rat-race balanced mixer for 1296 MHz

Details for an easily built mixer for the 1296-MHz amateur band which can be used in both receiving and transmitting applications

The heart of most successful uhf ssb transceivers is a bilateral mixer, either singly or doubly-balanced. In previous articles[1,2] I have published designs for several such mixers. All have been built successfully by a number of readers, but each exhibited design characteristics which restricted universal reproducibility. I have thus received numerous requests, primarily from amateurs in Europe and Asia, to develop a mixer which could be built from readily available materials, without specialized dielectrics, advanced metalworking techniques, or expensive commercial microcircuits.

Actually, such a mixer was published some time ago by Paul Wade, WA2ZZF.[3,4] His mixer used a microstripline quadrature hybrid, and can be easily etched on a double-sided, glass-epoxy printed-circuit board at minimal cost. As a receive converter, the unit yields an outstanding noise figure because of its inherently low conversion loss.

Unfortunately, the Wade mixer falls a bit short of the mark in transmit service, due in part to its limited dynamic range, moderate isolation, and difficulties in obtaining a good wideband impedance match. The rat-race mixer described here overcomes some of these limitations and preserves the reproducibility of Wade's design.

mixer anatomy

Basically, any passive mixer assembly can be functionally divided into three segments, as shown in **fig. 1**. The coupler serves to apply components of the rf and local-oscillator (LO) signals to the mixer diodes in the correct phase relationship, and may consist of transmission-line delay networks, resistive or reactive power dividers, balun transformers, coaxial or waveguide directional couplers, hybrid couplers, or some combination. The coupler may be built with lumped constants, coaxially, with toroidal transformers, in stripline, or in microstrip.

The nonlinear network in which sum and difference frequencies are generated is represented by the diode array of **fig. 1**. Unbalanced mixers (which afford no isolation between the LO and rf ports) use a single diode, while most single-balanced mixers use a matched diode pair. Double-balanced mixers typically include four diodes in either a ring or bridge arrangement, while special-purpose mixers which offer image cancellation or extra-wide dynamic range may contain an array of eight or more diodes.

Diode selection is based upon noise figure, conversion efficiency, and the signal amplitude requirements of the system. Point-contact cartridge diodes, such as the 1N21 series, were the accepted standard in microwave mixers for many years. These devices are still used in high-power radar applications where diode burnout immunity and ease of replacement are major considerations.

By H. Paul Shuch, WA6UAM, 14908 Sandy Lane, San Jose, California 95124

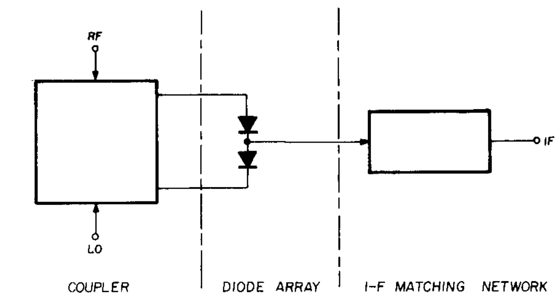


fig. 1. Basic anatomy of a balanced mixer. The coupler may take several forms as shown in fig. 2. The i-f matching network is designed to match the impedance of the diodes to 50 ohms.

The current favorite, so far as the uhf experimenter is concerned, is the Schottky barrier or *hot-carrier* diode. These diodes are available in low-cost glass packages from such microwave industry leaders as Aertech, Alpha, Hewlett-Packard, Microwave Associates, Parametric Industries and others, and combine low conversion loss with excellent immunity to rf burnout. An additional advantage, so far as balanced mixers are concerned, is that the manufacturing variations for hot-carrier diodes are minimal. This yields, for any two diodes of the same part number, rf characteristics which are closely matched, thereby eliminating the need for selecting matched pairs or quads of diodes to achieve good mixer balance.

Where the ultimate in conversion efficiency is required (especially at the higher microwave frequencies), tunnel diodes excel. However, their high cost and relative susceptibility to rf overload have limited their acceptance by radio amateurs.

Regardless of the diodes which are selected for the mixer's nonlinear network, it is unlikely that they will provide a good impedance match to 50 ohms at the i-f port. Bear in mind that diode impedance varies with diode current, which in turn is a function of local-oscillator injection level, applied dc bias, and the diodes' dc return path. The complex impedance of the i-f port, under the desired operating conditions, should be transformed to 50 ohms. To minimize intermodulation responses, this transformation should be effective at both the desired i-f frequency *and* the undesired mixing product (usually the *sum* frequency). This will serve to eliminate reflections at any frequency from re-entering the nonlinear network through the mismatched i-f termination. The effects of image frequency termination are discussed in detail in reference 5, as well as section 2.10 of reference 6.

The required impedance transformation at the i-f port can be accomplished by applying conventional techniques to the design of L, T, or pi networks. These networks also serve to suppress any components of the rf or LO signals which may be present at the i-f port because of mixer imbalance.

hybrid selection

The generalized balanced mixed circuit in **fig. 1** allows considerable latitude in the selection of coupling elements for applying the LO and rf signals to the mixer diodes. Hybrid couplers are available for dividing the input signals into two equal components, which are either in phase, 180° out of phase, or in phase quadrature.[7] Although mixers have been designed around virtually every imaginable coupler, the arrangements considered for this design were two versions of the 90° branch hybrid or quadrature power divider, and two types of 180° ring

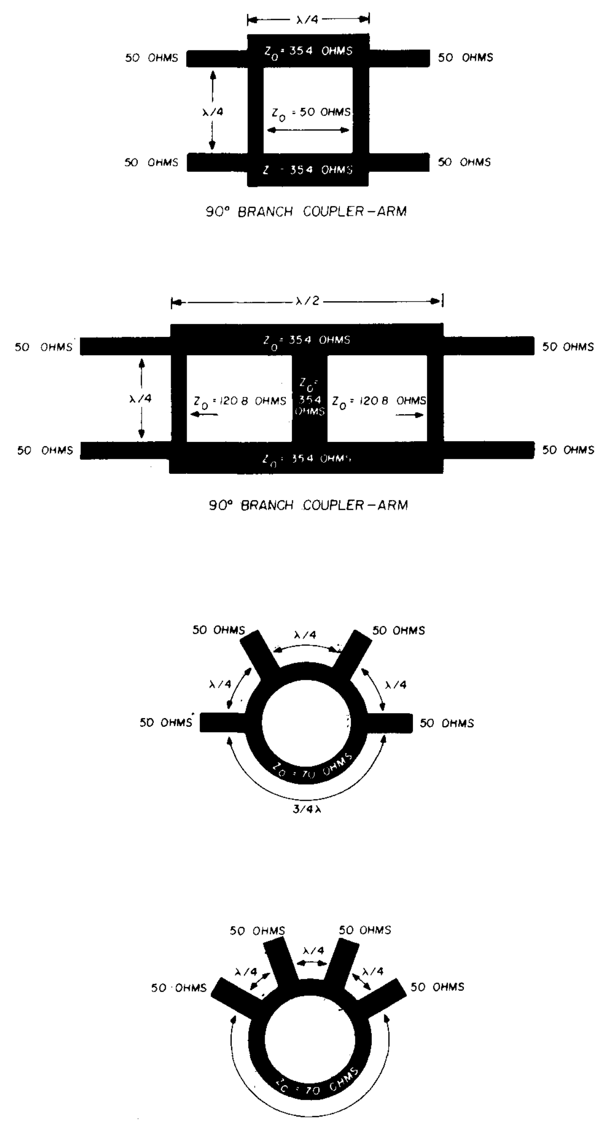


fig. 2. Four types of microwave hybrid couplers which are used in single-balanced diode mixers. Performance of the various types is compared in table 1.

hybrid or *ratrace* (see **fig. 2**). Each of these hybrids can be easily built with etched microstripline, and each offers certain performance advantages which should be considered.

Assuming an rf operating frequency of 1296 MHz, a 144-MHz i-f would suggest a LO frequency of 1152 MHz. Since the mixer hybrid must pass both rf and LO components, it is reasonable to specify 1224 MHz, the mean of these two frequencies, as the design center frequency for the hybrid. The ripple passband of the hybrid must, of course, include both the rf and the LO frequencies; thus the design must permit an operating bandwidth of 144 MHz, or 12%. Physical construction of the hybrid in microstripline, however, could introduce several sources of error as to actual center frequency. Because of the effect of variations in substrate dielectric constant, or that of cumulative dimensional tolerances, conservative design philosophy suggests characterizing the hybrid over a somewhat greater bandwidth. For this study a 20% operating bandwidth was assumed.

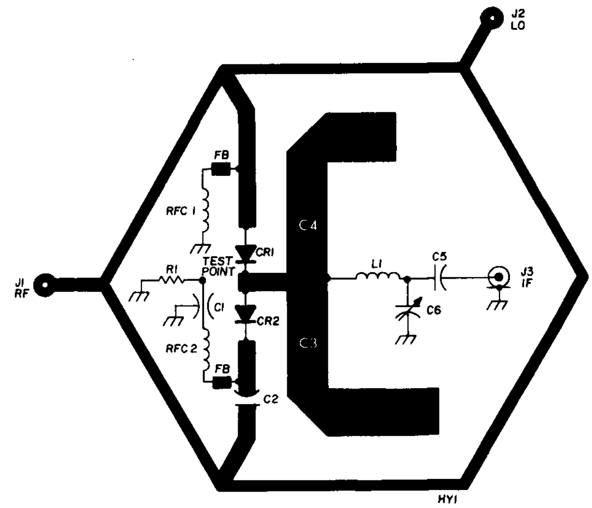
Table 1 compares various operating characteristics of the couplers shown in **fig. 2** over this 20% bandwidth. Information regarding vswr, isolation, and imbalance was determined from published design charts;[8] the relative microstripline losses at the center frequency were derived empirically.

Since all of the listed hybrid characteristics contribute in varying degrees to the overall performance of the resulting mixer, a somewhat subjective tradeoff process is necessary to select the optimum mixer hybrid. I began by excluding the popular 90° branch coupler because of its high vswr and relatively poor isolation. Similarly, I eliminated the extended ring hybrid on the basis of its high stripline losses and poor amplitude balance. In selecting between the two remaining candidates, I opted for minimizing amplitude imbalance and stripline losses, trading off the resulting slight degradation in vswr and isolation. The form factor of the final mixer was a further consideration, although I must admit that a toss of a coin may have been just as scientific!

table 1. Performance comparison of mixer hybrids over a 20% bandwidth.

hybrid type	vswr	amplitude imbalance	isolation	relative insertion loss
90° branch – 2 arm	1.45	0.7 dB	14.0 dB	1.0
90° branch – 3 arm	1.12	0.5 dB	25.3 dB	1.7
180° ring – 3/2λ	1.14	0.4 dB	23.0 dB	1.5
180° ring – extended	1.40	0.9 dB	23.0 dB	2.0

It is interesting to note that other uhf experimenters have also selected the 3/2 wavelength, 180° ring hybrid for mixer service.[9,10,11] All have achieved respectable mixer performance.



C1	1000 pF feedthrough capacitor
C2	100 pF chip capacitor (ATC 100B or equivalent)
C3	25-ohm open-circuit microstripline, 1 quarter-wavelength long at 1152 MHz (see fig. 4)
C4	25-ohm open-circuited microstripline, 1 quarter-wavelength long at 1296 MHz (see fig. 4)
C5	0.001 μF ceramic capacitor
C6	10-40 pF cermic trimmer capacitor
J1, J2	SMA coaxial receptacle (E.F. Johnson 142-0298-001)
J3	BNC coaxial receptacle (UG-1094/U)
L1	4 turns no. 20 (0.8mm), air wound, 3/8" (9.5mm) diameter, 1/2" (13mm) long
R1	10 ohm, ¼ watt carbon composition resistor
RFC1, RFC2	miniature 0.33 μH molded rf choke with ferrite bead slipped over hot end
Z1	70-ohm rat-race hybrid at 1224 MHz (see fig. 4)
CR1, CR2	hot-carrier diodes (Hewlett-Packard HP 5082-2817)

fig. 3. Schematic diagram of the rat-race balanced mixer for 1296 MHz. Full-size printed-circuit layout for the etched circuit board is shown in fig. 4.

The decision to use microstripline construction on fiberglass-epoxy PC board was due primarily to the success which Wade achieved with this medium, and partly due to my frustration in trying to duplicate the results of others. Rat-race mixers of slab-type[9] or coaxial[10] construction demand greater patience and mechanical ability than I possess, and the slight, almost immeasurable performance advantage of etching microstripline couplers on expensive Teflon substrates[11] didn't seem worth the effort.

i-f selection

Factors governing the selection of a conversion system's intermediate frequency include the band width capabilities of hybrid junctions, image rejection limitations in practical bandpass filters, the availability of i-f equipment or components, and spurious responses (related to possible harmonic relationships between signal, LO, and i-f). Unfortunately, the first of these considerations seems to suggest selection of a low i-f, the second generally favors a high i-f, and the third all too often dictates selection of an i-f which violates the fourth!

I have built various conversion systems for 1296 MHz, using amateur 28, 50, 144, and 432 MHz bands as a receive and transmit i-f. My experiences tend to favor the 2-meter i-f as a good compromise between mixer bandwidth and image rejection. The recent proliferation of 2-meter ssb transceivers further supports this choice. However, the actual operating frequency within the band must not be selected arbitrarily. For example, placing a 1296.0-MHz signal at a 144.0-MHz i-f would require a 1152.0-MHz LO. More than one experimenter (myself included) has started with a 48.0-MHz crystal oscillator, multiplied by 24 to 1152 MHz, and ended up with a strong interfering signal at 144 MHz on the receiving dial.

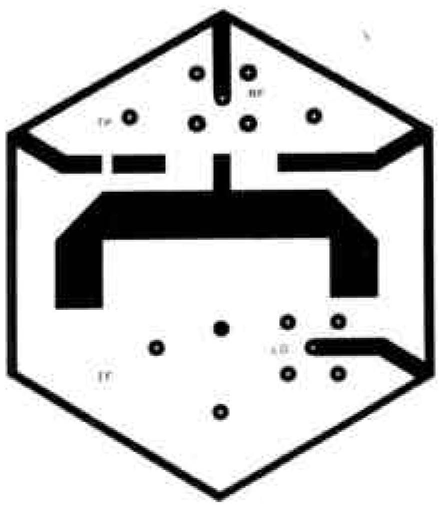


fig. 4. Full-size layout for the rat-race mixer circuit board. Drilling instructions are shown in fig. 5.

The spurious signal, of course, is the third harmonic of the crystal oscillator. If you try to circumvent this difficulty by starting at 96.0 MHz and multiply by 12, it's possible to end up with transmitted spurious signals from the ninth harmonic of the injected i-f signal.

Another constraint on the i-f selection is the undesirability of having a popular operating frequency in the 1296-MHz band fall at (or worse, just past) the end of the i-f tuning range. For best results, 1296.0 MHz should fall in the middle of the tuning dial. In my present system, this dictates an i-f of 145.1 MHz; a 1150.9-MHz LO derived from a 95.9083-MHz crystal keeps me free from birdies.

Although most of my activity on 1296 MHz is on ssb, the beauty of a linear translation scheme is that it's compatible with virtually any mode. This mixer will accommodate fm, a-m, video, or whatever. Depending on the mode, tradition, rather than technology, may govern the selection of operating and i-f frequencies. A group planning narrow-band fm simplex, for example, might choose to place 1290.52 MHz on 146.52 MHz. Nonetheless, the above considerations deserve attention, especially when selecting the LO multiplying scheme.

The mixer design presented here will actually accommodate an i-f between about 70 and 150 MHz, with little noticeable performance variation. Obviously, great care should be exercised when selecting the actual i-f and oscillator frequencies.

construction

Fig. 3 shows a schematic diagram of the ring hybrid or rat-race mixer for the 1296-MHz amateur band. Note that the microstripline hybrid, which is normally built as a circular trace with a circumference 3/2 wavelengths long, is shown as a hexagon with quarter-wavelength sides. I used this same simplification in an earlier mixer,[12] as did Dick Bingham, WB6BDR.[11] Neither of us noticed any measurable degradation over the usual circular arrangement. Leroy May's successful rat-race mixer (reference 9) used a triangular layout, and this led me to believe that the layout itself is relatively unimportant. The 70-ohm characteristic impedance of the ring, however, is critical, and requires a 0.05 inch (1.3mm) microstripline width for G-10 circuit board.

Aside from the diode bias path (to be discussed

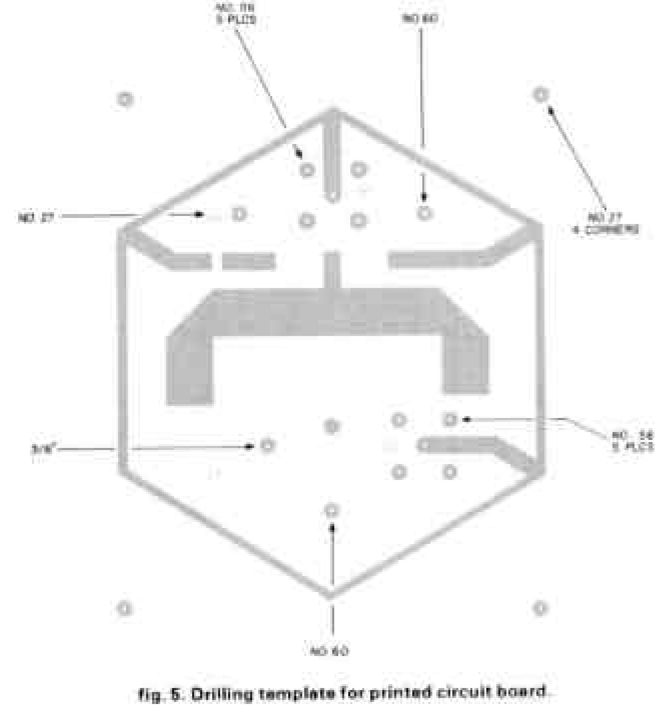


fig. 5. Drilling template for printed circuit board.

shortly), the bulk of this mixer design, including the i-f port matching network, is borrowed directly from Paul Wade's design[4] and will not be discussed here. I should point out, however, that the pi-network matching network at the i-f port does little to properly terminate the image component; the importance of this was discussed previously. For mixer applications which dictate maximum freedom from intermodulation distortion, the user should consider adapting the Bridge-T interstage isolator circuit.[14]

Fig. 4 is a full-scale layout for the rat-race mixer. The pattern should be etched on 1/16 inch (1.5mm) thick G-10 fiberglass-epoxy printed circuit laminate, double-clad with 1 ounce copper (1.4 mils or 36 microns thick). One side of the board is unetched and serves as a groundplane for the microstriplines on the etched side. Drill the board as shown in **fig. 5**.

Assemble the mixer as shown in **fig. 3** and the photographs. When mounting the SMA connectors at the LO and rf ports, be sure to countersink the groundplane side of the board at the connector center conductor to avoid a short to ground. Assembling the mixer is straightforward, except that the leads of the diodes must be bent carefully to prevent damage to the glass diode package.

Once assembled, only one mixer adjustment is required: matching to the i-f port. This can be done by injecting a signal into the rf port, connecting the i-f port to a 2-meter receiver, and tuning capacitor C6 for maximum signal level. Alternatively, with the rf port driving a power meter, inject a 3mW, 2-meter signal into the i-f port, and tune C6 for maximum output. In either case, the LO port must be driven with a clean 5 to 10 mW signal in the vicinity of 1152 MHz and the i-f port must be terminated in 50 ohms. The 50-ohm load can be provided by tuning the mixer with a fixed, 50-ohm pad inserted between the i-f port and the 2-meter transmitter or receiver.

Fig. 6 shows the isolation of this mixer, as measured on a Hewlett-Packard 8507A Automatic Network Analyzer. The isolation of the assembly is greater than 20 dB from 1050 MHz to over 1300 MHz, and at least 30 dB over the anticipated operating bandwidth; isolation over a 20% bandwidth is quite close to that predicted in **table 1**.

bias considerations

Wade operates his balanced mixers in the *starved-LO* mode.[3,4] That is, he applies a rather low level of LO injection (typically 1 mW) to the diodes, and supplements this low LO drive with dc bias. By varying the dc bias, the impedance of the diodes can be controlled, providing an improved match to the mixer hybrid. Obviously, it is far easier to generate the required dc bias than it is to increase LO injection by 10 dB.

Other advantages of DC mixer bias were reported by Pound as far back as 1948:[6] "Accompanying the reduced LO power requirement is a reduction in the reaction of the local-oscillator circuit on the signal circuit in the mixer. The over-all noise figure becomes less dependent upon the amount of incident local-oscillator power at the crystal, because the conversion loss does not increase so rapidly as the local-oscillator drive is decreased. Finally, the i-f conductance of the crystal is less dependent on the amount of local-oscillator drive."

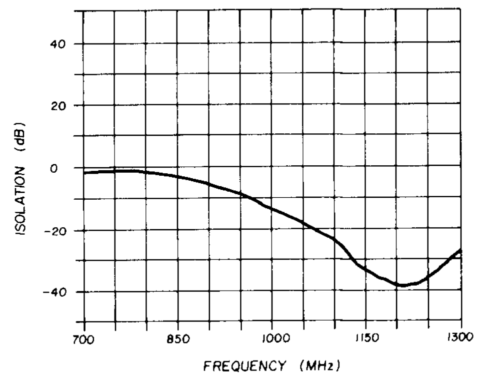


fig. 6. Isolation of the rat-race balanced mixer, as measured with a Hewlett-Packard 8507A Automatic Network Analyzer.

Starved-LO operation was attempted in one of my bilateral conversion systems, but with disastrous results. In transmit mode application of 1 mW of i-f injection resulted in a severely distorted rf output, measuring several dB below the power level which the characteristic conversion loss of the mixer would suggest. Further, a spectrum analyzer revealed numerous unwanted frequency components which were not previously a problem. It appeared that the dynamic range of a balanced mixer in the *starved-LO* mode was far below that of a similar mixer with the customary +3 dBm (2 mW) per diode injection level. This conclusion was confirmed by Harlan Howe:[8] "Naturally, intermodulation products and saturation levels will be the same as if the LO drive were unsupplemented by dc power." Thus *starved-LO* operation was abandoned for this mixer in favor of a full 4 to 10 mW of LO injection. A similar choice is indicated for any balanced mixer used in transmitter service, or any time large-signal handling capability is important.

It will be noted from the schematic in **fig. 3** that, although external dc bias is not used in this design, the diode's self-bias return is brought out through feedthrough capacitor C1. Since the LO signal is effectively rectified by the diodes, a dc voltage will appear across R1; the magnitude of the dc voltage is a function of applied LO injection level. Thus, the feedthrough capacitor is a convenient test point for measuring (and optimizing) LO injection, as indicated in **fig. 7**. The object is to minimize conversion loss, which is a direct function of LO injection (see **fig. 8**).

Like other microwave experimenters, in recent years I have sought to master the techniques of microstripline design and construction by developing individual circuits on etched circuit boards. Thus my

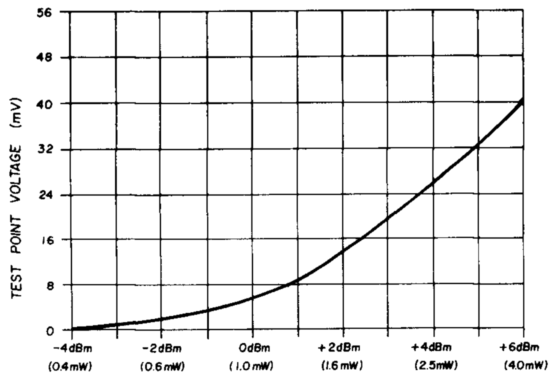


fig. 7. Since the diodes rectify the LO signal, a dc voltage measurement can be used to check LO injection level. Plotted here is the test-point voltage (mV) vs LO injection for the rat-race balanced mixer.

early 1296-MHz systems consisted of numerous modules, each containing a single stage, each matched to 50 ohms, and all inter-connected by coaxial cable. This approach at best is a crude utilization of microstripline technology. One of the main benefits to be derived from the etched-substrate approach is that numerous associated circuits may be built as an integral unit, thereby minimizing interconnections, reducing cost, and improving reliability.

I have made several attempts to integrate circuits onto common substrates. My process of system integration began with a two-stage preamplifier,[12] progressed to a combined balanced mixer, image filter, and LO filter,[2] and culminated in a complete transverter-on-a-board.[13]

Unfortunately, acceptance of these integrated assemblies by amateur microwave enthusiasts has not been overwhelming. It was brought to my attention by numerous readers that the tasks of tuneup and testing present major problems when multiple, interactive stages are involved, especially when the available test equipment is limited to a grid-dip oscillator and a number 47 lightbulb! Individual stages, on the other hand, may be readily tested into 50 ohms, and then placed into the desired system with few adjustments. Joe Reisert has been promoting such a modular approach for some time; his articles are highly recommended.[15,16,17]

My 1296-MHz systems have recently gone through a process of de-integration (not to be confused with *dis*integration) with a return to small modules, each containing a single stage, all stages interconnected with 50-ohm coax.[18] This mixer is one such module. Unlike my previous mixer, the one presented here contains no rf or LO filters. Filters will of course be required in most applications but are easily added to the system as individual modules after they have been tuned and tested.[19]

A word about rf cabling and connectors is in order. Whenever possible I recommend the use of high quality microwave connectors such as type SMA. The JCM series of coaxial connectors from E.F. Johnson are low cost, SMA-compatible units exhibiting excellent rf properties through 4 GHz. For microstripline launchers I recommend E.F. Johnson part number 142-0298-001, and I use their 142-0161-001 connectors on all jumper cables. These connectors are priced in the $3.00 range and are available from electronics distributors in many parts of the United States.

Of all the considerations surrounding the selection of interconnecting coaxial cable, cost and availability are the major factors for amateur applications. Obviously, low loss and constant impedance must also be considered. Semi-rigid coax, such as Uniform Tubing UT-141,* perform exceptionally well, but are virtually unobtainable in many parts of the world. A good second choice is ¼ inch (6.5mm) diameter flexible coax, if the lengths are short. Desirable features are double shielding, Teflon dielectric, and a silver-plated, solid center conductor. One cable meeting these requirements is RG-142/U, but its cost per foot discourages many experimenters. Nonetheless, a moderate investment in jumper coax can spare you a world of grief. Other usable cables which cost considerably less include types RG-141/U, RG-223/U, and RG-55/U. As a last resort, RG-58/U may be used, but its length must be kept to an absolute

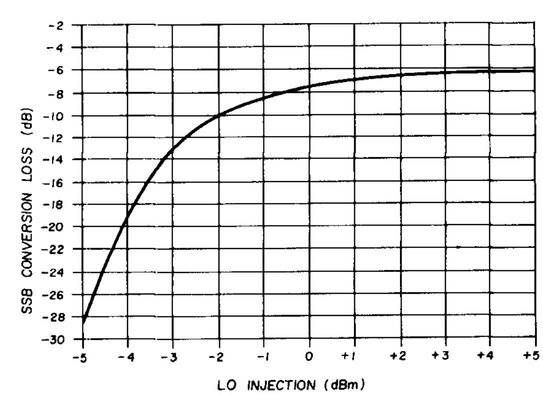


fig. 8. Conversion loss of the rat-race single-balanced mixer as a function of local-oscillator injection.

*Not to be confused with RG-141/U, which is a ¼ inch (6.5mm) diameter flexible cable.

minimum. Just remember that most 1296 operators use RG-58/U to build calibrated attenuators! All of the flexible cable types listed here will accept the recommended SMA plug.

parts availability

The components required to build the rat-race mixer described in this article are available from various sources in the United States; the printed-circuit board may be etched from the full-size artwork shown in **fig. 4**. For those uhf experimenters who don't have the facilities to etch their own boards, commercially etched, drilled, and plated boards are available from Microcomm.*

*An etched, drilled, and plated circuit board for the rat-race mixer is available from Microcomm, 14908 Sandy Lane, San Jose, California 95124, for $6.50 post paid within the United States and Canada ($7.00 elsewhere). A wired and tested mixer is also available; Microcomm will *not* offer a complete kit of parts.

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