AN686

ANTENNAS FOR THE Si4455/435x RF ICs

1. Introduction

This application note provides guidelines and design examples to help users design antennas for the next generation EZRadio® RF ICs. The matching principles for the Si4455 are described in detail in “AN693: Si4455 Low Power PA Matching”. For the Si435x, the RX match design methodology of the Si446x family can be used as described in detail in “AN643: Si446x/4362 RX LNA Matching”.

Besides the matching RF performance and the long-term reliability (the critical maximum peak voltage on the output pin), performance strongly depends on the PCB layout (the layout design principles are described in detail in “AN685: Layout Design Guide for the Si4455/435x RF ICs”) and also on the antenna design. For optimal performance, Silicon Laboratories recommends the use of the antenna design hints described in the following sections.

2. Design Recommendations when Using Si4455/435x RF ICs

The Si4455 transceiver RF chip uses Class-E TX matching network and a 4-element matching balun on the RX side in Direct Tie configuration (where the TX and RX paths are connected together directly without any additional RF switch). Meanwhile, the Si435x receiver RF chip uses only the 4-element matching balun. On the RF stick or RF pico board there is an opportunity to select between a PCB antenna or an SMA connector (to use a 50 Ω SMA antenna) by soldering a SMD0805 0 Ω resistor to the proper pin.

The printed antenna possibility is basically devoted to low-cost handy applications. Typically a low-cost remote uses a printed antenna (IFA, BIFA or loop) and typically has a rectangular shape with one side significantly longer than the shorter side. This is because this kind of shape is convenient to hold in the user’s hand. The board typically has a separate area for the antenna as this is required to achieve good RF radiation performance.

A typical shape and form factor is shown in Figure 1. Here the typical usage of the Si4455 stick demo is shown. The goal is to have good radiation in the front direction (shown by the red arrow in Figure 1) and to have maximum range when the remote is held in the typical manner by the customer.

Figure 1. Typical Remote Construction and Hand Position

Some general rules of thumb to design small PCB antennas for good RF performance:

- In the case of single-ended monopole-type antennas (ILA, IFA, spiral), a large continuous ground plane metallization is required at the feeding point of the antenna. Typically, this ground metal is formed by the RF and other circuit areas with all the gaps filled with ground metal at the top and bottom PCB layers. This is important as the ground plane is an obligatory part of these types of antennas. The lack of big enough ground metal causes strong degradation in radiation and efficiency. It also causes radiation pattern deterioration and matching problems (the real part of the antenna impedance decreases as the radiation resistance decreases).
- Avoid isolated metal islands by connecting all filling metals together at the top and bottom layer by using as many grounding vias as possible and connect them to the ground. This is necessary to avoid parasitic patch antennas and thus to minimize PCB radiation. The usage of many parallel vias decreases the series parasitic inductances and helps to form a more equal potential ground metallization along the board.
- Avoid using internal loops and long wires in the antenna area to obviate parasitics resonances and antenna detuning caused by them.
- Always be aware of potential parasitic de-tuning effects (e.g., push buttons, hand effect, detuning caused by the plastic housing etc.). They are critical, especially at higher frequencies, and usually bench tuning is required to compensate for them entirely.
- For good RF performance and low current consumption, it is necessary to match the antenna impedance well to the optimum termination impedance determined by the applied RFIC (it is usually 50 Ω, and this is the case with Si4455 as well if the proposed matching circuit is used).
- Ensure as large a free area on the module as possible for the PCB antenna to achieve maximum antenna gain (this is especially critical at lower frequencies as the achievable gain is proportional to the antenna size/lambda ratio).
- In the case of single-ended monopole-type antennas, the radiation pattern is determined by the antenna and the ground plane together. Also the hand effect has a strong influence. Therefore, the proper design of the radiation pattern is more difficult. Typically, it is difficult to design remotes to radiate to the front direction according to Figure 1. With differential antennas, the ground metal has much less influence on the radiation pattern, and thus it is more tunable. The differential BIFAs shown later in this document typically radiate in the desired way as shown in Figure 1.

Layout design guidelines for the Si4455/Si435x RF IC (see “AN685: Layout Design Guide for the Si4455/435x RF ICs”) are also recommended for review before the antenna design.

3. PCB Antennas for Si4455/435x RF ICs

In this section, PCB antenna layouts, descriptions of their operation, and measurement results using the Si4455/435x RF ICs are shown. In all cases, the applied antennas are matched/tuned to have 50 Ω input impedance, thus it is also necessary to use a matching network between the RF IC and the antenna (the matching principles are described in detail in “AN693: Si4455 Low Power PA Matching”).

Furthermore, all of the shown antennas are E-field radiators, so impedance tuning should be done carefully due to the potential de-tuning effects (e.g., the user’s hand, plastic housing, etc.).

The Si4455 transceiver and the Si435x receiver RF chips use the same PCB antennas. Of course, the antenna parameters depend on the operating frequency, but the antennas are reciprocal and linear, thus the same antenna can be used for transmitting and receiving.

3.1. Single-Ended IFA antenna for the Si4455/Si435x RF ICs

A typical single-ended IFA (inverted-F) antenna applied in the 4355-PRXB315B development board designed to work at 315 MHz is shown in Figure 2. Here the tuning arm of the antenna uses two layer curls in a spiral antenna fashion to reduce the area occupied by the antenna.

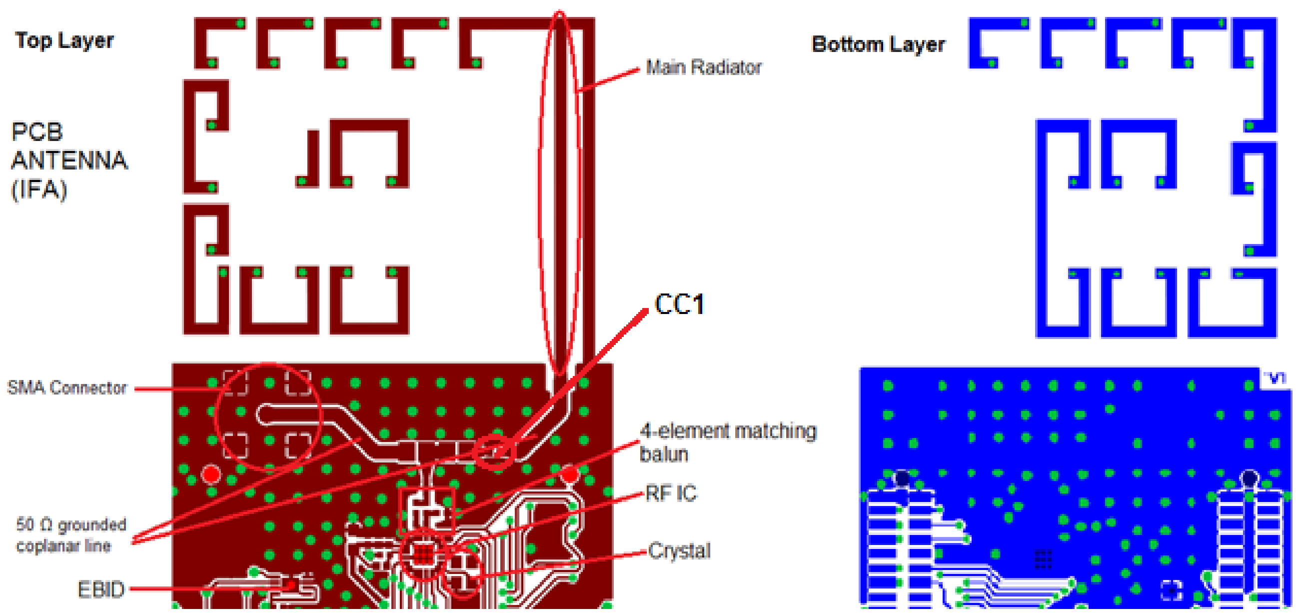


Figure 2. Single-Ended IFA used in the 4355-PRXB315B Development Board

When considering the antenna layout design, it is necessary to keep at least 2 mm space between the entire antenna and the border of the PCB to ensure a reliable antenna input impedance and radiating characteristic.

The advantages of this monopole-type IFA antenna are as follows:

- It has a simple structure, and it can be easily tuned to a 50 Ω input impedance.
- It has a single-ended input port which can be connected directly to the single-ended input of the 4-element RX matching balun circuit.

Since the IFA antenna is a monopole-type antenna, its radiating performance strongly depends on the size and shape of the ground plane especially at this low 315 MHz band. The effects of the user’s hand and the plastic housing also influence the E-field radiator. But the main disadvantage of using this type of antenna in remotes is its radiating characteristic, due to the main radiator position (see in Figure 2); it has good radiation in the sidelong directions but poor to the front. Fortunately, this is only a problem in line-of-sight propagation, and if the user holds the board in the typical way as shown in Figure 1. If the user holds the board plane perpendicular to the link direction or there is multipath propagation due to reflections (e.g., an indoor environment), this antenna can be advantageous as its mainlobe gain is good: typically ~-5…0 dBi with a big ground plane and ~-10 dBi with a smaller (applied in this example) ground plane.

To have good radiation in the front direction (shown by the red arrow in Figure 1) according to typical customer habits, a differential BIFA antenna is recommended. Most Si4455 transceivers and Si435x receivers use this type of PCB differential BIFA antenna.

3.1.1. Simulation Procedure of the Applied IFA Antenna in Sonnet

In this section, the simulation setup and results of the applied printed IFA antenna for the Si435x RX module are shown.

The antenna is designed to a 1.55 mm thick FR4 substrate. Due to memory and process time limits, the geometry was simplified: basically the circuit area is represented by a homogeneous ground metal and the resolution is 0.25 mm both in the X and Y direction. The Sonnet EM simulator used is a planar 2.5D simulator. It simulates the planar structure in a waveguide in which the PCB is in the cross section of the waveguide (Figure 3). In order to simulate the radiation accurately, the box walls have to be at least a lambda away from the simulated structure. So here the walls are 100 cm (in case of 315 MHz) away from the structure.

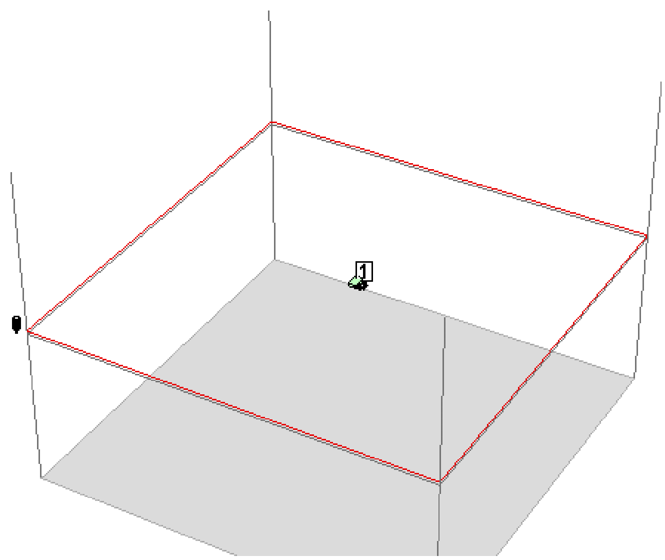


Figure 3. 3D View of the Simulated Structure by Sonnet in a Waveguide

The radiation is shown according to the Sonnet coordinate system (Figure 4). The theta should be below 90 degrees to remain above the horizon. At theta = 90 degree (PCB plane) the simulated radiation is not valid. In the radiation plots the theta varying between 0 and 90 degrees and four phi cuts (0, 90, 180 and 270) are plot. As shown in Figure 4, the phi 0 and 180 values direct to the right and left of the editor window, respectively. The phi values 90 and 270 direct to the top and bottom of the editor window, respectively. At theta=0 the radiation is perpendicular to the PCB plane.

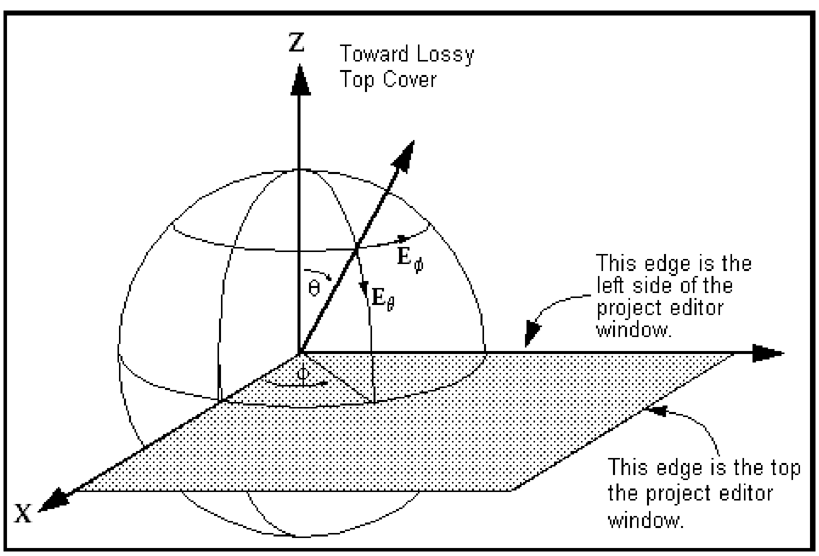


Figure 4. Sonnet Radiation Coordinate System

The simulated remote with printed IFA is shown in Figure 5.

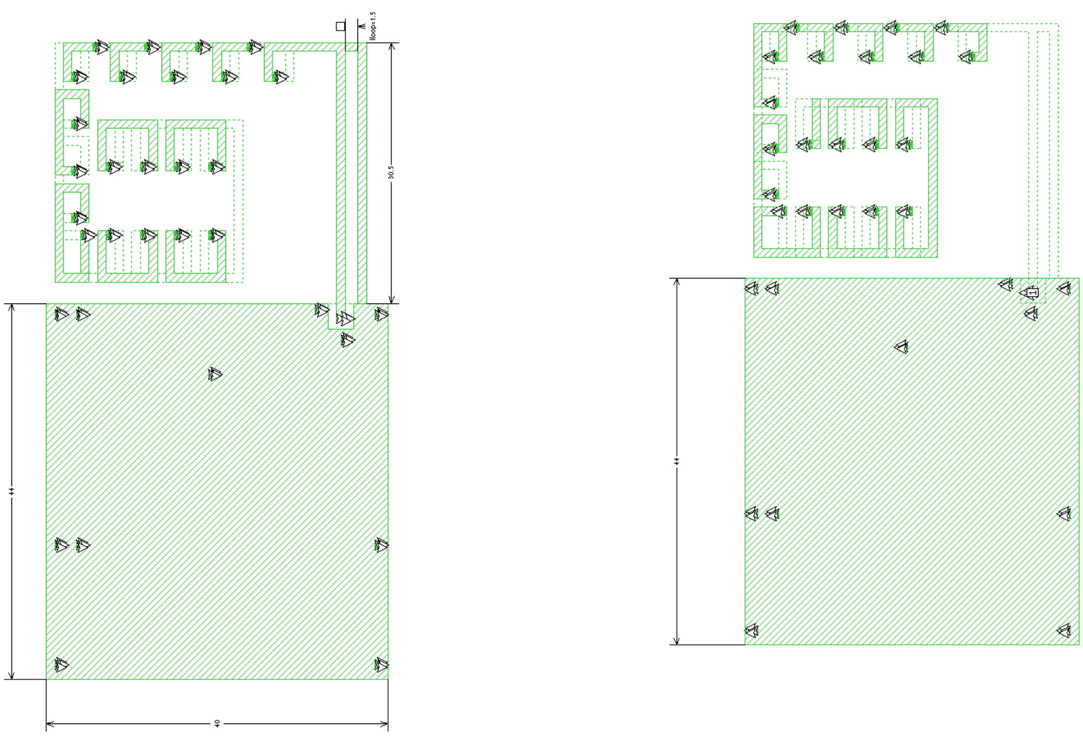


Figure 5. Remote Layout (Top and Bottom Layers) Fine Tuned via Silicon Laboratories Simulations

Simulation results can be seen in Figure 6, where one can observe that the input impedance is very close to 50 Ω.

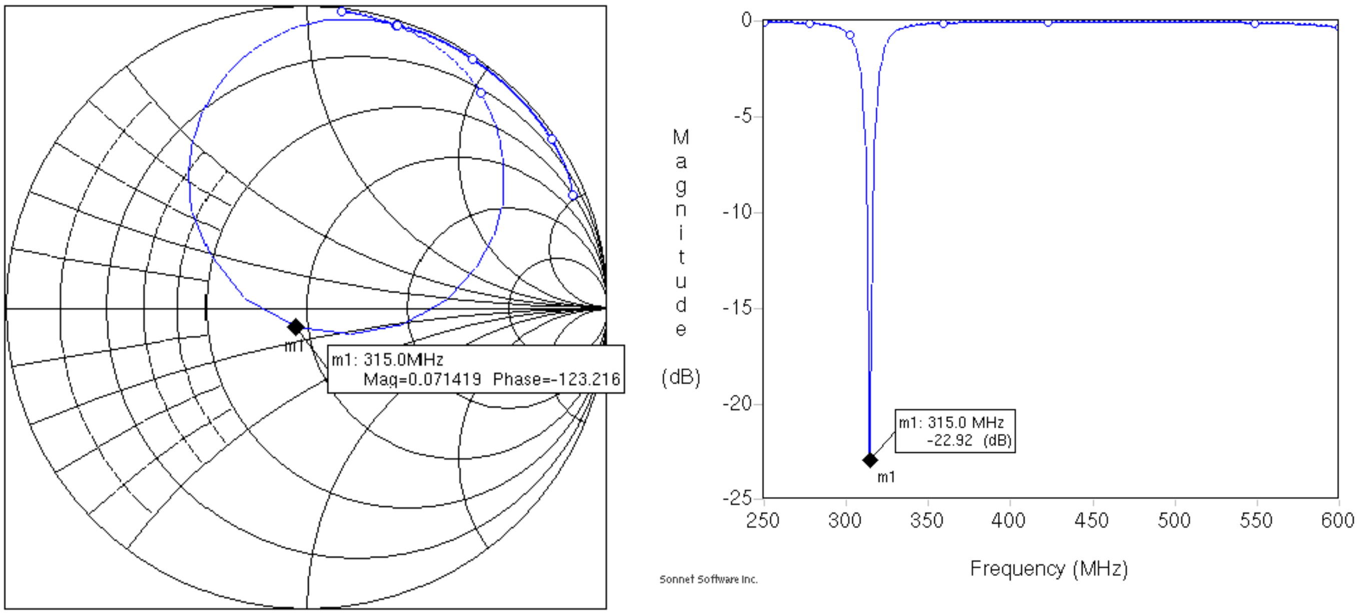


Figure 6. Simulated Impedance at 315 MHz of the IFA Antenna (on the Smith Chart and Cartesian)

For tuning the input impedance of the IFA antennas, consider the following.

- The resonant frequency is determined by the total length of the antenna.
- The input impedance is influenced by the position of the feedback grounding arm of the antenna. The impedance depends on the distance between the antenna input and the grounding point; if these points are closer to each other then the input impedance will be lower.

The simulated radiation characteristic can be seen in Figure 7. The remote radiates mostly to the sidelong (i.e., to Phi = 90 and 180 degrees) directions. The maximum antenna gain is around –11.5 dBi due to the small ground plane size.

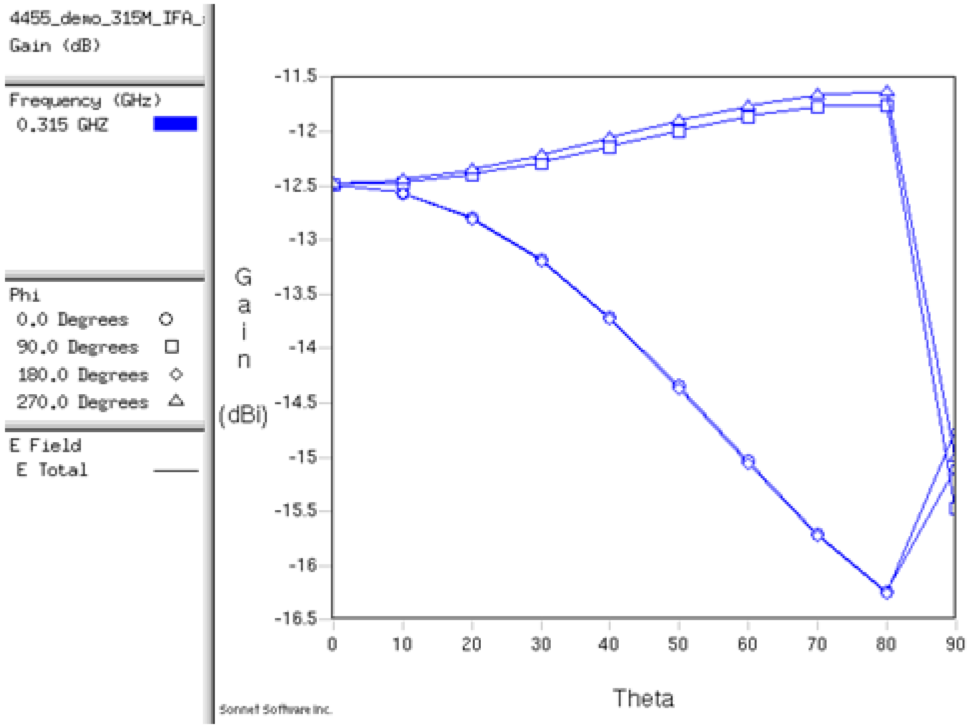


Figure 7. Simulated Radiation Characteristic at 315 MHz

3.1.2. Measurement Results of the Applied IFA Antenna

The impedance measurement result can be seen in Figure 8, where one can observe that the input impedance is very close to 50 Ω. For the fine impedance tuning, an additional series 10 pF (CC1, see Figure 2 on page 3) is also required.

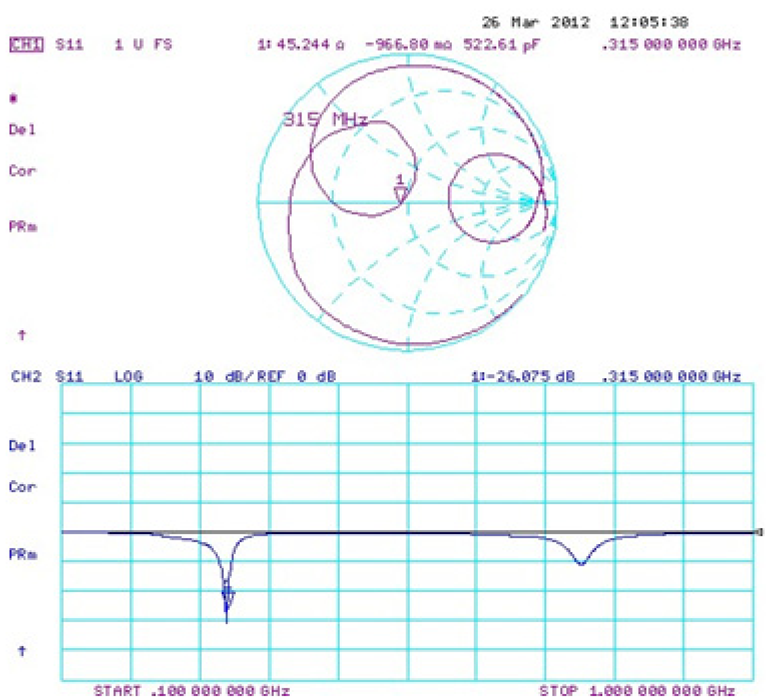


Figure 8. Measured Input Impedance of the Applied IFA at 315 MHz

3.2. Differential BIFA Antenna for the Si4455/435x RF ICs

As was mentioned previously, to achieve good radiation to the front direction (shown by the red arrow in Figure 1 on page 1) according to typical customer habits, a differential BIFA antenna is recommended. Most Si4455 transceivers and Si435x receivers use this type of PCB differential BIFA (balanced inverted F Antenna).

In the case of differential antennas, the ground plane does not much influence the radiation characteristic, thus this type of antenna can be designed in a more reliable way than the single-ended antennas in small size remote control applications.

A typical BIFA antenna applied in the 4455-LED-434 development board is shown in Figure 9. Here, the tuning arm of the antenna uses two layer spiral fashioned curls to reduce the area occupied by the antenna.

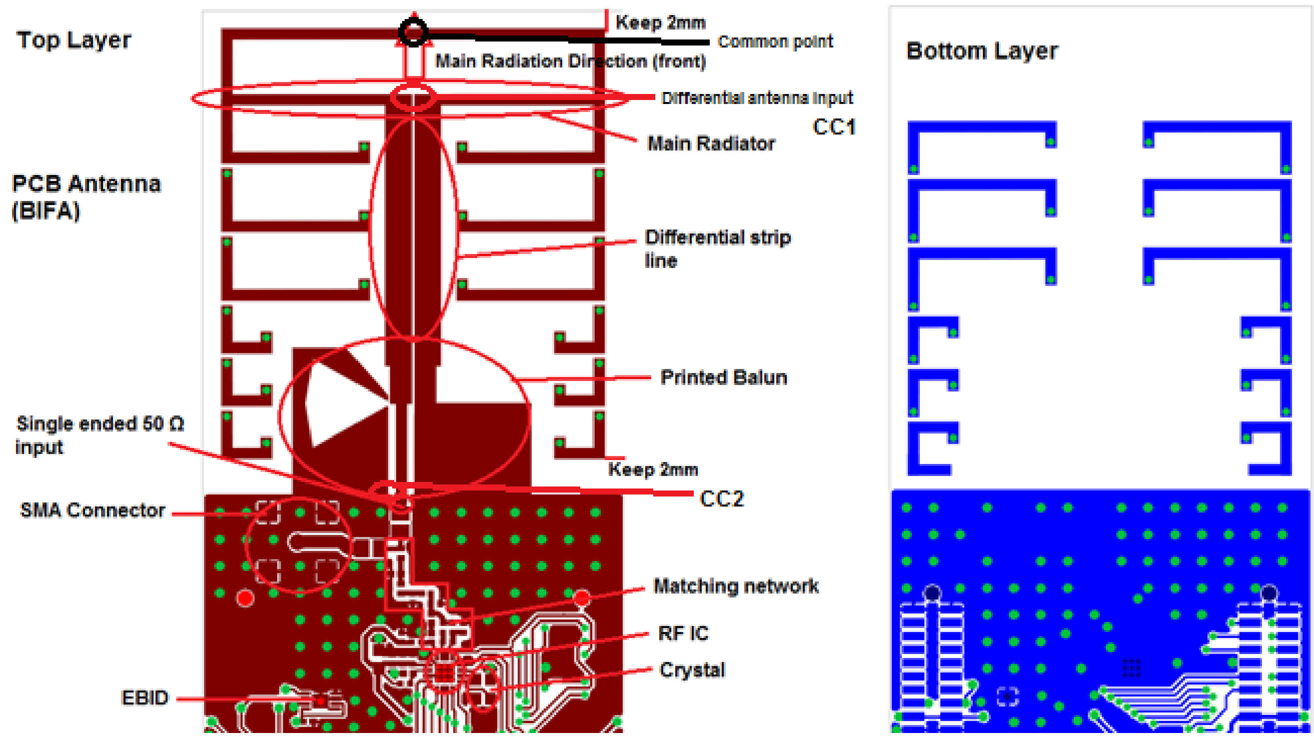


Figure 9. Differential BIFA used in 4455-LED-434 Development Boards

As the Si4455 matching has a single-ended output and the differential BIFA has a differential input, a balun is required between the two to make a balanced-to-unbalanced conversion. In order to save cost, a fully printed balun was designed without any discrete components.

The 90 Ω differential strip line between the balun and the BIFA makes the impedance match. It is basically a transmission line transformation, which converts the impedance of the BIFA such that together with the printed balun it is in a series resonance with the proper nearly 50 Ω residual impedance.

The BIFA antenna with the strip transformation and with the printed balun transformer (see on Figure 9) has a single-ended 50 Ω input, thus it can be connected directly to the single-ended output of the Si4455 matching given in "AN693: Si4455 Low Power PA Matching". In the case of Si435x receivers these same types of BIFA antennas with their strip lines and printed balun transformers can be used. Here, the single-ended input of this structure is connected to the single-ended output of the Si435x 4-element RX LNA matching discrete balun detailed in "AN643: Si446x/Si4362 RX LNA Matching."

The main radiator of the antenna is the dipole at the top (see on Figure 9) which is perpendicular to the feeding strip line. The function of the curled arms is to tune the antenna impedance.

Furthermore, it is also necessary to keep at least 2 mm space between the antenna traces and the PCB cutting edges to ensure a reliable antenna input impedance and tuning.

The most important advantage is in the radiation characteristic, because the main radiation is to the front and back direction and also to the top and bottom perpendicular to the PCB plane. This is due to the position of the main radiator dipole. The sidelong radiation is small as those directions are parallel with the dipole axe. The expected main directions of radiation can be seen in Figure 10.

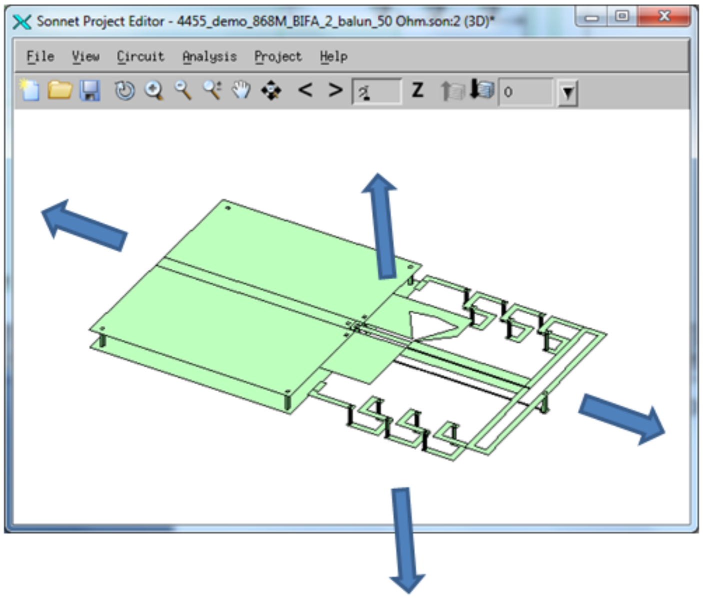


Figure 10. Main Directions of Radiation of the BIFA Antenna

3.2.1. Simulation Procedure of the Applied BIFA Antenna at 434 MHz in Sonnet

The simulation setup of the applied printed BIFA antenna is the same that was introduced in the beginning of "3.1.1. Simulation Procedure of the Applied IFA Antenna in Sonnet" on page 4 (see Figure 3 and Figure 4). The antennas are also designed to a 1.55 mm thick FR4 substrate.

The simulated remote with BIFA is shown in Figure 11. The Phi = 0 degrees direction in the simulation is also shown.

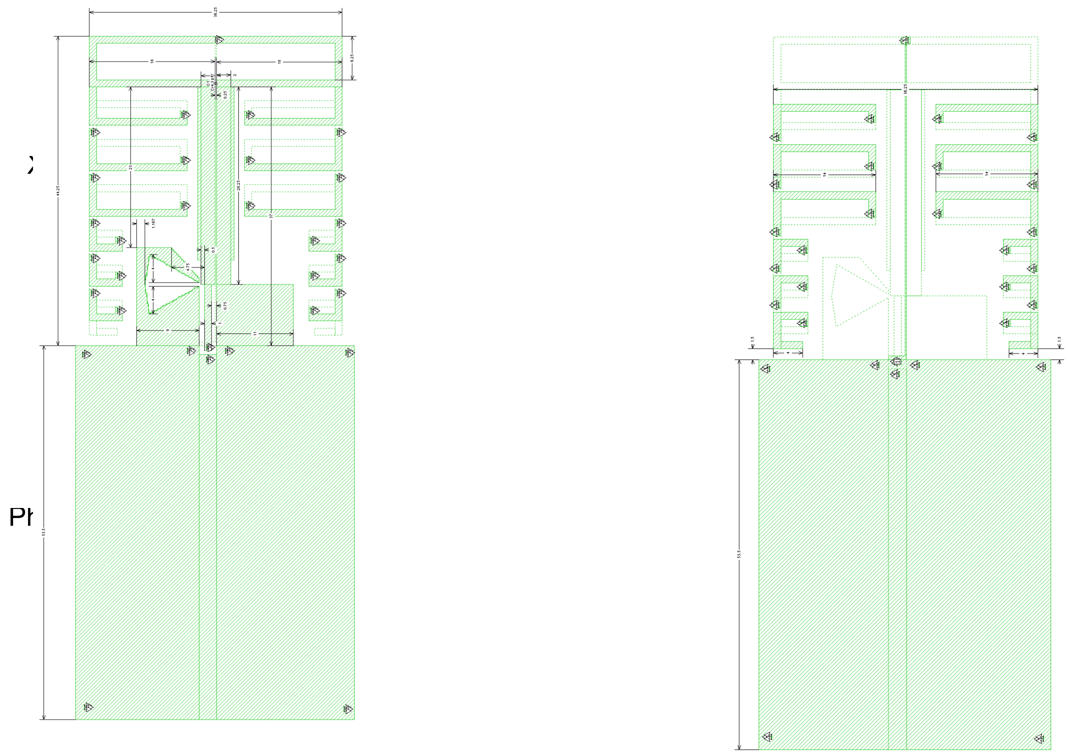


Figure 11. Remote Layout (Top and Bottom Layers 434 MHz BIFA) Fine Tuned via Silicon Laboratories EM Simulations

Simulation impedance results at the single-ended pin of the balun can be seen in Figure 12, where one can observe that the input impedance is a series resonance with nearly 50 Ω residual impedance.

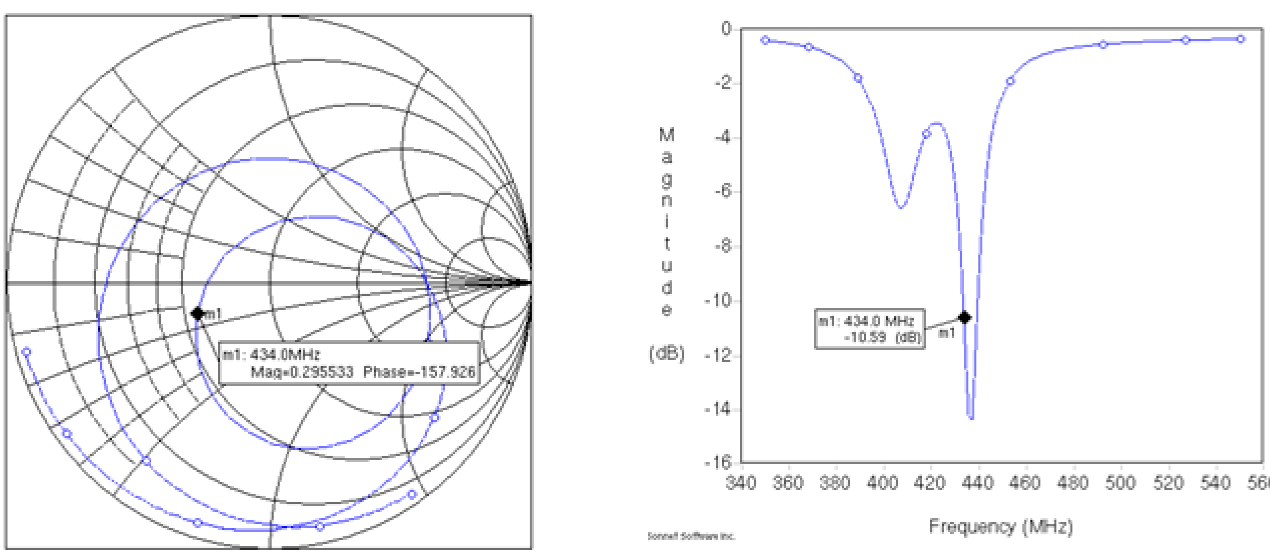


Figure 12. Simulated Impedance at 434 MHz of the BIFA Antenna (on the Smith Chart and Cartesian)

For tuning the input impedance of the BIFA antennas, consider the following.

- The resonant frequency is determined by the total length of the antenna and by the length of the strip line.
- The input impedance is influenced by the position of the common arm of the antenna (the impedance depends on the distance between the differential antenna input and the common point as shown in Figure 9; if these points are closer to each other then the input impedance will be lower) and by the characteristic impedance of the strip line.

The simulated radiation characteristic can be seen in Figure 13, where one can observe that the remote radiates mostly to the front and back direction (Phi = 0 and 180 degrees) where the maximum antenna gain is around –10 dB. Besides the antenna radiates quite well to one of the side directions (Phi = 90) as well, which shows that there is some coupling between the antenna and the balun causing some phase errors. This is just a feature, not a problem, as having good radiation to more directions is advantageous.

The antenna radiates to the top direction (Theta = 0 degrees). The bottom direction (Theta = 180 degrees) cannot be investigated in Sonnet as it is below the PCB plane.

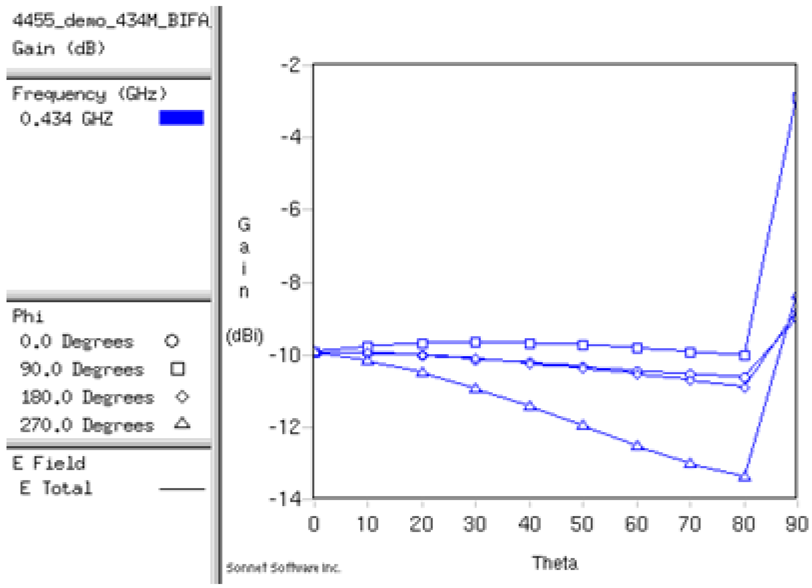


Figure 13. Simulated Radiation Characteristic at 434 MHz

3.2.2. Measurement Results of the Applied BIFA Antenna at 434 MHz

3.2.2.1. Impedance Measurement

The impedance measurement result at the single-ended input of the balun can be seen in Figure 14, where one can observe that the input impedance is very close to 50 Ω. For the fine impedance tuning, an additional parallel 4.3 pF (CC1, see Figure 9) is placed between the differential BIFA antenna inputs.

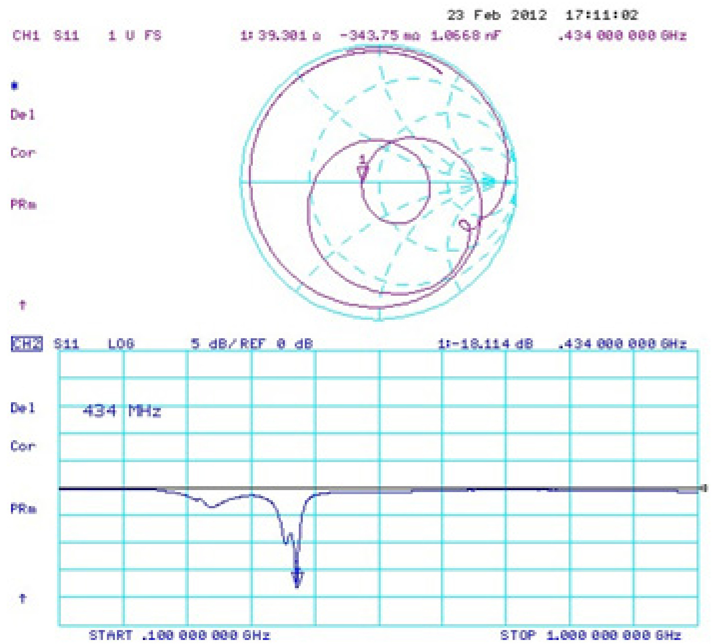


Figure 14. Measured Single-Ended Input Impedance of the Applied BIFA with Strip Line Transformation and Balun at 434 MHz

3.2.2.2. Antenna Radiation Measurements

Silicon Laboratories has measured the gain and radiation characteristic of this type of BIFA antenna to be certain of its performance. For these measurements, the coordinate system used is presented in Figure 15.

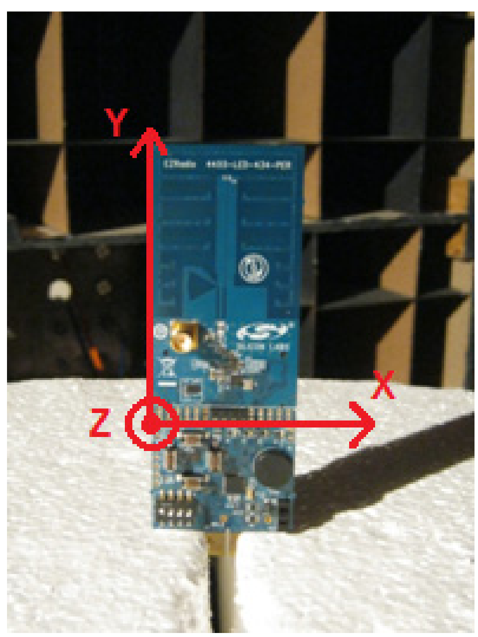


Figure 15. DUT with Coordinate System

Directivity of the BIFA antenna in the most commonly used position according to typical costumer habits (this is when the board is horizontal—in XY plane—and 0 degrees is the Y red arrow in Figure 15) can be seen in Figure 16, where the main direction of radiation can be observed mainly in the front and back directions. Interestingly, the asymmetric sidelong radiation cannot be seen in the figure.

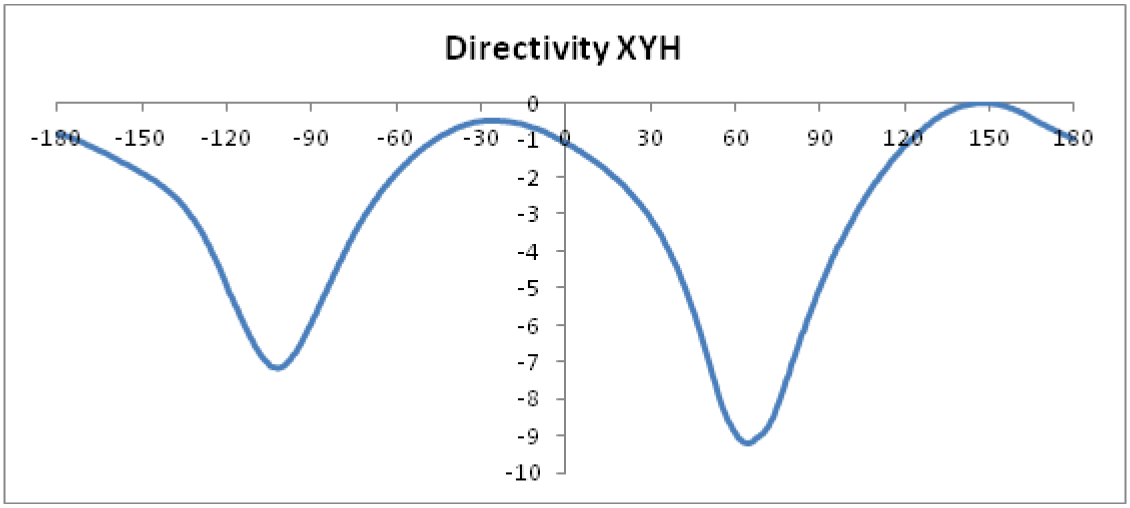


Figure 16. Directivity in the XY Cut with Horizontal Reference Antenna

To check the applied BIFA antenna radiation performance, the complete RFStick (4455-LED-434) was measured in an antenna chamber. The measurement results can be seen in Table 1.

From the measurement results (measured in the main radiation cuts) it can be seen that the module is ETSI compliant and the maximum radiated power is approximately 1.7 dBm in EIRP which means the applied BIFA antenna gain is around –9 dB at 434 MHz (delivered power to the antenna is about +11 dBm).

Table 1. 4455-LED-434 RF Stick Radiated Power Measurements

Cut	Pol.	Freq.	f [MHz] 434	EMC regulation limit in EIRP [dBm]	Measured radiated power in EIRP [dBm]
XY	H	Fund	434	12,14	1,73
XY	H	2nd	868	–33,88	–46,26
XY	H	3rd	1302	–27,86	–52,46
XY	H	4th	1736	–27,86	–37,67
XY	H	5th	2170	–27,86	–38,54
XY	H	6th	2604	–27,86	–30,33
XY	H	7th	3038	–27,86	–36,28
XY	H	8th	3472	–27,86	–32,32
XY	H	9th	3906	–27,86	–36,39
XY	H	10th	4340	–27,86	–31,03
XY	H	11th	4774	–27,86	–31,32
XY	H	12th	5208	–27,86	–37,55
XY	V	Fund	434	12,14	–12,57
XY	V	2nd	868	–33,88	–52,26
XY	V	3rd	1302	–27,86	–50,46
XY	V	4th	1736	–27,86	–41,67
XY	V	5th	2170	–27,86	–45,54
XY	V	6th	2604	–27,86	–34,13

Table 1. 4455-LED-434 RF Stick Radiated Power Measurements (Continued)

Cut	Pol.	Freq.	f [MHz] 434	EMC regulation limit in EIRP [dBm]	Measured radiated power in EIRP [dBm]
XY	V	7th	3038	–27,86	–37,88
XY	V	8th	3472	–27,86	–35,02
XY	V	9th	3906	–27,86	–38,39
XY	V	10th	4340	–27,86	–33,03
XY	V	11th	4774	–27,86	–32,52
XY	V	12th	5208	–27,86	–38,55
XZ	H	Fund	434	12,14	–1,27
XZ	H	2nd	868	–33,88	–45,86
XZ	H	3rd	1302	–27,86	–50,46
XZ	H	4th	1736	–27,86	–36,37
XZ	H	5th	2170	–27,86	–41,54
XZ	H	6th	2604	–27,86	–31,43
XZ	H	7th	3038	–27,86	–35,88
XZ	H	8th	3472	–27,86	–32,02
XZ	H	9th	3906	–27,86	–37,39
XZ	H	10th	4340	–27,86	–31,43
XZ	H	11th	4774	–27,86	–34,52
XZ	H	12th	5208	–27,86	–37,55
XZ	V	Fund	434	12,14	0,23
XZ	V	2nd	868	–33,88	–50,26
XZ	V	3rd	1302	–27,86	–50,46
XZ	V	4th	1736	–27,86	–38,67
XZ	V	5th	2170	–27,86	–42,54
XZ	V	6th	2604	–27,86	–28,43
XZ	V	7th	3038	–27,86	–34,18
XZ	V	8th	3472	–27,86	–34,02
XZ	V	9th	3906	–27,86	–32,89
XZ	V	10th	4340	–27,86	–31,43
XZ	V	11th	4774	–27,86	–29,52
XZ	V	12th	5208	–27,86	–35,55

3.2.2.3. Range Measurement

Finally, the outdoor range between two identical BIFA modules (4455-LED-434 development boards) is also investigated with the following parameters:

- Delivered power to the antenna is approximately +11 dBm
- Radiated power is approximately +1.7 dBm in EIRP (antenna gain is around –9 dB)
- Data rate: 2.4 kbps
- 2-level FSK modulation, deviation: 30 kHz

The measured maximum range is approximately 1 km. The measurement result can be seen in Figure 17. It was measured in Budapest along the Danube river in the presence of strong GSM interferences.

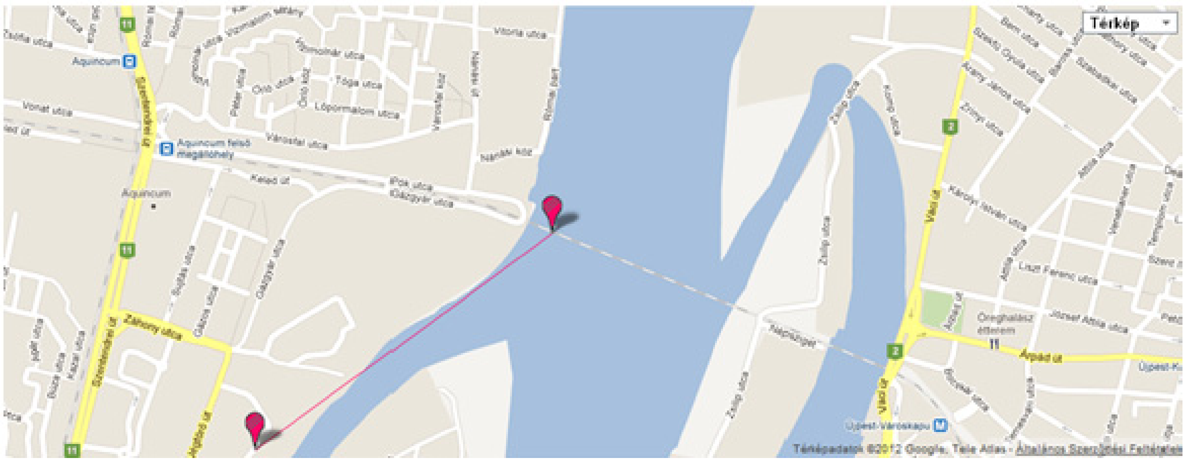


Figure 17. Range at 434 MHz, 1044 m

3.2.3. Simulation Procedure of the Applied BIFA Antenna at 868 and 915 MHz in Sonnet

The simulation setup of the applied printed BIFA antenna is the same as what was introduced in the beginning of the "3.1.1. Simulation Procedure of the Applied IFA Antenna in Sonnet" on page 4 (see Figure 3 and Figure 4). The simulation and tuning procedure is the same as described in "3.2.1. Simulation Procedure of the Applied BIFA Antenna at 434 MHz in Sonnet" on page 9. The antennas are designed to a 1.55 mm thick FR4 substrate.

The only difference between the 868 and 915 MHz solutions is the total length of the antenna. In the end of the two arms of the BIFA antenna, there are two 0 Ω SMD0402 resistors. If these are mounted, then the antenna is tuned to 868 MHz, if not the antenna is tuned to 915 MHz (see in Figure 18).

The simulated remote with BIFA is shown in Figure 18. The Phi = 0 degree direction in the simulation is also shown.

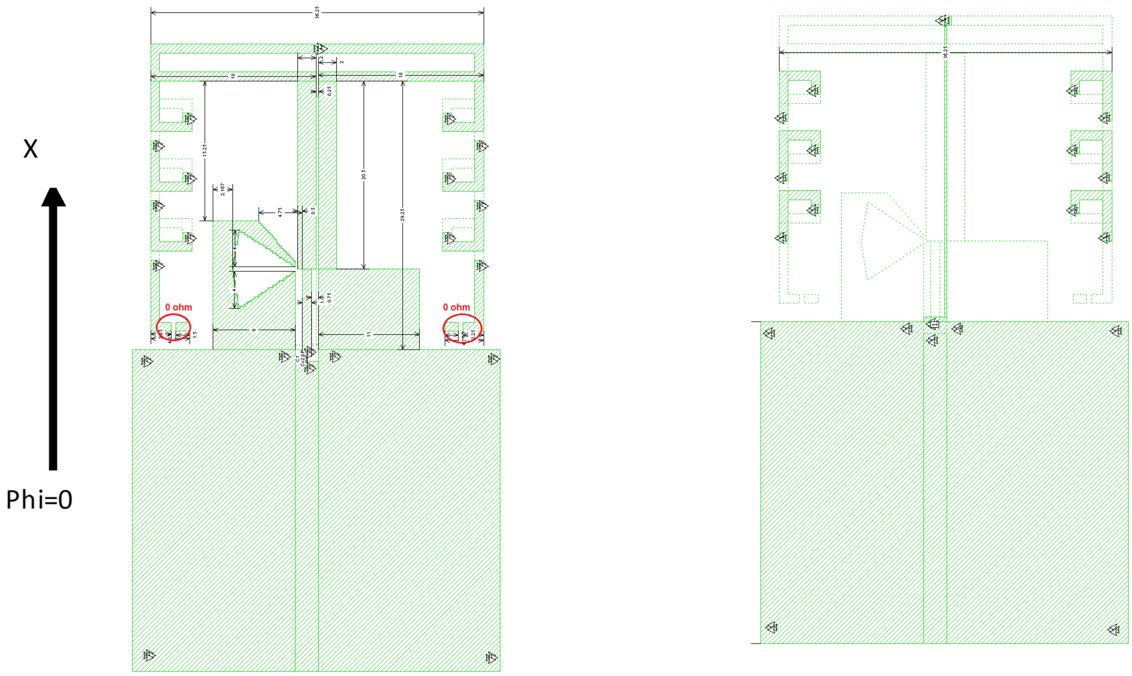


Figure 18. Remote Layout (Top and Bottom Layers 868 and 915 MHz BIFA) Fine Tuned via Silicon Laboratories EM Simulations

Simulation impedance results at the single-ended pin of the balun can be seen in Figure 19 and Figure 20, where one can observe that the input impedance is a series resonance with nearly 50 Ω residual impedance.

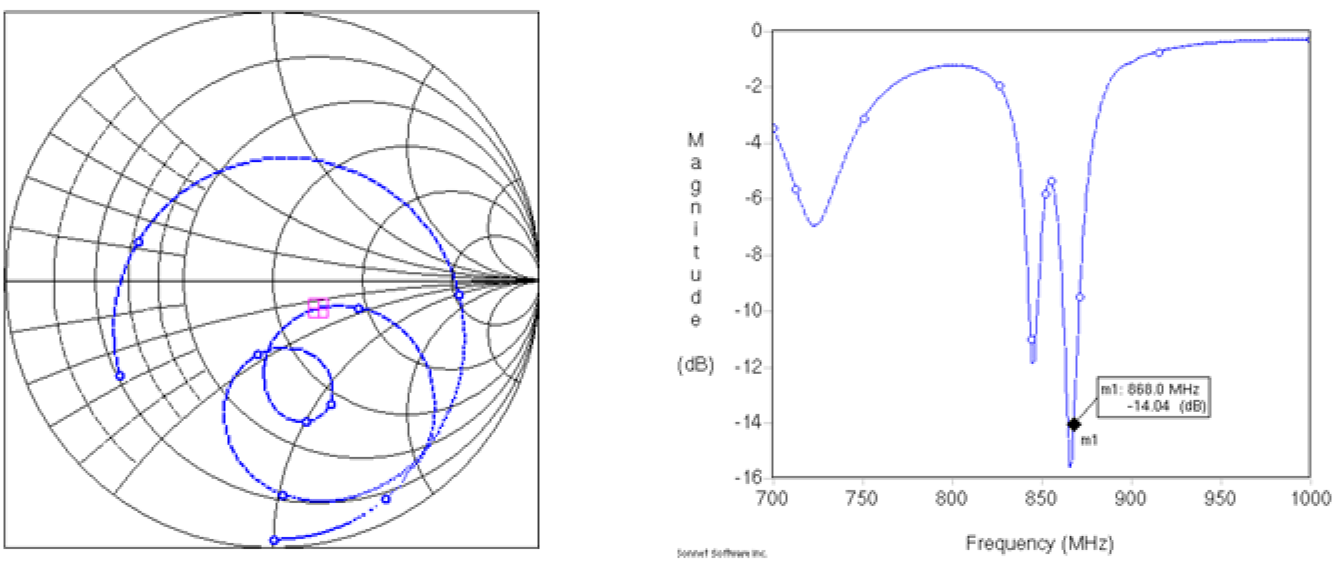


Figure 19. Simulated Impedance at 868 MHz of the BIFA antenna (on the Smith Chart and Cartesian)

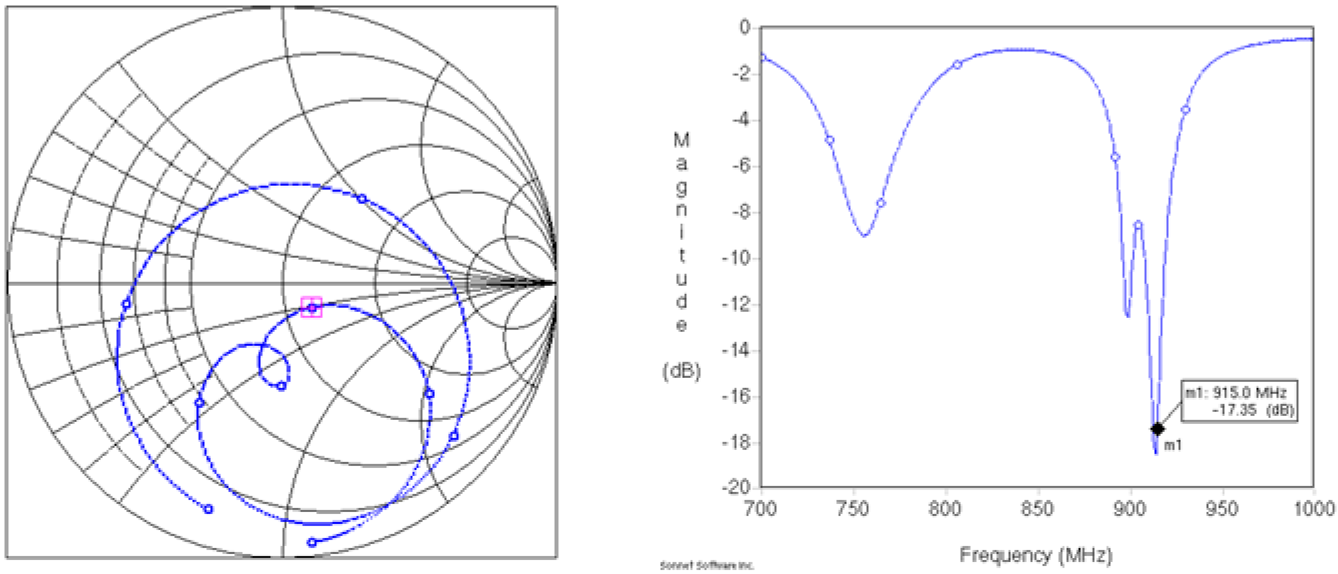


Figure 20. Simulated Impedance at 915 MHz of the BIFA Antenna (on the Smith Chart and Cartesian)

The simulated radiation characteristic can be seen in Figure 21 at 868 and 915 MHz as well, where one can observe that the remote radiates mostly to the front and back direction (Phi = 0 and 180 degrees) where the maximum antenna gain is around –3.5 dB at 868 MHz and –2 dB at 915 MHz (at higher bands the antenna size/ lambda ratio is larger, thus larger antenna gain can be achieved compared with the 434 MHz solution in "3.2.1. Simulation Procedure of the Applied BIFA Antenna at 434 MHz in Sonnet" on page 9).

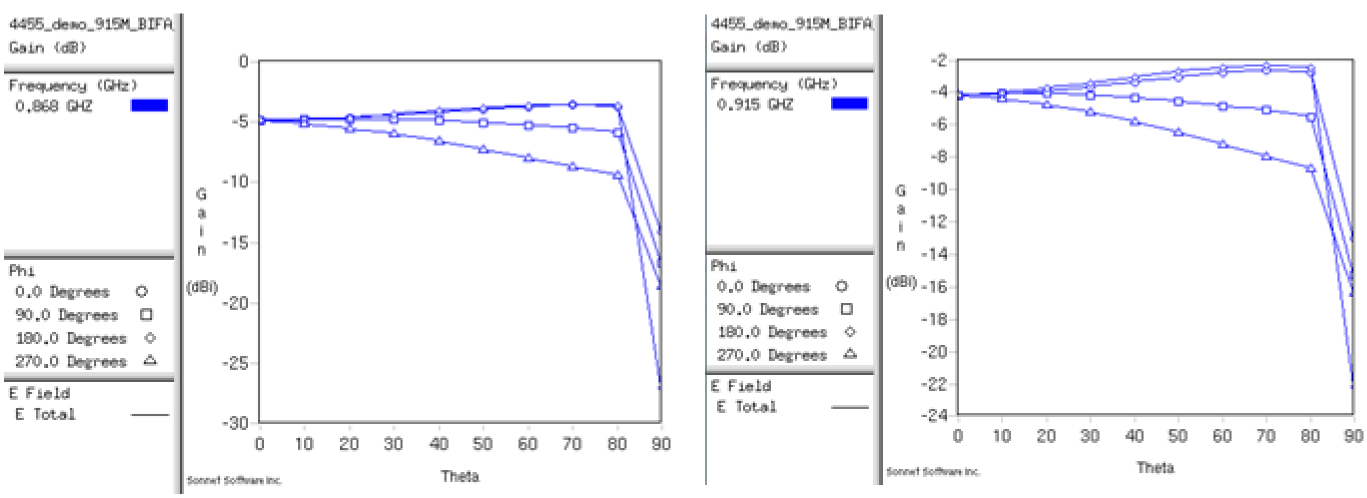


Figure 21. Simulated Radiation Characteristic at 868 and 915 MHz

3.2.4. Measurement Results of the Applied BIFA Antenna at 868 and 915 MHz

3.2.4.1. Impedance Measurement

The impedance measurement result at the single-ended input of the balun can be seen in Figure 22 and Figure 23, where one can observe that the input impedance is very close to 50 Ω. For the fine impedance tuning, an additional parallel 2 pF (CC2, see on Figure 9 on page 8) is placed at the single-ended input pin of the balun to the ground.

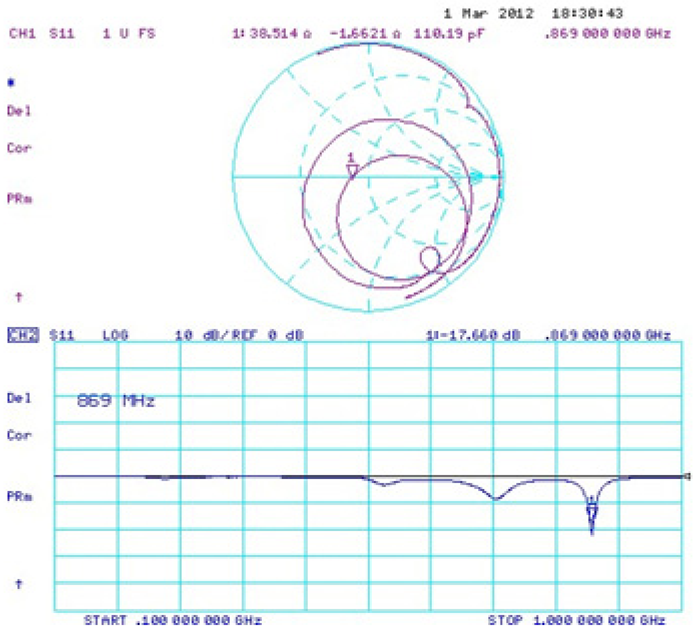


Figure 22. Measured Single-Ended Input Impedance of the Applied BIFA with Strip Line Transformation and Balun at 868 MHz

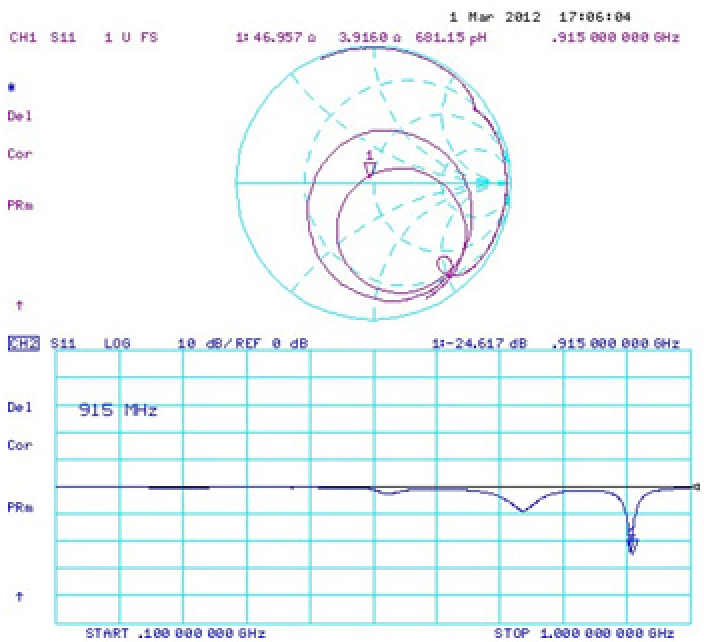


Figure 23. Measured Single-Ended Input Impedance of the Applied BIFA with Strip Line Transformation and Balun at 915 MHz

3.2.4.2. Antenna Radiation Measurements

To check the applied BIFA antenna radiation performance, the complete RFStick (4455-LED-868) was measured in an antenna chamber. The measurement results can be seen in Table 2.

From the measurement results (measured in the main radiation cuts), it can be seen that the module is ETSI compliant and the maximum radiated power is approximately 7 dBm in EIRP which means that the applied BIFA antenna gain is approximately –4 dB at 868 MHz (delivered power to the antenna is approximately +11 dBm).

Table 2. 4455-LED-868 RF Stick Radiated Power Measurements

Cut	Pol.	Freq.	f [MHz] 868	EMC regulation limit in EIRP [dBm]	Measured radiated power in EIRP [dBm]
XY	H	Fund	868	16,12	4,14
XY	H	2nd	1736	–27,86	–52,67
XY	H	3rd	2604	–27,86	–33,13
XY	H	4th	3472	–27,86	–35,22
XY	H	5th	4340	–27,86	–30,83
XY	H	6th	5208	–27,86	–39,15
XY	H	7th	6076	–27,86	–31,99
XY	H	8th	6944	–27,86	–46,20
XY	H	9th	7812	–27,86	–44,80
XY	H	10th	8680	–27,86	–43,73
XY	H	11th	9548	–27,86	–43,49
XY	H	12th	10416	–27,86	–43,64
XZ	V	Fund	868	16,12	6,94
XZ	V	2nd	1736	–27,86	–52,67
XZ	V	3rd	2604	–27,86	–35,43
XZ	V	4th	3472	–27,86	–41,82
XZ	V	5th	4340	–27,86	–30,63
XZ	V	6th	5208	–27,86	–38,55
XZ	V	7th	6076	–27,86	–31,99
XZ	V	8th	6944	–27,86	–42,50
XZ	V	9th	7812	–27,86	–39,00
XZ	V	10th	8680	–27,86	–38,73
XZ	V	11th	9548	–27,86	–36,99
XZ	V	12th	10416	–27,86	–35,64

To check the applied BIFA antenna radiation performance, the complete RFStick (4455-LED-915) was measured in an antenna chamber as well. The measurement results can be seen in Table 3.

From the measurement results (measured in the main radiation cuts), it can be seen that the module is

FCC-compliant when averaging applied with maximum 36% duty cycle. The maximum radiated power is –1 dBm in EIRP which means that the applied BIFA antenna gain is approximately –3 dB at 915 MHz (delivered power to the antenna is only approximately +2 dBm as to comply with FCC at the fundamental).

Table 3. 4455-LED-915 RF Stick Radiated Power Measurements

Cut	Pol.	Freq.	f [MHz] 915	EMC regulation limit in EIRP [dBm]	Measured radiated power in EIRP [dBm]	Max. duty cycle [%] to comply with FCC 36,11
XY	H	Fund	915	30,00	–1,69	
XY	H	2nd	1830	–21,09	–55,21	
XY	H	3rd	2745	–41,25	–32,40	36,11
XY	H	4th	3660	–41,25	–41,04	97,60
XY	H	5th	4575	–41,25	–38,06	69,27
XY	H	6th	5490	–21,09	–39,95	
XY	H	7th	6405	–21,09	–34,32	
XY	H	8th	7320	–41,25	–41,85	
XY	H	9th	8235	–41,25	–41,75	
XY	H	10th	9150	–41,25	–42,12	
XZ	V	Fund	915	30,00	–1,09	
XZ	V	2nd	1830	–21,09	–57,21	
XZ	V	3rd	2745	–41,25	–32,80	37,81
XZ	V	4th	3660	–41,25	–43,74	
XZ	V	5th	4575	–41,25	–39,96	86,21
XZ	V	6th	5490	–21,09	–43,25	
XZ	V	7th	6405	–21,09	–38,52	
XZ	V	8th	7320	–41,25	–41,35	
XZ	V	9th	8235	–41,25	–40,75	94,46
XZ	V	10th	9150	–41,25	–38,12	69,78

3.2.4.3. Range Measurement

The outdoor range between two identical BIFA modules is investigated with the following parameters:

- Delivered power to the antenna is approximately +11 dBm
- Radiated power is approximately +7 dBm in EIRP (antenna gain is around –4 dB)
- Data rate: 2.4 kbps
- 2-level FSK modulation, deviation: 30 kHz

The measured maximum range is larger than 1.1 km in both cases (the attainable ranges at 868 and 915 MHz are approximately the same) as can be seen in Figure 24. It was measured in Budapest along the Danube river in the presence of strong GSM interferences.

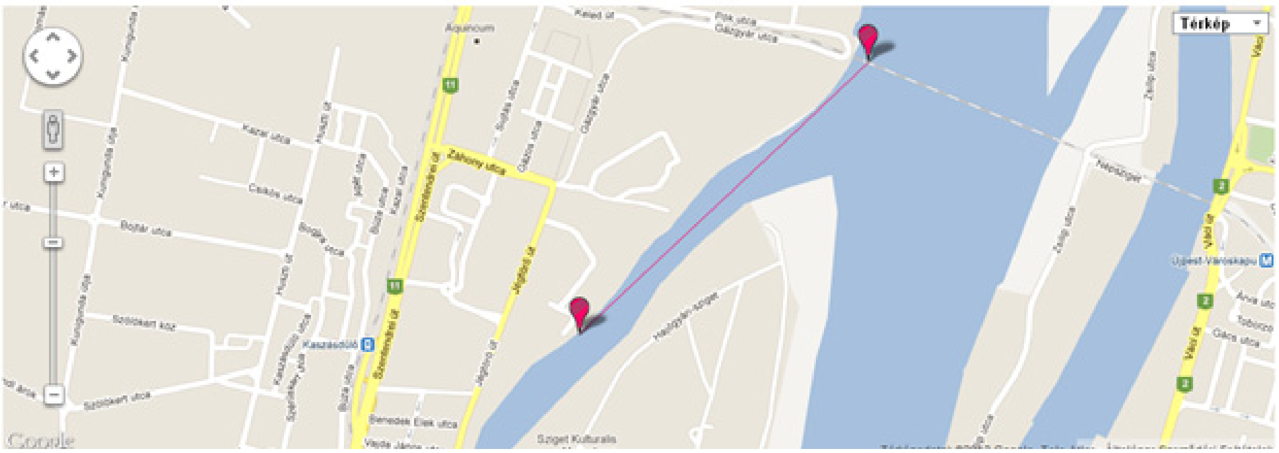


Figure 24. Range 868 and 915 MHz, 1125 m

4. SMA Antennas for Si4455/Si435x RF ICs

As was mentioned previously, the modules (RF sticks and pico boards) can be used with 50 Ω SMA antennas as well by soldering a SMD0805 0 Ω resistor to the proper pin. Since these SMA antennas are also tuned to 50 Ω, a matching network is required to use between the RF IC and the SMA antenna (the matching principles are described in detail in “AN693: Si4455 Low Power PA Matching”).

In this section, the comparison of various 50 Ω SMA monopole antennas for using pico boards is presented (RF Sticks are using the same type of monopole antennas).

4.1. Impedance Measurement Setup

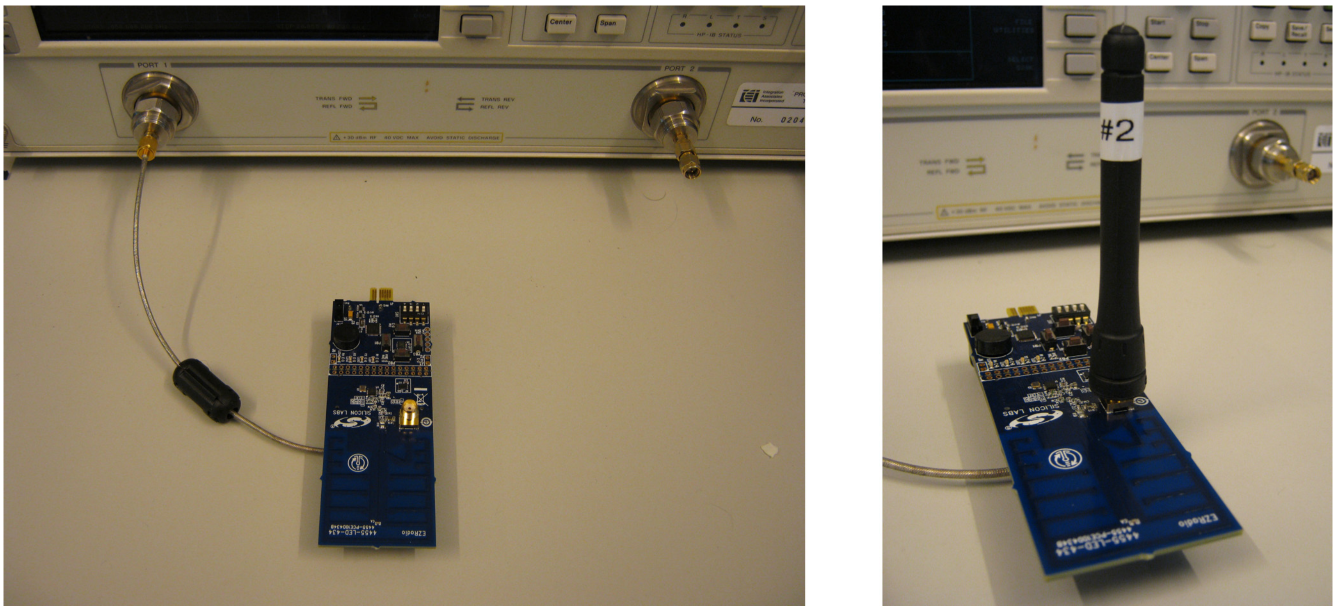


Figure 25. DUT on VNA (left) and DUT with SMA Antenna (right)

4.2. Range Measurement Setup

Figure 26. TX Unit Position (Google Earth) On a Bridge (Danube River)

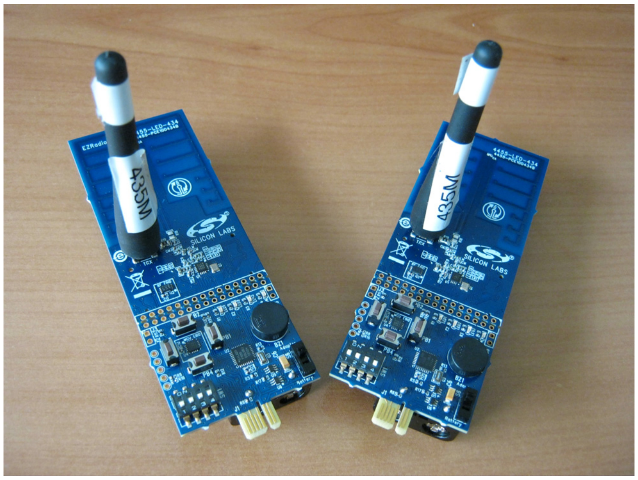


Figure 27. 4455-LED-434 Pico Boards used for the Range Tests

4.3. Measurement Results

4.3.1. S11 Measured Results

				S11					
No	**Name**	**Frequency**	**Manufacturer**	**169**	**315**	**434**	**470**	**868**	**915**
#1	H169-SMA	169 MHz	EAD Ltd.	–5,3					
#2	HT-A-150-6288	169 MHz	Shenzhen	–6,9					
#3	SPWL24169TI	169 MHz	Pulse	–3,6					
#5	HT-A-300-6288	315 MHz	Shenzhen		–15,8				
#6	SPWH24433TI	433 MHz	Pulse			–12,94			
#7	HT-A-400-6100	434 MHz	Shenzhen			–19,2			
#8	PTHE-435	435 MHz	Scan			–7			
#9	HT-A-450-6100	490 MHz	Shenzhen				–31,2		
#10	HT-A-850-3107	868 MHz	Shenzhen					–9,2	–7,3
#11	W5017	883 MHz	Pulse					–9,52	–8,7
#12	MINI-PT DUAL	892 MHz	Scan					–13	–14
#13	W1063	898 MHz	Pulse					–5,9	–21,5
#14	HT-A-900-3107	915 MHz	Shenzhen					–7,1	–5,6
#15	ANT-916-CW-QW-SMA	916 MHz	Antenna Factor					–12,5	–9,2
Note: Blue denotes peak S11.									

4.3.2. Range Measurement Results

				Range (Pico Board TX~10dBm)				
No	**Name**	**Frequency**	**Manufacturer**	**434**	**470**	**868**	**915**	**No**
#1	H169-SMA	169 MHz	EAD Ltd.					#1
#2	HT-A-150-6288	169 MHz	Shenzhen					#2
#3	SPWL24169TI	169 MHz	Pulse					#3
#5	HT-A-300-6288	315 MHz	Shenzhen					#5
#6	SPWH24433TI	433 MHz	Pulse	1217 m				#6
#7	HT-A-400-6100	434 MHz	Shenzhen	1211 m				#7
#8	PTHE-435	435 MHz	Scan	1210 m				#8
#9	HT-A-450-6100	490 MHz	Shenzhen	1190 m	N/A			#9
#10	HT-A-850-3107	868 MHz	Shenzhen			1163 m	1079 m	#10
#11	W5017	883 MHz	Pulse			1221 m	1148 m	#11
#12	MINI-PT DUAL	892 MHz	Scan			1054 m	1090 m	#12
#13	W1063	898 MHz	Pulse			1181 m	1112 m	#13
#14	HT-A-900-3107	915 MHz	Shenzhen			1081 m	1083 m	#14
#15	ANT-916-CW-QW-SMA	916 MHz	Antenna Factor			1065 m	1086 m	#15
Note: Yellow denotes peak range.								

4.4. Detailed S11 measurement results

4.4.1. 169 MHz—H169–SMA

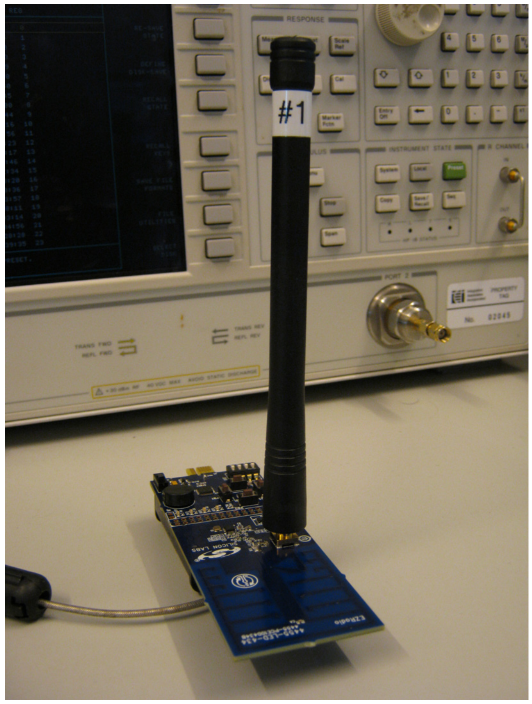


Figure 28. #1 H169–SMA

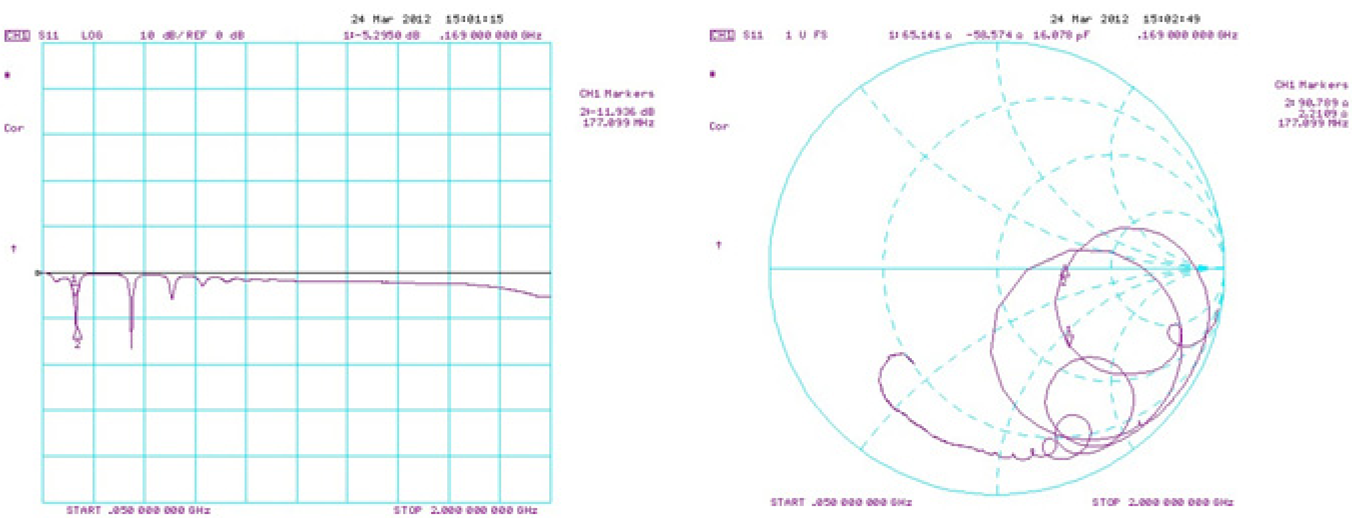


Figure 29. Measured Input Impedance

4.4.2. 169 MHz—HT–A–150–6288

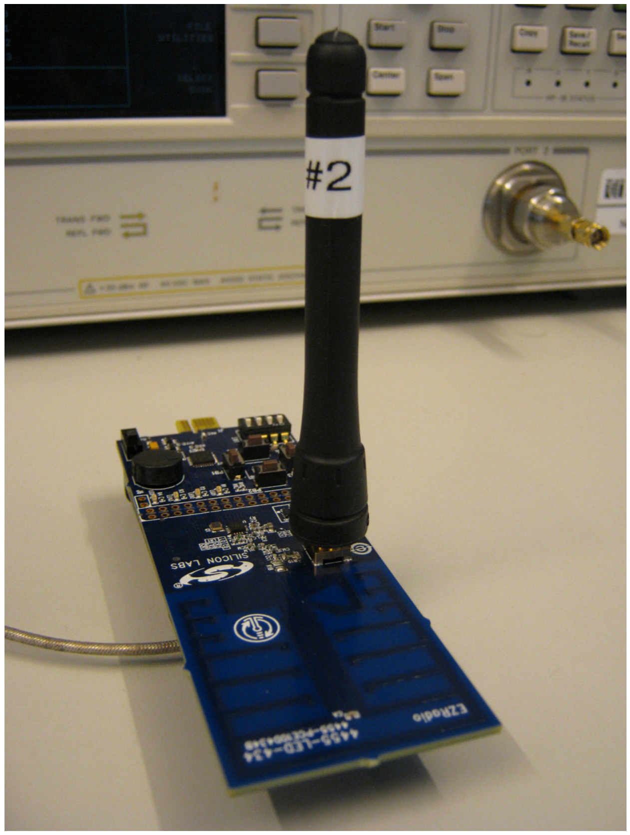


Figure 30. #2 HT–A–150–6288

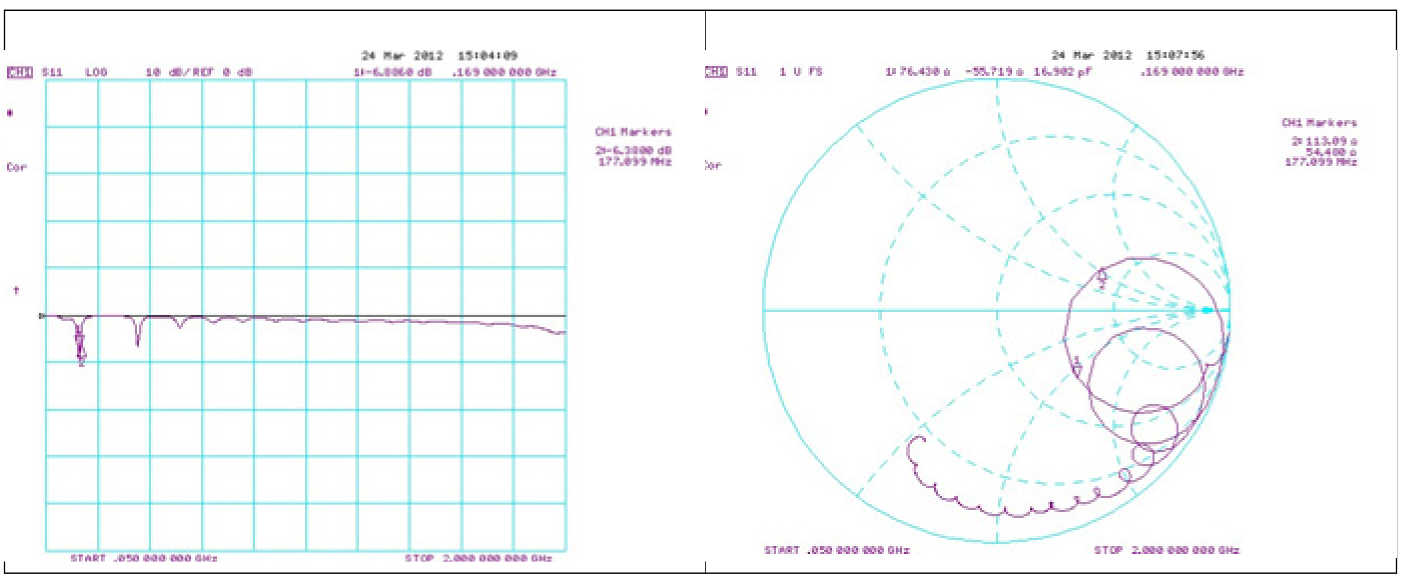


Figure 31. Measured Input Impedance

4.4.3. 169 MHz—SPWL24169TI

Figure 32. #3 SPWL24169TI

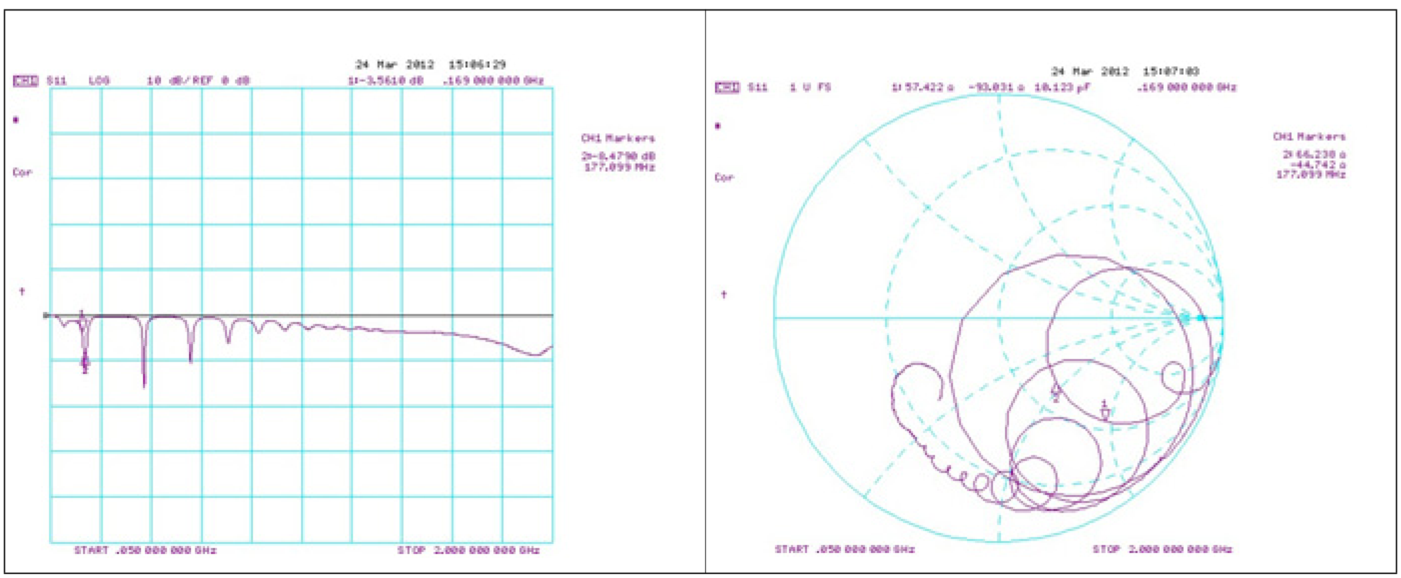


Figure 33. Measured Input Impedance

4.4.4. 315 MHz—HT–A–300–6288

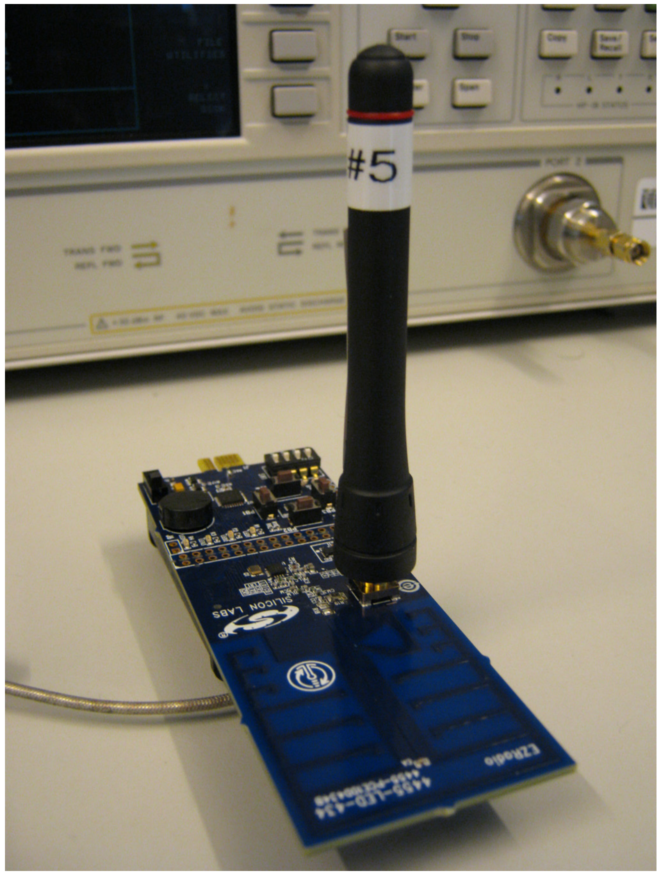


Figure 34. #5 HT-A-300-6288

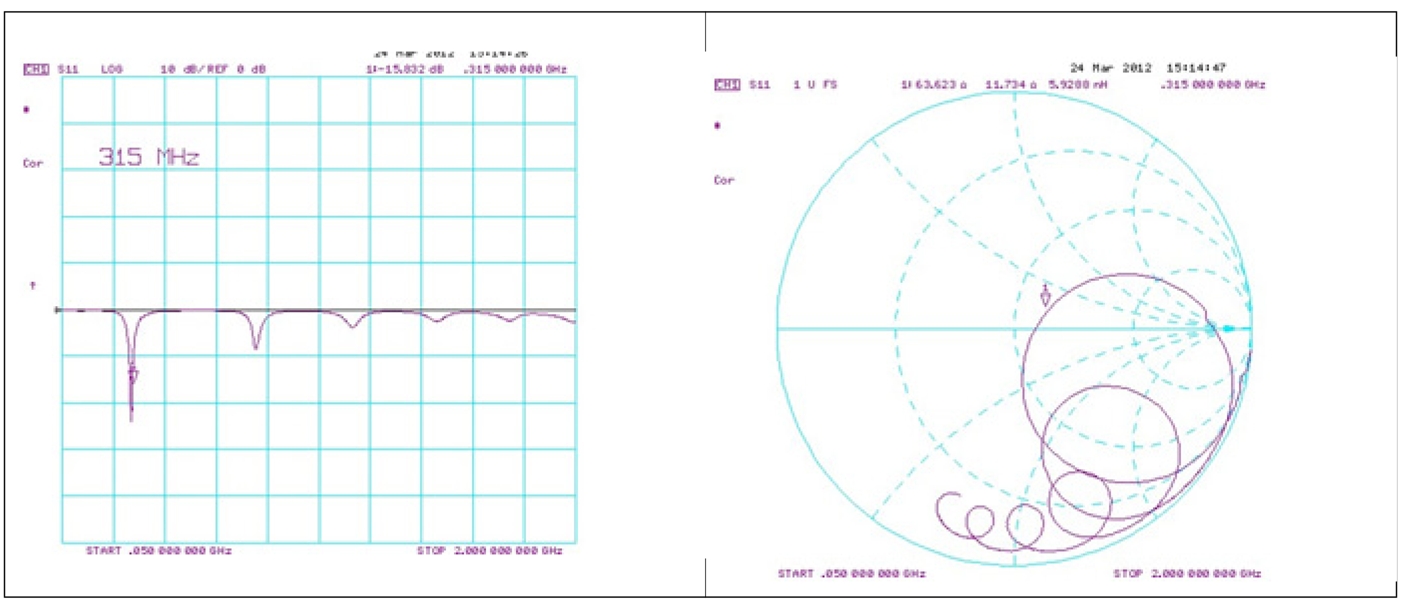


Figure 35. Measured Input Impedance

4.4.5. 433 MHz—SPWH24433TI

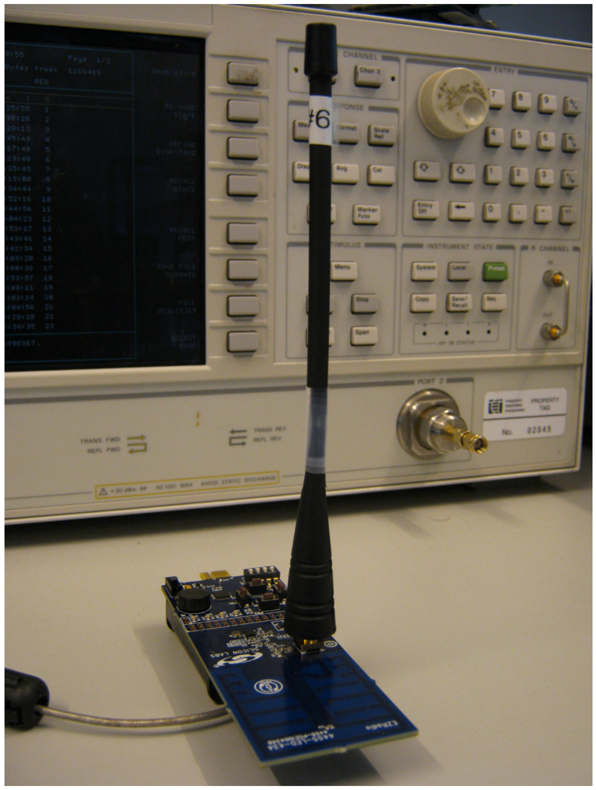


Figure 36. #6 SPWH24433TI

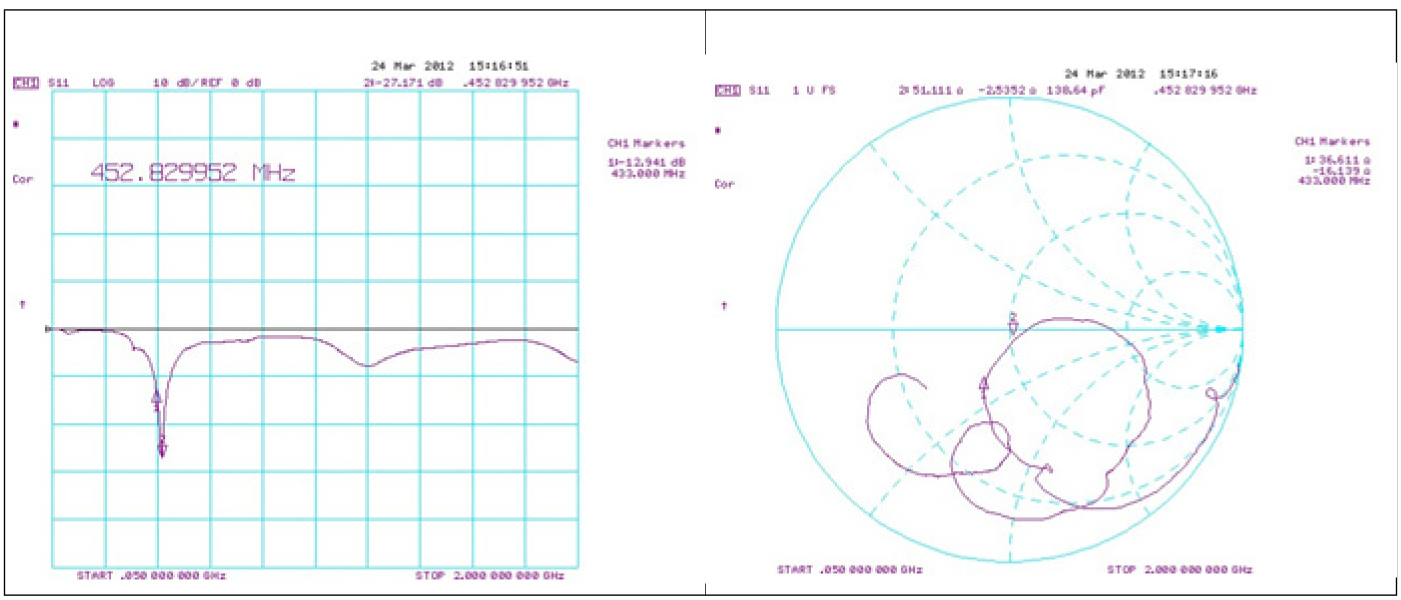


Figure 37. Measured Input Impedance

4.4.6. 434 MHz—HT–A–400–6100

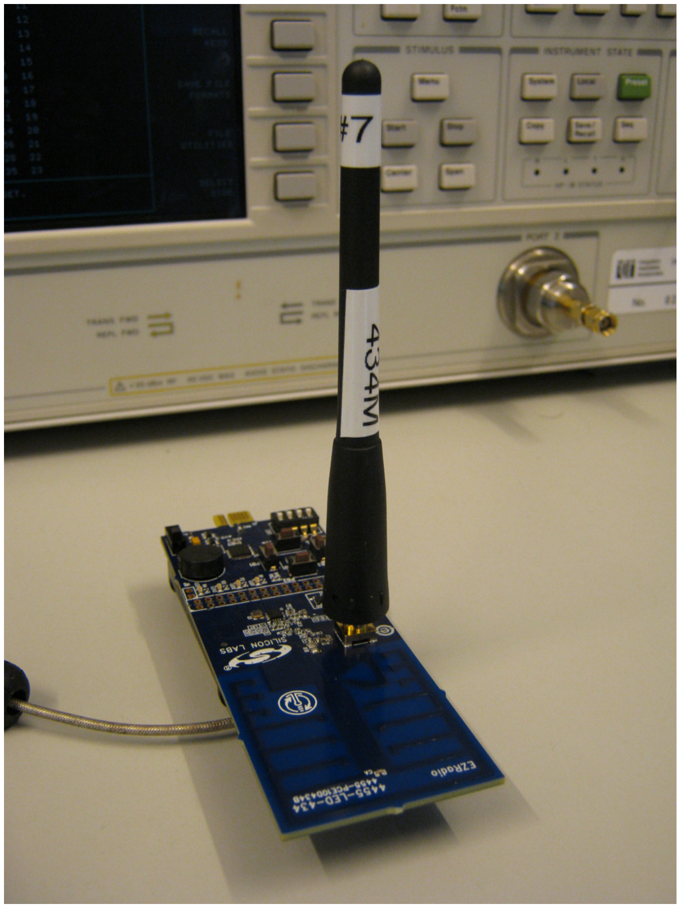


Figure 38. #7 HT–A–400–6100

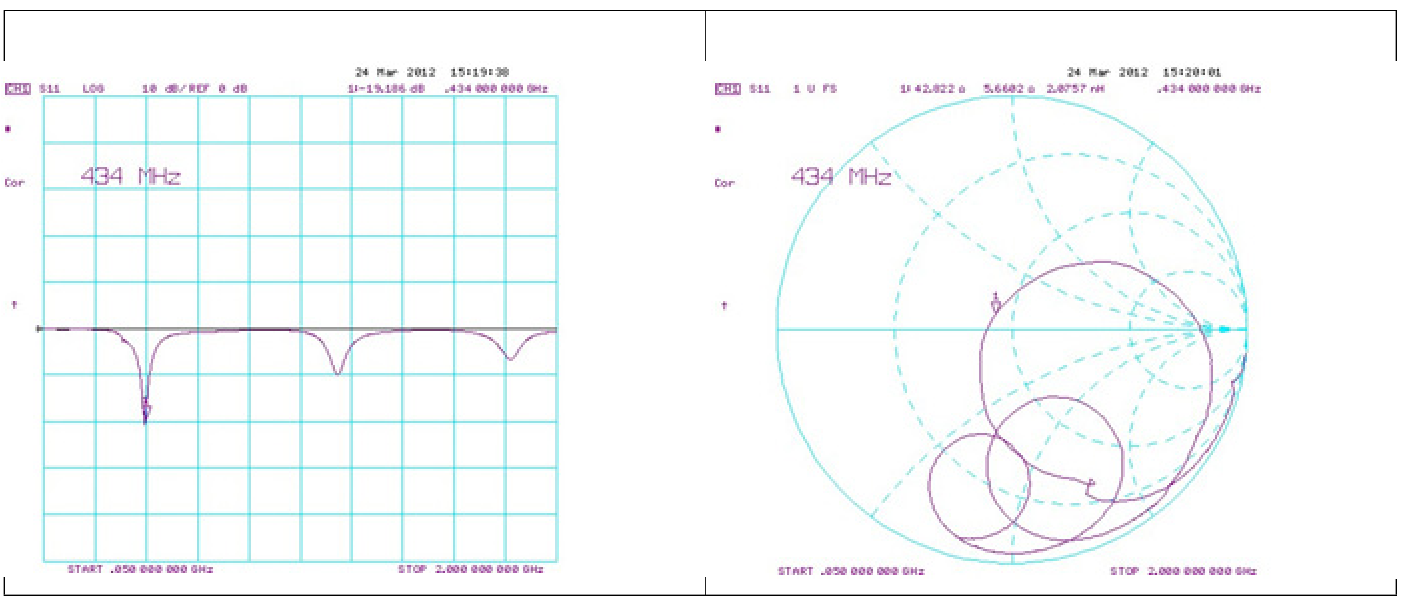


Figure 39. Measured Input Impedance

4.4.7. 435 MH—PTHE–435

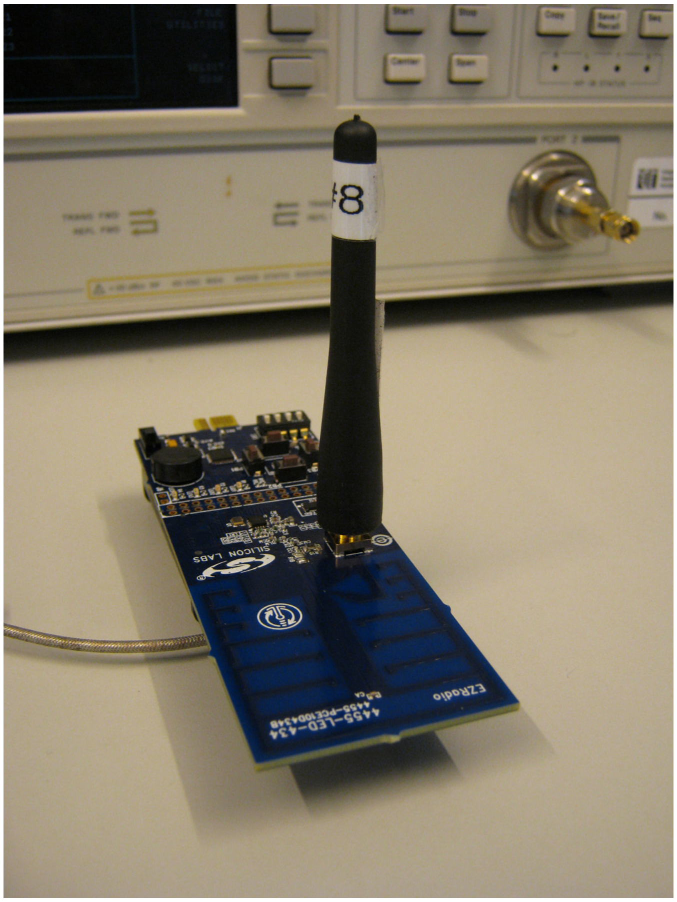


Figure 40. #8 PTHE–435

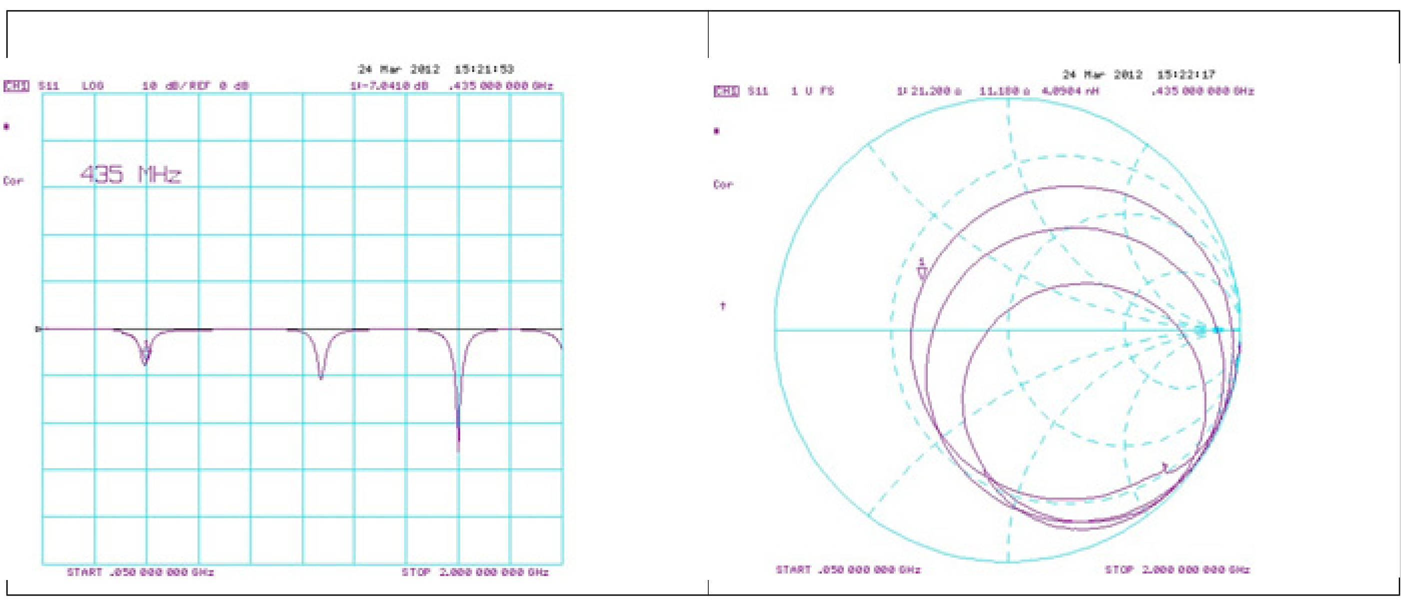


Figure 41. Measured Input Impedance

4.4.8. 490 MHz—HT–A–450–6100

Figure 42. #9 HT–A–450–6100

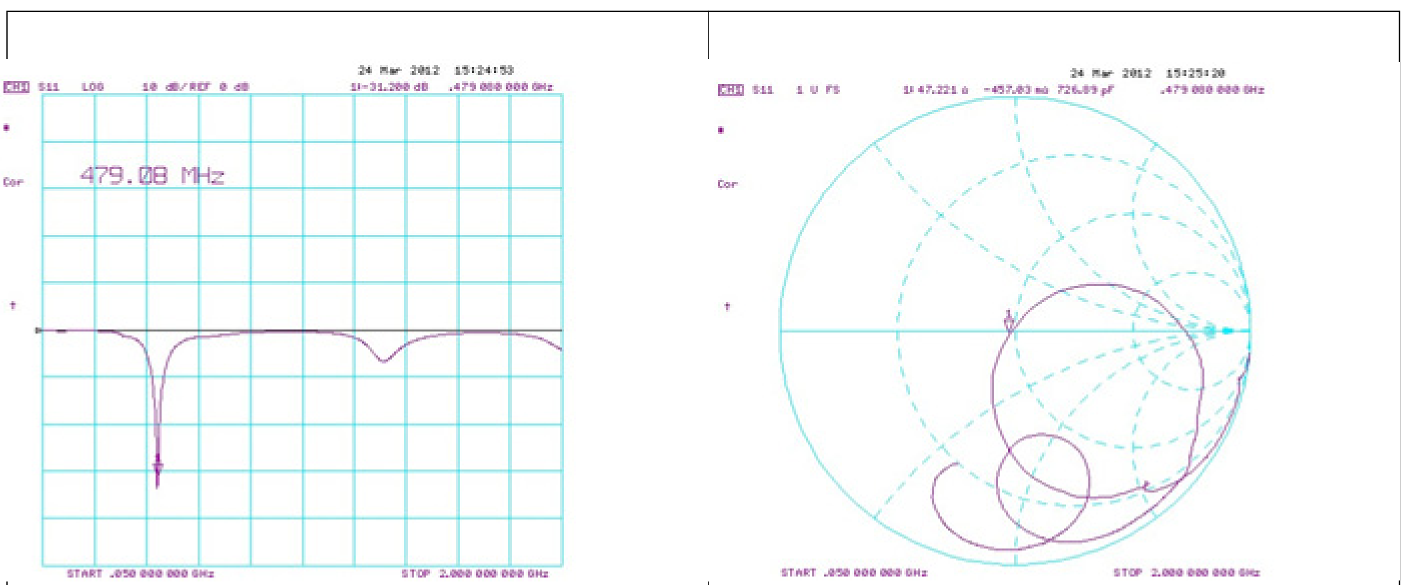


Figure 43. Measured Input Impedance

4.4.9. 868 MHz—HT–A–850–3107

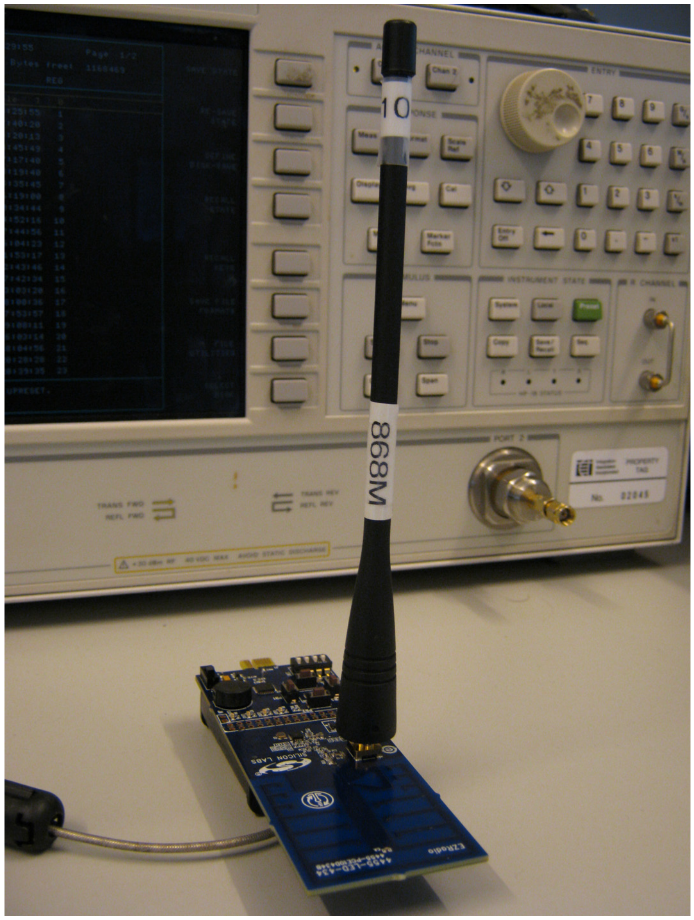


Figure 44. #10 – HT–A–850–3107

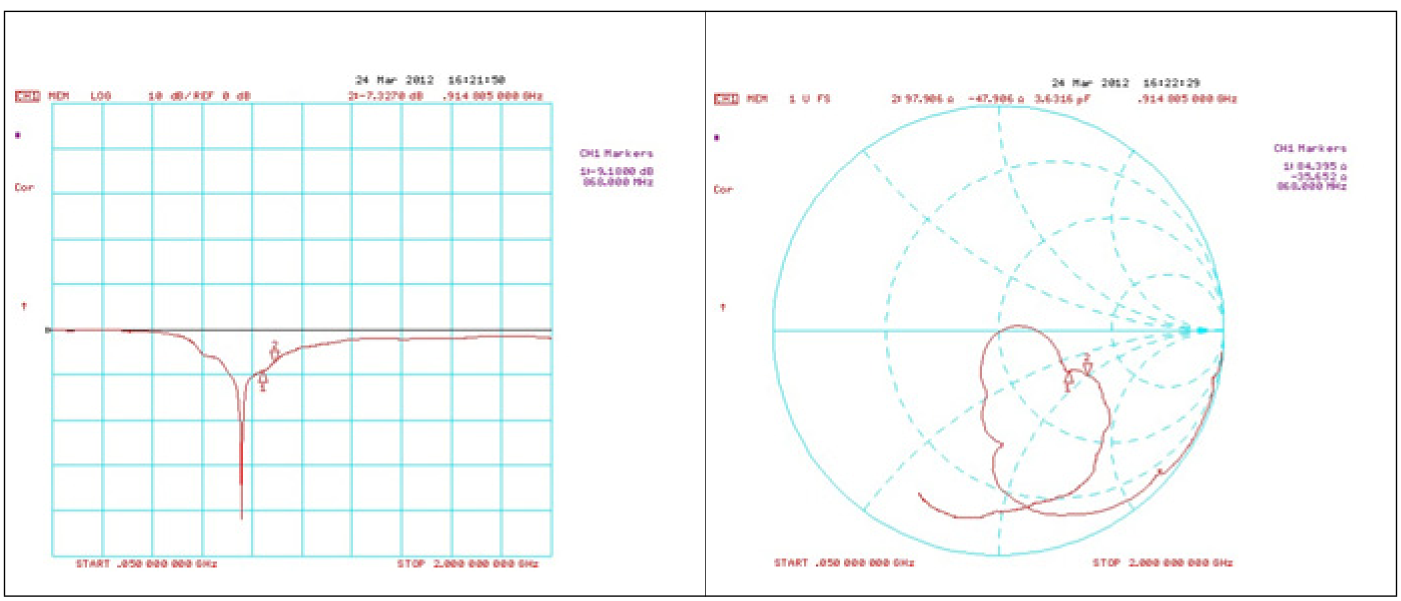


Figure 45. Measured Input Impedance

4.4.10. 883 MHz—W5017

Figure 46. #11 883 MHz—W5017

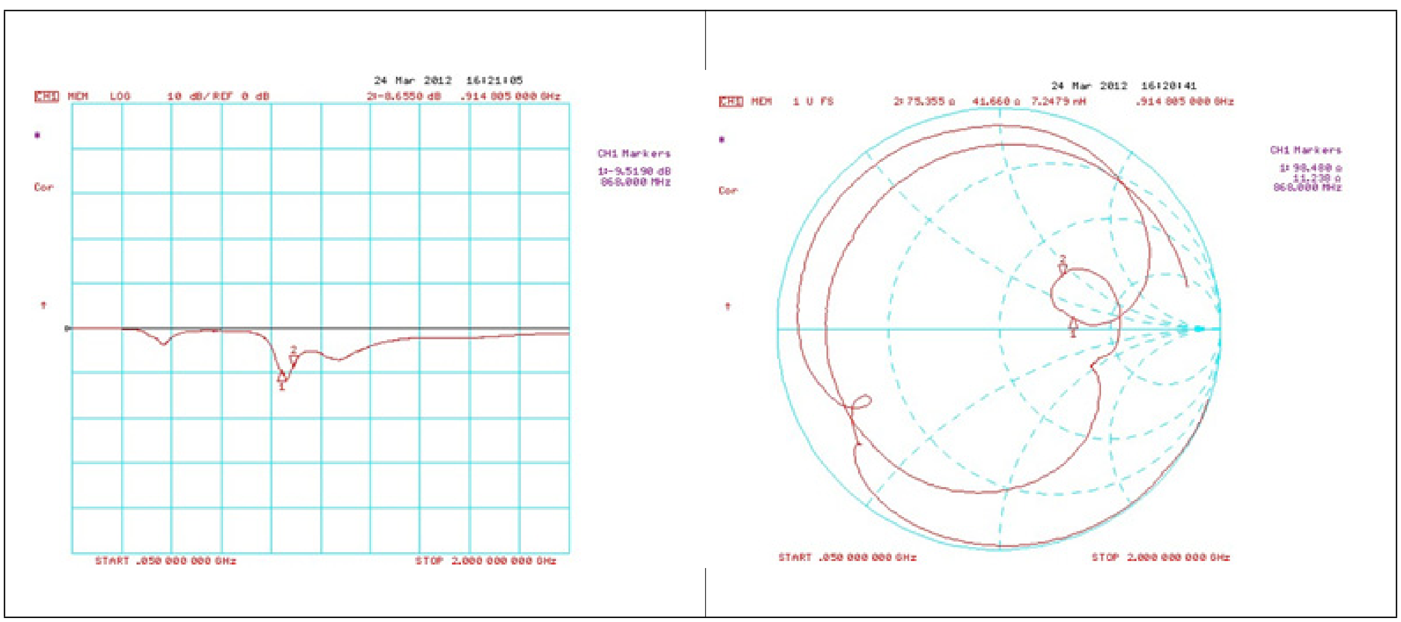


Figure 47. Measured Input Impedance

4.4.11. 892 MHz—MINI-PT DUAL

Figure 48. #12 892 MHz—MINI-PT DUAL

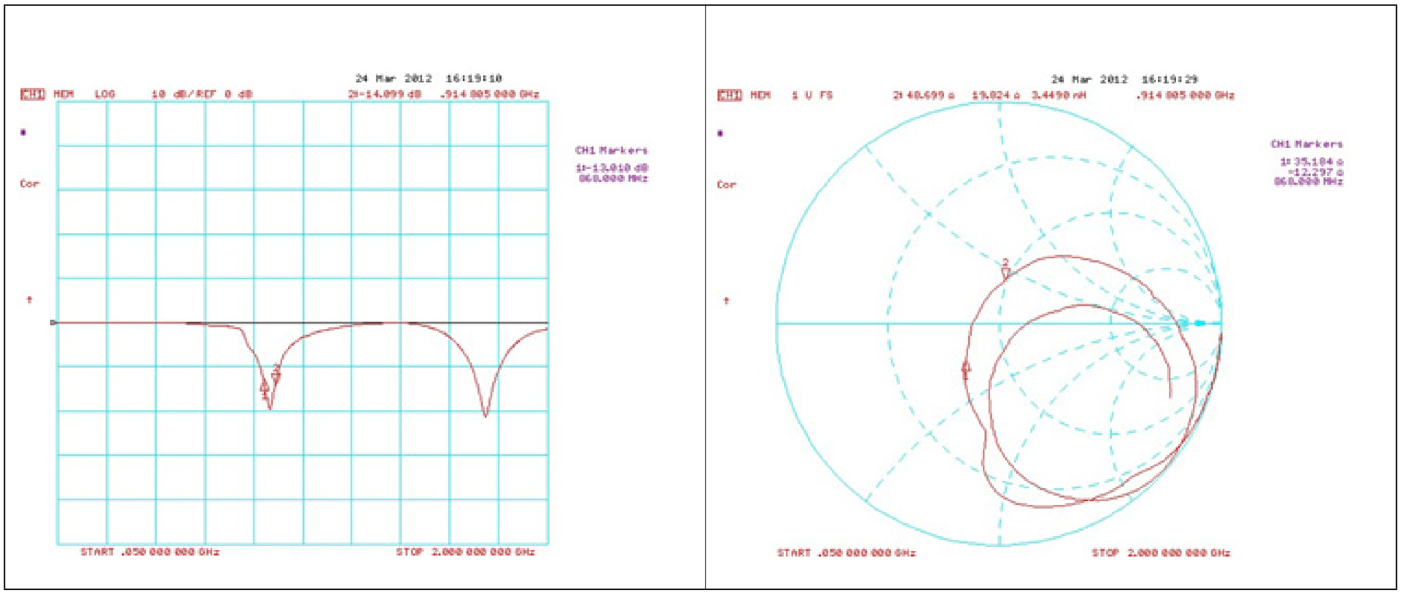


Figure 49. Measured Input Impedance

4.4.12. 898 MHz—W1063

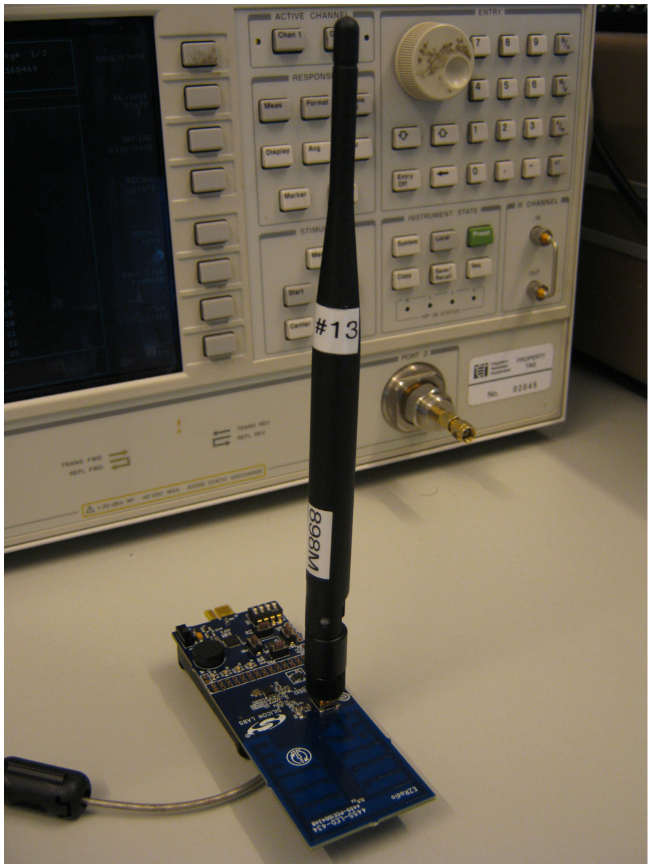


Figure 50. #13 898 MHz—W1063

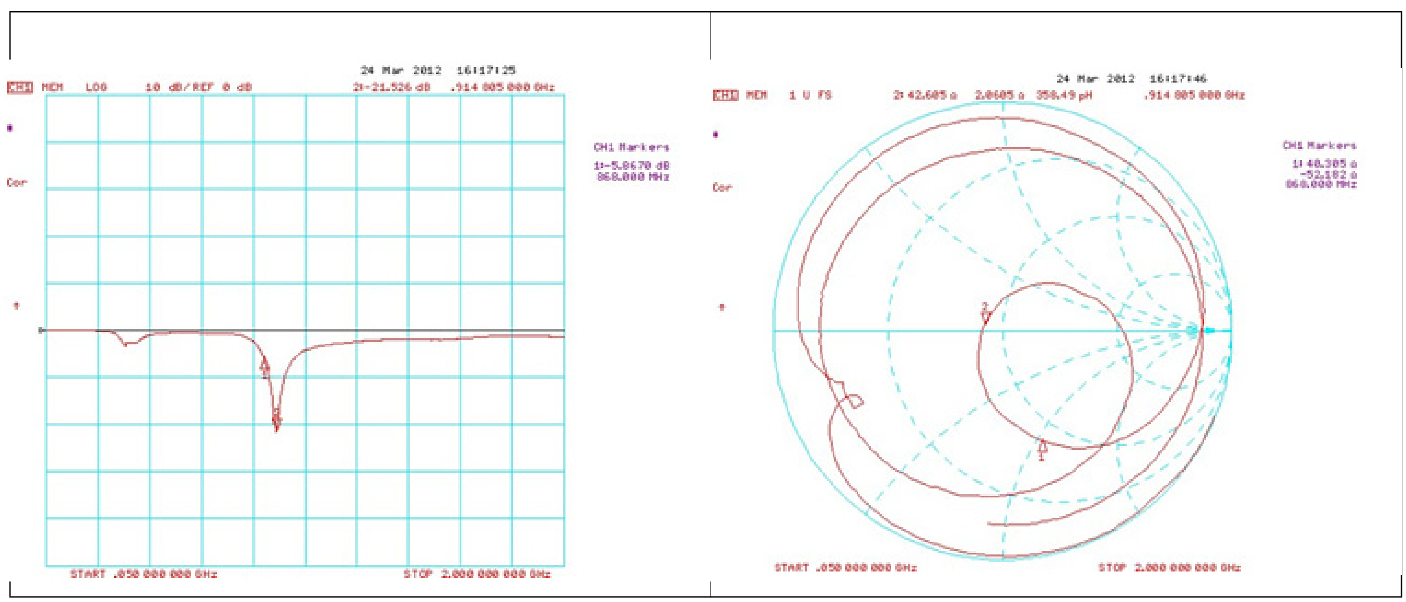


Figure 51. Measured Input Impedance

4.4.13. 915 MHz—HT–A–900–3107

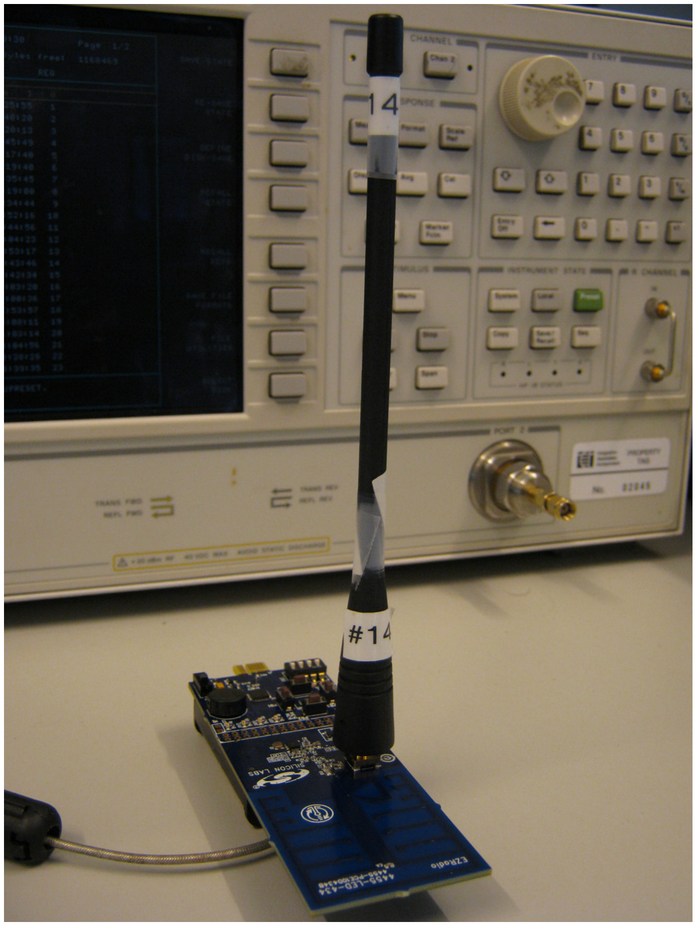


Figure 52. #14 HT-A-900-3107

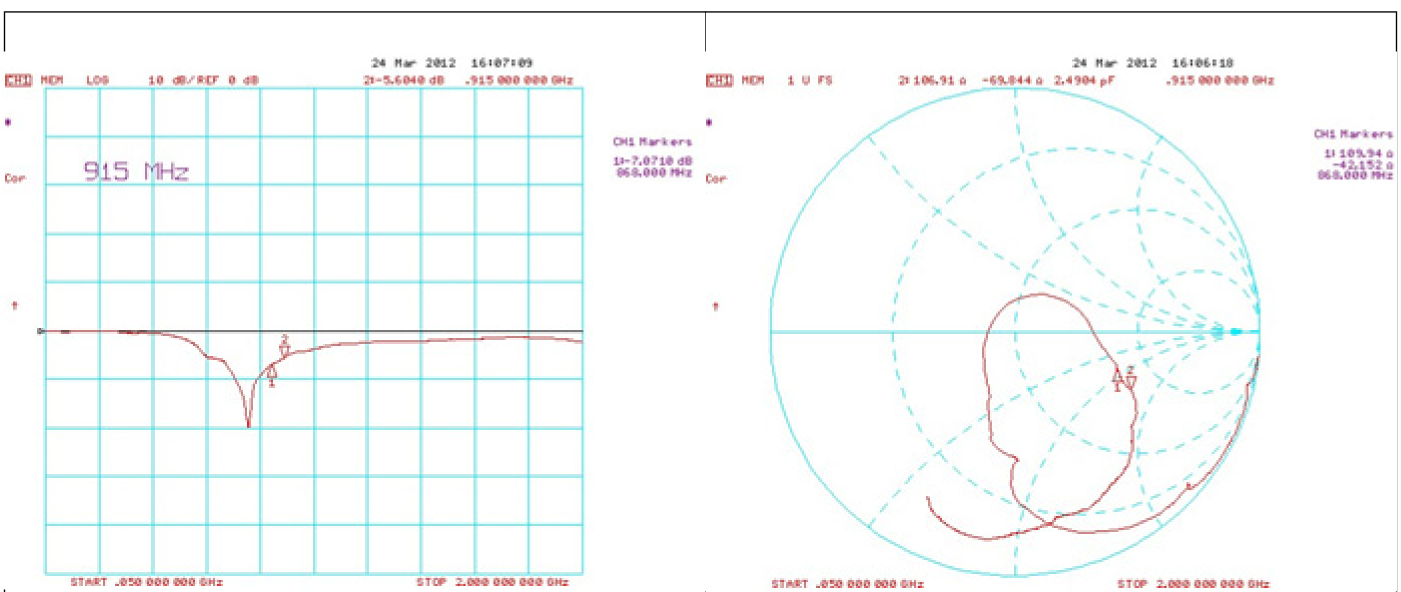


Figure 53. Measured Input Impedance

4.4.14. 916 MHz—ANT–916–CW–QW–SMA

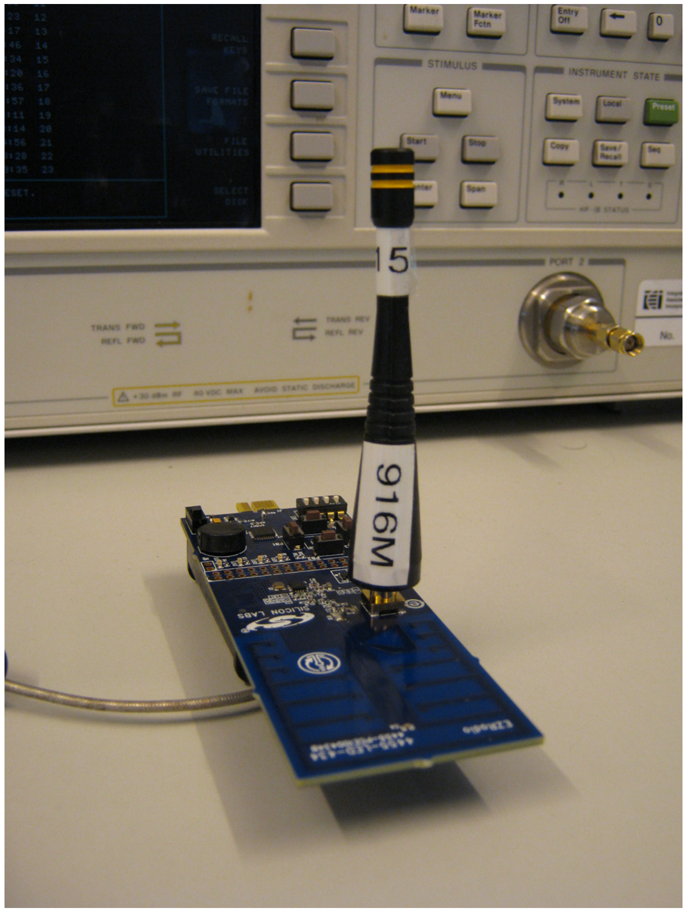


Figure 54. #15 ANT–916–CW–QW–SMA

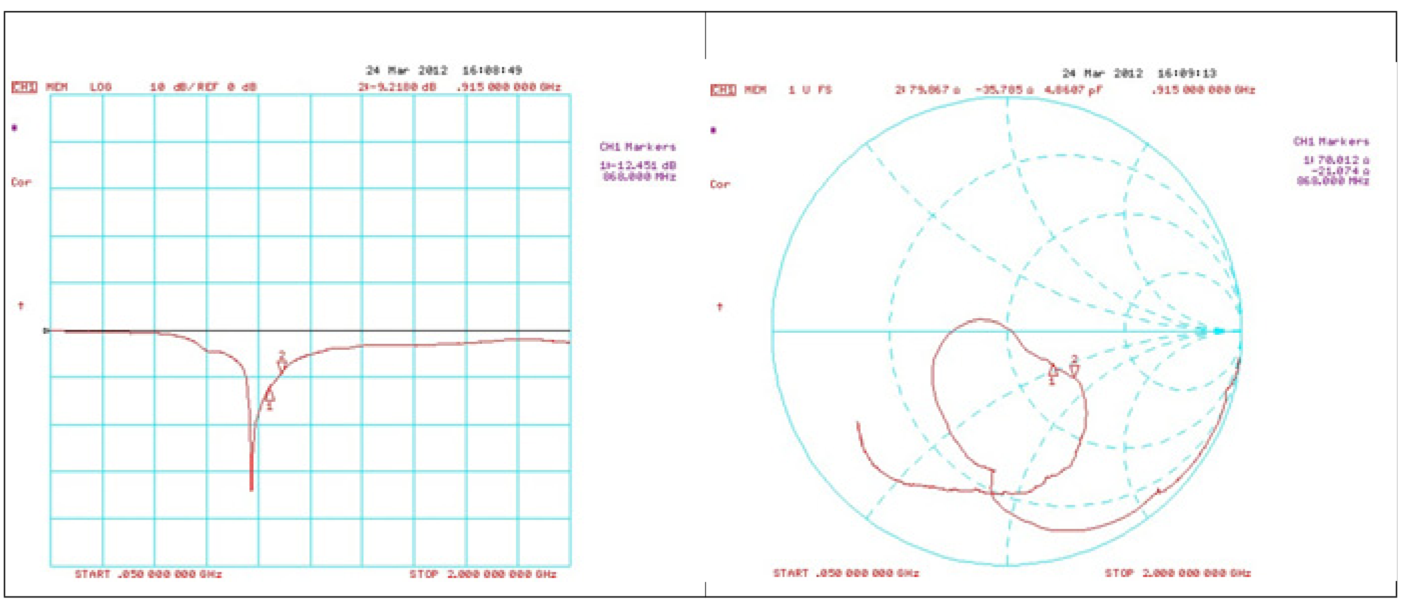


Figure 55. Measured Input Impedance

4.5. Range Measurement Examples

4.5.1. Measured Range at 434 MHz

Figure 56. 1% PER RX points at 434 MHz

Figure 57. RX–TX points at 434 MHz

4.5.2. Measured Range at 868 MHz

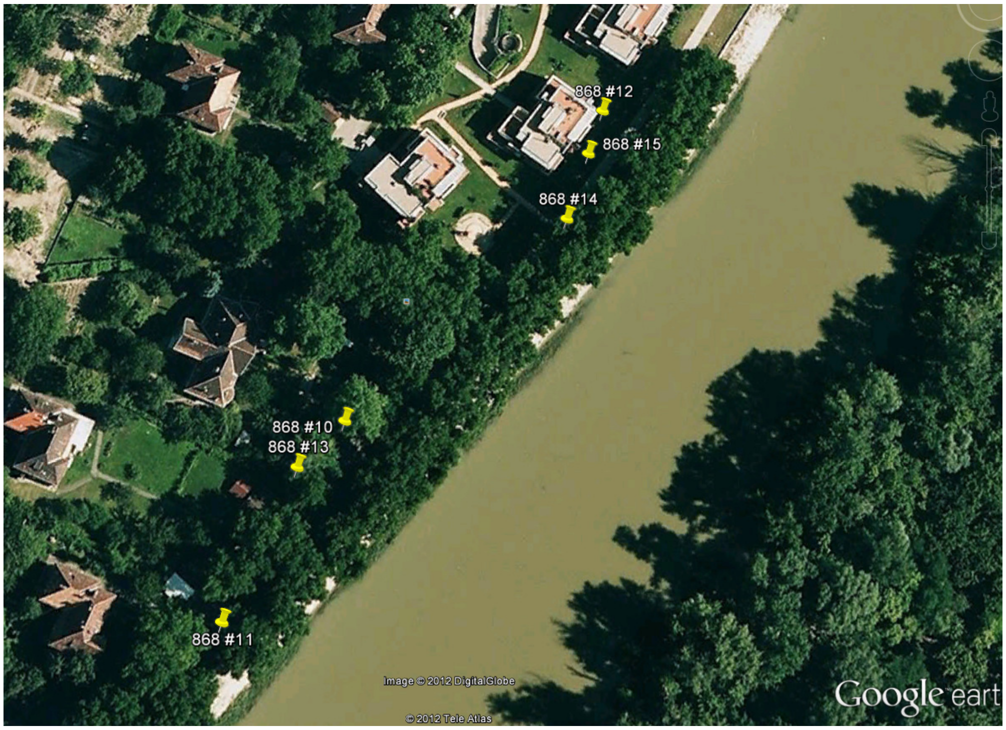


Figure 58. 1% PER RX points at 868 MHz

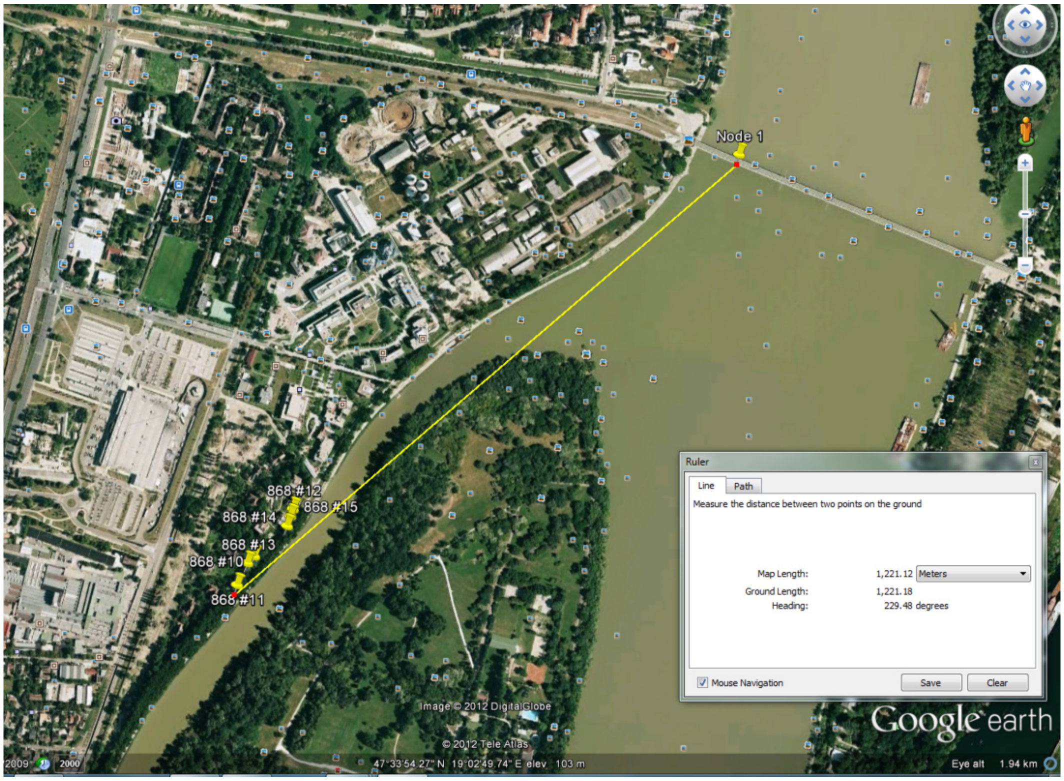


Figure 59. RX–TX points at 868 MHz

4.5.3. Measured Range at 915 MHz

Figure 60. 1% PER RX points at 915 MHz

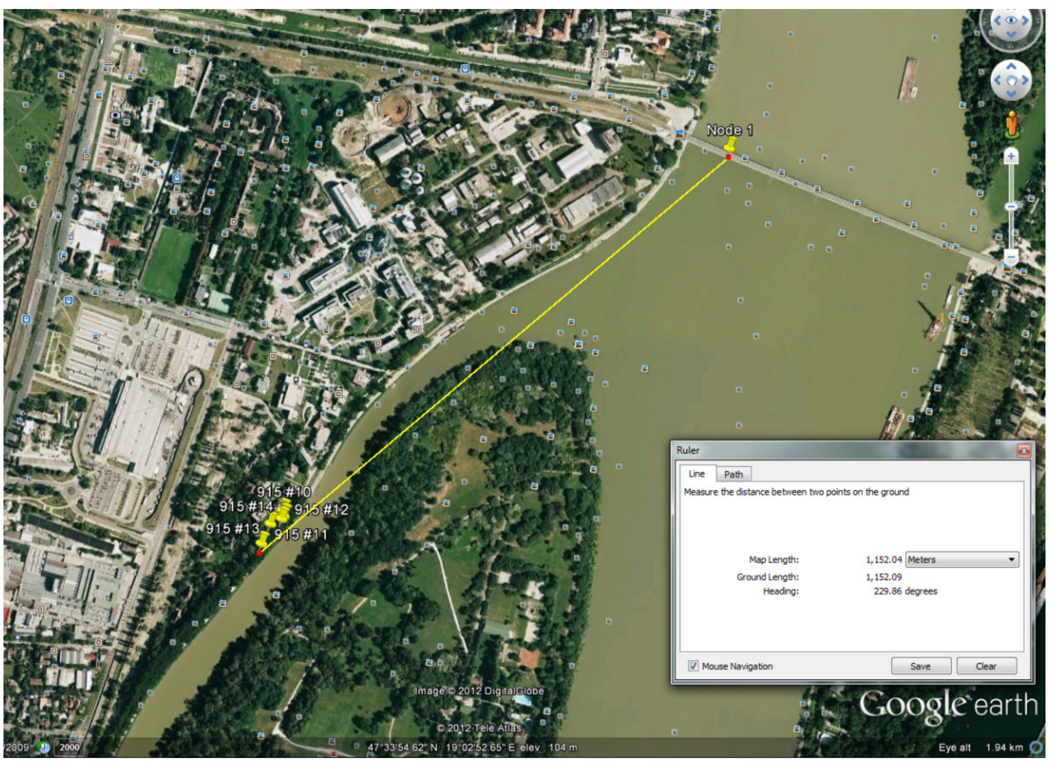


Figure 61. RX–TX points at 915 MHz

5. Antennas for the Si4012 RF IC

The Si4012 RF IC can use the same 50 Ω SMA and printed antennas that are used for the Si4455/435x RF ICs as described in Section 3 and Section 4. Since these SMA antennas are also tuned to 50 Ω, a matching network is also required to use between the Si4012 RF IC and the SMA antenna. This matching circuit comprises a 4-element matching balun, since the Si4012 RF IC has a differential PA output, and a filter network. The order of the filter network is determined by the harmonic suppression required by the standard of the band used. The matching principles are described in detail in “AN727: Si4012 Matching Network Guide” and the manufacturing pack including CAD and CAM files can be found on the www.silabs.com homepage.

5.1. Impedance Measurements for the Si4012-Based Boards

Because the sizes of the 4455/435x/4012 pico boards are approximately the same (with approximately the same ground planes), the input impedance of the SMA antennas using 4012-based boards is approximately equal to the impedance measurement results of the 4455/435x-based boards. These impedance measurement results can be found in Section 4 (Sections 4.3.1 and 4.4).

5.2. Range Estimation the Si4012-Based Boards

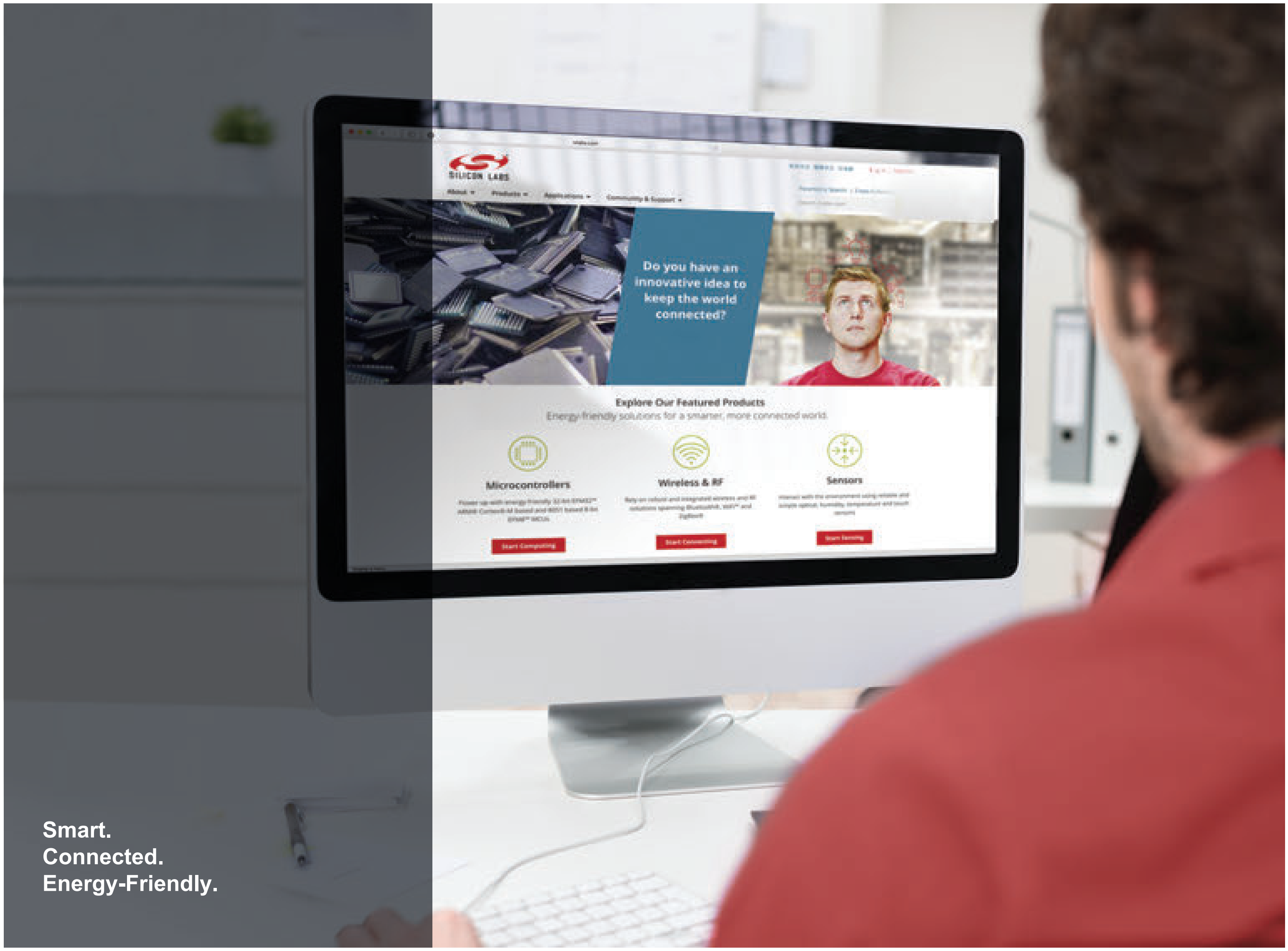
In these investigations, depending on the band, the 4012-PSC10B434 or 4012-PSC10B915 pico boards are used at the TX side of the link, while the 4355-PRXB434B or 4355-PRXB915B are used at the RX side. With these receivers, the sensitivities are identical to those of the 4455 pico boards. Assuming the same propagation conditions, the range can be estimated from the known TX output power differences between the 4455-based and 4012-based boards.

To calculate the estimated range, the value of the propagation constant is assumed to be 2.8 (outdoor, good propagation conditions).

At 434 MHz the difference in the maximum output power at the fundamental frequency is 1.7dB, which means that the estimated range that can be achieved with 4012-PSC10B434 pico board is about 87 percent of the range of the 4455-PCE10D434B development board, as described in section 4.3.2. Using the SPWH24433TI antenna, the estimated range for the Si4012 pico board is 1059 m; using the 434 MHz BIFA antenna the estimated range is about 907m.

At 915 MHz there is no difference in the maximum output power at the fundamental frequency due to the FCC limitation, which means that the estimated range that can be achieved with 4012-PSC10B915B development board is equal to the range of the 4455-PCE10D915B pico board. Using the W5017 antenna, this range is 1148 m; using the 915 MHz BIFA antenna, the estimated range is about 1125 m.

Due to the fact that these differences between the output powers at the fundamental frequencies are low (note that they are equal in the 915 MHz case), these estimations for the attainable ranges are quite accurate.



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