Si446x/Si4362 RX LNA Matching

1. Introduction

The purpose of this application note is to provide a description of the impedance matching of the RX differential low noise amplifier (LNA) on the Si446x/Si4362 family of RFICs.

It is desired to simultaneously achieve two goals with the matching network:

- Match the LNA input to the antenna source impedance (e.g., 50 Ω)
- Provide a single-ended-to-differential conversion function (i.e., a balun)

The matching procedure outlined in this document provides for achieving the goals listed above.

For those users who are not interested in the theoretical derivation of the match network, but are just concerned with quickly obtaining matching component values, refer to the Summary Tables shown in "4.1.7. Summary Tables of 3-Element Match Network Component Values vs. Frequency" on page 12 and "4.2.7. Summary Tables of 4-Element Match Network Component Values vs. Frequency" on page 19.

Measurements were performed on the Si4461-B0 chip but are applicable to other members of the Si446x family of chips (e.g. Si446x-B1, C0, C1, C2 and the Si4362 chip).

2. Match Network Topology

The LNA on the Si446x/Si4362 family of chips is designed as a differential amplifier and thus has two input pins (RXp and RXn) on the RFIC. It is necessary to design a network that not only provides a conjugate match to the input impedance of the LNA but also provides a balanced-to-unbalanced conversion function (i.e., a balun).

The LNA design is differential and thus the RXp and the RXn input pins may be considered interchangeable. Although the figures in this document may show the matching components connected to the RXp/RXn pins in a certain fashion, the pin connections may be reversed without change in functionality.

Use of two basic matching network topologies will be considered within this application note.

2.1. Three-Element Match Network

The simplest match network that may be fabricated from discrete components is comprised of three discrete elements. Two forms of the 3-element match network may be constructed: one with a highpass filter (HPF) response, and one with a lowpass filter (LPF) response. However, the form with a lowpass filter response is not realizable at all frequencies and input impedances. As a result, only the form with a highpass filter response is discussed within this document.

A 3-element (CR1-LR1-CR2) HPF matching network is shown in Figure 1. This matching network has the virtue of requiring a minimum number of components but results in slightly sub-optimal performance. It is not theoretically possible to achieve a perfectly balanced single-ended-to-differential conversion function with this matching network for input impedances with finite values of R_{LNA}. As will be demonstrated, the waveforms obtained at the RXp and RXn inputs to the RFIC will not be exactly 180° out of phase; the result is a very slight loss in conversion gain in the LNA and a small drop in overall sensitivity of the RFIC. The reduction in performance is typically less than 0.5 dB; many customers may view this as an acceptable trade-off for the reduction in the bill of materials (BOM).

The RXp and RXn inputs of the Si446x/Si4362 RX LNA internally contain high value (~15 kΩ) pull-down resistors to GND. As a result, supplying a DC voltage to these pins is not recommended; use of external AC-coupling to these pins is suggested. This is inherently supplied by capacitor CR2 of Figure 1.

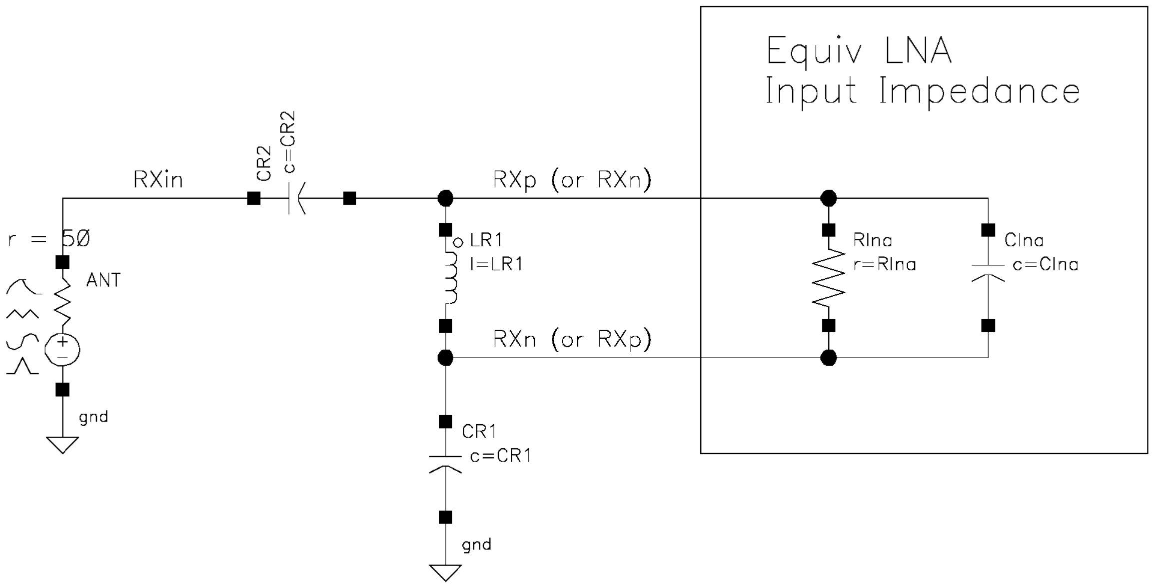

Figure 1. HPF Three-Element Match Network

2.2. Four-Element Match Network

For those customers concerned with obtaining optimal performance, the 4-element match network of Figure 2 is recommended. This match network can provide theoretically perfect phase balance between the RXp and RXn inputs (exactly 180° out-of-phase), thus optimizing LNA conversion gain and receiver sensitivity. The only drawback is the addition of one more component (an inductor) to the BOM. Use of this matching topology is also mandatory for circuit configurations in which the TX and RX paths are tied directly together without use of an RF switch. This is discussed in greater detail in "4.2.8. Use of 4-Element Match Network in Direct Tie Board Configurations" on page 22.

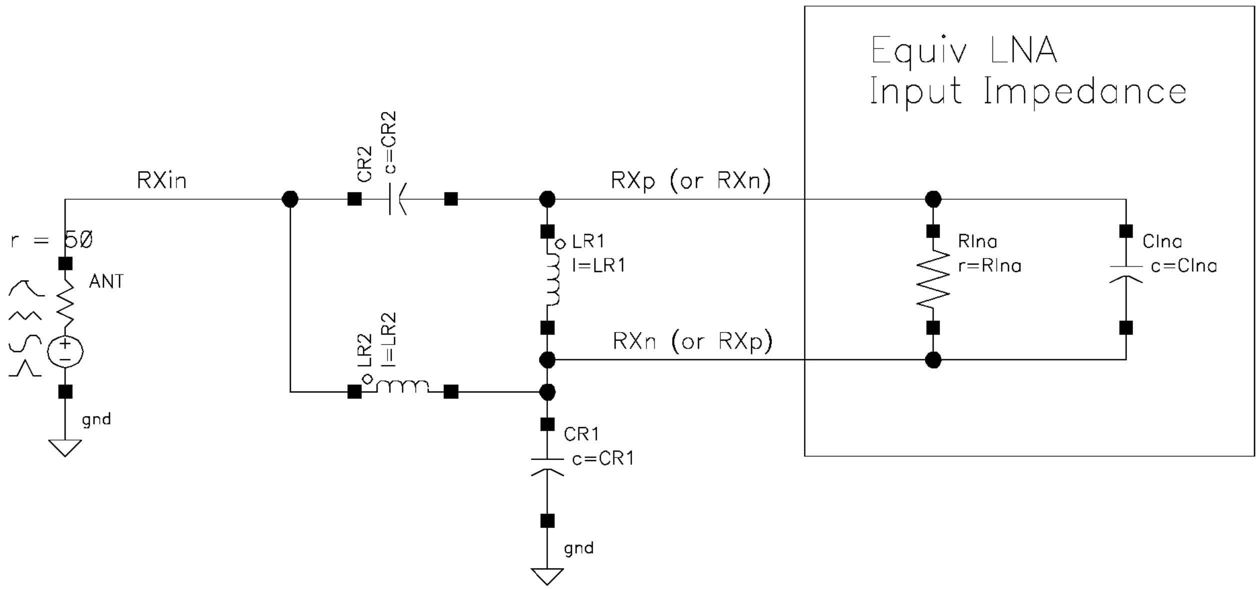

Figure 2. Four-Element Match Network

3. Si446x/Si4362 Differential LNA Input Impedance

Silicon Laboratories has measured the differential input impedance of the Si4461 RX LNA directly at the RXp/RXn input pins of the RFIC, with no matching network. Although this measurement was taken on a Si4461 chip, the data is applicable to other members of the Si446x family of chips and also on the Si4362, as the LNA is similar in all devices.

The plot shown in Figure 3 shows the measured differential input impedance in the RX mode of operation over the 140 to 960 MHz frequency band, with markers placed at various points throughout the frequency range.

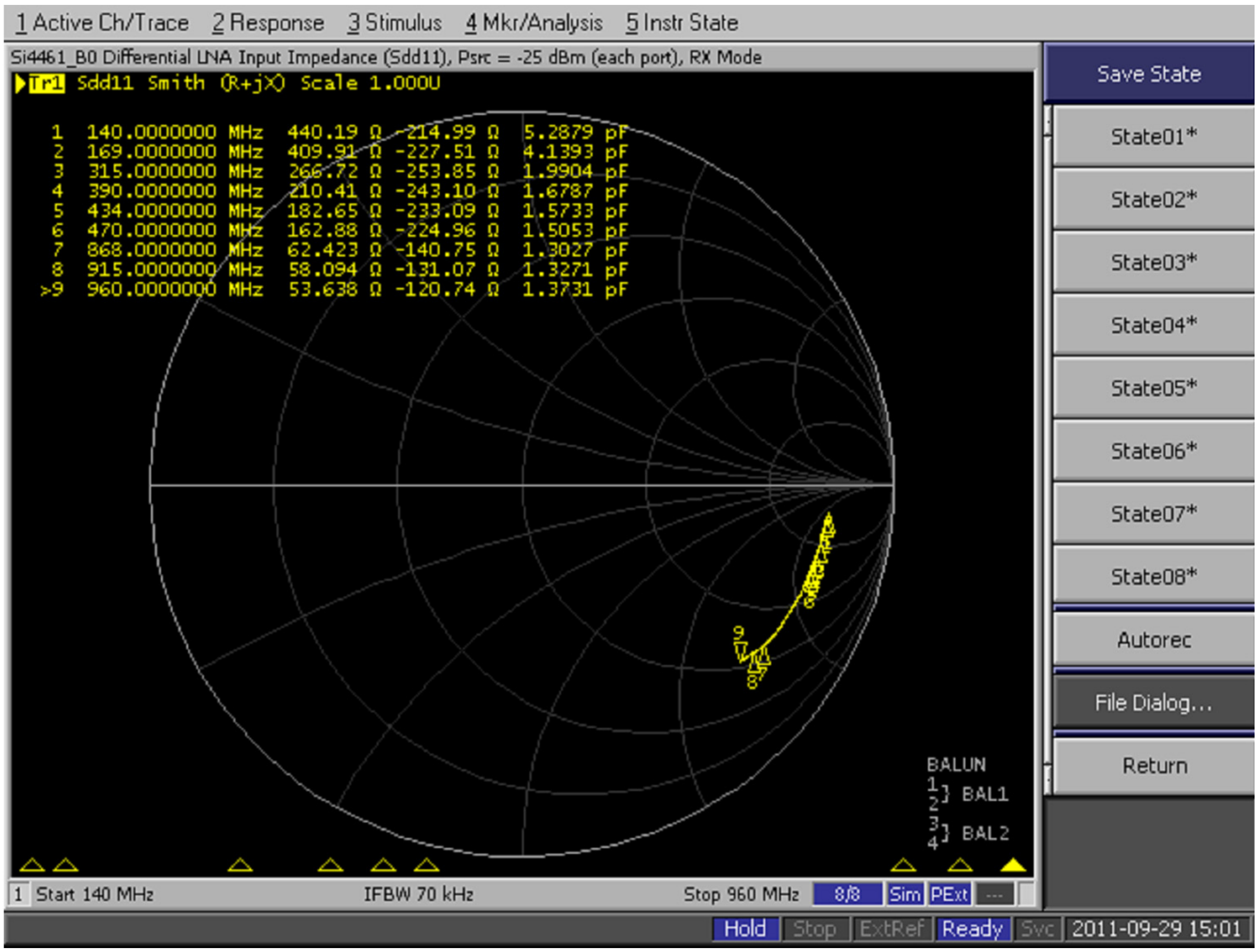

Figure 3. Si446x/Si4362 Differential RX LNA Input Impedance 140-960 MHz (RX Mode)

As can be seen from this curve, at any given single frequency the input impedance of the LNA may be considered as a resistance in parallel with a small amount of capacitance. That is to say, the input impedance of the LNA falls in the capacitive half of the Smith Chart across its entire operating frequency range.

The impedance curve shown in Figure 3 cannot be described by a single fixed value of resistance, placed in parallel with a single fixed value of capacitance. The equivalent values of parallel resistance and capacitance (R_{LNA} and C_{LNA} in Figure 1 and Figure 2) vary as a function of frequency. However, the variation with frequency is not rapid; it is possible to construct a moderately wideband (~100 MHz) matching network by simply designing for the value of R_{LNA} and C_{LNA} in the center of the desired frequency range.

From the differential input impedance values ($Z = R + jX$) shown in Figure 3, it is necessary to first calculate the equivalent input admittance, where $Y = 1/Z = G + jB$. It is then a simple matter to calculate the values of the equivalent input resistor and capacitor (i.e., R_{LNA} and C_{LNA} in Table 1) as $R_{LNA} = 1/G$ and $C_{LNA} = B/(2\pi F_{RF})$.

Silicon Laboratories has performed these computational steps on the measured S_{dd11} data of Figure 3, and the resulting equivalent values of R_{LNA} and C_{LNA} are shown in Table 1 as a function of frequency.

Table 1. Equivalent R_{LNA}-C_{LNA} from 140-960 MHz

Freq	R_{LNA}	C_{LNA}
140 MHz	545 Ω	1.02 pF
169 MHz	536 Ω	0.98 pF
200 MHz	530 Ω	0.96 pF
250 MHz	520 Ω	0.94 pF
300 MHz	512 Ω	0.95 pF
315 MHz	509 Ω	0.95 pF
350 MHz	499 Ω	0.95 pF
390 MHz	491 Ω	0.96 pF
400 MHz	488 Ω	0.96 pF
434 MHz	480 Ω	0.97 pF
470 MHz	474 Ω	0.99 pF
500 MHz	467 Ω	1.00 pF
550 MHz	460 Ω	1.01 pF
600 MHz	451 Ω	1.02 pF
650 MHz	437 Ω	1.04 pF
700 MHz	424 Ω	1.05 pF
750 MHz	414 Ω	1.07 pF
800 MHz	402 Ω	1.08 pF
850 MHz	387 Ω	1.09 pF
868 MHz	380 Ω	1.09 pF
900 MHz	362 Ω	1.10 pF
915 MHz	354 Ω	1.11 pF
955 MHz	327 Ω	1.14 pF
960 MHz	325 Ω	1.15 pF

4. LNA Matching Procedure for the Si446x/Si4362 RFIC

Armed with the measured values of unmatched differential input impedance of the Si446x/Si4362 LNA, it is now possible to proceed with constructing a matching network. For demonstration purposes, a frequency of 470 MHz is chosen to illustrate the examples.

4.1. Three-Element Matching Procedure

The matching procedure for the 3-element (CR1-LR1-CR2) HPF match is outlined below.

4.1.1. Step #1: Plot the LNA Input Impedance

The matching procedure begins with the equivalent parallel R_{LNA}-C_{LNA} circuit values obtained from Table 1. At 470 MHz, the equivalent circuit values are found to be R_{LNA} = 474 Ω and C_{LNA} = 0.99 pF. It is useful to plot this value on a Smith Chart, as shown in Figure 4.

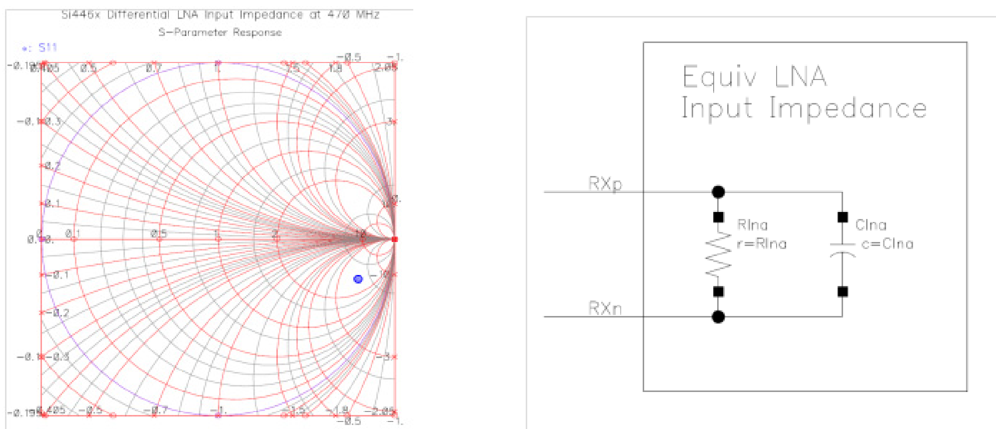

Figure 4. Step #1: Plot LNA Input Impedance

4.1.2. Step #2: Add Parallel Inductance L_{LNA} to Resonate with LNA Capacitance

Although Step #2 may technically be combined with the subsequent Step #3, the design equations are somewhat easier to manipulate if the equivalent LNA input capacitance C_{LNA} is first effectively cancelled (at the frequency of interest) by resonating it with a parallel inductance L_{LNA}.

$$L_{LNA} = \left(\frac{1}{(\omega_{RF})^2 C_{LNA}}\right)$$

Equation 1.

In the design example at 470 MHz, this value of inductance is calculated to be equal to L_{LNA} = 115.83 nH. After this amount of parallel inductance is added across the LNA inputs, the input impedance can be considered to be purely real and of a value equivalent to R_{LNA}. This is shown in Figure 5.

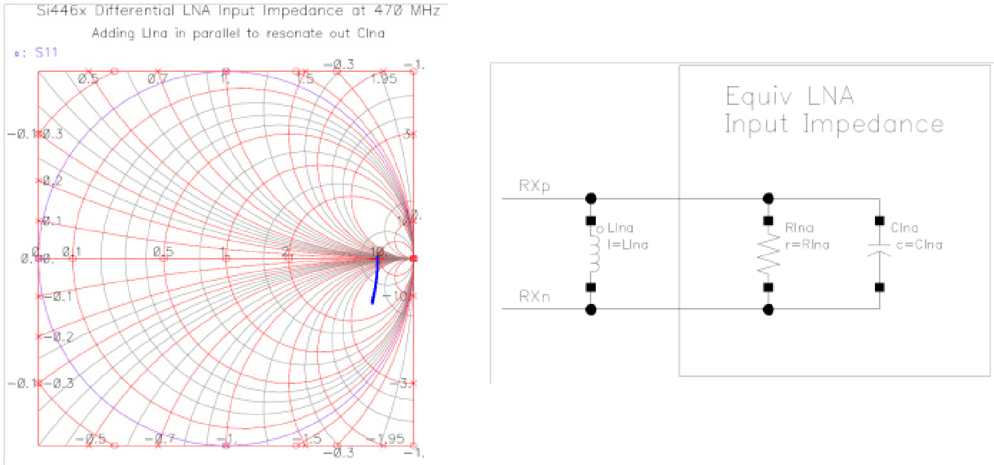

Figure 5. Step #2: Add Parallel Inductance to Resonate C_{LNA}

4.1.3. Step #3: Place Additional Matching Inductance in Parallel with LNA Input

Next an additional matching inductor L_M is placed in parallel with the LNA input network. The value of the inductance should be chosen to further rotate the susceptance on the Smith Chart along a line of constant conductance (in the -jBP direction) until the 50 Ω circle is reached (assuming the antenna source impedance is 50 Ω). The required value of matching inductance L_M is given by the following:

$$L_M = \frac{1}{\omega_{RF}\sqrt{\left(\frac{1}{50\Omega \times R_{LNA}}\right) - \left(\frac{1}{R_{LNA}}\right)^2}}$$

Equation 2.

Note: The mathematical derivations for all equations within this document are not shown. The full derivations are contained within a Mathcad worksheet developed by the Silicon Laboratories Application Team; this worksheet is available from Silicon Laboratories upon request.

Using this equation, or by employing graphical methods on the Smith Chart, the additional parallel matching inductance required to reach the 50 Ω circle is found to be L_M = 55.12 nH.

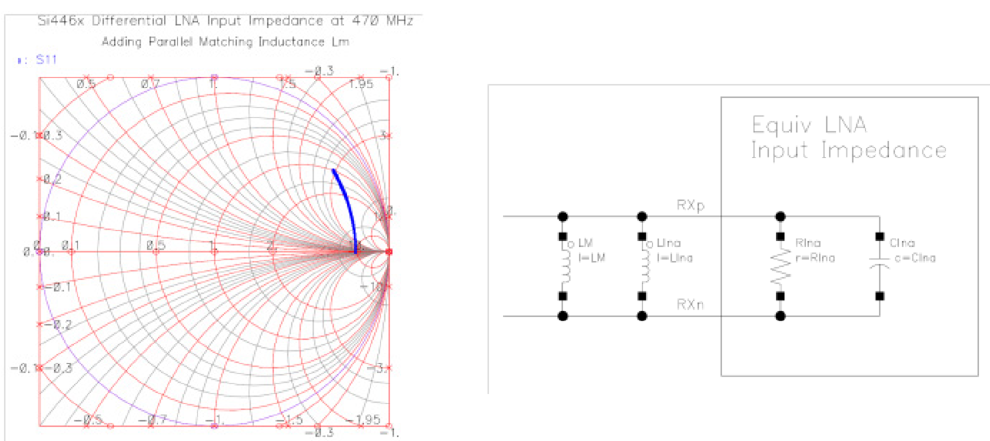

Figure 6. Step #3: Add Parallel Matching Inductance L_M

As L_{LNA} and L_M are in parallel with each other, they may be combined into one equivalent inductance LR1.

$$L_{R1} = \frac{L_{LNA} L_M}{L_{LNA} + L_M}$$

Equation 3.

Using this equation, it is quickly determined that a single inductor of value LR1 = 37.35 nH may be used in place of L_{LNA} and L_M.

4.1.4. Step #4: Determine Total Amount of Series Capacitive Reactance

It is next necessary to determine the total amount of series capacitive reactance ($-jX_{CTOTAL}$) required to match this point to 50 Ω. That is to say, it is desired to rotate the reactance along a line of constant resistance until arriving at the center of the Smith Chart. The required value of total capacitance is given by the following:

$$C_{TOTAL} = \frac{1}{\omega_{RF} \times 50\Omega \sqrt{\left(\frac{R_{LNA}}{50\Omega}\right) - 1}}$$

Equation 4.

Using this equation, or by employing graphical methods on the Smith Chart, the total series capacitance required to reach the 50 Ω origin of the Smith Chart is found to be C_{TOTAL} = 2.33 pF.

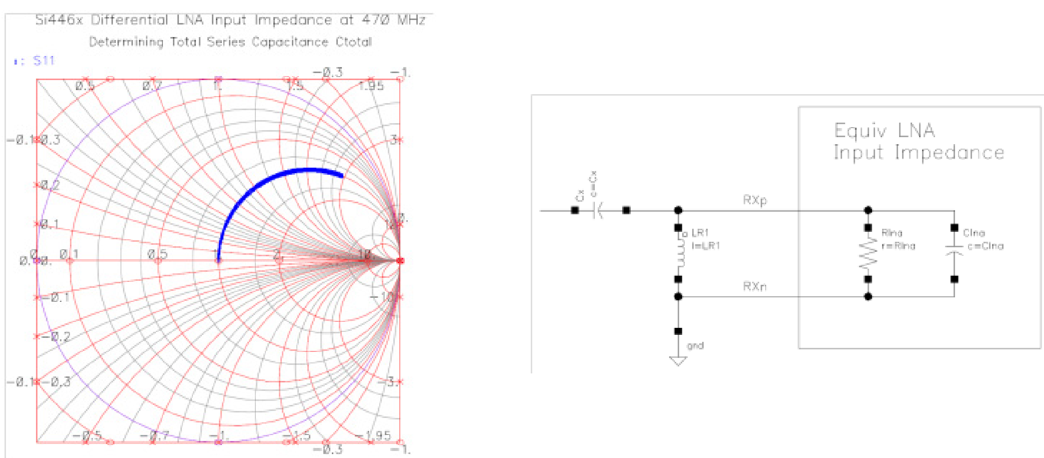

Figure 7. Step #4: Determine TOTAL Series Capacitive Reactance

4.1.5. Step #5: Allocate Total Series Capacitance Between CR1 and CR2

The final step is to properly allocate this total required series capacitive reactance between CR1 and CR2.

There are an infinite number of possible matching networks which achieve a perfect match to 50 Ω. However, only one of these solutions also achieves the best possible equal-amplitude-with-180°-phase relationship between the waveforms at the RXp / RXn inputs.

For example, it would be possible to set the value of CR1 so large that it provides essentially 0 Ω of capacitive reactance and essentially ac-shorts the RXn pin to GND. Under this condition, it would be possible to set the value of CR2 to provide all of the required series capacitive reactance (determined in Step #4 above) and still achieve a perfect match to 50 Ω. However, it is clear that the waveforms at the RXp and RXn nodes would not be balanced. The voltage at the RXn pin in this scenario would be zero (ac-shorted to GND by CR1). From an AC standpoint, this is equivalent to the schematic shown in Figure 7.

To properly allocate the total series capacitive reactance between CR1 and CR2, the required relationship between LR1 and CR1 must first be recognized. It is desirable for the voltages at the RXp and RXn pins to be equal in amplitude but opposite in phase, and thus the voltage developed “across” the parallel network of LR1-R_{LNA}-C_{LNA} must be twice the amplitude (and of opposite polarity) as the voltage that exists at the RXn node.

A portion of the parallel inductance LR1 is simply used to resonate out the capacitance C_{LNA}. As shown in Steps #2 and #3, it was useful to consider the inductance LR1 as consisting of two inductors in parallel: L_{LNA} and L_M, as re-drawn in Figure 8.

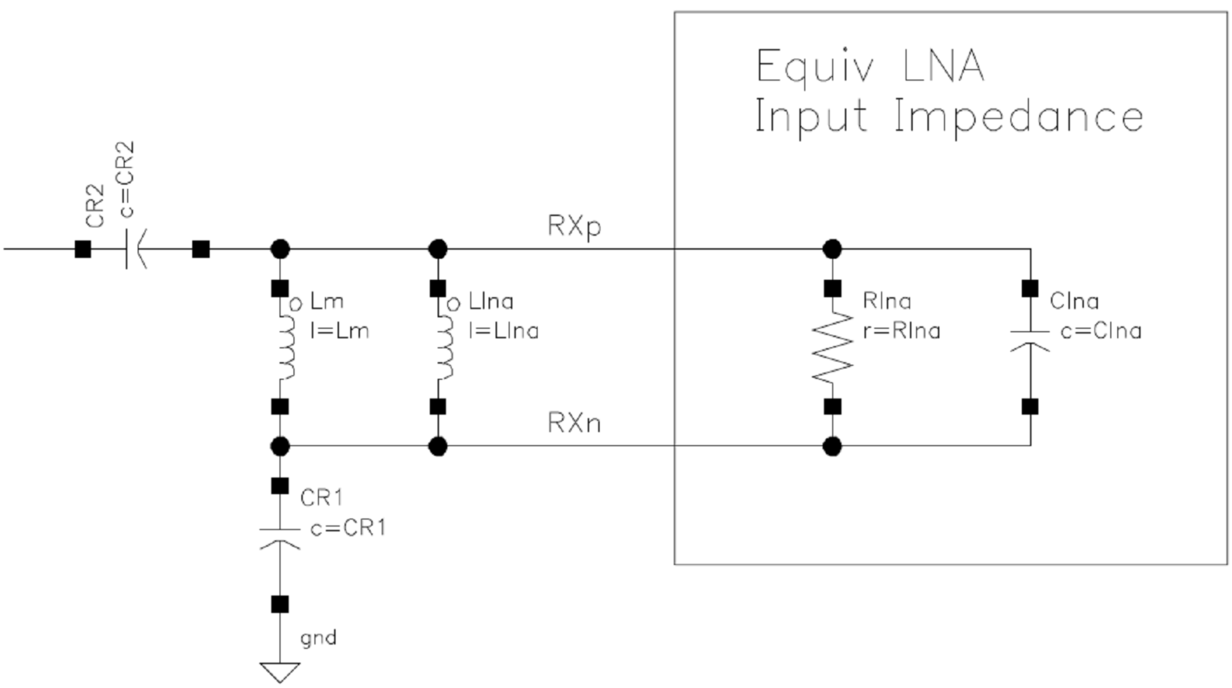

Figure 8. Resolving LR1 into Two Parts

The values of these two inductances have previously been determined to be L_{LNA} = 115.83 nH and L_M = 55.12 nH. As the inductance L_{LNA} is simply used to resonate with C_{LNA} at the desired frequency of operation, the match network may thus be re-drawn as shown in Figure 9.

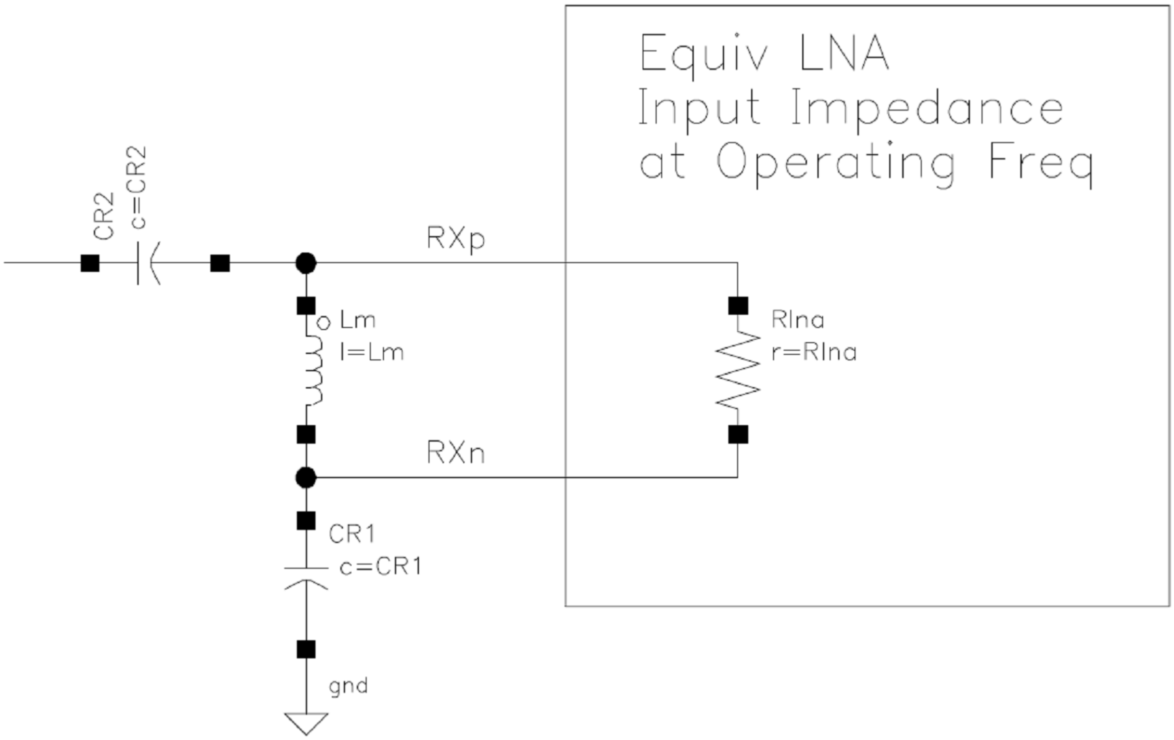

Figure 9. Equivalent Match Network at Operating Frequency

The voltage across L_M is desired to be twice the amplitude (and opposite in phase) to the voltage across CR1. Temporarily ignoring the effects of R_{LNA}, the following relationship is obtained:

$$X_{LM} = 2 \times X_{CR1}$$

Equation 5.

As the required value of inductance L_M has already been determined, the required value for CR1 follows immediately from the previously-derived equation for L_M.

$$CR1 = 2 \times \frac{\sqrt{\left(\frac{R_{LNA}}{50\Omega}\right) - 1}}{\omega_{RF} R_{LNA}}$$

Equation 6.

Using this equation, the value for this capacitor is determined to be CR1 = 4.16 pF. It is then a simple matter to allocate the remaining portion of total required series capacitive reactance to CR2.

$$CR2 = \frac{1}{\left(\frac{1}{C_{TOTAL}}\right) - \left(\frac{1}{CR1}\right)}$$

Equation 7.

From this equation, the value for the remaining capacitor is quickly found to be CR2 = 5.27 pF. Thus all of the components in the 3-element match network have been determined:

- CR2 = 5.27 pF
- LR1 = 37.35 nH
- CR1 = 4.16 pF

4.1.6. Phase Imbalance of RXp/RXn Signals

If the input impedance of the LNA were infinite (R_{LNA} =), this procedure would result in equal-amplitude perfectly-balanced (180° out-of-phase) waveforms at the RXp and RXn nodes. However, a finite value for R_{LNA} has the effect of shifting the phase of the signal developed across the parallel combination of LR1- R_{LNA} -C_{LNA}; thus the voltage developed at the RXp node can never be exactly 180° out-of-phase with respect to the voltage at the RXn node. This effect may be clearly seen in the simulated results of Figure 10; the differential voltages are equal in amplitude but not quite opposite in phase.

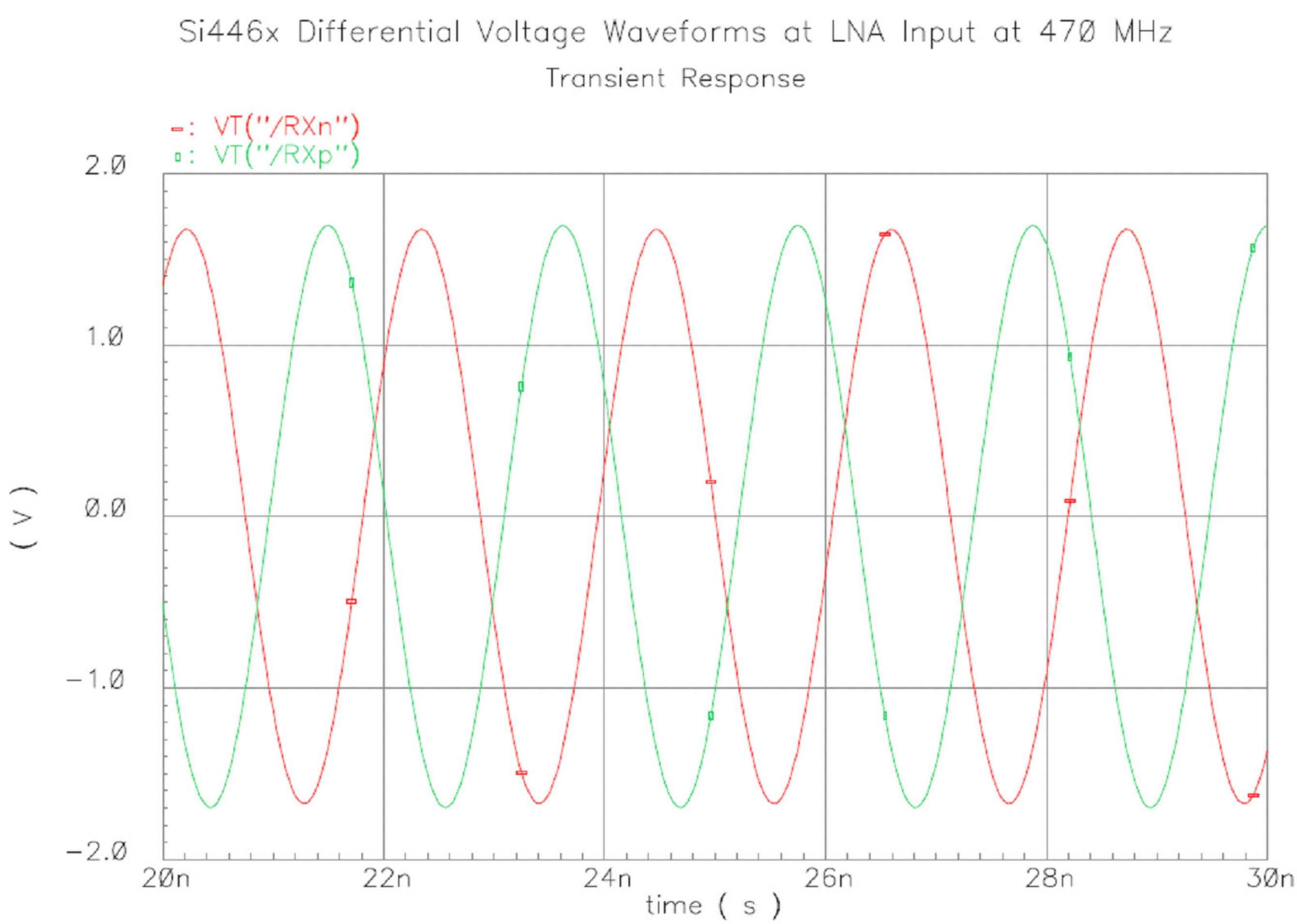

Figure 10. Differential Voltage Waveforms at LNA Input (3-Element Match)

As stated earlier, the 3-element match network provides slightly less-than-optimal performance when compared to a perfect balun. However, the difference is usually quite small (< 0.5 dB degradation) and is often acceptable.

4.1.7. Summary Tables of 3-Element Match Network Component Values vs. Frequency

Some users may not be greatly interested in the theoretical development of the matching network, but are concerned only with quickly obtaining a set of component values for a given desired frequency of operation. For those users, the resulting calculated component values for the 3-element match network for multiple frequencies across the operating range of the Si446x/Si4362 RFIC are summarized below. The calculations in this table assume the antenna source impedance is Z_{ANT} = 50 + j0 Ω.

Table 2. 3-Element Match Network Component Values (Calculated)

Freq	R_{LNA}	C_{LNA}	CR1	LR1	CR2
140 MHz	545 Ω	1.02 pF	13.12 pF	170. 48 nH	16.07 pF
169 MHz	536 Ω	0.98 pF	10.96 pF	137.41 nH	13.47 pF
200 MHz	530 Ω	0.96 pF	9.30 pF	112.90 nH	11.47 pF
250 MHz	520 Ω	0.94 pF	7.51 pF	86.25 nH	9.30 pF
300 MHz	512 Ω	0.95 pF	6.30 pF	68.71 nH	7.83 pF
315 MHz	509 Ω	0.95 pF	6.02 pF	64.56 nH	7.49 pF
350 MHz	499 Ω	0.95 pF	5.46 pF	56.20 nH	6.83 pF
390 MHz	491 Ω	0.96 pF	4.94 pF	48.59 nH	6.20 pF
400 MHz	488 Ω	0.96 pF	4.83 pF	46.88 nH	6.07 pF
434 MHz	480 Ω	0.97 pF	4.48 pF	41.83 nH	5.66 pF
470 MHz	474 Ω	0.99 pF	4.16 pF	37.37 nH	5.28 pF
500 MHz	467 Ω	1.00 pF	3.94 pF	34.18 nH	5.01 pF
550 MHz	460 Ω	1.01 pF	3.60 pF	29.75 nH	4.61 pF
600 MHz	451 Ω	1.02 pF	3.33 pF	26.18 nH	4.28 pF
650 MHz	437 Ω	1.04 pF	3.12 pF	23.10 nH	4.05 pF
700 MHz	424 Ω	1.05 pF	2.93 pF	20.54 nH	3.84 pF
750 MHz	414 Ω	1.07 pF	2.77 pF	18.39 nH	3.65 pF
800 MHz	402 Ω	1.08 pF	2.63 pF	16.57 nH	3.49 pF
850 MHz	387 Ω	1.09 pF	2.51 pF	14.97 nH	3.39 pF
868 MHz	380 Ω	1.09 pF	2.48 pF	14.44 nH	3.37 pF
900 MHz	362 Ω	1.10 pF	2.44 pF	13.47 nH	3.37 pF
915 MHz	354 Ω	1.11 pF	2.42 pF	13.04 nH	3.38 pF
955 MHz	327 Ω	1.14 pF	2.40 pF	11.85 nH	3.45 pF
960 MHz	325 Ω	1.15 pF	2.39 pF	11.73 nH	3.45 pF

The above analysis assumes use of ideal discrete components in the matching network. However, surface-mount 0603- or 0402-size components themselves contain parasitic elements that modify their effective values at the frequency of interest. Additionally, the analysis presented above does not make allowance for any PCB parasitics, such as trace inductance, component pad capacitance, etc. Furthermore, it is convenient to use the nearest-available 5% or 10% component value; the component values shown above represent results of exact mathematical calculations.

As a result, it will almost certainly be necessary to “tweak” the final matching values for a specific application and board layout. The above component values should be used as starting points, and the values modified slightly to zero-in on the best match to the antenna source impedance (e.g., 50 Ω), and the best RX sensitivity.

Silicon Laboratories has empirically determined the optimum matching network values at a variety of frequencies, using RF Test Boards designed by (and available from) Silicon Laboratories. Wire-wound inductors (Murata LQW15A 0402-series and LQW18A 0603-series) were used in all of these matching examples. Multi-layer inductors (such as Murata LQG15HS 0402-series) may also be used; however, the insertion loss of the match may be increased slightly due to the higher loss of these inductors. By comparing the empirical values of Table 3 with the calculated values of Table 2, the reader may observe that the component values are in close agreement at frequencies below 500 MHz. However, somewhat larger deviations in value occur at higher frequencies, primarily due to the unmodeled parasitic effects of the PCB traces and discrete components. As mentioned previously, the calculated matching component values of Table 2 should be used as a starting point and adjusted for best performance.

Table 3. 3-Element Match Network Component Values (Optimized)

Freq	R_{LNA}	C_{LNA}	CR1	LR1	CR2
169 MHz	536 Ω	0.98 pF	10.0 pF	150 nH	13.0 pF
315 MHz	509 Ω	0.95 pF	5.6 pF	68 nH	7.5 pF
390 MHz	491 Ω	0.96 pF	4.7 pF	51 nH	6.2 pF
434 MHz	480 Ω	0.97 pF	4.3 pF	43 nH	5.6 pF
470 MHz	474 Ω	0.99 pF	3.9 pF	39 nH	5.1 pF
868 MHz	380 Ω	1.09 pF	2.0 pF	18 nH	3.0 pF
915 MHz	354 Ω	1.11 pF	1.8 pF	16 nH	3.0 pF
955 MHz	327 Ω	1.14 pF	1.8 pF	15 nH	2.7 pF

A 3-element RX match at 470 MHz was built and tested, using CR1=3.9 pF, LR1=39 nH, and CR2=5.1 pF. The measured input impedance (S11) is shown in Figure 11.

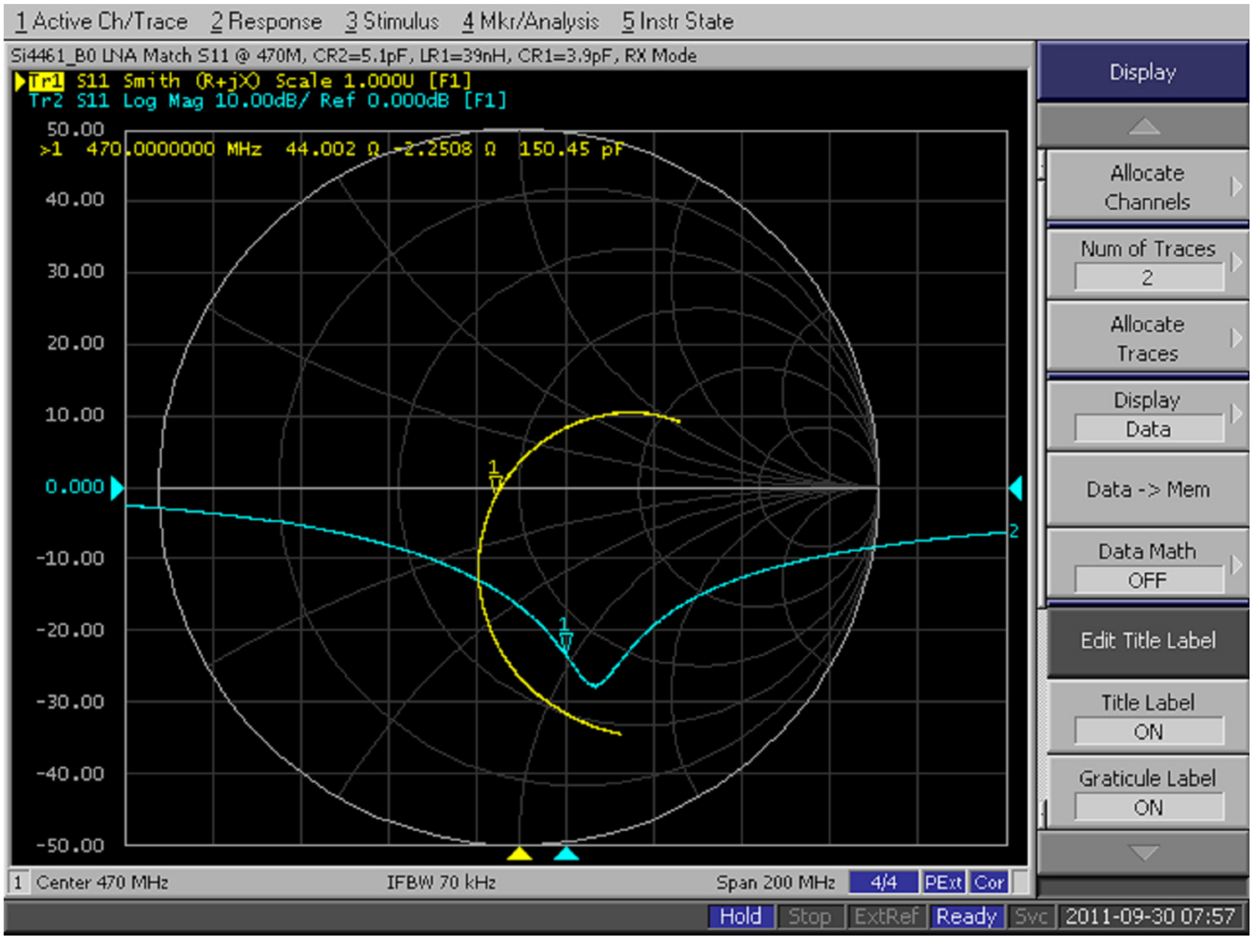

Figure 11. Input Impedance of 3-Element Match at 470 MHz

4.2. Four-Element Matching Procedure

As discussed previously, it is possible to achieve a theoretically-perfect match with the 4-element match network shown in Figure 2. The complete mathematical derivation of the equations for the required component values is beyond the scope of this application note; a Mathcad worksheet containing the complete derivation is available from Silicon Laboratories upon request.

The matching procedure for the 3-element network was readily understood and explained by plotting each step on a Smith Chart. This graphical approach is somewhat less intuitive for the 4-element matching procedure. Therefore, a combination of graphical and textual descriptions of the main steps in the mathematical derivation is presented, along with the important equations resulting from following these steps.

4.2.1. Step #1: Voltage at the RXn Node (V_{RXn})

If a network is created to successfully match to a purely-real input impedance of Z_{IN} = 50 Ω, the input current I_{IN} will also be purely real (arbitrarily assuming an input voltage from the source generator V_{IN} of unity magnitude and zero phase). This input current passes through capacitor CR1 to develop the voltage at the RXn node (V_{RXn}). It is apparent that this voltage V_{RXn} exhibits a –90° phase shift with respect to the input current I_{IN}, due to the capacitive reactance of CR1.

4.2.2. Step #2: Voltage at the RXp Node (V_{RXp})

The voltage at the RXp node (V_{RXp}) is desired to be equal in amplitude to V_{RXn} but opposite in phase. For this condition to be satisfied, the voltage *across* the LNA input pins must be *twice* the amplitude of V_{RXn}, as well as exactly opposite in phase. That is to say, if the phase of V_{RXn} is –90°, the phase of V_{RXp} must be +90°.

4.2.3. Step #3: Splitting the Input Current

Although the phase of the voltage across the LNA input pins must be +90°, the input impedance of the LNA network is not purely inductive (unless $R_{LNA} = \infty$). Thus, for the voltage across the LNA network to be purely reactive, the phase of the current through the LNA network must compensate for the phase shift introduced by R_{LNA}. As a result, it is necessary that the current through the LNA network be different from the current through CR1.

Thus the purpose of inductor LR2 is to split the input current I_{IN} into two different components, with the current passing through the LNA network being of the appropriate phase to produce a voltage of opposite phase to V_{RXn}.

4.2.4. Equations for Component Values

Following these derivational steps, it is possible to obtain the following set of design equations for the necessary component values.

$$LR2 = \frac{\sqrt{Re(Z_{ANT}) \times R_{LNA}}}{\omega_{RF}} = \frac{\sqrt{50\Omega \times R_{LNA}}}{\omega_{RF}}$$

Equation 8.

$$CR2 = \frac{1}{(\omega_{RF})^2 LR2}$$

Equation 9.

$$CR1 = 2 \times CR2$$

Equation 10.

$$L_{LNA} = \frac{1}{(\omega_{RF})^2 C_{LNA}}$$

Equation 11.

$$L_M = 2 \times LR2$$

Equation 12.

$$LR1 = \frac{L_{LNA} L_M}{L_{LNA} + L_M}$$

Equation 13.

Continuing the design example at 470 MHz, the component values for a 4-element match network are calculated as follows:

- CR1 = 4.40 pF
- LR1 = 54.87 nH
- CR2 = 2.20 pF
- LR2 = 52.13 nH

4.2.5. Phase Balance of RXp/RXn Signals

It was previously stated that an advantage of the 4-element match network was the ability to achieve perfect phase balance (180 degrees) between the RXp and RXn input nodes. This effect may be clearly seen in Figure 12; the differential voltages are now both equal in amplitude *and* perfectly opposite in phase.

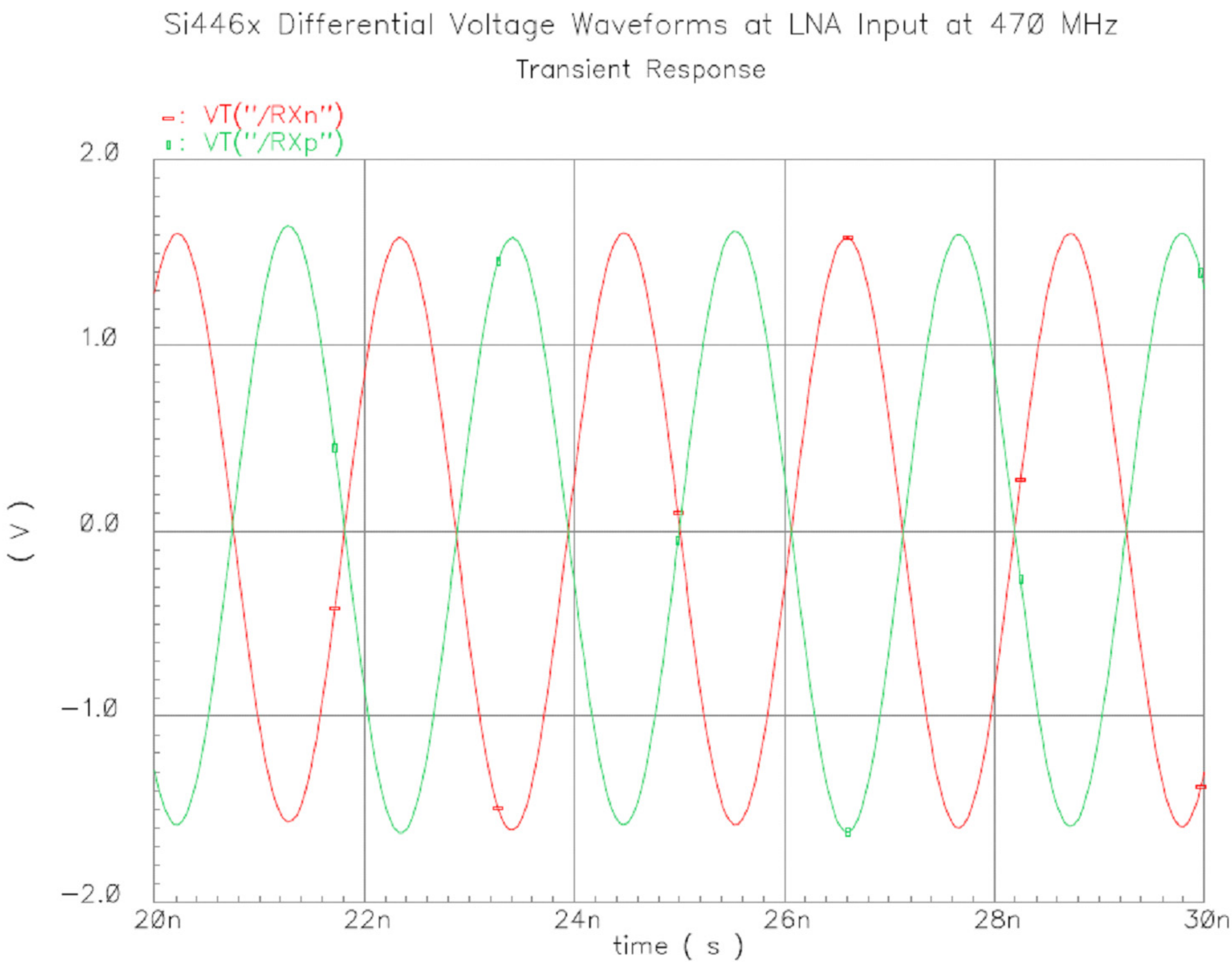

Figure 12. Differential Voltage Waveforms at LNA Input (4-Element Match)

4.2.6. Graphical Interpretation of 4-Element Match

It is informative to consider a graphical interpretation of the 4-element match using a Smith Chart. In practicality, it is simpler to use the design equations to obtain the required component values. However, the reader may gain insight into the behavior and functionality of the match by tracing its impedance progression on a Smith Chart.

The investigation is simplified if the LNA input impedance is temporarily considered to be purely real (i.e., C_{LNA} = 0 pF). Although this situation does not exist in practice, the input capacitance of the LNA may be easily canceled at the desired frequency of operation by placing a parallel inductance L_{LNA} across the RXp/RXn input pins, as discussed in "4.1.2. Step #2: Add Parallel Inductance L_{LNA} to Resonate with LNA Capacitance" on page 6. After cancellation of the input capacitance C_{LNA}, the "starting" point on the Smith Chart for the matching procedure then becomes $Z_{LNA} = R_{LNA} + j0 = R_{LNA}$.

If considering ***only*** the input impedance (while ignoring differential signal balance), the entire match circuitry may be redrawn as shown in Figure 13. While this schematic does not represent the ***physical*** arrangement of components of the match, its input impedance is identical to that of the actual circuit. Furthermore, representation of the match network in this “ladder” form simplifies plotting the progression of the impedance match on a Smith Chart.

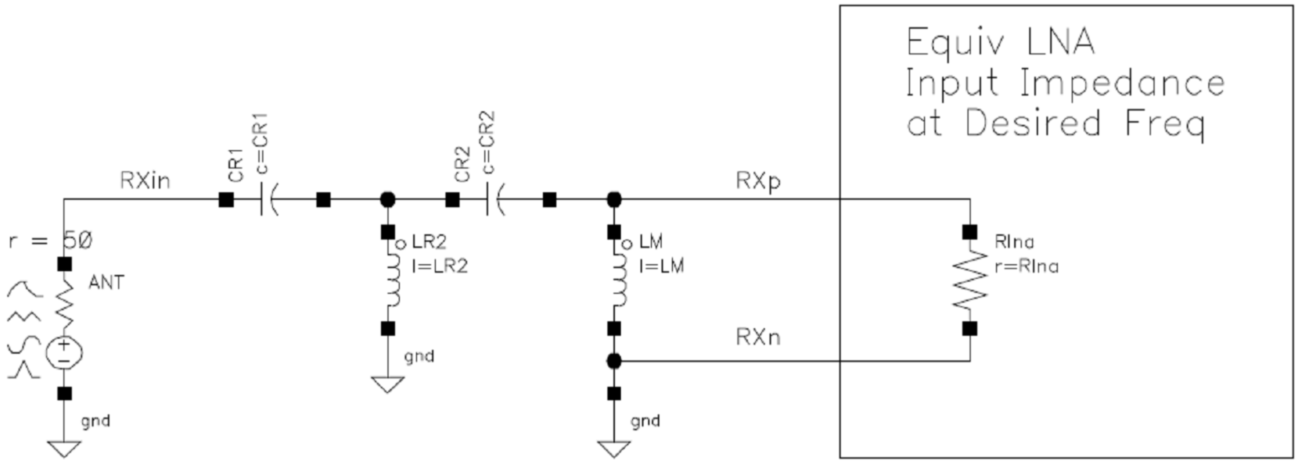

Figure 13. 4-Element Match (re-drawn in ladder form)

Equation 8 may be manipulated as follows:

$$X_{LR2} = \omega_{RF}LR2 = \sqrt{Re(Z_{ANT}) \times R_{LNA}} = \sqrt{50\Omega \times R_{LNA}}$$

Equation 14.

This equation states that the inductive reactance of LR2 is equal to the geometric mean of the antenna source impedance (e.g., 50 Ω) and the real part of the LNA input impedance R_{LNA}. Equation 9 states that the reactance of CR2 is equal to the reactance of LR2 (i.e., together they resonate at the desired frequency of operation). Equation 12 then further indicates that the matching inductor L_M is equal to 2 x LR2, while indicates that CR1 is equal to 2 x CR2.

It is informative to consider the Q-factors formed by R_{LNA} in parallel with L_M, and by CR1 in series with R_{ANT}.

$$Q_{LNA} = \frac{R_{LNA}}{X_{LM}} = \frac{R_{LNA}}{\omega_{RF}L_M} = \frac{R_{LNA}}{2\omega_{RF}L_{R2}} = \frac{R_{LNA}}{2 \times \sqrt{50\Omega \times R_{LNA}}} = \left(\frac{1}{2}\right)\sqrt{\frac{R_{LNA}}{50\Omega}}$$

Equation 15.

$$Q_{ANT} = \frac{X_{CR1}}{R_{ANT}} = \frac{X_{CR2}}{2 \times R_{ANT}} = \frac{X_{LR2}}{2 \times R_{ANT}} = \frac{\sqrt{50\Omega \times R_{LNA}}}{2 \times 50\Omega} = \left(\frac{1}{2}\right)\sqrt{\frac{R_{LNA}}{50\Omega}}$$

Equation 16.

It is well known that the locus of all impedance points with the same Q-factor describes an ellipse on a Smith Chart. These last two equations indicate that the impedance at two of the internal nodes within the 4-element match share the same Q-factor and thus fall upon the same ellipse (constant-Q curve) on a Smith Chart. This is illustrated in the impedance progression plot of Figure 14.

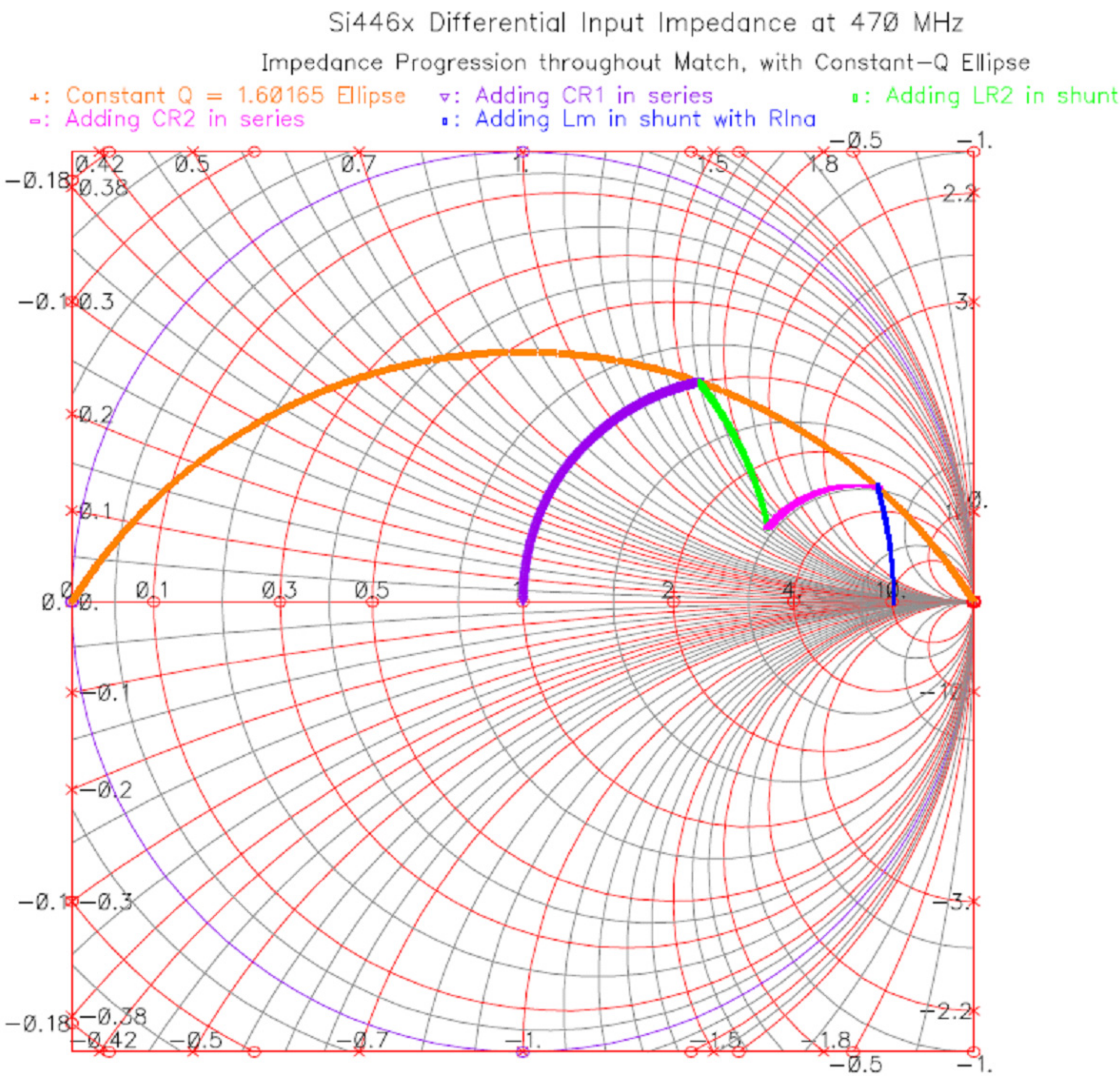

Figure 14. Impedance Match Progression Plot (with constant-Q Ellipse)

In this plot, the impedance path on the Smith Chart is traced as each successive component in the match is added. The plot begins on the purely-real axis at $Z = R_{LNA} + j0$. The dark blue curve describes the change in impedance as the matching inductor L_M is added in parallel with R_{LNA}, the pink curve describes subsequently adding on series capacitor CR2, and so on. Using the component values in the design example at 470 MHz, the calculated LNA Q value is ~1.6 as shown in Equation 17.

$$Q_{LNA} = \left(\frac{1}{2}\right)\sqrt{\frac{R_{LNA}}{50\Omega}} = \left(\frac{1}{2}\right)\sqrt{\frac{513\Omega}{50\Omega}} = 1.60165$$

Equation 17.

As predicted in the earlier discussion, it is found that the endpoints of two of the segments in this impedance progression plot fall directly upon the Q = 1.60165 elliptical curve.

This then suggests a graphical solution to the problem of constructing a 4-element match network:

- Plot both R_{LNA} and R_{ANT} on the Smith Chart
- Calculate Q = (1/2) * SQRT(R_{LNA} / R_{ANT})
- Construct a constant-Q ellipse on the Smith Chart with this value of Q
- Plot the intersection of the constant-R_{ANT} impedance circle (e.g., 50 circle) with this ellipse
- Plot the intersection of the constant-G_{LNA} admittance circle with this ellipse
- These four points (R_{ANT}, R_{LNA}, two Q-intersection points) describe four of the five segment endpoints of the impedance progression plot
- The fifth endpoint is graphically obtained from the segments (series CR2, shunt LR2) that must be traversed to connect the two constant-Q points.

The corresponding component values are readily obtained by denormalizing each shunt or series path traversed on the Smith Chart.

Note: Using the equations is easier.

4.2.7. Summary Tables of 4-Element Match Network Component Values vs. Frequency

Some users may not be greatly interested in the theoretical development of the matching network, but are concerned only with quickly obtaining a set of component values for a given desired frequency of operation. For those users, the resulting calculated component values for the 4-element match network for multiple frequencies across the operating range of the Si446x/Si4362 RFIC are summarized in Table 4. The calculations in Table 4 assume the antenna source impedance is Z_{ANT} = 50 + j0 Ω.

Table 4. 4-Element Match Network Component Values (Calculated)

Freq	RLNA	CLNA	CR1	LR1	CR2	LR2
140 MHz	545 Ω	1.02 pF	13.77 pF	289.69 nH	6.89 pF	187.69 nH
169 MHz	536 Ω	0.98 pF	11.51 pF	230.20 nH	5.75 pF	154.15 nH
200 MHz	530 Ω	0.96 pF	9.78 pF	186.19 nH	4.89 pF	129.55 nH
250 MHz	520 Ω	0.94 pF	7.90 pF	138.84 nH	3.95 pF	102.63 nH
300 MHz	512 Ω	0.95 pF	6.63 pF	108.07 nH	3.32 pF	84.88 nH
315 MHz	509 Ω	0.95 pF	6.34 pF	100.91 nH	3.17 pF	80.58 nH
350 MHz	499 Ω	0.95 pF	5.76 pF	86.58 nH	2.88 pF	71.85 nH
390 MHz	491 Ω	0.96 pF	5.21 pF	73.63 nH	2.60 pF	63.96 nH
400 MHz	488 Ω	0.96 pF	5.09 pF	70.77 nH	2.55 pF	62.15 nH
434 MHz	480 Ω	0.97 pF	4.73 pF	62.31 nH	2.37 pF	56.82 nH
470 MHz	474 Ω	0.99 pF	4.40 pF	54.87 nH	2.20 pF	52.13 nH

Table 4. 4-Element Match Network Component Values (Calculated) (Continued)

Freq	RLNA	CLNA	CR1	LR1	CR2	LR2
500 MHz	467 Ω	1.00 pF	4.16 pF	49.72 nH	2.08 pF	48.66 nH
550 MHz	460 Ω	1.01 pF	3.82 pF	42.57 nH	1.91 pF	43.87 nH
600 MHz	451 Ω	1.02 pF	3.53 pF	36.93 nH	1.77 pF	39.85 nH
650 MHz	437 Ω	1.04 pF	3.31 pF	32.16 nH	1.66 pF	36.18 nH
700 MHz	424 Ω	1.05 pF	3.12 pF	28.23 nH	1.56 pF	33.09 nH
750 MHz	414 Ω	1.07 pF	2.95 pF	24.97 nH	1.48 pF	30.52 nH
800 MHz	402 Ω	1.08 pF	2.81 pF	22.27 nH	1.40 pF	28.22 nH
850 MHz	387 Ω	1.09 pF	2.69 pF	19.93 nH	1.35 pF	26.03 nH
868 MHz	380 Ω	1.09 pF	2.66 pF	19.17 nH	1.33 pF	25.27 nH
900 MHz	362 Ω	1.10 pF	2.63 pF	17.78 nH	1.31 pF	23.80 nH
915 MHz	354 Ω	1.11 pF	2.62 pF	17.16 nH	1.31 pF	23.14 nH
955 MHz	327 Ω	1.14 pF	2.61 pF	15.47 nH	1.30 pF	21.32 nH
960 MHz	325 Ω	1.15 pF	2.60 pF	15.30 nH	1.30 pF	21.15 nH

Similar to the 3-element match network, it will almost certainly be necessary to “tweak” the final matching values for a specific application and board layout due to parasitic effects of PCB traces and non-ideal discrete components. The above component values should be used as starting points, and the values modified slightly to zero-in on the best match to the antenna source impedance (e.g., 50 Ω), and the best RX sensitivity.

Silicon Laboratories has empirically determined the optimum matching network values at a variety of frequencies, using RF Test Boards designed by (and available from) Silicon Laboratories. Wire-wound inductors (Murata LQW15A 0402-series and LQW18A 0603-series) were used in all of these matching examples. Multi-layer inductors (such as Murata LQG15HS 0402-series) may also be used; however, the insertion loss of the match may be increased slightly due to the higher loss of these inductors. By comparing the empirical values of Table 5 with the calculated values of Table 4, the reader may observe that the component values are in close agreement at frequencies below 500 MHz. However, somewhat larger deviations in value occur at higher frequencies, primarily due to the unmodeled parasitic effects of the PCB traces and discrete components. As mentioned previously, the calculated matching component values of Table 4 should be used as a starting point and adjusted for best performance.

Table 5. 4-Element Match Network Component Values (Optimized)

Freq	R_{LNA}	C_{LNA}	CR1	LR1	CR2	LR2
169 MHz	536 Ω	0.98 pF	12.0 pF	220 nH	6.2 pF	150 nH
315 MHz	509 Ω	0.95 pF	6.2 pF	100 nH	3.0 pF	82 nH
390 MHz	491 Ω	0.96 pF	5.1 pF	75 nH	2.4 pF	62 nH
434 MHz	480 Ω	0.97 pF	4.7 pF	62 nH	2.2 pF	56 nH
470 MHz	474 Ω	0.99 pF	3.9 pF	56 nH	2.2 pF	51 nH
868 MHz	380 Ω	1.09 pF	3.0 pF	20 nH	1.0 pF	24 nH
915 MHz	354 Ω	1.11 pF	3.0 pF	18 nH	1.0 pF	22 nH
955 MHz	325 Ω	1.15 pF	2.4 pF	18 nH	0.9 pF	22 nH

A 4-element RX match at 470 MHz was built and tested, using CR1=3.9pF, LR1=56nH, CR2=2.2pF, and LR2=51nH. The measured input impedance (S11) is shown in Figure 15.

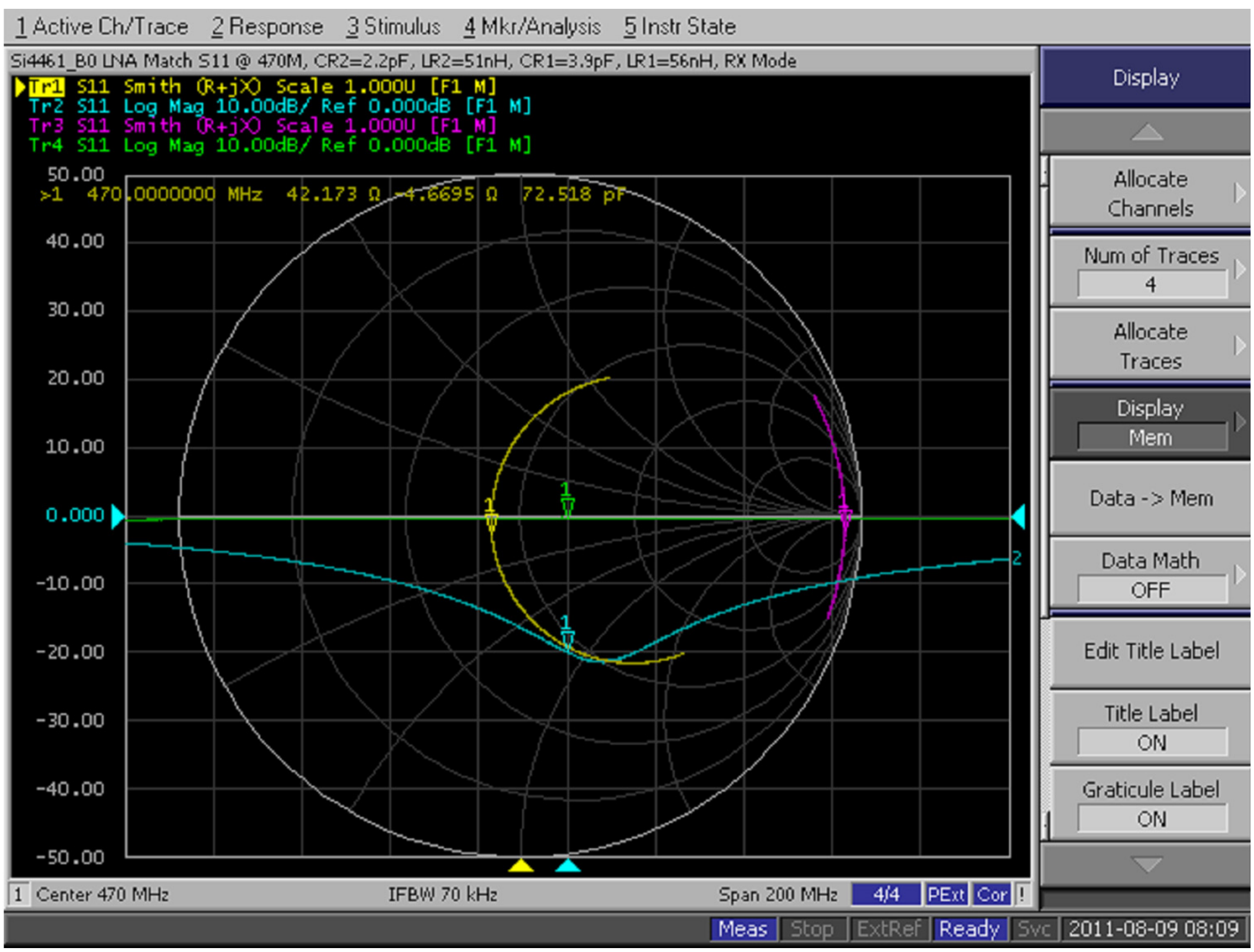

Figure 15. Input Impedance of 4-Element Match at 470 MHz

4.2.8. Use of 4-Element Match Network in Direct Tie Board Configurations

Silicon Laboratories has developed a referenced design board configuration in which the TX and RX paths are tied directly together at a common point without the use of an RF switch. This board configuration is referred to as a Direct Tie board configuration. Careful design procedure must be followed to ensure that the RX input circuitry does not load down the TX output path while in TX mode, and that the TX output circuitry does not degrade receive performance while in RX mode. This design procedure requires the ***mandatory*** use of the 4-element RX match topology; it is not possible to construct a Direct Tie match with use of the 3-element RX match topology.

The RX input circuitry of the Si446x/Si4362 chip contains a set of switches that aids in isolation of the TX and RX functions. This set of switches is implemented internally as shown in Figure 16.

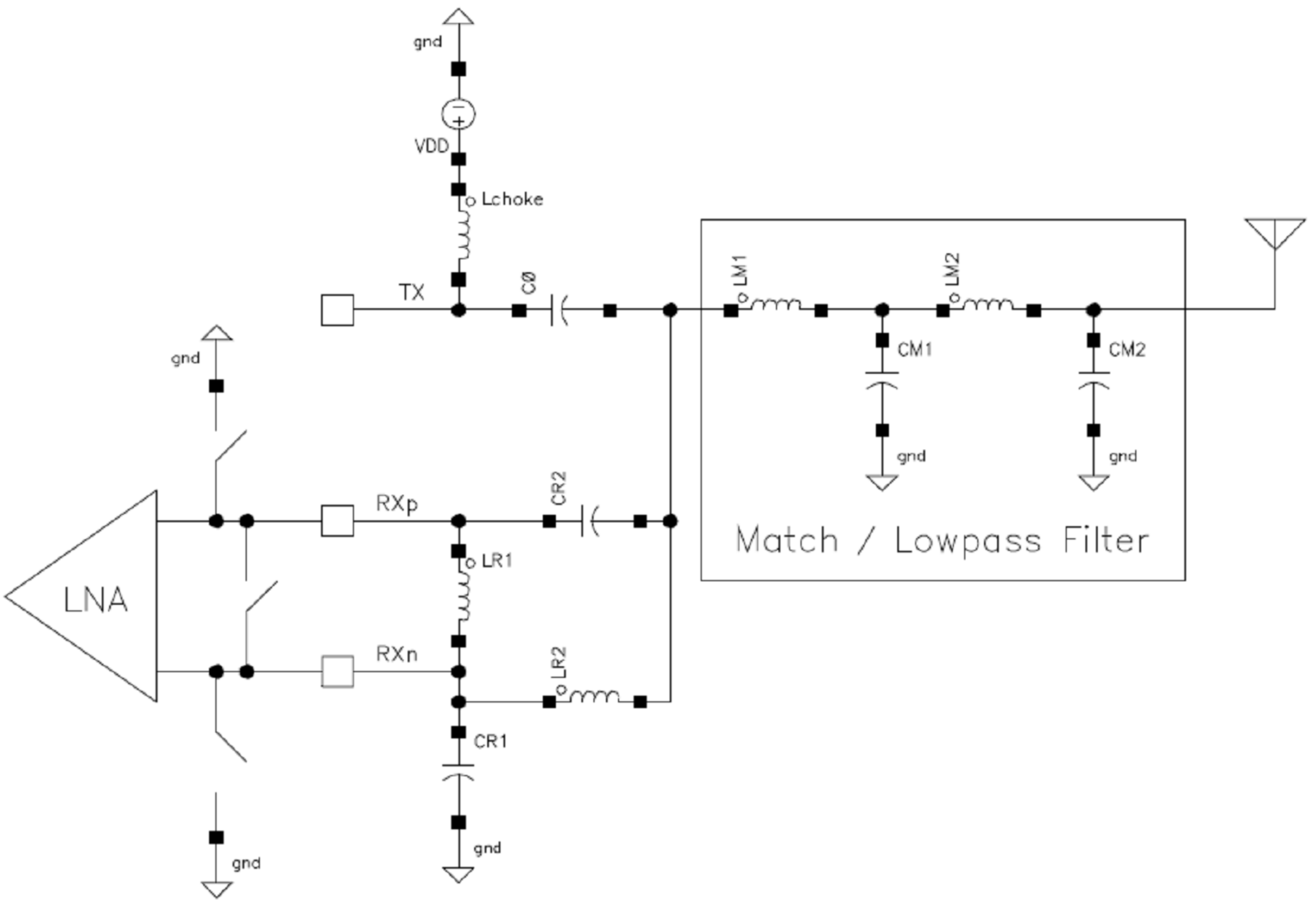

Figure 16. RX Input Switches for Direct Tie Operation

These three switches are activated and closed simultaneously upon entering TX mode; the switches remain open in all other modes, including RX mode. Closing these switches during TX mode effectively shorts the RXp and RXn input pins together and also shorts them to GND. The effective circuit may be re-drawn as shown in Figure 17. Inductor LR2 and capacitor CR2 have effectively been placed in parallel by the closure of the switches, and are connected to GND. If the values of these components are chosen for resonance at the desired operating frequency, a very high impedance is presented to the TX path resulting in very little degradation in TX output power. Also, by shorting the input pins of the LNA together and simultaneously to GND, the LNA is protected from the large signal swing of the TX signal. This feature allows connection of the TX path to the RX path without damage to the LNA.

Further information regarding the design of a Direct Tie match may be found in application note “AN627: Si4460/61/67 Low-Power PA Matching”.

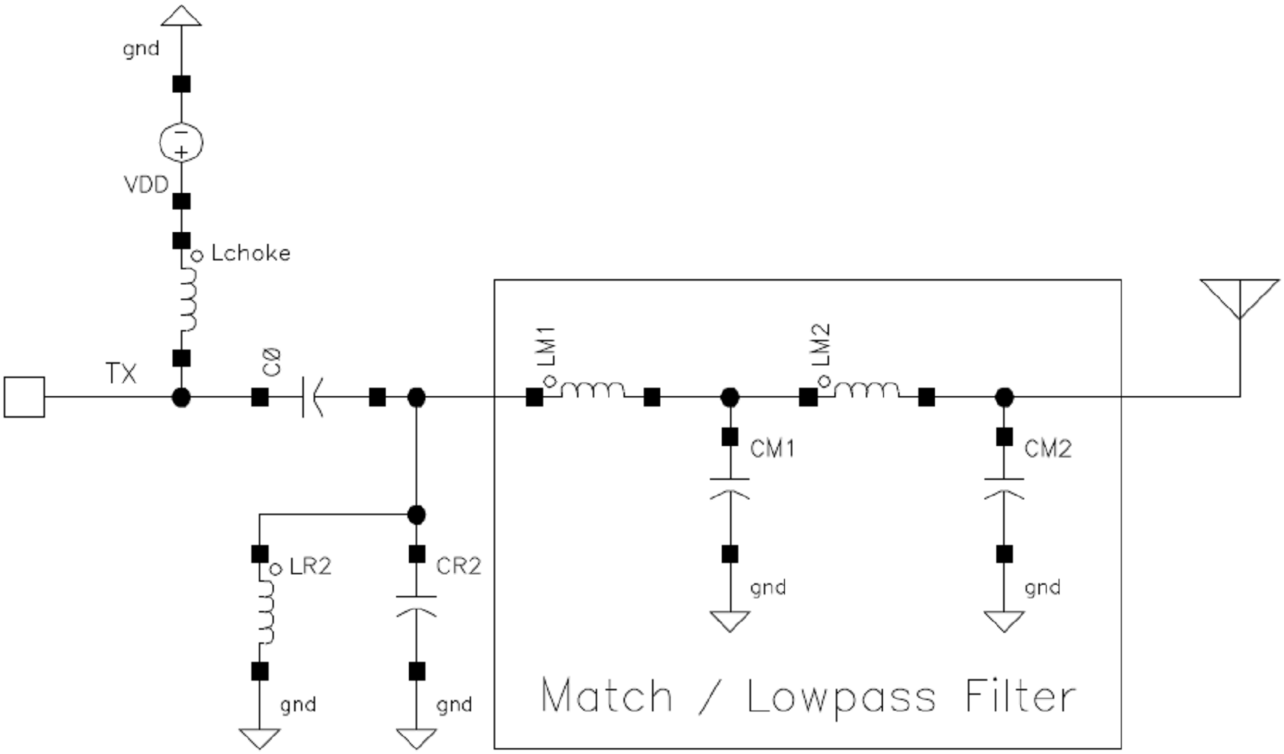

Figure 17. Effective Direct Tie Circuit in TX Mode

Document Change List

Revision 0.1 to Revision 0.2

- Replaced Si446x with Si446x/Si4362 throughout.
- Updated "1. Introduction" on page 1.

Revision 0.2 to Revision 0.3

- Clarified that RXp and RXn pins are interchangeable.

Revision 0.3 to Revision 0.4

- C0, C1, C2 added to B0 and B1 on page 1.
- Si4467 was added to Si4460/61.
- B0 was removed from Si4461_B0 on page 4.

NOTES:

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