Electromagnetic Analysis Speeds RFID Design

Modeling and analysis performed with a suite of planar three-dimensional electromagnetic (EM) simulation tools simplifies the design of RFID tags.

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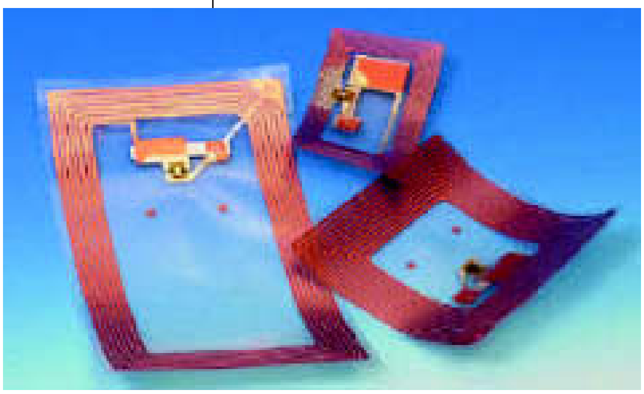
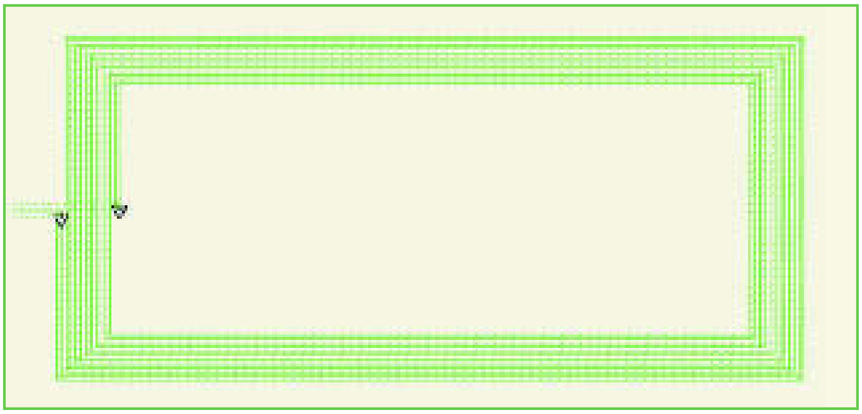
Radio-frequency identification (RFID) is one of the fast-growing wireless market segments. Strong competition among RFID suppliers, however, requires fast product design times and rapid time to market. Fortunately, fast and accurate electromagnetic (EM) analysis and simulation tools can shave design time. What follows is a demonstration of how software tools from Sonnet Software (Liverpool, NY) can quickly and accurately evaluate a 13.56-MHz inductor design for an RFID product.

The accuracy of the software is based on the use of Fast Fourier Transform (FFT) techniques while the processing speed is the result of Adaptive Band Synthesis (ABS) interpolation. In addition, the software's automated features, including parameterization and optimization, allow the designer to evaluate a large number of alternatives in a short period of time. As wireless markets consolidate, efficient use of effective computer-aided-engineering (CAE) tools, such as the Sonnet EM software, is a key to survival.

The EM software uses Maxwell's equations to analyze planar circuits. A user specifies a design geometry as input. Geometries can be drawn, or they can be imported as files in GDSII or AutoCAD format or from other simulation/analysis tools from Agilent Technologies (Santa Rosa, CA), Ansoft (Pittsburgh, PA), Applied Wave Research (El Segundo, CA), Cadence Design Systems (San Jose, CA), or Mentor Graphics (Beaverton, OR). Then, based directly on Maxwell's equations, Sonnet solves for the S-parameters or Z-parameters of the structure. Since the calculations are based on FFTs, they are



1. These RFID tags (courtesy of Texas Instruments, Dallas, TX) can be laminated into tags, cards, and almost any item that must be tracked and identified electronically.



2. The Sonnet suite was used to capture a typical six-turn RFID tag coil.

extremely accurate. There is no numerical integration used at any time. The EM software 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 systems have been designed at a variety of different frequencies, although 13.56 MHz is one of the more popular RFID frequencies. In operation, the tag coil **(Fig. 1)** draws power from the RF energy radiated by a reader coil. Then the RFID tag's integrated circuit (IC) alternately resonates and detunes the tag coil, thus modulating the tightly coupled reader coil with data stored in the tag IC. Unlike bar codes, which must be visible to be read, RFID tags can be read when hidden, even when used in conditions of snow, rain, or excessive heat. Since the power is supplied by the reader, the tag doesn't require a battery. The tags are extremely durable, often lasting longer than the equipment that they tag.

Figure 2 shows a typical RFID inductor modeled with Sonnet.[1] It is a planar inductor with six turns, each 0.5 mm wide and separated by 0.5 mm. The coil is 78 × 41 mm. The input port is on the left-hand side. Metal loss is included in the planar EM analysis of this inductor. Analysis time is about 1 minute per frequency. Because this analysis uses the Sonnet ABS interpolation, accurate data at 300 frequencies is calculated from EM analysis at only four frequencies, thus requiring only four minutes for a full analysis.

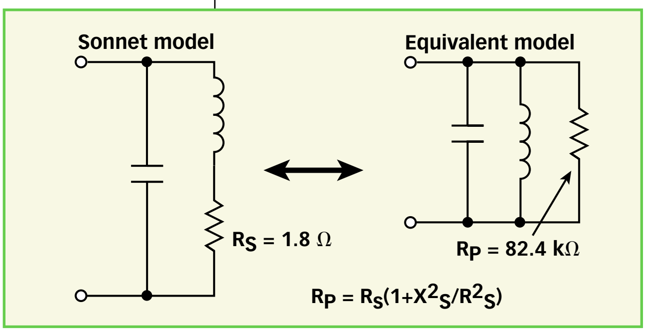
A lumped equivalent-circuit can be generated by using the Sonnet option "Analysis → Optional files → Add SPICE."[2] The result of this operation is a SPICE-format file. To perform an analysis on the equivalent circuit, two frequencies are required. For the purpose of checking the SPICE results, it is a good practice to create two SPICE files for comparison. For this example, the first SPICE file was generated from data at 12.1 and 13.3 MHz, with the resulting equivalent-circuit element values being C1 1 0 = 1.09 pF, L1 1 2 = 4523 nH, and RL1 2 0 = 1.71 Ω.

The second SPICE file was generated from data at the slightly higher frequencies of 13.3 and 14.65 MHz, with the resulting equivalent-circuit element values being C1 1 0 = 1.11 pF, L1 1 2 = 4521 nH, and RL1 2 0 = 1.77 Ω. Both analyses give almost exactly the same answer, implying that the SPICE model is an accurate representation of this inductor. With this confidence, the SPICE model can now be used in an RFID circuit design.

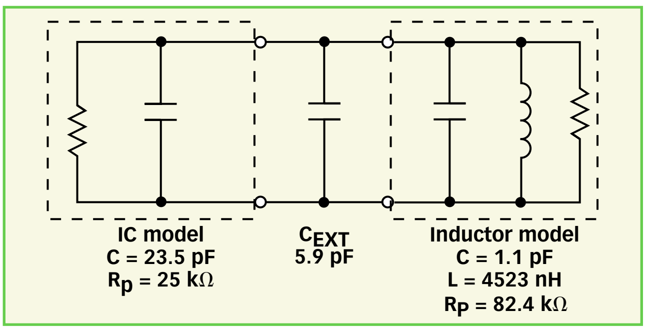
The Sonnet SPICE model of the inductor **(Fig. 3, left)** includes a resistor in series with the inductor. For some calculations, it is also desirable to know the equivalent parallel resistance, which can be easily calculated using the equation in Fig. 3. For a series resistance of 1.8 Ω, the equivalent parallel resistance is 82.4 kΩ. From the Sonnet generated SPICE model, the capacitance is 1.1 pF and the inductance is 4523 nH.

The RFID IC intended for the RFID circuit design has 23.5 pF total internal capacitance. The inductor 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, a total of 30.5 pF capacitance is needed. As a result, it is necessary to add a 5.9-pF external capacitor to tune the inductor to 13.56 MHz when it is connected to the RFID IC.

A schematic diagram of the entire



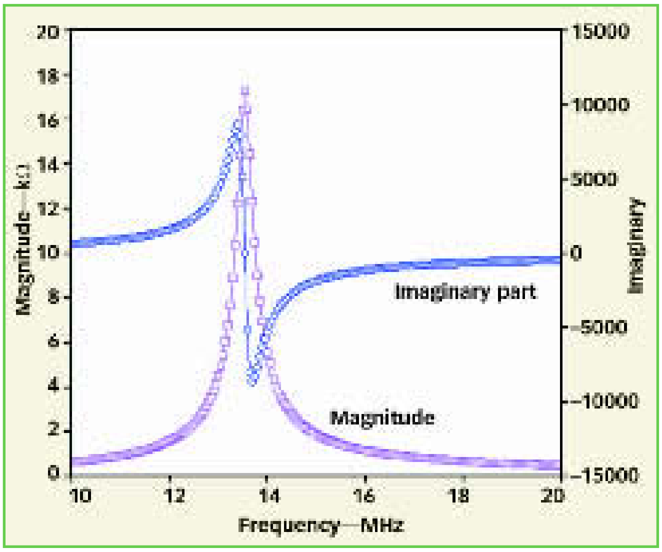
3. This SPICE lumped-element circuit (left) was synthesized by Sonnet. An equivalent circuit (right) of the SPICE model (right) can be useful for some calculations.



4. This equivalent circuit represents the entire tag coil circuit, including the RFID integrated circuit (IC), the external resonating capacitor, and the tag coil.

RFID tag coil circuitry is shown in **Fig. 4**, with the RFID IC on the left. The IC's manufacturer specifies 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 the resonant frequency. This is simply the parallel combination of the RFID IC internal resistance of 25 kΩ with the 82.4 kΩ equivalent parallel resistance of the coil, which yields a total resistance of about 19 kΩ. This is the impedance that the RFID IC sees at resonance.



5. Analysis of the complete RFID circuit shows the expected high impedance (magnitude) at the 13.56-MHz resonant frequency where the imaginary part of the impedance goes to zero.

The RFID circuit model represented in Fig. 4 is easily analyzed using any nodal circuit simulator, or with the simple nodal analysis tool available with the Sonnet software suite. The Sonnet netlist[2] for this circuit is as follows:

CAP 1 C = 23.5 pF (RFID IC model);
RES 1 R = 25000 Ω (RFID IC model);
CAP 1 C = 5.9 pF (external capacitor); and
PRJ 1 0 RFID_1.son Use sweep from RFID_1.son
DEF1P 1 Net Main

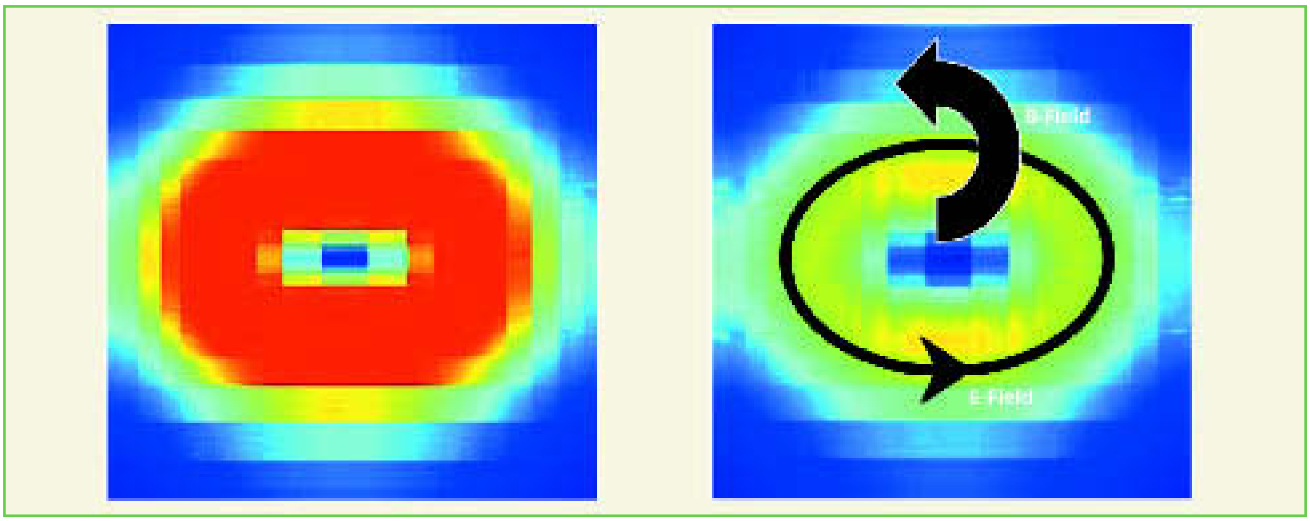
The fourth (PRJ) line is special. If needed, this line automatically launches a Sonnet EM analysis of the coil. If there have been no changes made in the coil layout since the last analysis, then the previous data is immediately used allowing very rapid trade-off analyses of the rest of the circuit.

The results of the planar EM analysis of the RFID circuit are shown in **Fig. 5**, where the input impedance (Z-parameter) is plotted. The magnitude of the impedance (close to 19 kΩ) can be seen at the 13.56-MHz resonance. The resonance occurs at the frequency for which the imaginary part of the input impedance is zero. (It should be noted that the entire analysis to this point can be performed using a free copy of SonnetLite software.[3] SonnetLite software is identical to the full-featured, commercial version of Sonnet software, but is limited in the size of the problem that it can handle.)

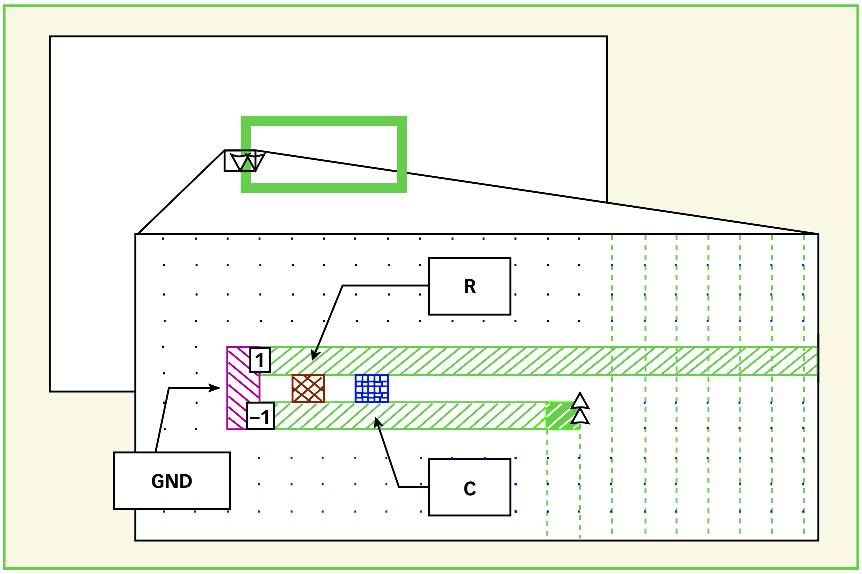
The inductor's fields are viewed by means of a "sense layer."[4] The Sonnet EM software suite only allows viewing of electric fields that are parallel, or tangential, to the surface of the substrate. Using this "sense layer" feature, strong E-fields are revealed in red while the blue color indicates an absence of electric-field (E-field) energy.

The left-hand side of **Fig. 6** shows the tangential E-field 25 mm above the inductor. The tangential E-field is strongest near the windings of the coil. The same is true 35 mm above the inductor (right-hand side of Fig. 6), although the fields are not as strong at this distance above the inductor.

Sonnet software does not plot the magnetic (B) field directly, although it is easy to see what the B-field does. From Maxwell's equations, it is known that the B-field "curls" around the E-field, in the manner that a B-field curls around a current-carrying wire. This is shown



6. Sonnet was used to calculate the tangential E-field of the RFID circuit at 25 mm (left) and 35 mm (right) above the coil. Although the software does not directly plot the B-field pattern, the graphic illustrates how the B-field would curl around the E-field.



7. Faster analysis time can be achieved by using an internal port. Lumped components can be included by modifying the surface impedances of small squares of resistive metal.

on the right-hand side of Fig. 6. Thus, by looking at the two-dimensional (2D) tangential E-field, it is possible to visualize the full three-dimensional (3D) B-field curling around the inductor.

The port used for all analyses so far has been at the far left-hand edge of the substrate. This box edge represents a side of a perfectly conducting box that contains the entire circuit. The box sidewall is a perfect ground reference and results in the highest possible analysis accuracy. As described in the Sonnet software documentation, the Sonnet de-embedding function can shift the reference plane from the actual port location at the box sidewall to the inductor. This removes the electrical effects of the long transmission line between the port and the inductor from all calculations.

A slightly less accurate port can also be used for the analysis,[5] using a port close to the inductor **(Fig. 7)**. In this analysis, a small resistor, R, has also been added. This resistor is a patch of metal with resistance is set to 25 kΩ/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 Ω/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 which, for the case of this analysis, does not pose a problem. The result using this port is almost the same as before.

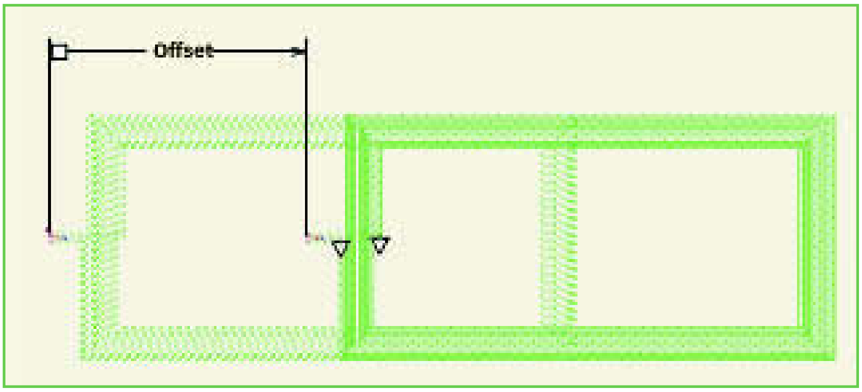
The software allows special metal types to be added by following the command sequence "Circuit → Metal Types → Add." The capacitor in this analysis is a "General" metal type with all values equal to zero except for XDC. Since there is no longer any transmission line to remove, and the port discontinuity is very small, the de-embedding function can be turned off (using the sequence Analysis → Setup → Advanced → uncheck de-embed).

How does coupling vary with offset between the reader coil and the tag coil? To check this,[6] a second inductor was added 50 mm above the first one **(Fig. 8)**, and the box containing the circuit was made larger. This is important in order to prevent the inductor from getting too close to the box sidewalls.

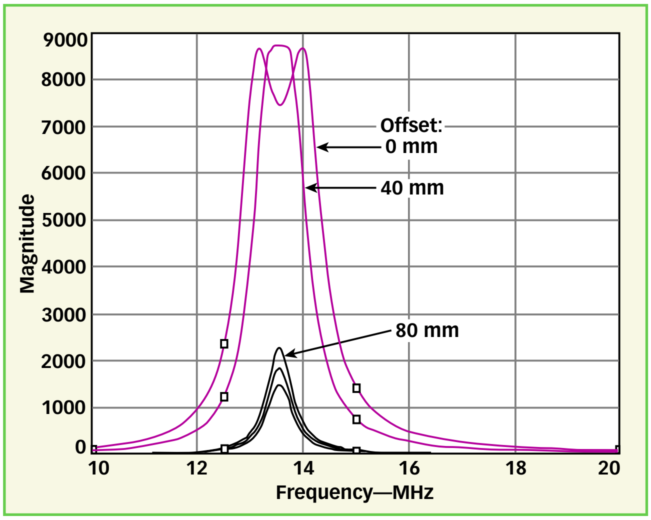
For the analysis, the offset was varied from 0 to 160 mm in 40-mm steps. The reader inductor is shown in Fig. 8 with an offset of 40 mm. Sonnet was set up to automatically calculate a full frequency sweep for each of the five reader coil positions. Each frequency sweep generates about 300 data points. Because the Sonnet ABS interpolation was used, analysis was only needed at only four frequencies to generate data at all 300 frequencies.

After completing the Sonnet analysis, it is possible to determine how much voltage is generated at the tag coil (port 1) when current enters the reader coil (port 2), which is simply the value of Z_{12}. For example, if Z_{12} is 9000 Ω, then 1 mA into the reader coil generates 9 V on the tag coil port. Since the Sonnet software layout includes the internal resistance of the RFID IC, a full 9 V will appear at the RFID IC to be used for operation.

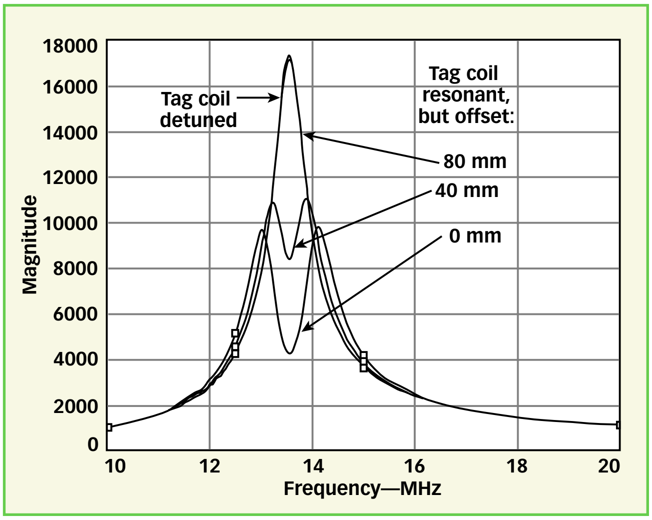
Figure 9 shows that for both 0- and 40-mm offsets, the value of Z_{12} is just under 9000 Ω. Thus, the RFID IC will have just under 9 V to operate for every 1 mA of current going into the reader coil.



8. Two RFID coils can be repeatedly analyzed as a function of their offset. The tag coil is represented by the dashed lines while the reader is shown by the solid lines.



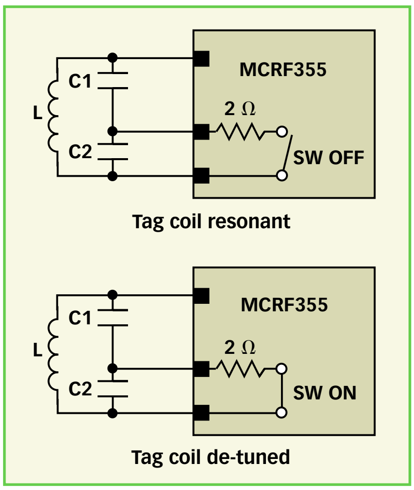
9. Coupling between two RFID coils is strong until the offset exceeds 80 mm.



11. No coupling occurs between coils when the tag coil is detuned or at large offsets (80 mm or more) from the reader coil.

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

When the tag coil gets enough power, it operates by repeatedly tuning and detuning the coil to resonance at 13.56 MHz. **Figure 10** (from ref. 7) shows an example from Microchip. When the tag resonant circuit is detuned, 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. Most RFIC chips operate by shorting out the entire inductor. The approach shown here (patented by Checkpoint Systems) simply detunes the circuit allowing a higher data rate.



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

When the tag coil is resonant, the input impedance of the reader coil is Z_{22}. When the tag coil is detuned, 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 present. In **Fig. 11**, this difference can be seen 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 Ω. When the tag coil is detuned 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 Ω, 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 Ω. If the offset is 40 mm, the resonant tag coil changes the reader coil input impedance to about 8000 Ω. At offsets of 80 mm and more, 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, Sonnet's EM and nodal analyses can be used to easily analyze RFID coils. The software helps precisely calculate the additional capacitance required when using a particular RFID IC. The analysis included metal loss and evaluated how the coupling between the RFID reader and tag change as the reader coil is moved. This study also demonstrated the use of Sonnet's new ABS interpolation, by allowing the analysis at just a few frequencies to generate equivalent results for analyses performed with hundreds of frequencies. In fact, all the EM analyses in this paper were performed with only four analyses per complete frequency sweep; analysis of the first coil configuration was performed with SonnetLite, a software package available free of charge from Sonnet Software. MRF

REFERENCES

1. This is a reference to the file named RFID_1.son. Copies of this file, and all others mentioned in this article, can be obtained at http://www.sonnetusa.com.
2. This is a reference to the file named RFID_1_net.son.
3. SonnetLite can be downloaded from http://www.sonnetusa.com.
4. Sonnet User's Guide, Vol. 1, Chap. 21, the relevant circuit is represented in files RFID_sense_25.son and RFID_sense_35.son.
5. This is a reference to the file named RFID_2.son.
6. This is a reference to the file named RFID_3.son.
7. Microchip (www.microchip.com), "microID™ 13.56 MHz RFID System Design Guide."