

TI UHF Gen2 IC Antenna Design

Reference Guide

October 2006



SCBU015

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Reference Guide



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Read This First

Edition One – October 2006

This is the first edition of the Texas Instruments (TI) *UHF Gen2 IC Antenna Design Reference Guide*.

This guide provides most of the relevant parameters to enable an RF antenna designer to make the most appropriate tradeoffs when developing antennas for Texas Instruments UHF Gen 2 Integrated Circuit (IC). It applies to the following products:

RI-UHF-11111-01, RI-UHF-00001-01

Note: An Integrated Circuit (IC) is often referred to as a ‘chip’ or when on a silicon wafer, as a ‘die’.

About This Guide

This Reference Guide (SCBU015, 11-07-21-702) is written for the use by TI partners who are engineers experienced with Radio Frequency Identification Devices (RFID).

Conventions

WARNING

A warning is used where care must be taken or a certain procedure must be followed, in order to prevent injury or harm to your health.

CAUTION

This indicates information on conditions that must be met or a procedure that must be followed, which if not heeded, could cause permanent damage to the equipment or software.

Note: Indicates conditions that must be met or procedures that must be followed, to ensure proper functioning of any equipment or software.

Information:

Indicates information that makes usage of the equipment or software easier.

If You Need Assistance

For more information, please contact the sales office or distributor nearest you. This contact information can be found on our web site at: <http://www.ti-rfid.com>.

Trademarks

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All other trademarks are the property of their respective owners.

Introduction

This chapter introduces you to the TI's UHF Gen2 IC.

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1.1 General

At UHF frequencies, longer read ranges and the ability to read large numbers of transponders as required by retail distribution, has led to the formulation of the EPC Gen2 specification. Retailers like Wal-Mart® and Target™ in the USA and Metro™ in EU have issued mandates to their suppliers to ship cases & pallets of goods/products with RFID Smart Labels attached. TI's UHF Gen 2 IC has been introduced so that converters can create inlays, straps and labels for case and pallet level retail supply chain applications. The IC's are based on EPCGlobal™ Gen2 (V1.0.9) approved in December of 2004.

TI's UHF Gen2 IC operates with extremely low power and yet provides long read and write ranges, fast data transfer and high Smart Label throughput, all of which are crucial for the following applications:

- Express parcel delivery
- Airline baggage handling
- Distribution logistics and supply-chain management
- Building access badges
- Asset tagging

1.2 Other Reference Documents

A detailed description of the command set, memory and operation of individual ICs is given in Texas Instruments' document "TI UHF Gen2 Protocol – Reference Guide" (SCBU001, 11-09-21-700). Additionally, the mechanical and electrical characteristics necessary for wafer conversion are described in the document "TI UHF Gen2 IC – Reference Guide" (SCBU015, 11-07-21-702)

1.3 1.3 Ordering Information and Part Numbers

The TI UHF Gen 2 IC is available in the following finishing options.

Table 1-1. Part Numbers

PART NUMBER	BACKGROUND	BUMPED	SAWN	MAPPED
RI-UHF-11111-01	Yes	Yes	Yes	Yes
RI-UHF-00001-01	No	No	No	Yes

Design Considerations

This chapter describes some of the decisions in the design of antennas for a Gen2 IC.

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2.1 Overview

Most UHF inlay antennas are a design compromise because of conflicting requirements. Form factor, the ability to function on a variety of different products/materials, orientation sensitivity, cost, and ease of manufacturing are all important tradeoffs in the overall design. There is no one 'right' design.

2.1.1 Implications of Form Factor

When we consider the antenna form factor, we are often constrained to create an antenna that must fit into a standard sized label, e.g., 4"× 2", 4"× 4", 6"× 4" etc. To achieve these lengths we have to move away from the half wavelength ($\frac{1}{2} \lambda$) of a standard dipole and, by the use of twists and turns, make the antenna shorter. At UHF frequencies a $\frac{1}{2}$ wavelength in free space is approximately 165 mm (6 $\frac{1}{2}$ "") and will decrease proportionally as one over the square root of the substrate dielectric constant. For example, if the substrate has a dielectric constant of 4 then the $\frac{1}{2}\lambda$ value of 6 $\frac{1}{2}$ " will reduce by a factor of 2. So it is important to consider the substrate dielectric constant early in the design. The shortening becomes more acute as we must also maintain a distance between the inlay and the label edge and an allowance for the margin between conductor and substrate edge.

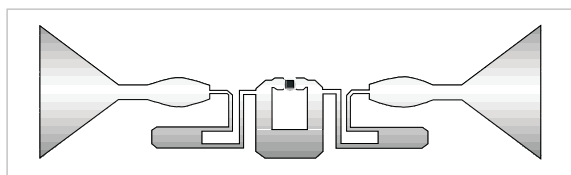


Figure 2-1. Texas Instruments UHF Reference Design

Trying to make even smaller sized antennas creates a further problem because the bandwidth is reduced, making it more difficult to make 'global' tags that are capable of operating over the whole frequency range from 860 MHz to 960 MHz.

2.1.2 Material Issues

If we consider the ability of a tag to operate when placed on different materials, we are often forced into choosing a specific dielectric range. In general, dry goods provide the least challenging materials to design antennas for, with liquids and metals at the other extreme. Liquids absorb the RF signals and have dielectric values of around 80 (air = 1), whereas the high permittivity of metals causes the signals to be reflected directly back to the inlay. Additionally, the inlay impedance will be significantly altered and shifted away from its optimal impedance thereby creating a serious mismatch to the attached die impedance. This large mismatch significantly reduces the power to the die limiting the ability of the die to turn on and communicate with the reader. Minimizing the width of an antenna can be helpful for such applications by limiting the area in contact with the dielectric material.

Most tags intended for direct application on non-friendly products/materials either use a spacer to separate the tag from the product or employ a specialist 'interposer' material designed to minimize the de-tuning effects.

Note: Designing antennas for unfriendly materials such as liquids and metals is outside the scope of this manual.

2.2 Die Impedance Measurement

Many methods can be used to determine the die impedance measurements. Texas Instruments' approach is to use the "Load Pull" technique.

2.2.1 The Load Pull Technique

The 'Load Pull' technique allows Texas Instruments to determine the die's impedance under actual dynamic load conditions. This is the most accurate way to determine the impedance. With this technique the die is attached to a Printed Wired Board (PWB) with SMA connectors to form the Device Under Test (DUT).

2.2.2 Load Pull Setup

The Load Pull setup is shown in [Figure 2-2](#).

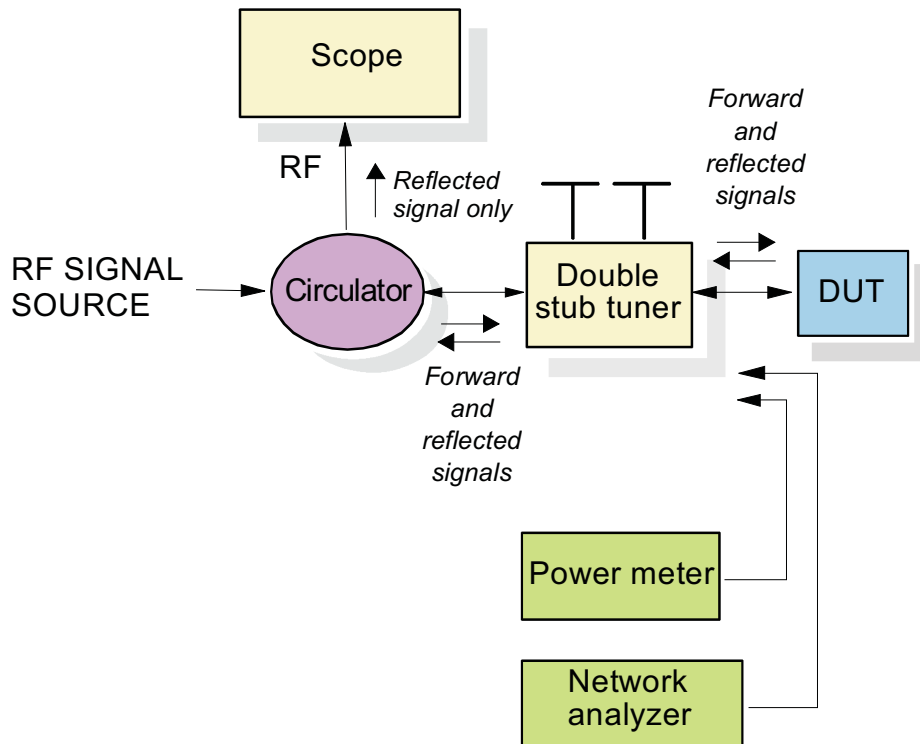


Figure 2-2. Load Pull Setup

2.2.3 Load Pull Method

A Query command signal is generated at the required frequency (e.g., 868 MHz) and at the appropriate power level and the Stub Tuner is adjusted for minimum reflected signal. This point is the conjugate impedance of the die, which we can measure with a Network analyzer.

This operation can now be repeated for different frequencies and power levels.

2.2.4 Load Pull Data

Using the load pull method, the die's parallel resistive and capacitive values for the following frequency bands have been found: 866 MHz (Europe), 915 MHz (North America), and 953 MHz (Japan).

Table 2-1. Die Load Pull Data

DIE PARALLEL IMPEDANCE			EUROPE 866.5 MHz	USA 915 MHz	JAPAN 953 MHz	UNIT
READ	-13 dBm nominal	Resistance	440	380	340	Ω
		Capacitance	2.8	2.8	2.9	pF
	-9 dBm minimum.	Resistance	360	330	300	Ω
		Capacitance	2.7	2.8	2.9	pF
WRITE	-9 dBm nominal	Resistance	380	340	320	Ω
		Capacitance	2.8	2.8	2.9	pF
	-6 dBm minimum	Resistance	250	240	230	Ω
		Capacitance	2.7	2.7	2.8	pF

We can see that as frequency increases, the real resistance of the die decreases and the capacitance will increase but only by a small amount. We can also note that the die input resistance will decrease as input power rises.

2.2.5 Conversion of Parallel to Series Impedance

Standard equations were used to convert the load pull data from Parallel to Series. This conversion allows us to use the Series impedance Smith Chart. Note. Parallel impedance data can be used with the Smith Chart in admittance mode.

Note: Some References to standard Books or Web sites are shown in Appendix B.

2.2.6 Antenna Series Conjugate Matching Values

For best operation, the antenna should present the conjugate of the impedances shown in [Table 2-1](#) to the die.

The resulting Series Antenna Conjugate Matched Impedance (resistive and inductive reactance) values are shown in [Table 2-2](#) and correlate with the values in [Table 2-1](#).

Table 2-2. Antenna Series Matching Values

ANTENNA SERIES IMPEDANCE			EUROPE 866.5 MHz	USA 915 MHz	JAPAN 953 MHz	UNIT
READ	-13 dBm minimum typical read	Resistance	9.4	9.9	9.5	Ω
		Inductance	11.8	10.5	9.3	nH
	-9 dBm read	Resistance	12.4	11.3	10.7	Ω
		Inductance	12.1	10.4	9.3	nH
	-6 dBm read	Resistance	17.2	18.1	14.5	Ω
		Inductance	11.6	10.5	9.3	nH
WRITE	-6 dBm Write	Resistance	11	11	10	Ω
		Inductance	11.7	10.5	9.3	nH

2.2.7 Inlay Sensitivity

One of the most important performance criteria for an inlay is its sensitivity especially over the RFID global frequency band (860 ~ 960 MHz). The inlays read range can be shown to be directly related to its sensitivity performance. Typically, inlay sensitivity can be accurately measured with the use of an anechoic chamber where measurement obstacles such as interference and multi-path signals are significantly reduced as to not affect the measurement accuracy.

2.2.7.1 Test Setup

The inlay under test (DUT) is placed within the chamber at a fixed distance (typically, 1 m) from the reader antenna (see Figure 2-3). The amount of power at the tag under tests' location can be accurately determined by the using the Friis radar equation. A signal generator that is pulsed modulated with a continuous Query command, is amplified to produce a maximum output of 4 watts (North American power level) from the reader antenna within the chamber. A secondary antenna within the chamber functions as a backscatter pickup antenna and is displayed on a spectrum analyzer set to zero span.

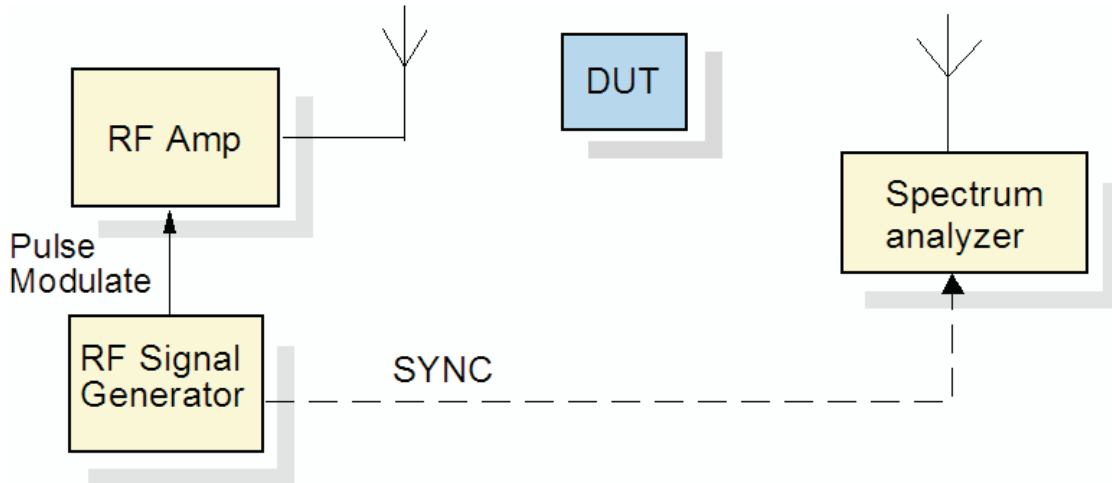


Figure 2-3. Anechoic Chamber Test Setup

The spectrum analyzer is also synchronized with the Query command modulated signal that allows the inlay's backscatter magnitude to be quantified and measured over frequency and different power levels.

2.2.7.2 Test Methodology

The signal generator output level is adjusted in 0.1 dB steps until the inlay stops backscattering. The resulting signal power level (in dBm's) at the inlay location can be easily determined and is a measure of the inlay's sensitivity at the supplied frequency. The frequency is changed and the test is repeated until all frequencies have been tested.

The system is initially calibrated from the signal generator output to the antenna. This establishes a known Effective Isotropic Radiated Power (EIRP), in dBm's for different signal generator output levels within the chamber. With a 1m fixed distance, the path loss in dBs is established thereby producing a known "sensitivity" signal power level (in dBm's) at the inlay under test location. This level can be determined by a simple calculation using Friis equation or measured with an externally calibrated power meter.

When TI's reference design inlay was tested, it showed a flat sensitivity response across the entire global band from 860 MHz to 960 MHz.

2.2.8 Model for Power Transfer

Maximum power transfer between the antenna and the die occurs when the antenna impedance is a conjugate match to the die impedance. This usually occurs over a very small frequency range because both antenna and die impedances vary with frequency. An antenna optimized for 860 to 960 MHz operation should be symmetrically centered at 908 MHz to offer the best match (see Section 5.2, "Centering Tips").

Models were simulated with Ansoft Designer™ from 865 to 960 MHz in 5 MHz steps and overlaid onto a Smith Chart.

In Figure 2-4, the antenna impedance for the die conjugate match (max power transfer) is shown near the edge of the Smith Chart in a high Q region.

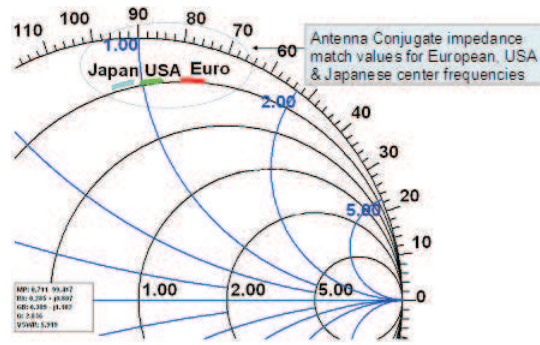


Figure 2-4. Smith Chart Data

Design Data

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3.1 Die Matching Values

The three tables below have been included to illustrate TI's die impedance at center frequency for three different standards regions.

Table 3-1. American Die Matching Values

AMERICA (915 MHz)		
PARAMETER	VALUE	UNIT
Input capacitance	~2.8	pF
Input resistance	~380	Ω

Table 3-2. European Die Matching Values

EUROPE (868 MHz)		
PARAMETER	VALUE	UNIT
Input capacitance	~2.8	pF
Input resistance	~440	Ω

Table 3-3. Japanese Die Matching Values

JAPAN (953 MHz)		
PARAMETER	VALUE	UNIT
Input capacitance	~2.9	pF
Input resistance	~340	Ω

The tables contain the die impedance required to design an antenna that could provide an optimum match to the die.

3.2 Smith Chart Example

Figure 3-1 below shows a Smith Chart plot of the Reference antenna (See Chapter 4).

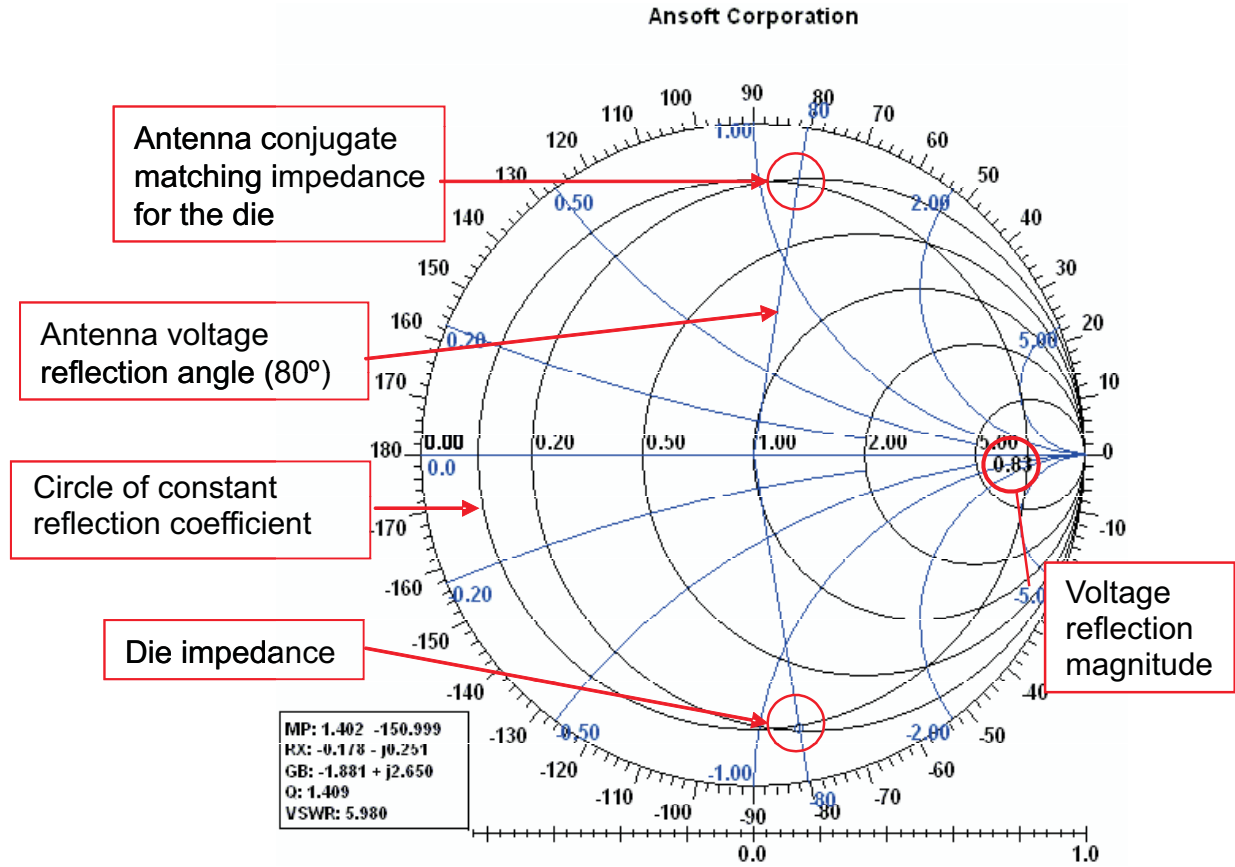


Figure 3-1. Reference Antenna Smith Chart

3.2.1 Smith Chart Explained

The die series equivalent impedance can be seen towards the bottom of the chart with a voltage reflection magnitude of 0.83 with an angle of -80 degrees. A circle of constant voltage reflection magnitude 0.83 is added that passes through the die impedance point. The antenna conjugate matching impedance will also lie on this circle.

When a mirror reflection angle is added, the interception point is the antenna conjugate matching point. This point is only for one frequency but the antenna will be centered around this frequency at mid band, e.g., 908 MHz.

This whole process can be done by hand – one would start by converting the given parallel die impedance to its series equivalent and plotting it on the Smith Chart. Next draw a constant circle through this point with the 50Ω point at its center. Then draw a line through the die impedance point from the center noting the angle where it cuts the outer edge. Now draw a line at the same angle from the center in the top (inductive) half of the chart, to where it cuts the circle. The intersection of the line and circle is the conjugate matching impedance of the antenna.

3.3 Effects of Varying Impedance

Although it has been found that near optimum sensitivity can be obtained with real impedances between 270 Ω and 700 Ω , we have observed that when the real part of the matching impedance is at the lower end of that range (200 to 250 Ω), the die functions with good sensitivity but the magnitude of the backscatter back to the reader is significantly reduced – resulting in readers not able to detect the low level backscatter.

Note: Antenna design for good reader performance will err towards the mid range of the allowed impedances.

3.4 Effects of Varying Capacitance

If the real part is fixed and the imaginary part is swept to match different die capacities, we see that the die behaves best for a relatively short range of target capacitance (approximately $\pm 10\%$). As the antenna impedance moves further from centered resonance (in either direction), the sensitivity drops and the backscattered magnitude approaches zero.

Note: A good antenna design will try to maintain resonance as much as possible at the expense of the real part.

Capacitance is a critical parameter.

3.5 Substrate Selection

The dielectric value of the substrate has a large effect on the gain and impedance of the antenna. Changes in the dielectric can cause the impedance and the electrical length of the antenna to change. The antenna length will vary as one over the square root of the dielectric constant. PET (Polyethylene Terephthalate) is a good choice as it is stable, flexible, has a melting point close to 250°C and can, if required, be easily printed with silver inks.

3.6 Conductor Material and Trace Size

A number of processes can be used for creating the conductor, For example:

- Printed Inks, e.g., silver
- Etched copper
- Etched aluminum
- Other techniques

Conductor material is primarily a tradeoff against cost. Silver has a better conductivity but because of the expense, size must be carefully controlled and concerns have been raised over its eco-friendliness when recycling silver. Reference designs with aluminum on 50 μm PET have been tested and no appreciable difference in performance over printed silver ink on 75 μm PET has been found.

The width of the tracks or traces is part of the antenna design and plays an important part in establishing the overall antenna impedance. Typical UHF antenna impedance will consist of distributive capacitance, inductance and resistance. There are usually manufacturing minimum width restrictions on printed or etched antennas and must be considered in initial designs.

3.7 Bonding Process

A number of different processes can be used to affix the IC to an antenna. The most common processes are:

- Anisotropic Conductive Film (ACF)
- Heat cured epoxy
- UV cured epoxy

Although each method will have a small effect of the performance, the choice of adhesive is a secondary consideration and different methods might be tested during evaluation.

3.8 Antenna Shape Considerations

In the introduction some of the issues associated with form factor were discussed. This section is concerned with the effects of shape on the electrical characteristics.

The amount of RF captured by the antenna (power taken from the electromagnetic field) and the amount of antenna backscatter (from tag to reader), is directly proportional to the antenna area or aperture.

Antenna gain is directly proportional to the antenna aperture. The antenna gain is typically 1.5 dBi to 1.9 dBi for a 3.5" RFID inlay. A standard $\frac{1}{2}$ wavelength dipole gain is 2.14 dBi.

3.9 Antenna Loop

Although the input to the IC is AC coupled allowing the use of an input inductor, having a closed loop in the antenna design (as in the reference design) has a number of advantages.

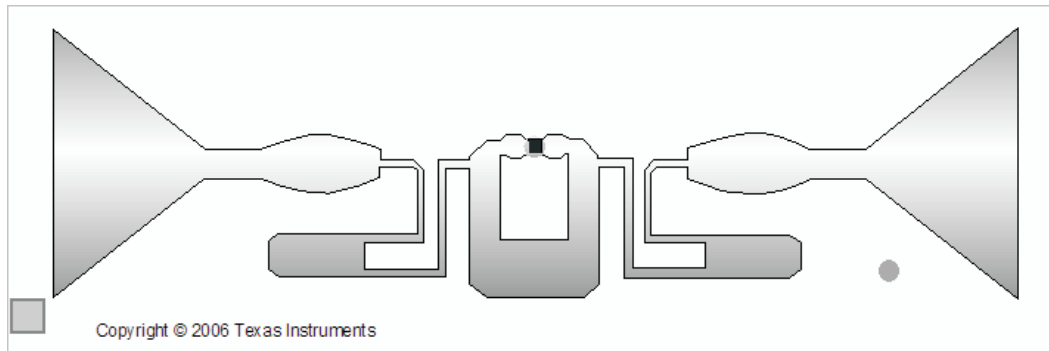


Figure 3-2. A Closed Loop Antenna Design

1. Although the IC is rated to an industry standard of 2000 volts of electrostatic discharge (ESD), the inner loop has a DC short circuit resistance which helps to eliminate high voltage discharge (ESD) from damaging the die input circuitry.
2. The inner loop inductance and the die input capacitance form a resonant circuit that will couple with the magnetic (H) field that is generated in the near field. This field will generate a voltage across the die input terminals and power the die for communications with a reader or printer. Near Field in the UHF band is a technique that is growing rapidly and antenna designers should consider producing a loop that will resonate in the frequency band of interest.
3. The inner loop serves as an impedance match (like a transformer) making matching the die to the antenna easier for the designer.
4. The inner loop attachment point to the antenna can be raised or lowered to shift the antenna impedance to the desired location on the Smith Chart.
5. Making the inner loop trace thinner or thicker can lower or increase the antenna impedance.

3.10 Design Validation

Because of the high number of variables involved in the design of a suitable antenna, it is likely that multiple iterations of the design will be necessary.

Reference Design

This chapter details a reference design.

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4.1 Design Criteria

These reference designs are intended for global operation on UHF friendly materials and are specifically matched to Texas Instruments' Gen2 IC's (RI-UHF-00001-01) or straps (RI-UHF-STRAP-02).

Note: Straps are small (8 mm × 3 mm) aluminum on PET substrates that already have the IC attached. They greatly simplify the process of bonding an IC to an antenna.

4.2 Antenna Reference Design

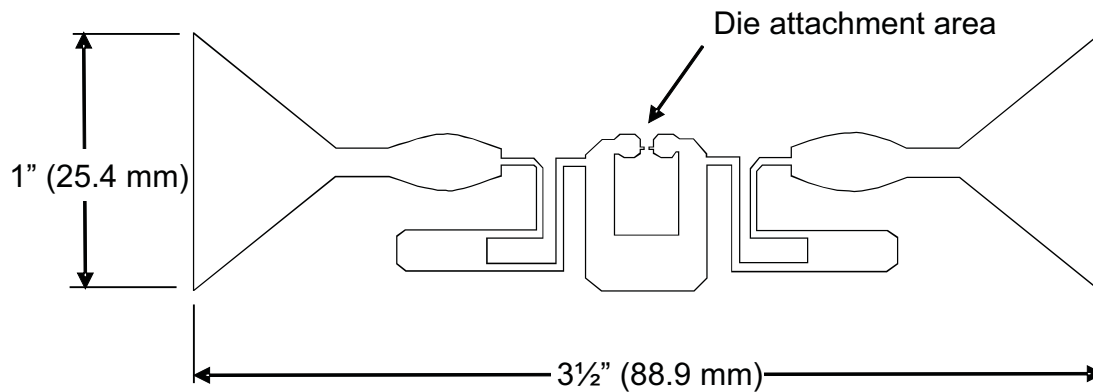


Figure 4-1. IC Reference Antenna

4.2.1 Die Attachment

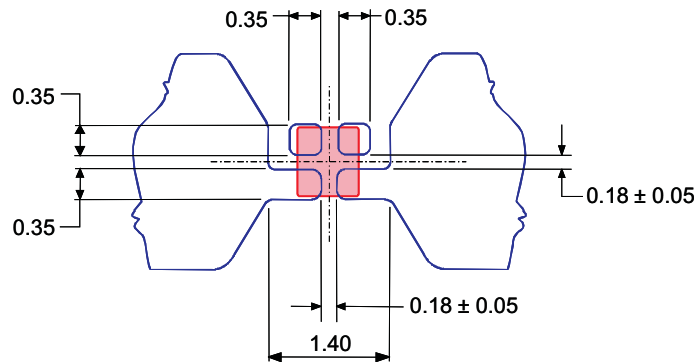


Figure 4-2. Die Attachment Detail

4.3 IC Reference Design Impedance Plot

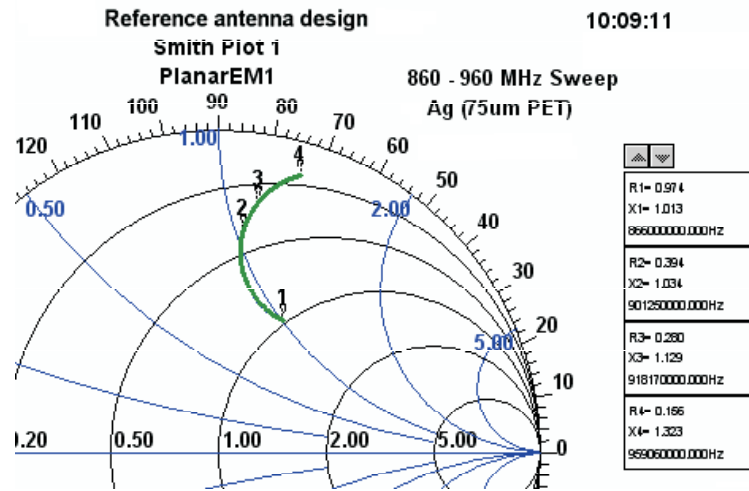


Figure 4-3. Reference Antenna 860 – 960 MHz Sweep

4.3.1 Rotating the Impedance

Increases in the area of the reference design shown below have the effect of lowering and causing a counter-clockwise rotation of the impedance.

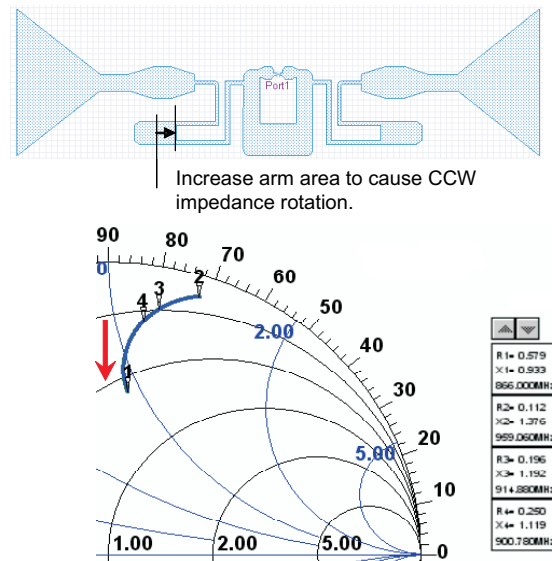


Figure 4-4. Changing the Reference Design Impedance

4.3.2 Reference Design Antenna Gain

In [Figure 4-5](#), the plot for 860 to 960 MHz shows a typical family of gain curves for our reference design. The gain in the far field is typically +1.78 dBi.

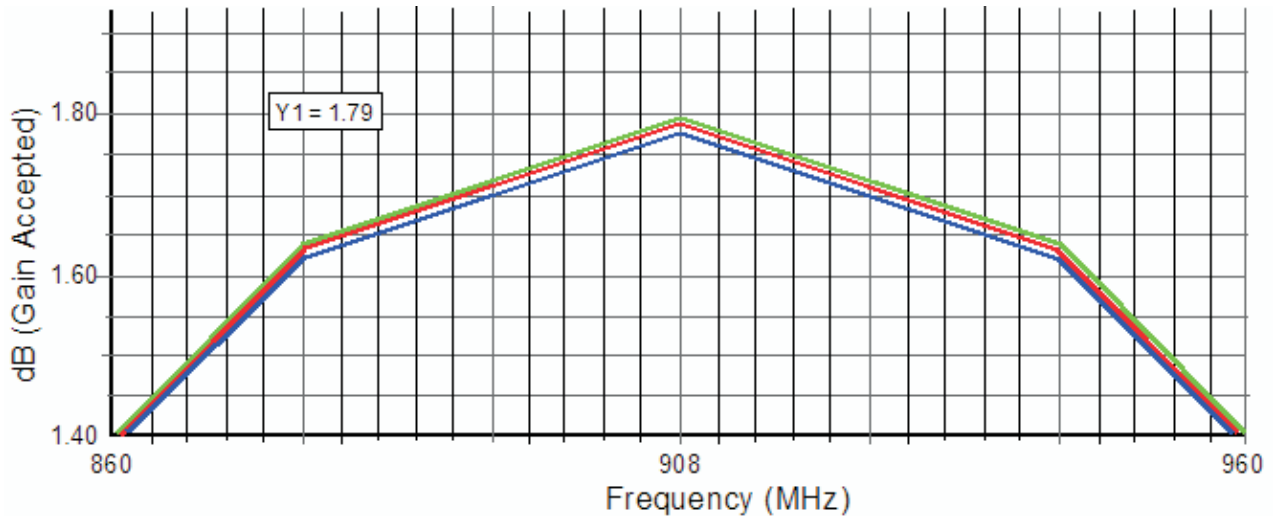


Figure 4-5. Reference Design Antenna Gain

4.4 Strap Reference Design

This design incorporates tolerance marks for correct strap placement. The typical strap (8 mm × 3 mm) has an attached die and is installed within the designated area as shown in [Figure 4-6](#).

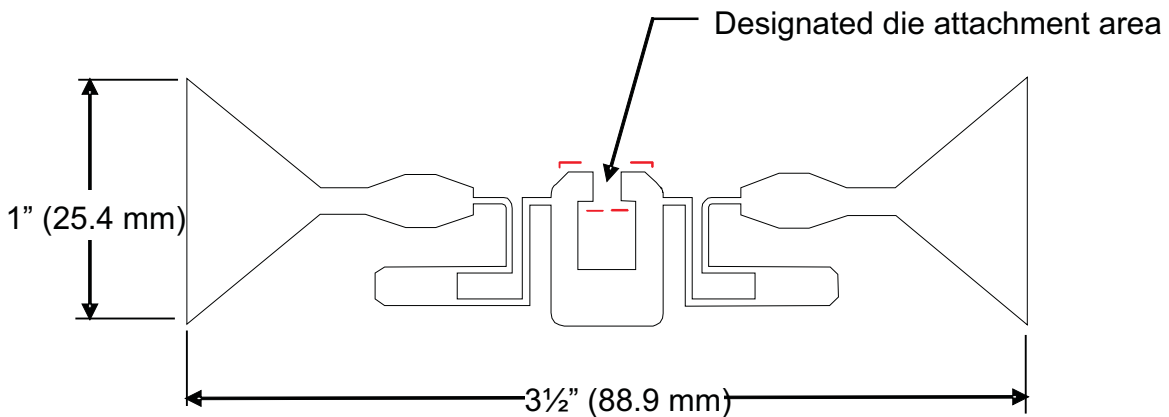


Figure 4-6. Strap Reference Antenna

4.4.1 Strap Antenna Design Impedance Plot

Once a strap (with die) is attached to an antenna the impedance must be swept over the entire global RFID frequency band from 860 MHz to 960 MHz. The impedance sweep data or results are then plotted on a standard Smith Chart as illustrated in [Figure 4-7](#).

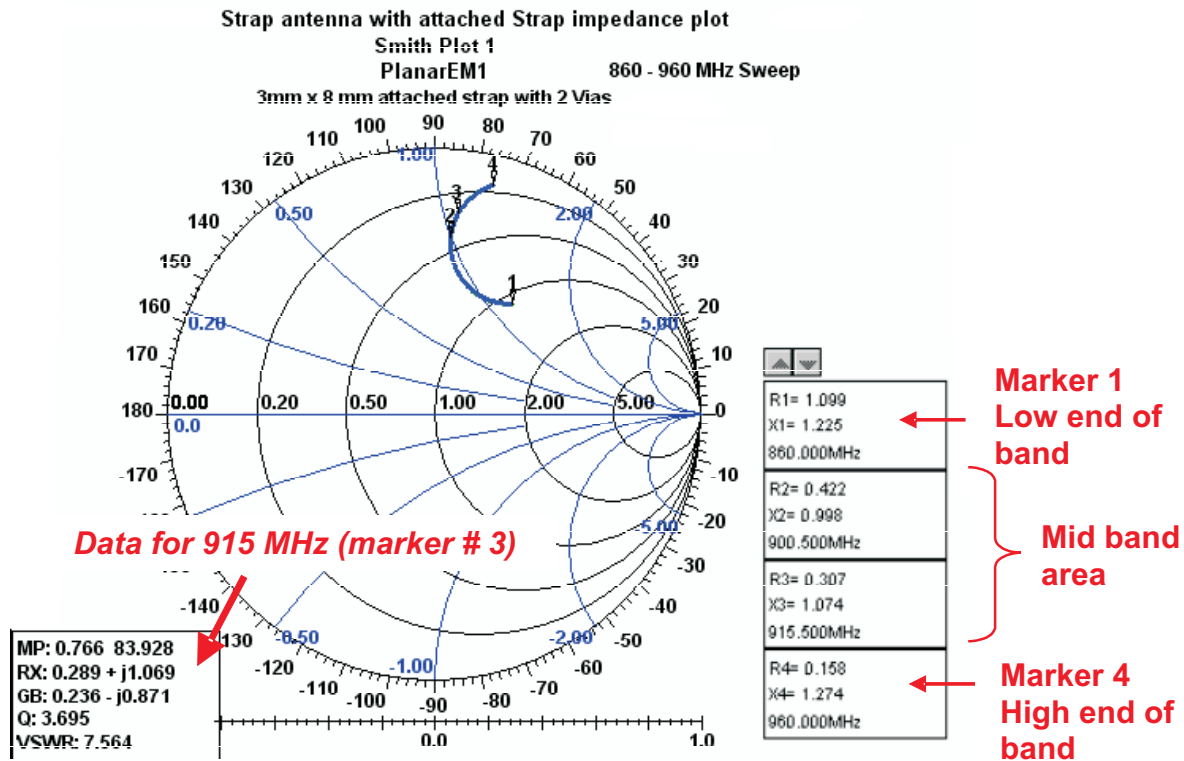


Figure 4-7. Strap Antenna Impedance Plot

The Smith Chart is an extremely useful RF tool for the antenna designer. Once the impedance sweep results are plotted on a Smith Chart the antenna designer can easily compare the antenna impedance plot (across the entire frequency band) to the preferred impedance match required to match the die impedance. Typically, the antenna impedance at mid band (marker #3) should be very close to the die conjugate match impedance at mid band, that is, it is desirable to have the impedance sweep at 915 MHz pass through the die conjugate match impedance point for 915 MHz.

This is illustrated in [Figure 4-7](#) as marker #3 passes through the die conjugate match impedance. The plot of the impedance sweep is shown to rotate in a clockwise direction on the Smith Chart, starting at 860 MHz (marker #1) and ending at 960 MHz (marker #4).

As an example, the impedance shown at marker #3 on the Smith Chart would provide a conjugate match for a die with an impedance of approximately 380 Ohms in parallel with 2.8 pF. The antenna at mid band resonance (915 MHz) would provide the required inductance to match the die capacitance. In addition, the antenna at mid band would provide the required resistive component that would equal the die resistive component. When these two conditions exist, a conjugate match is provided to the die and maximum power will transfer between antenna and die.

The Smith Chart illustrates that a small mismatch between antenna and die occurs at the band edges. In addition, the die resistance and capacitance will shift slightly over the RFID frequency band. The die impedance will also be affected by the signal power level incident on the antenna. The die capacitance will vary only slightly with increasing power levels while at the same time the die resistance will decrease slightly.

4.4.2 Strap Impedance

The strap measures 3 mm x 8 mm. The impedance of the strap at mid band is approximately 3.5 Ohms resistance in series with a small capacitance of 0.095 pF. When the die is attached this impedance is added to the die impedance to obtain the combined strap and die impedance.

Hints and Tips

This chapter describes hints and tips that may make your design easier.

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5.1 Mismatch Loss

A mismatch loss exists between the antenna and the die, any time the die impedance and antenna impedance are not conjugate matches. As a true conjugate only exists at one frequency, mismatch loss occurs most of the time – it is the amount of loss that is important. For example, if the antenna and the die impedances are out by a factor of 2:1, a mismatch loss of 0.5 dB will occur and this means that approximately 10% of the power delivered from the antenna to the die will be reflected back. If alternately, the ratio was 3:1 then approximately 33% of the power would be lost. Sensitivity and read range will be directly affected by any mismatch loss between die and antenna.

Mismatch loss between the die impedance and the antenna impedance is the most critical parameter (with antenna gain next) that establishes tag performance.

Obtaining the centering impedance that provides the conjugate impedance match for a die at exactly one frequency, or a limited bandwidth, is relatively easily achieved using the Smith Chart. However, designing an antenna such that its swept impedance (for example from 860 to 960 MHz) passes through this point, is a much more challenging task. Not only does the impedance have to pass close to the impedance centering point but needs to be symmetrically centered, so that the return losses are the same at the band edges (860 and 960 MHz) and minimum at the center (908 MHz).

The final antenna design should have a return loss better than – 9.5 dB (2:1 VSWR) at the band ends and –10 dB to –15 dB at the center. Accomplishing this task requires multiple trimming on parts of the antenna.

5.2 Centering Tips

It is very important to center the antenna impedance around the die conjugate matching impedance over the frequency range of interest. If designing a global antenna for 860 ~ 960 MHz it is important to center the antenna impedance at the geometrical mean frequency. The geometrical mean is the square root of the product of the limits.

e.g., $\sqrt{(860 \times 960)} = 908 \text{ MHz}$

5.3 Antenna Bandwidth

The antenna bandwidth is related to the antenna Q-factor and determines the frequency range over which the inlay will operate. For example, an antenna with 100 MHz bandwidth would be expected to function from 860 – 960 MHz with good performance. Q can be determined by dividing the center frequency by the bandwidth. For example, dividing a 915 MHz center frequency by a 100 MHz bandwidth will give the loaded Q for a typical UHF inlay.

The unloaded Q-factor of the antenna is much higher than the loaded Q-factor. The unloaded Q-factor is essentially the inner loop resistance (at say 915 MHz) divided by the inner loop inductive reactance and may be found to be 200 or greater. The product of the Q-factor and the inductive reactance represent a parallel resistance (very large, typically greater than 10 K Ω) which is across the die input terminals. This impedance must be large to not shunt the die input signal.

Bandwidth can typically be increased by enlarging the area associated with the ends of the antenna.

Making the antenna longer will lower the antenna loaded Q-factor and increase the bandwidth. The antenna Q-factor will increase (lower bandwidth) proportionally as the antenna length is shortened.

5.4 Impedance Plots

The Smith Chart is typically used to plot the antenna and die impedance over the given frequency range of interest. It is used to determine the antenna conjugate matching impedance for the die. The center of the Smith Chart is normally 50Ω but can be normalized to the die input impedance making the chart useful for other calculations such as power reflection voltages, display of the voltage reflection coefficient (Γ) of the antenna with respect to the die impedance which is not the center of the chart. It is possible to predict the inlay (antenna and die) read range performance, expected antenna sensitivity and many other parameters, using standard techniques found in many text books.

Terms and Abbreviations

A list of the abbreviations and terms used in the various TI manuals can be found in a separate manual:

TI-RFid™ Product Manual Terms & Abbreviations

Literature number SCBU014 (11-03-21-002)

References

The following references offer information on different aspects of antenna design:

1. <http://www.rfcafe.com>
2. ISBN 0-672-21868-2, SAMS, RF Circuit Design
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