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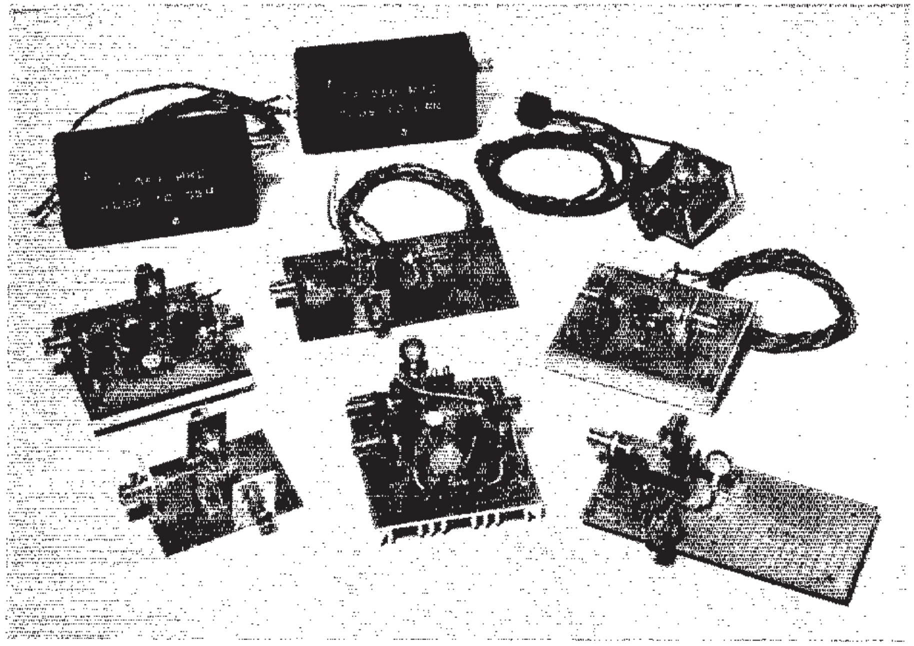
Modern Receiver Mixers for High Dynamic Range



The VMP4 VMOS offers a new approach to mixer design. For quality communications equipment it provides improved port-to-port isolation and relatively high immunity to strong in-band and out-of-band signals.

By Doug DeMaw,* W1FB and George Collins,** ADØW

Designers and users of modern communications receivers and transmitters are necessarily interested in high dynamic range and port-to-port isolation in the mixer stages of the equipment. A quality communications receiver for medium- or high-frequency band use will exhibit high dynamic range in order to provide relative immunity to strong in-band or out-of-band signals. Furthermore, the system should be relatively free of spurious responses that cause "birdies" across the receiver tuning range.

Acknowledging the importance of gain distribution and noise figure in the early stages of a receiver, we concentrate, therefore, on the mixer performance. In a typical quality design of the day we try to ensure a "crunch-proof" status for the rf amplifier, mixer and post-mixer amplifier. For the most part, this requires that each of those stages be capable of handling a substantial amount of signal power without gain compression or undue IMD products being generated. It is not unusual to find a VMOS power FET or a large CATV (cable television) type of bipolar transistor being used as an rf amplifier ahead of the mixer. A VMP4 VMOS device or a 2N5109 bipolar transistor can be used to obtain high dynamic performance in an rf amplifier. The same or similar devices are often used as post-mixer broadband amplifiers in high-performance communications receivers.[1,2]

Our objective is to select a mixer that has sufficient port-to-port isolation to minimize the effects of LO energy appearing in the mixer output. Similarly, the signal energy should be well suppressed at the remaining ports of the mixer. Furthermore, if the mixer requires a high level of LO power to provide optimum performance, difficulty may be encountered in keeping the LO energy isolated from the other circuits in the receiver. Our choice, therefore, must be one that involves a minimum amount of trade-offs while ensuring good mixer performance.[3]

Mixer Options

The choice between passive and active mixers in a given design should be based on performance objectives, with consideration of the circuitry that precedes and follows the mixer. A singly or doubly balanced mixer is preferable to a single-ended mixer in the interest of isolation between the ports. The doubly balanced version will afford the best performance in that respect.

The active mixer will yield conversion gains of less than unity to as great as 20 dB, depending upon how it is used. Perhaps the least acceptable of the better mixer options is a pair of small-signal, dual-gate MOSFETs of the 40673 family. Many communications receivers use such devices in a broadband, singly balanced arrangement. Although this may be cost-effective to the manufacturer, high dynamic range will be hard to achieve without a sacrifice in noise figure at the higher frequencies. If an rf amplifier is used to improve the noise performance, care must be taken to keep the gain only

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[1]References appear on page 23.

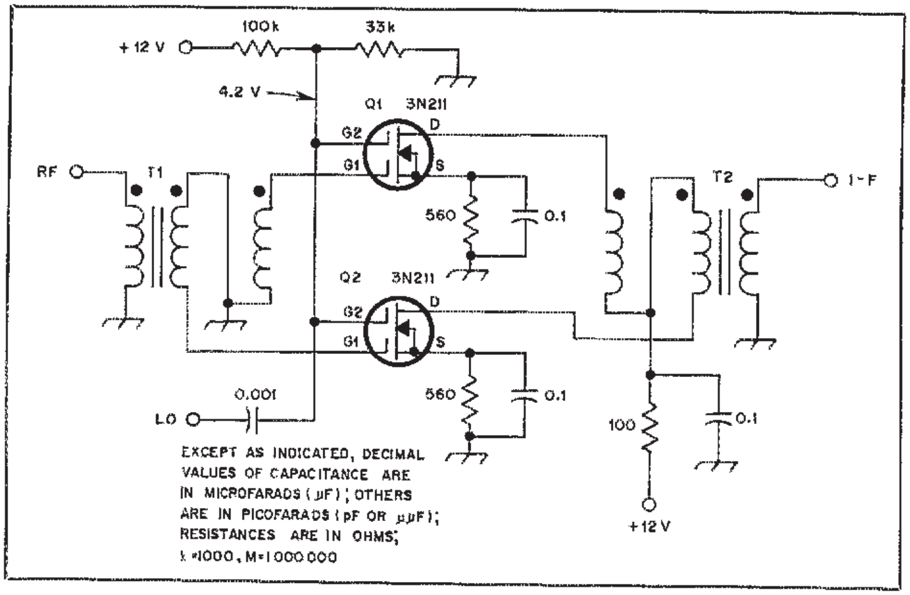


Fig. 1 — Reference mixer that uses small-signal dual-gate MOSFETs in a broadband, singly balanced setup. Conversion gain is −5 dB because of the low terminal impedances and broadbanding. With an LO injection of 8 volts pk-pk and an input signal level of −10 dBm PEP, the third-order output intercept is +17 dBm. Gate bias and LO injection has been optimized. Narrowbanding and careful impedance matching would yield conversion gains up to +15 dB.

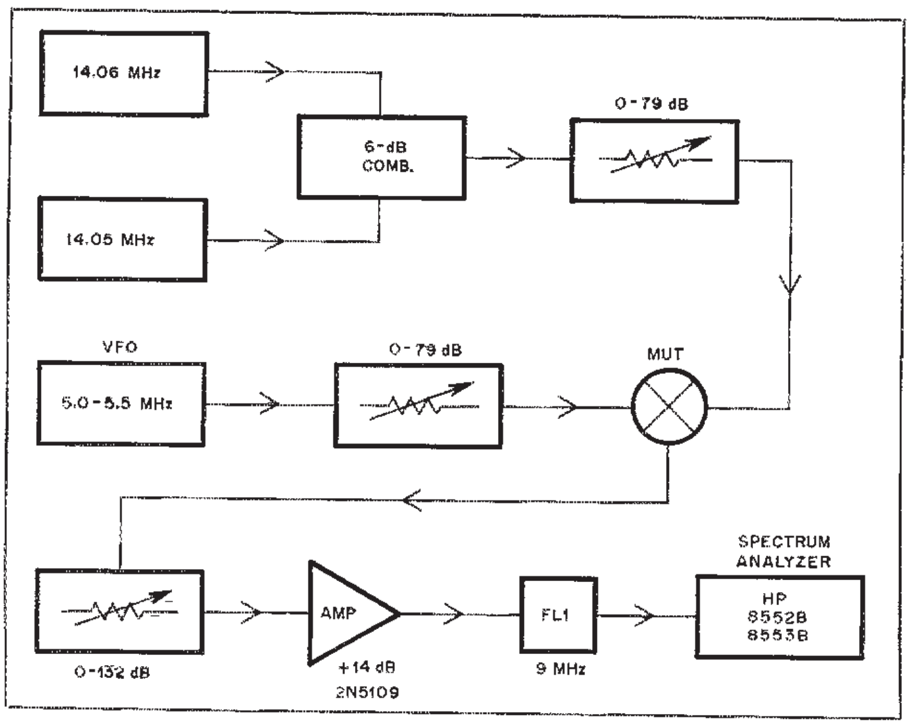


Fig. 2 — Block diagram of the test fixture used in evaluating the mixers treated in this article.

high enough to ensure the desired receiver noise figure. Too much gain will cause the mixer to collapse in the presence of strong signals. Most receivers that use small-signal FETs in a singly balanced scheme (Fig. 1), and with a MOSFET rf amplifier ahead of the mixer, exhibit an IMD characteristic of 80 to 85 dB if the design has been done with care. A gain compression of 1 dB occurs between 115 and 125 dB on the average, referenced to the receiver MDS (minimum discernible signal). A receiver with these characteristics might be entirely acceptable in some signal environments. But much greater dynamic range is necessary in high signal-density locations, such as shipboard and in large communications centers where transmitters are operating on several frequencies simultaneously.

Active mixers can be valuable in terms of conversion gain, with narrow-band types yielding the higher gain figures. The usual trade-off between bandwidth and gain must be accepted when using broadband mixers. The amount of conversion gain desired will depend on the filter losses before and after the mixer, and the available overall gain after the mixer.

Passive mixers of the diode-ring, doubly balanced variety are capable of excellent dynamic range and port-to-port signal isolation. The shortfall is, of course, fairly high LO power requirements (+7 to 15 dBm) and a conversion loss on the order of 8 dB. It is almost mandatory to employ an rf amplifier ahead of the diode-ring mixer to provide a low noise figure. A diplexer may be used after the mixer to ensure a 50-ohm termination at all frequencies, thereby aiding the IMD characteristic.[4] If the i-f filter has a high insertion loss (10 dB for most mechanical filters), a post-mixer, large-signal amplifier is worthwhile. It can be terminated by a 50-ohm pad of specified attenuation to ensure a constant load and to protect the i-f filter from damage when very high signal levels are present at the receiver input.

It is apparent from the foregoing discussion that a lot of decision making is necessary when deciding what mixer to use. Whatever the choice is, high dynamic range should be the criterion. This can be achieved with passive or active mixers. The remainder of this article addresses various mixers and their performance characteristics. The laboratory test procedure used by the authors is also discussed.

Mixer Evaluation Method

Two-tone tests of the various mixers were performed with a signal separation of 10 kHz at 14.050 and 14.060 MHz. A +8 dBm output level was available from each spectrally clean, crystal-controlled generator. A 6-dB combiner followed the two generators. Output from the combiner was routed through a Tektronix 2701 attenuator (0 to 79 dB), then to the mixer under test (MUT).

LO power was generated by a Trio-Kenwood 5-MHz VFO, to which filtering and additional amplification was added. The LO source delivered +16 dBm. A second Tektronix 2701 attenuator was connected between the LO source and the MUT LO port.

I-f output from the mixers was routed through an HP 355C/D attenuator (0 to 132 dB) to a broadband class A 2N5109 +14-dB amplifier which had a +40 dBm output intercept. A 2.4-kHz bandwidth KVG 4-pole crystal-lattice filter with an IL (insertion loss) of −5 dB followed the post-mixer amplifier. Output from the filter was supplied to an HP 8553/8552B spectrum analyzer through a 500- to 50-ohm matching transformer. Other broadband transformers were used to provide a proper interface between the test modules and MUTs. Those transformers are not shown in the test-setup block diagram of Fig. 2. A 7-pole, T-section Chebychev low-pass filter was used at the output of the 2N3866 broadband post-LO amplifier to ensure that all LO harmonics were 70 dB or greater below peak LO output.

Plessey SL6440C IC Mixer

A recent product to the IC market is the Plessey SL6440C programmable high-level mixer. It is advertised as having a +30 dBm output intercept point and a +15 dBm compression point (1 dB). The internal circuit of the IC had not been revealed at the time this article was written, but it is presumed that the inner workings are not too unlike those of the Motorola MC1496G, with the exception of greater dissipation capability for the SL6440C. The manufacturer rates the mixer as having a −1 dB (typical) conversion gain when the IC is terminated in 50 ohms. In our tests a 200-ohm termination was used at the input and output of the IC, yielding a conversion gain on the order of +8 dB maximum.

Fig. 3 contains the circuit of the SL6440C as it was configured for laboratory analysis. R1 was used to adjust the quiescent current of the mixer. Table 1 shows the test results at various LO and signal-input levels. The spectral displays of Fig. 4 show the LO and LO harmonics to i-f-port isolation (A). With 0 dBm of LO input power the isolation was 29 dB. The 2f LO isolation was measured at −72 dB.

Spectral photograph B of Fig. 4 shows the rf port to i-f port isolation as being 48 dB when the LO level was 0 dBm and the rf-input level was −10 dBm, PEP. Photograph C is the two-tone output of the mixer. Table 2 contains data on conversion gain, intercept numbers and port isolation with various I_p amounts. These data were compiled with an LO injection of 0 dBm and an rf input of −5 dBm.

One might conclude from the foregoing test results that the Plessey SL6440C is indeed a worthy device which is capable of providing high dynamic range without conversion loss. The I_p values used in these tests were the maximum safe levels

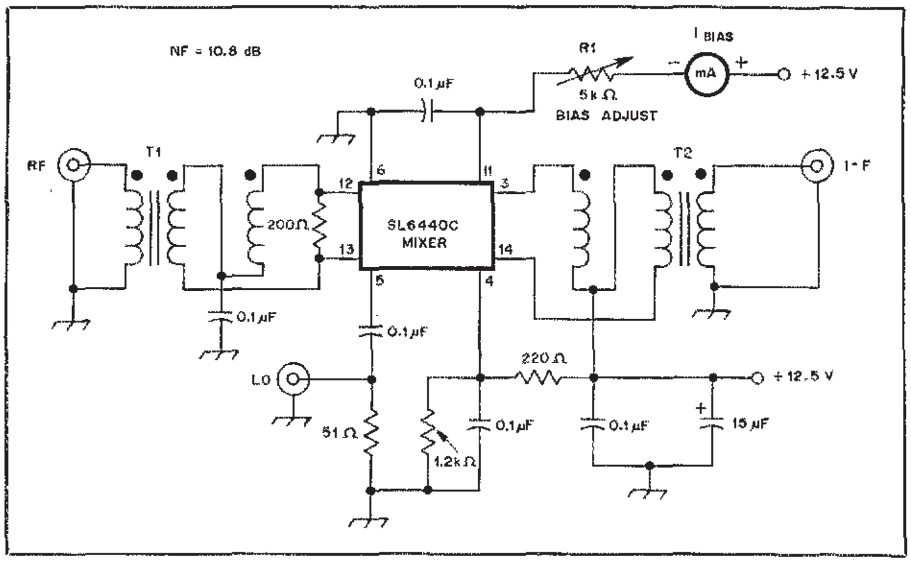


Fig. 3 — Test circuit for the Plessey SL6440C mixer IC.

Table 1

Test Results at Various LO and Signal-Input Levels

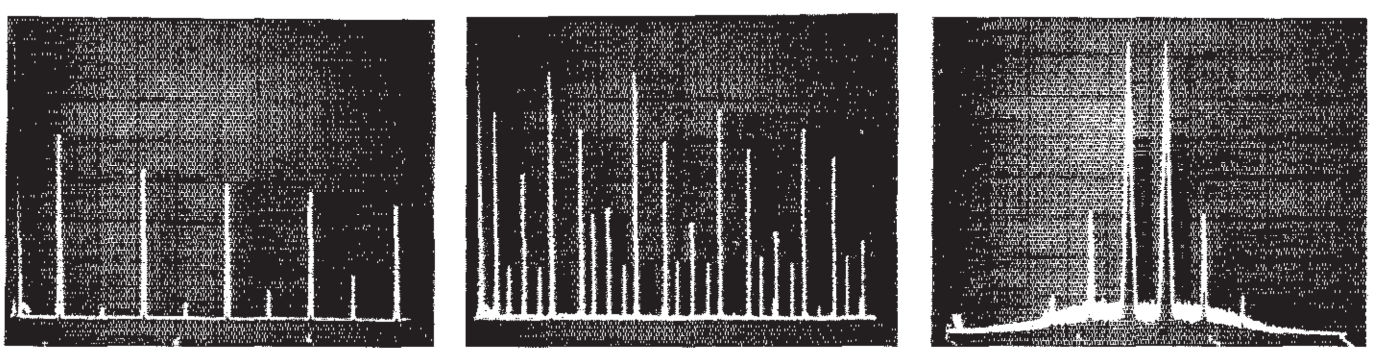
LO Level (dBm)	*Input Level (PEP, dBm)*	*Third-Order Output Intercept (PEP, dBm)*	*Conversion Gain (dB)*
0	+3	24	7
0	0	29	8
0	−5	31	8
0	−10	31	8
0	−15	29	8
−3	+3	25	7
−3	+1	28	8
−3	0	29	8
−3	−5	30	8
−3	−10	31	8
−3	−15	30	8
−10	+2	23	7
−10	0	29	8
−10	−5	31	8
−10	−10	31	8
−10	−15	29	8
−15	+2	25	7
−15	0	29	8
−15	−5	31	8
−15	−10	31	8
−15	−10	31	8
−15	−15	29	8

Table 2

Data on Conversion Gain, Intercept Numbers and Port Isolation

I_p Current (Pin 11, mA)	*Conversion Gain (dB)*	*Third Order Output Intercept (dBm)*	*LO-to-RF Isolation (dB)*
5.0	5.5	18	27
5.5	6.0	19	27
6.0	6.5	20	27
6.5	7.0	21	27
7.0	7.0	22	27
7.5	7.0	23	27
8.0	7.0	24	27
8.5	7.0	25	27
9.0	7.5	26	27
9.5	7.5	26	27
10.0	7.5	27	27
10.5	7.5	28	27
11.0	7.5	28	27
11.5	8.0	29	27
12.0	8.0	29	28
12.5	8.0	30	28
13.0	8.0	31	28
13.5	8.0	31	28

LO input = 0 dBm. Rf input = dBm



(A) (B) (C)

Fig. 4 — Spectograph A shows the LO suppression at the i-f port of the SL6440C with no rf signal applied. LO injection is 0 dBm. Center frequency is 25 MHz, bandwidth is 100 kHz, vertical scale is 10 dB/div. and horizontal scale is 5 MHz/div. Display B shows the output spectrum with 0 dBm of LO power and −10 dBm of rf signal applied to the mixer. Analyzer bandwidth in this example is 30 kHz. Two-tone output is displayed at C with the vertical scale being 10 dB/div. and the horizontal scale at 10 kHz/div. Center frequency is 9 MHz and bandwidth is 0.3 kHz.

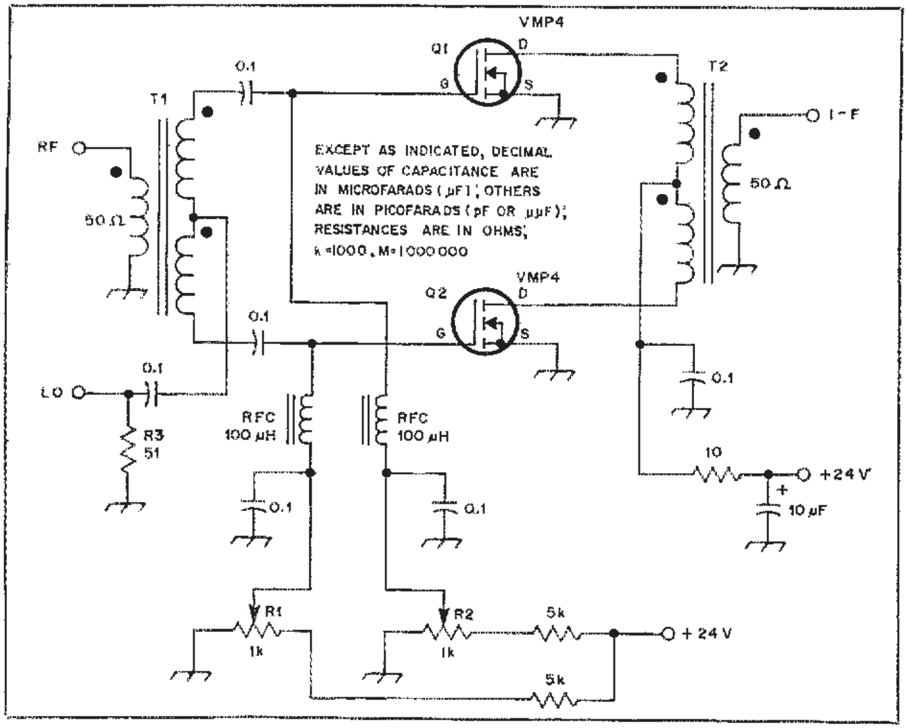


Fig. 5 — Circuit for the VMOS power FETs in a singly balanced arrangement. Split dc feed to the gates was used to provide dynamic balance.

Table 3

Results with Various Levels of Gate Voltage and Drain Currents

LO (dBm)	*Rf Input[1] (dBm)*	*Gain (dB)*	I_D[2] *(mA)*	*Gate[3] Volts*	*Third O.I. (dBm)*
+16	+8	15	75	1.0	42.5
+16	+5	15	63	1.0	43.5
+16	+2	15	56	1.0	44.0
+16	−1	15	54	1.0	44.0
+16	−4	15	52	1.0	45.0
+16	−7	15	52	1.0	*
+16	+8	16	115	1.5	42.0
+16	+5	16	105	1.5	44.0
+16	+2	16	100	1.5	45.0
+16	−1	16	97	1.5	45.0
+16	−4	16	96	1.5	44.5
+16	−7	16	96	1.5	*
+16	+8	16	180	2.0	39.0
+16	+5	17	170	2.0	42.5
+16	+2	17	165	2.0	43.0
+16	−1	18	160	2.0	44.5
+16	−4	18	160	2.0	43.0
+16	−7	18	160	2.0	43.0

*IMD products below measurement system noise floor.
[1]All signal levels referenced to PEP.
[2]Total current.
[3]Both gates at same voltage.

of dc current without heat sinking the IC. A package limitation of 1.2 watts is specified for temperatures up to 25° C, with derating set at 8 mW/° C above 25° C. Maximum program current is 50 mA.

Singly Balanced VMOS Power FET Mixer

The VMOS power FET has characteristics that suggest its ability to perform well in a high-level balanced mixer circuit. For this reason it was included in the mixer evaluation program to determine how it would compare to other high-level mixers. A pair of VMP4 vhf devices was selected for testing in a singly balanced mixer. Other VMOS devices, such as the VN66AK, should offer nearly comparable hf-band performance at lower cost. The VMP4s were chosen mainly because they could be adapted easily to heat sinking, owing to the strip line package format.

Fig. 5 contains the test circuit used by the authors. The rf and LO signals were applied to the gates of the FETs, permitting the sources to be grounded. Earlier tests of the same FETs in a circuit recommended by a manufacturer (rf signal injected on the sources and LO injection on the gates) yielded substantially degraded mixer performance. Instability was also manifest when the forward gate voltage was increased beyond 1.9. Stability could not be obtained without excessive resistive loading of the broadband transformers, so the circuit was abandoned in favor of the one in Fig. 5. Bias controls R1 and R2 were included to help establish dynamic balance of Q1 and Q2. R3 was added to establish a known impedance at the LO injection point during laboratory analysis. Without the resistor, the port impedance is in excess of 500 ohms.

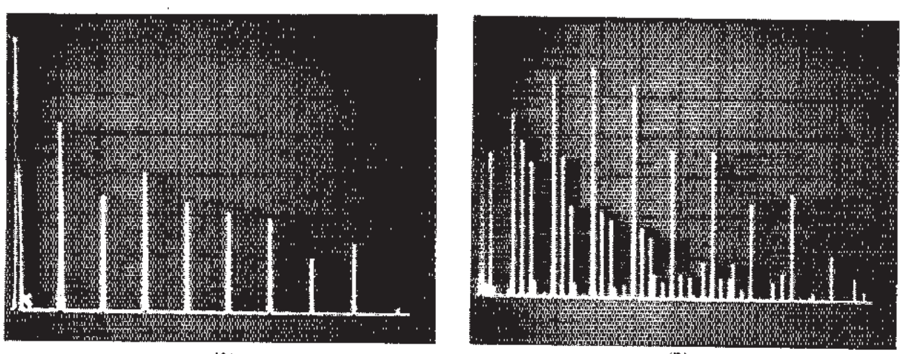
Table 3 shows the results obtained with various levels of gate voltage, rf-signal input and quiescent drain currents. LO injection was maintained at +16 dBm. It can be seen that a variety of operating conditions yielded good output intercepts. The resultant conversion gain is somewhat higher than is desired for most receiver applications. If this circuit is used it will probably require inclusion of an attenuator pad after the mixer to tailor the effective gain to a suitable level for the stages that follow the mixer.

As one would suspect, port isolation follows the format that is common to singly balanced mixers. With the circuit of Fig. 5 the isolation was 38 dB when R1 and R2 were adjusted for best suppression of the output responses. This condition was realized when one gate had 2 volts and the other had 1.85 volts. Fig. 6 shows the spectral output of the mixer under a balanced condition. Photograph A shows the LO isolation and photograph B illustrates the LO and rf isolation.

The authors have concluded that VMOS power-FET mixers are worth considering when high dynamic range is desired (without concern for the high values of quiescent drain current in a 24- to 28-volt dc type of system). It follows that a quad of power FETs in a doubly balanced mixer circuit would offer improved performance over that provided by the mixer in Fig. 5.

High-Level Diode-Ring DBM

If the designer is willing to accept a trade-off between dynamic range and conversion gain, the doubly balanced diode-ring mixer is worthy of consideration. Our



(A) (B)

Fig. 6 — Spectral display A shows the LO/i-f port isolation for the VMP4 balanced mixer with +16 dBm of LO injection and no rf signal applied. Spectrograph B reveals the rf/i-f isolation with +16 dBm of LO power and 0 dBm of rf signal input.

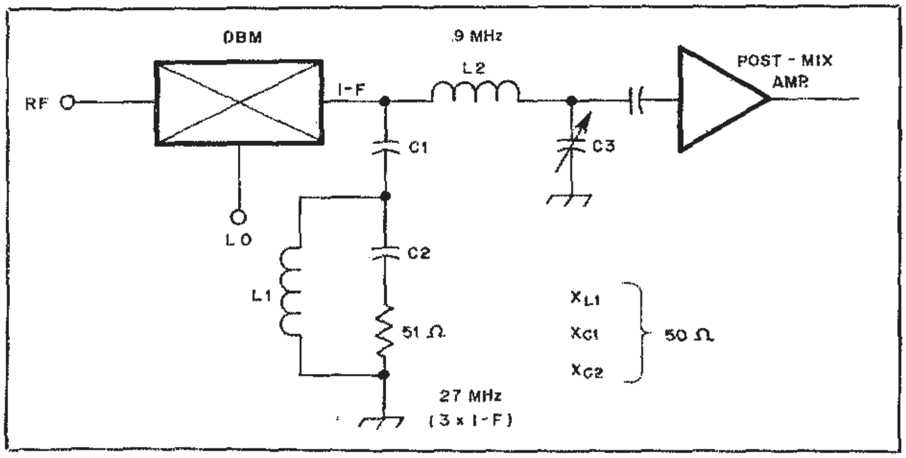


Fig. 7 — Method for adding a diplexer to the output of a diode-ring mixer to enhance the IMD performance. The high-pass network is terminated in 51 ohms and is designed for 3 × i-f. An L network provides an impedance match between the mixer output (50 ohms) and the input of the post-mixer amplifier.

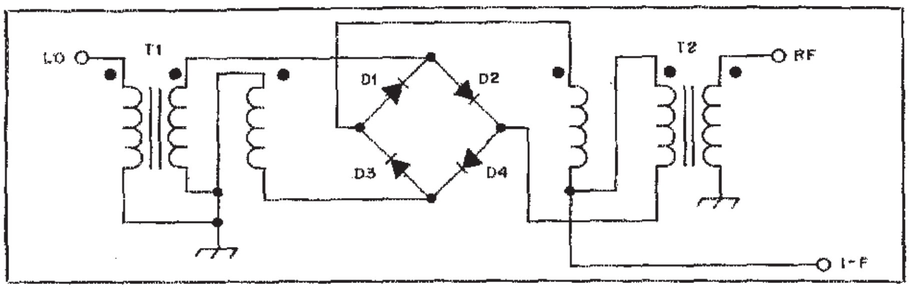


Fig. 8 — Diagram of the SRA-1H diode-ring, high-level mixer used in the performance tests.

Table 4

Test Results for the SRA-1H Diode-Ring High-Level Mixer

LO (dBm)	*RF (dBm, PEP)*	*I-f (dBm, PEP)*	*Gain (dB)*	*Third-Order O.I. (dBm, PEP)*
+9	+8	0	−8	+19.0
+9	+5	−2	−7	+22.0
+9	+2	−5	−7	+23.5
+9	−1	−8	−7	+24.5
+9	−4	−11	−7	+26.5
+9	−7	−14	−7	*
+12	+8	+1	−7	+25.0
+12	+5	−2	−7	+26.0
+12	+2	−5	−7	+27.0
+12	−1	−8	−7	+27.0
+12	−4	−11	−7	*
+12	−7	−14	−7	*
+15	+8	+1	−7	+30.0
+15	+5	−2	−7	+30.0
+15	+2	−4	−6	+31.0
+15	−1	−7	−6	+31.0
+15	−4	−10	−6	*
+15	−7	−13	−6	*
+17	+8	+1	−7	+33.0
+17	+5	−1	−7	+33.5
+17	+2	−4	−6	+33.0
+17	−1	−7	−6	+31.0
+17	−4	−10	−6	*
+17	−7	−13	−6	*

*Measurement limited by post mixer/filter IMD.

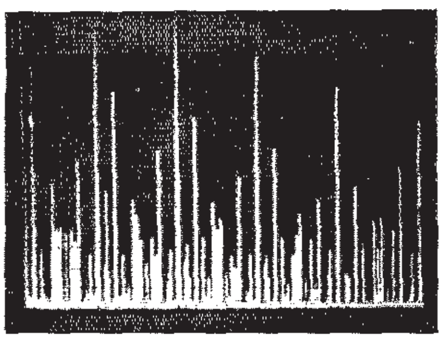


Fig. 9 — Output display of the SRA-1H high-level, diode-ring mixer with an LO power of +17 dBm and an rf signal input of +8 dBm. The large number of spurs emphasizes the importance of filtering at the mixer output.

tests included an analysis of the Mini-Circuits Lab SRA-1H DBM module. The test setup was essentially the same as for the previous mixers treated in this article. Tests were conducted with and without a diplexer connected to the mixer output. The results were essentially identical, since the test-setup terminations provided the desired 50-ohm port characteristic. In an actual receiver where absolute source-impedance levels are not always known, a diplexer of the type shown in Fig. 7 can be beneficial in providing the mixer with a 50-ohm termination at all frequencies. The high-pass branch of the diplexer is resonant at approximately three times the i-f. Improvements of 2 to 3 dB in mixer IMD are not uncommon when a diplexer is added to a ring mixer.

Test results for the SRA-1H (Fig. 8) are listed in Table 4. The conversion-gain spread follows the predicted amount, ranging from −6 to −9 dB over an LO injection excursion of +6 to +17 dBm. A spectral display of the mixer output is shown in Fig. 9. Owing to the LO power needed for this mixer it became necessary to make one change in the test setup used for the other mixers discussed here: The 2N3866 post LO amplifier was followed by an MRF-511 CATV transistor to elevate the available LO power to +27 dBm. The second harmonic from the LO source was measured at greater than 50 dB below the peak power of the fundamental.

Summary

The implications of the test results in this article are that large-signal devices provide high dynamic-range numbers when careful attention is given to biasing and LO levels. Certainly, a receiver is only as good as its mixer in terms of large-signal accommodation. Schottky ring mixers still offer a good compromise between dynamic range and moderate LO injection power. The penalty is in conversion loss, but a major advantage is seen in the passive feature of the diode-ring mixer, since the device does not impose dc current drain on the power supply.

The Plessey SL6440C high-level mixer IC offers the advantage of having excellent dynamic range, conversion gain and moderate dc current requirements. The LO-injection level is significantly lower than that required for a diode-ring mixer, and the package format lends itself well to the design of miniature equipment.

VMOS power FETs open the door to very high dynamic-range numbers at the cost of bulk and high dc-current requirements. LO-injection requirements are fairly high, and heat sinking of the active devices is necessary. Owing to the relatively high amplitude of the mixer-output spurs, a doubly balanced VMOS mixer would be preferable to a singly balanced version. The VMOS balanced mixer may not, in many instances, be cost-effective unless low-priced VMOS FETs are used in preference to the VMP4s specified in this article. The latter are in the $20 price class when purchased in single-lot quantity.

Indications are that small-signal devices, such as the 40673 and 3N211, are poor choices when high dynamic range is a design criterion. They are entirely acceptable for use in many low- and medium-cost hobby and entertainment receivers where high signal levels are not a problem. QST

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