APPLICATION NOTE

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New low-power single sideband circuits

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INTRODUCTION

Several new integrated circuits now permit RF designers to resurrect old techniques of single-sideband generation and detection. The high cost of multi-pole crystal filters limits the use of the SSB mode to the most demanding applications, yet the advantages of SSB over full-carrier AM and FM are well documented (Ref 1 &2). The use of multi-pole filters can now be circumvented by reviving some older techniques without sacrificing performance. This has been made possible by the availability of some new RF and digital integrated circuits.

DESCRIPTION

Figure 1 shows the frequency spectrum of a 10MHz full-carrier double-sideband AM signal using a 1kHz modulating tone. This well-known type of signal is used by standard AM broadcast radio stations. Full-carrier AM's advantage is that envelope detection can be used in the receiver. Envelope detection is a simple and economical technique because it simplifies receiver circuitry. Figure 2 shows the time domain "envelope" of the same AM signal.

The 1kHz tone example of Figures 1 and 2 serves as a simple illustration of an AM signal. Typically, the sidebands contain complex waveforms for voice or data communications. In the full-carrier double sideband mode (AM), all the modulation information is contained in both sidebands, while the carrier "rides along" without contributing to the transfer of intelligence. Only one sideband without the carrier is needed to effectively transmit the modulation information. This mode is called "single-sideband suppressed carrier". Because of its reduced bandwidth, it has the advantages of improved spectrum utilization, better signal-to-noise ratios at low signal levels, and improved transmitter efficiency when compared with either FM or full-carrier AM. A finite frequency allocation using SSB can support three times the number of channels when compared with comparable FM or AM full-carrier systems.
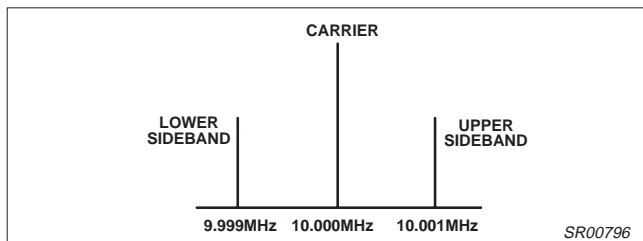

Figure 1. Frequency Domain Display of a 10MHz Carrier AM Modulated by a 1kHz Tone (Spectrum Analyzer Display)
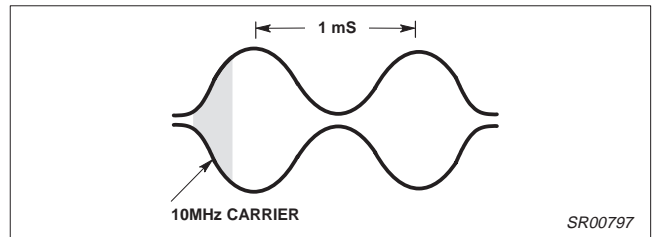

Figure 2. Time Domain Display of the Same Signal Shown in Figure 1. (Oscilloscope Display)

There are three basic methods of single-sideband generation. All three use a balanced modulator to produce a double-sideband suppressed carrier signal. The undesired sideband is then removed by phase and amplitude nulling (the phasing method), high Q multi-pole filters (the filter method), or a "third" method which is a derivation of the phasing technique called here the "Weaver" method for the apparent inventor. The reciprocal of the generator functions is employed to produce sideband detectors. Generators start with audio and produce the SSB signal; detectors receive the SSB signal and reproduce the audio. Since the sideband signal is typically produced at radio frequencies, it can be amplified and applied to an antenna or used as a subcarrier.

Reproduction of the audio signal in a full-carrier AM receiver is simplified because the carrier is present. The signal envelope, which contains the carrier and the sidebands, is applied to a non-linear device (typically a diode). The effect of envelope detection is to multiply the sideband signal by the carrier; this results in the recovery of the audio waveform. The mathematical basis for this process can be understood by studying trigonometric identities.

Since the carrier is not present in the received SSB signal, the receiver must provide it for proper audio detection. This signal from the local oscillator (LO) is applied to a mixer (multiplier) together with the SSB signal and detection occurs. This technique is called product detection and is necessary in all SSB methods. A major problem in SSB receivers is the ability to maintain accurate LO frequencies to prevent spectral shifting of the audio signal. Errors in this frequency will result in a "Donald Duck" sound which can render the signal unintelligible for large frequency errors.

Theory of Single-Sideband Detection

Figures 3 through 8 illustrate the three methods of SSB generation and detection. Since they are reciprocal operations, the circuitry for generation and detection is similar with all three methods. Duplication of critical circuitry is easy to accomplish in transceiver applications by using appropriate switching circuits.
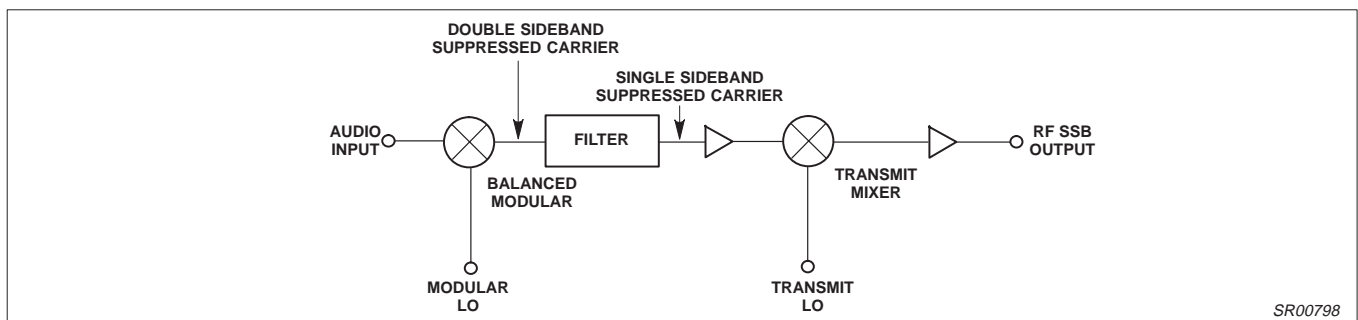

Figure 3.   Filter Method SSB Generator
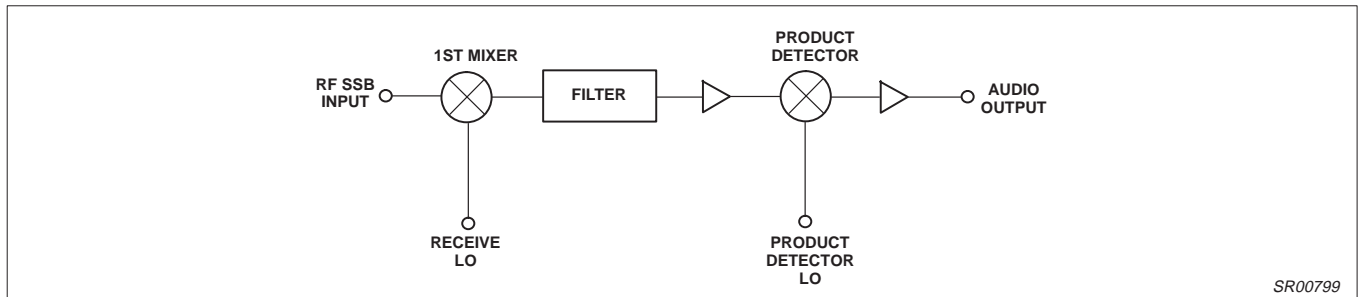
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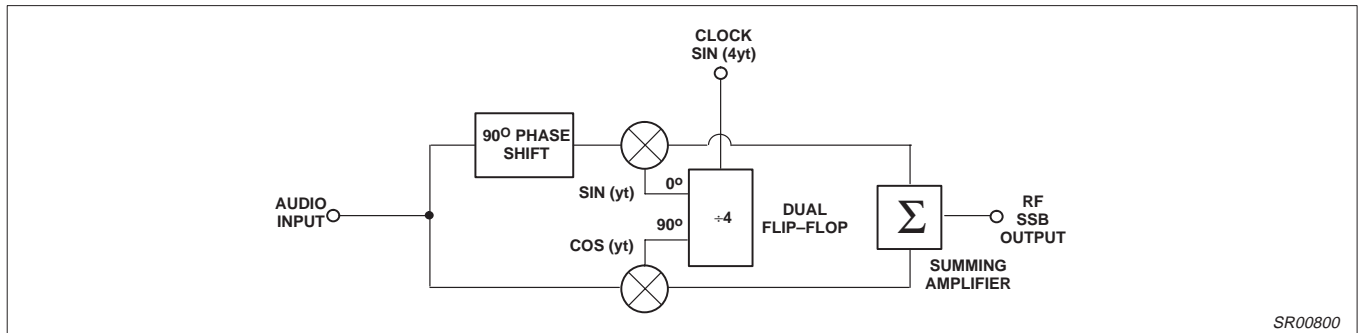

Figure 4. Filter Method SSB Detector

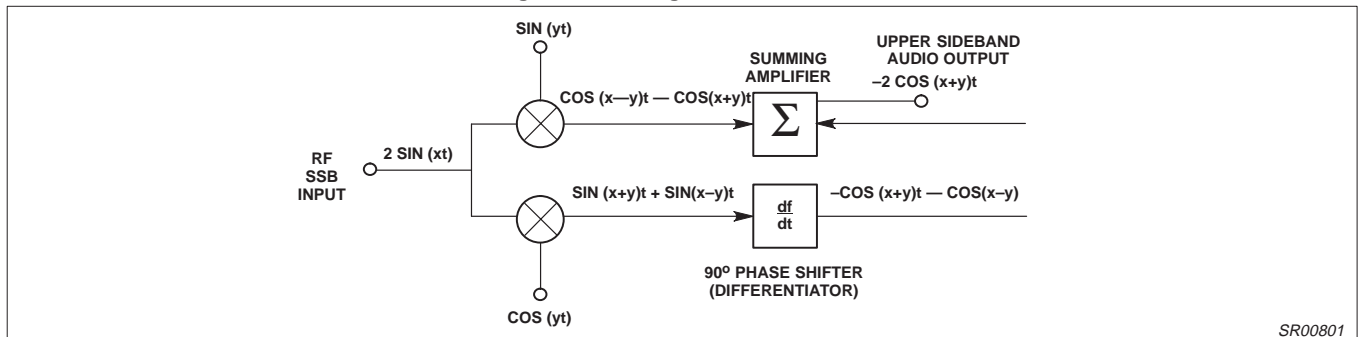**Figure 5. Phasing Method Generator**

Figure 6. Phasing Method Detector with Simplified Mathematical Model

Figures 3 and 4 show the generation and detection techniques employed in the filter method. In the generator a double sideband signal is produced while the carrier is eliminated with the balanced modulator. Then the undesired sideband is removed with a high Q crystal bandpass filter. A transmit mixer is usually employed to convert the SSB signal to the desired output frequency. The detection scheme is the reciprocal. A receive mixer is used to convert the selected input frequency to the IF frequency, where the filter removes the undesired SSB response. Then the signal is demodulated in the product detector. A major drawback to the filter method is the fact that the filter is fixed-tuned to one frequency. This necessitates the receive and transmit mixers for multi-frequency operation.

Figures 5 and 6 show block diagrams of a generator and demodulator which use the phase method. Figure 6 also includes a mathematical model. The input signal (Cos(Xt)) is fed in-phase to two RF mixers where "X" is the frequency of the input signal. The other inputs to the mixers are fed from a local oscillator (LO) in quadrature (Cos(Yt) and Sin(Yt)), where "Y" is the frequency of the LO signal. By differentiating the output of one of the mixers and then summing with the other, a single sideband response is obtained. Switching the mixer output that is differentiated will change the

selected sideband, upper (USB) or lower (LSB). In most cases the mixer outputs will be the audio passband (300 to 3000Hz). Differentiating the passband involves a 90 degree phase shift over more than three octaves. This is the most difficult aspect of using the phasing method for voice band SSB.

For voice systems, difficulty of maintaining accurate broadband phase shift is eliminated by the technique used in Figures 7 and 8. The "Weaver" method is similar to the phasing method because both require two quadrature steps in the signal chain. The difference between the two methods is that the Weaver method uses a low frequency (1.8kHz) subcarrier in quadrature rather than the broad-band 90 degree audio phase shift. The desired sideband is thus "folded over" the 1.8kHz subcarrier and its energy appears between 0 and 1.5kHz. The undesired sideband appears 600Hz farther away between 2.1 and 4.8kHz. Consequently, sideband rejection is determined by a low-pass filter rather than by phase and amplitude balance. A very steep low-pass response in the Weaver method is easier to achieve than the very accurate phase and amplitude balance needed in the phasing method. Therefore, better sideband rejection is possible with the Weaver method than with the phasing method.
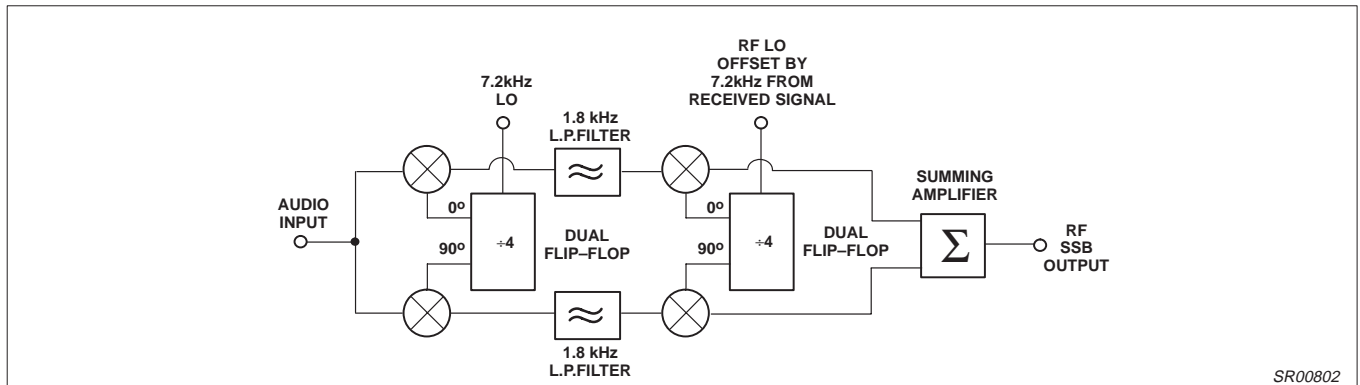
Figure 7. Weaver Method Generator

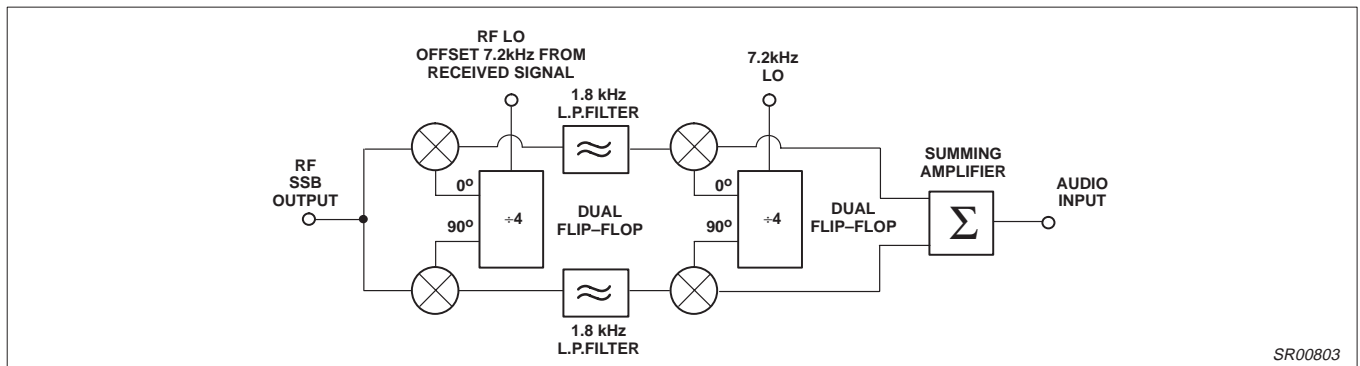**Figure 8. Weaver Method Detector**

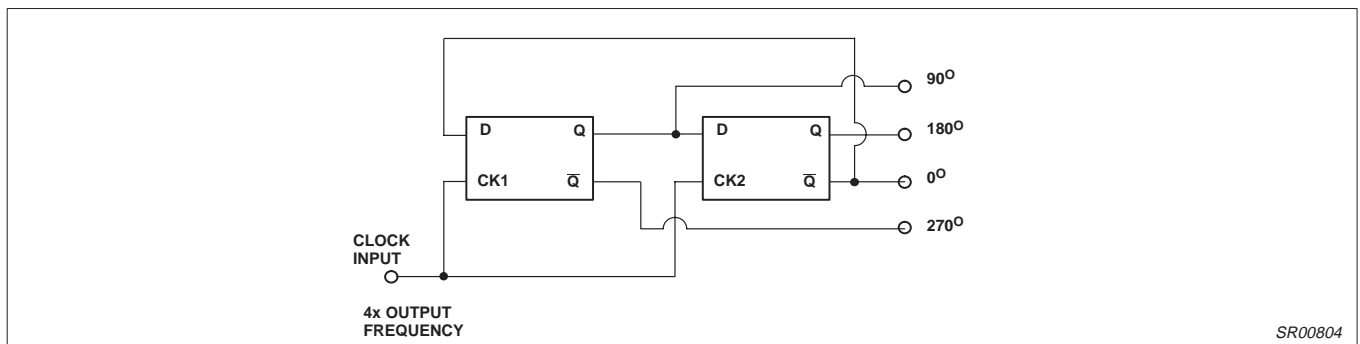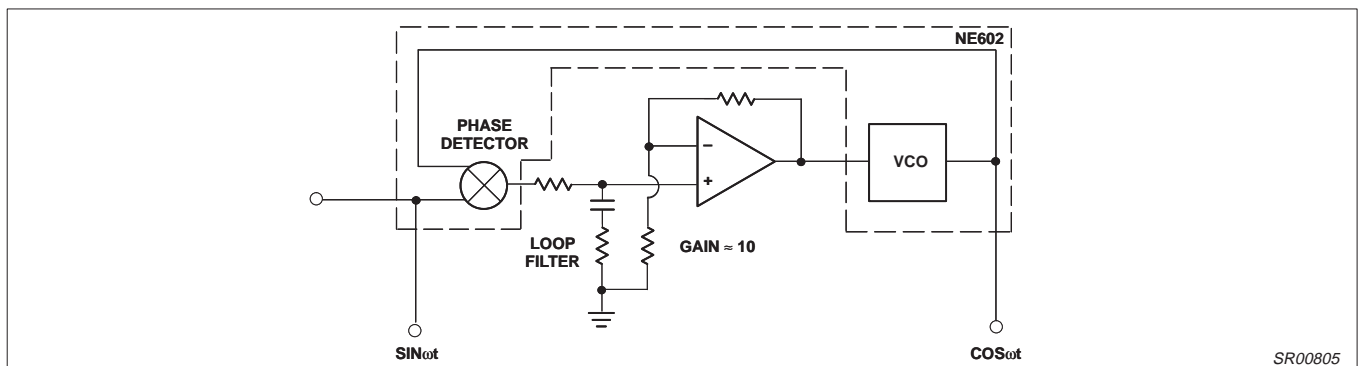**Figure 9. Dual Flip-Flop Quadrature Synthesis**

Figure 10. PLL Quadrature Synthesis

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Quadrature Dual Mixer Circuits

One of the two critical stages in the phasing method and both critical stages in the Weaver method require quadrature dual mixer circuits. Figures 9 and 10 show two methods of obtaining quadrature LO signals for dual mixer applications. Other methods exist for producing quadrature LO signals, particularly use of passive LC circuits. LC circuits will not maintain a quadrature phase relationship when the operating frequency is changed. The two illustrated circuits are inherently broad-banded; therefore, they are far more flexible and do not require adjustment. These circuits are very useful for SSB circuits, but also can be applied to FSK, PSK, and QPSK digital communications systems.

The SA602 is a low power, sensitive, active, double-balanced mixer which shows excellent phase characteristics up to 200MHz. This makes it an ideal candidate for this and many other applications.

The circuit in Figure 9 uses a divide-by-four dual flip-flop that generates all four quadratures. Most of the popular dual flip-flops can be used in different situations. The HEF4013 CMOS device uses very little power and can maintain excellent phase integrity at clock rates up to several megahertz. Consequently, the HEF4013 can be used with the ubiquitous 455kHz intermediate frequency with excellent power economy. For higher clock rates (up to 120MHz for up to 30MHz operation), the fast TTL 74F74 is a good choice. It has been tested to 30MHz operating frequencies with good results (>30 dB SSB rejection). At lower frequencies (5MHz) sideband rejection increases to nearly 40dB with the circuits shown. The ultimate low frequency rejection is mainly a function of the audio phase shifter. Better performance is possible by employing higher tolerance resistors and capacitors.

The circuit in Figure 10 shows another technique for producing a broadband quadrature phase shift for the LO. The advantage of this circuit over the flip-flops is that the clock frequency is identical to the operating frequency; however, phase accuracy is more difficult to achieve. A PLL will maintain a quadrature phase relationship when the loop is closed and the VCO voltage is zero. The DC amplifier will help the accuracy of the quadrature condition by presenting gain to the VCO control circuit. The other problem that can arise is that PLL circuits tend to be noisy. Sideband noise is troublesome in both SSB and FM systems,
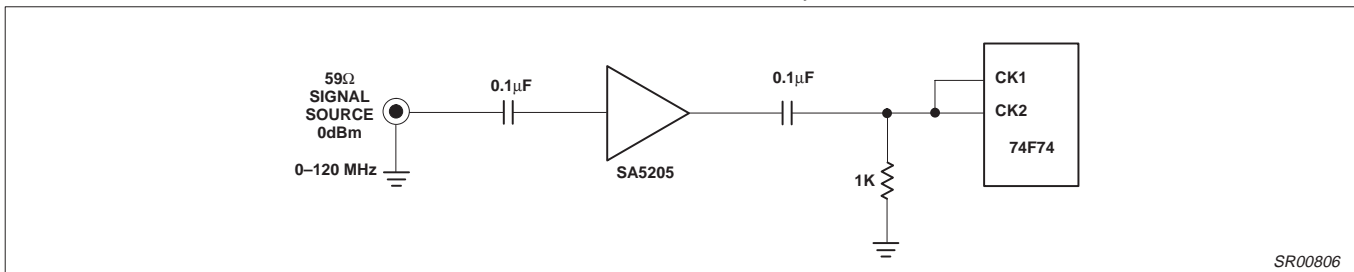

Figure 11. FAST TTL Driver from Analog Signal Source Using SA5205
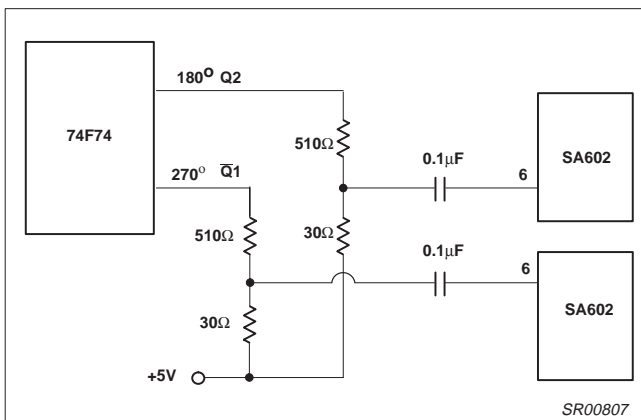

Figure 12. Interface Circuitry Between 74F74 and the SA602s

but SSB is less sensitive to phase noise problems in the LO.

Figure 11 shows a circuit that is effective for driving the 74F74, or other TTL gates, with a signal generator or analog LO. The SA5205 provides about 20dB gain with 50Ω input and output impedances from DC to 450MHz. Minimum external components are required. The 1kΩ resistor is about optimum for "pulling" the input voltage down near the logic threshold. A 50Ω output level of 0dBm can be used to drive the SA5205 and 74F74 to 100MHz. Two SA5205s can be cascaded for even more sensitivity while maintaining extremely wide bandwidth. An advantage of using digital sources for the LO is that low-frequency power supply ripple will not cause hum in the receiver front end. This is a common problem in direct conversion designs.

Figure 12 shows the interface circuitry between the 74F74 and the SA602 LO ports. The total resistance reflects conservative current drain from the 74F74 outputs, while the tap on the voltage divider is optimized for proper SA602 operation. The low signal source impedance further helps maintain phase accuracy, and the isolation capacitor is miniature ceramic for DC isolation.

Audio Amplifiers and Switching

Using active mixers (SA602) in these types of circuits gives conversion gain, typically 18dB. More traditional applications use passive
 diode ring mixers which yield conversion loss, typically 7dB. Consequently, the detected audio level will be about 25dB higher when using the SA602. This fact can greatly reduce the first audio stage noise and gain requirements and virtually eliminate the "microphonic" effect common to direct conversion receivers. Traditional direct conversion receivers use passive audio LC filters at the mixer output and low noise, discrete JFETs or bipolars in the first stages. The very high audio sensitivity required by these amplifiers makes them respond to mechanical vibration – thus the "microphonics" result. The conversion gain allows use of a simple op amp stage (Figure 13) set up as an integrator to eliminate ultra-sonic and RF instability. The SA5534 is well known for its low noise, high dynamic range, and excellent audio characteristics (Reference 12) and makes an ideal audio amp for the 602 detector.

The sideband select function is easily accomplished with an HEF4053 CMOS analog switch. This triple double-pole switch drives the phase network discussed in the next section and also chooses one of two amplitude balance potentiometers, one for each sideband. Figure 14 illustrates this circuit. A buffer op amp is used

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with the two sideband select sections to reduce THD, maintain amplitude integrity, and not change the filter network input resistance values. The gain distribution within both legs of the receiver was found to be very consistent (within 1dB), thus the amplitude balance pots may be eliminated in less demanding applications. The SA602s have excellent gain as well as phase integrity.

Audio Phase Shift Circuits

The two critical stages for the phasing method are a dual quadrature mixer and a broadband audio phase shifter (differentiator). There are several broadband, phase shift techniques available. Figure 15 shows an analog all-pass differential phase shift circuit. When the inputs are shorted and driven with a microphone circuit, the outputs will be 90 degrees out-of-phase over the 300 to 3000Hz band. This "splitting" and phase shift is necessary for the phasing generator. For phasing demodulation the two audio detectors are fed to the two inputs. The outputs are then summed to affect the sideband rejection and audio output.

Standard 1% values are shown for the resistors and capacitors, although better gain tolerances can be obtained with 0.1% laser-trimmed integrated resistors. Polystyrene capacitors are preferred for better value tolerance and audio performance. Two

quad op amps fit nicely into this application. One op amp serves as a switch buffer and the other three form a phasing section. The SA5514 quad op amps perform well for this application. Careful attention to active filter configurations can yield highly linear and very high dynamic range circuits. Yet these characteristics are much easier to achieve at audio than the common IF RF frequencies. This fact, coupled with the lack of IF tuned circuits, shielding, and higher power requirements make audio IF systems attractive indeed.

Figure 16 shows a "tapped" analog delay circuit which uses weighted values of resistors to affect the phase shift. Excellent phase and amplitude balance are possible with this technique, but the price for components is high. It should be stressed that the audio phase shift accuracy and amplitude balance are the limiting factors for SSB rejection when using the phase method; thus the higher cost may be justified in some applications.

Audio Processing

The summing amplifier is a conventional, inverting op amp circuit. It may be useful to configure a low-pass filter around this amplifier, and thus help the sharp audio filters which follow. Audio filters are necessary to shape the desired bandpass. Steep slope audio bandpass filters can be built from switched capacitor filters or from active filters
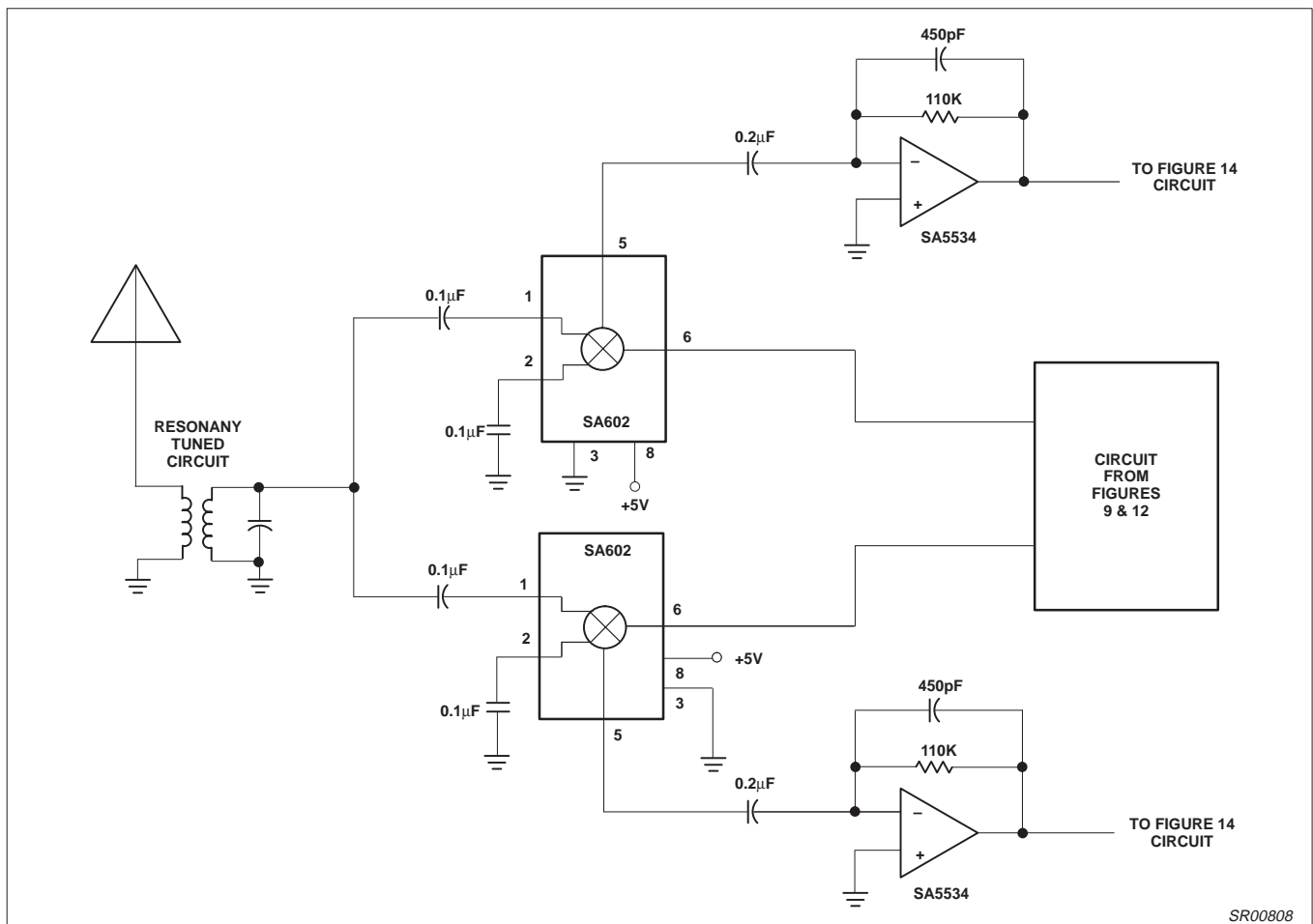

Figure 13. Phasing Method Detector for Direct Conversion Receiver

requiring more op amps. Switched capacitor filters have the disadvantage of requiring a clock frequency in the RF range.

Harmonics can cause interference problems if careful design techniques are not used. Also, better dynamic range is obtained with

active filter techniques using "real" resistors although much work is being done with SCF's and performance is improving.

Direct conversion receivers rely heavily on audio filters for selectivity. Active analog or switched capacitor filters can produce the high Q and dynamic ranges necessary. Signal strength or "S-meters" can be constructed from the SA602's companion part, the SA604. The "RSSI" or "received signal strength indicator" function on the 604 provides a logarithmic response over a 90dB dynamic range and is easy to use at audio frequencies. Finally, the AGC (automatic gain control) function can also be performed in the audio section. Attack and delay times can be independently set with excellent distortion specifications with the SA572 compandor IC. The audio-derived AGC eliminates the need for gain controlling and RF stage, but relies on an excellent receiver front-end dynamic range. In ACSSB (Amplitude Compandored Single-Side Band) systems transmitter compression and receiver expansion are defined by individual system specifications.

Phasing-Filter Technique
High quality SSB radio specifications call for greater than 70dB sideband rejection. Using the circuits described in this paper for the phasing method, rejection levels of 35dB are obtainable with good reliability. Coupled with an inexpensive two-pole crystal or ceramic filter, the 70dB requirement is obtained. Also, the filtering ahead of the SA602 greatly improves the intermodulation performance of the receiver. Figure 17 shows a complete SSB receiver using the Phasing-Filter technique. The sensitivity of the SA602 allows low gain stages and low power consumption for the RF amplifier and first mixer. A new generation of low power CMOS frequency synthesizers is now available from several manufacturers including the TDD1742 and dual chip HEF4750/51 solutions.

Direct Conversion Receiver
The antenna can be connected directly to the input of the SA602 (via a bandpass filter) to form a direct conversion SSB receiver using the phasing method. 35dB sideband rejection is adequate for many applications, particularly where low power and portable battery operation are required. Figure 13 shows a typical circuit for direct conversion applications.

There are many other applications which can make use of SSB technology. Cordless telephones use FM almost exclusively. Eavesdropping could be greatly reduced for systems which employ SSB rather than FM. Furthermore, the better signal-to-noise ratio will extend the range, and battery life will be extended because no carrier is needed.

SSB is also used for subcarriers on microwave links and coaxial lines. Telephone communications networks that use SSB are called FDM or Frequency Domain Multiplex systems. The low power and high sensitivity of the SA602 can offer FDM designers new techniques for system configuration.

Weaver Method Receiver Techniques
The same quadrature dual mixer can be used for the first stage in both the phasing and Weaver method receiver. The subcarrier stage in the Weaver method receiver can use CMOS analog switches (HEF4066) for great power economy. Figure 18 shows a circuit for the subcarrier stage. A 1.8kHz subcarrier requires a 7.2kHz clock frequency. If switched capacitor filters are used for the low-pass and audio filters, a single clock generator can be used for all circuits with appropriate dividers. Furthermore, if the receiver is used as an IF circuit, the fixed LO signal could also be derived from the same clock. This has the added advantage that harmonics from the various circuits will not interfere with the received signal.

Results
The circuit shown in Figures 13, 14, and 15 has a 10dB S/N sensitivity of 0.5μV with a dynamic range of about 80dB. Single-tone audio harmonic distortion is below 0.05% with two-tone intermodulation products below 55dB at RF input levels only 5dB below the 1dB compression point. The sideband rejection is about 38dB at a 9MHz operating frequency. The good audio specifications are a side benefit to direct conversion receivers. When used with inexpensive ceramic or crystal filters, this circuit can provide these specifications with >70dB sideband rejection.

Conclusions
Single sideband offers many advantages over FM and full-carrier double-sideband modulation. These advantages include: more efficient spectrum use, better signal-to-noise ratios at low signal levels, and better transmitter efficiency. Many of the disadvantages can now be overcome by using old techniques and new state-of-the-art integrated circuits. Effective and inexpensive circuits can use direct conversion techniques with good results. 35dB sideband rejection with less than 1μV sensitivity is obtained with the SA602 circuits. 70dB sideband rejection and superior sensitivity are obtained by using phasing-filter techniques. Either the phasing or Weaver methods can be used in either the direct conversion or IF section applications. The filter and phase-filter methods can be used in only the IF application.
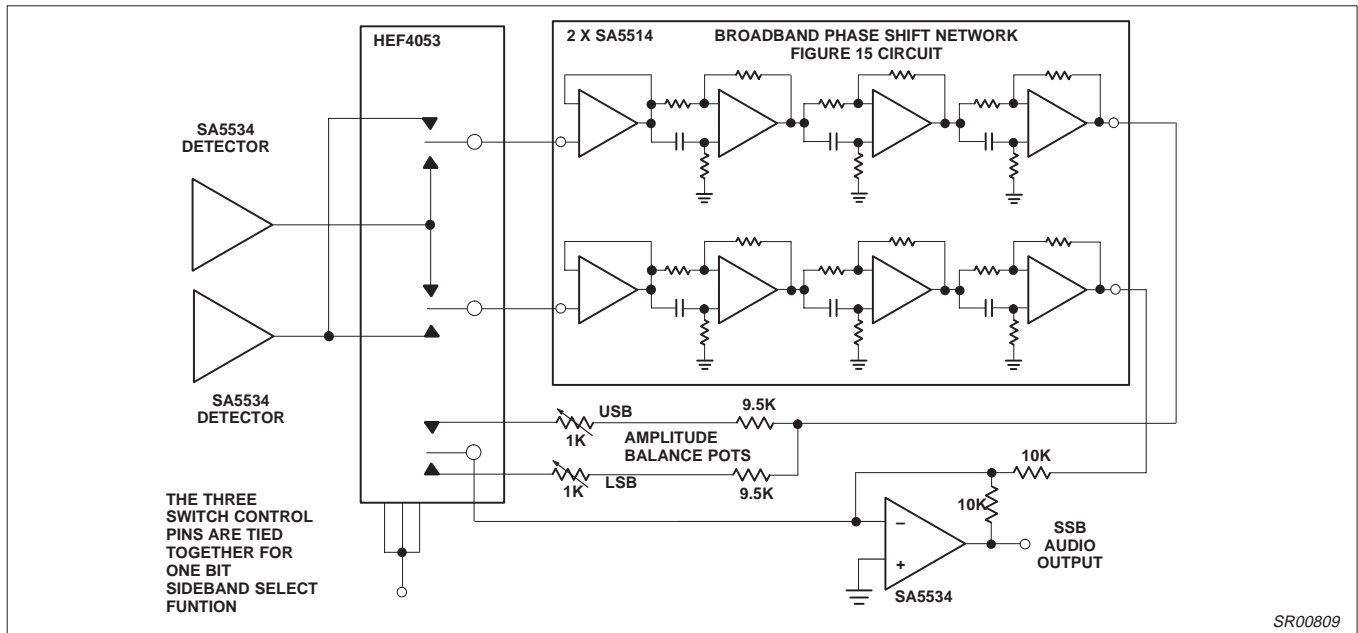
Figure 14. Sideband Select Switching Function

Figure 15.

CLOCK

VOICE
INPUT

TAPPED
DELAY LINE
N SAMPLES

RETICON TAD–32

R_1 R_2 R_3 R_{N-2} $=R_3$ R_{N-1} $=R_2$ $R_N = R_1$

VOICE 90°

WEIGHTED SUM

REFERENCE
CHANNEL

FIXED DELAY
N/2 SAMPLES

VOICE 0°

RETICON TAD–32
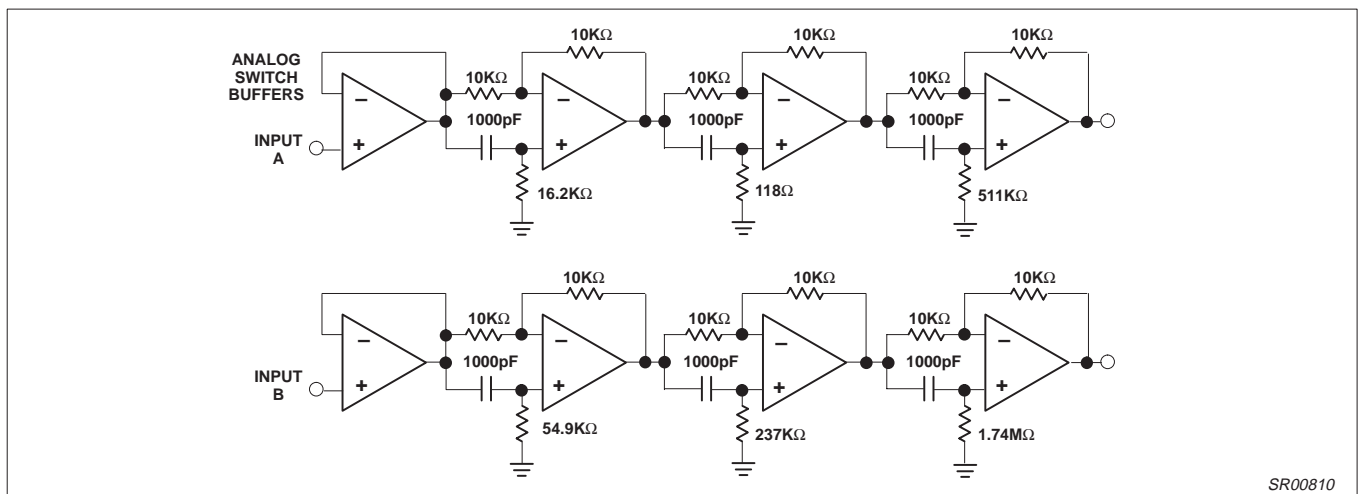
SR00811
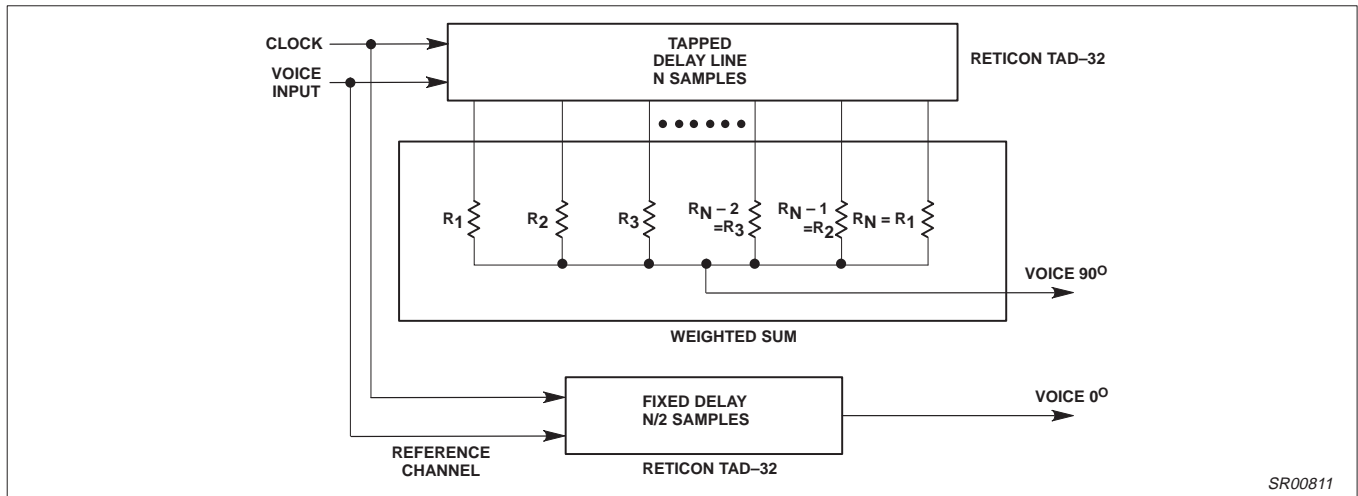
Figure 16. Broadband 90° Audio Phase Shift Technique Using Tapped Delay Line (Reference 4)

1ST MIXER

FRONT
END
FILTERS

FILTER

DIRECT
CONVERSION
PHASING SSB
RECEIVER

AUDIO FILTERS,
S–METER AND
AGC

AUDIO
AMP

SYNTHESIZED
LO

Receivers built using this technique can exhibit excellent characteristics without resorting to expensive multi-pole
filters or an IF amplifier chain.

SR00812
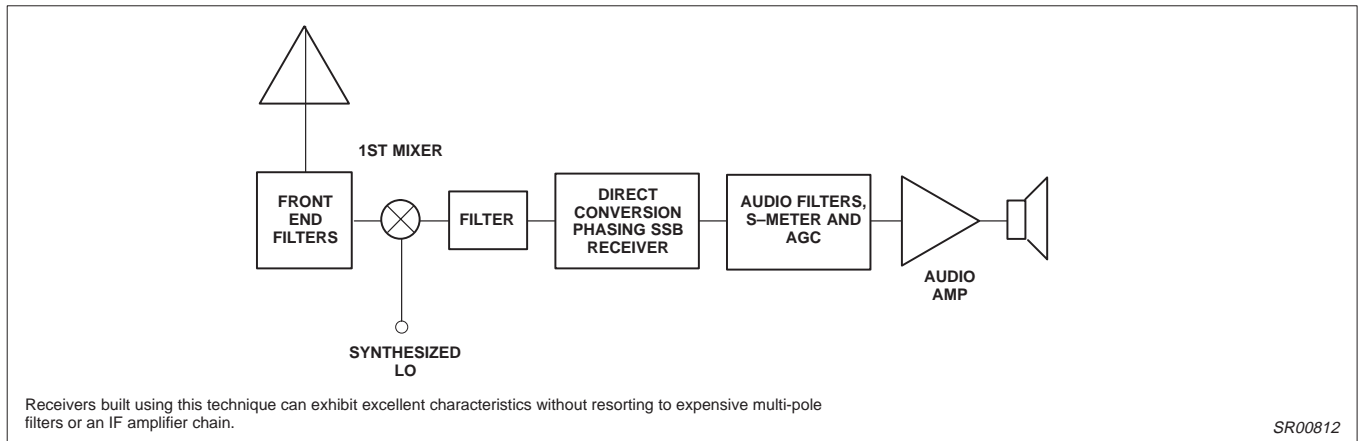
Figure 17. Complete Phasing-Filter Receiver
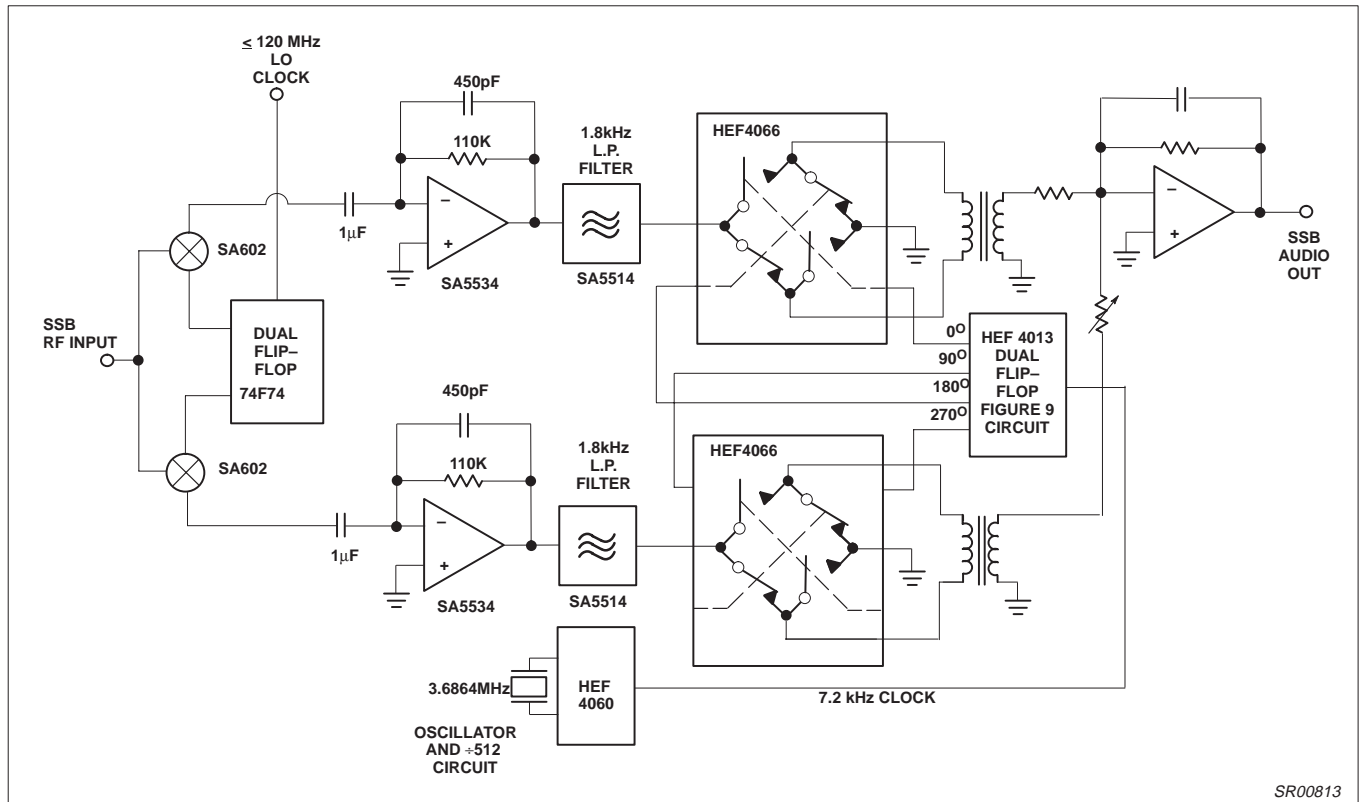
Figure 18. Weaver Method Receiver Concept Example for ≤ 30MHz Operation

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