



An RF205x Family Application Note

Matching Circuits and Baluns

RFMD Multi-Market Products Group

REVISION HISTORY

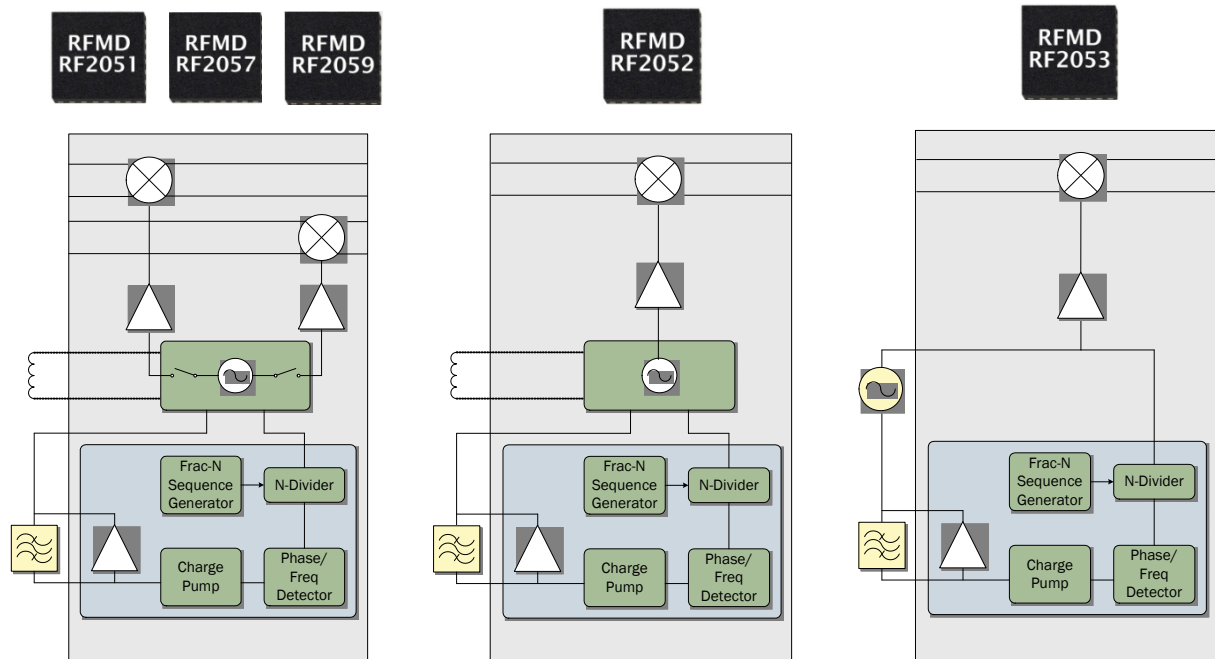
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Version 1.0	June 2008	Initial Draft	C.L-S
Version 2.0	September 2009	Updated. Added details on mixer port impedances in Section 2. Revised Section 5 on use of lumped element baluns. Section 6 added on further techniques for output matching. Added references in Section 7.	C.L-S

1. INTRODUCTION

The RF2051 is a dual monolithic mixer circuit with integrated frequency generation, a fractional-N synthesizer and VCO. The mixers are wideband, covering the frequency range 30MHz to 2500MHz on both input and output. This document also applies to other members of the RF205x series, all being variants with a single or dual mixer.

The mixers are double balanced Gilbert cells hence all of the ports are required to be balanced or differential. The mixer LO port is driven internally from balanced buffer amplifiers. For many applications the mixer input and outputs may be connected directly, via suitable matching, to balanced components. These may be SAW filters, LNAs, or IF amplifiers. For applications where the mixer will be connected to unbalanced, or single-ended, components an external balun circuit will be required. As well as the balanced to unbalanced conversion, the balun may also perform some impedance transformation, or matching, from the 50Ω or 75Ω system characteristic impedance.

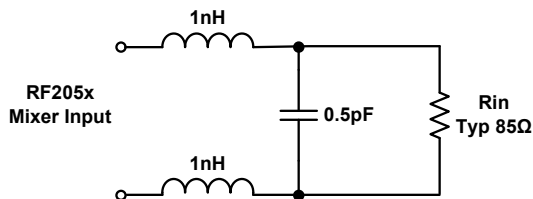
This document describes the implementation of baluns and matching circuits for the mixer ports of the RF205x family of devices. The most suitable implementation will depend on the application and frequency plan. The trade offs between different implementations are discussed.



2. THE RF2051 MIXER PORTS

2.1 MIXER INPUTS

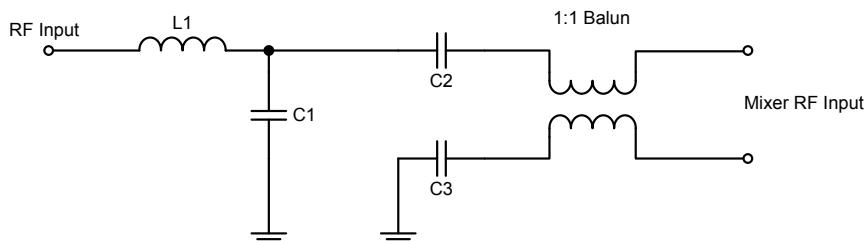
The mixer has a broadband common gate input. The input impedance is dominated by the resistance set by the mixer $1/g_m$ term, which is inversely proportional to the mixer current setting. There is also some shunt capacitance at the mixer input, the capacitance of the device gates. At higher frequencies there are parasitic impedances that become more significant, the bondwire inductance along with package and PCB stray capacitance. The model below gives a good approximation of the mixer input impedance.



The resistance term R_{IN} will be approximately 85Ω at the default mixer current setting (100). The following table shows how the resistance varies with mixer current setting:

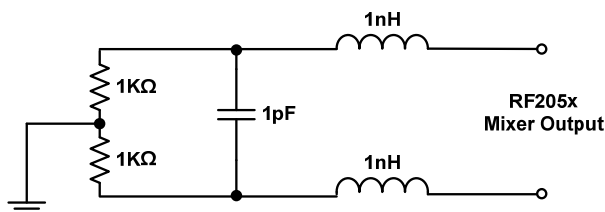
Mixer Current Setting	001	010	011	100	101
Mixer Current (mA)	15	20	25	30	35
Typical R_{IN} (Ω)	135.0	105.0	90.0	85.0	77.5

On the mixer input a balun and matching circuitry is required to convert from a 50Ω unbalanced source, to the complex balanced impedance. AC coupling is also required. This could take the form shown below:



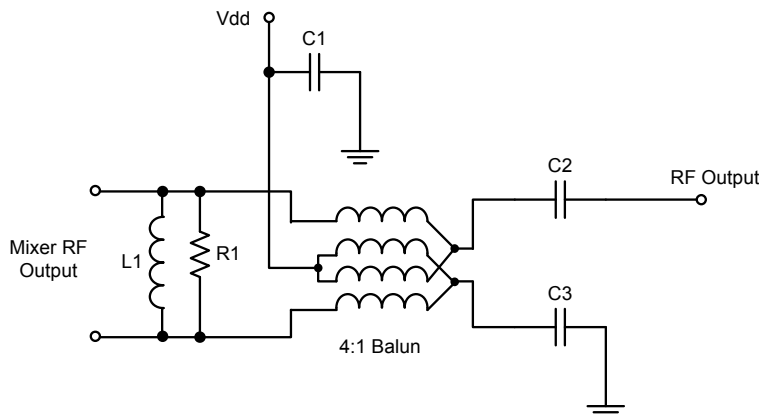
2.2 MIXER OUTPUTS

The following is a model showing the typical impedance of the RF205x differential mixer output. The mixer output is high impedance, a resistance of $2K\Omega$ to $3K\Omega$ in parallel with some capacitance. The bond wires each have inductance of about $1nH$. At higher frequencies the bond wire inductance and stray capacitance become more significant. The stray capacitance rolls off the conversion gain versus output frequency.



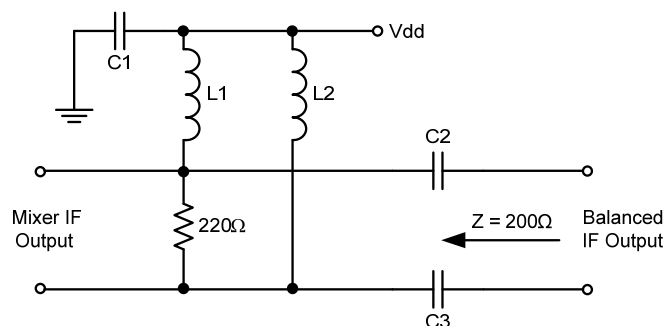
The mixer output does not need a typical conjugate match; it just needs to see a resistive load. The mixer output sources constant current, so a higher load resistance will give higher output voltage and gain. A shunt inductor can be used to resonate with the mixer output capacitance at the frequency of interest to improve the conversion gain. This inductor may not be required at lower frequencies where the impedance of the output capacitance is less significant.

The mixer output has been designed to drive a load resistance between 50Ω and 500Ω. Higher load resistance means higher voltage (and power) at the output, and so typically a 4:1 or 8:1 balun is used. The balun performs the balanced to unbalanced conversion required, as well as transforming the 50Ω unbalanced load to the desired 200Ω or 400Ω at the mixer output. The balun can also provide the DC supply voltage required on the mixer output pins. AC coupling will be required on the balun outputs. Typical circuitry for the mixer output is shown below:



The impedance (S_{22}) looking back from the 50Ω output will consist of the high mixer output resistance transformed through the balun, hence a large mismatch. A resistor (R1) placed across the mixer output of 220Ω for a 4:1 balun, or 510Ω for an 8:1 balun, will improve the output impedance. This will approximately halve the output voltage, and half of the power will be dissipated in the resistor, reducing conversion gain by around 6dB. A shunt inductance (L1) across the mixer output can be used to resonate with the output capacitance at the operating frequency.

To match the mixer output to a typical 200Ω balanced IF circuit, the following circuit could be used. The inductors L1 and L2 are used to supply the mixer from Vdd, and their value is selected so that their sum resonates with the mixer output capacitance at the IF frequency. The 220Ω shunt resistor in parallel with the mixer output resistance sets the impedance looking back into the mixer output to 200Ω. AC coupling is provided by C2 and C3, and power supply decoupling is provided by C1. The value of these capacitors needs to be chosen carefully dependant on the application frequency plan.



3. WIDEBAND TRANSMISSION LINE BALUNS

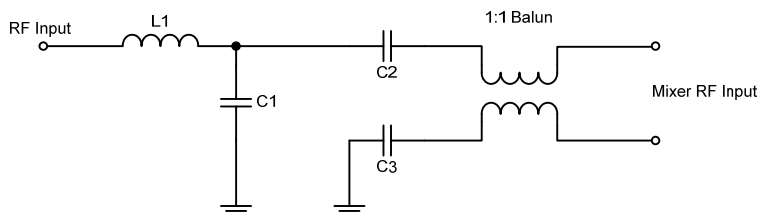
The RF205x family evaluation boards incorporate transmission line transformer baluns. This is to enable wideband evaluation and characterization of the device.

Wideband baluns are available from a number of manufacturers such as RFMD, Mini Circuits, M/A-Com, Synergy Microwave Corp and others.

These parts are ideal for broadband applications. They have the advantage that they give a good balanced load on the mixer ports over a wide frequency range, ensuring good LO and RF rejection at the output port. They can also be matched simply for narrowband applications, however depending on the application's requirements an optimized narrowband balun and matching (as described in Sections 4 and 5) could provide a better cost, size and performance trade-off.

3.1 MIXER INPUTS

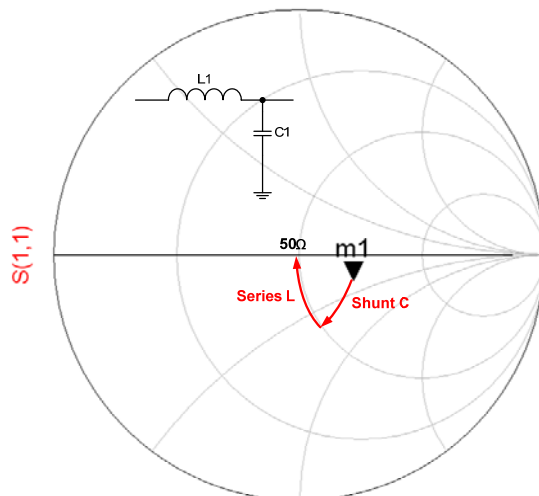
The following circuit could be used on the mixer inputs for a wideband application. This is the configuration on the RF205x evaluation boards.



The 1:1 balun is a Mini-Circuits TC1-1-13M transmission line transformer, covering 4.5MHz to 3000MHz.

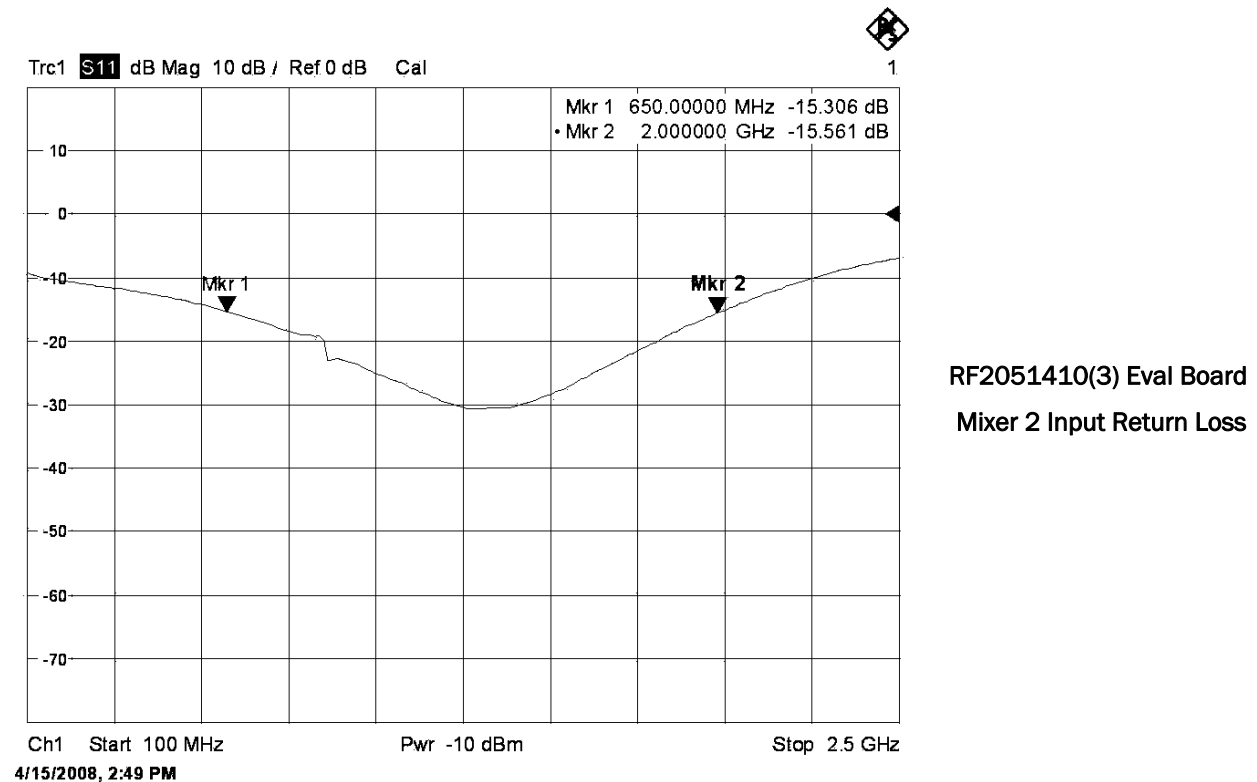
The value of AC coupling capacitors C2 and C3 should be chosen carefully to give good performance over the desired frequency range; 100pF was chosen for the evaluation boards.

The L-C matching circuit can be added to improve matching at frequencies of interest, as shown below. Above 1GHz a different matching topology may be required, as stray impedances take increasing effect.



Below is an input return loss plot for the RF2051 evaluation board taken at the SMA connector, with the default mixer current setting (4/30mA). The component values were as follows, with no matching.

Balun	TC1-1-13M
L1	0Ω Link
C2, C3	100pF
C1	No Fit



It can be seen that this configuration gives a good wideband input return loss, better than 15dB from around 650MHz to 2000MHz.

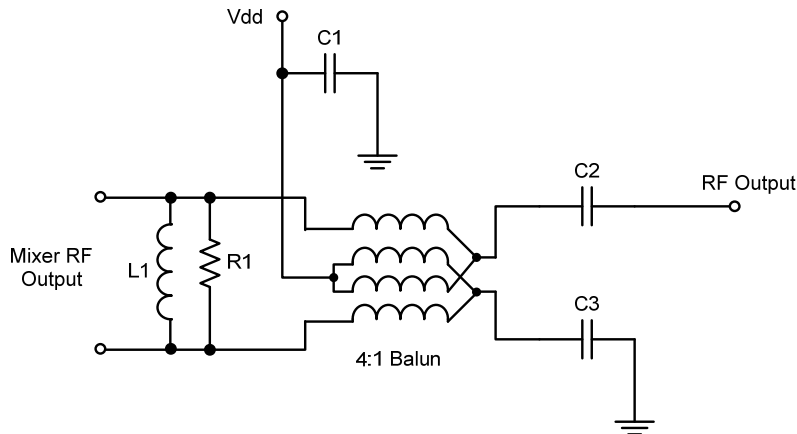
To improve the low frequency return loss the AC coupling capacitors could be increased to 1nF and L-C matching could be added. For example at 140MHz matching of L1 47nH and C1 8.2pF was required.

Above 2000MHz the balun performance starts to roll off, and the PCB and device parasitic impedances become more significant. Matching is hence required above 2000MHz. A different configuration from the L-C transformer could be required, dependant on the frequency of interest and the PCB layout.

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3.2 MIXER OUTPUTS

The following circuit could be used on the mixer outputs for a wideband application. This is the configuration on the RF205x evaluation boards.



The 4:1 balun is a Mini-Circuits TC4-19+ transmission line transformer, covering 10MHz to 1900MHz. For higher output frequencies the Mini-Circuits TC4-25+ could be used, covering 500MHz to 2500MHz. The secondary centre tap is used to provide the mixer DC supply.

The value of AC coupling capacitors C2 and C3, and decoupling capacitor C1, should be chosen carefully to give good performance over the desired frequency range; 100pF was chosen for the evaluation boards.

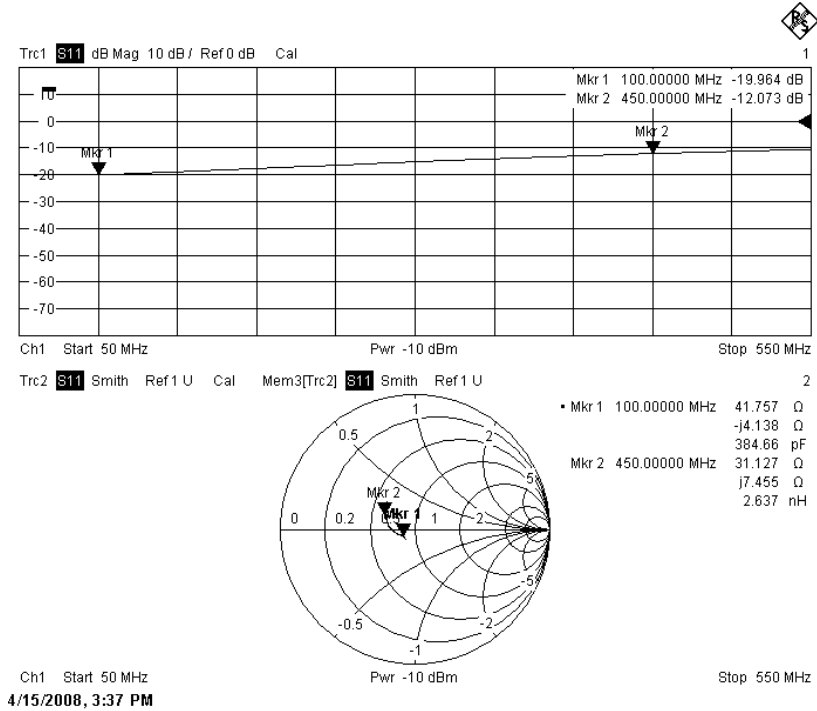
On the evaluation boards R1 and L1 have not been fitted. These components can be used to improve the output return loss at specific frequencies, if required.

A resistor R1 of 220Ω can be fitted across the mixer output to improve the real impedance looking back into the output port. However this will add loss. Inductor L1 can be added to improve matching at frequencies of interest, by resonating with the mixer output capacitance.

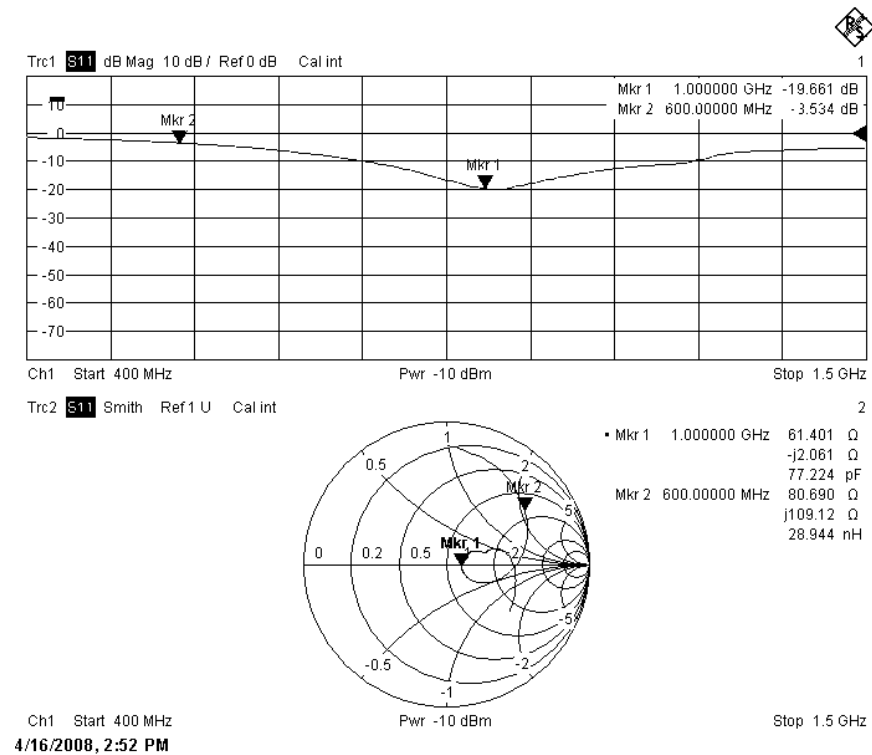
The following are component values that were found to optimise the output at specific frequencies.

Output Frequency	100MHz	500MHz	1000MHz
Balun	TC4-19+	TC4-25+	TC4-25+
R1	220Ω	220Ω	220Ω
C1, C2, C3	1nF	100pF	100pF
L1	No Fit	No Fit	33nH

Plots of the output return loss matched at 100MHz and 1 GHz are shown below.



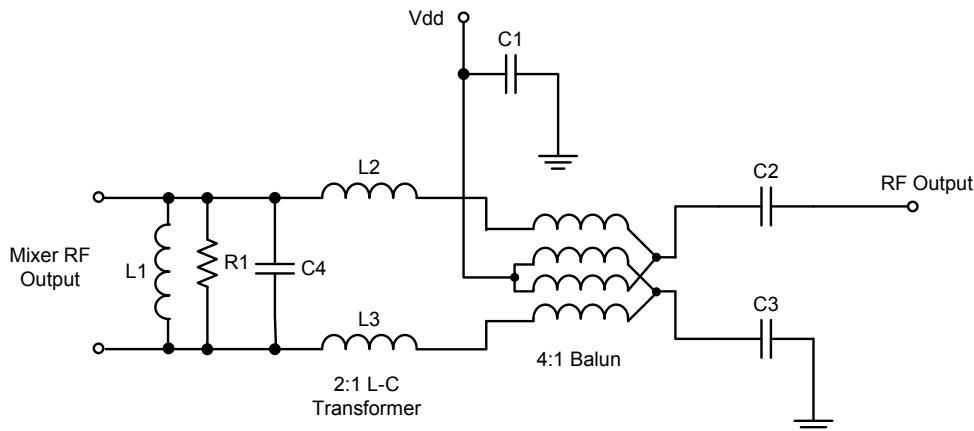
RF2051410(3) Eval Board
Mixer 1 Output Return Loss
Matched for 100MHz



RF2051410(3) Eval Board
Mixer 1 Output Return Loss
Matched for 1GHz

The conversion gain could be increased by using an 8:1 balun or even a 16:1 balun; however wideband devices are not available for the higher impedance ratios. For example Mini-Circuits TC8-1+ is an 8:1 balun, covering from 2MHz to 500MHz.

A 2:1 lumped impedance transformer can be used with a 4:1 balun to give a total transformation of 8:1. This could be an L-C transformer, a capacitive transformer, or even a tapped capacitor resonator. This approach also limits bandwidth. Below is an example schematic for a 4:1 balun transformer with an added 2:1 L-C transformer.



Note that L2 and L3 conveniently carry the mixer DC supply to the output pins. In this case R1 would be 510Ω, giving 400Ω in parallel with the mixer output resistance. The values of the L-C components in the 2:1 transformer, and the parallel inductor L1, need to be adjusted to give the best output match combined with the mixer output capacitance.

3.3 RECOMMENDED WIDEBAND TRANSFORMER BALUNS

The following are wideband transformer baluns recommended for use with the RF205x family mixers. These parts are all pin compatible.

	Frequency Range	Ω Ratio	Mini-Circuits Part No.	RFMD Part No.
Mixer Input	5MHz to 3000MHz	1:1	TC1-1-13M ***	RFXF9503
Mixer Output	10MHz to 1900MHz	4:1	TC4-19+ ***	RFXF6553
	500MHz to 2500MHz	4:1	TC4-25+	RFXF8553
	2MHz to 500MHz	8:1	TC8-1+ / TC8-1G2+	---

*** These are the baluns fitted on the standard RF205x evaluation boards.

4. NARROWBAND CERAMIC BALUNS

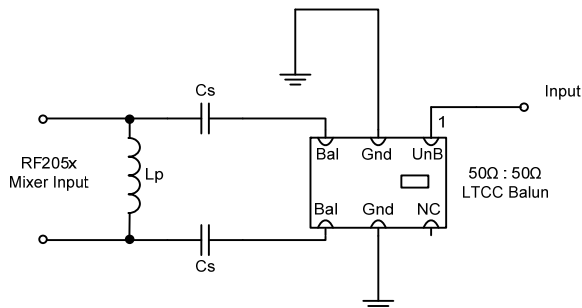
Narrowband ceramic baluns, LTCC, are available from several manufacturers including Murata (LDB series), TDK, Anaren, Wurth Electronik, and Johanson Technology. These are mainly available for the frequency bands that cover high volume applications, such as the cellular bands and the 2.4GHz ISM band. The most common package size is currently 0805. LTCC baluns with impedance ratios of 50Ω:50Ω and 50Ω:200Ω are available that are suitable for use with the RF205x devices.

These parts are ideal for high frequency narrowband applications, provided parts can be obtained for the required frequency range. Their advantages:

- Low cost in high volumes
- Small size
- Low loss performance

4.1 MIXER INPUTS

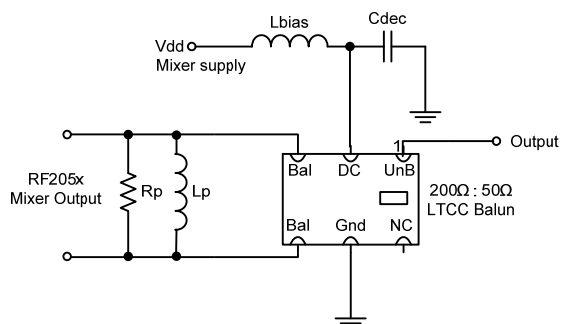
A 50Ω:50Ω LTCC balun can be used on the RF205x mixer input, and can be easily matched as shown below. This matching configuration gives the lowest component count since the series capacitors in the matching circuit also provide AC coupling.



Since the mixer input impedance real part is around 85Ω, dependant on frequency and current setting, a 100Ω:100Ω balun could be used and the matching circuit changed accordingly.

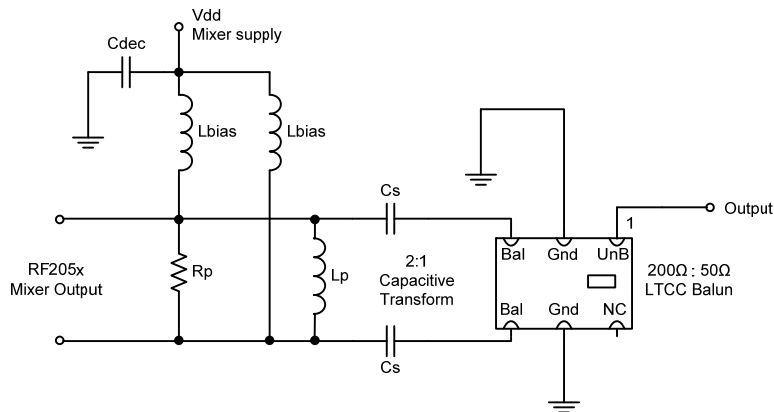
4.2 MIXER OUTPUTS

The simplest configuration would be to use a 50Ω:200Ω LTCC balun on the mixer output, configured with a DC feed to supply the mixer via the output pins. Again a parallel resistor and inductor can be used to improve the output match.



To improve the circuit gain, the mixer output load could be increased to 400Ω using an extra 2:1 transformation. Shown below is an example with a capacitive transformer. An L-C transformer could also be used, as shown above with the transformer type balun in Section 3.2.

The two capacitors, Cs, act as the capacitive transformer and also provide AC coupling. The mixer is supplied via the two chokes, Lbias, connected to the output pins. The parallel resistor Rp of 510Ω provides a good output resistive match. The parallel inductor, Lp, is used to resonate with the mixer output capacitance and the transformer reactance. The bias inductors will also have an effect on the resonant circuit. In practice the value of Lp can be selected to get close to the desired resonant frequency, then the value of the Lbias inductors can be varied to fine step to the exact frequency.



The 200Ω:400Ω capacitive transformer can be designed as follows. For each arm of the differential circuit;

$$Z_{in} = 200\Omega / 2 = 100\Omega$$

$$Z_{out} = 400\Omega / 2 = 200\Omega$$

Using a series to parallel conversion:

$$Z_{cap} = \sqrt{Z_{in} \cdot Z_{out} - Z_{in}^2}$$

And calculating the capacitance at the centre frequency:

$$C_s = \frac{1}{2 \cdot \pi \cdot F_o \cdot Z_{cap}}$$

To achieve good performance and a tuned match consistently in high volume production, careful consideration has to be given to variation in component values due to manufacturing tolerances.

Note that any narrowband solution will have the disadvantage that the mixer ports will not have a balanced load across all frequencies. This could mean that the LO and RF rejection at the output port are not as good as for a wideband transformer.

5. NARROWBAND LUMPED ELEMENT BALUNS

Narrowband baluns can be designed using lumped elements. They have several advantages:

- Low cost
- Small size: for example, four 0402 components

One of the difficulties with lumped element baluns is in implementing designs with standard component values. At higher frequencies and especially with higher impedance transforms the small component values required and the stray PCB parasitic components make design problematic.

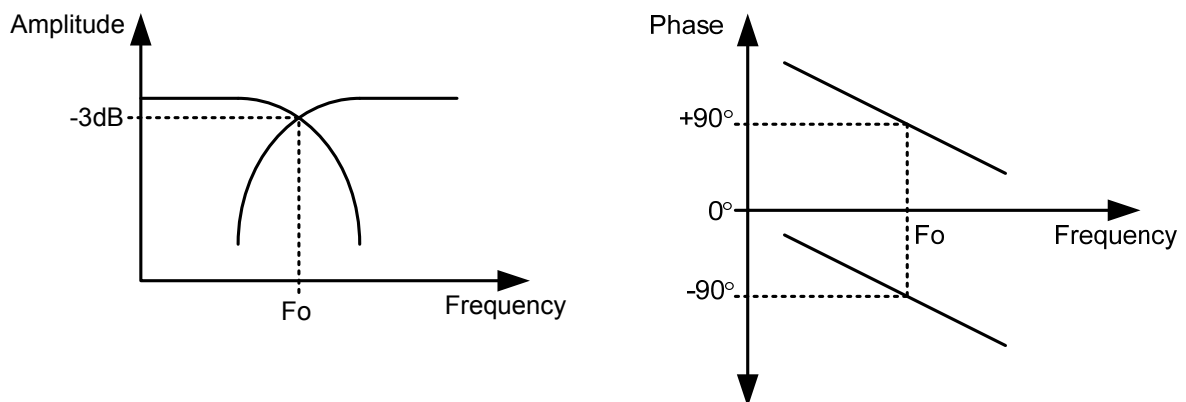
The main disadvantage is that the lumped element approach does not present the mixer port with true balanced impedance across all frequencies. The mixer will be unbalanced outside of the narrow operating bandwidth. This could mean that the LO and RF rejection at the output port are not as good as for a wideband transformer. In addition the lumped element balun does not offer good common mode suppression over a wide bandwidth, and the mixer noise figure and levels of output spurious will be increased. For this reason, use of lumped element baluns with the RF205x mixers is not generally recommended.

5.1 BACKGROUND

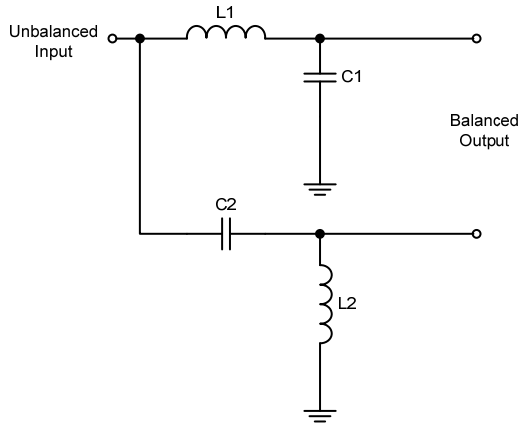
The simplest form of lumped element balun uses two L-C filter sections to provide 90° lead and lag phase shifts. The signals on the two balanced conductors are inherently 180° apart; each conductor has equal current flowing in opposing directions.

The fact that the two sections are formed with high and low pass filters highlights the problem with this balun topology; amplitude balance is only achieved at the centre frequency. Outside of the operating bandwidth the mixer will be presented with a large amplitude imbalance, degrading performance.

Typical phase and amplitude responses for the two sections of the balun are shown below:



The equations shown below are used to calculate the component values required to implement a balun with the desired impedance transform at a given centre frequency:



$$L1 = L2 = \frac{\sqrt{Z_u \cdot Z_b}}{2 \cdot \pi \cdot F_o}$$

$$C1 = C2 = \frac{1}{2 \cdot \pi \cdot F_o \cdot \sqrt{Z_u \cdot Z_b}}$$

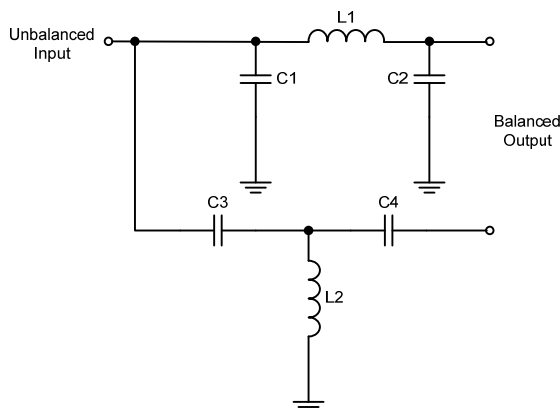
Where:

Z_u = Characteristic impedance of unbalanced port, Ω

Z_b = Characteristic impedance of balanced port, Ω

F_o = Centre frequency, Hz

A slightly more complex form of lumped balun uses an extra element in each arm, as shown below. A Pi circuit is used to give the -90° phase shift, and a Tee circuit gives the $+90^\circ$ phase shift. Again a balun can be designed that can also provide an impedance transform. The component values are calculated using the same formula as above. Generally this balun gives better return loss at the centre frequency, but will be more narrowband. This can easily be explained as you are making the high and low pass filters roll off faster and the circuit Q is increased. The extra element however can give more flexibility in optimizing the design and performance with standard component values.

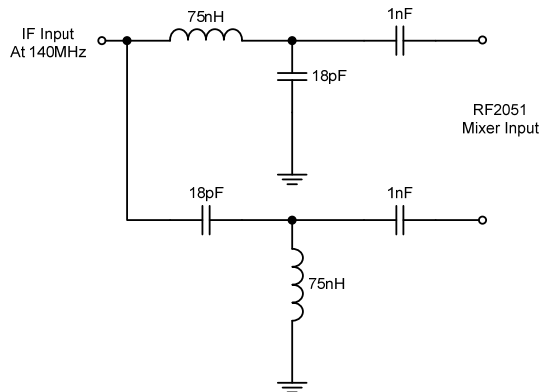


The lead and lag elements could also be achieved using quarter wavelength transmission lines in microstrip. This is not a very practical solution at these frequencies due to the physical size.

An alternative approach is to implement a lumped element version of a rat-race splitter. This is made up of a combination of low pass (Tee) and high pass (Pi) filter sections to achieve the 90° phase shifts between ports. This approach should give 20% bandwidth for a 50Ω to 100Ω balun. It has the same disadvantage of high amplitude imbalance out of band. Again, this splitter could be realized in microstrip, but would be physically large to implement especially at IF frequencies.

5.2 MIXER INPUTS

The following example shows a lumped balun designed for the mixer input at a centre frequency of 140MHz. The application is the IF input of an up-conversion mixer. These components realize the balun, and provide a match between the 50Ω line and the mixer input. The 1nF capacitors are for AC coupling the mixer input.



The following table shows balun components calculated for different frequencies, and rounded to the nearest standard component value. The conversion is 50Ω:85Ω, to match to the real part of the mixer input impedance.

50Ω:85Ω Balun Standard Component Values

Frequency	140MHz	500MHz	1000MHz	2000MHz	2500MHz
L1/L2 (nH)	75	22	10	5.1	3.9
C1/C2 (pF)	18	4.7	2.2	1.2	1.0

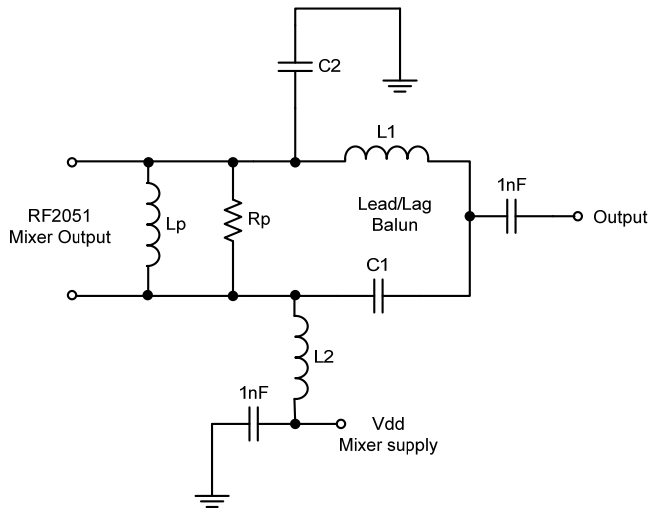
It can be seen that as frequency increases the component values reduce, and become harder to implement effectively. The PCB and device parasitic impedances become more significant at higher frequencies. For example the bondwire inductance on each mixer input pin of around 1nH becomes significant when compared to the required inductor value of 3.9nH at 2500MHz. Board layout is also critical at higher frequencies to minimize parasitic impedances. The lead/lag elements need to be tracked carefully to give equal lengths to ensure 90° phase shift on each arm of the balun. Again more significant as the frequency increases and wavelength decreases.

The AC coupling capacitor value must also be selected dependant on the application frequency.

5.3 MIXER OUTPUTS

The basic configuration for a lumped element balun for the mixer output is shown below. This example is for an output frequency of 140MHz. Note the mixer supply is routed via inductors L2 and Lp to the mixer pins. The unbalanced output is then AC coupled. Component values are shown for 4:1 and 8:1 baluns.

Matching Circuits and Baluns



Ratio	4:1	8:1
L1/L2	120nH	160nH
C1/C2	12pF	8.2pF
Rp	220Ω	510Ω

Note:

Resistor Rp chosen to give 200Ω / 400Ω in parallel with mixer output resistance.

Inductor Lp selected to resonate with mixer output capacitance.

The following table shows balun components calculated for different frequencies, and rounded to the nearest standard component value. The two impedance ratios are shown for comparison.

50Ω:200Ω Balun Standard Component Values

Frequency	140MHz	500MHz	1000MHz	2000MHz	2500MHz
L1/L2 (nH)	120	33	15	8.2	6.8
C1/C2 (pF)	12	3.3	1.6	0.8	0.6

50Ω:400Ω Balun Standard Component Values

Frequency	140MHz	500MHz	1000MHz	2000MHz	2500MHz
L1/L2 (nH)	160	43	22	12	10
C1/C2 (pF)	8.2	2.2	1.2	0.6	0.5

Again it can be seen that as frequency increases the component values reduce, even more so for the capacitor value as the impedance ratio increases. In particular the small capacitor values of less than 1pF required at 2000MHz and above are hard to implement, and stray capacitance becomes a problem.

The lumped element design, especially the 8:1, becomes more difficult to implement at the higher frequencies where PCB and device parasitic impedances become more significant. For example the bondwire inductance on each mixer output pin of around 1nH must be considered. Again the lead/lag elements need to be tracked carefully to give equal lengths to ensure 90° on each arm of the balun.

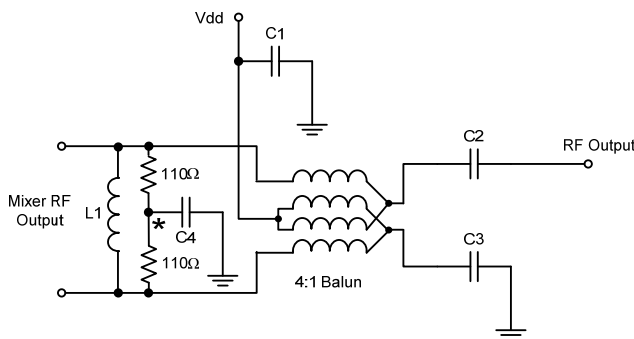
To avoid the problem of having to implement a balun with a high impedance ratio, a solution is to split the impedance transformation. For instance a 2:1 lumped element balun could be followed by a 2:1 matching transformer. Bear in mind that the matching network must route the DC supply to the mixer output pins, and have appropriate AC coupling. This solution will also have disadvantages. It will narrow the usable bandwidth, and it may be difficult to achieve good performance and a tuned match with variation in component values due to manufacturing tolerances.

6. FURTHER TECHNIQUES FOR MIXER OUTPUT MATCHING

The following techniques for matching the mixer output are aimed at increasing the level of common mode suppression in the output circuit. This will reduce any common mode noise and spurious at the mixer output, in particular high frequency harmonics.

6.1 WIDEBAND RESISTIVE OUTPUT MATCH

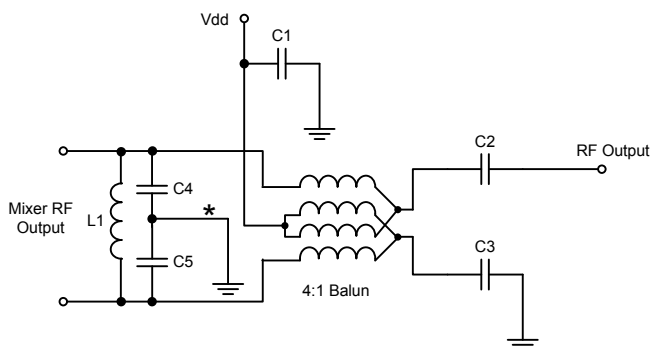
The idea is to split the matching resistor on the mixer output and connect to ground, in the case shown below using two 110Ω resistors with the 4:1 balun. This reduces the impedance to ground on each mixer output pin significantly, thereby aiming to reduce the level of any common mode noise and spurious at the balun output. The level of the wanted differential signal should of course be the same as for the 220Ω differential match. The ground connection is made via the decoupling capacitor C4, to prevent DC current flowing through the resistors from the mixer supply, Vdd. The decoupling capacitor C4 should be chosen carefully dependant on frequency. Two or more capacitors may be required to give a good wideband low impedance connection to the ground plane.



* Note that this point could be taken to the Vdd power plane. The power plane will then require suitable wideband decoupling to the ground plane.

6.2 NARROWBAND OUTPUT MATCH

This network uses two capacitors, C4 and C5 below, to decouple any high frequency common mode energy to ground directly on the mixer output. The shunt inductor L1 is chosen to resonate at the output frequency with the total capacitance presented by the mixer output (about 1pF) combined with C4 and C5. This forms a differential resonant circuit. The component values of the resonant circuit need to be chosen carefully. The circuit must decouple high frequency common mode energy effectively, for example an LO harmonic, while passing the desired output signal. The Q of the resonator needs to be set dependant on the bandwidth of the output signal and the amplitude rolloff and group delay variation that can be tolerated.



* Note that alternatively this point could be taken to the Vdd power plane. The power plane will then require suitable high frequency decoupling to the ground plane.

7. REFERENCES

1. The Design of CMOS Radio Frequency Integrated Circuits (Second Edition) by Thomas H. Lee
Useful for Chapter 3 on matching and lumped element balun design in Chapter 19.
2. RF Circuit Design by Chris Bowick
A classic source for information on matching and Smith charts.
3. Mini-Circuits web-site for transformer data sheets and app notes.
www.minicircuits.com
4. Agilent Technology's AppCad Program
Contains lumped element balun calculator program and tutorial.
www.hp.woodshot.com
5. Murata web-site for information on LTCC balun product range, LDB series.
Also has a downloadable tool "Murata Chip S-Parameter & Impedance Library" which is great for selecting RF components for supply decoupling, AC coupling and matching networks.
www.murata.com
6. RF Microelectronics by Behzad Razavi
Background on CMOS mixers.
7. Design of Broadband Lumped Element Baluns
by Dan Kuylenstierna and Peter Linner, IEEE transactions
8. Design of Broadband Lumped Element Baluns with Inherent Impedance Transformation
by Dan Kuylenstierna and Peter Linner, IEEE transactions
9. RF Mixer Design by Liam Devlin
A short paper on mixer design, which can be downloaded from the Plextek web-site. This contains useful background on balun implementations for double balanced mixers, including details of the lumped element rat race splitter.
www.plextek.co.uk