Sensitivity and Impedance Measurements of UHF RFID Chips

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***Abstract*—In this paper, we describe the sensitivity and impedance measurement method for UHF RF identification (RFID) chips. The measurements are performed using an RFID tester (RFID reader with variable output power and frequency) and a vector network analyzer. No special impedance matching is required: chips can be connected to standard 50-Ω connectors allowing the sensitivity and threshold impedance to be measured directly in a fast and efficient way. We present experimental data for two UHF Gen2 chips (NXP UCODE G2XM and Impinj Monza 2) in thin-shrink small outline packages. The results have been verified using two chip assemblies matched to 50 Ω. This method can also be applied to chips in other packages: flip-chip, strap, etc.**

***Index Terms*—Impedance, integrated circuits (ICs), RF identification (RFID).**

I. Introduction

RF IDENTIFICATION (RFID) is an automatic wireless data collection technology with long history roots [1]. In a passive RFID system, the reader transmits a modulated RF signal to the tag consisting of an antenna and an integrated circuit (IC) powered only by RF energy. The IC (chip) responds to the reader by changing its input impedance between two states (typically, high, power collecting, and low, close to short circuit), and thus modulating the backscattered signal. The first functional passive RFID systems with a range of several meters appeared in early 1970s. Since then, RFID has significantly advanced and experienced a tremendous growth with several books on RF and other aspects of passive UHF RFID systems published in recent years [2], [3].

Recently, a variety of ultra high-frequency (UHF) RFID Gen2 ICs became available on the market. Those chips have different power sensitivities, different Q factors, and different impedances. From tag antenna designer's point of view, the best chip impedance to work with is 50 Ω. However from the IC designer's point of view, realizing such impedance is difficult: all chips inherently have some capacitances, which result in complex input impedances with different dependences on input power and frequency.

Knowledge of sensitivity and impedance of RFID chips is critical for good RFID system design, including both tags and readers. The importance of these two characteristics cannot be overestimated: they define such fundamental RFID tag parameters as power sensitivity and maximum forward tag range. For example, in free space, the maximum forward tag read range is given by [4]

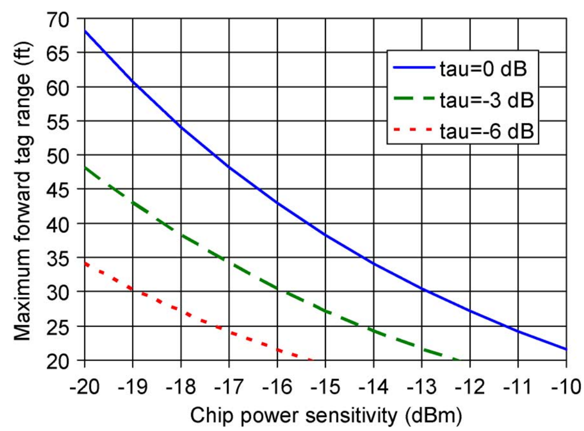

Fig. 1. Relationship between maximum RFID tag range (ft) and chip power sensitivity (dBm) for different values of power transmission coefficient. Other parameters: free space, 4-W EIRP, 915 MHz, 2-dBi tag antenna, perfect polarization match.

$$r_{tag} = \frac{\lambda}{4\pi}\sqrt{\frac{P_t G_t G p \tau}{P_{th}}} \tag{1}$$

where λ is the wavelength, P_t is the output power of the RFID reader transmitter, G_t is the gain of the reader antenna [$P_t G_t$ is the transmitted effective isotropic radiated power (EIRP)], G is the gain of the tag antenna, p is polarization mismatch between the tag and the reader antennas, and τ is the power transmission coefficient. The latter is also known as the impedance-matching coefficient between the chip and the tag antenna and is given by

$$\tau = \frac{4R_c R_a}{|Z_c + Z_a|^2} \tag{2}$$

where $Z_a = R_a + jX_a$ is the complex antenna impedance and $Z_c = R_c + jX_c$ is the complex chip impedance in a high (power collecting) state. This is the impedance that we are concerned with in this paper. Fig. 1 shows the relationship between the maximum tag range and the chip power sensitivity for different values of τ for a typical tag. As one can see, 3-dB variations in either chip sensitivity or impedance matching can change tag range by about 40%.

Knowledge of complex chip impedance at the threshold power allows one to design a good complex conjugate matched antenna for maximizing forward tag range. Knowledge of

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more complete chip impedance behavior (e.g., as a function of power) allows one to determine how the strength of the received backscattered signal will change as a function of distance. Improving that strength (e.g., by proper tag antenna design) can allow one to avoid dead zones and extend the backscatter RFID tag range, which is especially important for semipassive systems, where the return link is the range limiting factor (in current passive RFID systems, the limiting factor is the forward link).

There are several studies on measuring the impedance of RFID tag antennas alone and characterizing tags as a whole [5]–[9], but virtually no publications on measuring the chip impedance, except for a high level overview of RFID IC testing issues [10]. The chip impedance values are usually taken by tag designers from IC manufacturers' datasheets, which specify the impedance at the threshold power level, but just for one or two frequencies and often only for a bare die.

In this paper, we attempt to fill an existing gap by describing how we do our chip sensitivity and impedance measurements. While the method described here would seem simple and straightforward to any experienced microwave engineer, we felt that there was a need to describe that in a clear fashion for the benefit of the wide RFID engineering community. Since no special matching is required, the results can be obtained fast compared to time-consuming source–pull tuner reference based measurements typically used for characterization of nonlinear microwave devices [11]. We also included experimental data for two major UHF Gen2 chips available on the market (Impinj Monza 2[1] and NXP UCODE G2XM[2]) in thin-shrink small outline packages (TSSOPs) (these were picked because they are frequently used in rigid tags where solid and reliable chip attachment is needed). The measurement methodology described here can also be used for RFID chips in other packaging (flip-chip, strap, etc.).

II. Measurement Procedure

The procedure for measuring the power sensitivity and impedance of RFID chips is described below. The packaged chip is tested directly using a standard 50-Ω probe or connector without special matching. Two pieces of equipment are critical: the RFID tester for determining the minimum power sensitivity and vector network analyzer (VNA) for measuring the input impedance at various power levels. The RFID tester has the functionality of an RFID reader (can send commands to the tag and receive tag replies) and can also vary its output power and frequency. It allows one to find the RFID chip power sensitivity, which cannot be reliably found only from the impedance behavior versus power measured with the network analyzer. RFID chips may have RF front ends with very different characteristics, thus the chip power sensitivity threshold can only be determined using RFID-specific modulated commands. The power sensitivity may also depend on particular Gen2 command parameters (pulsewidth, modulation depth, etc.). In our measurements, we used specific values described later.

[1][Online]. Available: http://www.impinj.com/rfid/rfid-chips.aspx

[2][Online]. Available: http://www.nxp.com/products/identification/ucode/

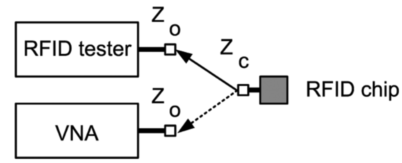

Fig. 2. Block diagram of the measurement setup.

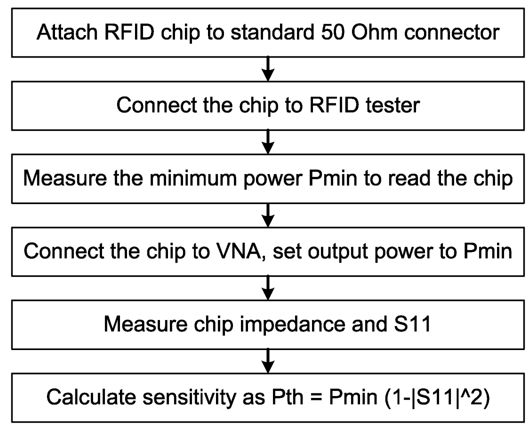

Fig. 3. Flow diagram of impedance and sensitivity measurements.

Proper equipment calibration is also important. RFID tester output power calibration must be performed (e.g., using a power meter) to the point (plane) where the RFID chip is attached. VNA calibration is a standard one-port calibration procedure and must also be performed to the same plane where the chip is attached.

For measuring RFID chip sensitivity, the following procedure was used. Each chip was soldered to a standard 50-Ω SMA connector assembly. The chip-connector assembly was connected to an RFID tester. The minimum power level $P_{\min}$ necessary to activate the chip was measured using the custom RFID reader equipment with variable output power and frequency. The same chip-connector assembly was then connected to the VNA whose output power was set to $P_{\min}$. At any moment, the RFID chip was connected either to an RFID tester or to a VNA, as shown in Fig. 2. Output impedance of both the RFID tester and VNA was $Z_o = 50\ \Omega$.

The VNA whose output power is set to $P_{\min}$ measures the complex impedance and S_{11} as follows:

$$|S_{11}|^2 = \left|\frac{Z_o - Z_c}{Z_o + Z_c}\right|^2. \tag{3}$$

The measured impedance is the sought chip impedance at the threshold power level. Since the chip-connector assembly is usually lossless and all input power is either reflected or absorbed in the chip, the threshold power sensitivity of the chip can be calculated as

$$P_{th} = P_{\min}\left(1 - |S_{11}|^2\right). \tag{4}$$

The flow diagram of the measurements is shown in Fig. 3.

III. Experimental Results

This section presents sensitivity and impedance measurements of two RFID chips in TSSOP packages: Impinj Monza 2

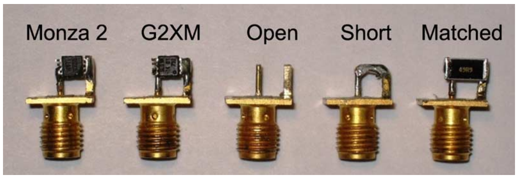

Fig. 4. Impinj and NXP RFID chips on 50-Ω SMA connectors.

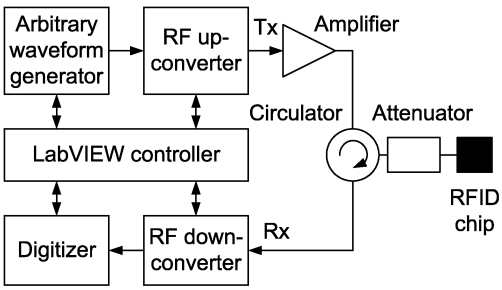

Fig. 5. Block diagram of RFID tester used in measurements.

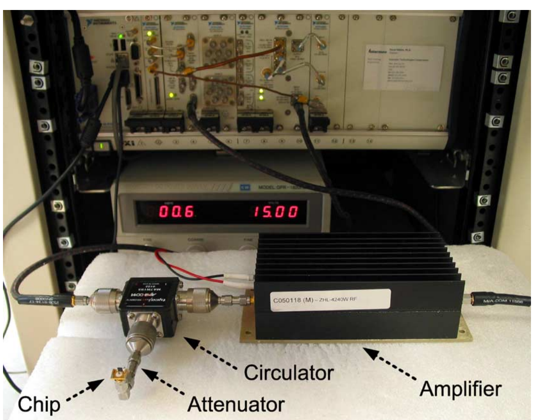

Fig. 6. Photograph of the testing setup with RFID chip connected.

and NXP UCODE G2XM. Both RFID chips were soldered to a 50-Ω subminiature A (SMA) (only one RF port of the Impinj chip was used) and are shown in Fig. 4 together with the calibration loads used in measurements.

The RFID tester was built on a National Instruments RF PXI hardware platform controlled by LabVIEW,[3] shown in Figs. 5 and 6. It included a Mini-Circuits ZHL-4240W power amplifier (because the same setup was also used for free-space tag testing at high EIRP values) and a M/A COM 7N195 circulator.

A 30-dB attenuator was included between the RFID chip and the circulator so that mismatched chip load would not affect the circulator parameters during measurements. The VNA was an Agilent E-series E5071C RF network analyzer.[4] Both the RFID tester and VNA had standard output impedances of 50 Ω and had calibrated power outputs with 0.1-dB accuracy. The calibration was done with an Agilent E4418B power meter. The RFID tester sent a Gen 2 *Query* command (1000) and detected the tag response by its RN16 reply. The command used Tari

[3][Online]. Available: http://www.ni.com/automatedtest/rfid.htm

[4][Online]. Available: http://www.agilent.com/find/ena

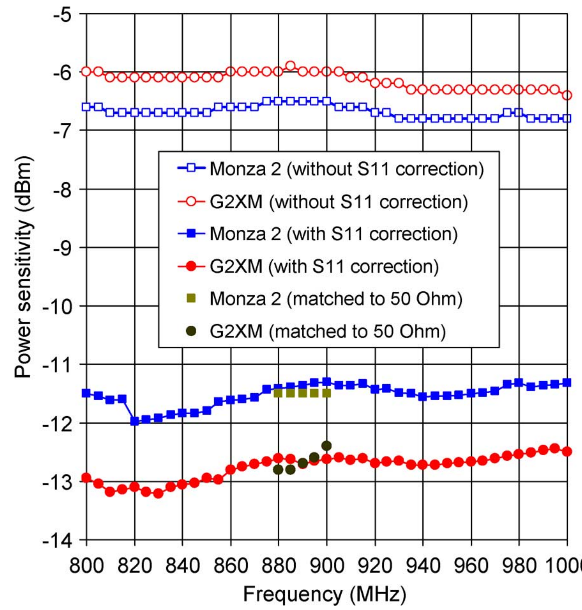

Fig. 7. Measured power sensitivity of RFID chips.

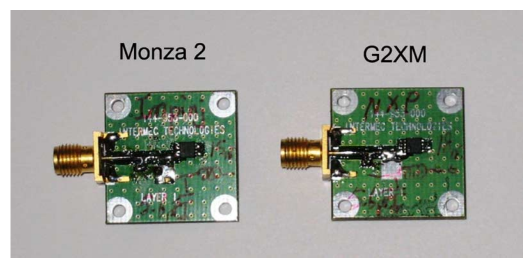

Fig. 8. Impinj Monza 2 and NXP G2XM RFID chip assemblies matched to 50 Ω.

value 24 μs, pulsewidth 12 μs, backlink data rate 40 kHz, and modulation depth 90%.

Fig. 7 shows the measured power sensitivity: raw data (without $S11$ correction factored in) and with $S11$ correction factor factored in using (4) (it was measured with a VNA at the output power level given by RFID tester measurements, the VNA was calibrated to the point of chip attachment). Note that the raw chip assembly sensitivity measured with the RFID tester depends on frequency only slightly, changing by less than 0.5 dB in 800–1000 MHz. This allows one to set the constant power level at the VNA (for $S11$ measurements) and still achieve a reasonable accuracy. For example, that power level can be set to the average raw power sensitivity of the chip-connector assembly.

To verify our measurement results, we also performed additional sensitivity measurements in a narrow band using a different method explained below. The comparison between the results is shown in Fig. 7. The additional measurements were done using two separate chip assemblies shown in Fig. 8. Since a packaged RFID chip with complex input impedance can, in general, be represented as either a parallel or series *RC* circuit, it can be easily matched to 50 Ω in a narrow band using a simple *LC*-type network. Impinj Monza 2 and NXP G2XM chips were mounted on a double-sided 60-mil printed circuit board (PCB) and matched in the 860–900-MHz frequency band to 50 Ω using a passive *LC*-type matching network shown in

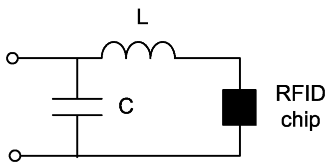

Fig. 9. Passive lossless *LC*-network used for matching chips to 50 Ω.

TABLE I
VALUES OF DISCRETE *L* AND *C* COMPONENTS USED FOR MATCHING MONZA 2 AND G2XM TO 50 Ω

	Impinj Monza 2	**NXP UCODE G2XM**
L	15 nH	18 nH
C	5.6 pF	5.6 pF

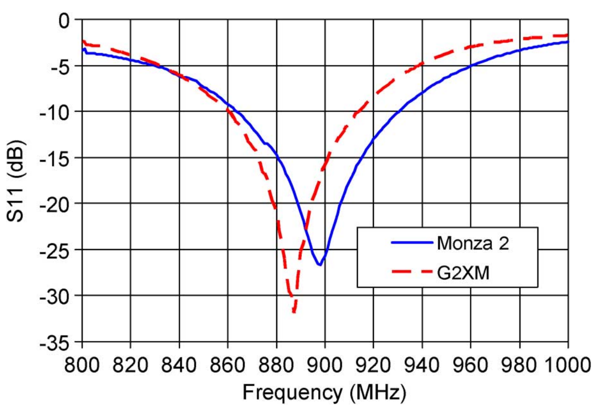

Fig. 10. Return loss of Monza 2 and G2XM RFID chip assemblies matched to 50 Ω.

Fig. 9. The values of the *L* and *C* components used for matching are given in Table I. The measured return loss of the 50-Ω matched assemblies is shown in Fig. 10.

The return loss of 50-Ω assemblies was less than −15 dB in a 880–900-MHz band. This band was used for verifying our original method. The sensitivities of these 50-Ω chip assemblies were measured directly using our RFID tester. The results are compared in Fig. 7 with the sensitivity results obtained from our original method, which agree very well (within the tolerance of nominal values and losses of discrete ceramic passive *L* and *C* components used for matching.

Figs. 11 and 12 give the impedance (resistance and reactance) of both chips measured by a VNA as functions of frequency (at threshold power) and absorbed power (at 900 MHz). While Smith chart representation is more common among microwave engineers, we choose to present impedances using rectangular plots to make reading the values easier. Plus, in practice, the RFID tag's antenna (source) impedance is always complex, and the Smith chart representation changes depending on the reference source impedance [12].

As one can see from Fig. 12, the measured "turn on" points (on resistance and reactance curves) where chips get powered up do not correspond to any special behavior features in impedance curves versus power. This means that RFID chip power threshold can only be reliably determined using RFID-specific modulated commands sent at different power

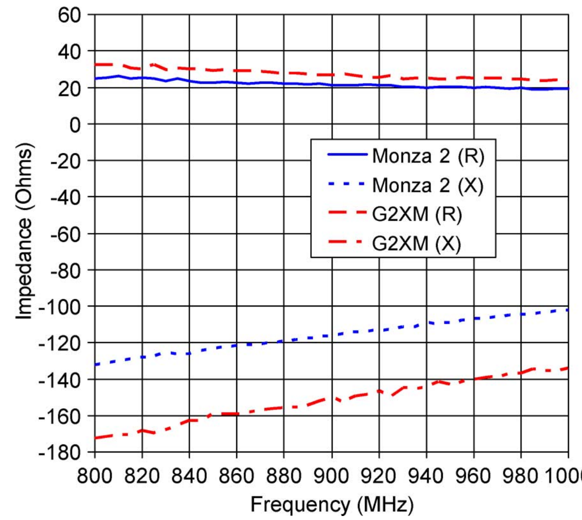

Fig. 11. Measured chip impedance versus frequency at the threshold power.

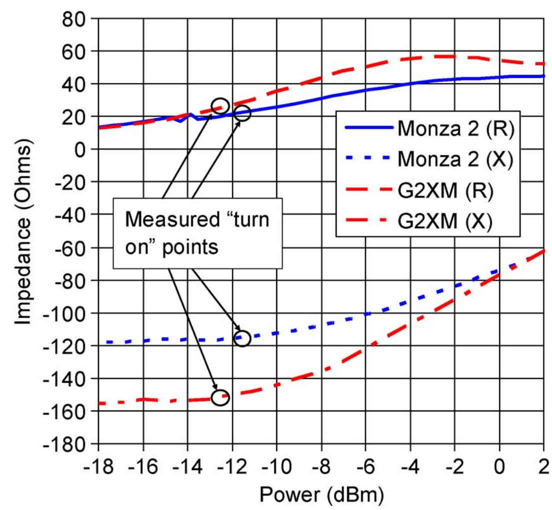

Fig. 12. Measured chip impedance versus absorbed power at 900 MHz.

TABLE II
MEASURED CHIP SENSITIVITIES AND IMPEDANCES OF MONZA 2 AND G2XM AT 900 MHz

	Impinj Monza 2	**NXP UCODE G2XM**
Pth	-11.4 dBm	-12.6 dBm
Z (at Pth)	21-j116 Ohm	26-j150 Ohm

levels. Table II gives measured chip sensitivities and impedances (at threshold power) for 900-MHz frequency for both chips (Monza 2 and G2XM).

In general, the impedance and sensitivity values of any bare Gen2 tag IC is defined by specific RF front-end realizations which have been well discussed in the existing literature [13]–[16]. The impedance of a packaged IC mounted on a tag antenna always depends on both the chip packaging method (bare die, TSSOP, etc.), mounting process (gluing, soldering, flip-chip, strap, etc.), and the structure it is mounted on (PCB, flexible substrate, etc.) with a corresponding effect on fabrication accuracy and reliability [17], [18]. While detailed circuit models for the package parasitic are available [19], at each particular frequency, parasitic effects can, in general, be lumped into simple equivalent circuits (e.g., parallel and series *RC* circuits mentioned earlier).

In this paper, for illustration of measurement procedure, the chip was mounted directly on a connector. In a practical tag design process, after choosing how the chip will be attached to an antenna, we mount it on the sample of material and perform impedance measurements using our method. Note that an RFID chip is fundamentally a voltage-sensitive device, which cannot distinguish whether the voltage developed on its terminals is due to the large incident signal from the mismatched source or a small signal from the matched source. Thus, sensitivity measurements described here can be used with different chip mounting methods as long as there are no losses between the connector or probe and the chip.

IV. Conclusions

In this paper, we have described the methodology for measuring the sensitivity and impedance of RFID chips and presented experimental results for two Gen2 RFID chips in TSSOP packages. The presented method is simple and practical since it does not require a special matching and allows one to obtain chip impedance and sensitivity in a fast and efficient way. Complex and time-consuming tuner measurements (where the measurement source impedance is adjusted until it is matched to the chip impedance) may result in only slightly more accurate threshold sensitivity and impedance results.

In this study, the impedance was measured for a high (power collecting) state of an RFID chip for read operation. Write sensitivity (usually the chip needs different power for read and write operations) can also be measured using our method. Measuring the impedance of the second (low) modulating state is more complicated and requires equipment combining VNA and RF signal generator (RFSG) functionalities capable of performing fast impedance measurements while sending RFID modulated commands. When this paper was in the process of final publication, we learned that this measurement was recently performed using a specialized setup with separate microwave instruments [20]. We believe that such a measurement can also be done entirely with National Instruments PXI RF hardware platform, which may become the topic of future work.

Current passive UHF RFID systems have a maximum range limited by the chip sensitivity in the forward link (reader-to-tag). That range is often used as a tag characteristic. With the emergence of semipassive (battery assisted) Gen2 chips, the reader sensitivity in the return link (tag-reader) will become the limiting factor, and the range can be expected to be used as a reader characteristic, at least for some time. This is where the knowledge of both chip impedance states as functions of frequency and power will become especially important for tag antenna designer in order to find a compromise between tag absorption and tag backscatter and maximize the smallest of the forward and reverse tag ranges.

Accurate knowledge of chip impedance and sensitivity also allows one to build 50-Ω matched chip assemblies (“conducted tags”), which can be used for a variety of purposes, from RFID reader troubleshooting to quick and efficient contactless measurements of various antenna characteristics [7], [8]. The latter application is especially important for small antennas where cables can affect the antenna performance.

We hope that the results presented in this paper will be useful for wide RFID community, including industry and university research laboratories. The measurement methodology described here can also be used for RFID chips in other packaging (flip-chip, strap, etc.) and operating at other frequency bands than UHF, such as the millimeter-wave band, which is also being considered for RFID applications [21].

Acknowledgment

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