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Integrated Synthesizer/Mixer Application Note

Matching Circuits and Baluns

For the RFFC207x and RFFC507x Product Families

RFMD Multi-Market Products Group

REVISION HISTORY

Version	Date	Description of change(s)	Author(s)
0.1	July 2011	Review andRevision for external posting	Eric Schonthal
0.0	July 2011	Initial Draft	Chris Lintell-Smith

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1. INTRODUCTION

The RFFC207x and RFFC507x are monolithic mixer circuits with integrated frequency generation, a fractional-N synthesizer and VCO. The mixers are wideband and can be used for up and down conversion. The RFFC207x mixers cover the frequency range 30MHz to 2700MHz, and the RFFC507x mixers cover up to 6000MHz.

Because the mixers are double-balanced Gilbert cells, 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.

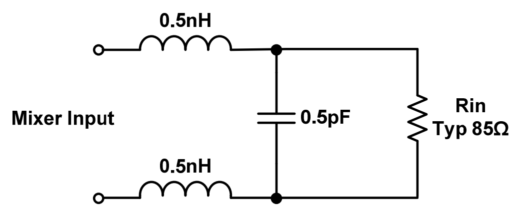
This document describes the implementation of baluns and matching circuits for the mixer ports of the RFFC207x and RFFC507x family of devices. The most suitable implementation will depend on the application and frequency plan. The trade-offs between different implementations are discussed.

2. THE MIXER PORTS

This section describes the differential mixer input and output ports. Simple models of the port impedances are given, along with requirements for the matching circuits and baluns.

2.1 MIXER INPUTS

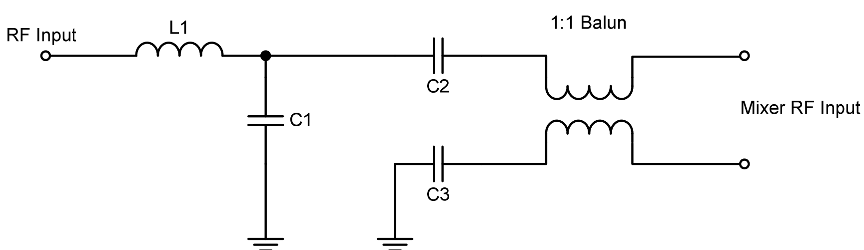
The mixer has a broadband common gate input. The input impedance is dominated by the resistance set by the mixer $1/g_m$ term, which is inversely proportional to the mixer current setting. There is also some shunt capacitance at the mixer input, the capacitance of the device gates. At higher frequencies there are parasitic impedances that become more significant, the bond wire inductance of about 0.5nH 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.

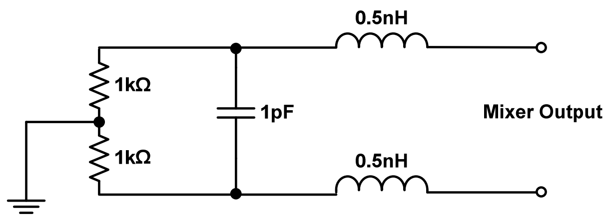
Mixer Current Setting	001	010	011	100	101
Mixer Current (mA)	5	10	15	20	25
Typical R_{IN} (Ω)	135.0	105.0	90.0	85.0	77.5

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

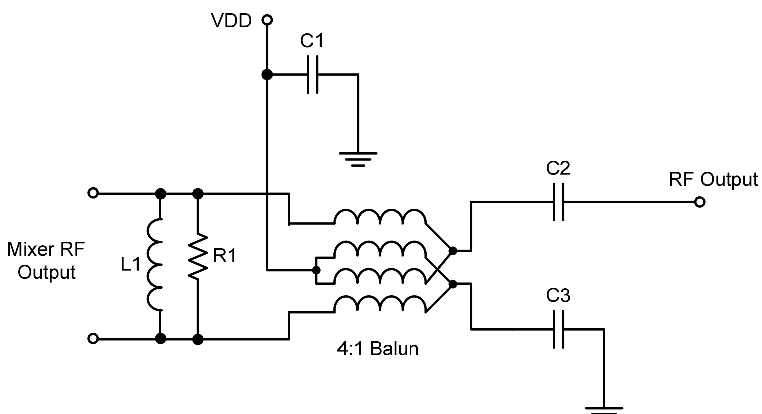
The following is a model showing the typical impedance of the differential mixer output. The mixer output is high impedance, a resistance of 2kΩ to 3kΩ in parallel with some capacitance. The bond wires each have inductance of about 0.5nH. At higher frequencies the bond wire inductance and stray capacitance 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.

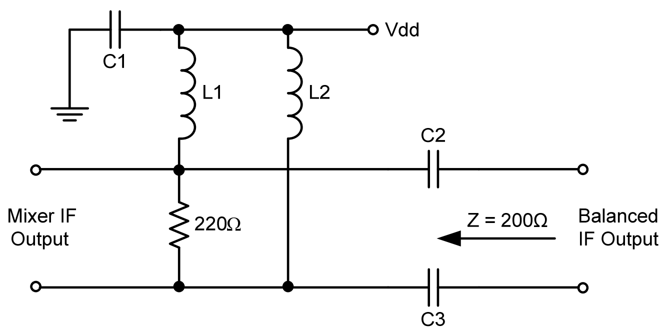
The mixer output has been designed to drive a load resistance between 50Ω and 500Ω. Higher load resistance means higher voltage (and power) at the output, and so typically a 4:1 balun is used. The balun performs the balanced-to-unbalanced conversion required, as well as transforming the 50Ω unbalanced load to the desired 200Ω at the mixer output. The disadvantage of having a higher load resistance is that the roll-off due to the mixer output capacitance will be more significant.

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 will improve the output impedance. However, 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.


C1
Vdd
L1
L2
C2
Mixer IF
Output
220Ω
Z = 200Ω
Balanced
IF Output
C3

3. WIDEBAND TRANSMISSION LINE BALUNS

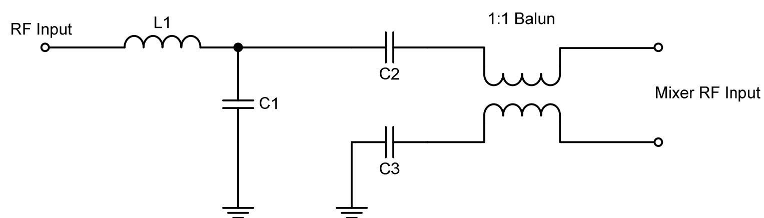
The RFFC207x family evaluation boards incorporate RFMD transmission line transformer baluns. This is to enable wideband evaluation and characterization of the device.

Wideband baluns are available from a number of other manufacturers such as Mini Circuits®, M/A-COM Technology Solutions, SYNERGY® MICROWAVE CORPORATION, and others.

These parts are ideal for broadband applications. They have the advantage of giving 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

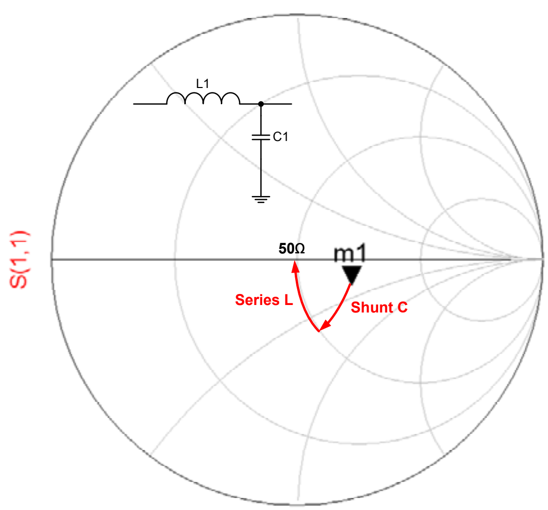
The following circuit could be used on the mixer inputs for a wideband application. This is the configuration on the RFFC207x evaluation boards.



The 1:1 balun is the RFXF9503 transmission line transformer, covering 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.

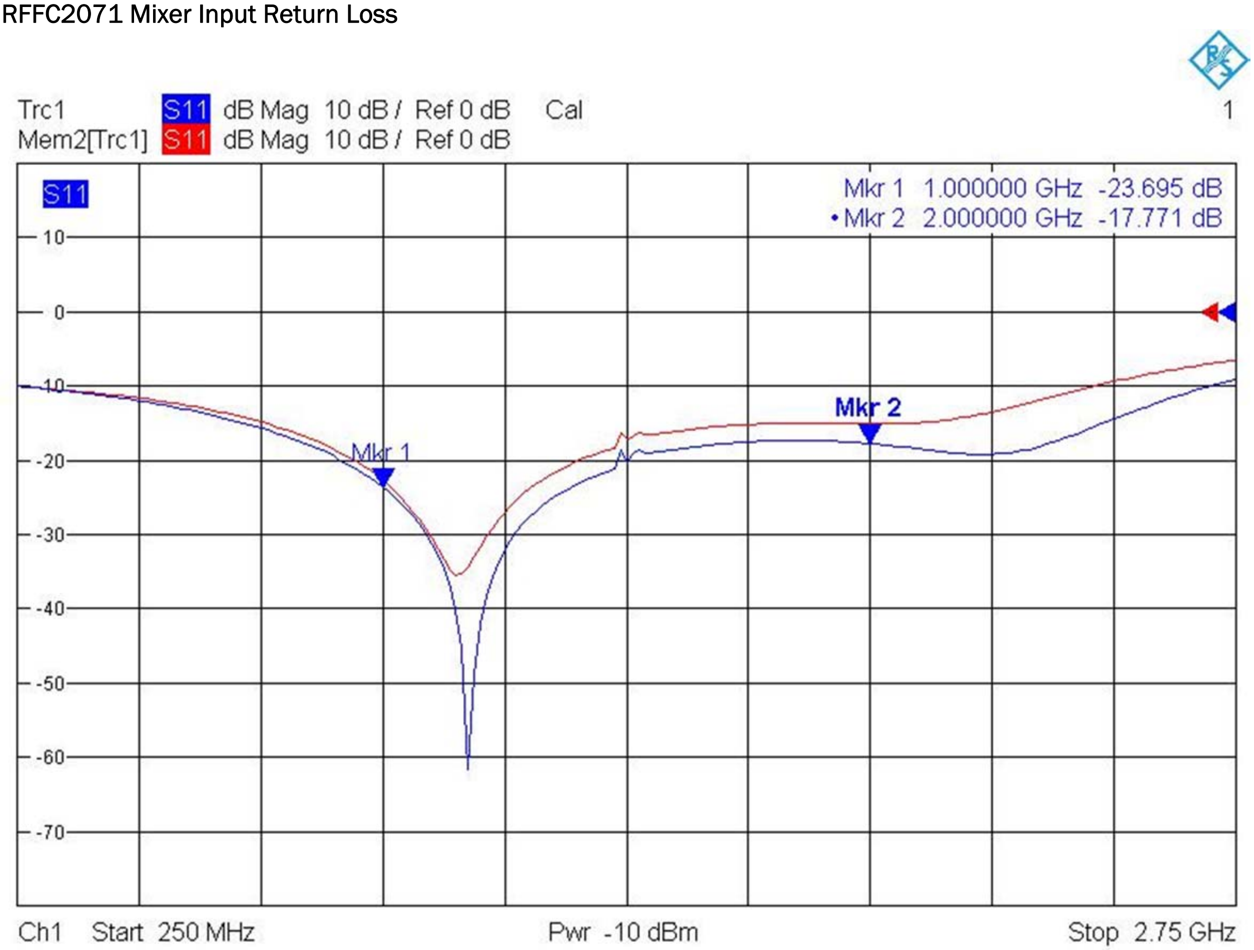
The L-C matching circuit can be added to improve matching at frequencies of interest, as shown below. Above 1GHz a different matching topology may be required, as stray impedances take increasing effect.



Below is an input return loss plot for the RFFC2071 evaluation board taken at the SMA connector input of each mixer, with the default mixer current setting (4/20mA). The red trace is for mixer 1, and the blue trace mixer 2. The component values were as follows, with no matching:

Balun	RFXF9503
L1	0Ω Link
C2, C3	100pF
C1	No Fit

RFFC2071 Mixer Input Return Loss



It can be seen that this configuration gives a good wideband input return loss, better than 15dB from 750MHz to over 2000MHz.

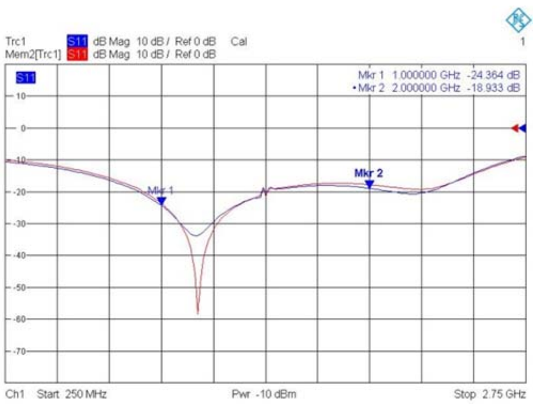
To improve the low frequency return loss the AC-coupling capacitors could be increased to 1nF and L-C matching could be added. For example at 140MHz matching of L1 47nH and C1 8.2pF was required.

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

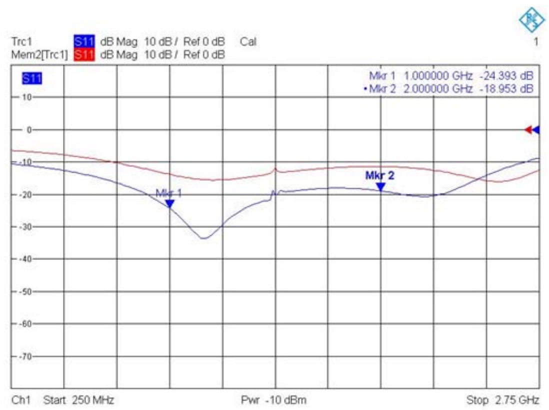
The following plots show the effect of the mixer current setting on the input return loss. The return loss improves with increased current as the resistance decreases towards 50Ω.

RFFC2071 Mixer 2 Input Return Loss

Red trace MIX_IDD = 4
Blue trace MIX_IDD = 5

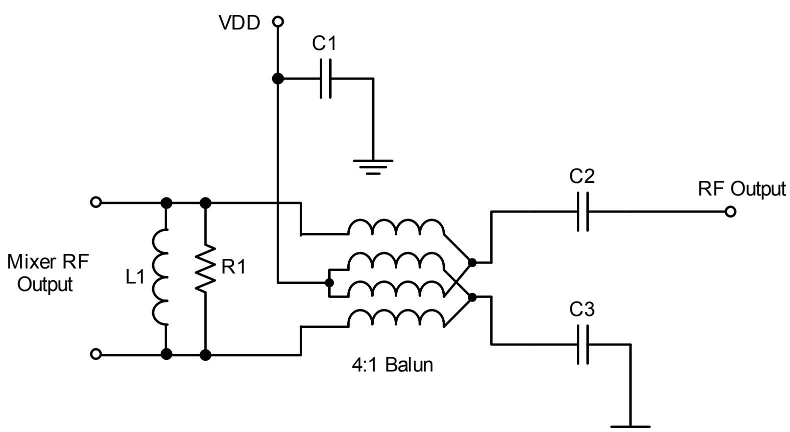


Red trace MIX_IDD = 1
Blue trace MIX_IDD = 5



3.2 MIXER OUTPUTS

The following circuit could be used on the mixer outputs for a wideband application. This is the configuration on the RFFC207x evaluation boards.



The 4:1 balun fitted as standard on the evaluation boards is the RFXF8553 transmission line transformer, covering 500MHz to 2500MHz. This part actually operates down well below the specified frequency of 500MHz. An alternative for lower output frequencies is the RFXF6553 transformer covering 10MHz to 1900MHz. The secondary center tap of the transformer is used to provide the mixer DC supply.

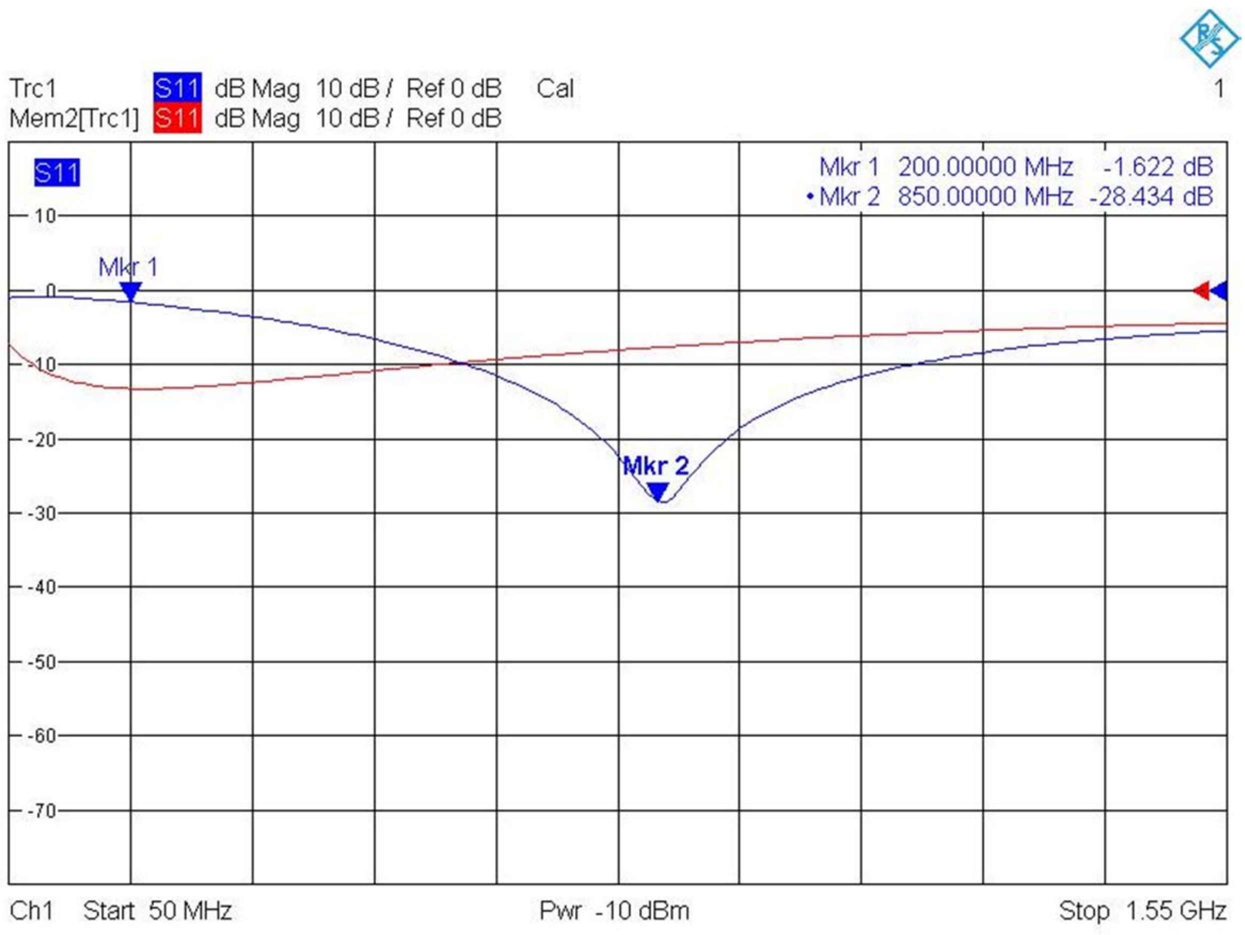
The value of AC-coupling capacitors C2 and C3, and decoupling capacitor C1, should be chosen carefully to give good performance over the desired frequency range; 100pF was chosen for the evaluation boards.

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. This is demonstrated in the plots below.

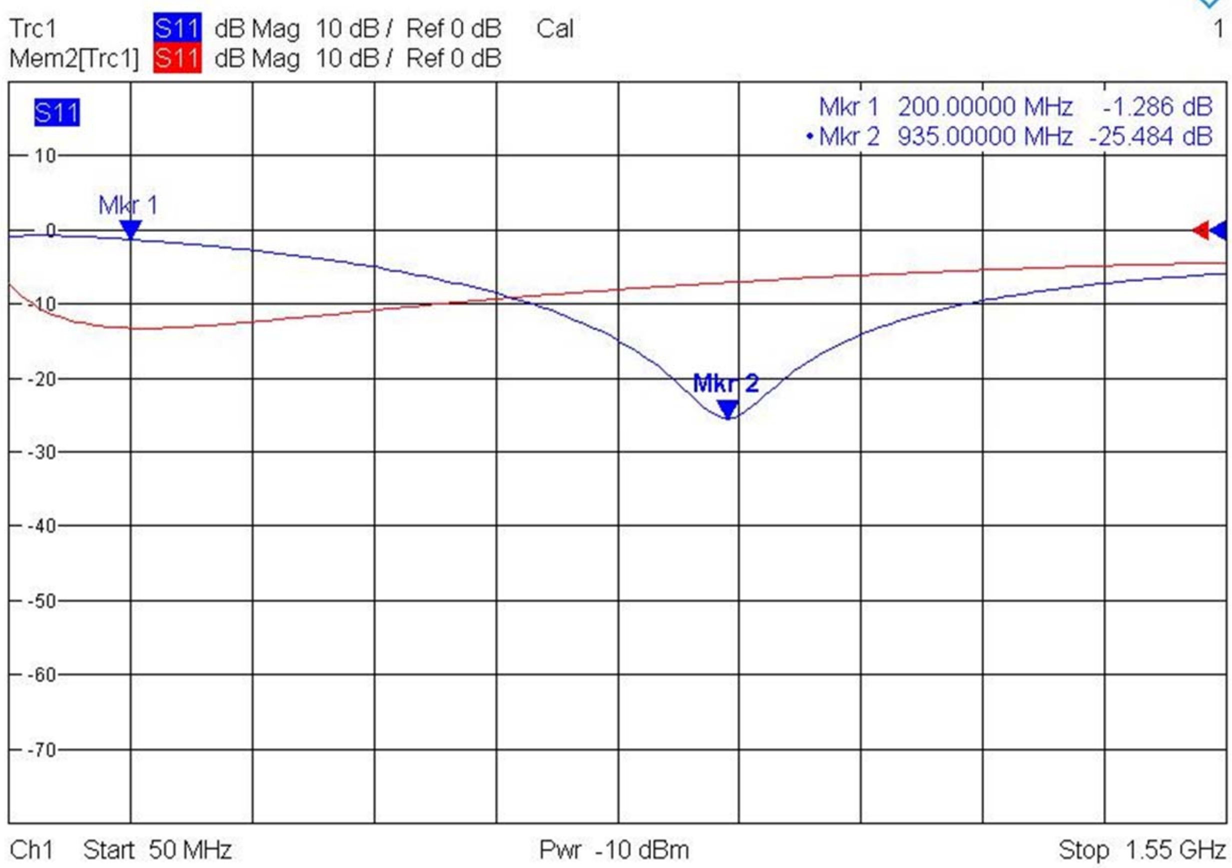
RFFC2071 Mixer 2 Output Return Loss

The red trace is the mixer output return loss with R1 of 220Ω fitted. The blue trace is R1 of 220Ω and L1 at 33nH, giving a good output match at 850MHz.

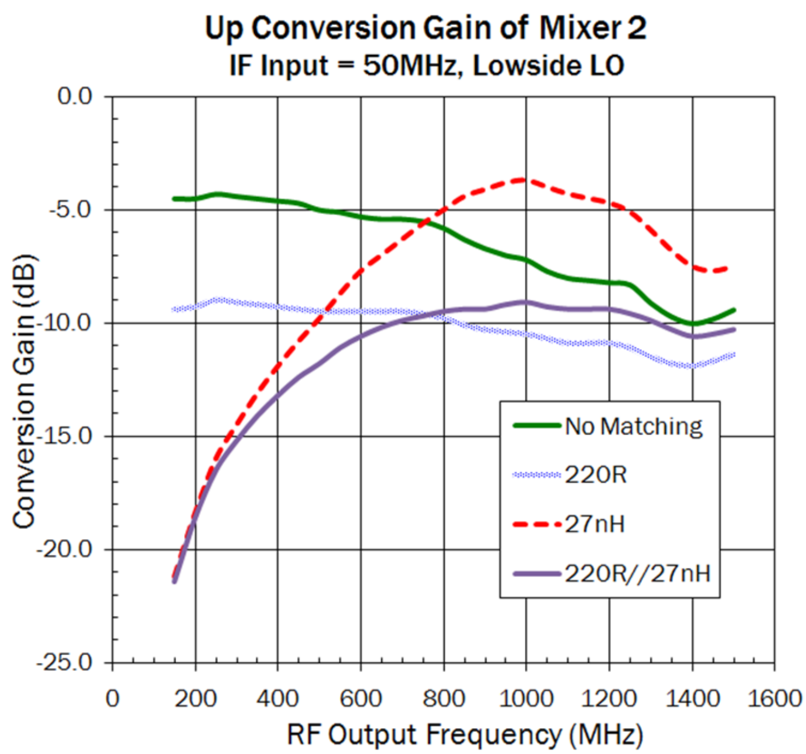


RFFC2071 Mixer 2 Output Return Loss

The red trace is the mixer output return loss with R1 of 220Ω fitted. The blue trace is R1 of 220Ω and L1 at 27nH, giving a good output match at 935MHz.

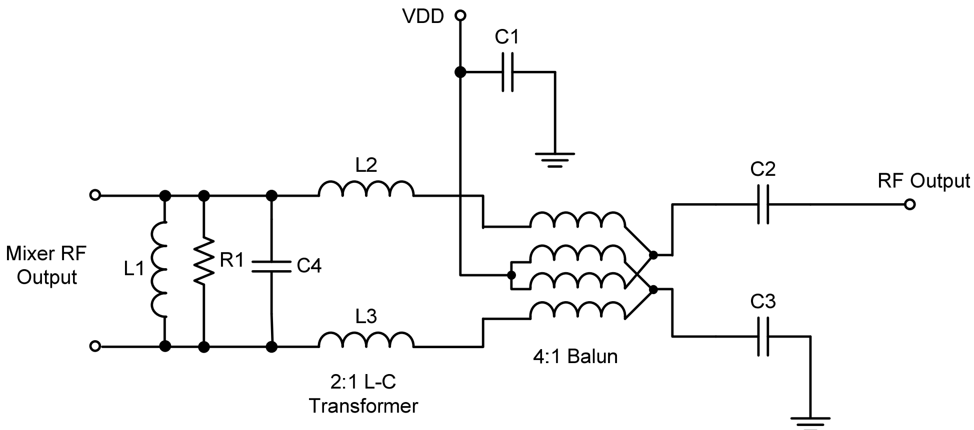


The plot below shows the conversion gain of the mixer versus output frequency for several output matching circuits with the RFXF8553 transformer. The plot with no matching shows the gain rolling off with frequency due to the output capacitance of the mixer. Adding the 220Ω resistor to improve output return loss reduces the gain by about 5dB, but note that the lower output load means that the roll-off is reduced. The 27nH shunt inductor is shown to peak the gain at the resonance around 950MHz to 1000MHz.



The conversion gain of the mixer 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.

4. NARROWBAND CERAMIC BALUNS

Narrowband ceramic baluns, LTCC hybrid types, are available from several manufacturers including Murata Manufacturing Company, Ltd. (LDB series), Anaren®, and Johanson Technology, Inc. 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, 50Ω:100Ω and 50Ω:200Ω are available that are suitable for use with the RFFC207x and RFFC507x devices.

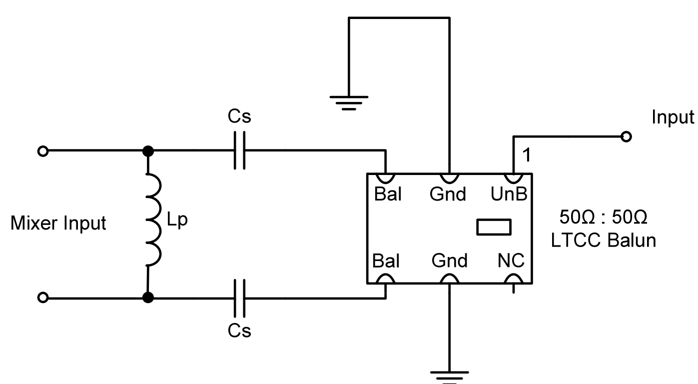
These parts are ideal for high frequency narrowband applications, provided parts can be obtained for the required frequency range. Their advantages:

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

The RFFC507x standard evaluation boards use Johanson Technology 3700MHz ceramic baluns on the RF ports. A 50Ω:50Ω balun is used for the RF input, part number 3700BL1500B050. A 50Ω:200Ω balun is used for the RF output, part number 3700BL1500B200. The IF ports are fitted with the RFXF9503 and RFXF8553 transmission line transformers, see section 3 above.

4.1 MIXER INPUTS

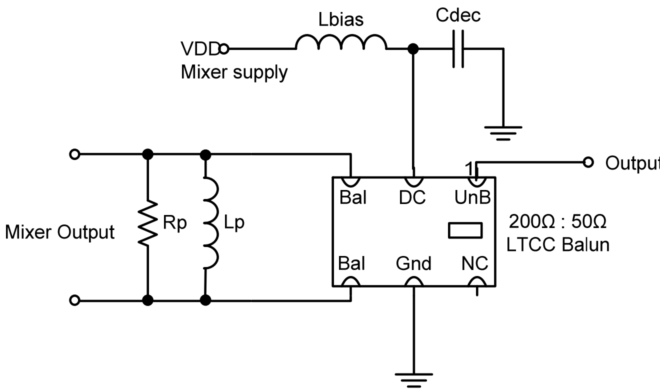
A 50Ω:50Ω LTCC balun can be used on the mixer input, and can be easily matched as shown below. This matching configuration gives the lowest component count since the series capacitors in the matching circuit also provide AC coupling.



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.



For the RFFC507x mixers a different approach is required when the output frequency is above approximately 4500MHz. The output capacitance of the mixer becomes increasingly difficult to match with a shunt inductor, especially since the output bondwires contribute significant inductance of 0.5nH each. It is recommended to lower the output impedance by using a 50Ω:100Ω or 50Ω:50Ω balun, or by using the shunt resistor Rp. Further information is contained in a separate note, see Reference 2.

It is worth checking the internal configuration of the LTCC balun used, especially on the mixer output. The DC connections vary dependant on the way the balun has been implemented.

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 they are for a wideband transformer. The common mode rejection ratio (CMRR) of the output balun and matching circuit is important, as this can affect the noise floor and spurious levels at the mixer output. The CMRR of the balun will degrade as phase and amplitude imbalance increase.

5. NARROWBAND LUMPED-ELEMENT BALUNS

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

- Low cost
- Small size, (four 0402 components)

One of the difficulties with lumped-element baluns is in implementing designs with standard component values. Higher frequencies, and especially with higher impedance, transform the small component values required. In addition, the stray PCB parasitic components make design problematic.

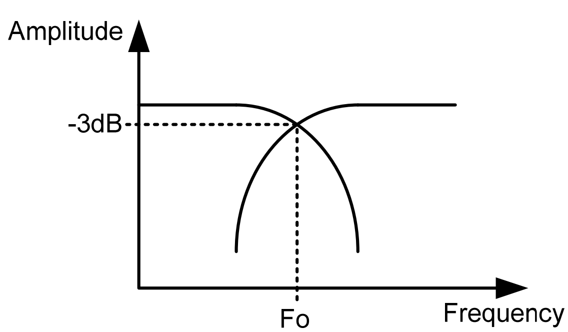
The main disadvantage is that the lumped-element approach does not present the mixer port with a true balanced impedance across all frequencies. The mixer will be unbalanced outside of the narrow operating bandwidth. This could mean that the LO and RF rejection at the output port are not as good as they are for a wideband transformer. In addition the lumped-element balun does not offer good common mode rejection 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 RFFC207x and RFFC507x mixers is not generally recommended, especially for the output ports where the balun CMRR is important.

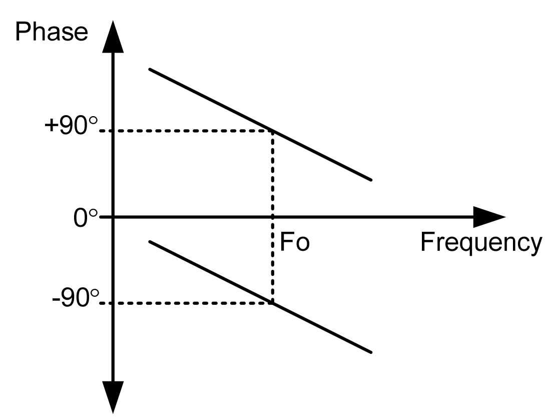
5.1 BACKGROUND

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.

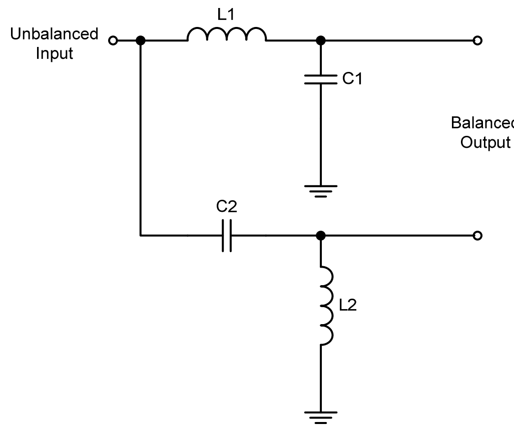
The fact that the two sections are formed with high- and low-pass filters highlights the problem with this balun topology, amplitude balance is only achieved at the center frequency. Outside of the operating bandwidth the mixer will be presented with a large amplitude imbalance, degrading performance.

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 center frequency.



$$L1 = L2 = \frac{\sqrt{Zu \cdot Zb}}{2 \cdot \pi \cdot Fo}$$

$$C1 = C2 = \frac{1}{2 \cdot \pi \cdot Fo \cdot \sqrt{Zu \cdot Zb}}$$

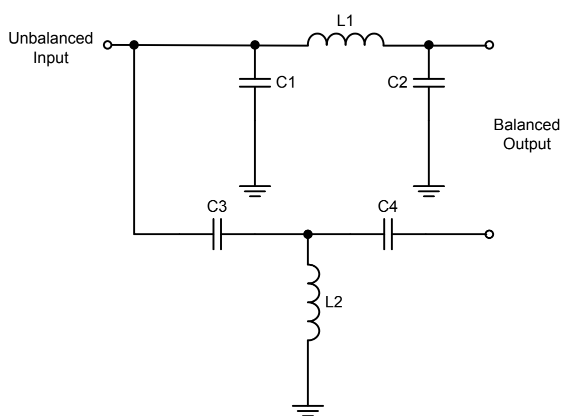
Where:

Zu = Characteristic impedance of unbalanced port, Ω

Zb = Characteristic impedance of balanced port, Ω

Fo = Center 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° 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 center 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.

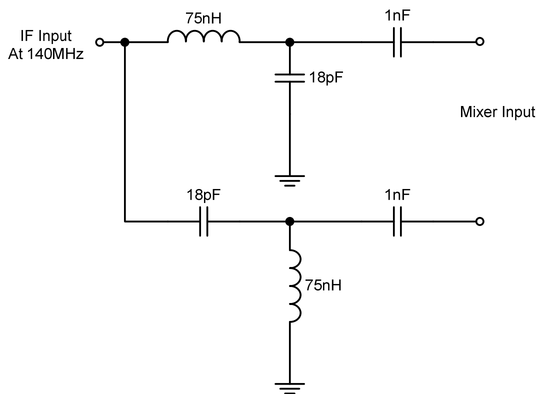


The lead and lag elements could also be achieved using quarter wavelength transmission lines in microstrip. This is not a very practical solution at these frequencies due to the physical size.

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 center 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

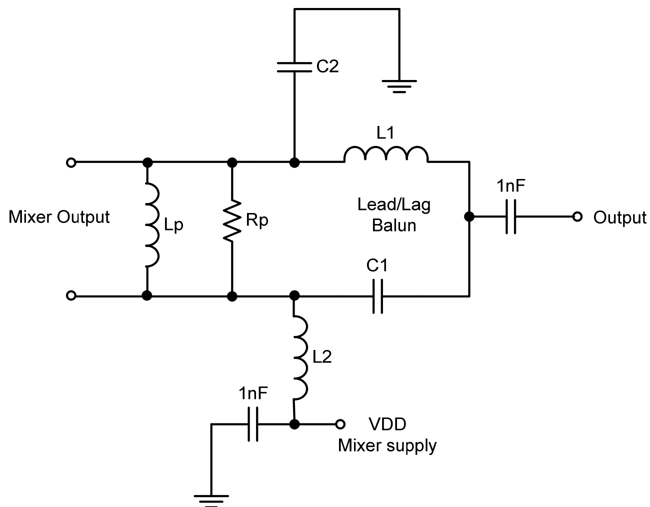
Frequency	140MHz	500MHz	1000MHz	2000MHz	2500MHz
L1/L2 (nH)	75	22	10	5.1	3.9
C1/C2 (pF)	18	4.7	2.2	1.2	1.0

Note 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 0.5nH 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.



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, note 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 0.5nH 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.

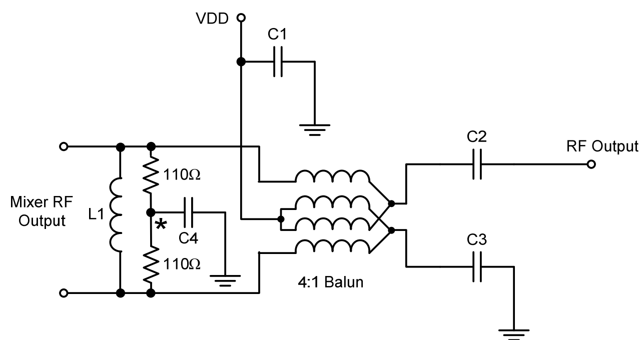
To avoid the problem of having to implement a balun with a high impedance ratio, a solution is to split the impedance transformation. For instance a 2:1 lumped-element balun could be followed by a 2:1 matching transformer. Bear in mind that the matching network must route the DC supply to the mixer output 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

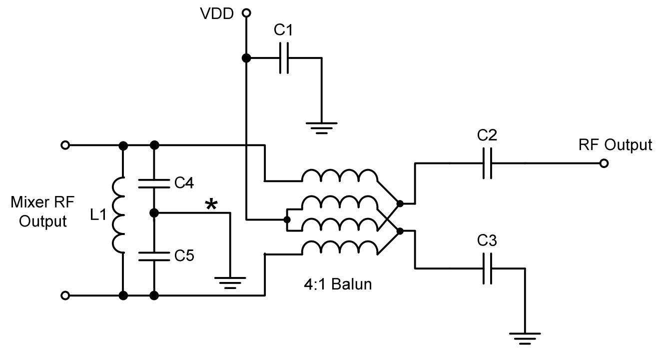
The idea is to split the matching resistor on the mixer output and connect to ground, in the case shown below using two 110Ω resistors with the 4:1 balun. This reduces the impedance to ground on each mixer output pin significantly, thereby aiming to reduce the level of any common mode noise and spurious 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, whilst 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 roll off 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.

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