LINZ CENTER OF MECHATRONICS GMBH

Application Note:

Determination of the equivalent circuit of a printed coil and matching to 50 Ω for an RFID-Application

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1. Executive Summary

This application note describes the measurement of various RFID reader antennas at 13.56 MHZ the determination of the equivalent circuit for the antenna and finally the matching of this antenna to an impedance of 50 Ω. The RFID antenna is realized as a printed coil on a FR4 substrate. The serial equivalent circuit is used to simulate the antenna in a microwave simulation program, for example in ADS. For matching the RFID antenna to an impedance of 50 Ω it is necessary to design a matching network. The design of this network is described in detail with a smith chart. After designing the matching network the simulation results are verified with measurement results. Therefore a reflection measurement of the RFID antenna combined with the calculated matching network is realized with the vector analyzer Bode 100.

2. Calibration

First the vector network analyzer Bode 100 must be calibrated in the frequency sweep mode to get precise measurement results.
To determine the series equivalent circuit of a printed coil antenna and to match this coil to an impedance of 50 Ω the frequency range mode has to be selected. This printed coil antenna is designed for a high frequency RFID system at 13.56 MHz. Therefore the following measurement settings are selected:

- start frequency: 100 kHz
- stop frequency: 40 MHz
- sweep mode: Linear
- number of points: 3201 (~12.5 MHz / point)
- reference resistance: 50 Ω
- measurement: reflection
- format: Smith chart

In this case the reflection on the output port has to be calibrated for an open circuit, a short and a load before the measurement can be performed.

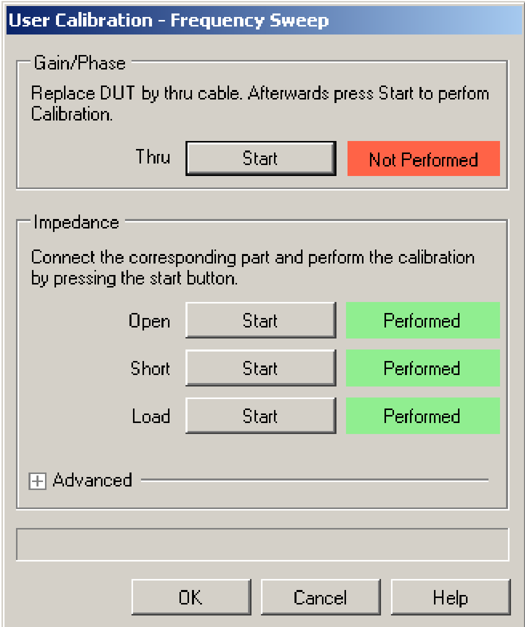

Figure 2-1: User Calibration Window

After the calibration the calibration is verified with significant loads as shown in Figure 2-2 to Figure 2-4. The Smith charts show that the Bode 100 was calibrated successfully.

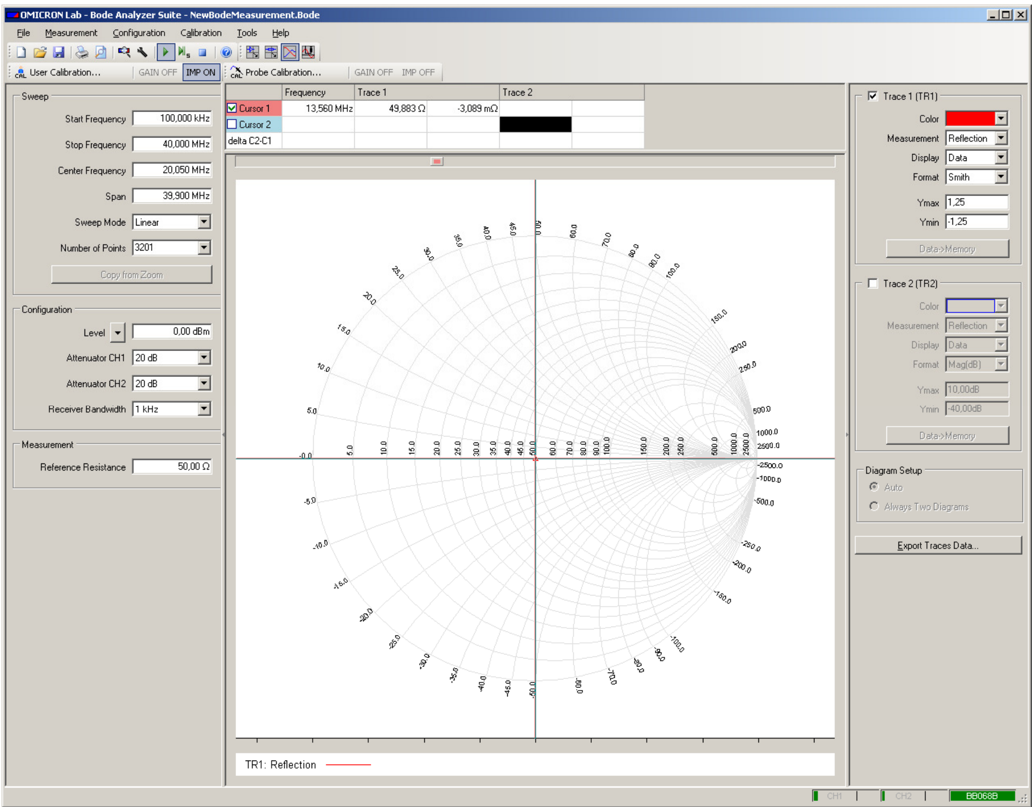

Figure 2-2: Load

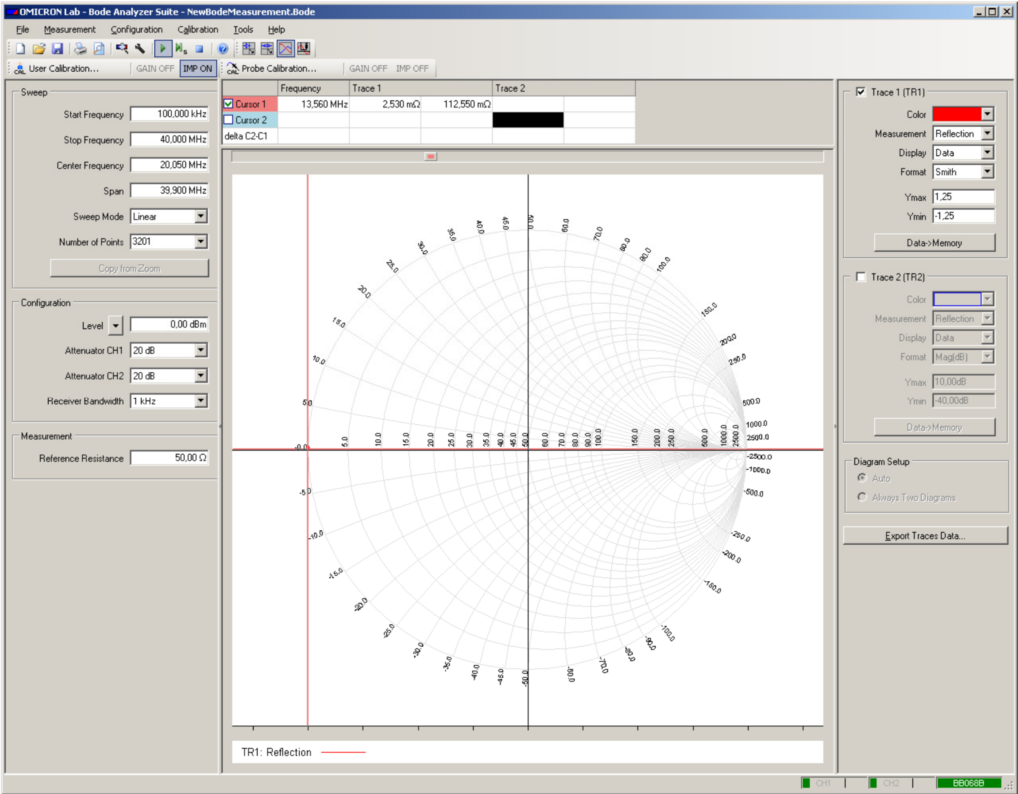

Figure 2-3: Short

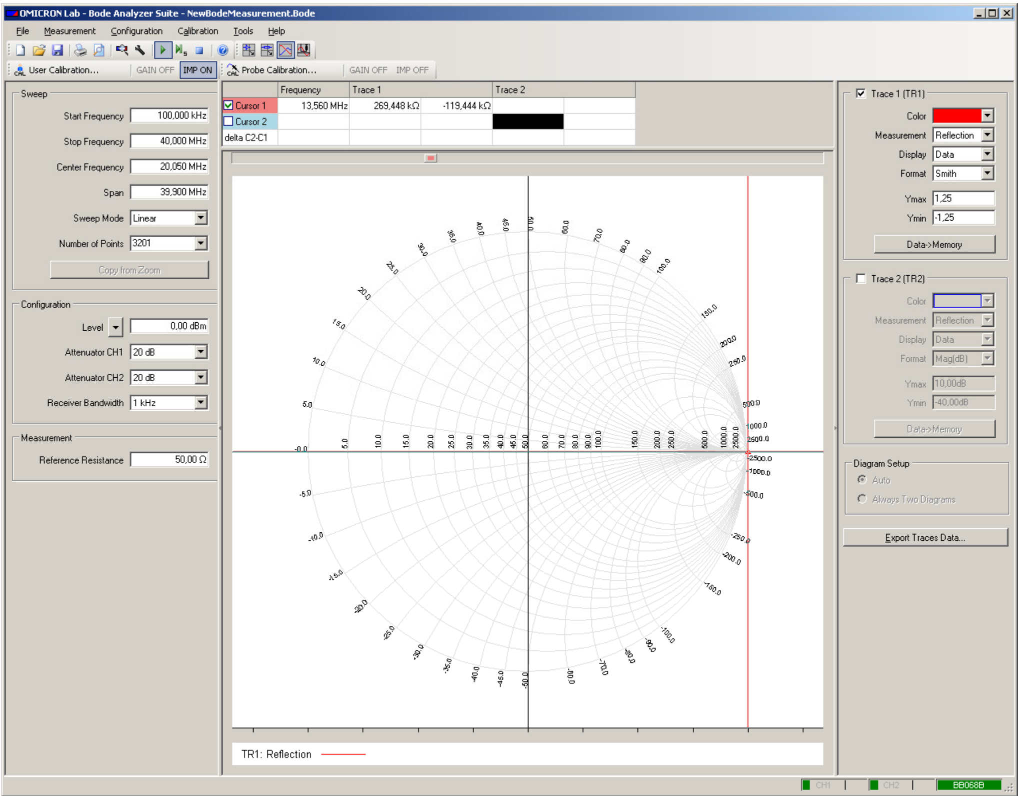

Figure 2-4: Open

3. Measurement of the impedance of a printed coil antenna

As shown in Figure 3-1 the RFID reader antenna is realized as printed coil. The RFID system is based on an inductive coupling between the RFID reader antenna and the RFID Tag. It is recommended to measure the RFID reader antenna at the final assembly position, because some metal parts of the RFID reader housing can have significant influence on the antenna properties, for example eddy currents in metal parts near the coil.

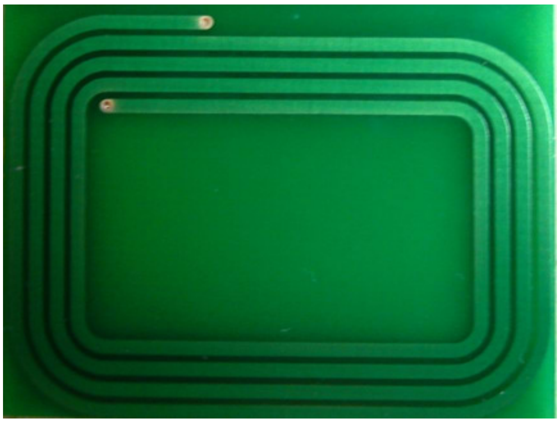

Figure 3-1: Photo of the printed coil antenna on a FR4 substrate

The series equivalent circuit of the printed coil is shown in Figure 3-2. It consists of the inductor itself, a serial resistor which represents the wire resistance and eddy current losses and a capacitor with results from the geometry of the copper track on the substrate.

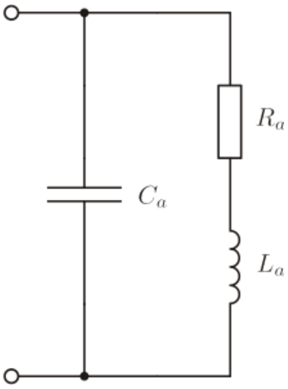

Figure 3-2: Series equivalent circuit of the printed coil

In Figure 3-3 the measured reflection coefficient of the printed coils is shown. At low frequencies the reflection is similar to a short in the Smith chart because of the low resistance of the copper tracks. At higher frequencies we see the typical frequency response of a coil and at the serial resonance frequency of the printed coil we are at the open-circuit point.

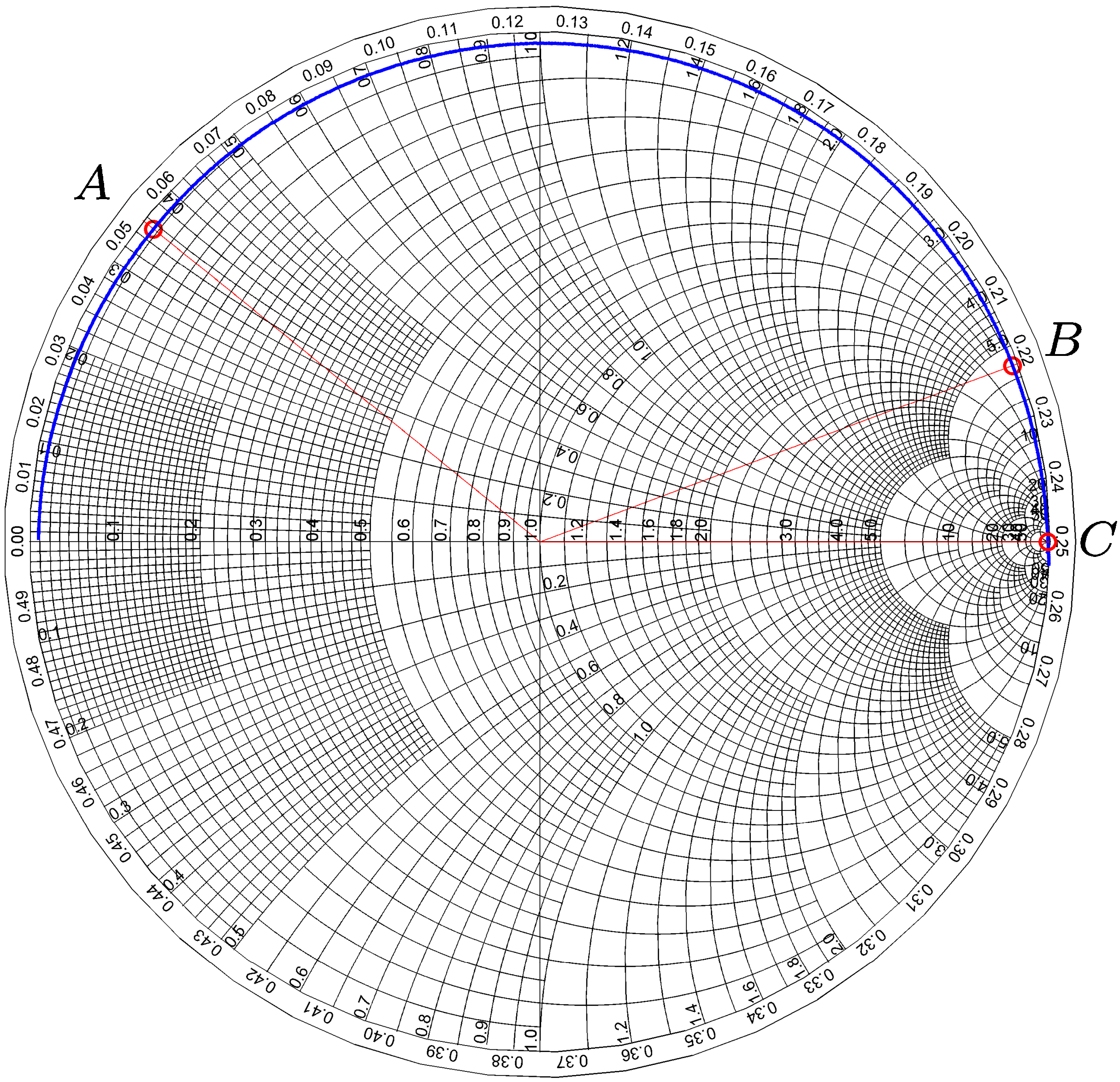

Figure 3-3: Measured reflection coefficient of the printed coil at (A) 1 MHz, (B) 13.56 MHz and (C) 35.02 MHz

At the typical operating frequency of the RFID system the following reflection coefficient is measured:

$$f_B = 13.56 \text{ MHz} \qquad (3\text{-}1)$$

$$r_B = 0.9263 + j0.3453 \qquad (3\text{-}2)$$

With this reflection coefficient the complex impedance of the antenna can be calculated at this frequency.

$$z_B = z_0 \, \frac{1+r_B}{1-r_B} \text{ where } z_0 = 50\ \Omega \qquad (3\text{-}3)$$

$$z_B = R_B + jX_B = 9.12 + j276.95\ \Omega \qquad (3\text{-}4)$$

To calculate the values of the elements from the series equivalent circuit the complex impedance at two characteristic frequencies is considered.

First the impedance at a frequency of 1 MHz (marked in the Figure 3-2 with an *A*) is used to get the serial resistance and inductance of the coil. For this low frequency it is possible to neglect the parallel capacitance.

$$f_A = 1 \text{ MHz} \tag{3-5}$$

$$z_A = R_s + jX_a = 0.729 + j17.72\ \Omega \tag{3-6}$$

$$R_s = 0.729\ \Omega \tag{3-7}$$

$$L_a = \frac{X_a}{2\pi f_A} \tag{3-8}$$

$$L_a = \frac{17.72\ \Omega}{2\pi\ 1\ \text{MHz}} = 2.82\ \mu\text{H} \tag{3-9}$$

The second characteristic frequency point is determined by the resonance frequency of the coil. At this point the reactance is zero and it is possible to determine the parallel capacitance of the coil together with the already calculated inductance of the coil at 1 MHz. The measured effective resistance at the resonance frequency describes the eddy current losses of the coil and will also be considered in the equivalent circuit.

$$f_C = 35.02 \text{ MHz} \tag{3-10}$$

$$z_C = R_p = 24151\ \Omega \tag{3-11}$$

$$C_a = \frac{1}{(2\pi f_C)^2 L_a} \tag{3-12}$$

$$C_a = \frac{1}{(2\pi\ 35.02\ \text{MHz})^2\ 2.82\ \mu\text{H}} = 7.33\ \text{pF} \tag{3-13}$$

In a next step the parallel resistor caused by eddy current losses has to be transformed to a serial resistance to get the values of the serial equivalent circuit.

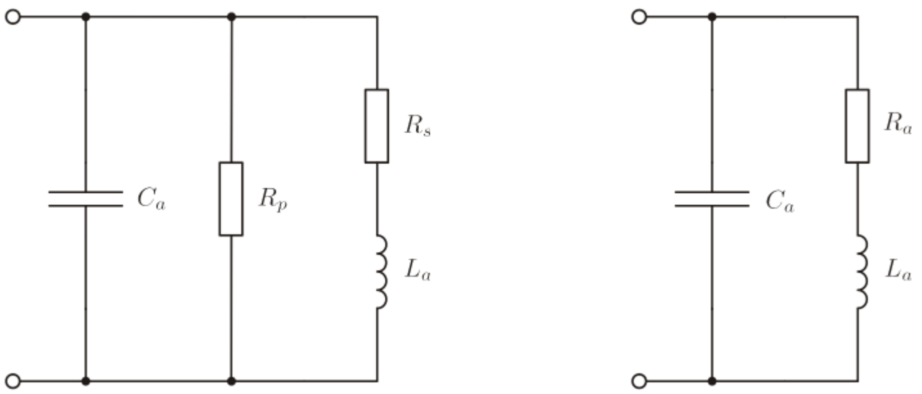

Figure 3-4: equivalent circuits of the printed coil

$$R_a = R_s + \frac{(2\pi f_B L_a)^2}{R_p} \quad \text{3-14}$$

$$R_a = 0.729\ \Omega + \frac{(2\pi\ 13.56\ \text{MHz}\ 2.82\ \mu\text{H})^2}{24151\ \Omega} = 3.12\ \Omega \quad \text{3-15}$$

Finally we get the values of all elements of the series equivalent circuit:

$$L_a = 2.82\ \mu\text{H} \quad \text{3-16}$$

$$R_a = 3.12\ \Omega \quad \text{3-17}$$

$$C_a = 7.33\ \text{pF} \quad \text{3-18}$$

4. Calculating the matching network

To get best performance of the RFID reader it is necessary to match the reader coil to the output impedance of the RFID reader chip at the operating frequency. The RFID reader chip impedance value is 50 Ω. By using a three element matching network it is possible to connect the antenna coil without any reflections to the RFID reader chip and additionally the operating bandwidth of the RFID system can be defined with the Q-factor of the circuit. This is necessary because the operating bandwidth of the RFID system is up to 2 MHz and can be defined by the Q-factor of the antenna.

In Figure 4-1 the matching network is shown. With the resistance R_Q it is possible to define the Q-factor and the two capacitors transform the complex impedance of the coil to the desired impedance of 50 Ω at the operating frequency.

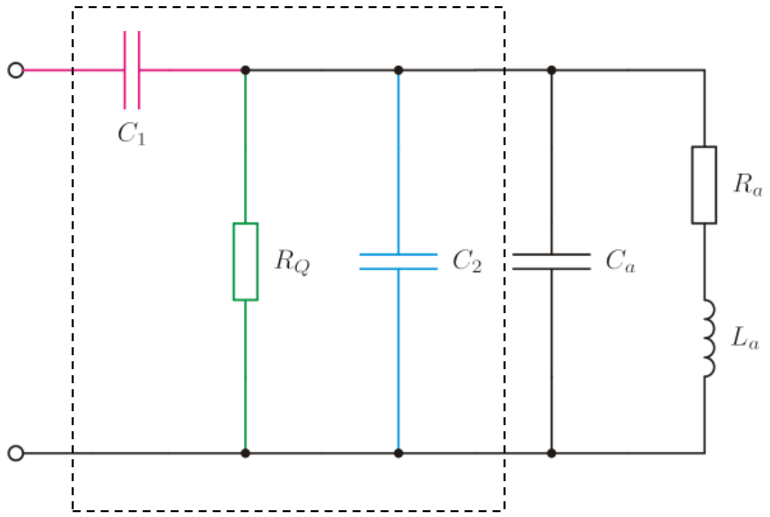

Figure 4-1: Matching network

The matching procedure for this matching network is explained in the Figure 4-2 with a Smith chart. The complex impedance at the operating frequency of the printed coil which has to be matched is marked with an *A* in Figure 4-2. The capacitor C_2 (marked blue) transforms the impedance to the point *B* depending on the value of C_2. The resistor R_p (marked green) defined by the operating bandwidth transforms the impedance to the point *C*. This point C is located on a circle with the property real(z) = 1. From point *C* to *D* the serial capacitor C_1 is used to reach the matching point.

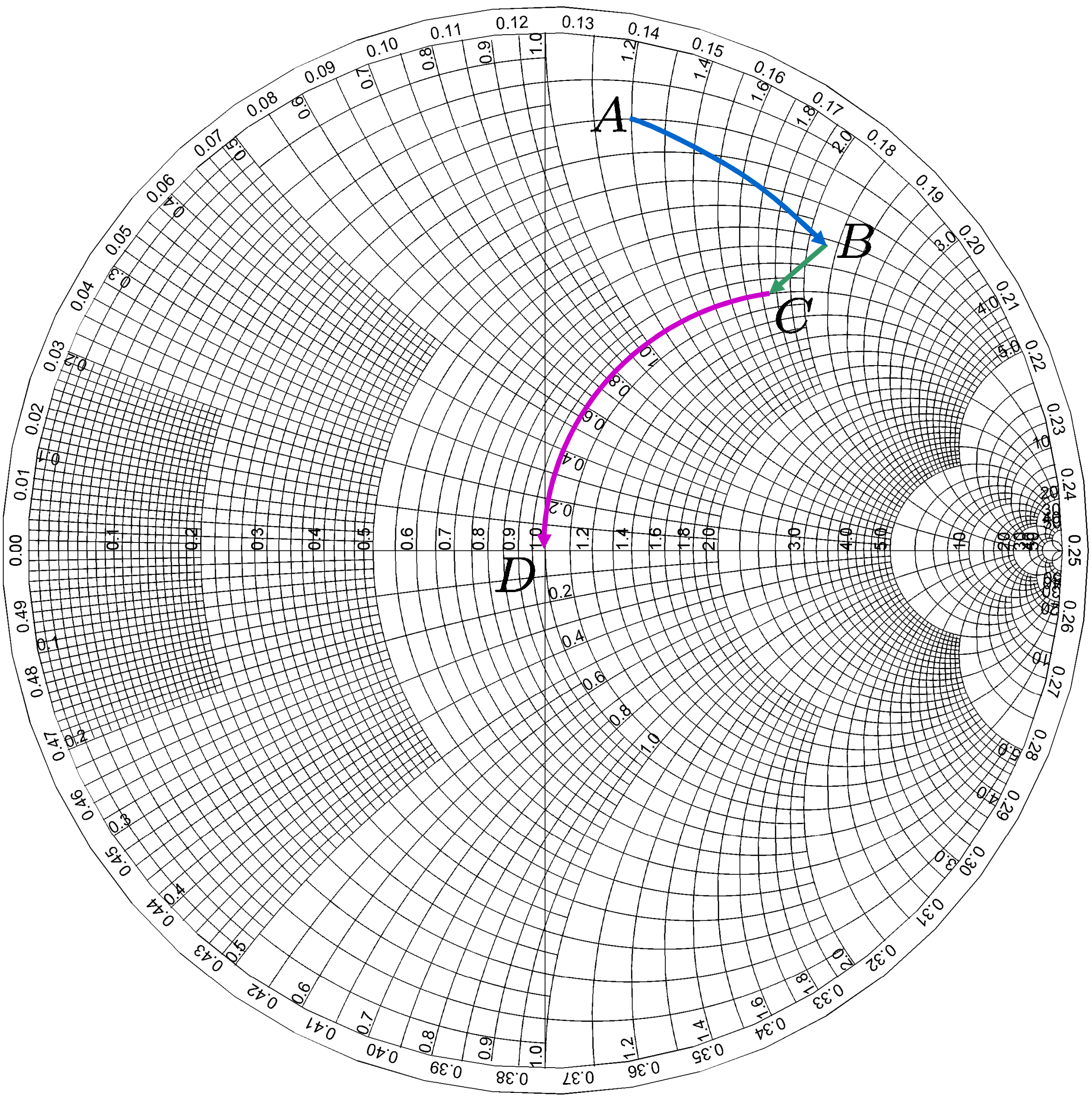

Figure 4-2: Matching procedure

With value of the Q-factor can be calculated with

$$Q = \frac{F_0}{BW} \quad \text{4-1}$$

$$Q = \frac{13.56\ \text{MHz}}{2\ \text{MHz}} = 2\ \text{MHz} = 6.78 \quad \text{4-2}$$

So it is possible to calculate the value of the resistor in the matching network.

$$Q = \frac{R_Q}{X_L} \quad \text{4-3}$$

$$R_Q = QX_L \quad \text{4-4}$$

$$R_Q = 6.78 \cdot 276.95\ \Omega = 1877.72\ \Omega \quad \text{4-5}$$

The described matching method in now used to match the measured coil antenna to the RFID reader chip and to determine the needed values of the capacitors in the matching network. In Figure 4-3 the resulting smith chart for this matching procedure is shown.

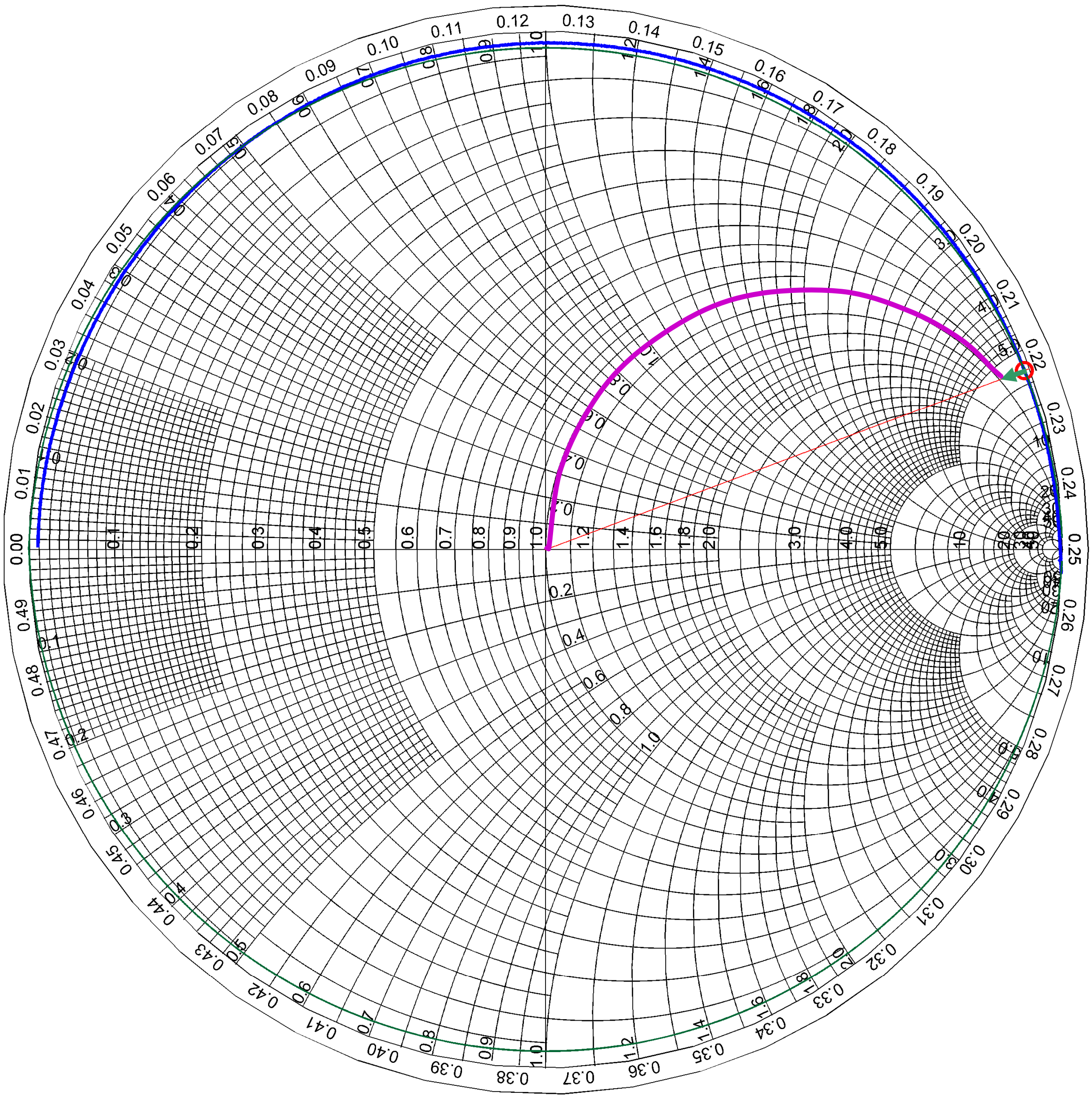

Figure 4-3: Matching procedure for the measured coil

5. Measurement of the coil with the matching network

The last step is to verify the matching circuit with the vector network analyzer Bode 100. In Figure 5-1 the measured reflection of the matching circuit is shown. The impedance at the output of the network is almost in the matching point at the operating frequency of 13.56 MHz. The differences to the calculated value are caused by the tolerances of the used capacitors.

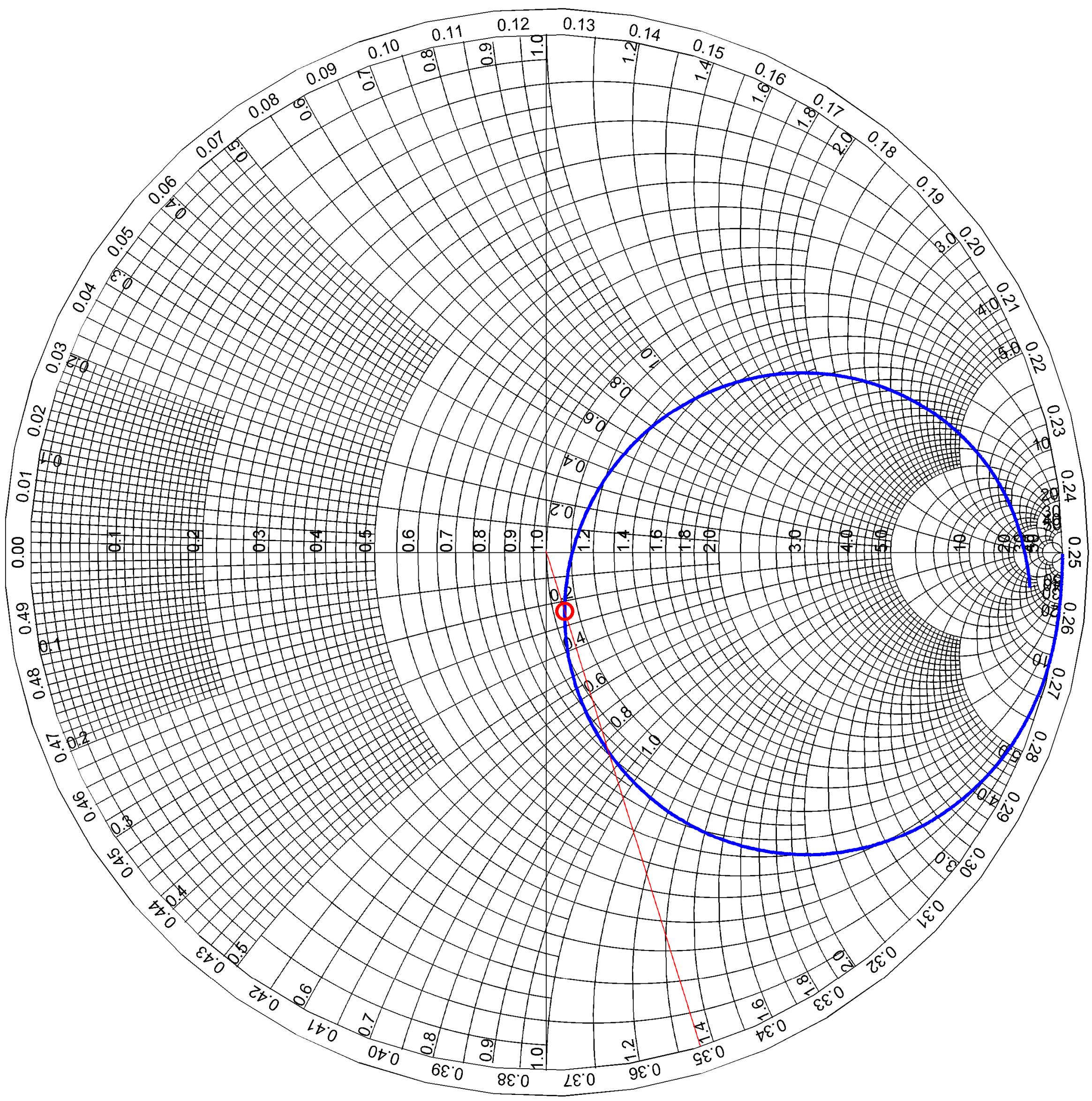

Figure 5-1: Measurement of the reflection coefficient of the coil with the matching network

6. Conclusion

With the vector network analyzer Bode 100 the series equivalent circuit of a printed coil can be determined easily. So it is possible to make complex simulations in a microwave simulation tool like ADS. Furthermore the complex impedance of the coil can be matched to the output of the RFID reader chip with an easy method based on a Smith chart. The vector network analyzer Bode 100 can be used to verify the calculated matching circuit together with the antenna coil very fast.

It has to be mentioned that it is easy to store and export the measurement data in a comma separated file. This function was used to export the measurement data to Matlab and allowed us to analyze and plot the Smith chart with this program. In short with this function it is possible to make powerful analysis of the data with any mathematical tool, for example with Matlab.