High-Performance, Single-Signal Direct-Conversion Receivers

The direct-conversion receiver described in August 1992 *QST* featured high dynamic range, low-distortion audio and a super SSB filter shape factor. What more could you ask for? How about adding an image-reject mixer to that basic design for great opposite-sideband rejection?

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Direct-conversion receivers are capable of outstanding performance. The The high-performance receiver described in August 1992 *QST*[1] has now been used from 25 kHz to 6 GHz with excellent results. Nicknamed "R1," that receiver works well and sounds good because it combines several desirable traits:

- high third-order, two-tone dynamic range;
- moderate noise figure;
- low distortion from antenna to speaker leads; and
- 60 dB of output signal-to-noise ratio.

The significant flaw in R1 is that it has no opposite-sideband rejection. This flaw can cause real problems when you try to use the receiver for serious listening. On the crowded HF bands, the opposite sideband is almost always occupied by an interfering signal or two. On VHF and microwaves, the noise in the opposite sideband reduces the signal-to-noise ratio by up to 3 dB.[2]

There are two ways to get rid of the opposite sideband: (1) a narrow filter before the downconverter; or (2) an image-reject mixer. A fixed-frequency direct-conversion receiver preceded by a narrow filter and tunable converter is a conventional superhet. The image-reject mixer is less familiar.

Fig 1 is the block diagram of an image-reject mixer, along with the mathematical relationships between the local oscillator (LO) and signals above and below the LO frequency. Readers comfortable with trigonometric identities may verify that signals above the LO frequency cancel at the output, while signals below the LO frequency add. Less ambitious readers may simply recognize the block diagram of a phasing SSB exciter (from any radio handbook published in the last 30 years), with the arrows turned around.

Old timers will remember the phasing-type SSB rigs of the 1950s and '60s. Those memories may be a bit less than fond. Maintaining amplitude balance to less than 0.1 dB and phase error of less than 1° in a bandswitched, vacuum-tube-and-paper-capacitor transmitter was truly a nightmare. The rigs often sounded bad on the air. Many operators just gave up trying to adjust their rigs after a while and transmitted poor signals until they could afford a filter-type SSB radio.

The situation is reversed today. The required phase and amplitude tolerances are easy to obtain with modern components, and a properly designed phasing exciter has fewer adjustments (and fewer spurs) than a filter rig!

Although image-reject mixers and phasing SSB receivers are scarce in the North American Amateur Radio literature, they are very common in professional circles and in other parts of the world. *SPRAT*, the journal of the G-QRP club, published in England, has presented *three* HF phasing receivers in the past year. Commercially, the Drake R8 shortwave receiver uses an image-reject mixer to downconvert from a VHF first IF to a 50-kHz second IF, and the Kenwood TS-950SDX uses a digital signal processing (DSP) phasing exciter and detector.

R1 Becomes R2

With a wealth of excellent technical material at hand, in particular the outstanding papers by Oppelt,[3,4] I did not have to start

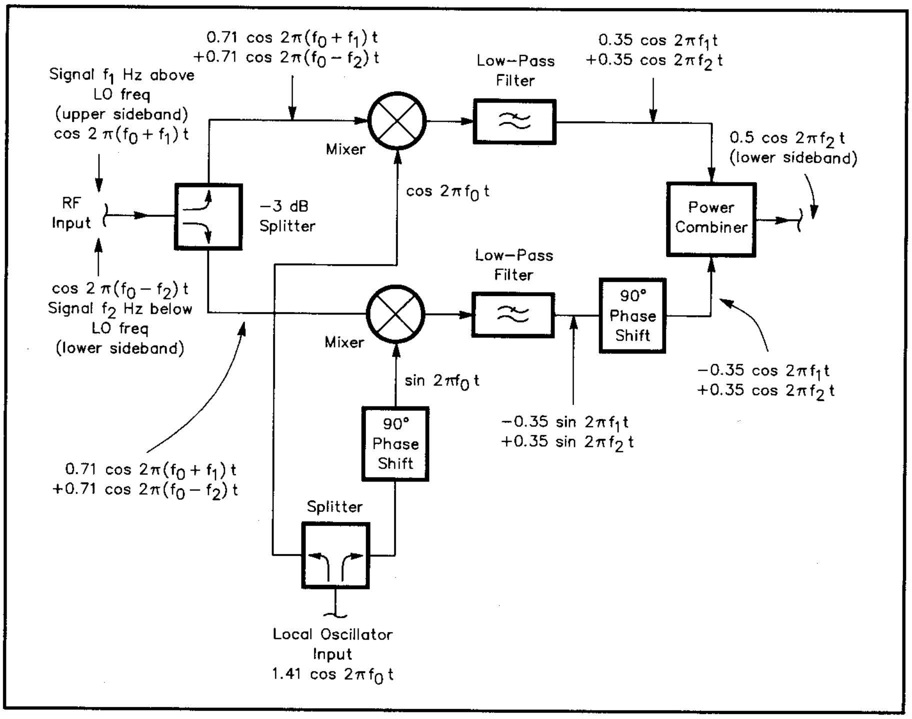

Fig 1—Block diagram of an image-reject mixer. The sines and cosines represent the local oscillator signal and signals above and below the LO frequency. Signals above the LO frequency cancel at the output, while signals below the LO frequency add.

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[1] Notes appear on page 40.

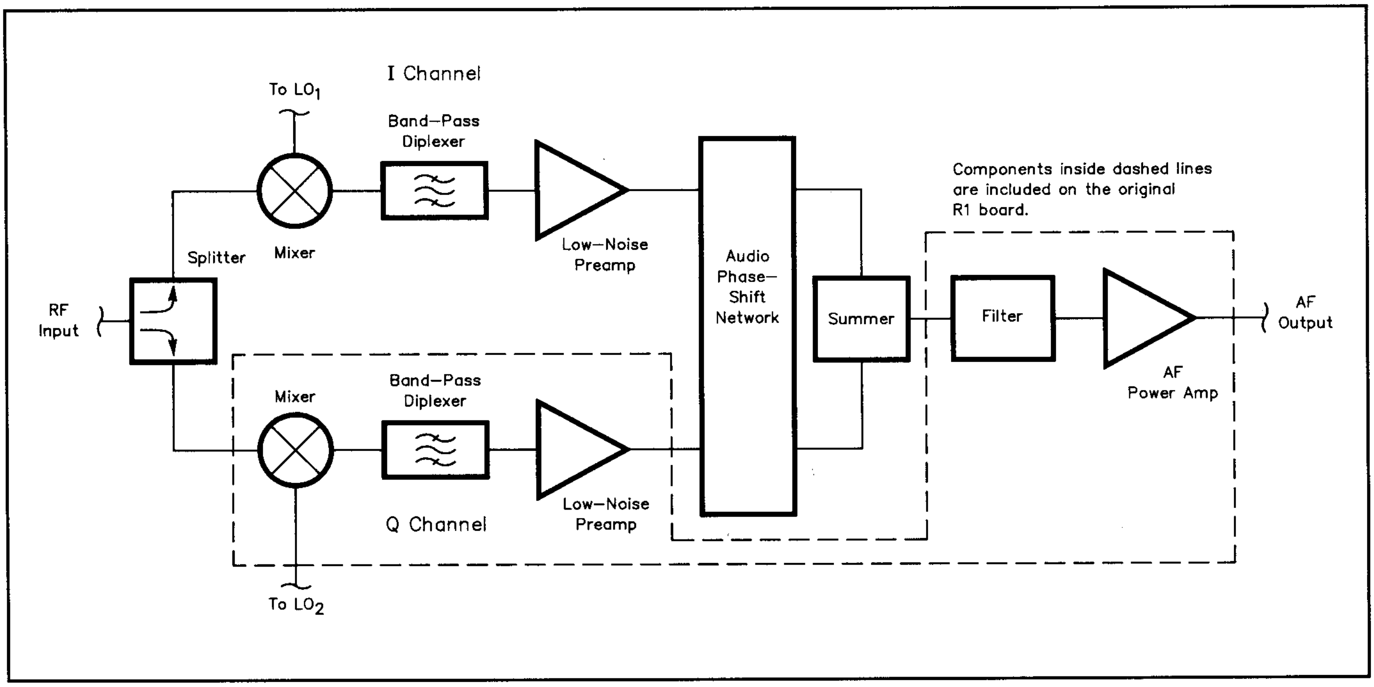


Fig 2—Block diagram of the R2 single-signal direct-conversion receiver. The sections inside the dashed lines are included on the original R1 board. Added are an RF splitter, second mixer diplexer and low-noise preamp, an audio phase-shift network and a summer.

from scratch to design a single-signal direct-conversion receiver. My goal was to add single-signal capability to the R1 board without degrading its otherwise outstanding performance.

Fig 2 is the block diagram of the R1 receiver board, with the necessary blocks added to suppress one sideband. The resulting receiver is called "R2." The additional parts on the R2 board are an RF splitter, a second mixer, diplexer and audio preamp, and an audio phase-shift network and summer using a pair of quad op amps. For maximum flexibility, the 90° phase-shift network for the LO is off the board. The complete schematic is shown in Fig 3. All of the parts fit comfortably on a 3½ × 5-inch double-sided PC board.[5]

Circuit Details

The first component the input signal sees is the RF input splitter. I used a Toko TK2518 because it's cheap ($2), small, and available from Digi-Key.[6] It is rated from 20 MHz to 600 MHz, but I tried one on 40 meters and it works. A Mini-Circuits PSC2-1 splitter worked fine as well, but it is a lot more expensive ($12) and will have to be mounted off the board. For operation below 20 MHz, a home-brew alternative to commercial splitters is shown in Fig 4. I am using the one in Fig 4 on 40 meters.

The RF level at each mixer is 3 dB below the RF-input signal level. That translates to an improvement in the input third-order intercept point. Since there is also a 3-dB (maximum) improvement in signal-to-noise ratio, the R2 board has intrinsically better dynamic range than the R1 board. I haven't built an R2 board with high-level mixers, but based on measurements of the high-level R1 board and the R2 board with SBL-1 mixers, it should have a two-tone, third-order IMD dynamic range of greater than 100 dB.

After the splitter, the input signals are multiplied with the 90°-out-of-phase LOs, filtered and amplified in a pair of identical channels. They are referred to as the I channel (for "*I*n phase") and the Q channel (for "*Q*uadrature," a fancy word for "90° out of phase"). Amplitude and phase-shift errors in the I and Q channels must be carefully controlled. If there is a difference in the conversion loss of the two mixers or the gain of an audio preamp, it can be compensated by adjusting the **AMPLITUDE BALANCE** potentiometer (R30).

If there is an amplitude difference that is a function of frequency, however, R30 can only correct for it at a single audio frequency. Since the diplexer network between the mixer IF port and the audio preamp in each channel has an amplitude and phase characteristic that varies rapidly with frequency over the audio range, it is necessary to carefully select the components marked with asterisks in the schematic. Each component needs to be within 1% of the value of its counterpart in the other channel. The matched pairs may vary from the schematic value by up to 10% with no significant change in performance, *but they must be within 1% of each other*. I bought 10 of each of the marked parts and matched them with an RLC bridge. I obtained four sets matched to within 1%, and built R1 boards with the extras.

In an ideal world with ideal components,

Fig 3 (see next page)—The R1 receiver board circuit board holds all of the non-frequency-sensitive components. The local oscillator, LO phase-shift network and front-end filter are located off the board. The resistors in the audio phase-shift networks (R20-R28 and R35-R43) are 1%-tolerance metal-film units. Other resistors are 5%-tolerance carbon-film or composition units. Inductors are Toko 10RB series fixed inductors. Polarized capacitors are aluminum electrolytics rated at 16 V dc. The capacitors in the audio phase-shift networks (C21-C23 and C26-C28) are 1%-tolerance XICON polyester-film units available from Mouser (see text and Note 5). The capacitors in the diplexers (C1, C3-C5, C11, C13-C15) and 300-Hz high-pass filter (C43, C44) are Panasonic type ECQ-E(F) 100-V, 10%-tolerance miniature metalized polyester film units. C32-C37 in the low-pass filter are Panasonic V-series 50-V, 5%-tolerance metalized film capacitors; C31 is a 50-V Panasonic P-series polypropylene capacitor. C38, C46 and C48 are disc-ceramic capacitors. The other capacitors can be metalized polyester or ceramic-disc capacitors. See Note 5 for part sources.

C2, C12—0.001-µF chip capacitor. These parts are necessary only if the board is used at VHF or UHF.

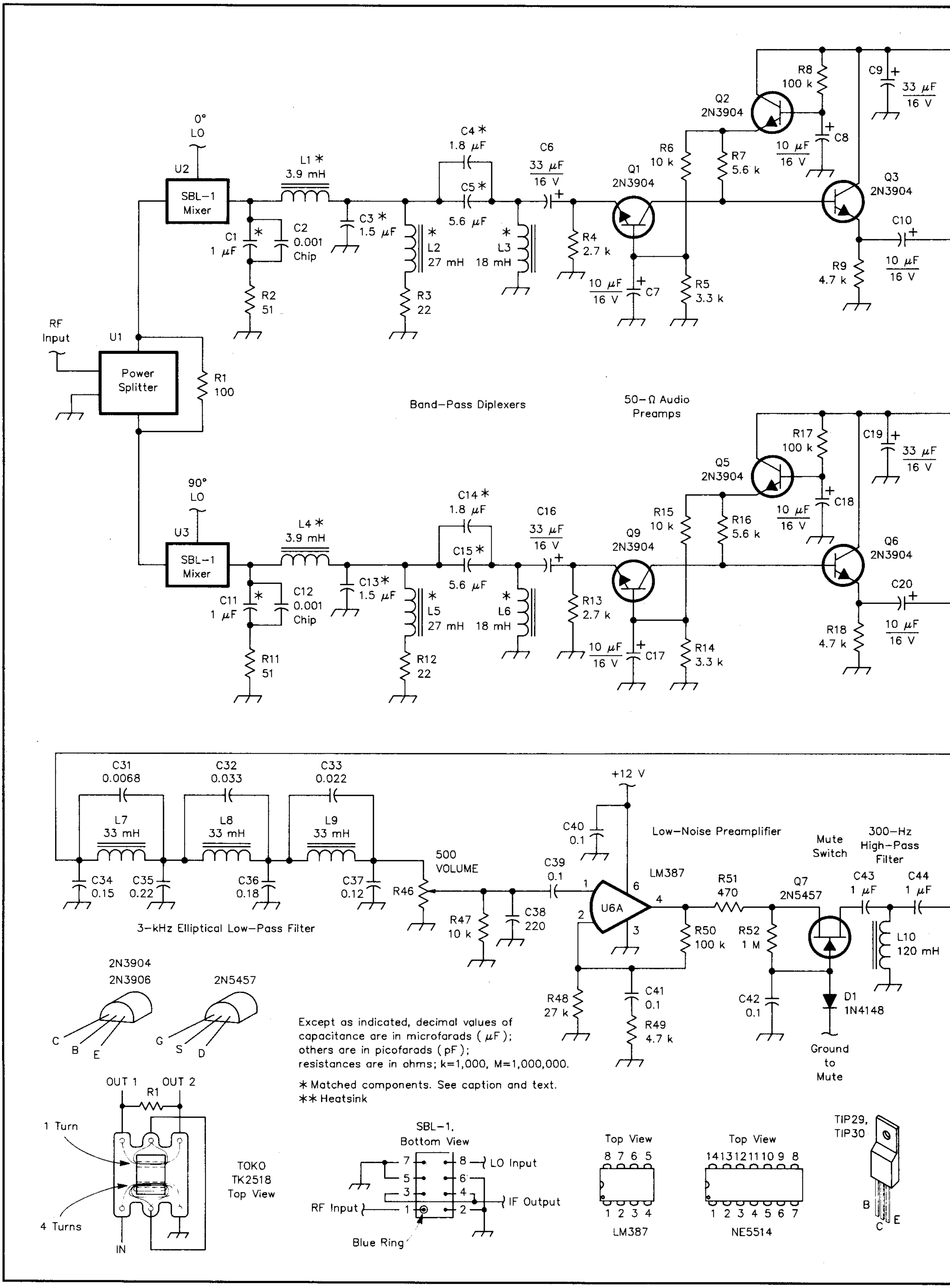
R30—10-kΩ single-turn PC-board-mount control (Panasonic MAG14 or equivalent).

R53—500-Ω audio-taper control.

R57—10-kΩ single-turn PC-board-mount control (Panasonic MAG14 or equivalent).

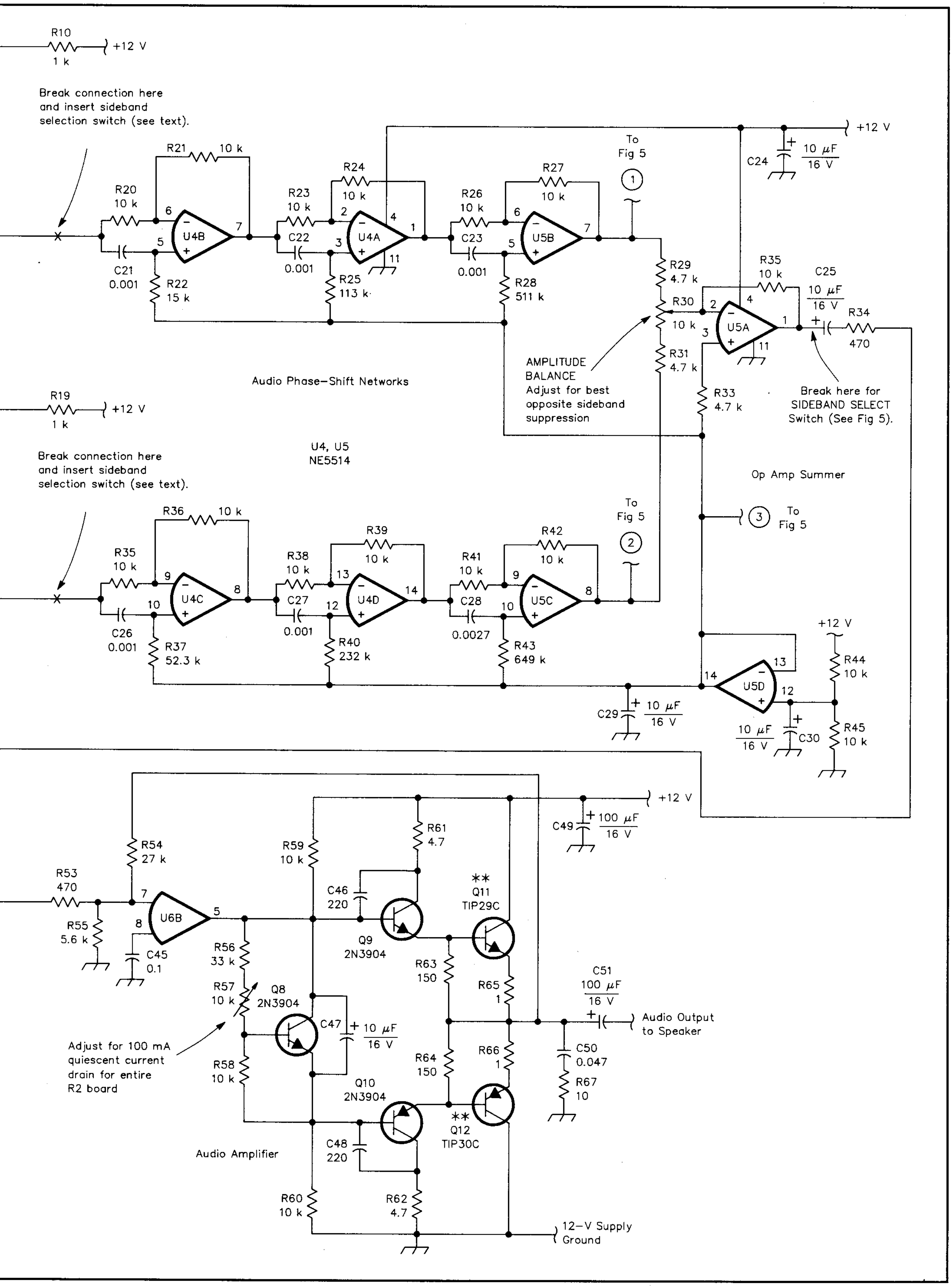
U1—Toko TK-2518 power splitter (this part is called a balun transformer in the Digi-Key catalog). See text.

U2, U3—Mini-Circuits SBL-1 double balanced mixer. Other mixers may be substituted if higher dynamic range is needed or other frequency ranges are desired.



Except as indicated, decimal values of capacitance are in microfarads (μF); others are in picofarads (pF); resistances are in ohms; k=1,000, M=1,000,000.

∗ Matched components. See caption and text.
∗∗ Heatsink


R10
1 k
+12 V
Break connection here
and insert sideband
selection switch (see text).
R21 10 k
R20 10 k
C21 0.001
R22 15 k
U4B
R23 10 k
R24 10 k
C22 0.001
R25 113 k
U4A
R26 10 k
R27 10 k
C23 0.001
R28 511 k
U5B
To Fig 5
1
C24
10 µF 16 V
+12 V
R29 4.7 k
R30 10 k
R31 4.7 k
R35 10 k
C25 10 µF 16 V
R34 470
U5A
R33 4.7 k
AMPLITUDE
BALANCE
Adjust for best
opposite sideband
suppression
Break here for
SIDEBAND SELECT
Switch (See Fig 5).
Audio Phase–Shift Networks
R19
1 k
+12 V
Break connection here
and insert sideband
selection switch (see text).
U4, U5
NE5514
Op Amp Summer
3
To Fig 5
To Fig 5
2
R36 10 k
R35 10 k
C26 0.001
R37 52.3 k
U4C
R38 10 k
R39 10 k
C27 0.001
R40 232 k
U4D
R41 10 k
R42 10 k
C28 0.0027
R43 649 k
U5C
C29 10 µF 16 V
U5D
+12 V
R44 10 k
R45 10 k
10 µF 16 V C30
+12 V
C49 100 µF 16 V
R54 27 k
R53 470
R55 5.6 k
U6B
C45 0.1
R59 10 k
R61 4.7
C46 220
Q9 2N3904
** Q11 TIP29C
R56 33 k
R57 10 k
Q8 2N3904
C47 10 µF 16 V
R58 10 k
R63 150
R65 1
C51 100 µF 16 V
Audio Output
to Speaker
C50 0.047
R67 10
R64 150
R66 1
Q10 2N3904
** Q12 TIP30C
Adjust for 100 mA
quiescent current
drain for entire
R2 board
C48 220
Audio Amplifier
R60 10 k
R62 4.7
12–V Supply
Ground

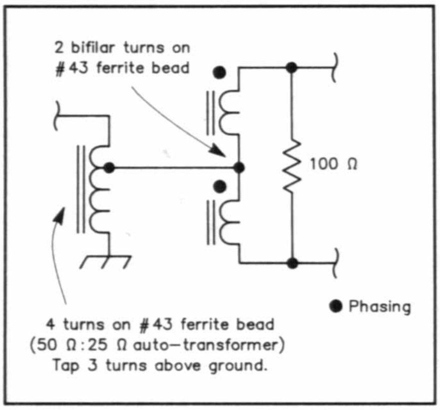


Fig 4—This home-brew in-phase splitter is an alternative to the commercial RF power splitter (U1) of Fig 3.

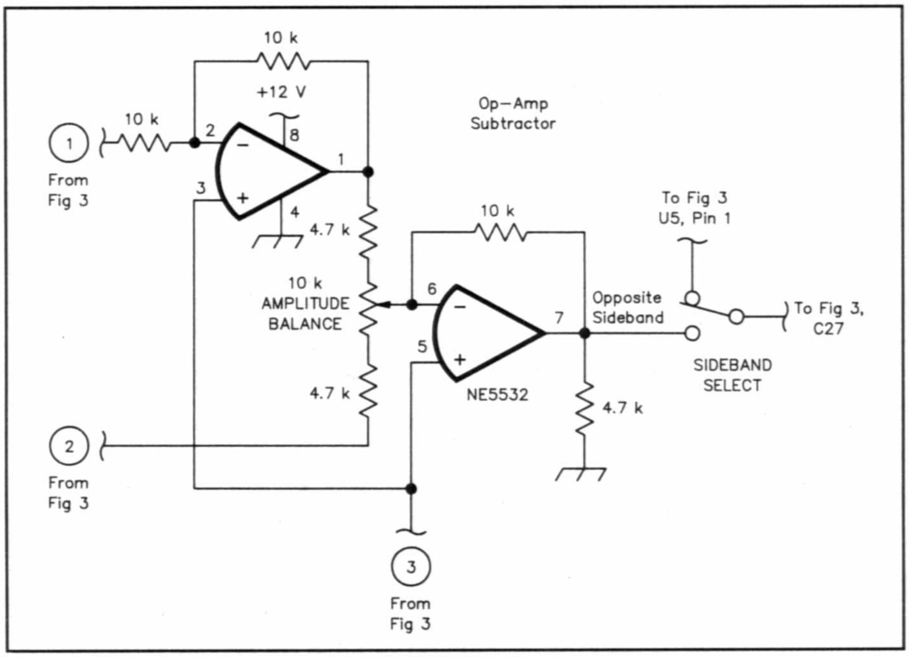


Fig 5—This subtractor circuit may be used to switch between sidebands or for simultaneous reception of both sidebands (see text).

it would be possible to have identical I and Q channels, a perfect 90° audio-phase-shift network, and thereby obtain infinite opposite-sideband suppression. Oppelt has done an excellent study of the errors introduced using real components (see Note 3). To paraphrase his many pages of analysis, it is trivial to build a receiver with 20 dB of opposite-sideband suppression, easy to get 30 dB, not too tough to obtain 40 dB, a real stretch to reach 50 dB, and quite likely impossible to hit 60 dB.

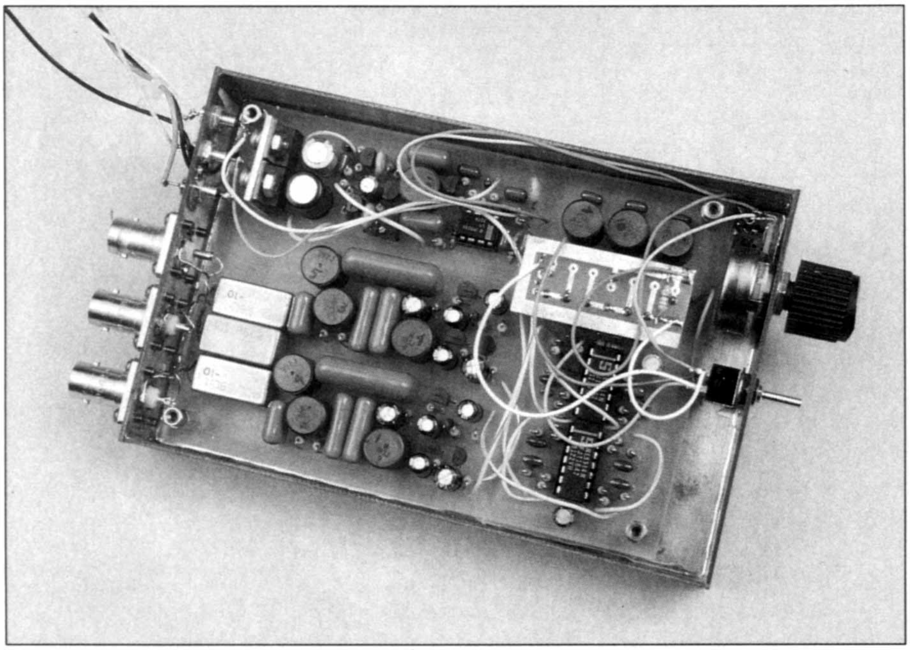
Since I wanted easy reproducibility and decent performance with off-the-shelf components, I settled on the "not-too-tough" 40 dB and designed my audio-phase-shift network accordingly. My phase-shift network is similar to the one used by Breed, but it uses the third-order coefficients calculated by Oppelt (see Note 4). In the audio phase-shift network, R20-R28, R35-R43, C21-C23 and C26-C28 must be within 1% of the schematic value. For the first prototype, I measured and selected six capacitors from a large bag obtained at a flea market, and then made up series combinations of 5% metal film resistors using a digital ohmmeter. For all the subsequent versions I have used off-the-shelf 1% resistors and capacitors (see Note 6). There is no performance difference.

The phase-shift network and combiner are capable of handling fairly large signals without distortion. The design goal was to have the preamplifier distort before the phase-shift network, since the performance of the preamplifier on the R1 board is well characterized. If distortion occurs between the RF splitter and op-amp summer, the distortion products will not have the proper phase relationship, and they will not be suppressed in the opposite sideband. The result will be that strong signals have worse opposite-sideband suppression than weak signals! This would be an unhappy circumstance indeed, but I have not encountered it at input signal levels well up into the millivolt range.

A DPDT sideband selection switch may be inserted at the points marked in Fig 3. I built one receiver that way, but I do not recommend that method of switching sidebands because the optimum setting of R30 is different for suppression of the upper or lower sideband. A better approach is to switch the 90°-shifted LO between the mixer LO ports.

The best approach is to add the op-amp subtractor circuit shown in Fig 5, with its own **AMPLITUDE BALANCE** pot. Then sideband selection is simply a matter of connecting the volume control to the appropriate sideband output with an SPDT **SIDEBAND SELECT** switch. An independent filter and audio output stage could be added if ISB reception is desired.

Many other audio-phase-shift networks may be used in place of the op-amp version



The 3.5 × 5-inch board R2 PC board layout follows the schematic of Fig 3 fairly closely. This version uses a Mini-Circuits PSC2-1 power splitter and a pair of SBL-1 mixers at the lower left-hand edge of the board. The mixers are followed by the diplexers and 50-ohm preamplifiers of the I and Q channels, followed by the audio phase-shift network (a pair of NE5514 quad op-amps) in the lower right corner. The three inductors and seven capacitors of the 1-kHz elliptical low-pass filter are arranged just above the op-amps, near the **VOLUME** control. A second filter, this one a 4-kHz Butterworth, is built on a separate PC board and glued (upside down) to the main R2 board. Filter bandwidth is switched from the front panel. The intermediate audio amplifier, 300-Hz high-pass filter, mute switch and audio power amplifier are on the top half of the board. All that is needed to make a complete receiver is a front-end filter, a VFO and 90° phase-shift network, and a speaker.

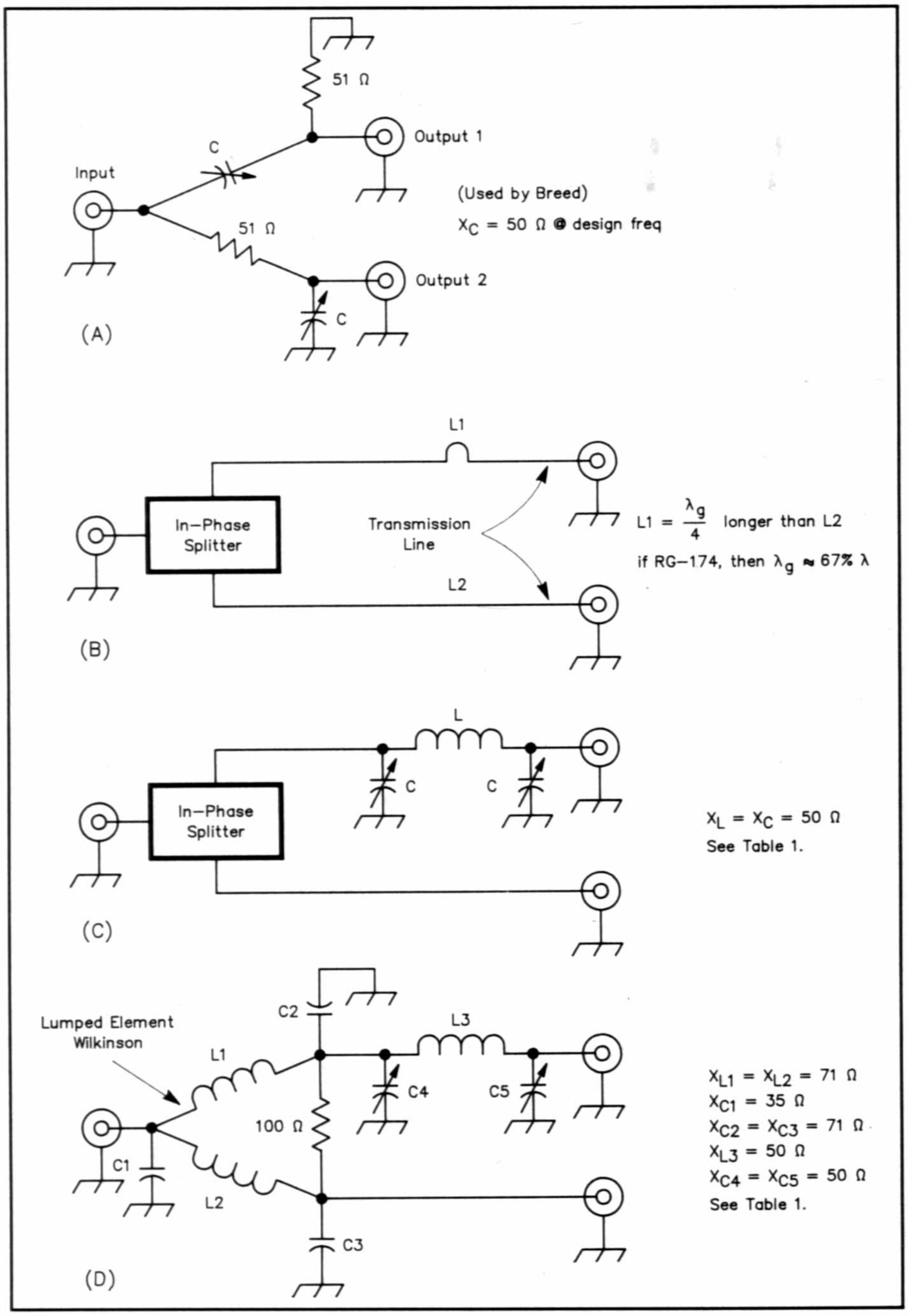
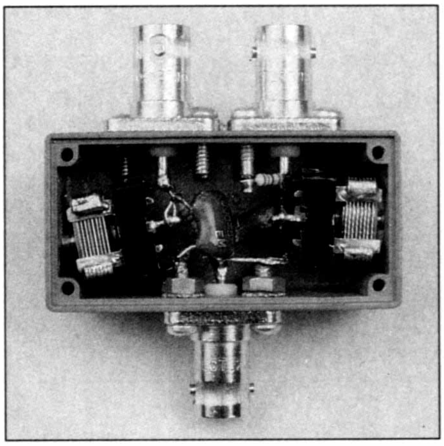


Fig 6—Four possibilities for a 90° LO phase-shift network. The simple RC network shown at A is fine for many MF/HF applications and has been used by the author on 40, 20 and 2 meters. The actual value of the capacitors depends on terminating impedances. Start with 450 pF on 7 MHz, 225 pF on 14 MHz and 22 pF on 144 MHz. See text. The circuit at B uses transmission lines and is practical at VHF and UHF. Examples: If L1 and L2 are made from RG-174, L1 is 69.1 inches longer than L2 at 28.5 MHz; 13.7 inches longer at 144.2 MHz and 8.86 inches longer at 222.1 MHz. The circuits at C and D will work better for more serious applications (see text). Component values for a variety of frequencies are shown in Table 1.



Close-up of the LO phase-shift network from Fig 6A. This version is built for 40 meters.

shown here. The I and Q channel signals may be digitized at the points marked X in the schematic, and all of the phase shifting, combining and filtering operations performed in DSP hardware and software. That will probably be the preferred receiver architecture for any band and any mode in the 21st century.

All of the circuitry after the op-amp summer is identical to the R1 receiver described in August '92 *QST*. Fig 3 shows component values for a 3-kHz elliptical low-pass filter. Information on other filters is given in the August '92 article. As with the R1 board, audio hiss may be objectionable during headphone listening. If you're bothered by hiss, add the RC networks described in the August '92 article to U6.

Receiver Construction

I built the first prototype using cut-up pieces of R1 boards interconnected over an unetched PC board ground plane. I followed good RF grounding techniques and hoped for the best with my audio grounds. It worked fine. On the single-board layout, I was much more careful with the audio grounds, and still didn't have any problems. The only instability I have found is audio feedback via magnetic coupling between a speaker lead (either one!) and the inductors in the diplexer stages. This is easy to cure by simply moving the speaker wires a few inches away from the inductors, but it can be a real puzzle if you don't expect it.

I built two more prototypes on single-sided PC boards to work out the bugs, and then produced a double-sided R2 board with plated-through holes (see Note 1). The R2 board has a number of jumpers to make it easier to try different filters and sideband-selection methods.

The R2 board is almost as easy to use as the R1 board. As explained in the August 1992 R1 article, a band-pass filter on the RF input is good practice, although a simple low-pass filter to suppress signals near the odd harmonics of the LO will suffice. On 40 meters, a narrow band-pass filter to attenuate broadcast stations may be necessary. Above 10 MHz, a preamp will be needed in quiet locations. The preamp will also help isolate the LO from the antenna. The R2 board may be used on any frequency from 1 to 500 MHz with the SBL-1 mixers shown in the schematic. Other mixers can be substituted for higher or lower frequencies.

If you do all the trig identities, follow the phase shifts through the schematic, and carefully connect everything, Murphy guarantees that you will end up with the wrong sideband. It is much easier to simply hook it up and then switch the LO connections if it's wrong. If you can convince Murphy that you really don't care, you have a 50% chance of getting it right the first time!

Local Oscillator

The R2 board with SBL-1 mixers needs two +7 dBm (nominal) LO signals, 90° out of phase. I have used all of the LO phase-shift techniques shown in Fig 6, and there are

Table 1
LO Phase-Shift Network Component Values

For the network in Fig 6C

Frequency (MHz)	*C (pF)*	*L (µH)*
3.525	903	2.26
7.05	452	1.13
14.05	227	0.566
21.05	151	0.378
28.5	112	0.279
50.1	63.5	0.159
144.2	22.1	0.0552
222.1	14.3	0.0358

For the network in Fig 6D

Frequency (MHz)	*L1, L2 (µH)*	*C1 (pF)*	*C2,C3 (pF)*	*C4,C5 (pF)*	*L3 (µH)*
3.525	3.21	1290	645	903	2.26
7.05	1.62	645	323	452	1.13
14.05	0.809	325	162	227	0.566
21.05	0.541	216	108	151	0.378
28.5	0.399	160	80	112	0.279
50.1	0.227	91	45	63.5	0.159
144.2	0.0789	31.6	15.8	22.1	0.0552
222.1	0.0512	20.5	10.2	14.3	0.0358

many others I have not tried. Since there may be a few degrees of phase error in the splitters and mixers, it is necessary to tweak the LO phase-shift network for best opposite-sideband suppression. Some phase-shift networks are easier to tweak than others—it is easier to adjust a trimmer capacitor than cut ⅛-inch pieces off RG-174 phasing lines!

The simple LO phase-shift network in Fig 6A has been used on 40, 20 and 2 meters by tacking in different capacitors and adjusting them for best opposite-sideband suppression. It works fine, but has two peculiarities:

- When adjusted for a 90° phase difference with loads connected to outputs 1 and 2, the output levels will be different.
- The phase at each output depends on the load impedance.

The LO-port impedance and conversion loss of the SBL-1 mixers are functions of drive level, so there is a complicated interaction between the adjustments of the network in Fig 6A and the **AMPLITUDE BALANCE** potentiometer (R30). In practice, you just tweak them both and forget the theory, but strange things can happen with the network in Fig 6A in the system.

Anything that changes the LO drive level at the input or the impedances connected to the outputs of the network will require readjustment of both the phase-shift network capacitors and the **AMPLITUDE BALANCE** control. One operator noted greatly reduced opposite-sideband suppression when he increased the supply voltage from 12 to 14!

The network in Fig 6A is easy to build and works well within the limitations described above. For more serious applications (especially if sideband selection or operation from a variety of supply voltages is anticipated), I recommend using one of the LO phase-shift networks shown in Fig 6C, Fig 6D and Table 1.

It is difficult to recommend an LO for a receiver board that may be used anywhere from VLF to microwaves! For HF use, *The ARRL Handbook*, *QRP Classics* and *Solid State Design* contain many suitable examples. For VLF and LF, old signal generators work fine, and they have incredible bandspread. At VHF and up, the literature is a bit sparse, but an HF VFO followed by a simple transverter works well. At higher frequencies, a VXO and multiplier chain may be used.

The cost of direct digital synthesis (DDS) is falling rapidly, and many of the DDS chips offer two outputs 90° out of phase. The phase-noise performance of low-cost DDS chips is not good enough for a high-performance direct-conversion receiver, but that will change in the future. Fig 7 is the block diagram of an all-mode receiver using a DDS chip for the LO and a DSP chip for the signal processing.

Tuning

There are two trimmer potentiometers on the R2 board and a single LO phase-shift adjustment off the board. It's not quite "no tune," but it's easier than even a simple superhet! R57 sets the quiescent current of the audio-output stage. It can be set for a total R2 board current of about 100 mA—it's not critical.

The **AMPLITUDE BALANCE** pot (R30) and the LO phase-shift adjustment can be set by

Crunch Time: We Test R2 in the ARRL November Sweepstakes

"That good, huh? Maybe I'll hook it up to my 40-meter beam and give it the acid test this weekend in CW Sweepstakes." Rick Campbell had just finished telling me how well his 40-meter R2 prototype (the one in the photos) stacks up against commercial radios. Playing the skeptic, I told Rick I'd connect the transceiver to a good antenna and try to use it on a weekend when the band was sure to be full of rock-crushing signals.

Saturday afternoon rolls around. Hmm...better hook up Rick's radio and listen to a few signals. Maybe I can even work a few people with that dinky (2-inch-square) 1-W transmitter. Out come the clip leads...let's see, we need 12 V, a keyer, headphones and an antenna...wow! this thing really does put out a watt...there's Mike, W9RE, warming up for Sweepstakes...he's *loud* but there's just a trace of his signal on the other side of zero-beat...this receiver *works.*

The contest starts. I call W9RE. He comes right back and gets my entire exchange without missing a beat. Must be a fluke. Next, W2RQ...then KW8N..and so it goes—42 contacts logged in the first hour. This might be fun! During the weekend I manage to squeeze in nine hours of operation, an hour here and an hour there amid raking about a billion leaves and other domestic activities. On Sunday night, the log shows 313 QSOs in 60 ARRL sections—all on 40 meters with Rick's 1-W transceiver.

The R2 receiver is impressive. I have a very low tolerance for poor receiver performance: I'd rather spend a sunny November afternoon picking up leaves one by one than working Sweepstakes with a lousy receiver. Fortunately, R2 sounds great—no IMD or blocking problems show up. CW signals please the ear. Compared to R2, signals on a commercial transceiver with 500-Hz filters sound harsh. Some audio hiss is noticeable during headphone listening, but that can be tamed with a couple of RC networks as explained in Rick's August 1992 *QST* article.

This receiver has no AGC, which I thought would be a problem after years of listening to radios that do a great job of flattening out signals on the band. After a while, my ears and brain figured out how to deal with a receiver without AGC, and I found myself adjusting the **VOLUME** control for only the weakest and strongest signals.

Although the CW filter in this version has a rather broad 700-Hz bandwidth, I had no problem tuning the band and separating stations from each other. Even with a band full of big signals, I only heard the opposite sideband on the strongest stations. Even then, it was just "oh, there's the other sideband." It was not a bother except when I cranked up the power supply voltage from 12 to 14 (this phenomenon is explained in the text).

Bottom line: This home-brew receiver holds its own, even under demanding conditions. Some radios are fun to build but less fun to use ("it doesn't work quite right, but after all it's only a home-brew rig," or "what do you expect for the money?"). I like projects you can build and enjoy without apologies. This is one of those projects.*—Mark Wilson, AA2Z* ear by tuning in a strong carrier on the wrong sideband and then alternately tweaking the two controls for a null.

I tune for best opposite-sideband suppression by setting a signal generator on the audio image ("wrong side of zero beat") and then alternately adjusting the phase shift and amplitude balance (R30) while watching the output on an audio-frequency level meter. I optimize the circuit at a frequency near the middle of the audio range, and then tune around to make sure the opposite-sideband suppression is good from 300 to 3000 Hz. I then adjust a step attenuator for the same signal level on the desired and undesired sideband and record the respective attenuator settings. The difference in step attenuator settings is the opposite-sideband suppression. Once the phase shift and amplitude balance are adjusted, they may be locked in place with nail polish. After a year and thousands of miles on the road, the first prototype shows no signs of needing alignment.

R2 Performance and Impressions

The R2 prototype with a 3-kHz elliptical filter was assembled and tested on the bench. There were no surprises—it was an R1 board with slightly better dynamic range, slightly better noise figure, and 41 dB of opposite-sideband suppression. The real shock came when I connected a 40-meter antenna and VFO. CW signals simply disappeared as I tuned through zero beat. Murphy had it connected for USB, and there was no way I could copy any LSB up in the phone band. It sounded too good—something was wrong with the picture.

I connected my old transceiver with its 2.4-kHz IF filter, and sure enough, CW signals were audible on the wrong sideband. I switched the antenna over to a Collins 75S-3C with its F455FB21 mechanical filter, and they were still there. After listening to the other radios, I returned to the R2. It sounded even better than before. Why?

I have been pondering this for about a year, and I've thought of several explanations. The first is that the commercial radios both have AGC, so the receiver gain is reduced on the desired sideband and increased on the undesired sideband—in other words, the AGC is trying to remove the IF selectivity from the system. I defeated the AGC on both radios and listened again. I could still hear low-frequency CW signals on the wrong sideband that were not audible on the R2. I made a few measurements and discovered that low-pitch CW signals (up to several hundred hertz) on the wrong side of zero beat are suppressed considerably less than 40 dB on both radios. The old Collins dipped below 40 dB at about 400 Hz, and the other radio went below 40 dB a little higher in frequency. The bottom line is that the R2 sounds better than I expected, because it has better selectivity than the radios I'm used to.

I demonstrated a 40-meter R2 at the QRP Hospitality Suite in Dayton this year. Several experienced HF CW operators were amazed when we could not find any CW signals that were strong enough to detect on the wrong sideband.

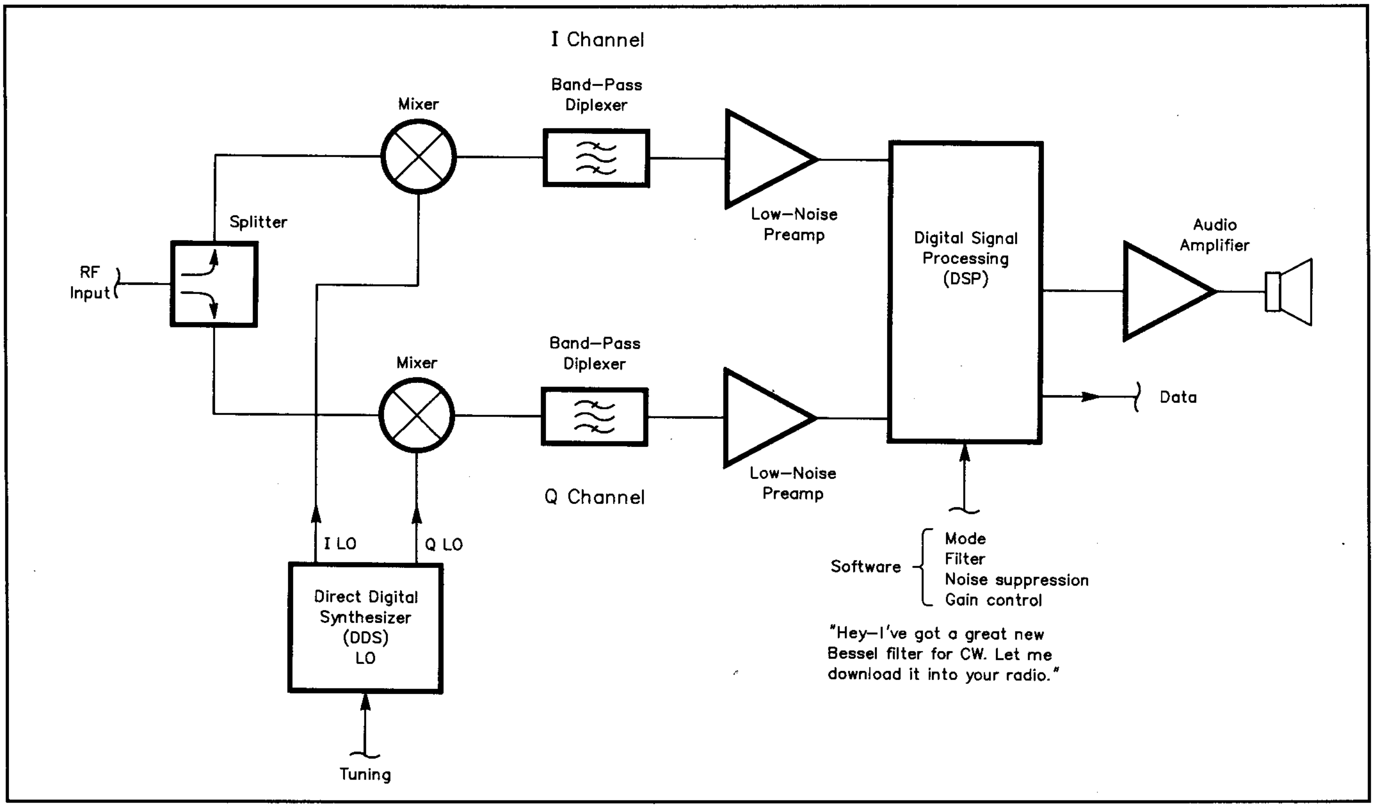
Comparison with a Superhet

Receiver fans will point out that the schematic in Fig 3 is as complicated as a superhet. If the image-reject direct-conversion receiver has so many parts, why not just "do it right" and build a superhet?

First, this is a high-performance direct-conversion design, with no attempt to reduce the parts count. It could be greatly simplified with only a small reduction in performance. Even in simplified form, it could still outperform most of the simple superhets I've encountered—especially those based on the ubiquitous NE602. The NE602 is not a bad part, but its limited dynamic range should confine its use to low-cost, low-current-drain, minimum-parts-count applications.

Direct-conversion receivers have a number of significant advantages over superhets. Because there is only one LO, there are no internally generated birdies. There are no image frequencies to filter out, and no spurious receiver tuning ranges at strange combinations of LO harmonics and the intermediate frequency. A low-pass front-end filter to reject signals near odd multiples of the LO frequency will ensure a spurious-free receiver.

Since direct-conversion receivers do all of their signal processing at audio, the input frequency is unrestricted. An R1 board with an SRA-3 mixer and an old signal generator for an LO works well below 25 kHz. At the other end of the spectrum, I have an R1 board



"Hey—I've got a great new Bessel filter for CW. Let me download it into your radio."

Fig 7—The R2 board can serve as a basic building block for a receiver of the future. Just add a direct-digital synthesizer for the LO and digital signal processing for the audio processing.

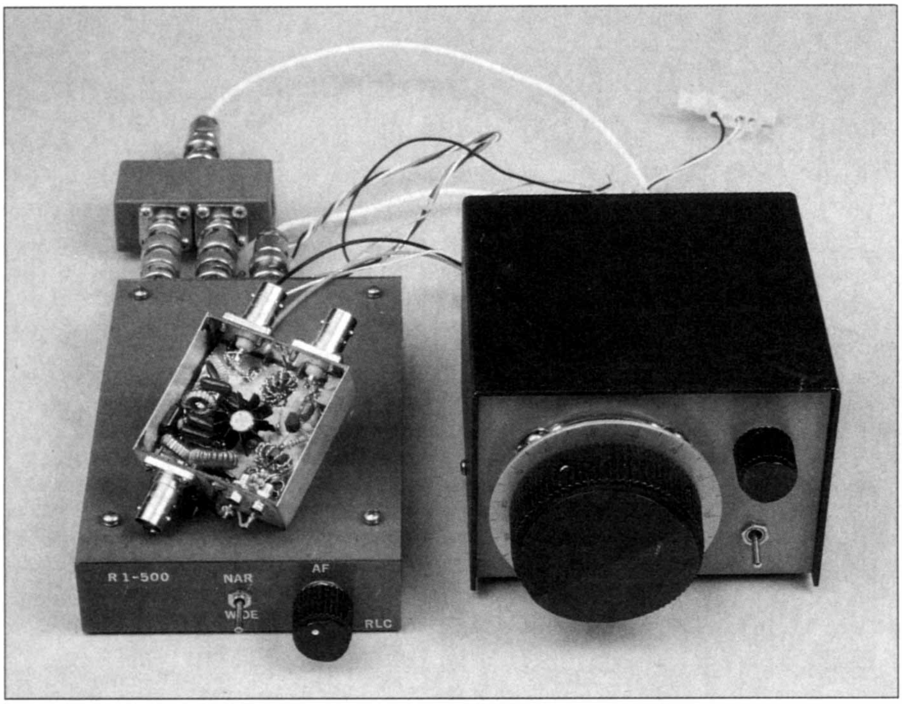


Fig 8—A simple modular 40-meter CW QRP transceiver built around an R2 board. R2 is built in the box on the lower left; the LO phase-shift network from Fig 6A is in the small box connected to rear of R2 with BNC connectors. A 7-MHz VFO is in the larger box on the right. Resting atop R2 is a 1-W CW transmitter with low-pass filter and break-in circuitry. The transmitter and VFO were borrowed from other published projects (see text). This transceiver acquitted itself well in the 1992 ARRL Sweepstakes—see the sidebar. *(photos by Kirk Kleinschmidt, NTØZ)*

with a printed rat-race mixer working at 5760 MHz.

A direct-conversion receiver can be combined with a VFO-controlled CW transmitter to build a transceiver that is simpler than a superhet transceiver. The only spurs are harmonics, which are reduced by the transmitter low-pass filter.

Direct-conversion receivers also have some disadvantages. The need for isolation between the antenna and LO makes direct conversion a poor choice for hand-held radios with integral whip antennas. At HF, a full-size outdoor antenna works best.

I do not recommend the direct-conversion, image-reject approach for a band-switched radio. It is easy to obtain good performance over a single amateur band, but the RF phase-shift network and amplitude balance must be tweaked when changing bands.

Finally, 41 dB is about the practical limit for opposite-sideband suppression in an easily reproduced analog design. While this is as good as some HF and most VHF SSB rigs, the fact remains that the basic superhet design is *capable* of better performance.

R2 Applications

The modular 40-meter QRP CW transceiver shown in Fig 8 features full break-in keying, 1 W output, a slow tuning rate, switched SSB and CW bandwidths, 93 dB two-tone, third-order IMD dynamic range, low-distortion audio, and true single-signal reception. The transmitter, VFO and break-in circuitry were borrowed from "The Ugly Weekender" and the "Optimized QRP Transceiver" in *The 1992 ARRL Handbook*.[8] The receiver is an R2 board with the RC LO phase-shift network from Fig 6A. It is a joy to operate.

The R2 board is small enough to build a high-performance portable HF CW transceiver in a smaller package than the popular commercial versions. For portable use, the receiver's audio power transistors can be removed to reduce the current drain, as discussed in August *QST*.

At Microwave Update '92, I demonstrated another interesting R2 application: a no-tune microwave transceiver, using a Down East Microwave no-tune 1296-MHz transverter with an R2 board and premixed VFO as a tunable 2-meter IF. The transmit IF uses an SSB/CW exciter board, which I'll describe in a future issue of *QST*. The use of image-reject techniques makes it possible to build single conversion microwave radios with any desired IF. I'll explore this concept more fully in a future *QST* article.

Conclusions

The image-reject, direct-conversion receiver is a viable approach to SSB and CW reception for many applications. When combined with high-performance, direct-conversion receiver techniques, it can provide basic receiver performance that surpasses many superhets. Image-reject techniques are in wide commercial use, and both Drake and Kenwood have recently introduced high-performance products that combine image-reject and superhet techniques. In the future, high-performance receivers will be built by combining a high dynamic range I and Q channel front end with a digital signal processor. Future Old Timers will sit around reminiscing about multiple-conversion superhets!

Acknowledgments

Dr Ward Helms, W7SXM, at the University of Washington, and Dr Ben Logan, WB2NBD, at Bell Labs taught me to look for unconventional solutions to problems. Without their influence I would be less inclined to pursue strange ideas like microwave transverters with no tuning and SSB receivers with no IFs.

Notes

[1] R. Campbell, "High-Performance Direct-Conversion Receivers," *QST*, Aug 1992, pp 19-28.

[2] R. Campbell, "Low Noise Receiver Analysis," in *Proceedings of Microwave Update '91*, published by the ARRL. Available from your local dealer or the ARRL Publications Catalog elsewhere in this issue (order no. 3703).

[3] R. Oppelt, "The Generation and Demodulation of SSB Signals Using the Phasing Method Part 1: Basic Theory," *VHF Communications*, vol 19, ed 2, summer 1987, pp 66-72.

[4] R. Oppelt, "The Generation and Demodulation of SSB Signals Using the Phasing Method Part 2: Signal Processing for a SSB/DSB/AM Transceiver Without Using Crystal Filters," *VHF Communications*, vol 19, ed 3, fall 1987, pp 130-140.

[5] Etched, plated and drilled PC boards (double-sided, with plated-through holes) for the R2 board are available from Applied Radio Science, PO Box 225, Houghton, MI 49931 for $20 postpaid (send an SASE for a catalog with current kit information). For individuals wishing to make their own PC boards, an etching template/part-overlay package for a single-sided version of the R2 PC board is available from the ARRL for an SASE. Address your request for the CAMPBELL R2 BOARD TEMPLATE to Technical Department Secretary, ARRL, 225 Main St, Newington, CT 06111.

[6] One source for SBL-1 mixers is Oak Hills Research, 20879 Madison St, Big Rapids, MI 49307, tel 616-796-0920). XICON 1% polyester film capacitors used in the audio phase-shift network are available from Mouser Electronics, 2401 Hwy 287 N, Mansfield, TX 76063, tel 800-346-6873, 817-483-4422, fax 817-483-0931. All other parts are available from Digi-Key, PO Box 677, Thief River Falls, MN 56701-0677, tel 800-344-4539, 218-681-6674, fax 218-681-3880.

[7] G. Breed, "A New Breed of Receiver," *QST*, Jan 1988, pp 16-23.

[8] R. Lewallen, "An Optimized QRP Transceiver," *QST*, Aug 1980, pp 14-19; also see Feedback, *QST*, Nov 1980, p 53. The Optimized QRP Transceiver also appears on pages 30-37 to 30-40 of *The 1993 ARRL Handbook*, and in the second printing of *QRP Classics* (available from the ARRL Bookshelf as #3169). R. Hayward and W. Hayward, "The 'Ugly Weekender,'" *QST*, Aug 1981, pp 18-21. The Ugly Weekender also appears on pages 30-33 to 30-36 of *The 1993 ARRL Handbook*. Etched, plated and drilled PC boards for the VFO/buffer are available from FAR Circuits, 18N640 Field Ct, Dundee, IL 60118-9269. Price is $4; add $1.50 for shipping and handling to each order. Use the board's **AUX OUT** output for the correct drive level for the SBL-1 mixer.