A Multimode Phasing Exciter for 1 to 500 MHz

In January, *QST* introduced you to R2, a single-signal direct-conversion receiver for the '90s. This month meet T2, a matching transmitter that generates SSB, CW and more.

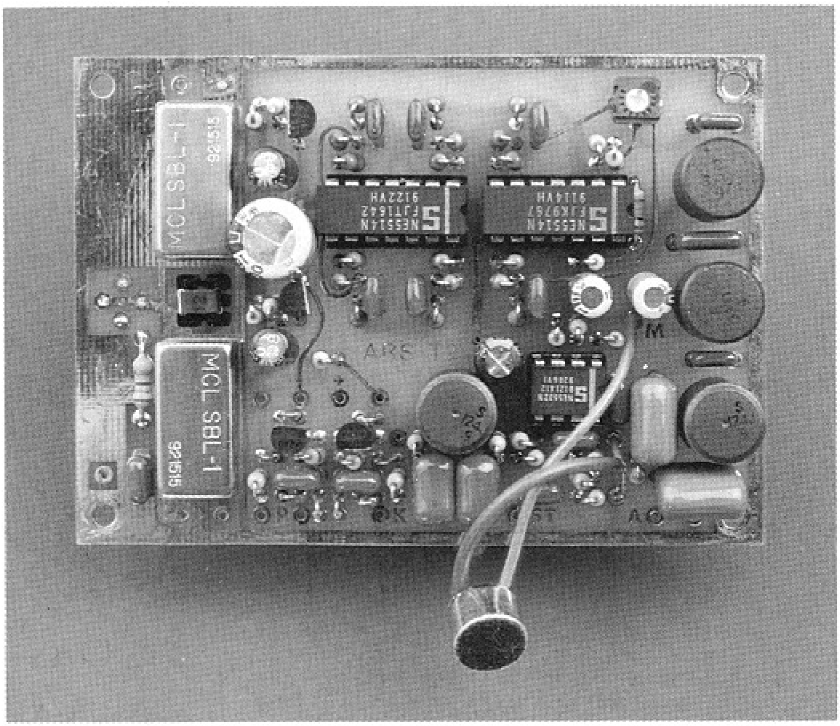
By Rick Campbell, KK7B
Department of Electrical Engineering
Michigan Technological University
Houghton, MI 49931

The high-performance direct-conversion receivers described in the references[1,2] may be easily paired with a CW transmitter to make a simple transceiver of very respectable performance. For QRP operation and VHF through microwave weak-signal work, CW is the preferred mode. Whether you enjoy CW operation, or simply use it as a tool to make otherwise impossible contacts, it's nice to be able to switch to a voice mode when the signals are strong and the technical ideas are flowing hot and heavy. Here is a little multimode exciter that makes a perfect companion to a direct-conversion receiver.

Circuit Description

Fig 1 is the block diagram of a direct RF phasing-type SSB exciter. This block diagram has appeared in every *ARRL Handbook* for 40 years, and readers are encouraged to review the basics in those pages.[3] In the 1950s, the blocks contained vacuum tubes, paper capacitors and possibly a Barker and Williamson 2Q4 audio phase-shift network plugged into an octal tube socket. The schematic in Fig 2 is an implementation of Fig 1 using modern components.

[1]Notes appear on page 31.



Close-up of the top of the 2.5 × 3.5-inch T2 PC board. The power combiner (U6) and mixers (U4, U5) are at the left-hand edge of the board. The audio phase-shift networks (U2, U3) are arranged along the upper half of the board. The audio high-pass (C11, L1, C12) and band-pass (C13-C15, L2, L3) filters are arranged along the right edge. The mike amplifier and sidetone generator (U1) are in the lower right portion, and the control and power-supply circuitry is at the lower left. The MMIC amplifier (U7) and low-pass filter components are located on the back side of the board.

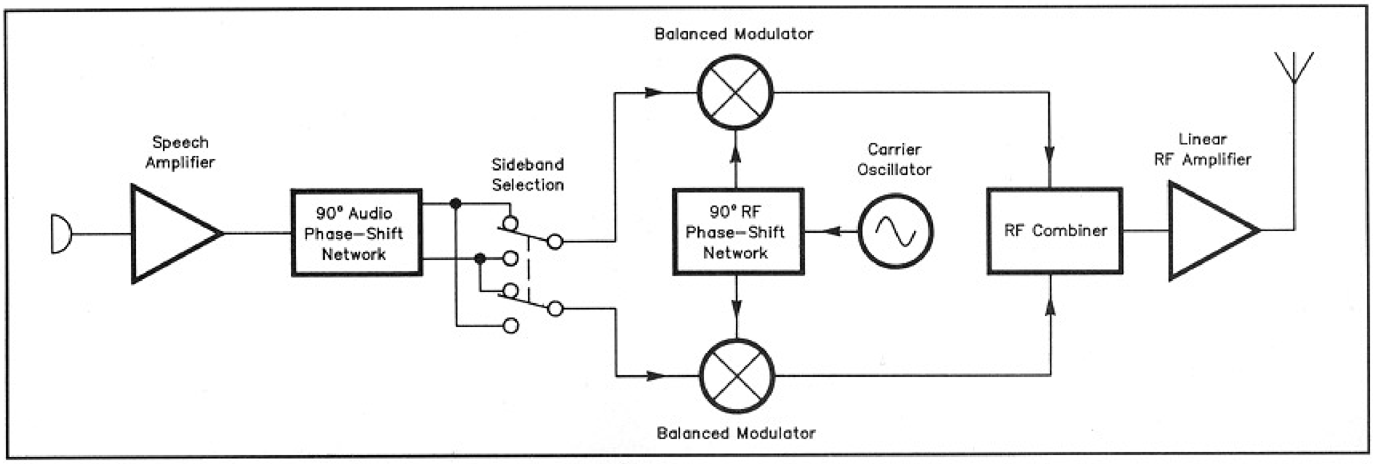


Fig 1—Block diagram of a phasing-type transmitter.

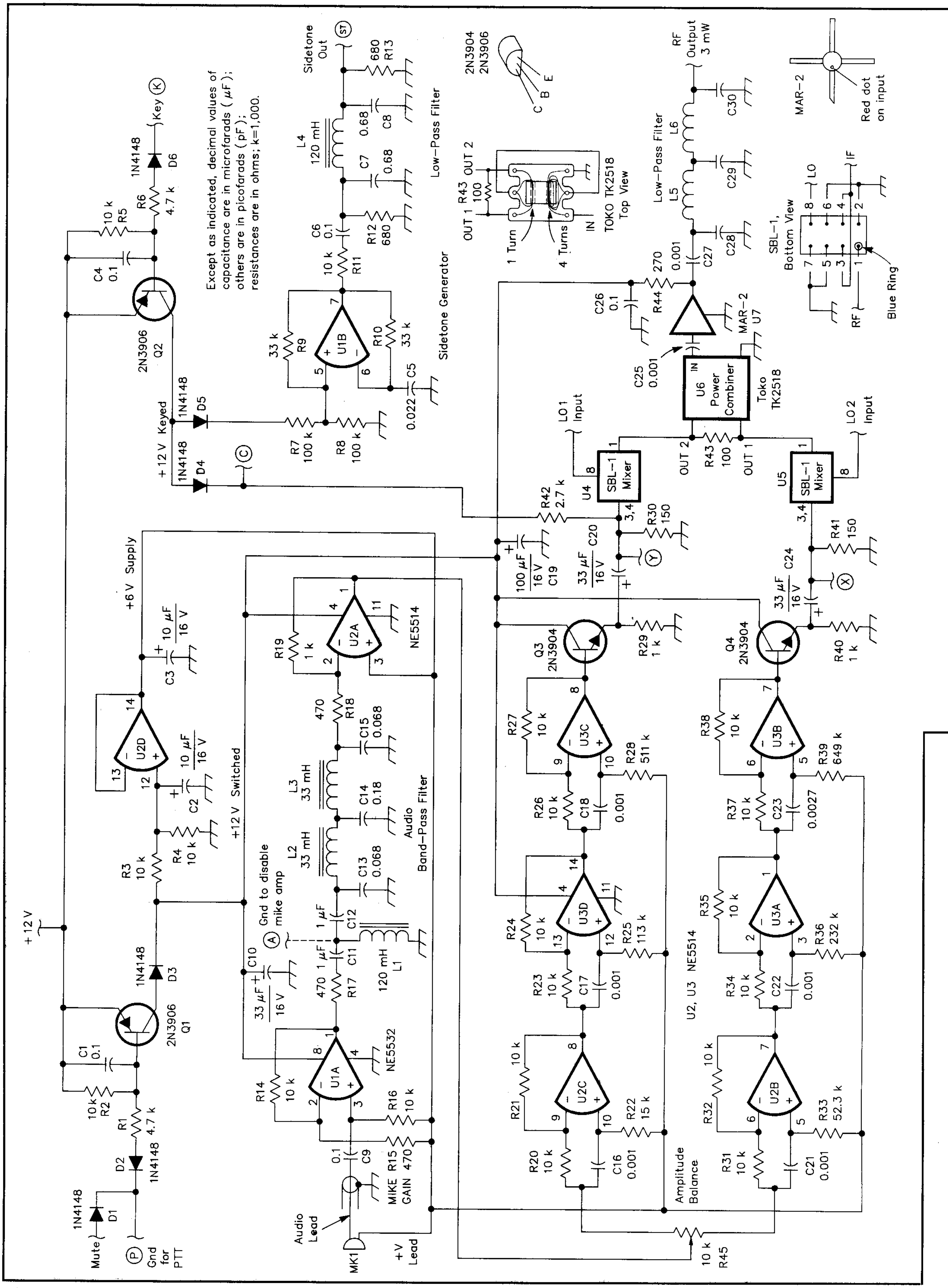

Except as indicated, decimal values of capacitance are in microfarads (µF); others are in picofarads (pF); resistances are in ohms; k=1,000.
Sidetone Generator
Sidetone Out
Low-Pass Filter
Audio Band-Pass Filter
Amplitude Balance
Gnd to disable mike amp
+6 V Supply
+12 V Switched
+12 V Keyed
+12 V
Mute
Gnd for PTT
Key
Audio Lead
+V Lead
MIKE GAIN
MK1
TOKO TK2518 Top View
1 Turn
4 Turns
OUT 1
OUT 2
IN
2N3904
2N3906
C B E
MAR-2
Red dot on input
RF Output 3 mW
SBL-1, Bottom View
Blue Ring
LO
IF
RF
LO1 Input
LO2 Input
SBL-1 Mixer
U6 Power Combiner
Toko TK2518
U2, U3 NE5514
NE5532
NE5514

Fig 2—The T2 transmitter circuit diagram. The local oscillator and LO phase-shift network are located off the board. The resistors in the audio phase-shift networks (R20-R28 and R31-R39) 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 (C16-C18 and C21-C23) are 1%-tolerance XICON polyester-film units available from Mouser. C7, C8 and C13-15 in the audio band-pass and sidetone low-pass filters are Panasonic V-series 50-V, 5%-tolerance metalized film capacitors. C28-C30 in the RF low-pass filter can be small 5%-tolerance leaded or chip components (see text). The other capacitors can be metalized polyester or ceramic-disc capacitors. See Note 7 for part sources.

C28-C30—See text and Table 1.
L5, L6—See text and Table 1.
MK1—Electret mike (Radio Shack 270-092 or Mouser 25LM045).
R45—10-kΩ, single-turn, PC-board-mount control (Panasonic MAG14 or equivalent).
U4, U5—Mini-Circuits SBL-1 double balanced mixer. Other mixers may be substituted if other frequency ranges are desired.
U6—Toko TK-2518 power combiner/splitter (this part is called a balun transformer in the Digi-Key catalog). See text.
U7—Mini-Circuits MAR-2 MMIC. See text.

Table 1
Fifth-Order Butterworth Low-Pass Filter Values

Frequency (MHz)	*C28, C30 (pF)*	*L5, L6 (µH)*	*C29 (pF)*
7	273	1.8	884
28	68	0.447	220
50	39	0.257	127
144	13.6	0.0893	44.1
222	8.9	0.0579	28.7
432	4.5	0.0298	14.7

Historians may enjoy comparing Fig 2 with Fig 11-5 on page 307 of the 1959 *ARRL Handbook.* The functions are identical, but virtually all the parts have changed! Following the op-amp microphone amplifier (U1A) is an LC audio band-pass filter, just like the old days, but designed using modern network theory and a computer circuit analysis program (*PSPICE*).[4]

The audio phase-shift networks (U2B, U3A, U3B and U2C, U3C, U3D) are the same as in the R2 receiver (see Note 2). Second-order (like the old 2Q4), third-order and fourth-order networks were explored for the audio phase-shift networks. Fourth-order networks work very well with ideal components, providing more than 45 dB of opposite-sideband suppression in my computer model. The third-order network with ideal components can provide more than 40 dB of opposite-sideband suppression. When 1% component variations were included in the computer models, the fourth-order network model degraded to within a few decibels of the third-order model. For this design, third-order networks with 1% off-the-shelf components are specified. This provides better opposite-sideband suppression than the phasing exciters of the 1950s and '60s, without requiring hand-selection of any components.

One critical area in a phasing SSB generator is the pair of audio amplifiers between the audio phase-shift network and the balanced modulators. These amplifiers have three requirements:

1) They must have identical phase shifts. This is most easily achieved by making them very broadband, by using large-value coupling capacitors.

2) They must have stable gain. If the gain of one of the amplifiers changes, the opposite-sideband suppression is reduced. Stable gain is most easily obtained by using feedback to set the gain, or using emitter followers with a gain slightly less than one.

3) They must have exceptionally low distortion. Any distortion introduced at this point has two equally undesirable effects: The distortion sends high-frequency audio harmonic energy into the balanced modulators; and the distortion products no longer have the desired 90-degree phase relationship.

The successful implementation of point 3 is what separates an acceptable phasing-type SSB generator from an unacceptable one. A phasing-type generator with 10% total harmonic distortion (THD) sounds pretty good on the air, because most of the 10% distortion falls outside the desired signal bandwidth and is rejected by the *receiver.* On either side of the transmitted signal, however, is a wide spectrum of garbage, kindly referred to as "splatter." To eliminate splatter, a phasing-type SSB generator must have audio amplifiers with THD well below 1%.

In contrast, a filter-type SSB generator may have large amounts of distortion in any of the stages preceding the filter. Distortion ("clipping") is often introduced intentionally to increase the average-to-peak-power ratio, or unintentionally by operators who turn up the mike gain to squeeze out the last milliwatt. A phasing-type SSB generator requires low-distortion audio and RF design from the input of the audio phase-shift network to the output of the RF combiner. This is why phasing-type SSB transmitters have a reputation for exceptional audio quality.

The emitter-follower drivers used here (Q3, Q4) were modeled on *PSPICE,* and have less than 0.3% THD when driving the IF ports of the SBL-1 double-balanced mixers (U4, U5). The onset of distortion in the emitter followers occurs above the desired drive level for the SBL-1s. The 150-ohm resistors (R30, R41) were added from the mixer IF ports to ground after I burned out a pair of SBL-1s by dumping the charge on the 33 µF coupling capacitors (C20, C24) through the mixer diodes.

The two double sideband (DSB) signals from the SBL-1 balanced modulators are combined in a Toko TK2518 splitter-combiner. This part is rated from 20 to 600 MHz, but it seems to work as low as 7 MHz in this application. A better choice for lower frequencies is a Mini-Circuits PSC2-1, which must be mounted off the board, or a homebrew replacement as shown in Fig 4 of the January *QST* receiver article (see Note 2).

After the combiner, the signals are amplified by U7, a Mini-Circuits MAR-2 MMIC (monolithic microwave integrated circuit). Readers unfamiliar with MMICs are in for a treat—this part has 50 ohm input and output impedances, boosts the signal up to a few milliwatts with low distortion, is unconditionally stable, and costs 99 cents. It also provides a constant load impedance for the combiner, so that opposite-sideband suppression is not a function of the following circuitry. You can read more about these remarkable devices in the 1987 *QST* series by Al Ward, WB5LUA.[5]

Following the MMIC amplifier is a fifth-order low-pass filter. I debated whether to include the low-pass filter on the PC board, since it is the *only* part of the exciter that must be changed for different bands. I finally included it because it allows the exciter to directly drive an antenna for milliwatt QRP work, or a transverter for the microwaves, or the IF port of a mixer in a heterodyne transmitter. For multiband applications, or for directly driving a linear amplifier, the low-pass filter components can be omitted, with jumpers replacing the inductors. Design equations for low-pass filter elements are given in Chapter 2 of any recent *ARRL Handbook,* and Table 1 gives typical values for a few amateur bands.

The PC-board low-pass filter artwork will accommodate chip capacitors or small leaded components. I prefer chip caps for frequencies above 30 MHz. The inductors can be air core at VHF and small toroids at HF. For lower frequencies, the low-pass components may be too large to fit on the PC artwork. A separate low-pass filter may be constructed off the board in that case.

Several different mixers were tried at U4 and U5 in the prototype exciters. Mini-Circuits SRA-2CM mixers will work up to 1000 MHz, and SBL-3s will work down to 25 kHz, with no other changes in the exciter. Options for LO phase-shift networks are discussed in January *QST*'s receiver article (see Note 2) and *The ARRL Handbook.*

More Power for T2

Once you have built a copy of T2 for your favorite band, the next logical question is, "How can I get more power?" Even the most dedicated QRP enthusiasts require more than 3 mW on occasion. Fortunately, League publications offer a number of good designs for a variety of frequencies and power levels.

If you're simply interested in CW operation, the amplifier sections of the QRP transceivers shown in Chapter 31 of the 1993 *ARRL Handbook* are a great place to start. Another place to look is in the projects described in *QRP Classics*.

You probably didn't build T2 just for CW operation, though. SSB operation requires *linear* amplifier stages. The following references describe linear amplifiers that operate over a wide range of frequencies and power levels.

- W. Hayward and D. DeMaw, *Solid State Design for the Radio Amateur*, published by the ARRL. Chapter 8 contains a variety of linear circuits.
- A. Ward, "Monolithic Microwave Integrated Circuits, Part 2" *QST*, Mar 1987, pp 22-28, 33. Describes low-power, broadband, no-tune amplifiers that work from 160 meters through UHF. Also covers combining MMICs for additional power. Later development: Mini-Circuits MAV-11 and Avantek MSA-1104 devices are good for 50 mW (linear) through 432 MHz.
- Z. Lau, "A 1.8 to 54 MHz 5-Watt Amplifier," *QEX*, May 1992, pp 7-8. Uses an MRF137 and a 28-V supply to generate a clean 5-W signal. A gain compensation stage allows it to be driven with 5-10 mW.
- W. Hayward, "Stable HEXFET RF Power Amplifiers," Technical Correspondence, *QST*, Nov 1989, pp 38-40. Shows several amplifiers using the IRF511. Gain and power output varies. Describes an 8-W, 3.5-14 MHz amplifier that runs on 13.5 V.
- Z. Lau, "PIN Diode-Switched Amplifier," Technical Correspondence, *QST*, Feb 1988, p 42. Describes a 1.4-mW input, 1-W output 40-meter amplifier using an MRF237.
- W. Hayward, "A QRP SSB/CW Transceiver for 14 MHz, Part 2" *QST*, Jan 1990, pp 28-31. Describes a 1-W, 20-m HEXFET amplifier and 100-mW 2N5859 driver.

For VHF or UHF work, Chapters 31 and 32 of the 1993 *ARRL Handbook* show how to get from mixer levels to useful power levels on 50, 144, 222 and 1296 MHz. For 432 MHz, see E. Krome, "A High-Performance, Easy-to-Build 432-MHz Transverter, Part 2," *QST*, Sep 1991, pp 18-21. For 903 MHz, see D. Mascaro, "903 MHz Linear Amplifiers," *QST*, Part 1—June 1990, pp 18-25; Part 2—July 1990, pp 28-31. A good general overview of the use of VHF and UHF hybrid power modules is B. Olson, "Hybrid Modules: Building with Bricks," *QEX*, Jul 1988, pp 13-14.—*Zack Lau, KH6CP*

Frosting the Cake

I like to build portable VHF and microwave rigs, and as soon as I work somebody on a 10-mile path I always go farther away and try again. That means at some point I have to switch from SSB to CW. Then we get our antennas aligned and switch back to SSB. The first prototype used just a resistor to unbalance one of the mixers for CW. I hand-wired all the TR switching and didn't put in a sidetone generator because it was too much trouble. I then had a really cute little microwave transceiver and a great big Morsematic keyer that I have to haul up the mountain because I was too lazy to put sidetone in the little microwave rig.

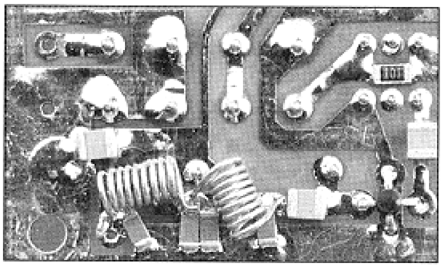
After the second prototype, I decided to put some convenience circuitry on the exciter circuit board to make it easy to build a transceiver.[6] The extra stuff includes Q2, for CW keying; Q1, the TR-switch transistor; and U1B, a sidetone generator. Since I have low tolerance for bad audio, I added a low-pass filter on the sidetone generator to convert the square wave output of the relaxation oscillator to a fairly decent sine wave. Point P is grounded to transmit, Point K is connected to the key for CW, and Point ST is a high-impedance sidetone output that can be routed to an appropriate spot in the receiver audio amplifier. Point A is grounded to disable the mike amp for CW. Interconnections will be discussed in more detail next month.

Other Modes

Old timers may remember that some of the early phasing transmitters offered CW, USB, LSB, AM, DSB suppressed carrier, and narrow-band FM (or PM) at the flip of a front-panel switch. It is possible to generate other voice modes besides USB and LSB with the T2 exciter.

- To generate AM, apply 12 V to point C (to insert carrier) and break the circuit at point X to disable the quadrature modulator.
- To generate narrowband PM, apply 12 V to point C and break the circuit at point Y to disable the modulator that is in phase with the carrier. Mathematicians may want to verify that a DSB suppressed-carrier signal plus a 90° phase-shifted carrier is in fact narrowband phase modulation. The more experimentally inclined can simply listen to the various signals on a multimode receiver (I did both!).

All kinds of advanced digital modes can be generated by injecting the appropriate signals at X and Y, but that's another story.



Close-up of the back side of the T2 PC board opposite the mixers. The MMIC amplifier (U7), its coupling capacitors (C25, C27) and the low-pass filter components (C28-C30, L5, L6) are soldered to this side of the board. R43 is also mounted on this side of the board, underneath the power combiner (U6). Although I used chip components for C25, C27-C30 and R43, small leaded components will work as well.

Performance and Applications

A 2-meter version of this exciter has 40 dB of carrier and opposite-sideband suppression. Distortion products are more than 30 dB down at +3 dBm (2 mW) output. The distortion spectrum falls off very rapidly outside the desired passband. The audio quality is about average for an AM broadcast station—noticeably superior to the average SSB signal on the ham bands. The +3 dBm output level is ideal for upconverting to the microwave bands, heterodyning with a VFO to the HF bands, working across town on 222.1 MHz or driving a linear-amplifier module.

For some applications (running the legal limit on a wide open HF band comes to mind), the casual use of a direct phasing exciter is inappropriate. The potential for interference is too high. A carrier suppressed 40 dB below 1500 watts is 150 milliwatts, and that is enough to work the world on a wide-open HF band. For rock-crushing signals on crowded bands, I recommend operating the phasing exciter at a fixed frequency, following it with a crystal filter, and heterodyning to the desired output frequency, as is done in the Kenwood TS-950SDX. Personally, I'd rather operate a really big bulldozer at a landfill than a legal limit amplifier on a crowded band (the two have a lot in common), but I can find dozens of applications for a multimode exciter that's smaller than most microphones and works on any ham band below 1000 MHz!

A phasing "QRP Gallon" (five watt) transmitter will only have 500 microwatts of carrier and opposite-sideband signal, and conditions have to be really good for 500 microwatts to interfere with anyone. See the sidebar "More Power for T2" for references to some suitable previously published power amplifiers.

On VHF through microwave frequencies, it is routine to make SSB and CW contacts out to a hundred miles or so with very low power from hilltops. A crystalcontrolled phasing exciter makes a nice companion to a multimode scanner at a scenic overlook. For the higher bands, the phasing exciter can serve as the IF for a transverter—details next month.

Tuning

The LO phase-shift network (not included on the board; see the January *QST* article referenced in Note 2) and **AMPLITUDE-BALANCE** pot (R45) can be set for best opposite-sideband suppression while listening to the wrong sideband on a receiver with good selectivity. I tack-soldered a 100-kΩ resistor from the output of the sidetone generator to the mike input to provide a tune-up tone. By alternately adjusting the LO phase-shift network and **AMPLITUDE BALANCE** pot, it should be possible to reduce the wrong-sideband tone by about 43 dB.

It is difficult to judge the carrier suppression in a direct phasing transmitter by listening to the signal in the station receiver unless the carrier oscillator and receiver are very well shielded. The carrier oscillator puts out at least 10 milliwatts, and the carrier signal will probably be loud in the receiver even with the antenna disconnected. I measure carrier suppression by heterodyning the exciter to a different frequency using a separate crystal oscillator and high-level double-balanced mixer.

I chose the audio amplifier gain for low-distortion SSB with the Radio Shack electret microphone shown in the schematic. For different microphones (or different operating habits), the value of R15 should be changed while listening to the audio and opposite sideband in the station receiver. I recognize that the absence of a front-panel mike gain control is an inconvenience, but the consequences of audio distortion in a phasing rig are far more serious than in a filter rig. R15 should be selected and then left alone. There is just too much temptation to turn up the gain a little to get that last half decibel out when working a weak signal!

The opposite sideband may be selected by reversing the LO connections at the mixers. It may be necessary to readjust the LO phase shift network and amplitude balance pot when changing sidebands.

Conclusions

The photos show how the parts are arranged on the PC board. This little SSB exciter board looks nice and works well from VLF to the low microwaves. The first prototype worked the first time I applied 12 V and an audio input signal. The problem with a fine-looking PC board layout is that it discourages further experimentation.

One of the requirements I impose on my projects is that they must be reproducible. In most cases that implies an engineering cycle that starts with a concept, explores lots of options, creates a block diagram and schematic, tests all of the circuitry on the computer and at the bench, lays out and etches a PC board, builds a prototype, debugs and tests the prototype and then lays out a second, third and often a fourth PC board. When I am finished, I am confident that anyone can put the parts on the PC board and build a working copy of my project.

That is not the only way to build a radio, and it is not necessarily the best way. Most homebrewers are familiar with a technique called "ugly" construction, in which the circuit is built, designed, tested, modified, redesigned, optimized, used on the air, and reoptimized in a continuous creative process. "Ugly" equipment is never finished, and always makes the best use of available parts and the homebrewer's talent. Ugly circuits often work better than nice-looking PC boards for two reasons:

- The continuous ground plane and short ground connections reduce or eliminate ground-current problems and improve shielding.
- The fact that the circuit is already ugly encourages further experimentation and improvement.

Building and improving ugly constructed RF projects is the best way to learn about RF design. As soon as you read about a new technique you can try it out on the bench. Ugly construction allows the homebrewer to be creative all the way through a project, and for me, that is the fun of ham radio.

Next month, I'll give more details about integrating the R2 and T2 boards into a station and show some interesting VHF and microwave applications.

Notes

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

[2]R. Campbell, "High-Performance Single-Signal Direct-Conversion Receivers," *QST*, Jan 1992, pp 32-40.

[3]This discussion appears in Chapter 18 of the 1985 through 1993 editions of *The ARRL Handbook*.

[4]*PSPICE1* Circuit Analysis Software is available from the Microsim Corp, 20 Fairbanks, Irvine, CA 92718, tel 714-770-3022.

[5]A. Ward, "Monolithic Microwave Integrated Circuits," *QST*, Part 1—Feb 1987, pp 23-29, 32; Part 2—Mar 1987, pp 22-28, 33.

[6]Etched, plated and drilled PC boards (double-sided, with plated through-holes) for the T2 board are available from Applied Radio Science, PO Box 225, Houghton, MI 49931 for $10 postpaid (send an SASE for a catalog with current kit information). For individuals who want to make their own PC boards, an etching template/part-overlay package for the T2 PC board is available from the ARRL for an SASE. Address your request for the CAMPBELL T2 BOARD TEMPLATE to Technical Department Secretary, ARRL, 225 Main St, Newington, CT 06111.

[7]One source for SBL-1 mixers and MAR-2 MMICs is Oak Hills Research, 20879 Madison St, Big Rapids, MI 49307, tel 616-796-0920. XICON 1%-tolerance 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.

Strays

QST congratulates...

◊ Seven FCC employees on being awarded the the Commission's highest honors, the Distinguished Service and the Meritorious Service awards. They were presented to FCC employees who have advanced the mission and objectives of the Commission through their sustained extraordinary or exceptional accomplishments. FCC Chairman Alfred Sikes (who resigned his post in January) presented the awards at an agency-wide ceremony December 16, 1992.

Distinguished Service Award gold medals were presented to Managing Director Andrew S. Fishel and Robert M. Pepper, chief of the Office of Plans and Policy.

Meritorious Service silver medals were presented to Janet S. Amaya, assistant chief of management and personnel in the Mass Media Bureau; James L. Ball, associate director of the Office of International Communications; Sheldon M. Guttman, associate general counsel of the Office of General Counsel; Michael B. Hayden, AK3F, chief of the Private Radio Bureau's Microwave Branch; and Alexander J. Zimny, N2EDP, engineer-in-charge of the FCC's New York City Field Operations Bureau.

◊ The following amateurs on 70 years of ARRL membership:
- Frank Gunther, W2ALS, Staten Island, NY
- Robert Morris, W2LV, Sparta, NJ
- Lewis Elicker Jr, W3ADE, Harrisburg, PA
- Bartow Huff, W5AHD, Lawton, OK
- Everett Gibbs, W8AQ, Canal Fulton, OH

◊ The following amateurs on 60 years of ARRL membership:
- Sidney Bear, W1ASP, New Haven, CT
- Laurence Stein Jr, W1BIY, Hingham, MA
- James Eckersley, K2IXE, Forked River, NJ
- George Montgomery, W3KVS, Washington, PA
- William Tucker, W4FXE, Hallandale, FL
- John Wallace, W6EP, Westlake Village, CA
- Harry Heffrin, W6MFH, Sacramento, CA
- Edward Van Peenen, W8DM, Kalamazoo, MI
- Edward Dervishian, W9VSU, Lincolnwood, IL

◊ The following amateurs on 50 years of ARRL membership:
- Frank Finger, NU1A, New London, NH
- Eli Rostler, W1MWM, Lowell, MA
- Joseph Hoffmann, W2DIJ, Daytona Beach, FL
- George Gable, W3EDO, York, PA
- Howard Bullock, W4LBM, Alexandria, VA
- William Vandal, W4LPD, Palm Bay, FL
- Vance Gildersleeve, K5CF, Poteau, OK
- Louis Lechenger, W5IHL, Houston, TX
- Norman Wehrli, W5JPC, Athens, TX
- Carson Nohrnberg, W6MKO, Berkeley, CA
- Roy Tucker, N6TK, La Mirada, CA
- Richard McNutt, W8CAT, White Lake, MI
- Carroll De Groff, W9OLY, South Bend, IN
- J. Harold Gibson, W9PQO, Fair Grove, MO
- G. Theodore Anderson, W9UHD, Tuscola, IL
- Jack Miller, W9WYN, Brookfield, IL
- Thornton Lyford, WØQIK, Arden Hills, MN