AN142522

RF Amplifier for NXP Contactless NFC Reader IC's

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Document information

Info	Content
Keywords	RFID, Antenna Design, RF Amplifier, Antenna Matching, contactless reader, NFC
Abstract	This application notes provides guidance on antenna and RF amplifier design for NXP contactless NFC reader devices, such as PN5xx and NXP contactless reader devices, such as MFRC52x.

founded by Philips

Revision history

Rev	Date	Description
1.0	20070801	Initial Version
2.1	20081020	Filter at RX removed, Tuning impedance changed
2.2	20081125	Minor changes on explanatory text

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1. Introduction

1.1 Purpose and Scope

Some of NXP contactless NFC reader IC's are designed for handheld devices and low power consumption which results in shorter read range performance. An RF amplifier can extend the usage of such devices to meet requirements for higher transmission performance and communication distance.

This application note is intended to give a practical guide to extend and optimize the transmission power performance and communication distance of NXP contactless NFC reader IC's. The document describes the design and dimension of antennas and RF amplifier circuits.

1.2 Reference documents

1. NFC specific datasheet
2. ISO/IEC 14443
3. ISO/IEC 18092: Near Field Communication – Interface and Protocol (NFCIP-1)

1.3 Reference Simulation Tools

1. RFSim99

2. How to use this document

The application note gives a practical guide to design antennas, calculate the matching components as well as implement an RF amplifier for NXP contactless NFC reader IC. It gives a guideline for complete RF circuit design, an introduction to the overall antenna design theory for RFID systems as well as a description of the transmitter matching resistance. Finally the matching procedure is described using a reference antenna which is connected to the amplifier circuit.

A guideline is given to design an antenna and the RF amplifier circuitry together with a tuning procedure. The guideline covers the following items:

2. RF field generation and data transmission
   a. Fig 1 shows the recommended amplifier circuit with all relevant components required to connect an antenna to NXP´s contactless NFC reader IC's. This circuit must not only ensure that energy and data can be transmitted to the target device but must also be designed to receive a target device´s answer.
   b. The antenna design part describes how to calculate the inductance of the antenna coil and gives basics hints on symmetry and environmental influences to be taken into consideration. The equivalent circuits and the relevant formulas are given as preparation for these calculations.
   c. Formulas to calculate the amplifier and the matching circuit
   d. Antenna tuning procedure
3. Receiver part
   a. Design and calculation of the receiver circuit.
4. Examples on how to calculate the RF parts for a given antenna design and given contactless reader IC.

Note: This application note cannot and does not replace any of the relevant datasheets.

Note: The term "Card" used in this document refers to a contactless smart card according to the ISO14443 or a contactless smart card according to the FeliCa scheme.

Note: Design hints on how to place the components on a PCB are not included.

Note: All tuning and measurement of the antenna always has to be performed at the final mounting position to consider all parasitic effects like metal influence on quality factor, inductance and additional capacitance.

3. Block Diagram

The amplifier solution is designed to communicate in four different reader/writer operating modes:

- Reader/Writer mode for communication with devices compliant to ISO/IEC14443A/B
- Reader/Writer mode for communication with devices compliant to MIFARE®
- Reader/Writer mode for communication with devices compliant to FeliCa
- NFCIP-1 mode for communication to NFC devices

The following requirements have to be met by the amplifier circuit for NXP contactless reader:

- **Generate the RF field**: The generated magnetic field has to be maximized considering the limits of the transmitter supply current and general emission limits.
- **Transmit data**: The coded and modulated data signal has to be transmitted in a way, that every card and NFC device is able to receive it. The signal shape and timing has to be considered.
- **Receive data**: The response of a card or NFC device has to be transferred to the receive input of the PN5xx considering the datasheet limits like maximum voltage and receiver sensitivity.

The operating distance of NXP contactless NFC reader IC's depends on:

- matching of the antenna,
- sensitivity of the receiver,
- antenna size used in the reader system,
- antenna size of the communication partner and
- external parameters (e.g. metallic environment and noise).

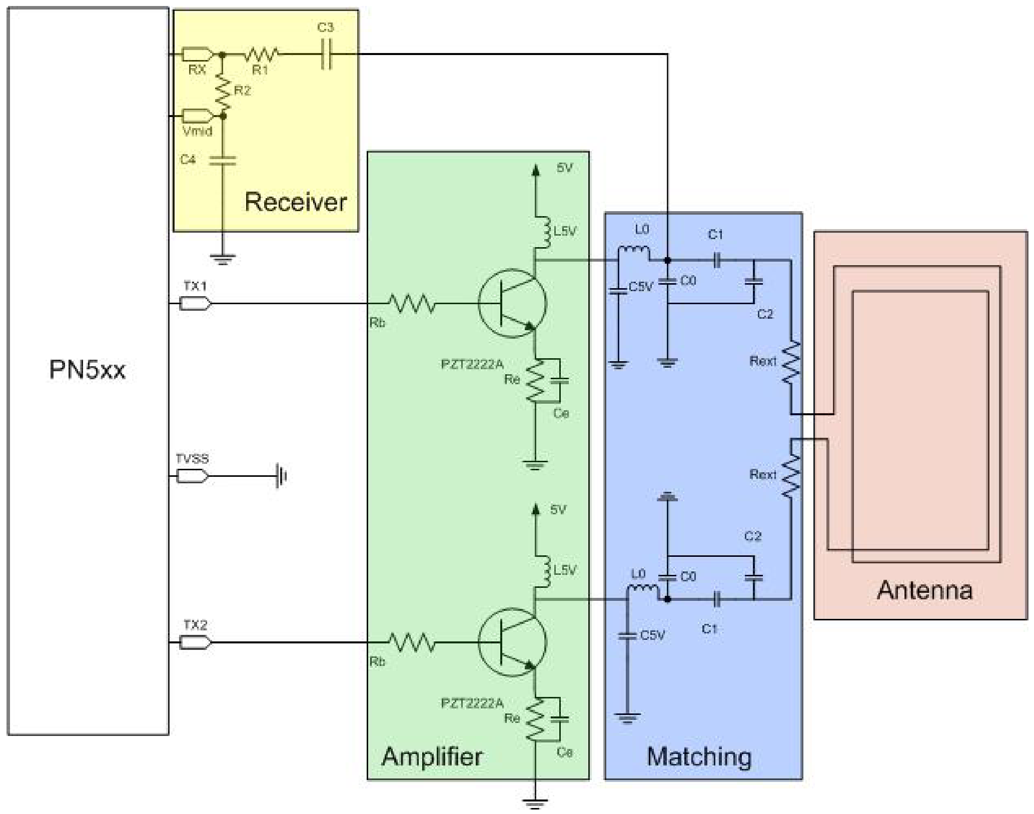


Fig 1. Block diagram of the complete RF part

Note: Fig 1 shows the RF part only. For proper operation, the analog and digital supplies plus the host interface also have to be connected to power supply.

Although some of theses blocks may contain only a few passive components, it is important to consider all blocks and complete functionality to guarantee proper function of the complete device:

- The amplifier uses a transistor circuit to amplify the digital signal of the NXP contactless reader IC.
- The matching circuit acts as an impedance transformation block.
- The EMC filter as part of the matching circuit reduces the 13.56 MHz harmonics and performs an impedance transformation.
- The antenna coil itself generates the magnetic field.
- The receiver part provides the received signal to the NXP contactless reader internal receiver stage.

Basically, the complete RF circuitry consists of eleven capacitors, five inductors, eight resistors, two transistors and the symmetrical antenna coil.

Note: A center tap connection of the antenna may be neglected without negative influence on the EMC performance of the circuitry.

4. Description of Symmetric Amplifier

The colored boxes as well as the schematic in Fig 1 show the different parts of the circuit. Each box will be separately discussed in the following chapters.

4.1 Matching of the symmetric amplifier – Overview

4.1.1 Amplifier Circuit

The Amplifier Circuit (TX-Path) (green box in Fig 1) consists of two emitter amplifiers where the transistors are used as a switch. The TX1 and the TX2 output of the NXP contactless reader chip generates a digital signal which is amplified by the transistors. The signal is directly connected to the matching circuit.

Note: The PN5xx has two transceiver pins: TX1 and TX2. By using the amplifier solution, the contactless reader transmission mode should be switched to *asynchronous mode*. This is done by setting the register 0x14 (TXControlReg) to 0x83.

The emitter amplifier consists of a resistor R_b which is connected to the base of the transistor. The resistor limits the current into the base. The collector of the transistor is connected via an AC – decoupling inductor (L5V) to the power supply. The quality factor of this inductor has to be at least more that 20 at 13.56MHz. At the same time the inductance L5V, in combination with C5V interacts as a 13.56 MHz oscillator. The resistor R_e and the capacitor C_e connect the emitter to GND. The matching circuit is connected to the collector of the transistor.

Note: It is possible to use any type of transistor which has a high transition frequency, a small collector capacitance and high total power dissipation. The concrete values of these three factors depend on the requirements of the application

4.1.2 Antenna Matching

Depending on the antenna PCB (red box in Fig 1), the necessary antenna matching (blue box Fig 1) consists of a symmetric arrangement of an EMC – filter (L0 and C0) plus a serial and parallel tuning capacitors, from the reader chip point of view. To regulate the quality factor of the antenna, the resistor R_q is added.

The capacitors and the resistors are used to both achieve the required 13.56MHz resonance frequency, and a quality factor for appropriately signal shaping according to ISO/IEC 14443.

The following equations in chapter 4.1.3 are used to calculate the matching components. Please keep in mind, that these values, slightly modified, are also required for fine tuning the components. This is necessary because of the direct influence of the amplifier circuit onto the phase shifting of the two signals on both sides of the antenna matching circuit. The maximum output is reached when the antenna is first tuned to 13.56MHz and the two ends of the antenna tuning circuit, connected to the amplifier, oscillate (in relation to GND) with 180 degree phase shift.

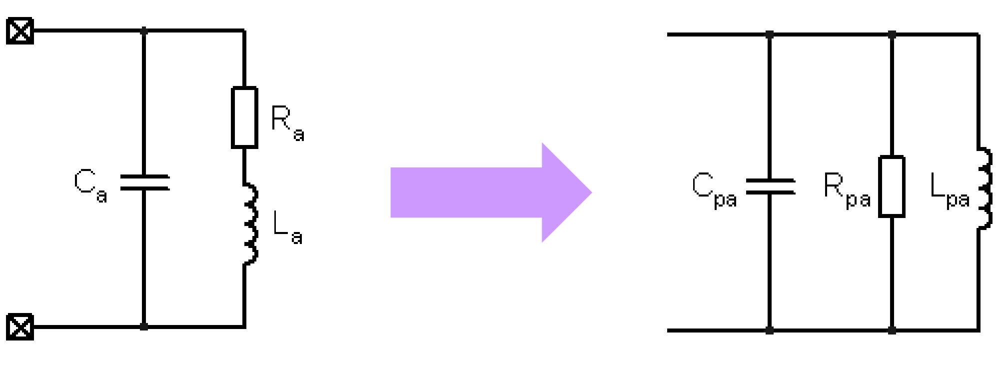
The electrical parameters of the antenna L_p, R_p and C_p have to be measured first.

Note: The matching of the antenna is very strong influenced by its environment. An assembled PCB or other metallic environment, like a display or housing will make a retuning necessary.

4.1.3 Mathematical Deduction

4.1.3.1 Calculation of the Equivalent circuit with the focus on the quality factor

Measuring the antenna by using a network analyzer or a RFA-Bridge, gives the inductance (L_a), the serial resistor (R_a), as well as the natural frequency (f_{nat}). To calculate the tuning capacitors, the components for the equivalent parallel circuit have to be calculated first.



(1) Dependent on the measurement equipment it could be necessary to calculate the equivalent circuit.

Fig 2. Conversion of a serial to a parallel Oscillator

The adjustment of the quality factor for the antenna has to be done during the calculation of the equivalent circuit. This is done by additional ohmic resistors, which changes the $R_{sges.}$ (Refer to Table 1 and chapter 6)

Table 1. Mathematical deduction to calculate the equivalent circuit

Step	Equation	Comment
1. Calculation of the R_{sges}	$$Q = \frac{\omega L_{pa}}{R_{sges}}$$	L_{pa}….Measured ω for 13.56MHz Q…chosen

Step	Equation	Comment
2. Out of R_{sges} one can calculate R_{pa}	$R_{pa} = \frac{(\omega L_{pa})^2}{R_{sges}}$	L_{pa}…done R_{pa}…done
3. Calculation of C_{pa}	$fnat = \frac{1}{2\pi\sqrt{(L_{pa} \cdot C_{pa})}}$	f_{nat}… Mearsured L_{pa}….Measured C_pa…done

4.1.3.2 Calculation of the tuning capacitors

Due to the filter structure, it is necessary to split the circuit to calculate the tuning capacitors. $R_{match} = Z_{match} <= 180$ Ohm

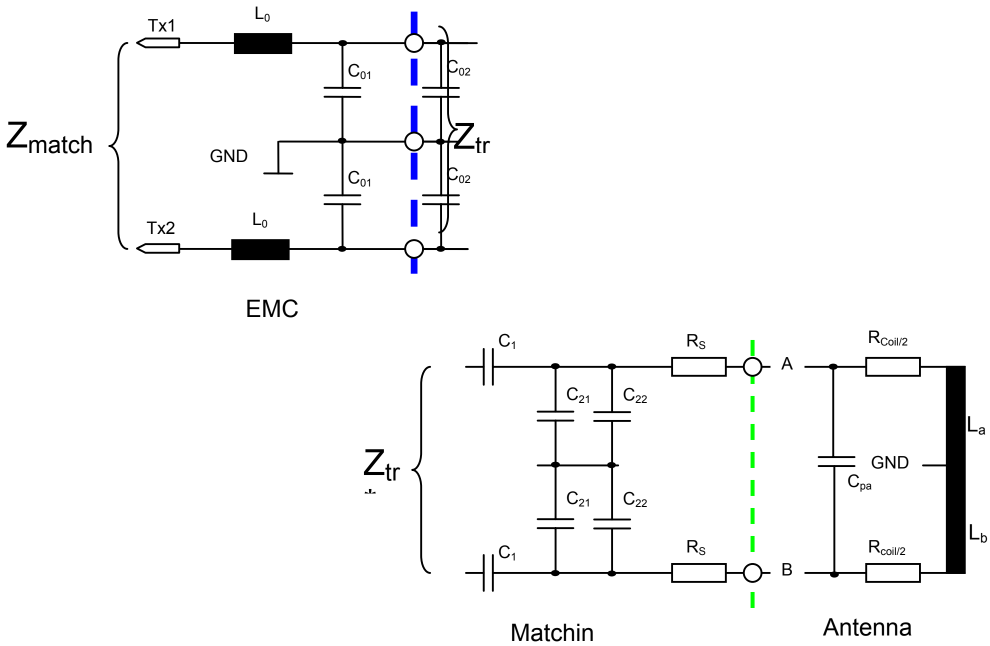


Fig 3. Split of the matching circuit because of the filter structure

$$Z_{tr} = R_{tr} + jX_{tr}$$

$$R_{tr} = \frac{R_{match}}{\left(1-\omega^2 \cdot L_0 \cdot C_0\right)^2 + \left(\omega \cdot \frac{R_{match}}{2} \cdot C_0\right)^2}$$

$$X_{tr} = 2 \cdot \omega \cdot \frac{L_0 \cdot \left(1-\omega^2 \cdot L_0 \cdot C_0\right) - \frac{R_{match}{}^2}{4} \cdot C_0}{\left(1-\omega^2 \cdot L_0 \cdot C_0\right)^2 + \left(\omega \cdot \frac{R_{match}}{2} \cdot C_0\right)^2}$$

Fig 4. Equations to calculate the tuning capacitors (part 1)

The split of the matching circuit allows calculating the matching capacities with following equations.

$$C_1 \approx \frac{1}{\omega \cdot \left(\sqrt{\frac{R_{tr} \cdot R_{pa}}{4}} + \frac{X_{tr}}{2} \right)}$$

$$C_2 \approx \frac{1}{\omega^2 \cdot \frac{L_{pa}}{2}} - \frac{1}{\omega \cdot \sqrt{\frac{R_{tr} \cdot R_{pa}}{4}}} - 2 \cdot C_{pa}$$

Fig 5. Equations for the calculation of the tuning capacitors (part 2)

Note: For calculating the tuning capacities NXP provides an Excel sheet [1] where all this calculations are done automatically.

4.1.4 Receive Path

The receiver path (yellow box at Fig 1) consists of a voltage divider and two capacitors. The capacitor C_3 is necessary to decouple DC voltage and the following resistor R_3 limits the voltage to prevent clipping at the R_X – pin of the NXP contactless reader IC.

To guarantee a well tuned receiver circuit, one needs to consider both: the voltage level and also the receive threshold. Refer also to the data sheet of the contactless reader IC.

5. Antenna Design

5.1 Antenna Inductance

The following two sections show the formulae to estimate the antenna inductance in free air.

To estimate antenna values under influence of metal (such as shielding planes or batteries in devices) simulation software is required which can calculate the antennas parameters in these environments.

5.1.1 Circular Antennas

The inductance can be estimated by the following formula (see also Fig 6):

$$L_a[nH] = \frac{24.6 \cdot N_a^{\ 2} \cdot D[cm]}{1 + 2.75 \cdot \dfrac{s[cm]}{D[cm]}} \qquad (1)$$

D Average antenna diameter

s Antenna width

N_a Number of turns

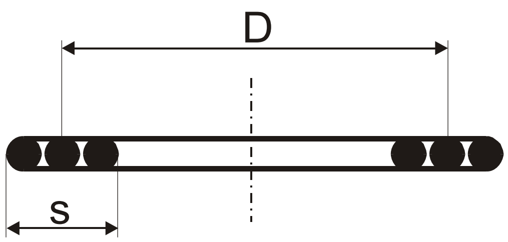


Fig 6. Circular Antenna

5.1.2 Rectangular Antennas

The inductance can be calculated by following formula (see also Fig 7):

$$L_a = \frac{\mu_0}{\pi} \cdot [x_1 + x_2 - x_3 + x_4] \cdot N_a^{\ 1.8} \qquad (2)$$

Table 2. Calculations for rectangular antenna

With:	
$d = \frac{2 \cdot (t + w)}{\pi}$	
$a_{avg} = a_o - N_a \cdot (g + w)$	$b_{avg} = b_o - N_a \cdot (g + w)$
$x_1 = a_{avg} \cdot \ln\left[\frac{2 \cdot a_{avg} \cdot b_{avg}}{d \cdot \left(a_{avg} + \sqrt{a_{avg}^2 + b_{avg}^2}\right)}\right]$	$x_2 = b_{avg} \cdot \ln\left[\frac{2 \cdot a_{avg} \cdot b_{avg}}{d \cdot \left(b_{avg} + \sqrt{a_{avg}^2 + b_{avg}^2}\right)}\right]$
$x_3 = 2 \cdot \left[a_{avg} + b_{avg} - \sqrt{a_{avg}^2 + b_{avg}^2}\right]$	$x_4 = \frac{a_{avg} + b_{avg}}{4}$

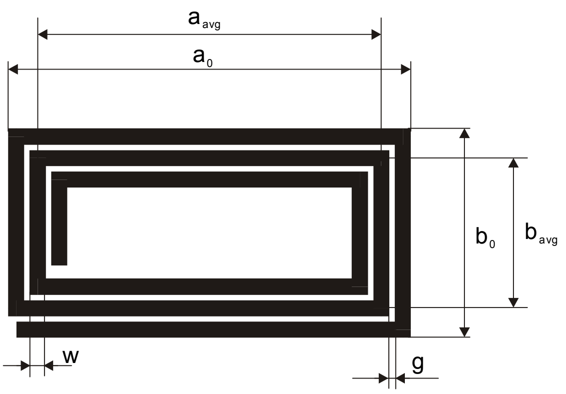


Fig 7. Rectangular antenna

Variables:

a_o, b_o	Overall dimensions of the coil
a_{avg}, b_{avg}	Average dimensions of the coil
t	Track thickness
w	Track width
g	Gap between tracks
N_a	Number of turns
d	Equivalent diameter of the track

5.2 Number of Turns

Depending on the antenna size, the number of turns should be chosen in a way to achieve an antenna inductance between 300 nH and 3 μH.

The parasitic capacitance should be kept as low to achieve a self-resonance frequency > 35 MHz.

For many applications and antenna sizes, the number of turns will be in the range **N_a = 1 - 6**.

A low number of turns is preferred to minimize the effects of coupling between antennas. The lower the numbers of turns are used, the smaller will be the influence of coupled devices such as a card or a 2^{nd} NFC device in “Card Mode”. It is especially important to minimize the detuning effect on the 1^{st} device in very close proximity between the antennas where this coupling has maximum impact. The overall performance loss due to low number of turns is negligible.

5.3 Antenna Quality Factor

The quality factor reflects the stored energy in the antenna. When the Q – factor is high the antenna needs more time to react on modulation, but radiates more energy. This directly influences the shaping of the radiated and modulated signal and the operating volume.

The bandwidth B –pulse width multiplied by T is defined as:

$$B \cdot T \geq 1 \tag{3}$$

With the bandwidth definition

$$B = \frac{f}{Q} \tag{4}$$

B multiplied by T results into

$$Q \leq f \cdot T$$
$$Q \leq 13.56 MHz \cdot 3 \mu s$$
$$Q \leq 40.68$$

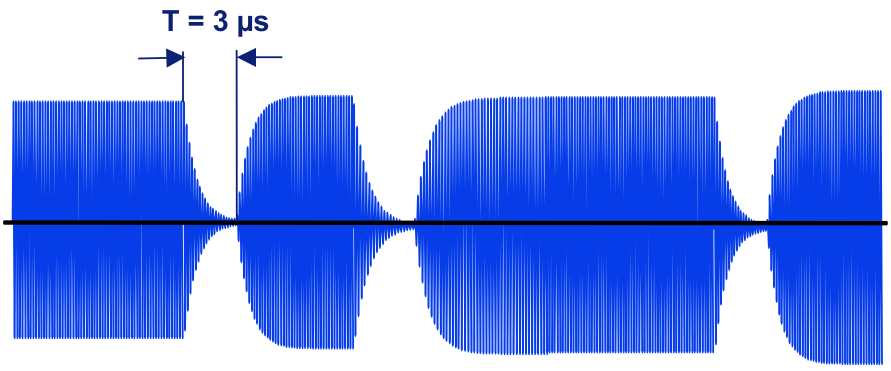


Fig 8. Pulse width definition

The recommended antenna quality factor to be used is defined to be **Q_a <= 30.**

6. Implementation Guideline

This chapter explains a step by step process to design and tune the amplifier circuit.

6.1 Antenna and tuning circuit

The example uses an antenna PCB with the size of 84 mm x 64 mm and 2 turns.

6.1.1 Measurement of the Antenna

Measure the inductance L_{pa}, the serial resistance R_s and the self-resonance frequency f_{nat} of the antenna with a network analyzer or equivalent equipment.

The example antenna has following values:

Table 3. Measured Values of Sample Antenna

Antenna	Value
L_{pa}	811nH
$R_{sAntenna}$	370mΩ
$f_{nat\ (of\ the\ Antenna)}$	89.7MHz

6.1.2 Calculation of the Resistance of the Equivalent Circuit

Calculation of the additional resistor R_{ext}, for a quality factor of 25
(refer to Table 1: Mathematical deduction to calculate the equivalent circuit).

A quality factor of 25 was chosen to guarantee the needed shaping for the modulation.

$$R_{sges} = \frac{\omega L_{pa}}{Q} = \frac{2 * \pi * 13.56MHz * 811nH}{25} = 2.76Ohm$$

$$R_{ext} = \frac{R_{sges} - R_{sAntenna}}{2} = \frac{2.76Ohm - 0.37Ohm}{2} = 1.2Ohm$$

Table 4. Description of the ohmic resistors for the sample antenna

Name	Description
$R_{sAntenna}$	Ohmic resistance of the Antenna; measured
R_{ext}	Additional calculated resistors needed to reach the quality factor Q of 25
R_{sges}	Complete resistance consist of the $R_{sAntenna}$ + 2* R_{ext}

6.1.3 Calculate out of R_{sges} the equivalent R_{pa}

$$R_{pa} = \frac{(\omega L_{pa})^2}{R_{sges}} = \frac{(2*\pi*13.56MHz*811nH)^2}{2.76Ohm} = 1.73kOhm$$

6.1.4 Calculation of the Parallel Capacity of the Antenna.

$$Cpa = \frac{1}{\omega_{nat}{}^2 Lpa} = \frac{1}{(2*\pi*89{,}7MHz)^2*811nH} = 3.88pF$$

Note: The capacitance is a behavior of the antenna and is calculated using the measured inductance and “natural frequency” of the antenna.

6.1.5 Calculation of the tuning Capacitances

$$C1 = \frac{1}{\omega \cdot \sqrt{\frac{R_{tr} \cdot R_{pa}}{4}} + \frac{X_{tr}}{2}} \approx 68pF$$

$$C2 = \frac{1}{\omega^2 \cdot \frac{L_{pa}}{2}} - \frac{1}{\omega\sqrt{\frac{R_{tr} \cdot R_{pa}}{4}}} - 2 \cdot C_{pa} \approx 280pF$$

Note: NXP provides an Excel sheet [1] to calculate the tuning capacitors

6.1.5.1 Simulation

The simulation shows the arrangement of the matching circuit plus its smith chart

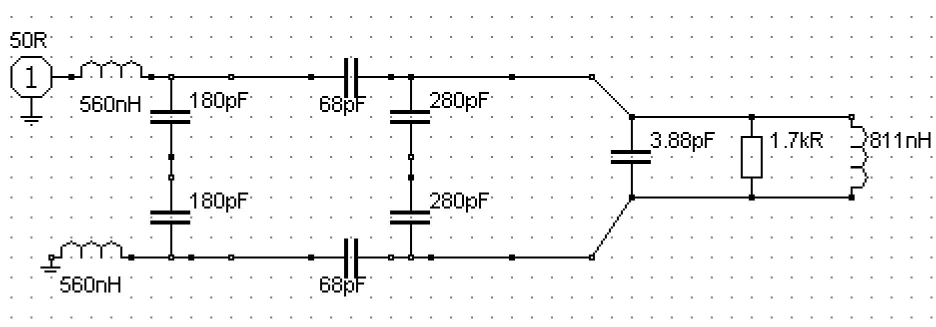
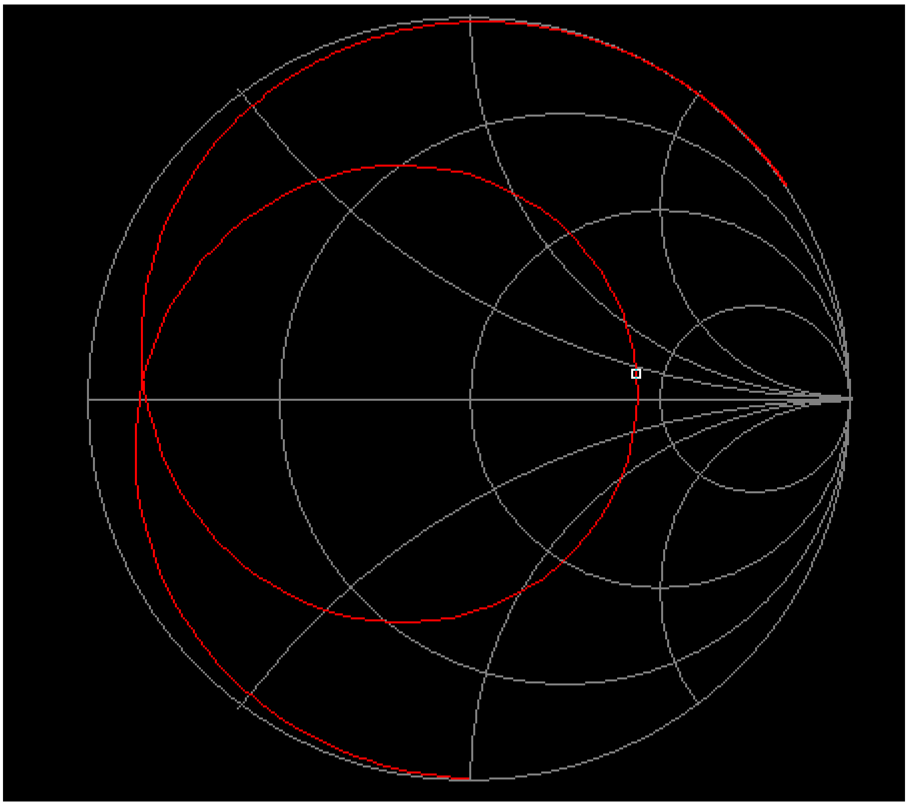


Fig 9. Simulation of the matching circuit



(1) Smith chart 10MHz to 30 MHz; Marker Z= 124,5 Ohm at 13.56MHz

Fig 10. Smith chart of the simulation

Table 5. Values of the Tuning Circuit

Component	Value
R_{ext}	1.2Ohm
C1	68pF
C2	280pF
C0	180pF
L0	560nH

6.2 Amplifier Circuit

The amplifier circuit (refer to Fig 11) consists of a symmetric arrangement of emitter amplifiers followed by a filter. The resistor R_b at the transistor base controls the input current. The components C_e and R_e in the emitter path of the transistor stabilize the biasing of the transistor. R_e limits the current and C_e acts in combination with R_b as a low pass. The antenna is connected to the collector and AC- decoupled connected to the power supply.

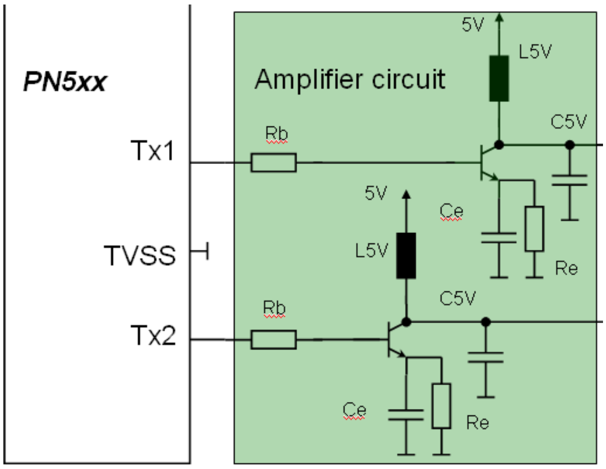


Fig 11. Amplifier Circuit

The main element of the amplifier is a symmetric arrangement of emitter amplifier.

The L_{5V} decouples the AC-signal from the DC- supply. It also acts in combination with C5V as a 13.56MHz oscillator to filter the digital signal coming from TX of the NXP contactless reader IC. To keep this decoupling as stable as possible, a quality factor of Q < 30 is recommended.

The antenna is connected to the collectors of the transistors.

Table 6. Component Values of the Receive Path

Components for receive filter	Values
R_b	22Ohm
C_e	22pF
R_e	18Ohm
L_{5V}	1,5uH, Q>=20 @ 13.56MHz
C_{5V}	91pF
T_1, T_2	PZT2222A

6.3 Receive Path

C_3 decouples the DC-voltage. The resistors R_1 and R_2 limit the voltage to prevent clipping at the Rx – pin of the NXP contactless reader IC.

Note: The voltage at R_X should never be higher than 3 Vpp (measured with a low capacitance probe). Increase the resistor R_1 if the voltage is too high.

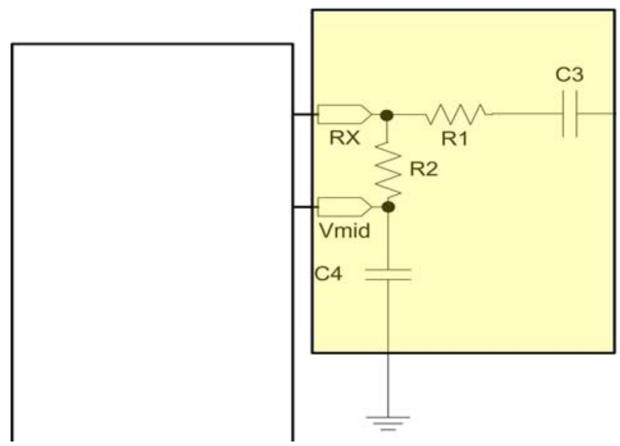


Fig 12. Receive path

Table 7. Component Values of the Receive Path

Components for receive filter	Values
R_1	3.3kOhm
R_2	1kOhm
C_3	1nF
C_4	100nF

6.4 Summary

6.4.1 Component list

Following Table 8 shows the component values of the complete amplifier circuit by using the antenna parameters found in 6.1.1.

Table 8. Values of the amplifier circuit

Components	Values
C_0	180pF
C_1	68pF
C_2	280pF
C_3	1nF
C_4	100nF
C_{5V}	91pF
C_e	22pF
L_0	560nH
L_{5V}	1.5uH, Q>=20 @ 13.56MHz
R_1	3.3kR
R_2	1kR
R_b	22R
R_e	18R
T_1, T_2	PZT2222A

7. Fine Tuning

A well matched antenna can be achieved by fine tuning the circuit. The adjustments needed to be done are based on the receiving and matching block.

- The resistor R_1 in the receiving path, in combination with R_2, is a voltage divider which regulates the voltage level at the R_X pin. The voltage level should not exceed 3 Vpp, but should be maximized for optimum R/W performance. The measurement of the voltage level at the R_X pin needs to be done with a low capacitance probe. Furthermore, those measurements needs to be done in the final housing/position as well as with different loads (targets) which detune the antenna and affects the RX signaling.
- In order to optimize the antenna tuning bring the antenna into its final housing/position and tune the antenna by changing C_1, C_2 and C_0. The optimum matching impedance for the antenna differ from design to design, but should be in the range between Z=100± j0 (@13.56 MHz) and Z=180± j0 (@13.56 MHz). A good starting point would be at Z=150± j0 (@13.56 MHz).

8. References

[1] AN166510 – Amplifier antenna matching calculation

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