Designing with MLX71120 and MLX71121 receivers using a SAW filter between LNA1 and LNA2

Scope

Many receiver applications, especially those for automotive keyless entry systems require good sensitivity and a SAW filter at the receiver input to reduce the possibility of interference both from inside and outside the automobile. If a SAW filter is added between the antenna and IC input, the sensitivity is reduced by the loss of the SAW filter, so most applications use an external discrete transistor for a low noise amplifier (LNA) between the SAW filter and the IC. The disadvantages of this are the extra cost of the transistor and its external components plus the requirement to turn it off when the receiver IC is in standby mode. Often the SAW filter is connected to an antenna, with hardly predictable and varying characteristics, when the receiver is assembled in a module with other components. This results in the SAW being mismatched so its pass-band response will not be flat, and the rejection of unwanted signals may be worse the values specified in the data sheet.

These problems can be avoided if the MLX71120 and MLX71121 receivers are used because they have two independent LNAs with good isolation between them. The SAW filter can simply be placed between LNA1 and LNA2 (LNA1-SAW-LNA2). The receiver sensitivity will then depend only on the LNA, and the circuit elements between LNA1 and LNA2 can be selected to match the SAW filter thus making it independent of the antenna. **Because of this, the blocking immunity of the receiver may actually be better than when the SAW filter is placed in front of the LNA**.

Below table summarizes the most important performance parameters of the proposed cascaded (LNA1-SAW-LNA2) configuration in comparison to the standard EVB population (SAW-LNA).

Parameter	LNA1-SAW-LNA2		SAW-LNA	
	ASK	FSK	ASK	FSK
Current draw - I_{CC} [mA]	10.8	11.3	9.8	10.2
Sensitivity - P_{MIN} [dBm]	-119	-110	-117	-107
Max. Input level - P_{MAX} [dBm]	-60	>0	-45	>0

Table 1 – MLX71121 Performance comparison

Figure 1 shows a typical circuit for a 433.92 MHz receiver in LNA1-SAW-LNA2 configuration.

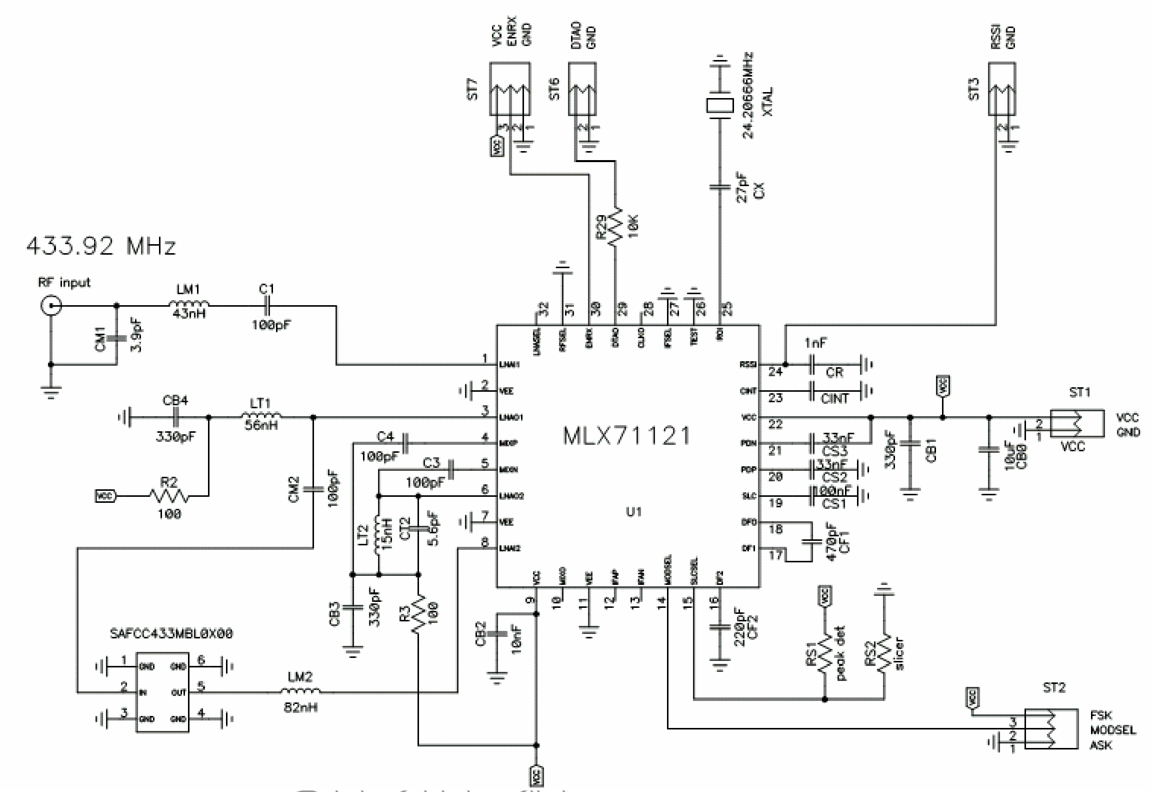
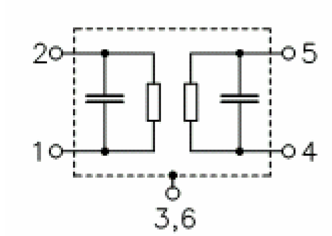


Figure 1 – Circuit with high-impedance SAW filter

SAW matching basics

Some data sheets for SAW filters show the equivalent internal input circuit for the filter, and some show the network the SAW filter should be terminated with. In general, the equivalent input circuit for a SAW filter is a parallel resistor and capacitor. If an inductor is shown, it is usually the complement of the internal capacitance and is intended to show what the termination of the filter should be. For example, one data sheet may show the following equivalent circuit:



This shows how the SAW filter looks like from the outside. Another data sheet gives this information for a 433.92MHz filter:

Input / Output Impedance (nominal)	1100Ω//110nH

This shows what the SAW filter would like to have connected to its terminals. If it was in the same format as the first data sheet, it would show 1100 Ohms in parallel with 1.22pF.

Designing a matching network

Normally, the lowest cost matching networks are desired, and there is usually more than one way to achieve the same result. One of them will usually use fewer inductors than the other.

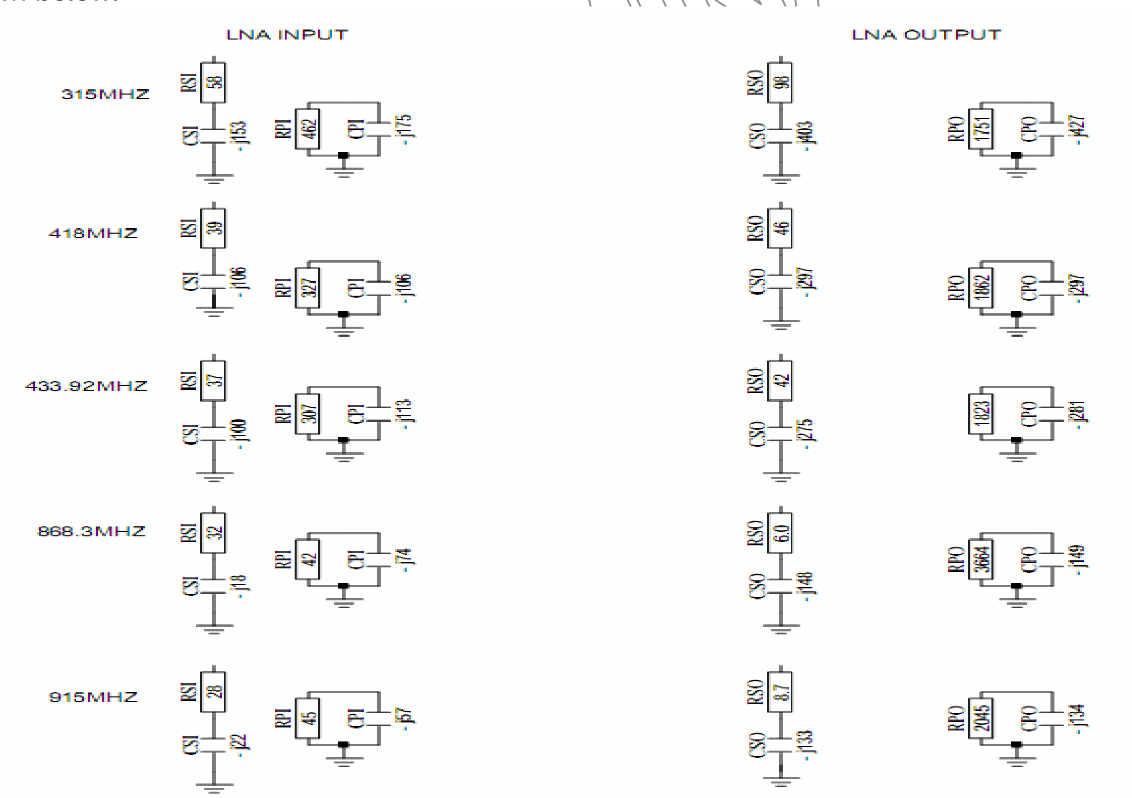
The first requirement is to be able to convert parallel RC networks to their series equivalent at the operating frequency. There are many RF design text books dealing with this topic.

The basic equations are:

for the series RC network: $Q_s = \frac{X_s}{R_s}$,for the parallel RC network: $Q_p = \frac{R_p}{X_p}$.

Where X is $\omega \times L$ or $-\frac{1}{\omega \times C}$ and $R_p = R_s(1+Q^2)$ and $Q = Q_p = Q_s$

The series and parallel equivalent input and output circuits for the MLX71120/21 LNAs are shown below.



The parallel input and output capacitance can be derived:

LNA parallel input capacitance = approx 3pF
LNA parallel output capacitance = approx 1.3pF
The equivalent resistances change with frequency.

Matching the input of LNA1 to the RF input

The designation LNA1 and LNA2 is arbitrary and is used here only to distinguish between the two LNAs. They are the same and can be interchanged to suit the PCB layout of the receiver.

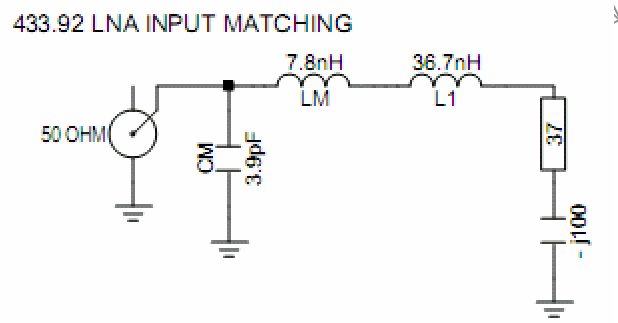
Use the series equivalent for the LNA input. First calculate the inductance to resonate with the LNA input capacitance. At 433.92MHz, 36.7nH has a reactance of j100 Ohms. This resonates with L1, 36.7nH, shown below.

Then match the 37 Ohms with 50 Ohms using a series L, shunt C matching network. A series C, shunt L matching network could also be used, but it would require an additional inductor.

In this case, LM=7.8nH, CM=4.4pF to match 37 Ohms to 50 Ohms at 433.92MHz.

Then combine the two inductors in series to get 44.5nH. The final component values will be 43 or 47nH and 3.9 or 4.0pF.

The circuit is shown below.



Other networks are possible. One example is a Pi matching network using the parallel equivalent circuits for the LNA input so that the output of the Pi network is the input capacitance of the LNA.

A matching network with an external C from the LNA input to ground should not be used because the extra capacitance ground may cause parasitic oscillations.

In the case of 50-Ohm SAW filters, the components between the SAW output and the LNA2 input are the same as for the antenna input.

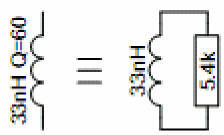
General information about matching the output of LNA1 to the SAW filter

This is a more complicated design problem because the LNA output is an open collector and power must be supplied through an inductor. At 433.92MHz, the parallel LNA output resistance is about 1.8k, and the capacitance is about 1.3pF. It would be possible to put an inductor across the SAW input to tune out the SAW capacitance and then just match the SAW resistance to the LNA output, but this would require two inductors. Also, if the impedance is high, the coupling capacitor in the matching network might be less than 1pF.

It may at first not seem possible, but the LNA output can be tuned and coupled to the SAW with a capacitor while matching the resistance and providing a reactive component which tunes with the SAW capacitance.

One way to design the matching network is to load the S parameters for the SAW filter into a circuit simulator and adjust the components by trial and error.
Referring to Figure 1, first, pick a convenient value for LT1, and then adjust CT1 and CM3 to give a flat top filter response.

Remember that the inductor is not perfect. It has a parallel resistance which depends on the Q of the inductor, this is: $R_p = Q \times \omega \times L$. An example for 433.92MHz is shown below:



The 5.4k resistor must be combined in parallel with the 1.8k of the LNA output resistance to give 1.35k.

If the Q of the inductor is too low, it may not be possible to match a SAW filter with a high input resistance. For example small multilayer inductors have a low Q at low frequencies.

In order to get enough gain from LNA1, the load impedance should be greater than about 600 Ohms. If the LNA gain is too low, the losses of the SAW filter and matching networks may result in a too small gain from the input of LNA1 to the input of LNA2, and the overall sensitivity of the receiver will be low.

Matching specific filters

Consider first the 1100 Ohm // 110nH SAW filter. As was mentioned above, this filter actually represents a 1.22pF internal capacitor to tune with a 110nH inductor for 433MHz.
The 1100 Ohm resistance is high enough for good LNA gain, so the SAW can be directly connected to the LNA output. If desired, a 100pF coupling capacitor can be added between the LNA and SAW.

The LNA output capacitance of the MLX71120/21 is about 1.3pF, so the inductor should be tuned to 1.22pF + 1.3pF = 2.52pF. This gives an inductance of 53.4nH so 56nH is used. This is shown in the circuit in Figure 1. In this case, it should be a wire-wound inductor so the Q is high enough to give a high R_p.

Matching the SAW filter output to the LNA input

One way is to design a Pi matching network which uses the internal input capacitance of the LNA and the SAW filter.

Another way is to use the series equivalent for the LNA input:
As was done above, 37nH tunes out internal –j100 Ohms.
A matching network of 73nH and 1.8pF matches the 37 Ohms of the LNA to the 1.1k of the SAW.

The SAW filter requires 110nH on the output to ground. When this is in parallel with the 1.8pF of the matching network, the result is 0.58pF, so the 1.8pF capacitor can be omitted. The net result is 37nH + 73nH = 110nH between the SAW and the LNA input.

However, when the RSSI output of the receiver is checked with a wide band FM signal or at different frequencies, it was not peaked. An 82nH inductor gives a better response indicating that the SAW filter equivalent circuit may be slightly incorrect.

Matching a low-impedance SAW filter

Now, consider a 433.92MHz filter with an internal equivalent of 390 Ohms in parallel with 2.1pF

Matching this to the LNA input is easy because 390 Ohms is close enough to the parallel LNA input resistance of 307 Ohms. The SAW can be connected through a 100pF capacitor to the LNA input. An inductor to ground on the SAW output must tune with the 2.1pF of the SAW plus 3.2pF of the LNA input: 2.1pF + 3.2pF = 5.3pF. This resonates with 25nH, so a 27nH coil can be used.

The 390 Ohms is too low for the LNA output load because the gain will be too low. This will result in low gain and poor sensitivity. Therefore, a network to transform the 390 Ohms of the SAW filter up to around 1k is needed.

The circuit in Figure 2 shows the final implementation.

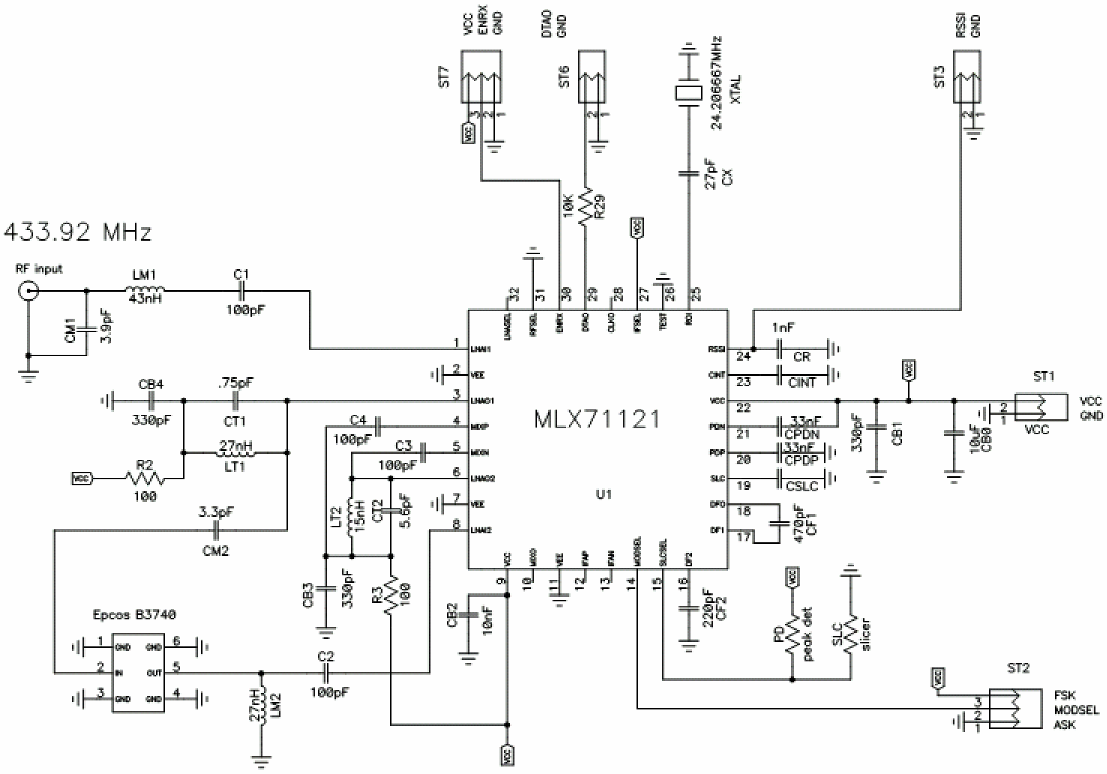


Figure 2 – Circuit with low-impedance SAW filter

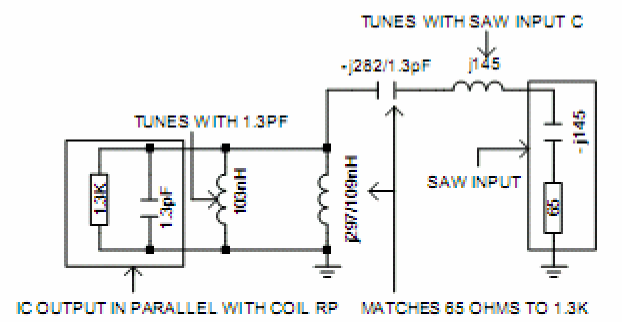
As was mentioned above, the values for the SAW, LNA, LT1, CM3, CT1 could be loaded into a simulation program and the values selected by trial and error.

The following design procedure can be used:

Convert the SAW input to its series equivalent: 65 – j145.

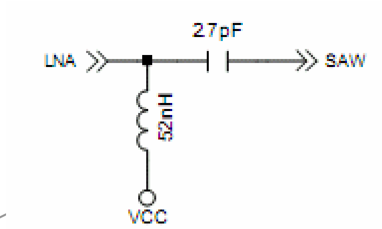
Add a – j145 (53nH) inductor in series with the saw input to tune out the – j145.

Design a matching network with a series C and shunt L to match the 65 Ohms to the output impedance of the MLX71120 in parallel with the coil R_p. In this case, the output resistance is 1.8k. If we assume the coil $Q_L = 50$, then $R_p = 4.5k$,
and the parallel combination is 1.3k. The diagram below shows all the elements.



The series combination of 1.3pF (- j282) and j145 gives a net result of – j137 which is 2.7pF at 433.92MHz.

The parallel combination of 103nH and 109nH gives 52nH, so the matching network looks like this:



The only problem with this network is that 52nH is not a standard coil value, and it does not allow for any adjustment of the tuning because of stray capacitances. It would be nicer to make it 27nH or 43nH because these values are already being used.

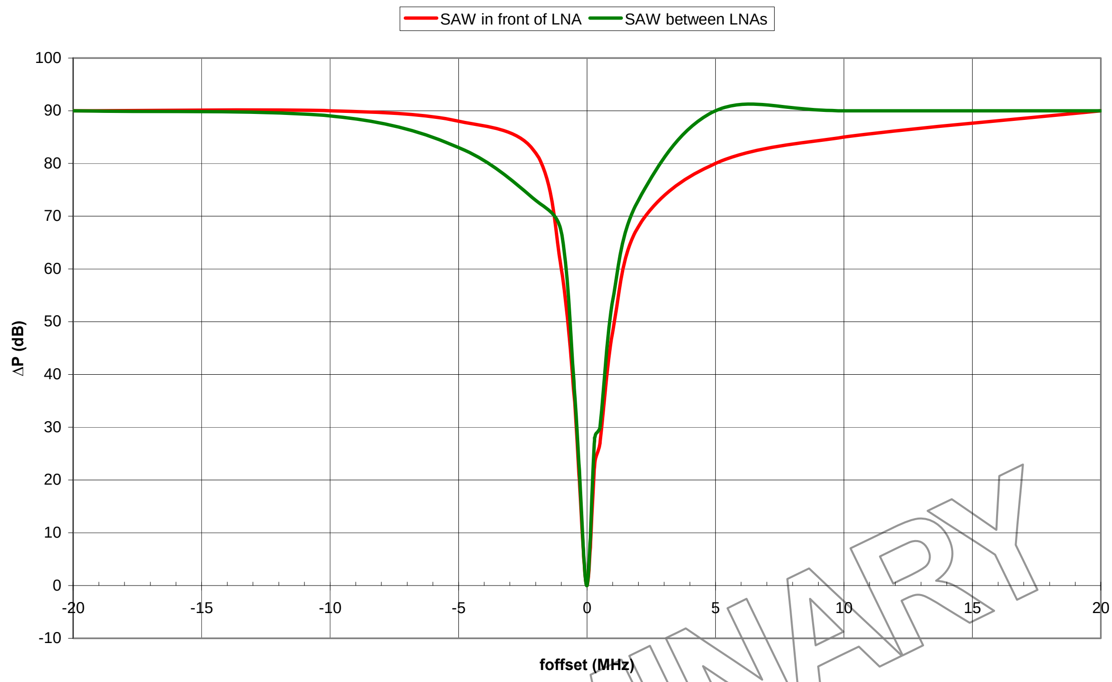
If we use 27nH and assume $Q_L = 50$, then $R_p = 3.7k$, so the net resistance with the LNA output is 1.22k. The matching network is now 1.34pF and 106nH, so the equivalent series C is 2.84pF. This is not critical, so 3.0 or 3.3pF can be used.

Since we are planning to use 27nH, and the matching network requires 106nH, there must be an equivalent 36nH across the LNA output. (The parallel combination of 36 and 106nH = 27nH.) The 36nH can be tuned with 3.74pF. Subtracting the 1.3pF of the LNA output gives 2.4pF, so an additional 2.2pF is needed across the LNA output. This can be adjusted to compensate for any stray C in the PCB. In Figure 2, the result for CT1 was 0.75pF. This is quite different from the calculated value, so it illustrates that adjustment of the elements in the tuned circuits is often necessary. The RSSI signal from the MLX71120 or MLX71121 is very helpful for making this adjustment.

Blocking Response

The isolation between LNA1 and LNA2 is greater than 55dB at 433.92MHz. This means that a receiver with the LNA1-SAW-LNA2 configuration will have a blocking performance as good as one with the SAW between the antenna and the LNA because the maximum attenuation of the SAW filter is about 58 to 60dB.

This is illustrated in the following graph:



Blocking response with different SAW locations

The red curve is measured with the SAW between the antenna and LNA and the green one with a SAW between LNA1 and LNA2.

It is important to note that the maximum attenuation of the SAW filter is influenced a lot by any mismatch on the input or output. And when it is connected to an antenna, the match will never be perfect. This causes reflections in the SAW filter, and these will change depending on the location and orientation of the antenna.

Spurious Responses

Since a receiver is not only susceptible to the desired signal but also to unwanted signals a SAW filter can help to reduce the so-called spurious responses.

Table 1 below is a list of spurious responses caused by mixing of harmonics of the RF and LO. These measurements were taken with the MLX71121 having an integrated IF filter with a bandwidth of 300kHz (3dB). Note that the rejection with the SAW at the RF input is better, but the sensitivity of the receiver is 5dB worse. Furthermore, the spurious response rejection of 55 to 80dB is usually enough to guarantee good performance. If an external LNA is used in front of the SAW filter to get better performance, it must be operated at a higher current, and there must be some provision for turning it on and off when the receiver is in standby or receive mode.

If better spurious response rejection is desired, the MLX71120 with an external 10.7MHz IF filter can be used. The external IF filter can provide a greater ultimate selectivity if its bandwidth is chosen smaller than the 300kHz (internal to MLX71121). Because of the dual conversion frequency plan of the MLX71120/21, most of the spurious responses do not appear. Table 2 shows the result with the same SAW filter as was used with the MLX71121. The external IF filter bandwidth is 180kHz.

Table 2: MLX71121 spurious responses with SAW at different locations					IFBW=300kHz
	harmonic number		Generator	level in dBuV	
	LO	RF	SAW-LNA	LNA1-SAW-LNA2	
629.9733	-3	-3	119	78	spurious
436.3200	-2	-3	80	69	spurious
242.6667	-1	-3	120	78	spurious
654.4800	-2	-2	>120	78	spurious
364.0000	-1	-2	120	67	spurious
728.0000	-1	-1	71	55	image
147.0400	0	-1	100	82	spurious
433.9200	**1**	**1**	**-1**	**-6**	**desired**
507.4400	2	2	>120	74	spurious
797.9200	3	2	>120	74	spurious
338.2933	2	3	>120	81	spurious
531.9467	3	3	115	79	spurious

Table 3: MLX71120 spurious responses with LNA1-SAW-LNA2				IFBW=180kHz
	harmonic number			
Generator Frequency	LO	RF	Generator Level in dBuV	
421.0023	-4	-6	112	spurious
322.3378	-3	-6	>120	spurious
223.6733	-2	-6	>120	spurious
386.8054	-3	-5	>120	spurious
268.4080	-2	-5	>120	spurious
150.0107	-1	-5	>120	spurious
483.5067	-3	-4	>120	spurious
335.5100	-2	-4	>120	spurious
187.5134	-1	-4	>120	spurious
447.3467	-2	-3	107	spurious
250.0178	-1	-3	>120	spurious
375.0267	-1	-2	>120	spurious
158.0667	0	-1	>120	IF
433.9200	**1**	**1**	**-6**	**desired**
341.9689	2	3	>120	spurious
256.4767	2	4	>120	spurious
404.4734	3	4	>120	spurious
205.1813	2	5	>120	spurious
323.5787	3	5	>120	spurious
441.9760	4	5	73	spurious
170.9845	2	6	>120	spurious
269.6489	3	6	>120	spurious
368.3134	4	6	>120	spurious
466.9778	5	6	>120	spurious

Component list for receiver circuits

Part	Values for Figure 1	Values for Figure 2	Tol.	Description
C1	100 pF	100 pF	±5%	DC blocking capacitor
C2	nip	100pF	±5%	DC blocking capacitor
C3	100pF	100pF	±5%	mixer input coupling capacitor
C4	100pF	100pF	±5%	mixer input decoupling capacitor
CM1	3.9pF	3.9pF	±5%	input matching capacitor
CM2	100pF	3.3pF	±10%	saw coupling/matching capacitor
CT1	nip	.75pF	±5%	LNA1 output tuning
CT2	5.6pF	5.6pF	±5%	LNA2 output tuning
CB0	10uF	10uF	±20%	decoupling capacitor
CB1,3	330pF	330pF	±10%	decoupling capacitor
CB2	10nF	10nF	±10%	IF decoupling capacitor
CF1	470 pF	470 pF	±10%	data low-pass filter capacitor, optimized for data rate of 4 kbps NRZ
CF2	220 pF	220 pF	±10%	data low-pass filter capacitor, optimized for data rate of 4 kbps NRZ
CF3	according to data sheet page 12		±10%	optional capacitor for noise cancellation filter
CP1	33 nF	33nF	±10%	positive PKDET capacitor
CP2	33nF	33nF	±10%	negative PKDET capacitor
CR	1 nF	1 nF	±10%	RSSI output low pass capacitor
CX	27 pF	27 pF	±5%	crystal series capacitor
LM1	43nH	43nH	±5%	input matching inductor
LM2	82nH	27nH	±5%	SAW-LNA2 matching inductor
LT1	56nH	27nH	±5%	LNA1 output tuning + SAW matching
LT2	15nH	15nH	±5%	LNA2 output tuning
SAW	SAFCC433M BL0X00	B3740		SAW filter
XTAL	24.20667 MHz	24.20667 MHz	20ppm	fundamental mode crystal