# A High-Dynamic-Range MF/HF Receiver Front End

Read a two-tone IMD dynamic range specification of over 100 dB for an MF/HF receiver and you'll probably also see the qualificatio "preamp off," "500-Hz IF bandwidth" and "signal spacing, 100 kH *This* front end hits 111 dB with preamp *on*, a 2.4-kHz IF bandwid and the ARRL standard test-signal spacing of 20 kHz.

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P roliferation of high-powered transmitters and electronic noise pollution imposes severe signal-handling requirements on modern receivers. Strong signal-handling capability has received significant attention from the manufacturers and reviewers of MF/HF amateur equipment during the last decade. Despite these technical advances, there is definitely room for some improve-
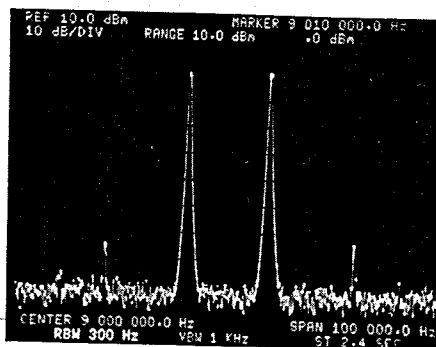
A spectrum analysis of the front end's performance, preamplifier off, while converting two 0-dBm (1 milliwatt) 14-MHz signals spaced 20 kHz apart to the front end's 9-MHz IF. These appear at 8990 and 9010 kHz, with the system's third-order intermodulation products (8970 and 9030 kHz) down 64 dB relative to either test signal. This equates to a third-order input intercept of +42 dBm. *(spectrum photograph by the author)*

ment. Yaesu's FT-1000, a state-of-tl transceiver, sports a claimed dynamic of 108 dB and an intercept poii +32 dBm (RF amplifier off, 500-I bandwidth, 50-kHz spacing). For a 2.4 bandwidth, this dynamic range would to 103.5 dB.

This article shows how to build a end which achieves a two-tone dyr range of 111 dB and an intercept po +33 dBm—with *20-kHz* test-tone spa RF amplifier *on*, and using an IF l width of 2.4 kHz. That this perform can be realized with a preamplifier ii is significant. It allows the realizatic a receiver that combines strong si handling capability with excellent s tivity—a challenge to any receiver desi The circuit can be adjusted using test e ment available to most construc minded amateurs, and its 50-ohm m

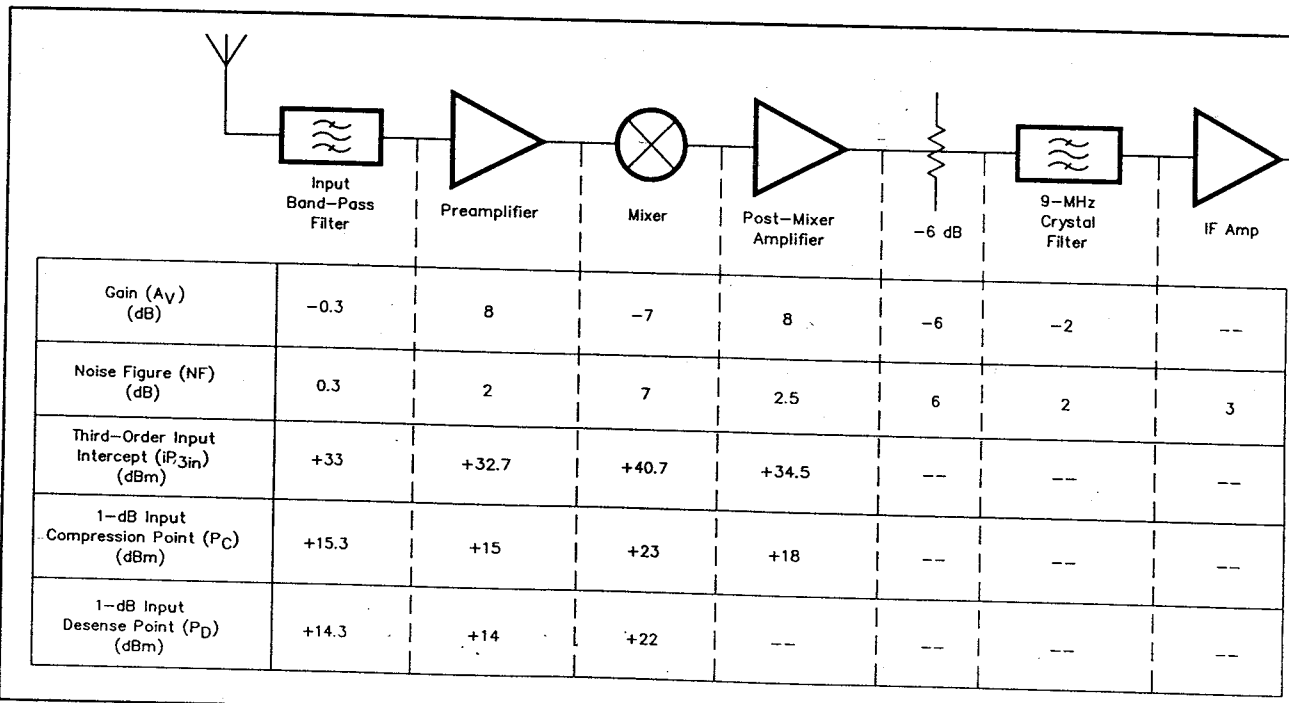|	Input Band-Pass Filter	Preamplifier	Mixer	Post-Mixer Amplifier	-6 dB	9-MHz Crystal Filter	IF Amp
Gain (A_V) (dB)	-0.3	8	-7	8	-6	-2	--
Noise Figure (NF) (dB)	0.3	2	7	2.5	6	2	3
Third-Order Input Intercept (iP_{3in}) (dBm)	+33	+32.7	+40.7	+34.5	--	--	--
1-dB Input Compression Point (P_C) (dBm)	+15.3	+15	+23	+18	--	--	--
1-dB Input Desense Point (P_D) (dBm)	+14.3	+14	+22	--	--	--	--

Fig 1—Stage-by-stage gain, noise figure, third-order input intercept, 1-dB compression point and 1-dB desensitization point performa of the high-dynamic-range front end.
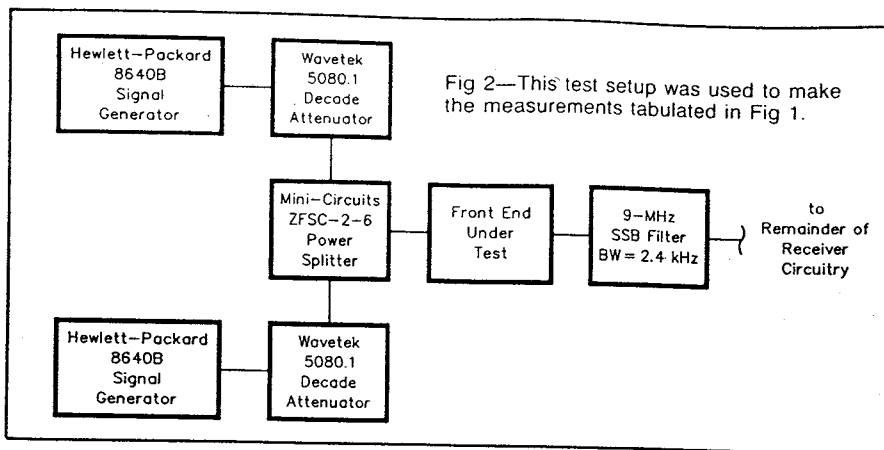
Fig 2—This test setup was used to make the measurements tabulated in Fig 1.

Table 1
Front-End Performance

Preamplifier	With	Without
Third-Order Input Intercept (IP$_{3in}$, dBm)	+33	+41
1-dB Input Compression Point (P$_c$, dBm)	+15.3	+23.3
1-dB Input Desensitization Point (P$_D$, dBm)	+14.3	+22.3
System Noise Figure (NF, dB)	6.6	12.9
Minimum Discernible Signal (MDS, dBm)	−133.4	−127.1
Sensitivity for 10 dB (S+N)/N Ratio in 50 Ω (Vs, μV RMS)	0.15	0.32
Spurious-Free Dynamic Range (SFDR, dB)*	111.0	112.1
Blocking Dynamic Range (BDR, dB)	147.7	149.4

*Also known as *two-tone dynamic range*; measured at ARRL Lab standard test-signal spacing of 20 kHz.

lar construction provides flexibility and encourages experimentation.

Front-End Design Considerations

The primary motivation was to design a front end capable of withstanding an abundance of strong signals several kilohertz away from a desired weak station. A traditional approach to this problem is the use of switchable preamplifiers and attenuators. Professional communications equipment sometimes employs PIN-diode attenuators,[1] correlating attenuation to signal level. Depending on the implementation, these methods may have one drawback: Sensitivity suffers, so the suppression of strong interfering signals is achieved at the cost of losing weak stations. Therefore, early in the design of this front end, it was decided that a preamplifier should precede the mixer to establish a low system noise figure.

Fig 1 shows a partial block diagram of a single-conversion receiver. This article covers only the preamplifier, mixer and the post-mixer amplifier in detail. A low-loss, band-pass input filter serves to protect the front end from strong out-of-band signals. The filter insertion loss is assumed to be 0.3 dB. For the sake of calculations, the IF amplifier noise figure is assumed to be 3 dB. Every block preceding the 9-MHz filter has 50-ohm input and output impedances. This greatly facilitates block replacement, promotes experimentation, and makes possible the removal of the preamplifier to connect the input band-pass filter directly to the mixer.

Measurement and Calibration Results

The measurement results are summarized in Fig 1. The preamplifier was evaluated at 14 MHz, and the mixer and post-mixer amplifier at 9 MHz. The test setup is shown in Fig 2. Table 1 summarizes the system measurement and calculation results.[2] Table 1 indicates that the preamplifier allows the achievement of a receiver sensitivity of 0.15 μV, on par with or better than any commercially produced MF/HF amateur

[1]Notes appear on page 28.

transceiver, while keeping third-order input intercept and dynamic range at the respectable levels of +33 dBm and 111 dB, respectively. Extensive experiments on 14 MHz prove the front end's performance to be quite adequate under the most adverse receiving conditions.

Those wishing more flexibility can implement a preamp on/off option, although the intent of the design was to avoid the need of this switch. Amateurs who find a sensitivity of 0.32 μV adequate for their needs may choose not to use the preamplifier at all. If this is done, the front end becomes truly "uncrunchable" with an impressive third-order input intercept point of +41 dBm and a spurious-free dynamic range of 112 dB. The 1-dB input desensitization point[3,4,5] reaches +22 dBm in this case—a signal level of 2.8 V RMS at the antenna connector!

Overall System Considerations

Although sensitivity and dynamic range are primarily determined by the quality of the front end, some of the remaining receiver stages are of considerable importance. The IF amplifier should have an input signal handling capability of several volts, its distortion characteristics should be adequate, and its noise figure must be low enough not to appreciably degrade the front end's noise figure. A good crystal filter is a must; its shape factor should be 1.8 or better, and its ultimate attenuation should exceed 100 dB. Cascading two filters—one before the IF amplifier, and one after—should be considered as a way of improving the selectivity and also reducing the wideband noise generated by the IF amplifier. The product detector should not degrade the signal coming from the IF strip, and the audio amplifier's frequency response should be tailored with low- and high-pass filtering. Finally, extra care should be taken when designing the local oscillator (LO). A poorly designed oscillator may negate improvements in the front-end's dynamic range. Excessively high close-in phase noise[6,7] may degrade the receiver's ability to separate closely spaced signals. If we assume that the crystal filter

provides out-of-band rejection of 100 dB at an offset of 2.0 kHz, the LO's phase noise must be better than −133 dBc/Hz at a 2.0-kHz offset to preserve the filter's performance. High far-out phase noise may raise the receiver noise floor; this can degrade the receiver's dynamic range. The dynamic range limited by phase noise
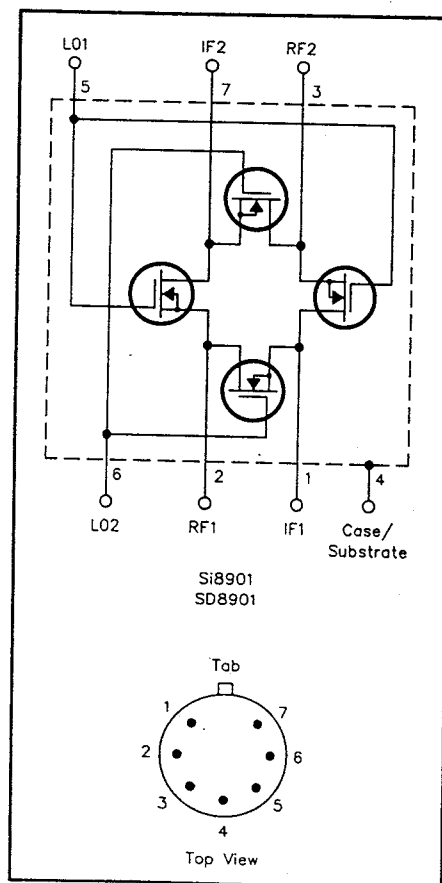

Si8901
SD8901

Top View

Fig 3—The front end uses a Siliconix Si8901 DMOS FET quad mixer. Siliconix has since discontinued this part, but an exact replacement (the SD8901) is available from Calogic Corporation.

should be equal to or better than the dynamic range limited by IMD.[8] Calculations show that the LO's far-out phase noise should be better than −145 dBc/Hz. Although the LO spectral-purity requirements are quite stringent, they can be met by employing an LC-type oscillator with a high-Q coil.

Circuit Description

Mixer

This stage received special attention since its characteristics have a profound effect on dynamic range. Numerous articles have been written covering the performance of different types of mixers. For those interested in this subject, the works cited at Notes 1, 5, 9, 10, 11 and Additional References 1 through 4 are recommended.

After an extensive survey and experimentation, it was concluded that a passive mixer with active devices can provide the highest input intercept point. The Siliconix Si8901—a monolithic quad DMOS FET designed by Ed Oxner, KB6QJ—was chosen for the mixer. This excellent device was specifically designed for mixer applications and truly belongs at every experimenter's bench. Siliconix Application Note
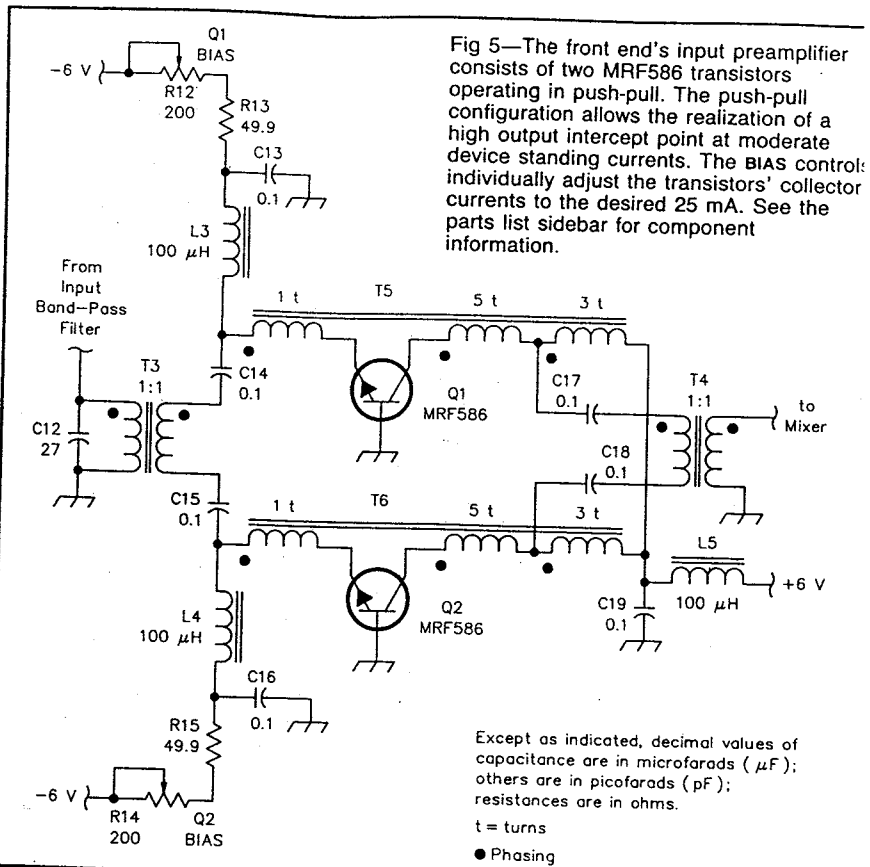

Fig 5—The front end's input preamplifier consists of two MRF586 transistors operating in push-pull. The push-pull configuration allows the realization of a high output intercept point at moderate device standing currents. The BIAS controls individually adjust the transistors' collector currents to the desired 25 mA. See the parts list sidebar for component information.

Except as indicated, decimal values of capacitance are in microfarads (μF); others are in picofarads (pF); resistances are in ohms.
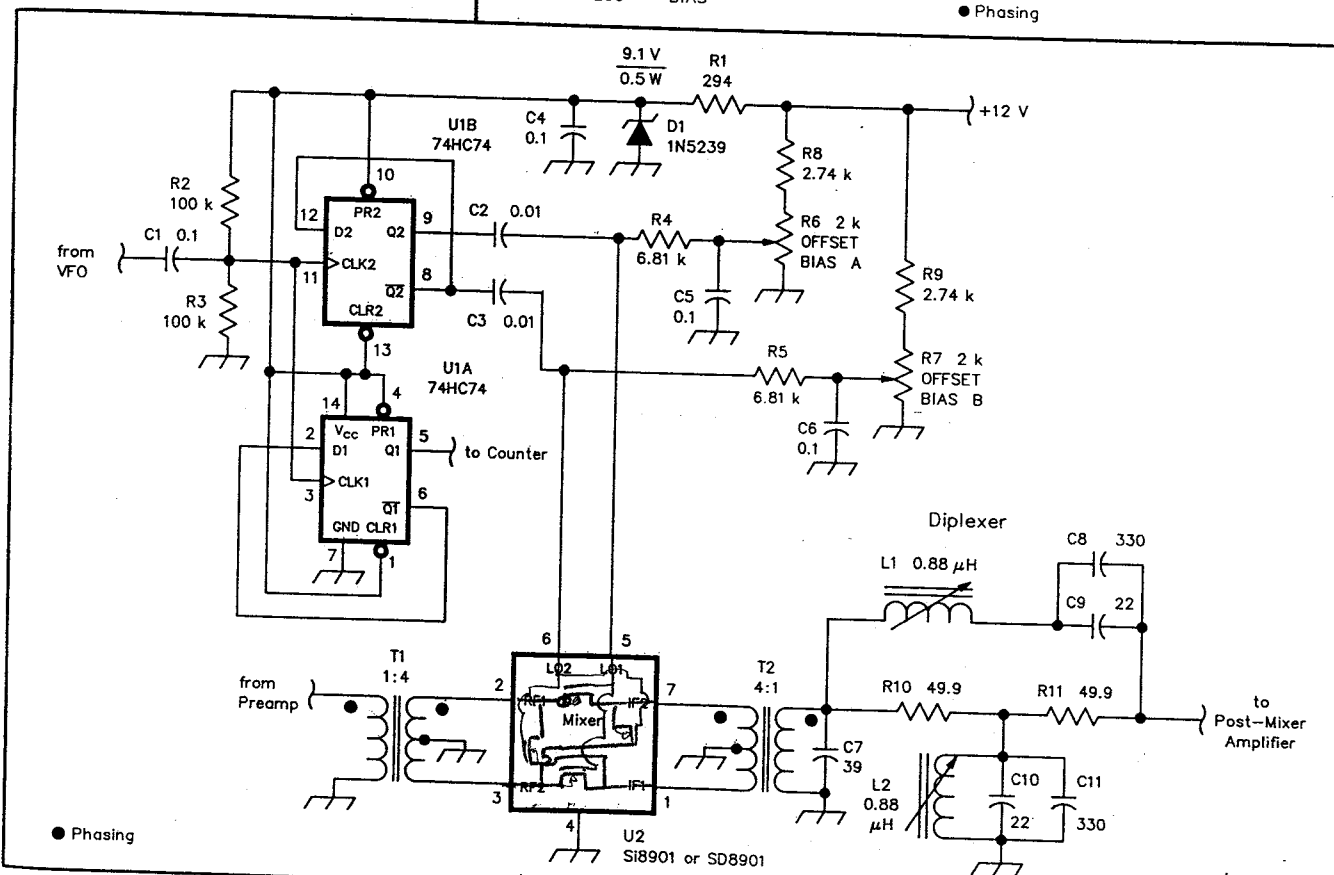
t = turns

● Phasing

Fig 4—The front end's mixer circuitry applies the Si8901/SD8901 in conjunction with a 74HC74 dual flip-flop, a diplexer network and a VFO operating in the 10.5-MHz region—twice the frequency necessary to convert 14-MHz signals to the system's 9-MHz IF. Both 74HC74 sections divide the LO frequency by two and square it; one section (U1A) provides LO output for a frequency counter, and the other (U1B) drives the mixer's LO port. The OFFSET BIAS controls adjust mixer balance. D1 sets the 74HC74's supply voltage at a level considerably higher than the part's specified 6-V maximum; see text. See the parts list sidebar for component information.
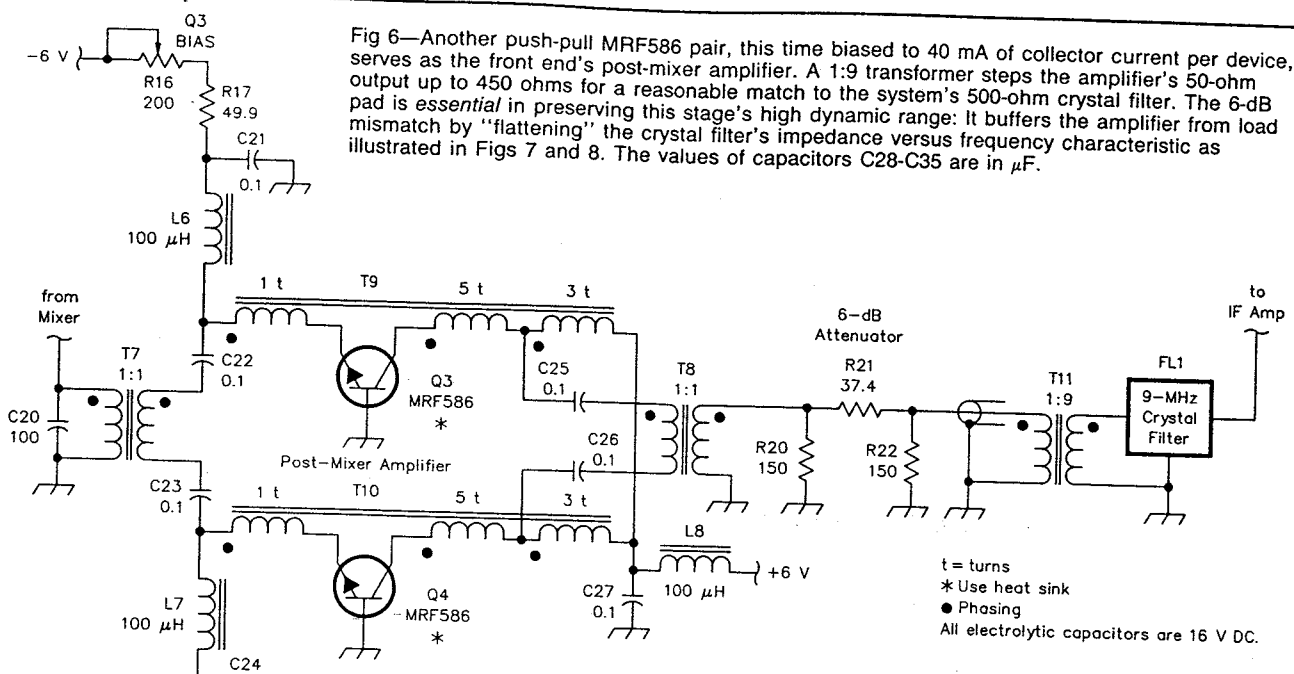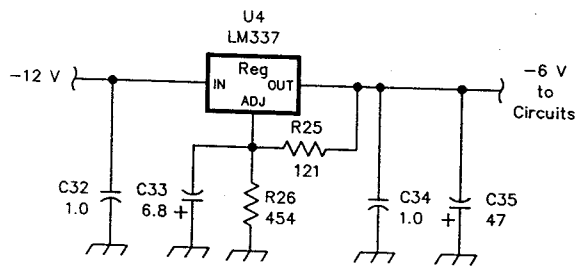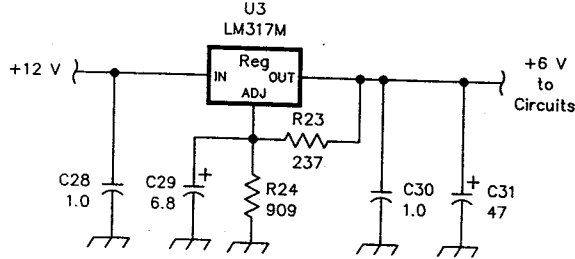
Fig 6—Another push-pull MRF586 pair, this time biased to 40 mA of collector current per device, serves as the front end's post-mixer amplifier. A 1:9 transformer steps the amplifier's 50-ohm output up to 450 ohms for a reasonable match to the system's 500-ohm crystal filter. The 6-dB pad is *essential* in preserving this stage's high dynamic range: It buffers the amplifier from load mismatch by "flattening" the crystal filter's impedance versus frequency characteristic as illustrated in Figs 7 and 8. The values of capacitors C28-C35 are in μF.

Q3 BIAS
−6 V
R16 200
R17 49.9
C21 0.1
L6 100 μH

from Mixer
T7 1:1
C20 100
C22 0.1
T9   1 t   5 t   3 t
Q3 MRF586 *
Post-Mixer Amplifier
C25 0.1
C23 0.1
T10   1 t   5 t   3 t
C26 0.1
Q4 MRF586 *
L7 100 μH
C24 0.1
R19 49.9
−6 V
R18 200
Q4 BIAS

T8 1:1
L8 100 μH   +6 V
C27 0.1

6-dB Attenuator
R21 37.4
R20 150
R22 150
T11 1:9
FL1 9-MHz Crystal Filter
to IF Amp

t = turns
* Use heat sink
● Phasing
All electrolytic capacitors are 16 V DC.

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

U3 LM317M
+12 V
Reg IN OUT ADJ
R23 237
C28 1.0
C29 6.8
R24 909
C30 1.0
C31 47
+6 V to Circuits

U4 LM337
−12 V
Reg IN OUT ADJ
R25 121
C32 1.0
C33 6.8
R26 454
C34 1.0
C35 47
−6 V to Circuits

AN85-2[9] provides detailed information needed for the design. Fig 3 shows the Si8901's circuitry and pinout. Fig 4 shows the mixer/diplexer schematic. T1 matches the 50-ohm source (the preamplifier) to U2's RF port, and T2 matches U2's IF port to a 50-ohm load—the post-mixer amplifier.

In a commutation mixer, there is a compromise between conversion loss and intermodulation distortion. The impedance

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Parts List for the High-Dynamic Range Front End

Unless indicated otherwise, all of the circuits' resistors are ¼-W 1% tolerance, and all of its capacitors are 20%-tolerance ceramic. C7-C12 and C20 are dipped mica, polyester film or epoxy-coated ceramic.

C7—39 pF ±10%.
C8, C10—330 pF ±5%.
C9, C11—22 pF ±5%.
C12—27 pF ±10%.
C20—100 pF ±10%.
D1—9.1-V, 0.5-W Zener diode, 1N5239 suitable. See text.
L1, L2—Toko 332PN-T1012Z (Digi-Key TK5130) 1.0-μH variable inductor.
L3-L8—100-μH RF choke.
Q1-Q4—Motorola MRF586 RF transistor. Use heat sink (Thermalloy 2228B or Aavid 3257) on Q3 and Q4.
R6, R7—2-kΩ multiturn potentiometer.

R12, R14, R16, R18—200-Ω multiturn potentiometer.
T1, T2—Mini-Circuits T4-1 4:1 RF transformer.
T3, T4, T7, T8—Mini-Circuits T1-1T 1:1 RF transformer.
T5, T6, T9, T10—homemade trifilar transformer wound with #32 enameled wire on Amidon BN-43-2402 core (Fair-Rite 2843002402) as per Fig 9.
T11—Mini-Circuits T9-1 9:1 RF transformer.
U1—74HC74 CMOS flip-flop.

U2—Calogic Corporation SD8901HD mixer (replaces the Siliconix Si8901HD). Siliconix has discontinued the Si8901; the Calogic SD8901 is an exact replacement.
U3—LM317MP adjustable voltage regulator IC.
U4—LM337MP adjustable voltage regulator IC.

A list of the names and addresses of parts suppliers, keyed to the components in this list, is available as detailed in Note 2.
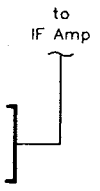
ratios of transmission-line transformers T1 and T2 are chosen to achieve low intermodulation distortion while keeping conversion loss at an acceptable level.

The LO waveform applied to U2 is of great importance. To achieve a high intercept point, the LO drive must approach an ideal square wave with a 50% duty cycle.[10,11] Flip-flop U1B divides the LO signal frequency by two and provides 50% duty cycle square waves at its complimentary outputs. The offset bias adjustment potentiometers, R6 and R7, allow compensation for mismatch among the Si8901's MOSFETs and ensure that the commutation mixer switches operate in a 50% duty cycle mode. U1A provides a signal that can be applied to a digital frequency counter.

The mixer's intercept point also depends on the LO drive level. Zener diode D1 establishes the power supply voltage for U1 and, therefore, the voltage swing at the mixer LO port. In the interest of obtaining a high intercept point, a 9.1-V diode is used at D1. This voltage exceeds the 74HC74's maximum supply specification. Experiments with samples from different manufacturers show that there is a considerable safety margin, however: The 74HC74s tested failed when the power supply was adjusted to around 11 V. Those who feel uncomfortable in exceeding the part's maximum rating may use a 6.8-V Zener diode at the cost of a few decibels in the intercept point value. Since double-balanced mixers are sensitive to IF port mismatches,[12] and a reactive load can cause an increase in conversion loss and degradation of the third-order intercept point, a band-pass diplexer follows the mixer. The diplexer comprises L1, C8, C9, L2, C10, C11, R10 and R11. The 9-MHz signal passes through this network with minimum attenuation, while out-of-passband signals over a wide frequency range are dissipated. Resistor R10 presents a 50-ohm impedance to the mixer, while R11 presents a 50-ohm impedance to the input of the post-mixer amplifier. C7 cancels the inductive reactance of the load presented to the mixer's IF port.

The measured performance of this circuit

is: third-order output intercept, +35 dBm; 1-dB output compression point, +16 dBm; 1-dB output desensitization (blocking) point, +15 dBm; insertion loss, 7 dB.

Preamplifier

To preserve the mixer's dynamic range, the preamplifier's output intercept point should exceed the mixer input intercept point by at least 3 dB, and its compression point should exceed the mixer's by at least 1 dB.[13] The preamplifier's design criteria are as follows: third-order output intercept, ≥ 45 dBm; 1-dB output compression point, ≥ 24 dBm; gain between 6 and 9 dB; noise figure <3.0 dB; −1-dB frequency response, 1.8-30 MHz.

If conventional resistive feedback techniques were used to meet the design objectives, the required transistor standing current would become prohibitively high, resulting in a high noise figure. Therefore, a combination of a "noiseless feedback" method[14-18] and a push-pull configuration was tried, and resulted in the circuit shown in Fig 5.

The MRF586 is a high-frequency transistor designed for use in low-noise, ultralinear amplifiers and packaged in a TO-205 case. Used in a common-base configuration, this device provides a low noise figure because its optimum source resistance is close to 50 ohms. Bias controls R12 and R14 allow the collector current of each transistor to be adjusted to the desired value of 25 mA. T3 matches the amplifier input to the 50-ohm band-pass input filter; T4 matches the preamp output to the mixer signal port.

Transformers T5 and T6 are designed to couple part of the collector signal back into the emitter (negative feedback), set the gain to 8 dB, and set the input and output impedances to 50 ohms. C12 cancels the inductive reactance of the source presented to the mixer's RF port at 14 MHz. (In a multiband receiver, this capacitor may be part of switchable preselector filters.) The measured performance of the circuit is: third-order output intercept, +48 dBm; 1-dB output compression point, +25 dBm; gain, 8.0 dB; noise figure, 2.0 dB; −1-dB

frequency response 1-40 MHz. This perfo mance fully meets the preamplifier desi goals.

Post-Mixer Amplifier

Although the post-mixer amplifi (Fig 6) uses the same basic configuratic as the preamplifier, its design criteria a different. The post-mixer amplifier's inp intercept point should exceed the mixer ou put intercept point by at least 3 dB, and i compression point should exceed th mixer's by at least 1 dB. The post-mix amplifier must therefore exhibit the characteristics: third-order input intercep ≥ 38 dBm; 1-dB input compression poin ≥ 17 dBm; gain between 6 and 9 dB; ar noise figure, <3.0 dB.

These design goals could easily be m if the post-mixer amplifier had a pure resistive termination. However, the ampl fier must drive a crystal filter, th impedance of which varies considerab with frequency. Connecting the post-mix amplifier to the crystal filter via a matcl ing transformer would severely degrade th amplifier's third-order intercept point. I serting resistive attenuation between th amplifier and filter reduces this effect to a acceptable level, as shown by Figs 7 and {

BIAS controls R16 and R18 allow adjus ment of the MRF586s' collector current t 40 mA per device. This value is 15 m higher than the preamplifier's device stanc ing currents to overcome the negativ effects of the reactive load on the pos mixer amplifier's intercept point. T11, transmission-line transformer, matches th crystal filter's impedance (500 ohms in th case) to the amplifier's 50-ohm output in pedance. C20 cancels the inductive read tance of the source presented to th amplifier's input. The measured perfoi mance of the post-mixer amplifier, term nated by a 9-MHz filter via the 6-dB pac is: third-order input intercept, +34 dBn 1-dB input compression point, +18 dBn gain, 8.0 dB; and noise figure, 2.5 dB. I spite of the measures taken, the input ir tercept point requirement has not been me Overall system measurements indicat however, that the mixer's third-order inpu
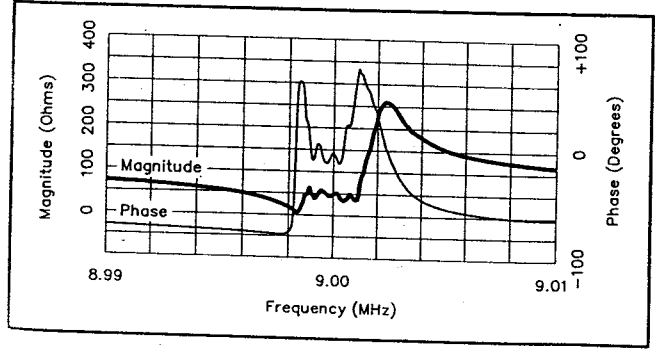

Fig 7—The crystal filter's input impedance as seen by the post-mixer amplifier through a 1:9 matching transformer. The reflections caused by this characteristic seriously degrade the amplifier's strong-signal performance if the 6-dB pad shown in Fig 6 is omitted.
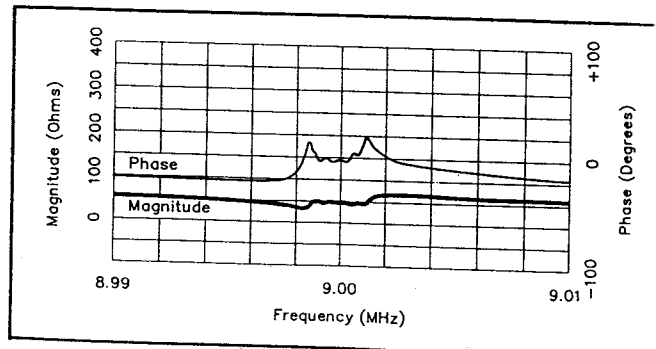

Fig 8—The filter impedance as seen by the amplifier through the 1:9 transformer and a 6-dB pad. The reflections still occur—they must for the filter to act as a filter—but the pad reduces their magnitude sufficiently to preserve the amplifier's high dynamic range.
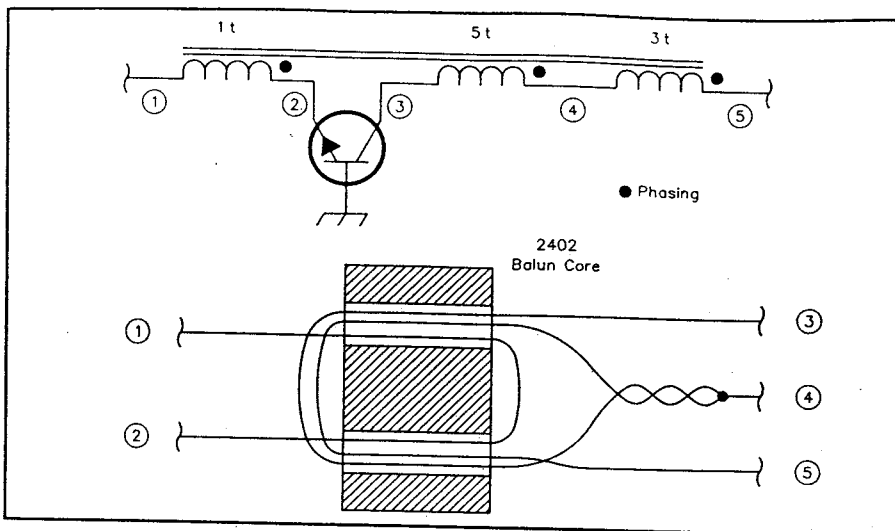
Fig 9—Transformers T5, T6, T9 and T10 are wound with #32 wire on two-hole ferrite cores (see the parts list sidebar for core information). Wind the 1-turn winding (1-2) first, the 3-turn winding (3-4) second and the 5-turn winding (4-5) third.

Construction

The three modules are enclosed in separate, unpainted aluminum boxes. Each module's components are mounted on Vector 8007 board (perforated, with a solid copper plane on one side). The circuit components are mounted on the solid copper side, which serves as a ground plane. Vector T68 pins serve as terminal posts as necessary. All modules' signal inputs and outputs are made via BNC connectors; RG-174 coaxial cable interconnects the modules.

Properly built and shielded, the amplifiers should not oscillate. Because they operate in push-pull, strict symmetry should be observed in constructing the upper and lower halves of each amplifier.

The matching transformers specified at T1 and T2 (1:4 ratio) T3, T4, T7 and T8 (1:1 ratio); and T11 (9:1) are commercial units. If home-built matching transformers are used instead, they should be transmission-line types and highly symmetrical. Transformers T5, T6, T9 and T10 are homemade as shown in Fig 9.

Alignment

Amplifiers

Adjust controls R12 and R14, **Q1 BIAS** and **Q2 BIAS** (Fig 5), for a collector current of 25 mA per device. Adjust controls R16 and R18, **Q3 BIAS** and **Q4 BIAS**, for a collector current of 40 mA per device.

Mixer

The diplexer inductors, L1 and L2, must be aligned first. If the mixer is a part of an assembled receiver, inject a signal (100 mV P-P at, say, 14.250 MHz) into the antenna terminal. Tune the receiver to this frequency and adjust L1 and L2 for maximum signal while observing the signal at the post-mixer amplifier's output on an oscilloscope.

As an alternative method, apply a 14.250-MHz, 100-mV P-P signal to the preamplifier input. Using another signal generator, apply 4 V P-P at 10.5 MHz to the input (**from VFO**) of U1 (Fig 4). Peak L1 and L2 as described above.

For optimum performance, adjust R6 and R7 (**OFFSET BIAS A** and **OFFSET BIAS B**) while viewing the mixer's output spectrum with a spectrum analyzer. A two-tone IMD test setup (Fig 2) is required. (Detailed information on performing this test can be obtained from the works cited in Notes 3, 4, 5 and 10, and Additional References 1 and 8.) Connect the spectrum analyzer to the post-mixer amplifier output. Adjust R6 and R7 to minimize third-order-IMD products. Monitor the mixer insertion loss while doing this; it should be around 7 dB.

If a spectrum analyzer is unavailable, another method can be used. A 9-MHz IF strip with defeatable AGC is required. Turn off its AGC, connect it to the post-mixer amplifier, and connect a scope to its output. Tune the front end's VFO to convert one of its third-order IMD products ($2f1 - f2$ or $2f2 - f1$, where $f1$ and $f2$ are the test-signal frequencies) to 9.000 MHz. Adjust R6 and R7 to minimize the level of this signal.

Summary

By properly applying known design principles, radio amateurs can construct a high-performance front end which combines a very high intercept point with excellent sensitivity. Used with a low-noise LO, the front end described in this article achieves a wide dynamic range even with its preamplifier stage in line. A receiver incorporating such a front end can provide strong-signal performance that rivals or exceeds that of most commercial equipment available to the amateur.

Notes

[1] U. Rohde, "Recent developments in circuits and techniques for HF communications receivers," *ham radio*, Apr 1980, pp 20-25.

[2] An information package detailing the calculations on which this data is based, as well as a list of suppliers for the components listed in the "Parts List for the High-Dynamic Range Front End" sidebar, is available free of charge from the Technical Department Secretary, ARRL, 225 Main St, Newington CT 06111. Please mark your request MAKHINSON FRONT-END TEMPLATE and include a business-size SASE.

[3] C. Drentea, *Radio Communication Receivers* (Blue Ridge Summit, PA: TAB Books Inc, 1982), pp 88-135.

[4] R. Watson, "Guidelines for receiver analysis," *Microwaves and RF*, Dec 1986, pp 113-122.

[5] Wideband signal processing component catalog, VARI-L Company, Denver, CO.

[6] J. Grebenkemper, "Phase Noise and Its Effects on Amateur Communications," Part 1, QST, Mar 1988, pp 14-20; Part Two, QST, Apr 1988, pp 22-25. Also see Feedback, QST, May 1988, p 44.

[7] P. Chadwick, "Phase Noise Intermodulation and Dynamic Range," *Frequency Dividers and Synthesisers IC Handbook*, Plessey Semiconductors, 1988.

[8] See Note 7.

[9] E. Oxner, "Designing a Super-High Dynamic Range Double-Balanced Mixer," Application Note AN 85-2 (Santa Clara, CA: Siliconix, 1986).

[10] V. Drozdov, *Lyubitel'skie kv Transiveri* (Amateur HF Transceivers), in Russian, Moscow, USSR, 1988.

[11] See Note 9.

[12] P. Drexler, "Effect of Termination Mismatches on Double-Balanced Mixers," *Microwave Journal*, Jan 1986, pp 187-190.

[13] E. Red, "Daten, Fakten, HF-Grundschaltungen, 50 ohm-Technik," in German or Russian, Franzis-Verlag GmbH, Munich, 1986.

[14] See Note 1.

[15] U. Rohde, "High dynamic range receiver input stages," *ham radio*, Oct 1975, pp 26-31.

[16] D. Norton, "High Dynamic Range Transistor Amplifier Using Lossless Feedback," *Microwave Journal*, May 1976, p 53.

[17] J. Reisert, "High dynamic range receivers," *ham radio*, Nov 1984, pp 97-105.

[18] See Note 13.

Additional References

1. D. DeMaw, *Practical RF Design Manual* (Englewood Cliffs, NJ: Prentice-Hall Inc, 1982), pp 23-25.

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intercept point has been degraded by less than 1.5 dB (40.7 dB versus 42 dB) and is still very high.

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