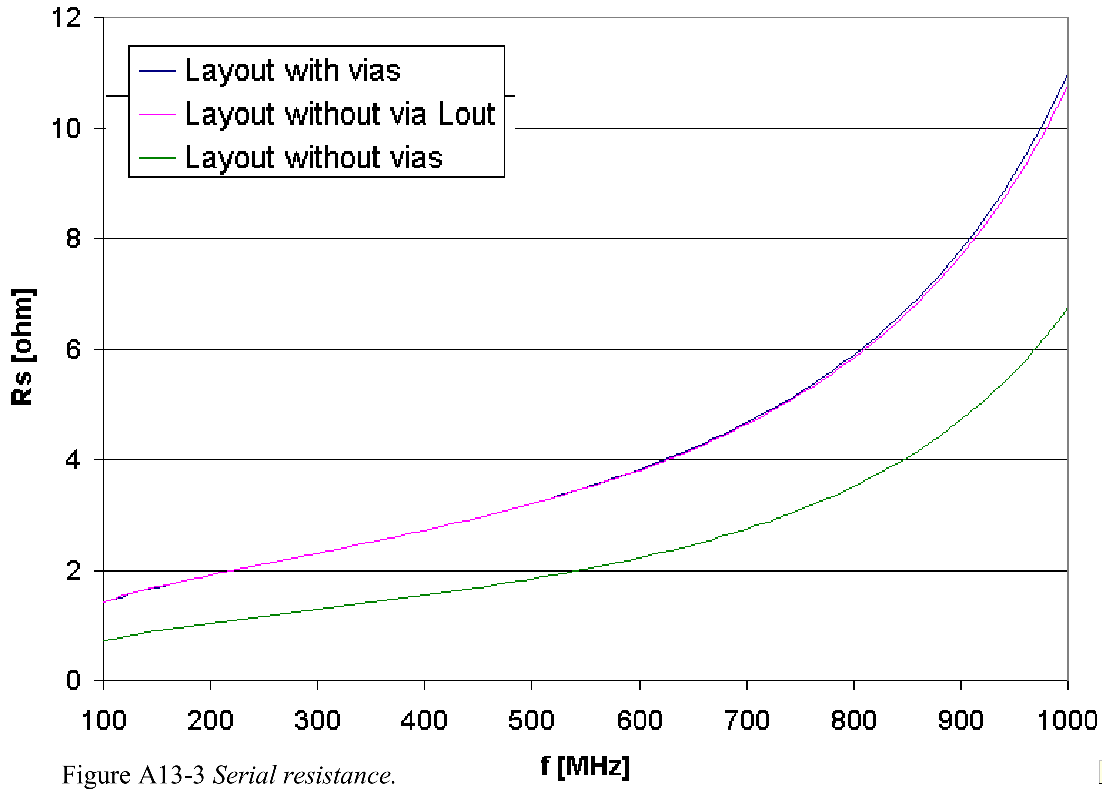


Figure A13-3 *Serial resistance.*

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Title: Coils on PCB

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