Electromagnetic Analysis Speeds RFID Design

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Over the last several years, RFID has become a major market. With a large number of vendors, success will be determined by achieving a short time-to-market for the most creative ideas. In order to realize a short time-to-market, fast and accurate electromagnetic analysis is an absolute requirement. This paper demonstrates using the Sonnet electromagnetic analysis to evaluate a 13.56 MHz RFID inductor design accurately and rapidly. Sonnet's extreme accuracy is a result of being based on the FFT (Fast Fourier Transform), and Sonnet's speed is the result of the revolutionary new ABS (Adaptive Band Synthesis, introduced with Version 8.0) interpolation, both used in this design. In addition, Sonnet's automated features, including parameterization and optimization, allow the designer to evaluate a large number of alternatives in an incredibly short period of time. As the wireless markets consolidate, making the most efficient use of the best CAD tools, including Sonnet for electromagnetic analysis, is key to survival.

Sonnet uses Maxwell's equations to analyze planar circuits. The user specifies the geometry as input. Geometries can be drawn, or they can come from Agilent, AWR, Cadence, Mentor, Ansoft, GDSII, or AutoCAD. Then, based directly on Maxwell's equations, Sonnet solves for the S-parameters, or Z-parameters if desired. The calculations are based on the FFT (Fast Fourier Transform) so that they are the most accurate possible. There is no numerical integration used at any time. Sonnet analyzes a circuit contained in a rectangular shielding box. The top cover can be removed to allow radiation. Sonnet works well with nearly any number of substrate layers and the layers can be nearly any thickness, all with full accuracy and speed.

RFID has become popular over the last few years for tracking equipment, goods, animals, etc. Often operating at 13.56 MHz, the "tag" coil (shown in Figure 1) draws power from the RF energy radiated by a "reader" coil. Then, the IC on the RFID tag alternately resonates and de-tunes the tag coil, thus modulating the tightly coupled reader coil with data stored in the tag IC. While one must see a bar code in order to read it, an RFID can be read even though it is hidden. It can be used in snow, rain, and heat with no problem. Since the reader supplies all power, the tag does not need a battery. The tags are extremely durable, often lasting longer than the equipment that they tag.

Figure 2 shows a typical RFID inductor [1] as captured using Sonnet. It is a planar inductor with six turns, each 0.5 mm wide and separated by 0.5 mm. The coil is 78mm x 41 mm. The input port is on the left hand side. Metal loss is included. Analysis time for this inductor is about 1 minute per frequency. Because this analysis uses the Sonnet ABS interpolation, accurate data at

300 frequencies is calculated from electromagnetic analysis at only four frequencies. This entire analysis takes only four minutes.

By using the Sonnet Option “Analysis->Optional files->Add SPICE”, a lumped equivalent circuit is generated [2]. The output, shown in Table 1, is in SPICE format. Analysis at two frequencies is required. To check the SPICE results, it is always good to use Sonnet to create two SPICE files. In this case, the first SPICE file is generated from data at 12.1 and 13.3 MHz. The result is:

```
C1 1 0    1.09pf
L1 1 2    4523nh
RL1 2 0   1.71
```

The second SPICE file is generated from data at 13.3 and 14.65 MHz with the following result:

```
C1 1 0    1.11pf
L1 1 2    4521nh
RL1 2 0   1.77
```

Both analyses give almost exactly the same answer. This means that the SPICE model generated by Sonnet is working well for this circuit. We shall use this SPICE model to design the rest of the RFID circuit.

In Figure 3, the Sonnet SPICE model is on the left. The Sonnet model includes a resistor in series with the inductor. This is most realistic. However, for some calculations, we would also like to know what the equivalent parallel resistance is. This is easily calculated using the equation in the figure. For a series resistance of 1.8 Ohms, the equivalent parallel resistance is 82.4 kOhms. From the Sonnet generated SPICE model, the capacitance is 1.1 pF and the inductance is 4523 nH.

The RFID IC we wish to use has a total of 23.5 pF of internal capacitance. The inductor, as calculated by the Sonnet SPICE model, already has 1.1 pF of capacitance. In order to make a 4523 nH coil resonant at 13.56 MHz, we need a total of 30.5 pF. Thus, we must add an external capacitor of 5.9 pF to tune the inductor to 13.56 MHz when it is connected to the RFID IC.

Figure 4 shows a schematic of the entire tag coil circuit. The RFID IC is on the left. As specified by the manufacturer, it has both an internal capacitance and resistance. The external 5.9 pF capacitor is in the center. The inductor model generated by Sonnet is on the right.

It is useful to calculate the total impedance of the resonant circuit at resonance. This is simply the parallel combination of the RFID IC internal resistance of 25 kOhms with the 82.4 kOhms equivalent parallel resistance of the coil. The total resistance is about 19 kOhms. This is the impedance that the RFID IC sees at resonance.

The circuit of Figure 3 is easily analyzed using any nodal circuit simulator. There is even a simple nodal analysis available with Sonnet. The Sonnet netlist for this circuit [2] is as follows:

```
CAP 1 C=23.5      ; RFID IC Model
RES 1 R=25000   ; RFID IC Model
CAP 1 C=5.9       ; External Capacitor
PRJ 1 0 RFID_1.son Use sweep from RFID_1.son
DEF1P 1 Net Main
```

The PRJ line is special. If needed, this line automatically launches a Sonnet electromagnetic analysis of the coil. If there have been no changes in the coil layout since the last analysis, then the previous data is immediately used allowing very rapid tradeoff analyses of the rest of the circuit.

Figure 5 shows the result of the analysis. The input impedance (Z-parameter) is plotted. The magnitude of the impedance (close to 19 kOhms) is seen at the 13.56 MHz resonance. The resonance occurs at the frequency for which the imaginary part of the input impedance is zero.

Of special note is that the entire analysis up to this point can be performed using the free SonnetLite [3] (SonnetLite is identical to the full Sonnet analysis except for the size of problem that can be analyzed).

To see the inductor fields, we can use a "sense layer" [4]. Sonnet only allows viewing of electric fields that are parallel, or tangential, to the surface of the substrate. In these views, red is strong E-field. Blue is almost no E-field.

The left side of Figure 6 shows tangential E-field 25 mm above the inductor. The tangential E-field is strongest near the windings of the coil. The same is true at 35 mm above the inductor, on the right side of Figure 6, only now the fields are less strong.

Sonnet does not plot B-field directly, but it is easy to see what the B-field does. From Maxwell's equations, we know that the B-field "curls" around the E-field. This is just like B-field curling around a current carrying wire. This is shown on the right side of Figure 6. Thus, by looking at the 2-D tangential E-field, we can easily visualize the full 3-D B-field curling around the inductor.

The port we have used for all the analyses so far has been at the far left edge of the substrate. At the box edge, we have a side of the perfectly conducting box that contains the entire circuit. This box sidewall gives a perfect ground reference and results in the highest possible accuracy. As described in the Sonnet documentation, the Sonnet de-embedding can shift the reference plane from the actual port location at the box sidewall to the inductor. Thus, the long transmission line connecting the port to the inductor is removed from all calculations.

We can also use a slightly less accurate port [5]. Shown in Figure 7, the port is close to the inductor. In addition, we have added a small resistor, "R". This is a patch of metal whose resistance is set to 25 kOhm/square. One square of this resistance exactly models the internal resistance of the RFID IC. The square marked "C" has a metal with surface reactance set to –399.5 Ohms/square. One square of this special reactive metal exactly models the 23.5 pF RFID IC internal capacitance and the 5.9 pF external capacitance at 13.56 MHz. Note that this reactance stays constant at all frequencies. Thus, it is exactly accurate only near the resonant frequency, but, for this case, that is no problem. The result using this port is almost the same as before.

Special metal types are added by using "Circuit->Metal Types->Add". The capacitor is a "General" metal type with all values equal to zero except for XDC. Since there is no longer any transmission line to remove, and the port discontinuity is very small, we can turn de-embedding off (Analysis->Setup->Advanced->uncheck de-embed).

How does coupling vary with the offset between the reader coil and the tag coil? To check this [6], we added a second inductor 50 mm above the first one, Figure 8. We also made the box containing the circuit bigger. This is important because we do not want the inductor to get too close to the sidewalls.

For the analysis, we varied the offset from 0 mm to 160 mm in steps of 40 mm. The reader inductor is shown above with an offset of 40 mm. Sonnet is set up to automatically calculate a full frequency sweep for each of the five reader coil positions. Each frequency sweep generates about 300 data points. Because the Sonnet ABS interpolation is used, analysis at only four frequencies is needed to generate data at all 300 frequencies.

After completing the Sonnet analysis, we can determine how much voltage is generated at the tag coil (port 1) when we put current into the reader coil (port 2). This is just the value of Z_{12}. For example, if Z_{12} is 9000 Ohms, then 1 mA into the reader coil generates 9 volts on the tag coil port. Since the Sonnet layout includes the internal resistance of the RFID IC, a full 9 volts will appear at the RFID IC to be used for operation.

Figure 9 shows that for both 0 mm offset and for 40 mm offset, the value of Z_{12} is just under 9000 Ohms. Thus, the RFID IC will have just under 9 Volts to operate for every 1 mA of current going into the reader coil.

The value of Z_{12} drops off quickly for 80 mm or more offset. At this location, the reader coil has just passed beyond the edge of the tag coil. For large offsets, the tag coil gets only about 2 Volts for every 1 mA flowing into the reader coil.

When the tag coil gets enough power, it operates by repeatedly tuning and de-tuning the coil to resonance at 13.56 MHz, Figure 10 (from [7]). When the tag resonant circuit is de-tuned, the tag coil has no effect on the impedance of the reader coil. When the tag coil is resonant, it couples strongly to the reader coil and changes the reader coil impedance. It is this change in impedance that is read by the reader.

When the tag coil is resonant, the input impedance of the reader coil is Z_{22}. When the tag coil is de-tuned, the tag coil has no effect on the reader coil. In this case, the reader coil impedance is the same as if there is no tag coil there at all. In Figure 11, we see this difference directly. By sensing this change in coil impedance, the reader can read the information sent by the tag coil.

When there is a large offset between the reader coil and tag coil, the tag coil has no effect on the reader coil. The reader coil has an input impedance of about 18000 Ohms. When the tag coil is de-tuned by the RFID IC, the tag coil will also have no effect on the reader coil. In this case, the reader coil input impedance will also be 18000 Ohms, regardless of where the tag coil is located.

When there is 0 mm offset between the tag coil and the reader coil, the resonant tag coil couples strongly to the reader coil. The reader coil input impedance then drops to about 4000 Ohms. If the offset is 40 mm, the resonant tag coil changes the reader coil input impedance to about 8000 Ohms. At 80 mm offset and above, there is little change. At 80 mm offset, the reader coil has moved so there is no overlap with the tag coil. There is also almost no coupling. Repeating this analysis using a reader coil two times bigger also shows that there is little coupling when there is little overlap between the coils.

In conclusion, we have shown how Sonnet's EM and nodal analyses can be used to easily analyze RFID coils. We precisely calculated the additional capacitance required. We also included metal loss and evaluated how the coupling between the RFID reader and tag change as the reader coil is moved.

We have also demonstrated the use of Sonnet's new ABS interpolation. ABS generates accurate results at over 300 frequencies after a full EM analysis at just a few frequencies. In fact all the EM analyses in this presentation were done with only four analyses per complete frequency sweep.

References

[1] File: RFID_1.son. Copies of this file, and all others in this paper, can be obtained at http://www.sonnetusa.com.
[2] File: RFID_1_net.son.
[3] SonnetLite can be downloaded from http://www.sonnetusa.com.
[4] **Sonnet User's Guide**, Vol. 1. Chapter 21. Circuit in files RFID_sense_25.son and RFID_sense_35.son.
[5] File RFID_2.son.
[6] File: RFID_3.son.
[7] "microID™ 13.56 MHz RFID System Design Guide", http://www.microchip.com.

Figures

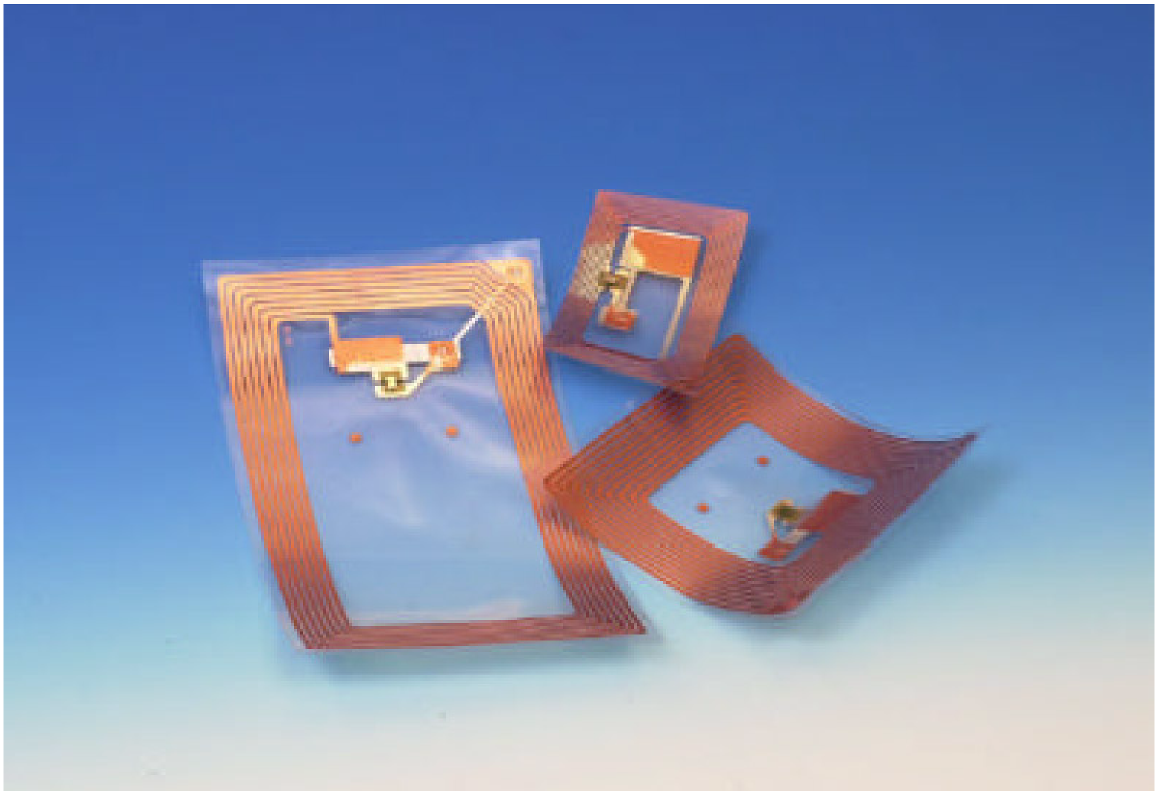

Figure 1. Texas Instruments' "Tag-It" can be laminated into tags, cards, etc.

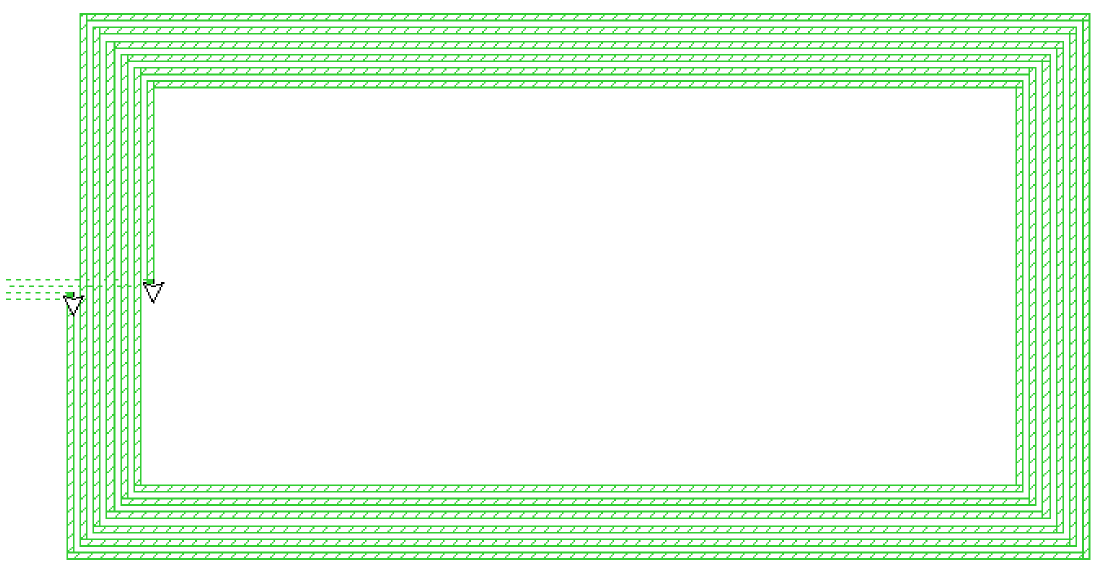

Figure 2. A typical 6-turn RFID Tag coil as captured in Sonnet.

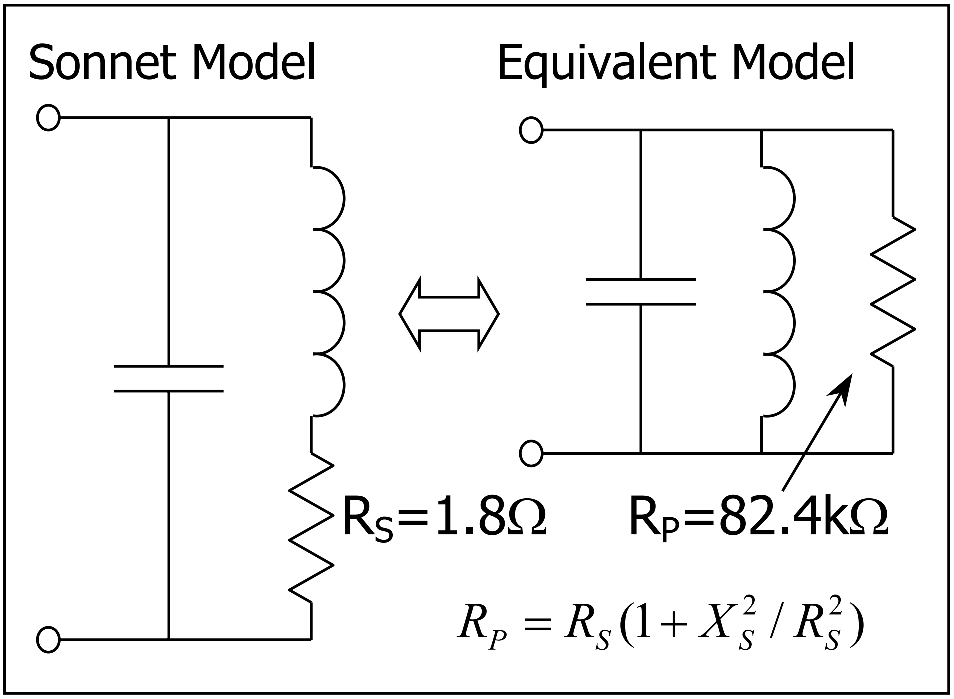

Figure 3: On the left is the SPICE lumped circuit synthesized by Sonnet. On the right is an equivalent lumped circuit useful for certain calculations. See text for inductance and capacitance.

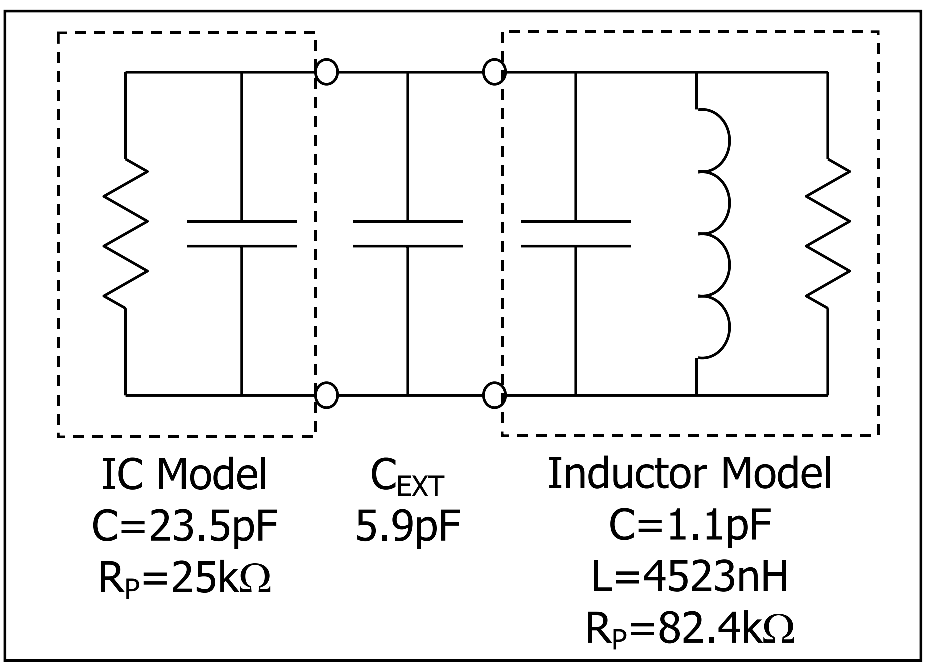

Figure 4. Equivalent circuit of the entire tag coil circuit, including the RFID IC, the external resonating capacitor, and the tag coil itself.

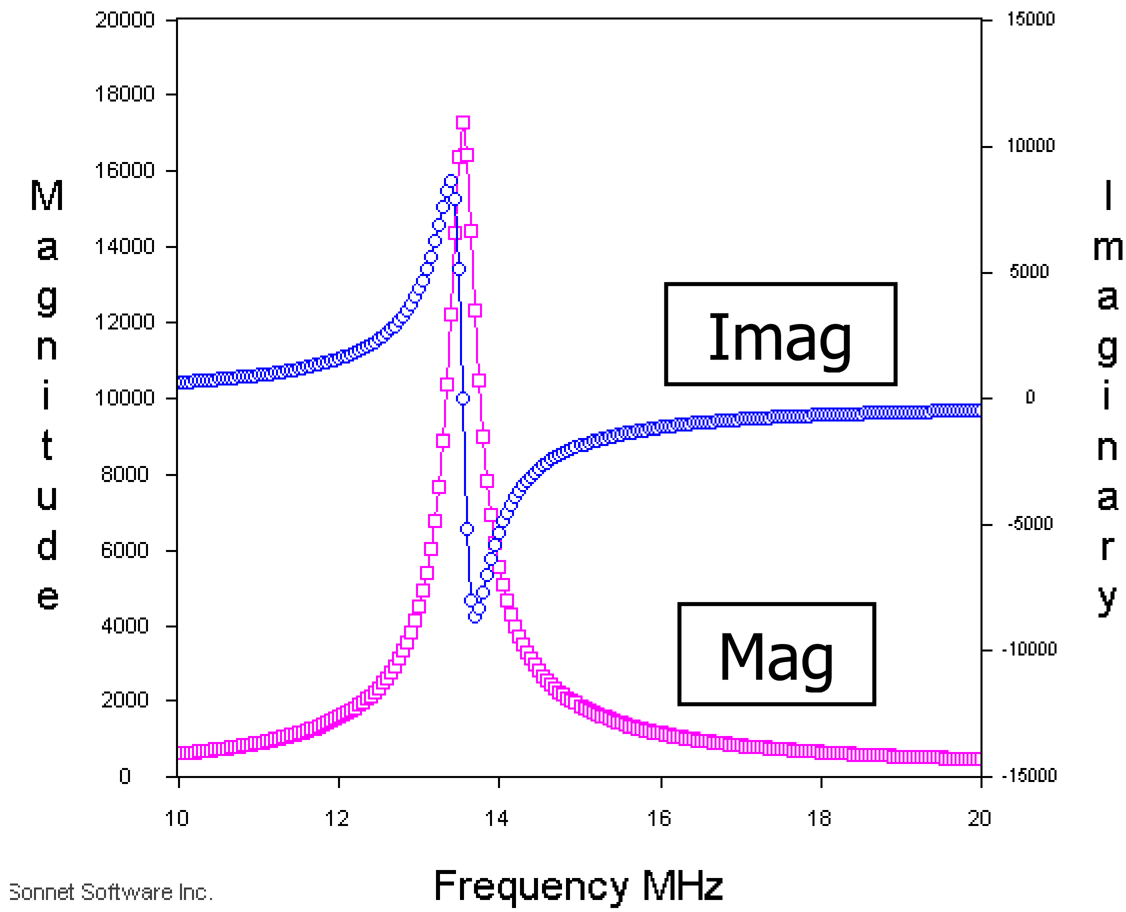

Figure 5. Analysis of the complete RFID circuit shows the expected high impedance ("mag" curve) at the 13.56 MHz resonance (frequency where the imaginary part is zero).

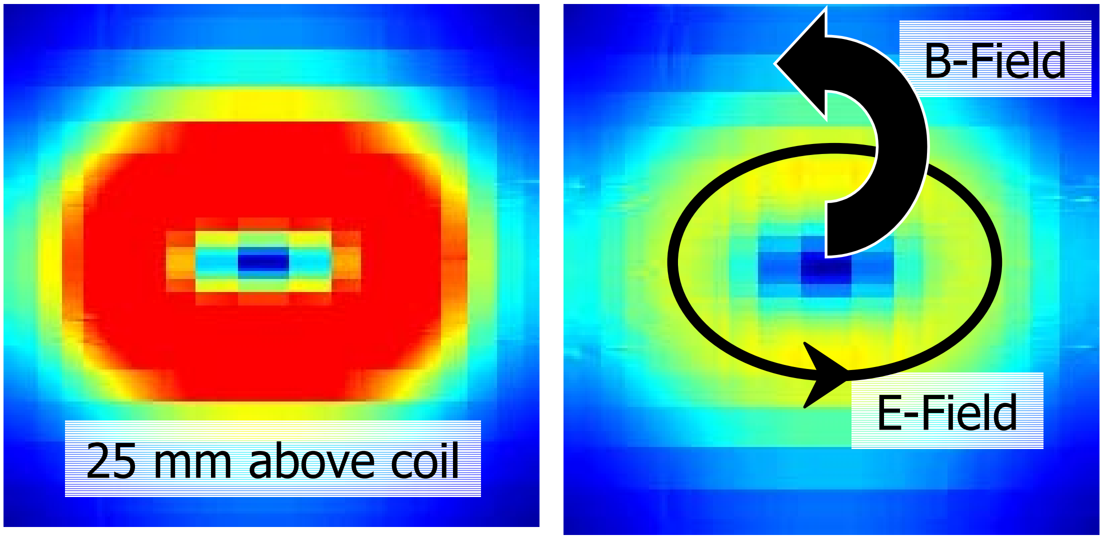

Figure 6. The tangential E-field as calculated by Sonnet, 25 mm (left) and 35 mm (right) above the coil as calculated by Sonnet. Sonnet does not directly plot B-field, however the B-field "curls" around the E-field as illustrated here on the right.

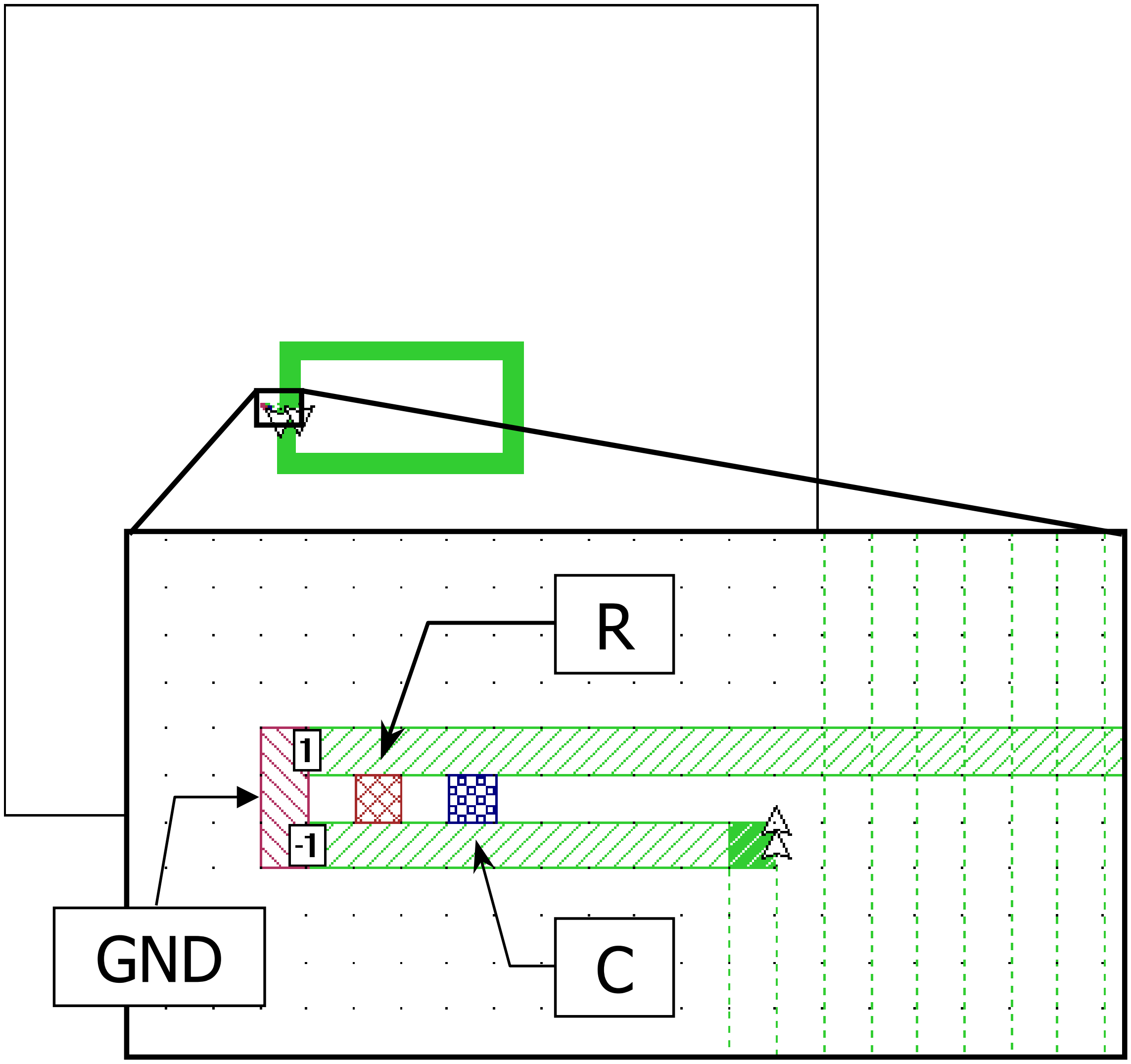

Figure 7. An internal port can be used for a faster analysis. The lumped components can be included by modifying the surface impedances of small squares of metal.

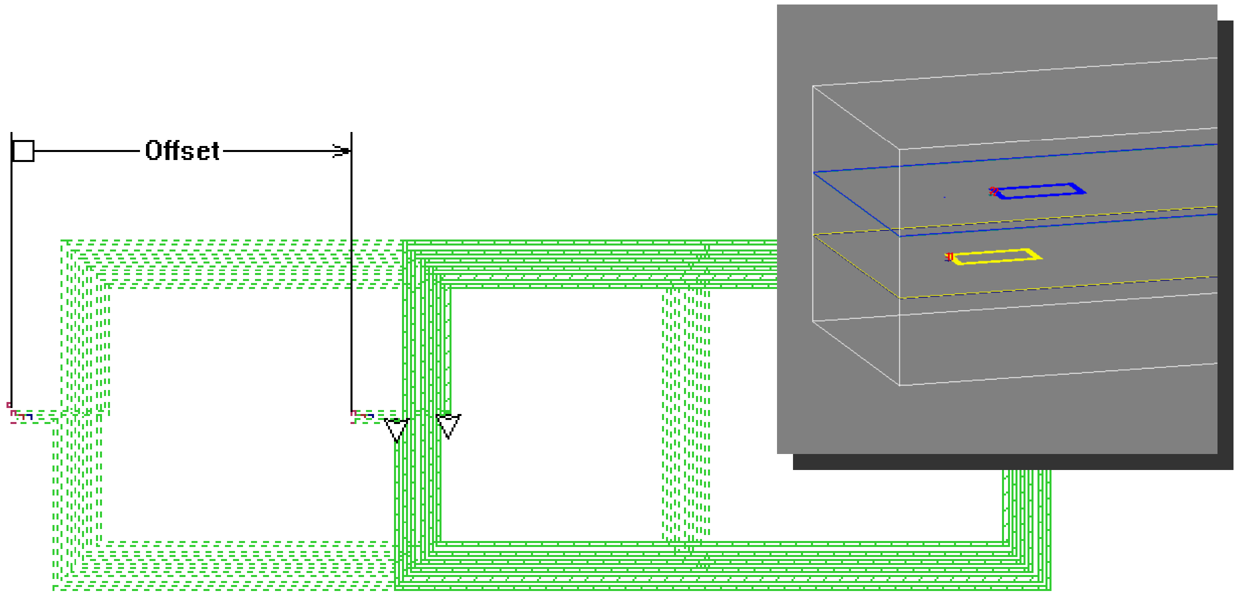

Figure 8. Two inductors can be repeatedly analyzed as a function of their offset. Here the tag coil is shown in dashed lines and the reader coil in solid lines. They are offset vertically by 50 mm. The horizontal offset, set to 40 mm, is indicated in the figure.

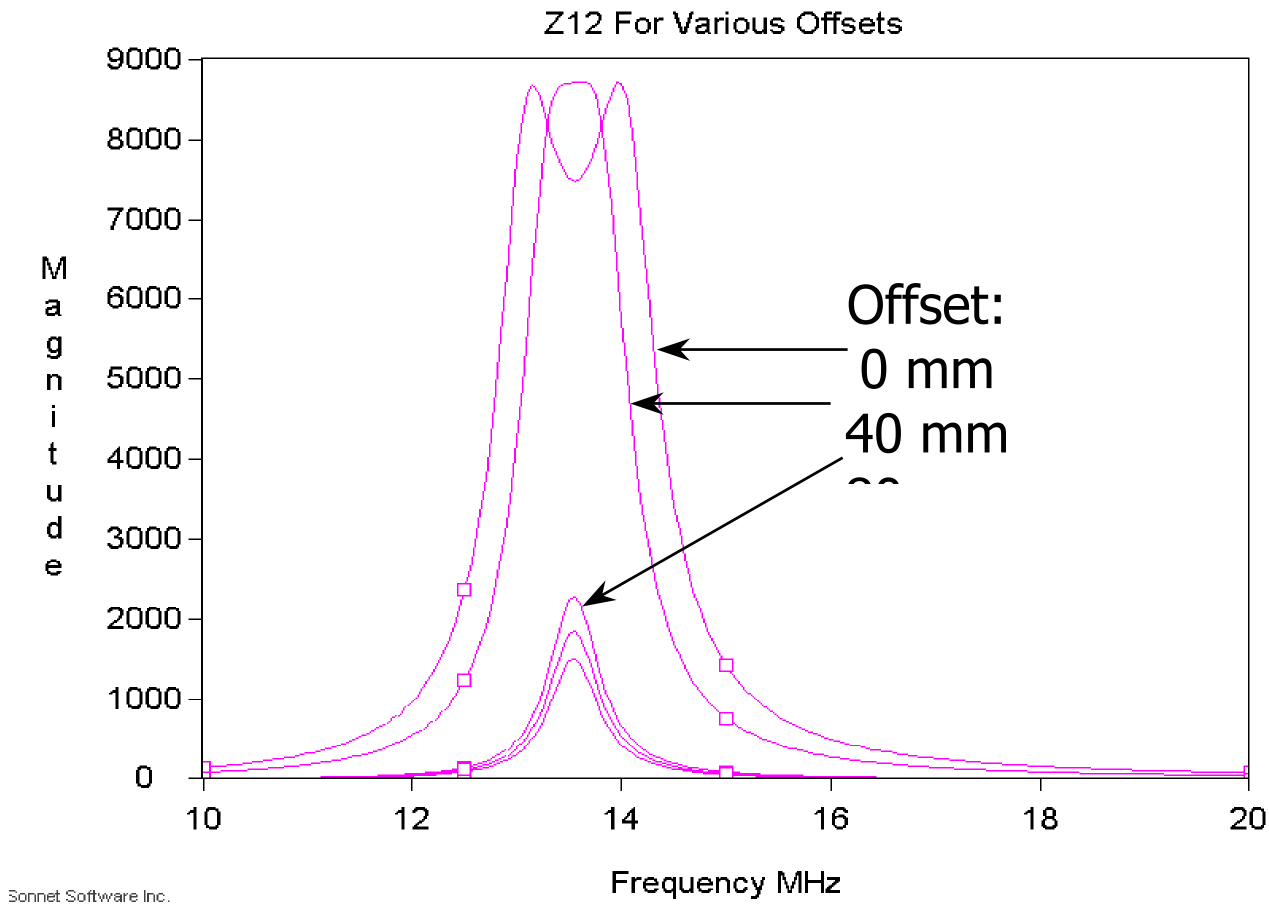

Figure 9. Coupling between the two inductors is strong until the offset exceeds 80 mm.

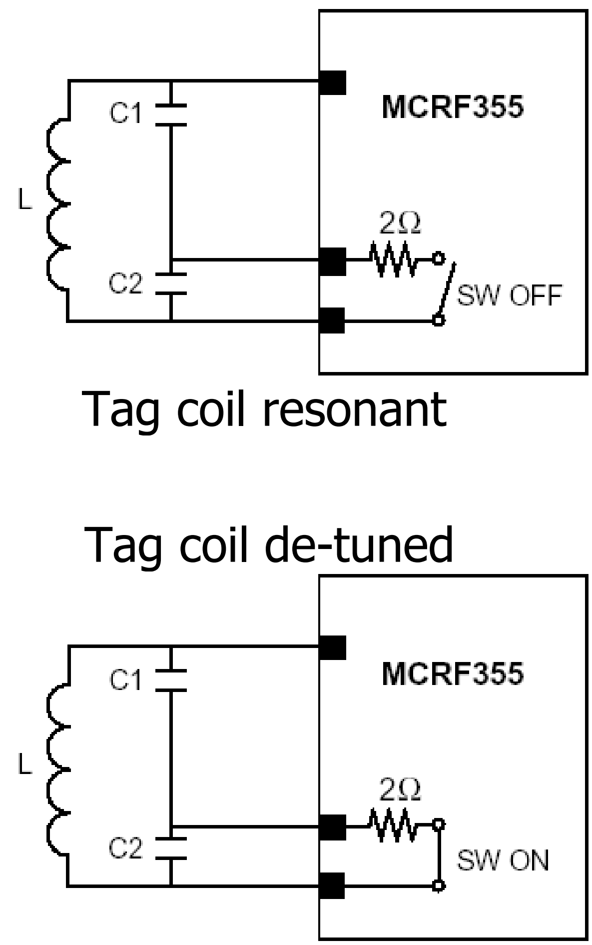

Figure 10. The RFID IC operates by alternately tuning and de-tuning the tag coil for resonance at 13.56 MHz.

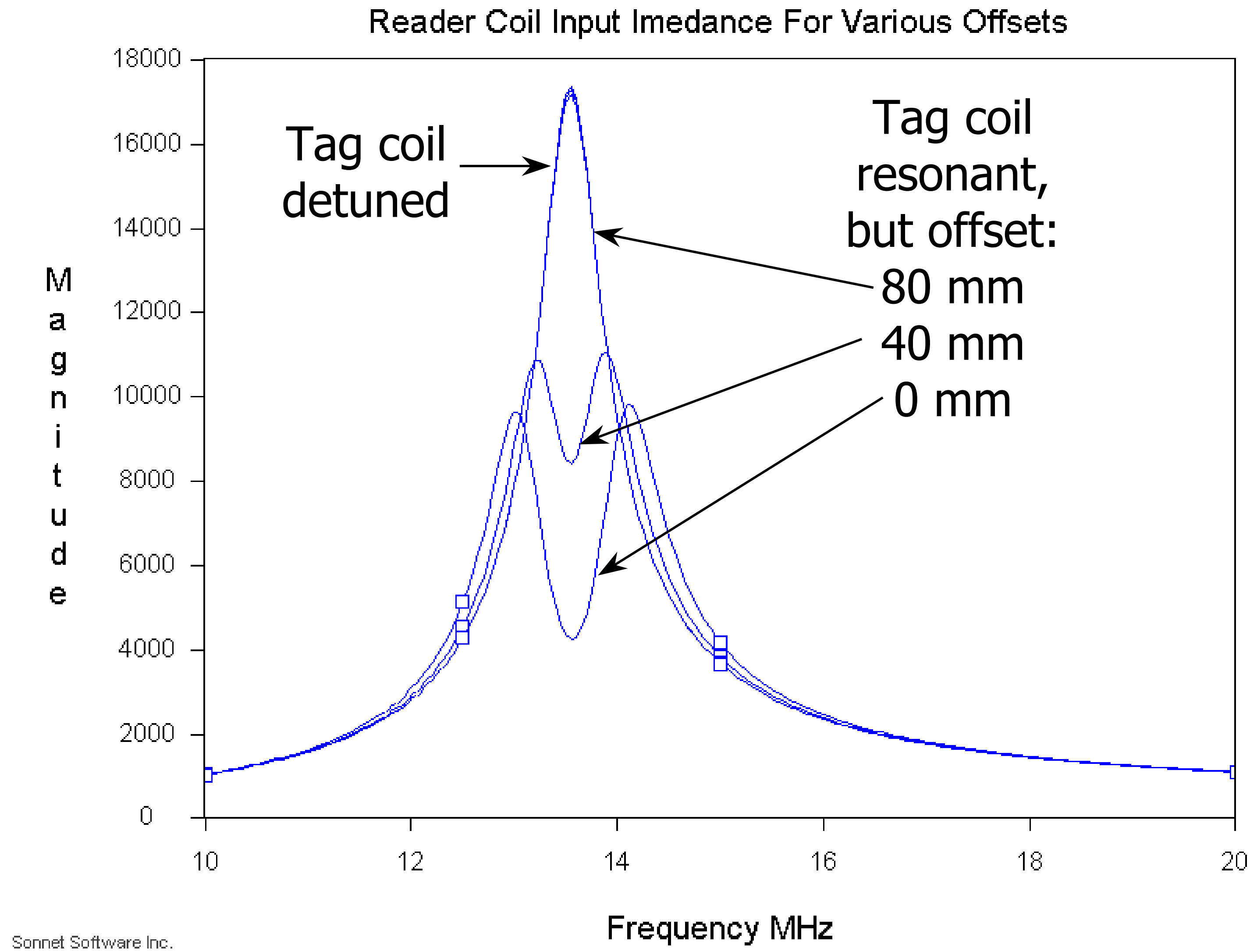

Figure 11. Input impedance of the reader coil when the tag coil is tuned to resonance. When the tag coil is de-tuned, there is no coupling.