AN1993

High sensitivity applications of low-power RF/IF integrated circuits

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Document information

Info	Content
Keywords	12 dB SINAD, 20 dB SINAD, crystal filter, ceramic filter, VHF, UHF, image frequency, FM broadcast receiver, ASK, FSK
Abstract	This application note discusses four high sensitivity receivers and Intermediate Frequency (IF) strips that utilize intermediate frequencies of 10.7 MHz or greater. Each circuit utilizes a low-power VHF mixer and high-performance low-power IF strip. The circuit configurations are: 45 MHz or 49 MHz to 10.7 MHz narrowband; 90 MHz to 21.4 MHz narrowband; 100 MHz to 10.7 MHz wideband; and 152.2 MHz to 10.7 MHz narrowband. Each circuit is presented with an explanation of component selection criteria (to permit adaptation to other frequencies and bandwidths). Optional configurations for local oscillators and data demodulators are summarized.

Revision history

Rev	Date	Description
v.3	20140813	Application note; third release Modifications: • Updated Figure 9, Figure 12, Figure 14, Figure 16, and Figure 20.
v.2	20140804	Application note; second release Modifications: • The format of this application note has been redesigned to comply with the new identity guidelines of NXP Semiconductors. • Legal texts have been adapted to the new company name where appropriate. • "SA602" changed globally to "SA602A" • Section 3 "The problem": deleted (old) fourth paragraph • Section 4 "The solution", first paragraph: fifth and sixth sentences rewritten • Section 4.1 "The mixer", second paragraph, first sentence changed from "interference must be correct" to "impedance/noise match must be optimized" • Section 4.3 "Basic considerations", second paragraph, fourth sentence: changed from "(1.5 Ω nominal)" to "(1.5 kΩ nominal)" • Figure 18 "Oscillator configurations": pin numbers are corrected • Section 10 "Data demodulation", second paragraph: (old) third sentence replaced with (new) third and fourth sentences.
v.1	19970820	Application note; first release

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1. Introduction

Traditionally, the use of 10.7 MHz as an intermediate frequency has been an attractive means to accomplish reasonable image rejection in VHF/UHF receivers. However, applying significant gain at a high IF has required extensive gain stage isolation to avoid instability and very high current consumption to get adequate amplifier gain bandwidth. By enlightened application of two low-power ICs, NXP Semiconductors SA602A and SA604A, it is possible to build highly producible IF strips and receivers with input frequencies to several hundred MHz, IF frequencies of 10.7 MHz or 21.4 MHz, and sensitivity less than 2 μV (in many cases less than 1 μV). The SA605 combines the function of the SA602A and the SA604A. All of the circuits described in this application note can also be implemented with the SA605. The SA602A and SA604A were utilized for this application note to permit optimum gain stage isolation and filter location.

2. The basics

First, let us look at why it is relevant to use a 10.7 MHz or 21.4 MHz intermediate frequency. 455 kHz ceramic filters offer good selectivity and small size at a low price. Why use a higher IF? The fundamental premise for the answer to this question is that the receiver architecture is a heterodyne type as shown in Figure 1.

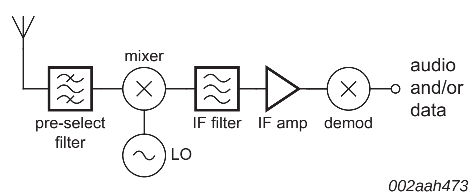
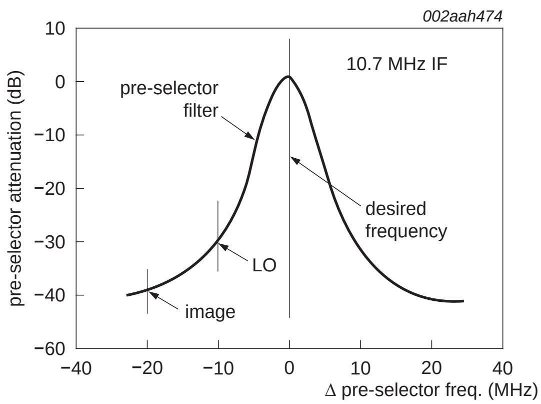


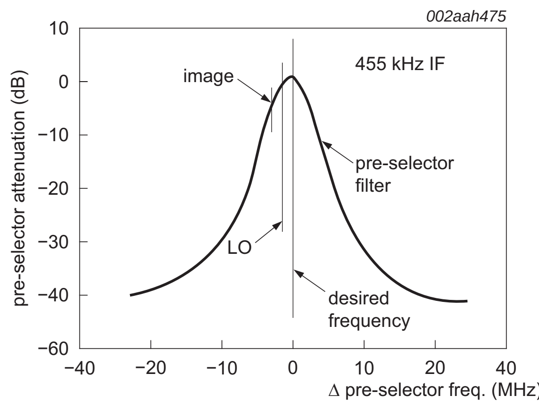
Fig 1. Basic heterodyne receiver

A pre-selector (band-pass, in this case) precedes a mixer and local oscillator. An IF filter follows the mixer. The IF filter is only supposed to pass the difference (or sum) of the Local Oscillator (LO) frequency and the preselector frequency.

The reality is that there are always two frequencies which can combine with the LO: the pre-selector frequency and the 'image' frequency. Figure 2 shows two hypothetical pre-selection curves. Both have 3 dB bandwidths of 2 MHz. This type of pre-selection is typical of consumer products such as cordless telephones and FM radio. Figure 2a shows the attenuation of a low-side image with 10.7 MHz. Figure 2b shows the very limited attenuation of the low-side 455 kHz image.



a. Attenuation of low-side image with 10.7 MHz



b. Attenuation of low-side 455 kHz image

Fig 2. Effects of pre-selection on images

If the single conversion architecture of Figure 1 were implemented with a 455 kHz IF, any interfering image would be received almost as well as the desired frequency. For this reason, dual conversion, as shown in Figure 3, has been popular.

In the application of Figure 3, the first IF must be high enough to permit the pre-selector to reject the images of the first mixer and must have a narrow enough bandwidth that the second mixer images and the intermod products due to the first mixer can be attenuated. There is more to it than that, but those are the basics. The multiple conversion heterodyne works well, but — as Figure 3 suggests — compared to Figure 2 it is more complicated. Why then, don't we use the approach of Figure 2?

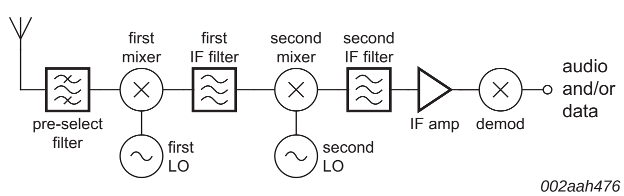


Fig 3. Dual conversion

3. The problem

Historically there has been a problem: stability! Commercially available integrated IF amplifiers have been limited to about 60 dB of gain. Higher discrete gain was possible if each stage was carefully shielded and bypassed, but this can become a nightmare on a production line. With so little IF gain available, in order to receive signals of less than 10 μV it was necessary to add RF gain and this, in turn, meant that the mixer must have good large signal handling capability. The RF gain added expense, the high-level mixer added expense, both added to the potential for instabilities, so the multiple conversion started looking good again.

But why is instability such a problem in a high gain, high IF strip? There are three basic mechanisms. First, ground and the supply line are potentially feedback mechanisms from stage-to-stage in any amplifier. Second, output pins and external components create fields which radiate back to inputs. Third, layout capacitances become feedback mechanisms. Figure 4 shows the fields and capacitances symbolically.

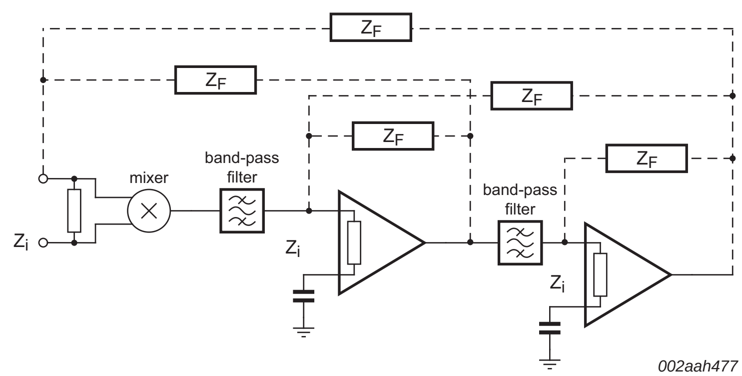


Fig 4. Feedback paths

If Z_F represents the impedance associated with the circuit feedback mechanisms (stray capacitances, inductances and radiated fields), and Z_i is the equivalent input impedance, a divider is created. This divider must have an attenuation factor greater than the gain of the amplifier if the amplifier is to remain stable.

- If gain is increased, the input-to-output isolation factor must be increased.
- As the frequency of the signal or amplifier bandwidth increases, the impedance of the layout capacitance decreases, reducing the attenuation factor.

4. The solution

The SA602A is a double balanced mixer suitable for input frequencies in excess of 500 MHz. It draws 2.5 mA of current. The SA604A is an IF strip with over 100 dB of gain and a 25 MHz small signal bandwidth. It draws 3.5 mA of current. The circuits in this application note demonstrate ways to take advantage of this low current and 75 dB or more of the SA604A gain in receivers and IF strips. Good layout, impedance planning and gain distribution are used to achieve stable performance.

4.1 The mixer

The SA602A is a low-power VHF mixer with built-in oscillator. The equivalent circuit is shown in Figure 5. The basic attributes of this mixer include \conversion gain to frequencies greater than 500 MHz, a noise figure of 4.6 dB at 45 MHz, and a built-in oscillator which can be used up to 200 MHz. LO can be injected.

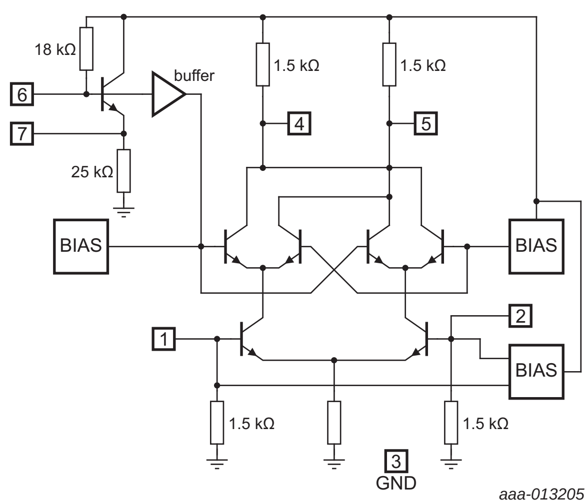


Fig 5. SA602A equivalent circuit

For best performance with any mixer, the impedance/noise match must be optimized. The input impedance of the SA602A is high, typically 3 kΩ in parallel with 3 pF. This is not an easy match from 50 Ω. In each of the examples which follow, an equivalent 50 : 1.5 k match was used. This compromise of noise, loss, and match yielded good results. It can be improved upon. Match to crystal filters require special attention, but are not given focus in this application note.

This oscillator is a single transistor with an internal emitter follower driving the mixer. For best mixer performance, the LO level needs to be approximately 220 mV_{RMS} at the base of the oscillator transistor (pin 6). A number of oscillator configurations are presented at the end of this application note. In each of the prototypes in the application note, the LO source was a signal generator. Thus a 51 Ω resistor was used to terminate the signal generator. The LO is then coupled to the mixer through a DC blocking capacitor. The signal generator is set for 0 dBm. The impedance at the LO input (pin 6) is approximately 20 kΩ. Thus, required power is very low, but 0 dBm across 51 Ω does provide the necessary 220 mV_{RMS}.

The outputs of the SA602A are loaded with 1.5 kΩ internal resistors. This makes interface to 455 kHz ceramic filters very easy. Other filter types are addressed in the examples.

4.2 The IF strip

The basic functions of the SA604A are ordinary at first glance: limiting IF, quadrature detector, signal strength meter, and mute switch. However, the performance of each of these blocks is superb. The IF has 100 dB of gain and 25 MHz bandwidth. This feature is exploited in the examples. The signal strength indicator has a 90 dB log output characteristic with very good linearity. There are two audio outputs with greater than 300 kHz bandwidth (one can be muted greater than 70 dB). The total supply current is typically 3.5 mA. This is the other factor which permits high gain and high IF.

Figure 6 shows an equivalent circuit of the SA604A. Each of the IF amplifiers has a 1.6 kΩ input impedance. The input impedance is achieved by splitting a DC feedback bias resistor. The input impedance is manipulated in each of the examples to aid stability.

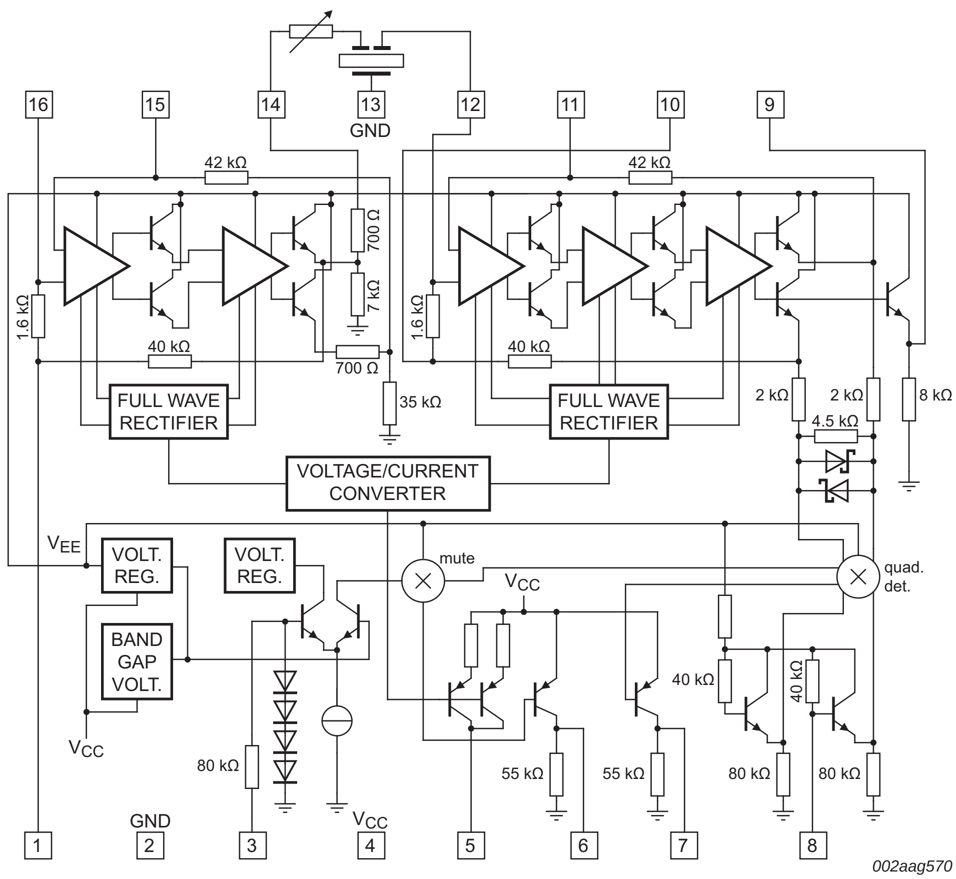


Fig 6. SA604A equivalent circuit

4.3 Basic considerations

In each of the circuits presented, a common layout and system methodology is used. The basic circuit is shown symbolically in Figure 7.

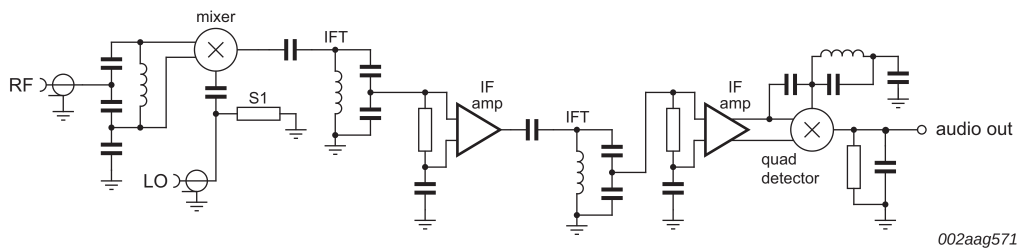


Fig 7. Symbolic circuit

At the input, a frequency selective transformation from 50 Ω to 1.5 kΩ permits analysis of the circuit with an RF signal generator. A second generator provides LO. This generator is terminated with a 51 Ω resistor. The output of the mixer and the input of the first limiter are both high-impedance (1.5 kΩ nominal). As indicated previously, the input impedance of the limiter must be low enough to attenuate feedback signals. So, the input impedance of the first limiter is modified with an external resistor. In most of the examples, a 430 Ω external resistor was used to create a 330 Ω input impedance (430 Ω || 1.5 kΩ). The first IF filter is thus designed to present 1.5 kΩ to the mixer and 330 Ω to the first limiter.

The same basic treatment was used between the first and second limiters. However, in each of the 10.7 MHz examples this inter-stage filter is not an L/C tank — it is a ceramic filter. This is explained in the first example. After the second limiter, a conventional quadrature detector demodulates the FM of FSK information from the carrier and a simple low-pass filter completes the demodulation process at the audio outputs.

As mentioned, a single layout was used for each of the examples. The board artwork is shown in Figure 8. Special attention was given to:

1. Creating a maximum amount of ground plane with connection of the component side and solder side ground at locations all over the board.
2. Careful attention was given to keeping a ground ring around each of the gain stages. The objective was to provide a shunt path to ground for any stray signal which might feed back to an input.
3. Leads were kept short and relatively wide to minimize the potential for them to radiate or pick up stray signals.
4. RF bypass was done as close as possible to supply pins and inputs with good (10 μF) tantalum capacitor completing the system bypass.

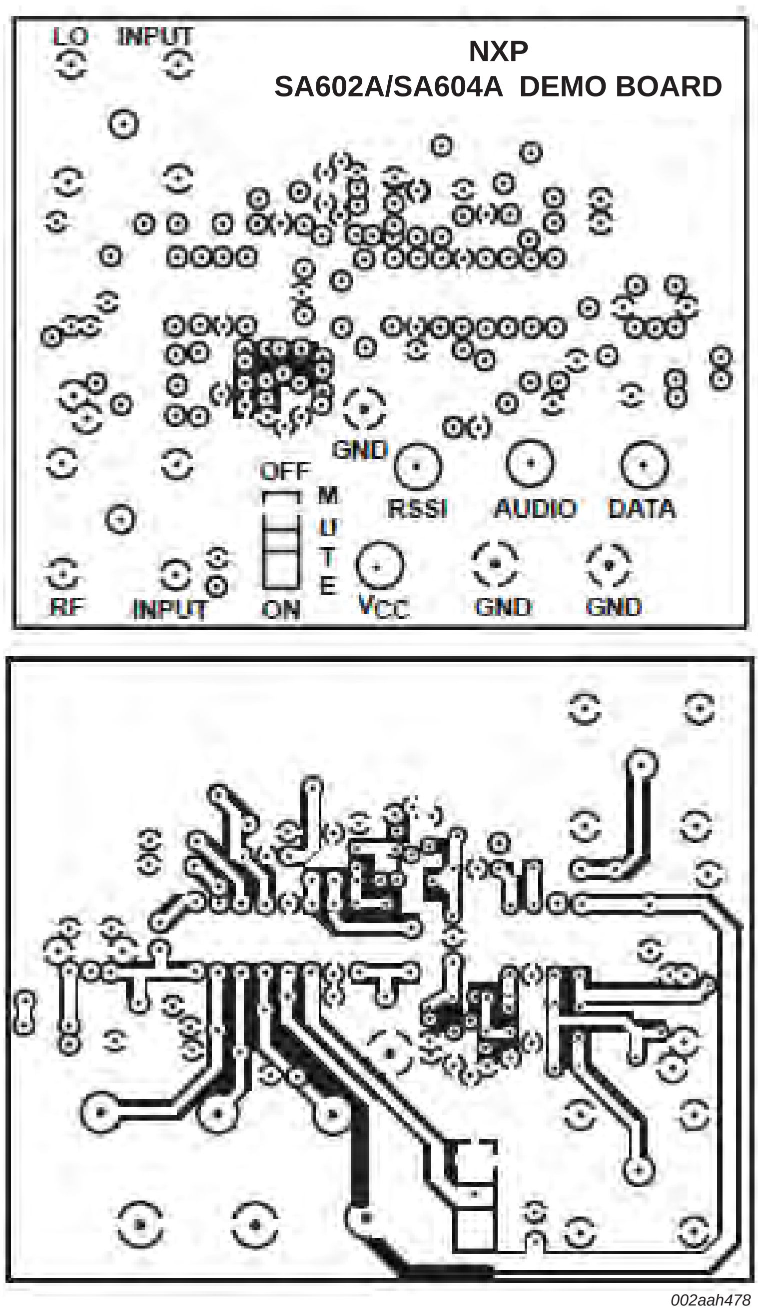


Fig 8. **Circuit board layout**

5. Example: 45 MHz to 10.7 MHz narrowband

As a first example, consider conversion from 45 MHz to 10.7 MHz. There are commercially available filters for both frequencies, so this is a realistic combination for a second IF in a UHF receiver. This circuit can also be applied to cordless telephone or short range communications at 46 MHz or 49 MHz. The circuit is shown in Figure 9.

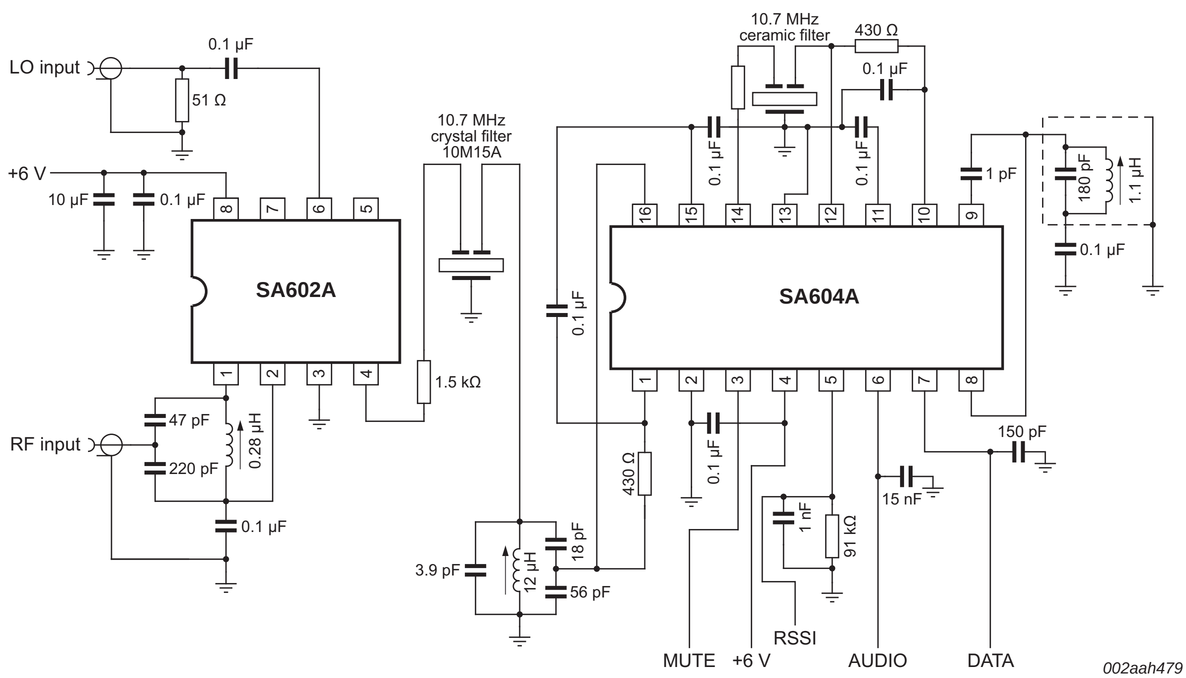


Fig 9. SA602A/SA604A demonstration circuit with RF input of 45 MHz and IF of 10.7 MHz ± 7.5 kHz

The 10.7 MHz filter chosen is a type commonly available for 25 kHz channel spacing. It has a 3 dB bandwidth of 15 kHz and a termination requirement of 3 kΩ / 2 pF. To present 3 kΩ to the input side of the filter, a 1.5 kΩ resistor was used between the SA602A output (which has a 1.5 kΩ impedance) and the filter. Layout capacitance was close enough to 2 pF that no adjustment was necessary. This series-resistance approach introduces an insertion loss which degrades the sensitivity, but it has the benefit of simplicity.

To improve sensitivity, the secondary side of the crystal filter is terminated with a 10.7 MHz tuned tank. The capacitor of the tank is tapped to create a transformer with the ratio for 3k : 330. With the addition of the 430 Ω resistor in parallel with the SA604A 1.6 kΩ internal input resistor, the correct component of resistive termination is presented to the crystal filter. The inductor of the tuned load is adjusted off resonance enough to provide the 2 pF capacitance needed. (Actual means of adjustment was for best audio during alignment).

If appropriate or necessary for sensitivity, the same type of tuned termination used for the secondary side of the crystal filter can also be used between the SA602A and the filter. If this is desired, the capacitors should be ratio 1.5 k : 3 k. Alignment is more complex with tuned termination on both sides of the filter. This approach is demonstrated in the fourth example.

A ceramic filter is used between the first and second limiters. It is directly connected between the output of the first limiter and the input of the second limiter. Ceramic filters act much like ceramic capacitors, so direct connection between two circuit nodes with different DC levels is acceptable. At the input to the second limiter, the impedance is again reduced by the addition of a 430 Ω external resistor in parallel with the internal 1.6 kΩ input load resistor. This presents the 330 Ω termination to the ceramic filter which the manufacturers recommend.

On the input side of the ceramic filter, no attempt was made to create a match. The output impedance of the first limiter is nominally 1 kΩ. Crystal filters are tremendously sensitive to correct match. Ceramic filters are relatively forgiving. A review of the manufacturers' data shows that the attenuation factor in the passband is affected with improper match, but the degree of change is small and the passband stays centered. Since the principal selectivity for this application is from the crystal filter at the input of the first limiter, the interstage ceramic filter only has to suppress wideband noise. The first filter's passband is right in the center of the ceramic filter passband. (The crystal filter passband is less than 10 % of the ceramic filter passband). This passband relationship is illustrated in Figure 10.

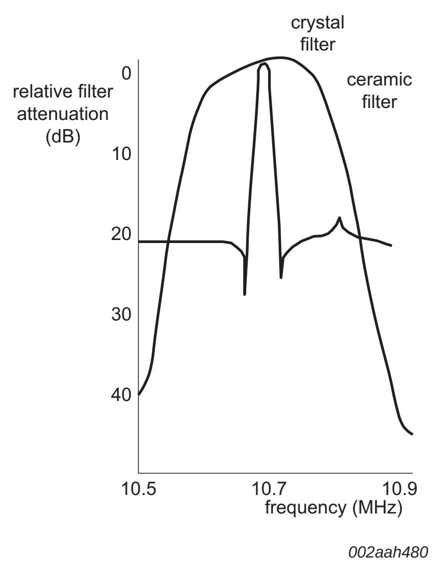
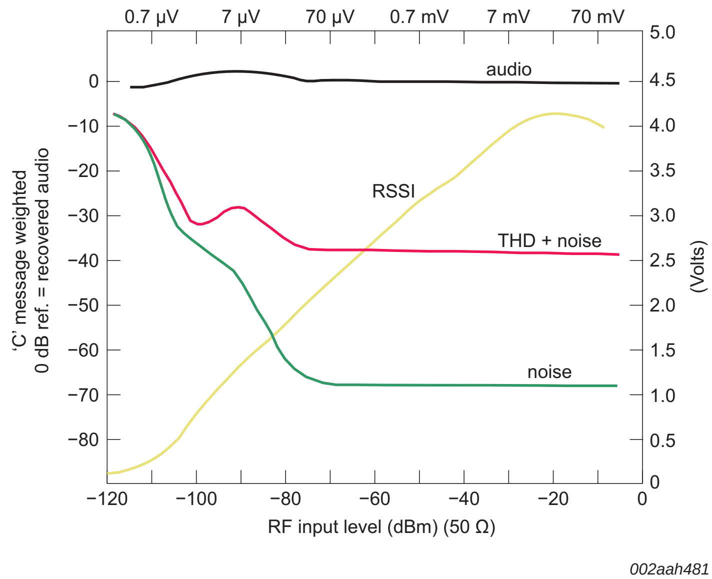


Fig 10. Passband relationship

After the second limiter, demodulation is accomplished in the quadrature detector. Quadrature criteria is not the topic of this application note, but it is noteworthy that the choice of loaded Q affects performance. The SA604A is specified at 455 kHz using a quadrature capacitor of 10 pF and a tuning capacitor of 180 pF. (180 pF gives a loaded Q of 20 at 455 kHz). A careful look at the quadrature equations (Ref. 3) suggests that at 10.7 MHz a value of about 1 pF should be substituted for the 10 pF at 455 kHz.

The performance of this circuit is presented in Figure 11. The –12 dB SINAD (ratio of Signal-to-Noise And Distortion) was achieved with a 0.6 μV input.



45 MHz RF input

55.7 MHz LO (0 dBm)

10.7 MHz IF

15 kHz IF bandwidth

7 kHz deviation

Fig 11. VHF or UHF second conversion (narrowband)

6. Example: 90 MHz to 21.4 MHz narrowband

This second example, like the first, used two frequencies which could represent the intermediate frequencies of a UHF receiver. This circuit can also be applied to VHF single conversion receivers if the sensitivity is appropriate. The circuit is shown in Figure 12.

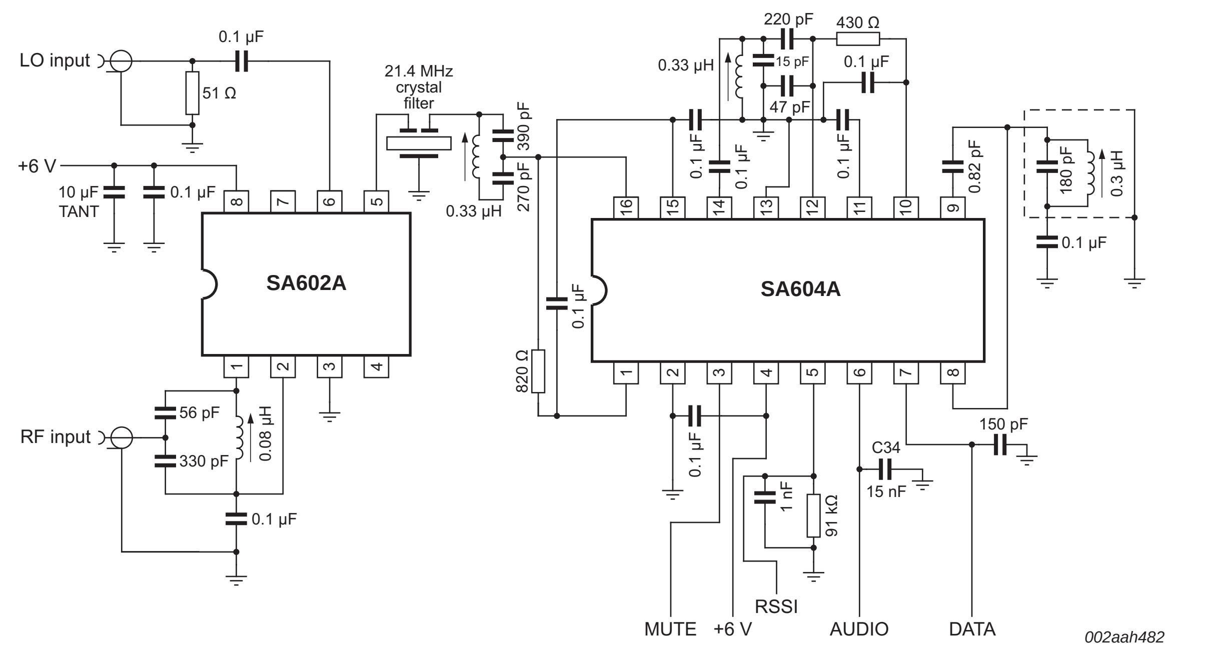
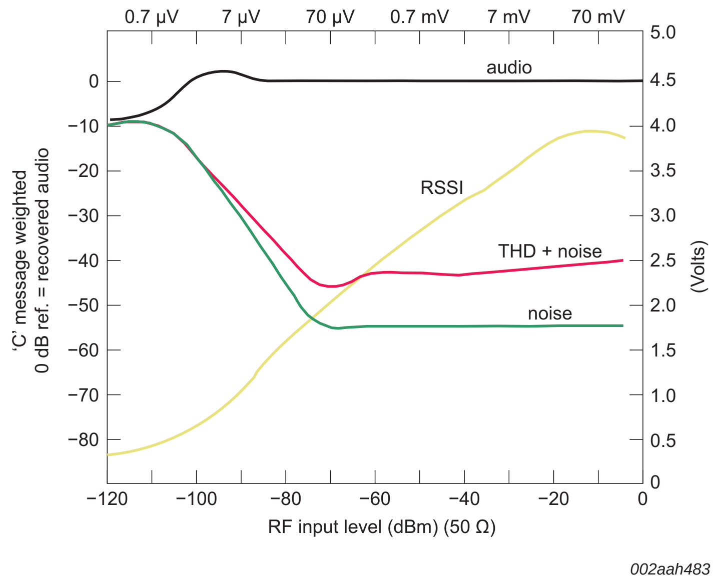


Fig 12. SA602A/SA604A demonstration circuit with RF input of 90 MHz and IF of 21.4 MHz ± 7.5 kHz

Most of the fundamentals are the same as explained in the first example. The 21.4 MHz crystal filter has a 1.5 kΩ/2 pF termination requirement so direct connection to the output of the SA602A is possible. With strays, there are probably more than 2 pF in this circuit, but the performance is good nonetheless. The output of the crystal filter is terminated with a tuned impedance-step-down transformer as in the previous example. Interstage filtering is accomplished with a 1kΩ : 330 Ω step-down ratio. (Remember, the output of the first limiter is 1 kΩ and a 430Ω resistor has been added to make the second limiter input 330 Ω). A DC blocking capacitor is needed from the output of the first limiter. The board was not laid out for an interstage transformer, so an 'XACTO' knife was used to make some minor modifications. Figure 13 shows the performance. The +12 dB SINAD was with 1.6 µV input.



90 MHz RF input

68.6 MHz LO (0 dBm)

21.4 MHz IF

15 kHz IF bandwidth

7 kHz deviation

Fig 13. UHF second conversion (narrowband) or VHF single conversion (narrowband)

7. Example: 100 MHz to 10.7 MHz wideband

This example represents three possible applications:

- Low cost, sensitive FM broadcast receivers
- SCA (Subsidiary Communications Authorization) receivers
- Data receivers.

The circuit schematic is shown in Figure 14. While this example has the greatest diversity of application, it is also the simplest. Two 10.7 MHz ceramic filters were used. The first was directly connected to the output of the SA602A. The second was directly connected to the output of the first IF limiter. The secondary sides of both filters were terminated with 330 Ω as in the two previous examples. While the filter band-pass skew of this simple single conversion receiver might not be tolerable in some applications, to a first order the results are excellent. (Please note that sensitivity is measured at +20 dB in this wideband example.) Performance is illustrated in Figure 15. +20 dB SINAD was measured with 1.8 μV input.

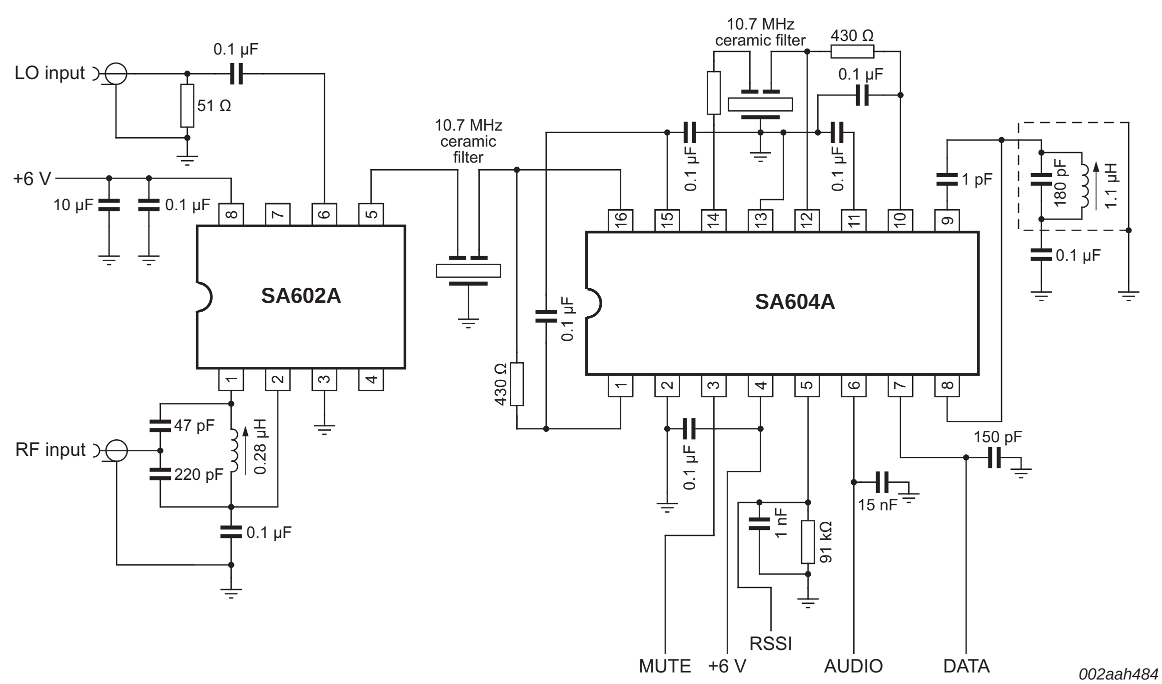
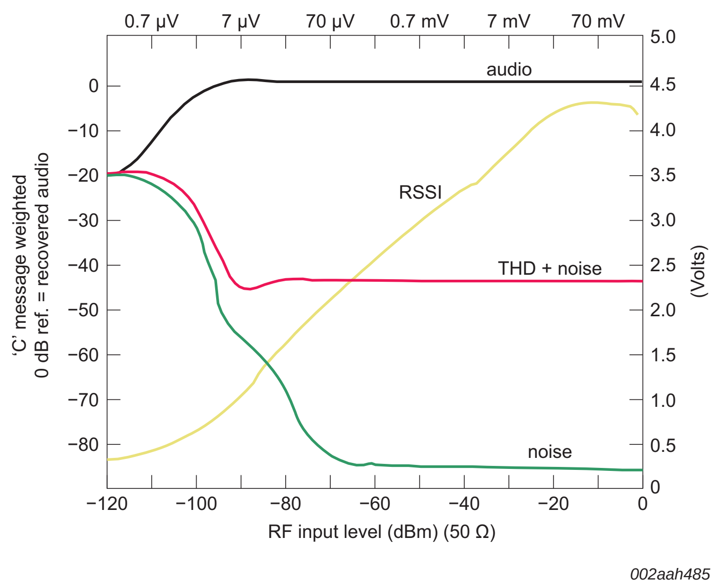


Fig 14. SA602A/SA604A demonstration circuit with RF input of ~100 MHz and IF of 10.7 MHz ± 140 kHz



94.7 MHz RF input

84 MHz LO (0 dBm)

10.7 MHz IF

280 kHz IF bandwidth

75 kHz deviation

Fig 15. FM broadcast receiver (wideband)

8. Example: 152.2 MHz to 10.7 MHz narrowband

In this example (see Figure 16) a simple, effective, and relatively sensitive single conversion VHF receiver has been implemented. All of the circuit philosophy has been described in previous examples. In this circuit, tuned-transformed termination was used on the input and output sides of the crystal filter. Performance is shown in Figure 17. The +12 dB SINAD sensitivity was 0.9 μV.

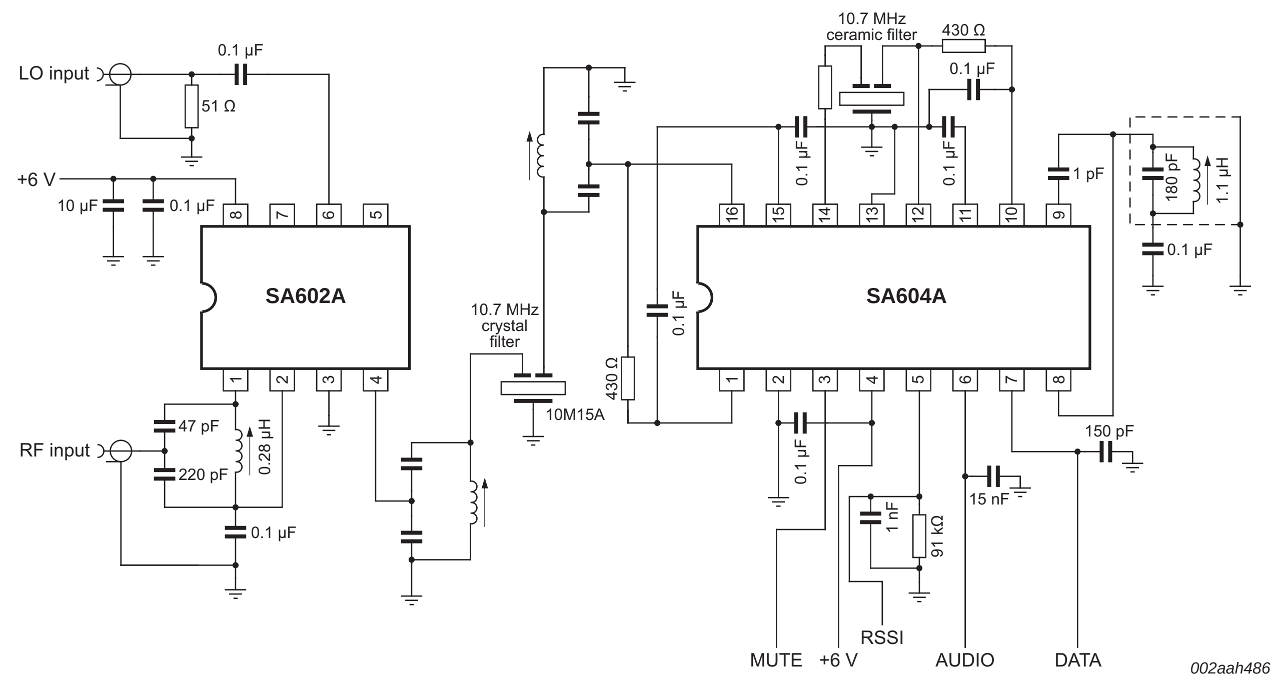
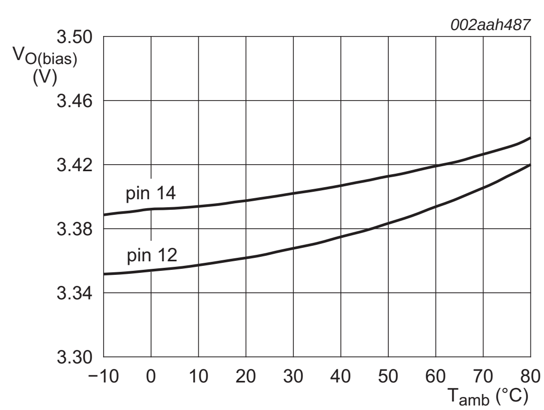


Fig 16. SA602A/SA604A demonstration circuit with RF input of 152.2 MHz and IF of 10.7 MHz ± 7.5 kHz

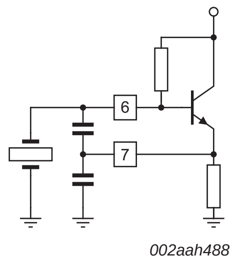


V_{CC} = 5.0 V; 152.2 MHz RF input; 141.5 MHz LO (0 dBm); 10.7 MHz IF; 15 kHz IF bandwidth; 7 kHz deviation.

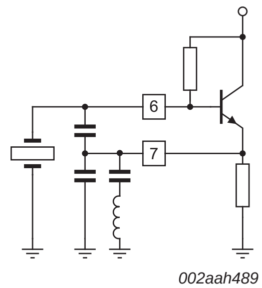
Fig 17. VHF single conversion (narrow band)

9. Oscillators

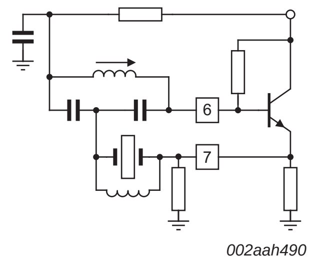
The SA602A contains an oscillator transistor which can be used to frequencies greater than 200 MHz. Some of the possible configurations are shown in Figure 18 and Figure 19.



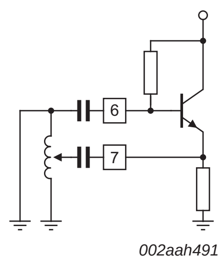
a. Fundamental Colpitts crystal



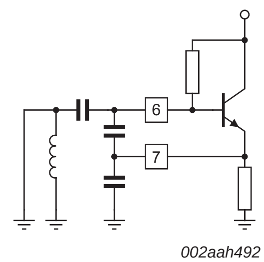
b. Overtone Colpitts crystal



c. Overtone Butler crystal

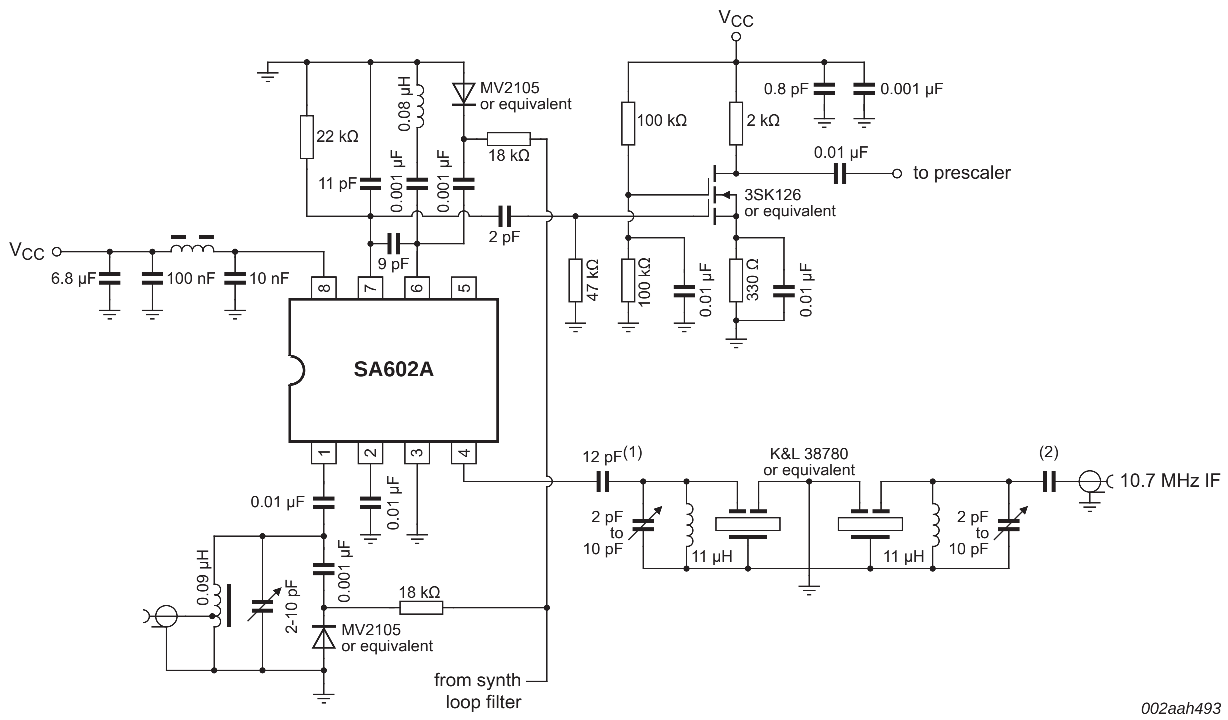


d. Hartley L/C tank



e. Colpitts L/C tank

Fig 18. Oscillator configurations



(1) Permits impedance match of SA602A output of 1.8 kΩ || 8 pF to 3.0 kΩ filter impedance.

(2) Choose for impedance match to

Fig 19. Typical varactor tuned application

9.1 L/C

When using a synthesizer, the LO must be externally buffered. Perhaps the simplest approach is an emitter follower with the base connected to Pin 7 of the SA602A. The use of a dual-gate MOSFET improves performance because it presents a fairly constant capacitance at its gate and because it has very high reverse isolation.

9.2 Crystal

With both of the Colpitts crystal configurations, the load capacitance must be specified. In the overtone mode, this can become a sensitive issue since the capacitance from the emitter to ground is actually the equivalent capacitive reactance of the harmonic selection network. The Butler oscillator uses an overtone crystal specified for series mode operation (no parallel capacitance). It may require an extra inductor (L_o) to null out C_o of the crystal, but otherwise is fairly easy to implement (see references).

The oscillator transistor is biased with only 220 μA. In order to assure oscillation in some configurations, it may be necessary to increase transconductance with an external resistor from the emitter to ground. 10 kΩ to 20 kΩ are acceptable values. Too small a resistance can upset DC bias (see references).

10. Data demodulation

It is possible to change any of the examples from an audio receiver to an amplitude shift keyed (ASK) or frequency shift keyed (FSK) receiver or both with the addition of an external op amp(s) or comparator(s). A simple example is shown in Figure 20. ASK decoding is accomplished by applying a comparator across the Received Signal Strength Indicator (RSSI). The RSSI tracks IF level down to below the limits of the demodulator (–120 dBm RF input in most of the examples). When an in-band signal is above the comparator threshold, the output logic level changes.

FSK demodulation takes advantage of the two audio outputs of the SA604A. Each is a PNP current source type output with 180° phase relationship. With no modulating signal present, the quad tank is tuned for the center of the IF pass band and both audio outputs are loaded with the same value of capacitance. If a signal is received which is frequency shifted from the IF center, one output voltage will increase and the other will decrease by a corresponding absolute value. Thus, if a comparator is differentially connected across the two outputs, a frequency shift in one direction drives the comparator output to one supply rail, and a frequency shift in the opposite direction causes the comparator output to swing to the opposite rail. Using this technique, and L/C filtering for a wide IF bandwidth, NRZ data at rates greater than 4 Mbit/s have been processed with the new SA605.

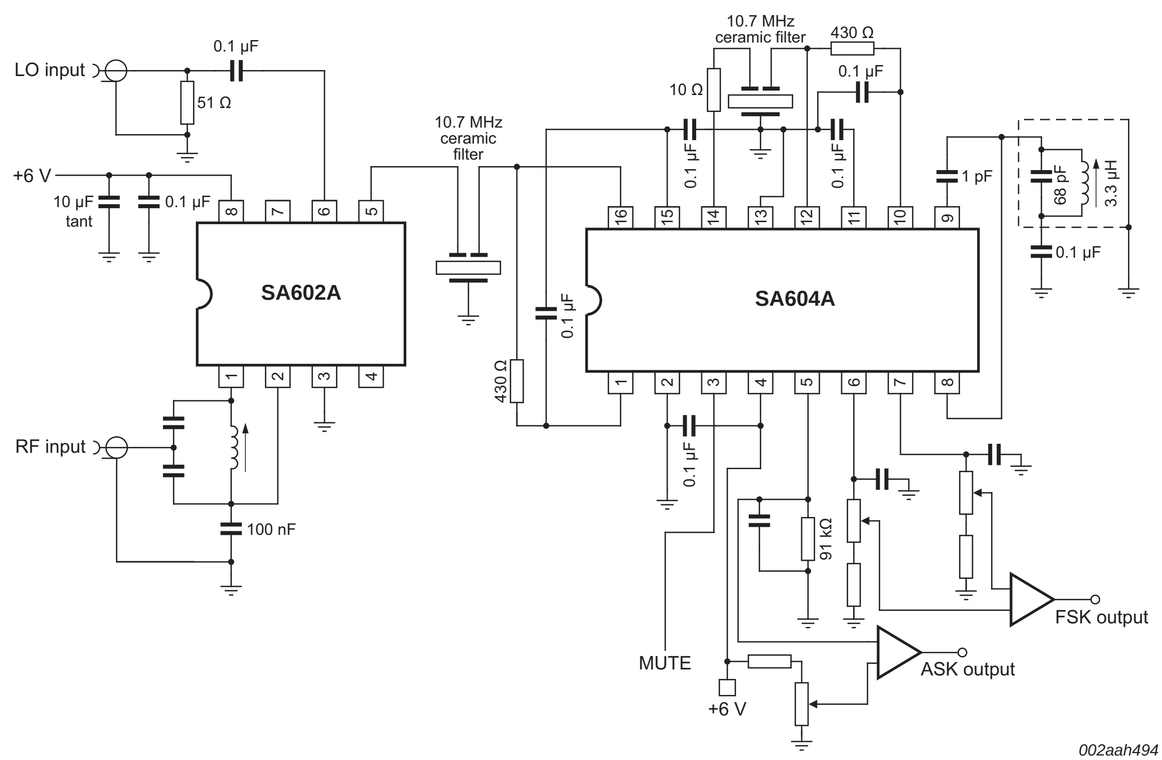


Fig 20. Basic SA602A/SA604A data receiver

11. Summary

The SA602A, SA604A and SA605 provide the RF system designer with the opportunity for excellent receiver or IF system sensitivity with very simple circuitry. IFs at 455 kHz, 10.7 MHz and 21.4 MHz with 75 dB to 90 dB gain are possible without special shielding. The flexible configuration of the built-in oscillator of the SA602A/SA605 add to ease of implementation. Either data or audio can be recovered from the SA604A/SA605 outputs.

12. Abbreviations

Table 1. Abbreviations

Acronym	Description
ASK	Amplitude Shift Keying
FSK	Frequency Shift Keying
IC	Integrated Circuit
IF	Intermediate Frequency
L/C	inductor-capacitor network
LO	Local Oscillator
MOSFET	Metal-Oxide Semiconductor Field-Effect Transistor
NRZ	Non-Return to Zero
RF	Radio Frequency
RMS	Root Mean Squared
RSSI	Received Signal Strength Indicator
SINAD	Signal-to-Noise And Distortion ratio
THD	Total Harmonic Distortion
UHF	Ultra High Frequency
VHF	Very High Frequency

13. References

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15. Contents

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