AN2866
Application note

How to design a 13.56 MHz customized tag antenna

Introduction

RFID (radio-frequency identification) tags extract all of their power from the reader's field. The tags' and reader's antennas form a system of coupled inductances as shown in *Figure 1*. The loop antenna of the tag acts as a transformer's secondary.

The efficient transfer of energy from the reader to the tag depends on the precision of the parallel resonant RLC loop antennas tuned to the carrier frequency (usually 13.56 MHz).

The purpose of this application note is to give a step-by-step procedure to easily design a customized tag antenna.

Figure 1. RFID tag coupled to a reader's magnetic field

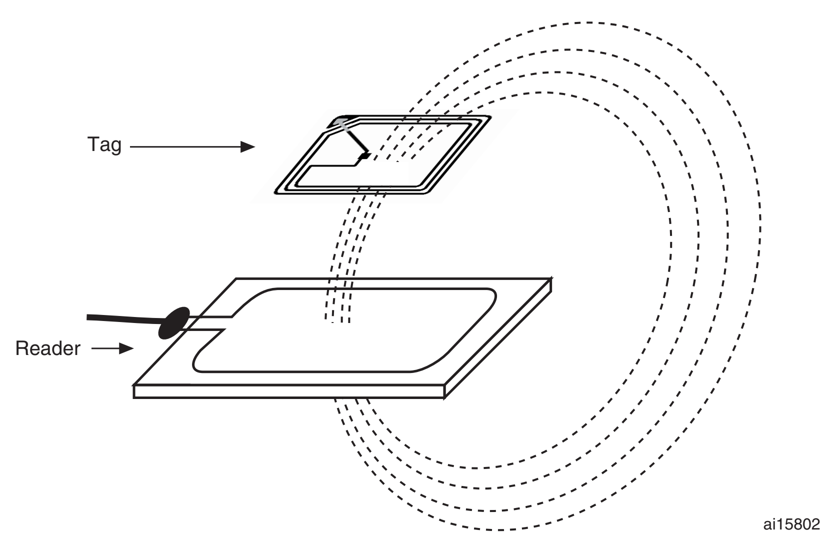
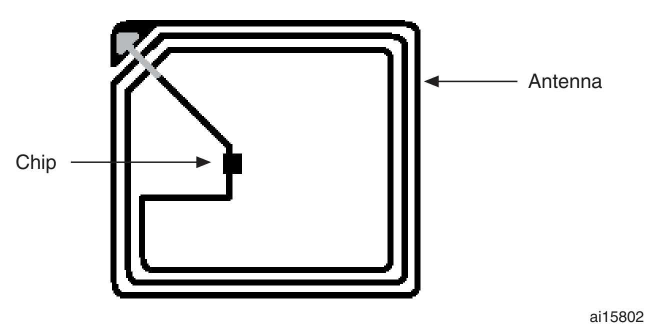


Figure 2. An antenna designed for a specific chip and frequency



Contents

List of tables

List of figures

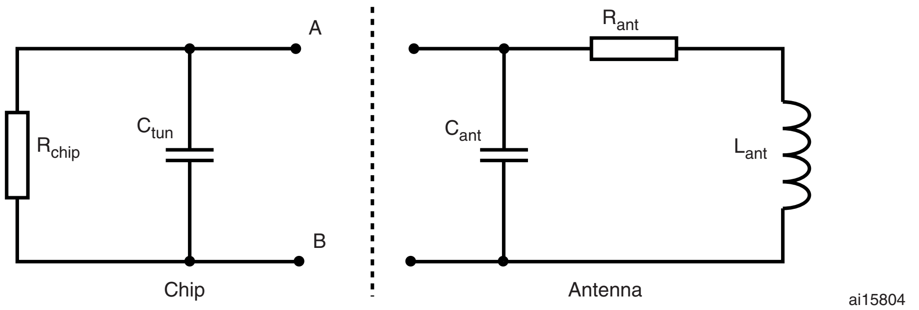
1 Simplified equivalent inlay circuit

The chip and its antenna can be symbolized using their equivalent electrical circuit.

Figure 3 shows the equivalent electrical circuit of the chip (parallel association of a resistance which emulates the current consumption of the chip and a capacitance added to the chip to ease tuning).

The antenna is a wire, so its equivalent electrical circuit is a wire with a resistance symbolized by R_{ant}. The antenna also has an inductance denoted by L_{ant}. The capacitance C_{ant} is the representation of parasitic elements (produced by the bridge).

Figure 3. Equivalent circuit of a chip and its antenna



2 Equivalent inlay circuit

The schematic shown in *Figure 3* is but a first approach to the problem because it does not take into account the connection between the chip and the antenna. The assembly phase of the chip onto the antenna may lead to the introduction of parasitic elements. These parasitic elements are symbolized by two resistances and a capacitance as shown in *Figure 4* and *Figure 5*.

The equivalent circuit of the antenna may include either a series (see *Figure 4*) or a parallel (see *Figure 5*) resistance.

Figure 4. Equivalent circuit of a chip, its antenna (modeled with a series resistance) and connections

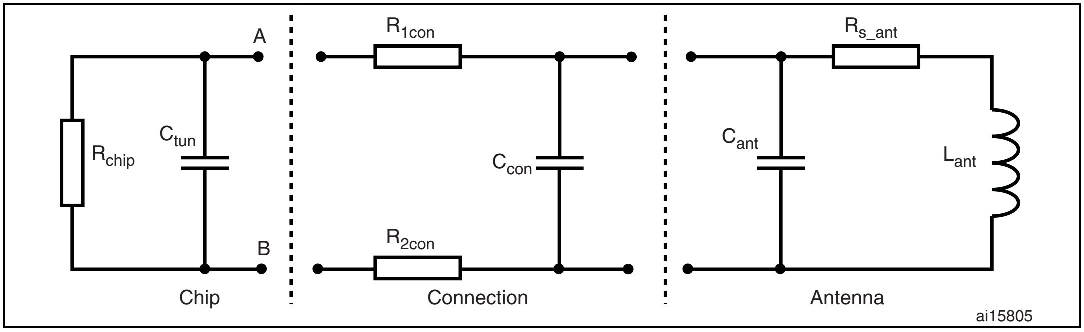
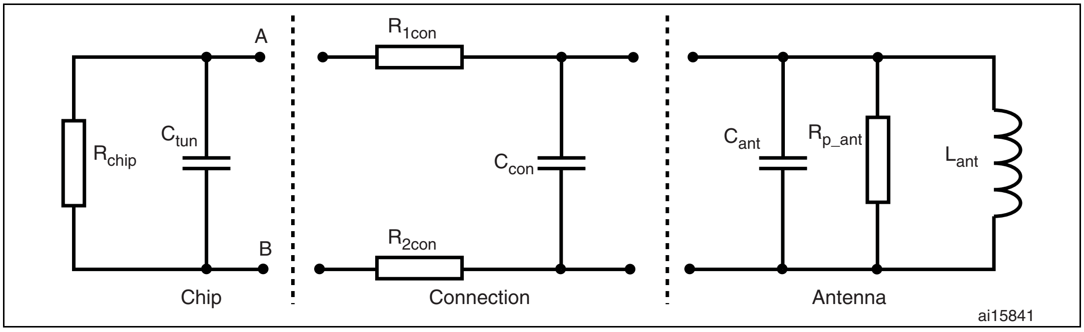


Figure 5. Equivalent circuit of a chip, its antenna (modeled with a parallel resistance) and connections



The symbols in *Figure 4* and *Figure 5* correspond to:

R_{chip}: current consumption of the chip for a given power value

C_{tun}: tuning capacitance of the chip

R_{con}: equivalent parasitic resistance generated by the connection between the chip and the antenna

C_{con}: equivalent parasitic capacitance generated by the connection between the chip and the antenna

C_{ant}: equivalent parasitic capacitance of the antenna coil

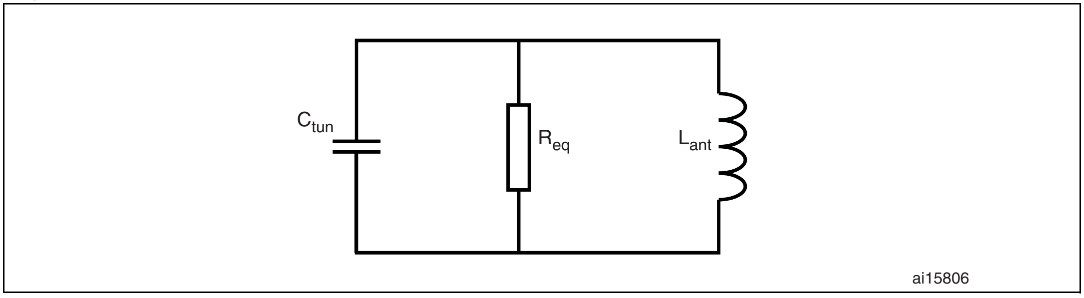
R_{s_ant}: Antenna coil series resistance

R_{p_ant}: Antenna coil parallel resistance

L_{ant}: Antenna coil inductance

This equivalent circuit (*Figure 4*) can also be simplified as illustrated in *Figure 6* (use the simplified circuit for calculations).

Figure 6. Simplified equivalent circuit of a chip, its antenna and connections



R_{eq} is calculated as follows:

$R_{eq} = \frac{R_{chip} \times R_{p\_ant}}{R_{chip} + R_{p\_ant}}$ with $R_{p\_ant} = R_{s\_ant} \times \left(1 + \left(\frac{L_{ant} \times \omega}{R_{s\_ant}}\right)^2\right)$ where ω is the angular frequency.

3 Calculating the antenna coil inductance

The resonant frequency f_0 of a parallel resonant LC circuit can be calculated by:

$$f_0 = \frac{1}{2\pi\sqrt{L_{ant} \cdot C_{tun}}}$$

The coil inductance at the carrier frequency resonance is: $L_{ant} = \frac{1}{(2\pi f_0)^2 \cdot C_{tun}}$.

The quality factor Q of the simplified circuit is calculated as follows: $Q = \frac{R_{eq}}{2\pi \cdot f_0 \cdot L_{ant}}$.

Example of the calculation of an antenna coil inductance:

$$L_{ant} = \frac{1}{(2\pi \times 13.56\ \text{MHz})^2 \cdot 21\ \text{pF}} = 6.56\ \mu\text{H}$$

Table 1. Antenna coil inductances for different C_{tun} values at a given tuning frequency

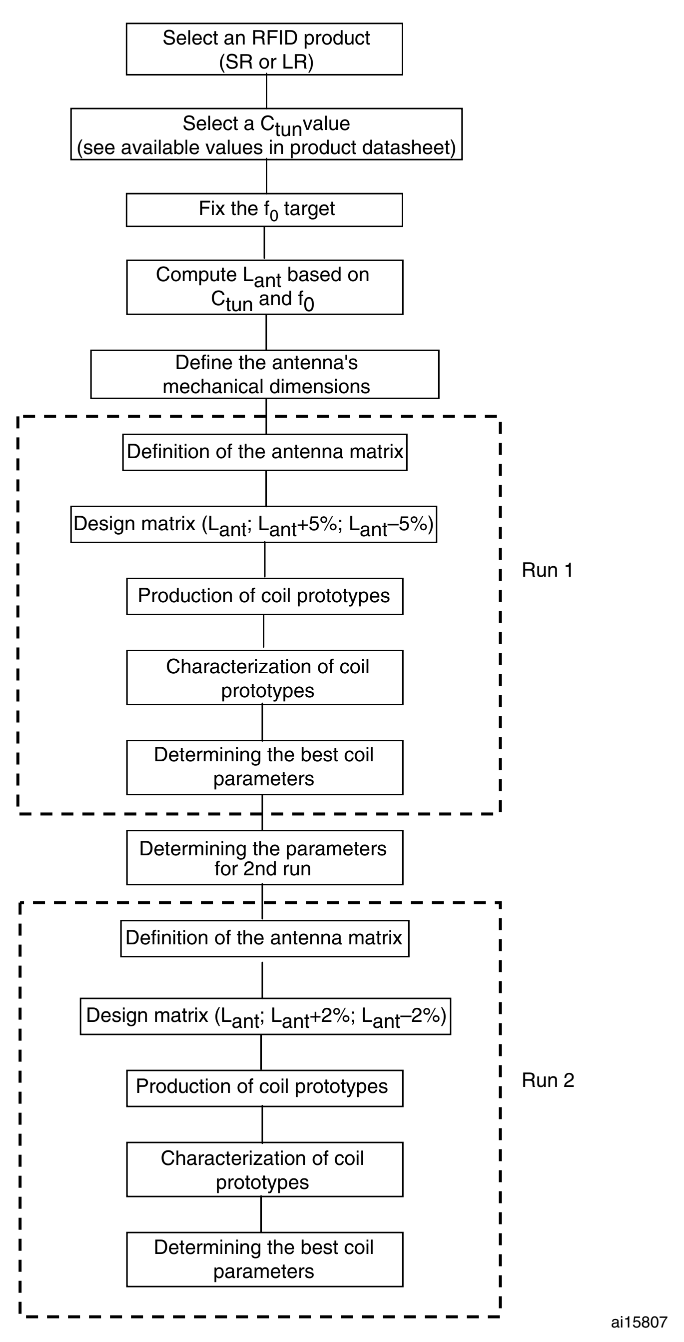
Product	C_{tun} (pF)	Tuning frequency (MHz)	Antenna coil inductance (µH)
LR (long-range)	21	13.56	6.56
	28.5	13.56	4.83
	23.5	13.56	5.86
	97	13.56	1.42
SR (short range)	64	13.56	2.15
	64	14.40	1.90

Figure 7 describes the steps of the antenna design procedure that gives an easy and reliable method of designing an antenna coil prototype.

This procedure uses the C_{tun} capacitance of the chip, a software tool called **antenne.exe**, and tools to produce antenna coil prototypes.

By determining dimensions and values, the execution of the first run gives the best out of three coils meeting the requirements. Usually, the best results appear after the second run.

Figure 7. Antenna design procedure



4 Designing the antenna coil

In the paragraphs below, the antenna inductance is calculated for different types of antenna coils.

4.1 Inductance of a circular loop

$L_{ant} = \mu_0 \times N^{1.9} \times r \times \ln\left(\frac{r}{r_0}\right)$, where:

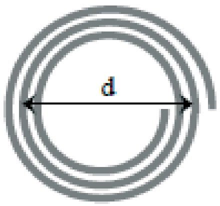
- r is the mean coil radius in millimeters
- r_0 is the wire diameter in millimeters
- N is the number of turns
- $\mu_0 = 4\pi \cdot 10^{-7}$ H/m
- L is measured in Henry

4.2 Inductance of a spiral coil

$L_{ant} = 31.33 \times \mu_0 \times N^2 \times \frac{d}{8d + 11c}$, where:

- d is the mean coil diameter in millimeters
- c is the thickness of the winding in microns
- N is the number of turns
- $\mu_0 = 4\pi \cdot 10^{-7}$ H/m
- L is measured in Henry

Figure 8. Spiral coil



ai15812

4.3 Inductance of an antenna with square coils

$L_{ant} = K1 \times \mu_0 \times N^2 \times \frac{d}{1 + K2 \cdot p}$, where:

- d is the mean coil diameter
  d = $(d_{out} + d_{in})/2$ in millimeters, where: d_{out} = outer diameter
  d_{in} = inner diameter
- p = $(d_{out} - d_{in})/(d_{out} + d_{in})$ in millimeters
- K1 and K2 depend on the layout (refer to *Table 2* for values)

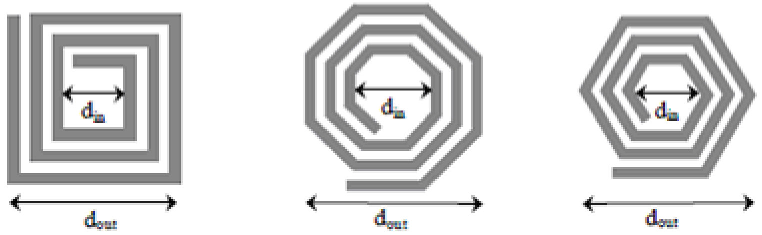


Figure 9. Square coils

Table 2. K1 & K2 values according to layout

Layout	K1	K2
Square	2.34	2.75
Hexagonal	2.33	3.82
Octagonal	2.25	3.55

The software tool (**antenne.exe**) uses the Grover method (see *Equation 1: : Grover method*) to calculate the inductance of rectangular planar antennas. *Figure 10* shows the software user interface.

The software gives a good approximation of the antenna inductance L_{ant}. This can be checked by comparing the software results to measurements of the inductance of a real antenna on an impedance meter.

Equation 1: Grover method

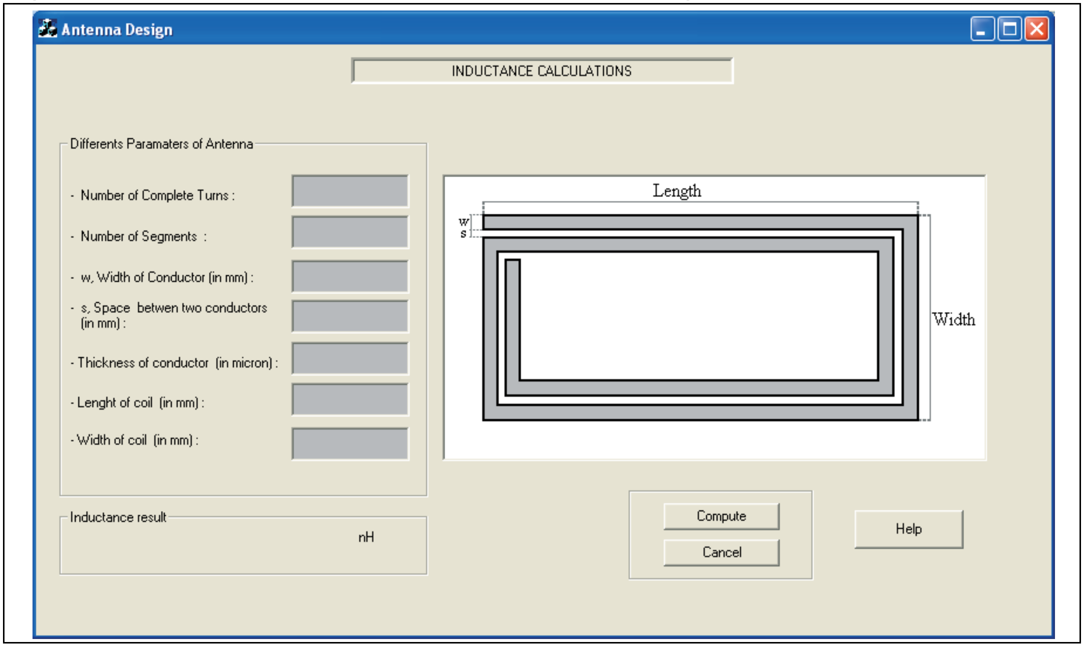
$L_{ant} = L_0 + \sum M$, where:

- M is the mutual inductance between each of the antenna segments
- L_0 is as defined in *Equation 2*

Equation 2: $L_0 = \sum_{j=1}^{s} L_j$, where:

- s is the number of segments
- L_j is the self inductance of each segment

Figure 10. User interface screen of the planar rectangular coil inductance calculator



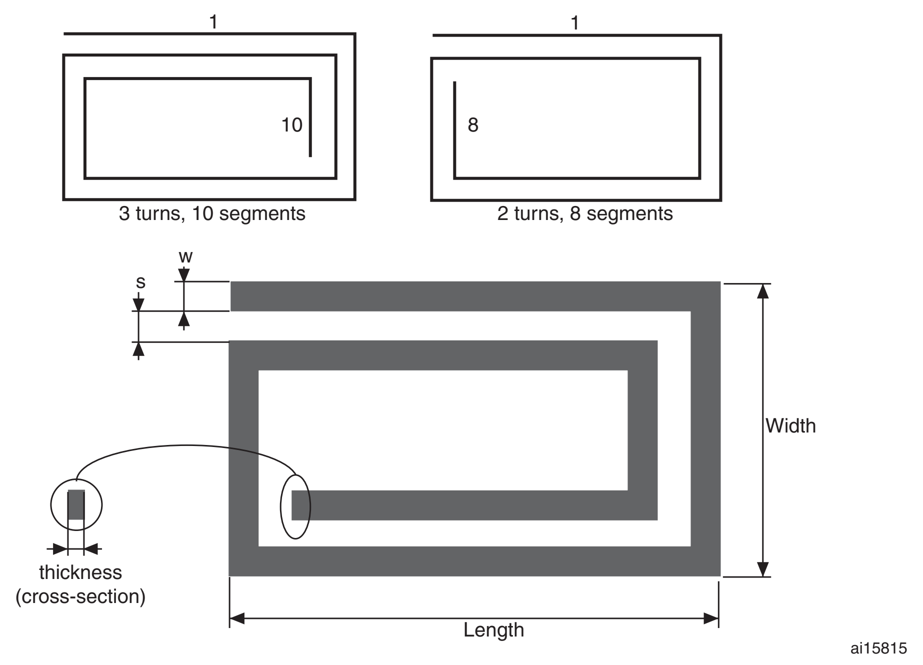
Examples:

The following antenna parameters have to be fed to the software to compute the antenna coil inductance:

- the number of turns
- the number of segments
- w: the conductor width in millimeters
- s: the conductor spacing in millimeters
- the conductor thickness in micrometers)
- Length in millimeters
- Width in millimeters

The number of turns is incremented each time a segment is added to a complete turn.

Figure 11. Rectangular planar antennas



Once the antenna coil inductance has been calculated, a prototype coil is realized. The value of the so-obtained prototype must then be validated by measurement. This can be done using either a contactless or a non-contactless method. *Section 5* and *Section 6* describe these methods.

5 Contactless measurement method

This section describes a contactless verification method of antenna coil prototypes. The results presented here are based on a short-range (SR) tag antenna initially designed to have the following characteristics:

- Antenna dimensions: 38 mm × 38 mm (A3)
- Tuning frequency: 14.4 MHz

5.1 Antenna coil prototype verification with an analyzer

Equipment needed:

- Impedance analyzer
- Prototype antenna coil
- Reference capacitor

The equivalent circuit of the antenna coil can be determined using the appropriate measuring instruments (see *Figure 12*) and following the instructions described in *Section 5.1.2*.

5.1.1 Preparing the equipment and connections

The reference capacitor is used to simulate the presence of the chip on the prototype coil. Connect it to the coil using an appropriate test fixture (to have as little interference as possible). The coil is now ready for measurements.

This example measurement uses the 7405-901 Eaton/Alitech (singer) 6 cm loop probe connected to the reflection interface of the Hp 8712ET network analyzer.

Figure 12. Measurement equipment


Network analyser

Loop probe

Antenna coil prototype
+ reference capacitor

ai15816

5.1.2 Instructions

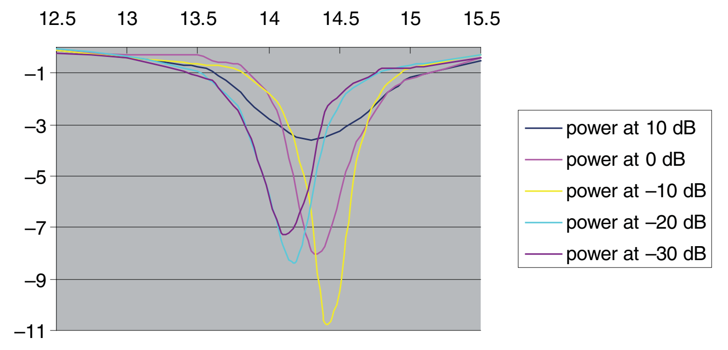
The network analyzer must be in reflection mode.

Measurement conditions (case of a short-range RFID tag):

- Start frequency: 10 MHz
  End frequency: 15 MHz
- Power: –10 dB (which is the minimum detection level, the lowest field required to power the chip)

The coil must be in the field generated by the network analyzer via the loop probe (measurements made at about 0.5 cm from the probe).

Figure 13. Resonance traces of the prototype at different powers



5.2 Antenna coil prototype verification without an analyzer (first method)

There is another method of measuring the antenna coil inductance, that does not require an impedance analyzer.

Equipment needed:

- Signal generator
- Oscilloscope
- Reference capacitor
- Loop antenna

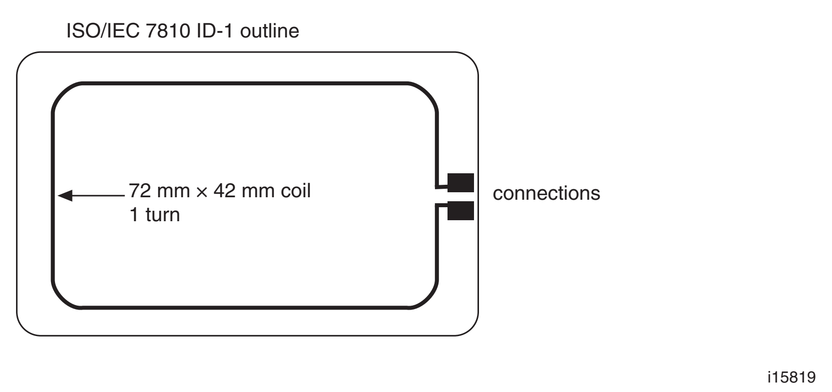
The equivalent circuit of the antenna coil can be determined using the appropriate measuring instruments (see *Figure 14*) and following the instructions described in *Section 5.2.2*.

5.2.1 Preparing the equipment and connections

The reference capacitor simulates the presence of the chip on the prototype coil. Connect it to the coil using an appropriate test fixture (to have as little interference as possible). The antenna coil is now ready for measurements.

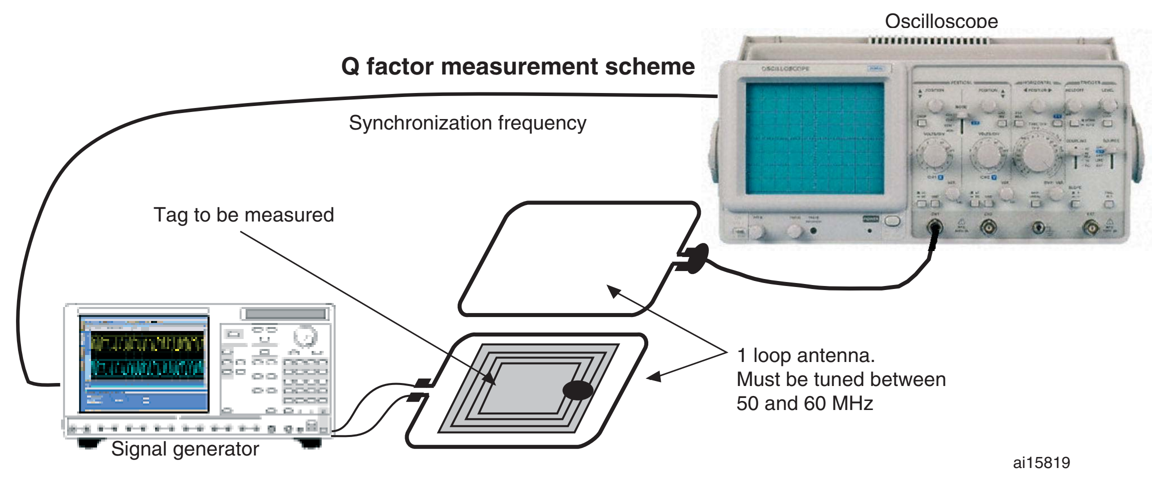
Connect an ISO 10373-7 standard loop antenna (see *Figure 13*) to the signal generator, (you may need an additional series resistor depending on the power you want to generate). The loop antenna can now generate a field.

Figure 14. ISO standard loop antenna



To make the analysis, connect a second ISO standard loop antenna (see *Figure 14*) (with a 50 Ω input resistance) to the oscilloscope, and place it in the field generated by the first loop antenna as shown in *Figure 15*. The coil prototype is coupled to the signal generator (no contact).

Figure 15. Without an analyzer: first measurement method



The measurement method is now operational.

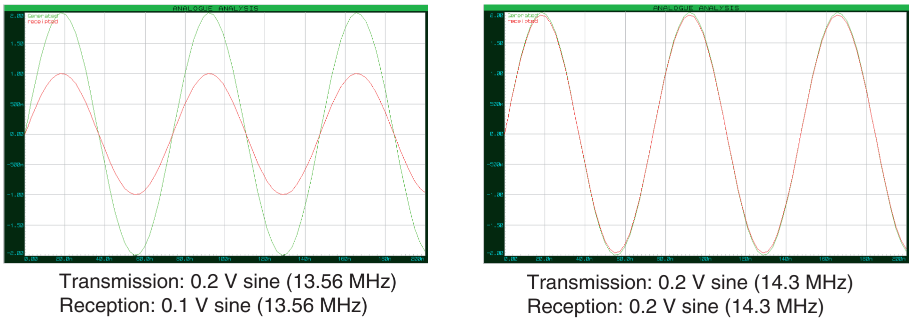
5.2.2 Instructions

To make the measurements place the prototype coil right in the transmission loop probe (with the reception loop probe at about 0.5 cm from the prototype coil).

Generate a signal (sine 13.56 MHz) at a voltage of 0.25 V (corresponds approximately to a power of –10 dB). Then vary the transmission frequency in order to obtain as high a signal level as possible on the reception side. Use the oscilloscope to determine the signal level and thus determine the resonant frequency).

Figure 16 shows two signal waveforms (the standard loop antenna transmission in green and the standard loop antenna reception in red) at different transmission frequencies.

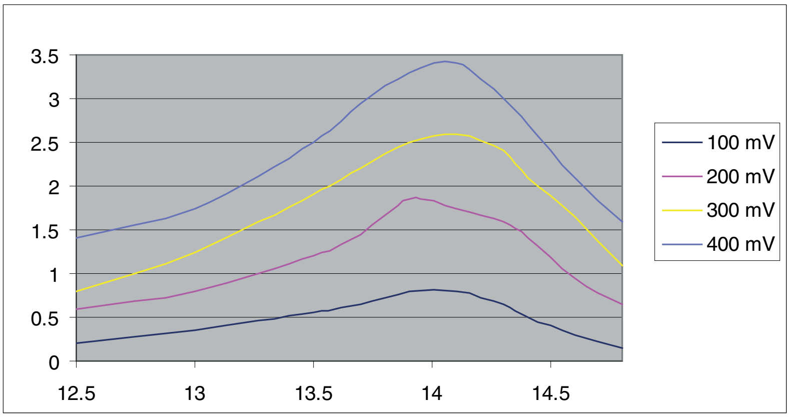
Figure 16. Oscilloscope views



ai15820

Figure 17 provides a synthesis of the measurements made. It is obtained by plotting characteristic points for different frequencies at a given voltage. Each resonance trace represents a synthesis for a definite voltage transmission.

Figure 17. Synthesis of resonance traces for different voltages



ai15821

Note: 1 Without a tag: the scope trace must be as flat as possible. It is the reason why the antenna connected to the generator must not be tuned at 13.56 MHz.

2 With a tag on the antenna: the scope trace shows the resonance of the system without any contact.

6 Non-contactless (contact) measurement method

This section describes a non-contactless verification method of antenna coil prototypes. The results presented here are based on a short-range (SR) tag antenna initially designed to have the following characteristics:

- Antenna dimensions: 38 mm × 38 mm (A3)
- Tuning frequency: 14.4 MHz

6.1 Without an analyzer (second method)

Equipment needed:

- Signal generator
- Oscilloscope
- Reference capacitor
- Loop antenna

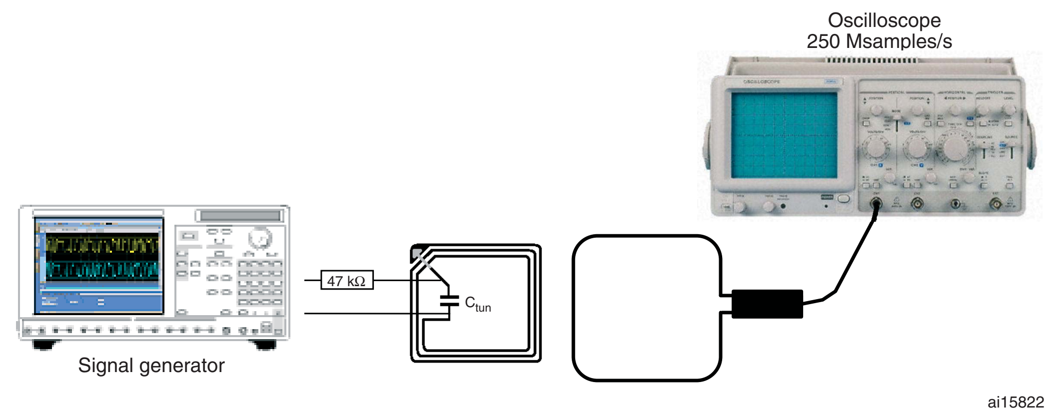
The equivalent circuit of the antenna coil can be determined using the appropriate measuring instruments (see *Figure 18*) and following the instructions described in *Section 6.1.2*.

6.1.1 Preparing the equipment and connections

The reference capacitor simulates the presence of the chip. Connect it to the coil using an appropriate test fixture (to generate as little interference as possible). The coil is now ready for measurements.

To make the analysis, connect a second ISO standard loop antenna (see *Figure 14*) (with a 50 Ω input resistance) to the oscilloscope, and place it in the field generated by the first loop antenna as shown in *Figure 18*.

Figure 18. Measurement circuit



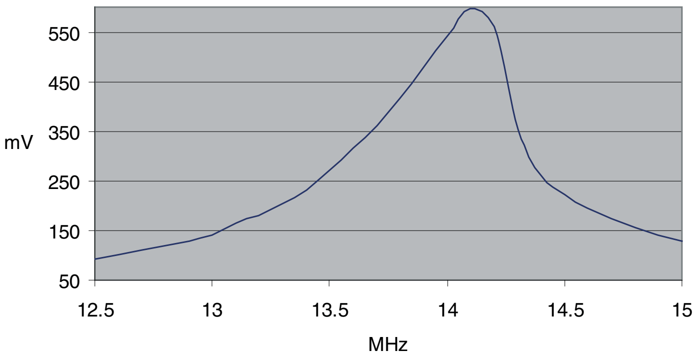
The measurement circuit is now operational.

6.1.2 Instructions

Measurements are made with the coil prototype physically connected to the signal generator.

Generate a signal (sine 13.56 MHz) at a 10 V voltage. Then vary the transmission frequency (from 12.5 MHz to 15 MHz), in order to obtain as high a signal level as possible on the reception side. Use the oscilloscope to determine the signal level and thus determine the resonant frequency (see *Figure 19*).

Figure 19. Determining the resonance frequency



6.1.3 Example using an LRI2K device

In this example, the selected device is a long-range RFID tag named LRI2K. The initial design target for the inlay antenna is:

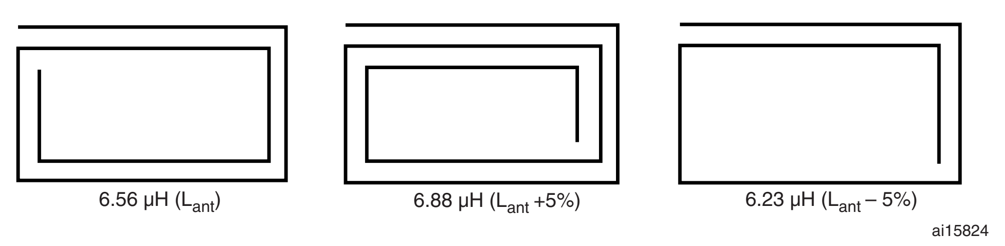
- Dimensions: the antenna must fit within an ISO ID1 format credit card
- Frequency tuning target: 13.6 MHz

Procedure

Follow the steps described below:

1. Choose the tuning capacitance of the product: 21 pF
2. Determine the objective Inductance: $L_{ant} = \frac{1}{(2\pi \cdot f_0)^2 \cdot C_{tun}} = 6.56\ \mu H$
3. Define the antenna’s mechanical dimensions: 45 × 75 (mm)
4. Definition of the test matrix: use the calculated L_{ant} value, then, take two more or less close values depending on the precision required:
   - 6.56 µH (L_{ant})
   - 6.88 µH (L_{ant} +5%)
   - 6.23 µH (L_{ant} –5%)
5. Production of antenna coil samples:

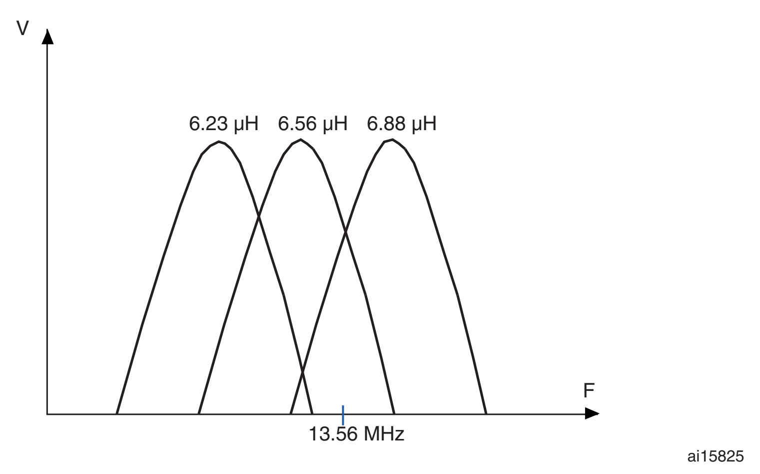
Figure 20. Coil samples



6. Characterization of antenna coil samples

   The coil samples are characterized using the Hp 8712ET analyzer in reflection mode and the 7405-901 Eaton/Alitech (singer) 6 cm loop probe. The probe generates a field and analyzes the response field.

Figure 21. Coil characterization



7. Determining the best coil parameter

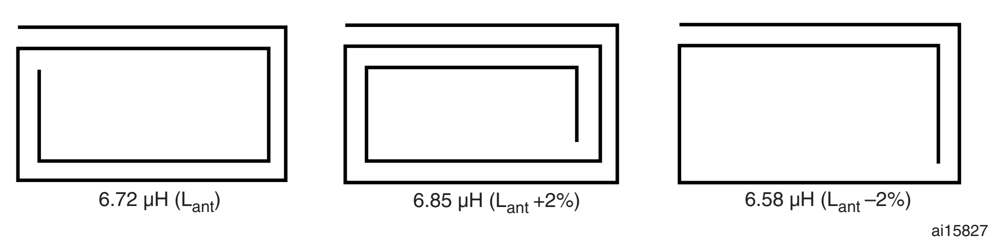
   Figure 21 shows that the ideal tuning is between L_{ant} and L_{ant} +5%.

   The average of the two is given by:

$$L_{ant} = \frac{(L_{ant}) + (L_{ant} + 5\%)}{2} = 6.72\ \mu H$$

8. Definition of the test matrix: use the new calculated L_{ant} value, then, take two more or less close values depending on the precision required:
   - 6.72 µH (L_{ant})
   - 6.85 µH (L_{ant} +2%)
   - 6.58 µH (L_{ant} –2%)
9. Production of antenna coil samples:

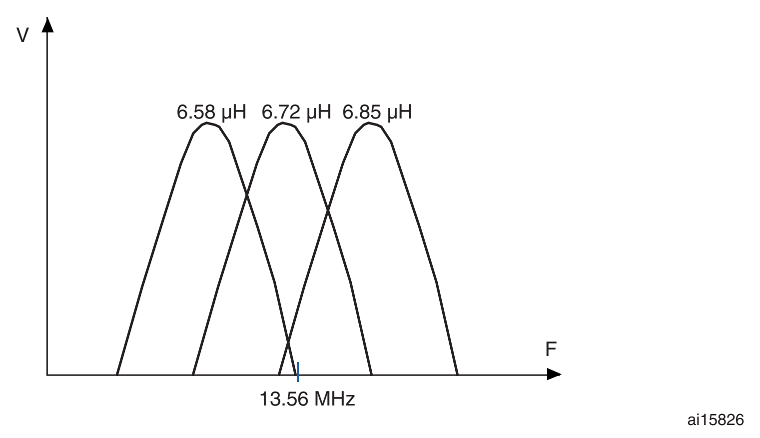
Figure 22. New coil samples



10. Characterization of the coil samples

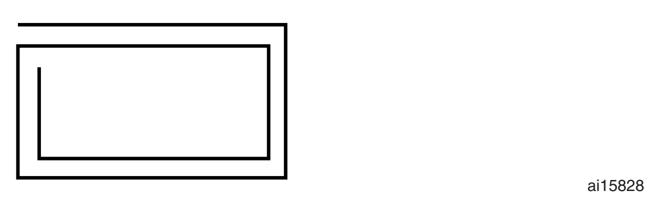
    As shown in *Figure 23*, the ideal tuning is close to L_{ant}.

Figure 23. Second coil characterization



11. Conclusion: the best coil prototype is the one tuned at a little more than 6.72 µH (illustrated in *Figure 24*).

Figure 24. Best antenna coil prototype



7 Frequency versus application: recommendations

Before designing the tag antenna it is important to know which frequency has to be used in your application.

- Long-range (LR) products are usually tuned between 13.6 MHz and 13.7 MHz (for distance optimization).
- Standard short-range SR products are usually tuned between 13.6 MHz and 13.9 MHz (for distance optimization).
- Short-range products used as transport tickets are usually tuned between 14.5 MHz and 15 MHz (for stack optimization).

These targeted frequencies should take into account the frequency shift due to the final label material and environment. Let us take the example of a sticker tag with a paper label:

> Paper and adhesive decrease the inlay antenna frequency by about 300 kHz. It is therefore necessary to tune the initial inlay at about 13.9 MHz instead of the specified 13.6 MHz.

8 Revision history

Table 3. Document revision history

Date	Revision	Changes
15-Jan-2008	1	Initial release.

Please Read Carefully:

Information in this document is provided solely in connection with ST products. STMicroelectronics NV and its subsidiaries (“ST”) reserve the right to make changes, corrections, modifications or improvements, to this document, and the products and services described herein at any time, without notice.

All ST products are sold pursuant to ST’s terms and conditions of sale.

Purchasers are solely responsible for the choice, selection and use of the ST products and services described herein, and ST assumes no liability whatsoever relating to the choice, selection or use of the ST products and services described herein.

No license, express or implied, by estoppel or otherwise, to any intellectual property rights is granted under this document. If any part of this document refers to any third party products or services it shall not be deemed a license grant by ST for the use of such third party products or services, or any intellectual property contained therein or considered as a warranty covering the use in any manner whatsoever of such third party products or services or any intellectual property contained therein.

UNLESS OTHERWISE SET FORTH IN ST’S TERMS AND CONDITIONS OF SALE ST DISCLAIMS ANY EXPRESS OR IMPLIED WARRANTY WITH RESPECT TO THE USE AND/OR SALE OF ST PRODUCTS INCLUDING WITHOUT LIMITATION IMPLIED WARRANTIES OF MERCHANTABILITY, FITNESS FOR A PARTICULAR PURPOSE (AND THEIR EQUIVALENTS UNDER THE LAWS OF ANY JURISDICTION), OR INFRINGEMENT OF ANY PATENT, COPYRIGHT OR OTHER INTELLECTUAL PROPERTY RIGHT.

UNLESS EXPRESSLY APPROVED IN WRITING BY AN AUTHORIZED ST REPRESENTATIVE, ST PRODUCTS ARE NOT RECOMMENDED, AUTHORIZED OR WARRANTED FOR USE IN MILITARY, AIR CRAFT, SPACE, LIFE SAVING, OR LIFE SUSTAINING APPLICATIONS, NOR IN PRODUCTS OR SYSTEMS WHERE FAILURE OR MALFUNCTION MAY RESULT IN PERSONAL INJURY, DEATH, OR SEVERE PROPERTY OR ENVIRONMENTAL DAMAGE. ST PRODUCTS WHICH ARE NOT SPECIFIED AS "AUTOMOTIVE GRADE" MAY ONLY BE USED IN AUTOMOTIVE APPLICATIONS AT USER’S OWN RISK.

Resale of ST products with provisions different from the statements and/or technical features set forth in this document shall immediately void any warranty granted by ST for the ST product or service described herein and shall not create or extend in any manner whatsoever, any liability of ST.

ST and the ST logo are trademarks or registered trademarks of ST in various countries.

Information in this document supersedes and replaces all information previously supplied.

The ST logo is a registered trademark of STMicroelectronics. All other names are the property of their respective owners.

© 2009 STMicroelectronics - All rights reserved

STMicroelectronics group of companies

Australia - Belgium - Brazil - Canada - China - Czech Republic - Finland - France - Germany - Hong Kong - India - Israel - Italy - Japan - Malaysia - Malta - Morocco - Singapore - Spain - Sweden - Switzerland - United Kingdom - United States of America

www.st.com