03 Loop Antennas
3rd unit in course 3, RF Basics and Components

Dipl.-Ing. Dr. Michael Gebhart, MSc

RFID Qualification Network, University of Applied Sciences, Campus 2
WS 2013/14, September 30th
Content

- What is a loop antenna?
- Production technologies
  - Etched antenna
  - Embedded wire antenna
  - Electroplated antenna
  - Printed antenna
  - Assembly
- Antenna design for Readers and Cards
  - Inductance, resistance, capacitance
- Antenna equivalent circuit element value measurement
- Ferrite foils
- Tolerances
  - Production tolerance, temperature dependency
What is a loop antenna?

The loop antenna is a distributed component with inductance (L) as main element and capacitance (C) and resistance (R) as parasitic network elements.

For simulation it must be represented by an equivalent circuit network of lumped elements. Over a wide frequency range this can be a loose coupled reactive ladder network of resonance circuits - it has several resonances in frequency domain.

At 13.56 MHz carrier frequency we use the fundamental (lowest) resonance. So we can simplify the equivalent circuit e.g. to a parallel resonance circuit (since losses are mainly determined by chip current consumption in Proximity Systems).

Note: This is a narrow-band approximation only!
Design-Targets for loop antennas

- Assuming a simplified parallel resonance circuit, the following applies:

\[ f_{\text{RES}} = \frac{1}{2\pi \sqrt{L_A C_A}} \]  
\[ Q_A = R \sqrt{\frac{C}{L}} \]  
\[ M = N \cdot I \cdot A \]

- Self-resonance shall be higher than operating frequency
  - **Cards:** target value together with chip input cap (no matching network) \( \Rightarrow L_A \)

- Quality factor shall be higher than a target value
  - **Cards:** \( Q_A > 10 Q_T \), to keep antenna losses low \( \Rightarrow R_A \) (serial \( \text{max.} \), parallel \( \text{min.} \))

- Magnetic momentum shall be high
  - allowable current (effective & reactive)
Design-Targets for loop antennas

- **Starting point for Readers:**
  - Pre-defined antenna size, antenna technology, RF power
  - Target criterions: Contactless performance Spec ($H_{MIN}$, Modulation, RX sensitivity to Load Modulation....
    - for coupling (Reader antenna to test device) and $H_{MIN}$ criterion estimate required total current (e.g. using Biot-Savart law),
    - for loop antenna size (and environment) try number of turns to meet $L_A$ range specification (e.g. NFC typ. 0.3 … 1.5 µH) ➔ antenna current
    - for protocol, data rate, modulation, etc. estimate max. $Q_{SYS}$ (@ 13.56)
    - with matching, this defines a maximum allowable $Q$ for the antenna (operating at resonance 13.56 MHz) ➔ $Q_A$ (@ 13.56) must be larger
    - Take into account coupling effects (inductance variation...)
    - Verify, if reader RF power is sufficient to operate this antenna
Production Technologies: Etching

- **Process:** Standard Printboard process. Conductor is etched out. Good design rules (0.1 mm typ.)

- **Material:** Copper, Alu (lower costs)
  - thickness: 35 µm, 20 µm, 16 µm, 8 µm, ...

- **Assembly:** Copper allows welding, crimping, soldering and conductive glueing. Conductive glueing can be problematic for Alu because of corrosion, soldering is not possible.

- **Performance:**
  - Low parasitic capacitance significant, may be used for design (mainly bridge cap)
  - Coils of high Q-factor, lowest (best) tolerances

- **Applications:** Reader antennas, Vicinity Label antennas (accurate resonance frequency…)}
Production Technologies: Embedded Wire

- **Process:** Wire heated by ultrasound is melted into Card substrate.

- **Material:** Copper wire
  - HF: 112 µm, 80 µm
  - LF: 50 µm, 30 µm, 20 µm

- **Assembly:** All processes possible, welding preferred

- **Performance:**
  - Low parasitic capacitance (~ 1…3 pF)
  - Coils of high Q-factor, although tolerances are higher than for etching, as the coil shape can be changed during lamination.

- **Application:** Typical contactless personal card.
Production Technologies: Electroplating

- **Process:** First, a very thin conductive seed-layer is sputtered on the substrate. Then several µm of copper are deposited in a galvanic process.

- **Material:** Copper

- **Assembly:** Copper allows welding, crimping, soldering and conductive glueing

- **Performance:**
  - Coils of medium / high Q-factor, but high tolerances due to variable thickness over production and fiber-structures on the border.

- **Application:** E.g. contactless personal card.
Production Technologies: Printing

- **Process:** Conductive ink or paste is used to print the conductor,

- **Material:** e.g. silver ink, carbon ink, polymer paste

- **Assembly:** Mostly conductive glueing (pressure dependent, tolerances) or crimping

- **Performance:**
  - High resistance (e.g. 250 $\Omega$ before lamination, 20 $\Omega$ after lamination) $\Rightarrow$ low Q

- **Applications:** Alternative for contactless personal cards
Antenna and assembly technology overview

**Antenna Technologies**
- Embedded Wire Antenna
- Etched Antenna
- Printed Antenna
- Galvano Antenna

**Assembly Technology**
- Crimping
- Welding
- Soldering (not Alu)
- Conductive Glueing

**Conductor materials:** Copper, aluminum, conductive paste (e.g. silver ink)

**Chip packages:** Module (8 x 5 mm), Flip-Chip, Strap, bumped wafer
13.56 MHz loop antenna appearance....

- NFC & Reader loop antenna
- Card & Label loop antenna

---

Overlay

Printing layer

Seal layer

Prelam

Seal layer

Printing layer

Overlay
The World of SmartCards

- ISO/IEC14443........The Contactless Proximity Air Interface for person-related applications was standardized 1 decade ago.
- Applications in Government (e-Passports, driver license, health card...), Payment (Contactless Credit Cards), Public Transport (Ticketing), Secure Access Control, etc. are successfully deployed.
- The same battery-less, proven secure chip technology now migrates into objects e.g. SD-Cards, watches, USB-Sticks, which requires small antennas. Very High Data Rates ~ 10 Mbit/s also allow new applications. This requires more accurate chip characterization and tolerance consideration.

Standards (ISO/IEC)
- 7810.........Card geometry (e.g. ID-1 format) and physical properties
- 7811-3/-3...Embossing (letters raised in relief)
- 7811.........magnetic stripe cards
- 7812.........optical character recognition cards
- 7813.........bank cards
- 7816.........contact cards with ICs
- 10373.........test methods

ID-1 (ISO/IEC7810) Card format: 85.6 x 54 mm
Card geometry specifications.
In the first step, antenna geometry and material properties are defined.

**Antenna geometry**

- $a_0$ (maximum) length in mm,
- $b_0$ (maximum) width in mm,
- $w$ conductor track width in mm,
- $g$ track gap in mm,
- $t$ track thickness in mm
- $N$ number of turns
Loop antenna design - inductance

- The multi-turn loop of rectangular cross-section is re-calculated to one average loop of circular cross-section:

**equivalent conductor diameter**

\[
d = 2 \sqrt{\frac{t \cdot w}{\pi}}
\]

**average length**

\[
a_{avg} = \sqrt{\frac{a_0^2 + [a_0 - 2N \cdot (g + w)]^2}{2}}
\]

**average width**

\[
b_{avg} = \sqrt{\frac{b_0^2 + [b_0 - 2N \cdot (g + w)]^2}{2}}
\]

- \(E\) is the fitting parameter of the model, it depends on edges, radius, etc. Typical value is 1.65 (range is 1.6 …. 1.85).

- Inductance of this average loop is constituted of mutual inductance (for parallel conductor parts)….\

\[
M_1 = \frac{\mu_0}{2\pi} \left[ a \cdot \ln \left( \frac{2 \cdot a \cdot b}{d \cdot (a + \sqrt{a^2 + b^2})} \right) - 2b + \sqrt{a^2 + b^2} \right]
\]

\[
M_2 = \frac{\mu_0}{2\pi} \left[ b \cdot \ln \left( \frac{2 \cdot a \cdot b}{d \cdot (b + \sqrt{a^2 + b^2})} \right) - 2a + \sqrt{a^2 + b^2} \right]
\]

...and self-inductance for straight parts

\[
L_1 = \frac{\mu_0 \cdot a}{16\pi} \quad L_2 = \frac{\mu_0 \cdot b}{16\pi}
\]

- Finally, all parts are summarized and a number of turns is taken into account in \(\mu\)H.

\[
L_A = \left( 2M_1 + 2M_2 + 2L_1 + 2L_2 \right) \cdot N^E
\]
Loop antenna design - inductance

- Main parameter for loop antenna design is inductance. For an air coil, this can be estimated from geometry.
  - Geometry of a several turn loop antenna is re-calculated to one average loop (length x width).
  - A rectangular conductor cross-section is approximated by a circular cross section of equal area.

\[ d = 2 \sqrt{\frac{t \cdot w}{\pi}} \]

- Between all parallel current lines, we consider mutual inductance from geometry ...

\[ M_1 = \frac{\mu_0}{2\pi} a \cdot \ln \left[ \frac{2 \cdot a \cdot b}{d \cdot (a + \sqrt{a^2 + b^2})} \right] - 2b + \sqrt{a^2 + b^2} \]

- ...and self-inductance....

\[ L_1 = \frac{\mu_0 \cdot a}{16\pi} \]

- ...then we can add up all terms and take into account the number of antenna turns \( N \) to the power of \( E \) (close to 2).

\[ L_A = \left( 2M_1 + 2M_2 + 2L_1 + 2L_2 \right) \cdot N^E \]
Loop antenna design - resistance

Antenna losses are the result of conductor DC-resistance, and AC-losses due to skin effect. Depending on substrate material, additional (e.g. dielectric) losses may also be significant.

- Serial DC-resistance for the planar spiral antenna can be calculated from the conductor track to

\[ R_{DC} = \frac{2N(a_0 + b_0) - 2(N - 1)(w + g)}{\sigma \cdot t \cdot w} \]

- Skin effect losses are difficult to model, especially for rectangular conductor cross-sections, and in the magnetic field influence of neighbour turns. An approximation is

\[ R_{AC} \approx R_{DC} \left[ 1 + \frac{d^2 \cdot f \cdot \mu_0 \cdot \sigma}{4 \cdot 48} \right] \]

- The equivalent parallel antenna resistance can be calculated for one frequency (typ. carrier at 13.56 MHz)

\[ R_A = \left( \frac{2\pi f L_A}{R_{SERIAL}} \right)^2 \]

- If the optimum achievable chip performance should not be significantly degraded, \( R_A > 10 \) \( R_C \) should apply. This also means, the transponder operational \( Q \)-factor is mainly determined by the chip, \( R_T \sim R_C \).
Loop antenna design - capacitance

- Parasitic capacitance for planar loop coils consists of up to 3 contributions:

  - **Bridge capacitance**
    - The conductor bridge between end of inner turns and end of outer turn builds up a plate capacitor

  - **Turn capacitance**
    - Considers area and distance between (n-1) turns, and voltage phase-shift

  - **Electrical length**
    - Resonance condition if the el. track length is equal to half the wavelength of a resonance frequency
Antenna equivalent parameter measurement

- The complex impedance of a loop antenna can be measured with an Impedance Analyzer (or a Network Analyzer) over frequency.

- An equivalent circuit consisting of lumped elements is extracted from such a trace.

- Most simple this can be a parallel resonant circuit, consisting on Inductance $L_A$, Resistance $R_A$ and Capacitance $C_A$. This is most accurate for the carrier frequency.

- $L_A$ is measured at low frequency out of $\text{Im}\{Z\}$ (where $C_A$ can be neglected).

- $C_A$ is calculated from self-resonance frequency and $L_A$

\[
f_S = \frac{1}{2\pi \sqrt{L_A C_A}} \quad \rightarrow \quad C_A = \frac{1}{(2\pi f_S)^2 L_A}
\]

- $R_A$ either can be measured as $\text{Re}\{Z\}$ at 13.56 MHz, or can be calculated from

\[
R_A = \frac{(2\pi f_C)^2}{R_{s\,DC}} + \sqrt{\frac{f_S}{f_C}} \cdot R_{FSKIN}
\]
Measurement with Agilent 4395A (1)

- **Switch on Instrument**
  - Preset

- **Use Impedance-Analyzer Mode**
  - Meas => Analyzer Type => Impedance Analyzer

- **Choice of frequency range 1 – 100 MHz**
  - Start => 1 => MHz
  - Stop => 100 => MHz
  - Sweep => number of points => 801 => x1

- **Set to Inductance Measurement**
  - Meas => More => Ser (Ls)

- **Calibrate Instrument**
  - Cal => Cal Kit => 3,5 mm => Return
  - Cal => Calibrate Menu
  - connect calibration kit to test fixture and check good connection,
  - Open, Short, Load, Done
  - Leave 50-Ohm reference connected and check successful calibration using...
  - Scale Ref => Autoscale
  - A horizontal trace over frequency must show up with 50 Ohms (no frequency dependency) else repeat procedure.
Measurement with Agilent 4395A (2)

- Compensate Fixture (measurement adaptor)
  - Cal => Fixture Compen => Compen Menu
  - Connect a SMA-connector with open contacts to fixture
  - => Open
  - solder open contacts to get a short
  - => Short, Done
  - Check: Flat trace over frequency

- Actual measurement of antenna parameters
  - Meas => Ser(Ls)
  - Marker => 1 => MHz
  - Read out value
  - Meas => More => Ser(Rs)
  - Read out value
  - Meas => More => Ser(Ls)
  - Manually set the marker to the zero crossing, Read out the (resonance) frequency
  - Meas => More => Prl(Rp)
  - Read out Rp at fres
Measurement with Agilent 4395A (3)

Inductance
- $L_s$ at 1 MHz

Serial resistance
- $R_s$ at 1 MHz

Resonance frequency reactive component = 0 (e.g. $L_s$)

Parallel resistance
- $R_p$ max at $f$
Ferrite foil - functional principle

- Ferrite material can conduct the magnetic flux multiple times better than free air.
- If the application requires an NFC antenna to be very close to a metal plate, a thin ferrite foil can help to isolate the antenna from the metal.

- It is important to note, compared to an antenna in free air, the contactless performance will still be degraded - but not completely blocked.
- Only a part of the magnetic flux is conducted in thin ferrite - presence or absence of metal in close coupling below will de-tune the antenna matching!
If the application requires an NFC antenna to be very close to a metal plate, a thin ferrite foil can help to isolate the antenna from the metal.

- Air coil allows no function very close to metal plate,
- Equal function in ~ 10 mm distance,
- In free air the air coil will perform always better...
Ferrite foil - 2 types are available

**Polymer „absorber“ sheets**

- Re ($\mu_R$) $\sim$ 20 ... 60,
- mechanically very flexible,
- available also on reels (simple antenna production process)
- higher conductivity (losses)

**Sintered ferrite sheets**

- Re ($\mu_R$) $\sim$ 100 ... 200,
- mechanically rather rigid,
- available in sheets (e.g. 200 x 200 mm)
- very low conductivity losses
NFC antennas on ferrite foils

- Smart mobile devices are very thin and compact, offer little extra space.
- Metal parts or other RF components may be very close to NFC antenna (e.g. antenna on battery pack)
- Ferrite Foils can conduct the magnetic flux and allow dense packaging
- **Real part of** $\mu_R$ **determines how much magnetic flux can be conducted** („**good**“ property) - should be very high (e.g. 120 ... 160)
- **Imaginary part of** $\mu_R$ **means HF losses** („**bad**“ property) - should be low (e.g. < 3)

\[
\mu_r' = \text{Re}(\mu_r) \\
\mu_r'' = \text{Im}(\mu_r)
\]
Example: NFC Antenna

- Inductive Loop antenna (planar spiral coil), $H$-field antenna
- Conductor on ferrite foil, to isolate antenna from metal and electronic PCB

### Antenna Geometry Data

<table>
<thead>
<tr>
<th></th>
<th>Dimension</th>
<th>Air Coil</th>
<th>Coil on ferrite</th>
</tr>
</thead>
<tbody>
<tr>
<td>ferrite outline</td>
<td>mm</td>
<td>---</td>
<td>39 x 39</td>
</tr>
<tr>
<td>antenna outline</td>
<td>mm</td>
<td>35 x 35</td>
<td>35 x 35</td>
</tr>
<tr>
<td>track width</td>
<td>mm</td>
<td>0.4</td>
<td>0.4</td>
</tr>
<tr>
<td>track gap</td>
<td>mm</td>
<td>0.4</td>
<td>0.4</td>
</tr>
<tr>
<td>number of turns</td>
<td></td>
<td>4</td>
<td>4</td>
</tr>
</tbody>
</table>

### Equivalent Circuit Element Values

<table>
<thead>
<tr>
<th></th>
<th>Dimension</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Inductance $L_A$</td>
<td>µH</td>
<td>1.314</td>
</tr>
<tr>
<td>Capacitance $C_A$</td>
<td>pF</td>
<td>2.351</td>
</tr>
<tr>
<td>Resistance $R_A$</td>
<td>Ω</td>
<td>0.58</td>
</tr>
</tbody>
</table>

- Inductive Loop antenna (planar spiral coil), $H$-field antenna
- Conductor on ferrite foil, to isolate antenna from metal and electronic PCB
Loop antenna production tolerances

- Production tolerances require to measure an average of several parts
- Errors differentiate into offset (deterministic) and variance (random)
  - Soft substrate (e.g. Cards) can shrink during lamination process
  - Ferrite foils have typically
    +/− 15 % tolerance of μr
  ➔ may be +/− 7.5 & for $L_A$

- Example: NFC antenna on ferrite foil
  - Matching network for $Q \sim 7$
  - 8 samples measured @ 25 °C
  - Avg. impedance $17.84 + j 1.78 \, \Omega$
Temperature dependency for NFC antenna

- **Air coil (blue)**
- **Coil on ferrite (red)**
  - Specific conductance has a significant temperature gradient
  - $L$ on ferrite has a temp. dependency
Temperature dependency for NFC antenna

- Impedance towards the chip TX (due to impedance adjustment network $Q \sim 10$) varies significantly over temperature!

![Diagram of NFC antenna impedance network](image)

- $L_0$ in nH560
- $C_0$ in pF220
- $C_1$ in pF16
- $C_2$ in pF192,5
Thank you for your Audience!

Please feel free to ask questions...