quiet! preamp at work

Understanding preamplifiers means understanding all the important parameters of receiver performance

For years, the standard technique employed by Radio Amateurs to improve receiver sensitivity has been to precede their receivers with one or more stages of preamplification. Invariably a preamplifier that performs well on the bench will actually *degrade* the actual on-the-air system sensitivity. This article explores the relationship between gain, noise figure, bandwidth, distortion, and sensitivity in an attempt to answer the classic preamp question, "If a little is good, is a lot better?"

sensitivity

Sensitivity is a measure of the weakest input signal that will produce a specified output signal-to-noise ratio. We can quantify receiver performance in terms of *minimum discernible signal* sensitivity, which is the input level producing an output signal-to-noise ratio of unity; *tangential signal sensitivity* , which generally refers to the input level needed to produce an output signal-plus-noise to noise ratio of 6 dB or the RF level required to produce a detected signal which is 8 dB above the RMS noise level[1]; or *threshold,* which refers to the input amplitude required to produce a specified level of receiver quieting and is frequently employed in FM systems. All of these sensitivity measures are a function of the receiver circuitry's internally generated noise, bandwidth, and distortion.

Of these three parameters, the receive bandwidth can be considered fixed for a given application, and would ideally be wide enough to pass all the modulation sidebands of the desired signal, yet sufficiently narrow to exclude both background noise and any adjacent-channel signals. Because the response bandwidth of modern receivers is established primarily in the IF stages, it is relatively independent of the parameters of any preamplifier employed.

Both noise and distortion, on the other hand, are very much influenced by preamplifier performance. Most Radio Amateurs are now aware that preamplifier gain, by itself, does not necessarily assure an improvement in receiver sensitivity. Rather, to be beneficial in a system, the preamplifier must generate an internal noise level significantly lower than that generated by the receiver it precedes. The noise relationships in a cascade of stages are quantified by the now-familiar Friis Equation.[2] A well-known rule of thumb derived from the Friis Equation is that if a preamp's gain exceeds by at least 10 dB the noise figure of the receiver it precedes, the noise performance of the preamplifier will dominate the cascade.

Yet the above relationship serves merely to confuse the Amateur who measures a new preamp at a regional VHF Conference at, say, 3 dB noise figure for 15 dB gain, brings it home, installs it in front of a 10 dB noise-figure receiver, and finds its sensitivity actually degraded. What has been overlooked? Probably the effects of distortion.

distortion

A linear amplifier is one whose output signal is an exact replica of the input signal, measured in either

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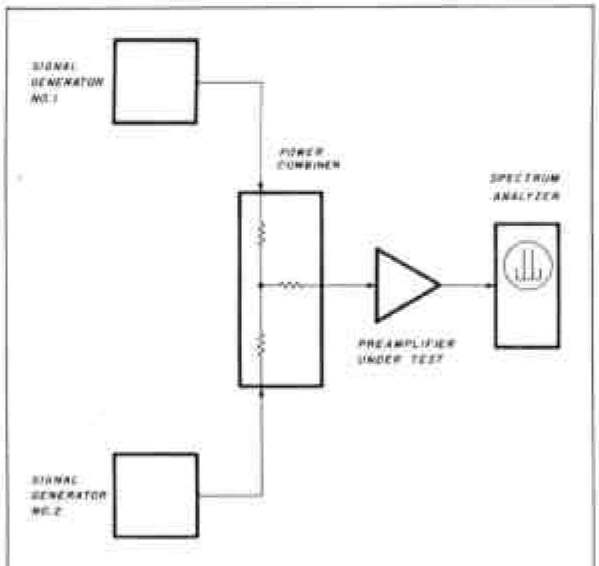

fig. 1. Two-tone intermodulation distortion test configuration.

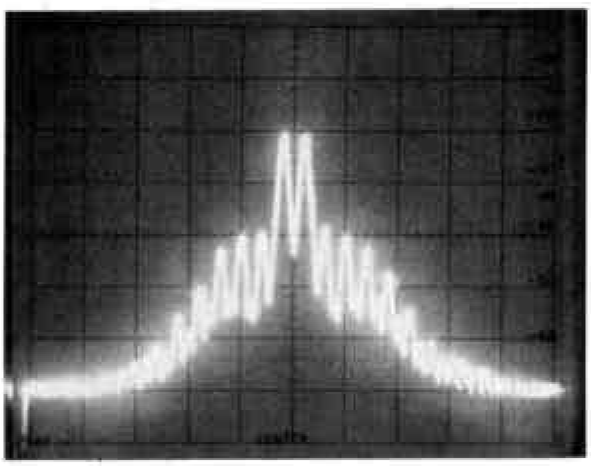

fig. 2. Typical intermodulation distortion spectrum display. Note the next pair of "signals" (IMD) are 20 dB down from the primary two-tone output.

the time or frequency domains, differing only in its increased amplitude. Try as we might, we cannot build truly linear amplifiers in the real world. Any nonlinearity introduced by an amplifier will manifest itself as a deviation from sinusoidal response when viewed in the time domain, or as the generation of new frequencies when measured in the frequency domain.

In a receive preamplifier, as in any non-linear device, the distortion products generated are integer multiples (harmonics) of the input frequency, plus their various sums and differences. Normally these distortion products would not degrade receiver sensitivity, as they would fall outside of the receiver's passband. Rare, however, is the receiver to which only a single input signal is applied. In our crowded spectra, we can anticipate countless signals of varying amplitudes within the passbands of our preamplifiers, only one of which (at a time) can be said to constitute "signal." All potentially interfering waveforms must, from a communications standpoint, be classified as noise.

It is these multiple input signals that give rise to both intermodulation (mixing of in-band signals) and cross-modulation (mixing of signals from in-band with out-of-band) distortion. When the harmonics of one signal mix with the harmonics of another, the resulting distortion products can fall within the receiver passband, degrading sensitivity.

dynamic range

Neglecting distortion effects, the weakest signal to which a receiver can respond is a function of its bandwidth and noise performance. If the multiple input signals applied to a receive system are all relatively low in amplitude, their distortion products may fall below this sensitivity limit, and be negligible. But if the input signals are of sufficient amplitude, their distortion products may appear strong enough to degrade reception of the desired signal. Thus, noise figure of a receiver generally determines the weakest signal to which it can respond. Maximum spurious free input signal, a function of a receiver's linearity, establishes an upper limit for the range of signal amplitudes to which the receiver can respond without generating perceptible distortion. The difference between sensitivity and maximum spur-free input levels is called spurious-free dynamic range, and represents a primary limitation in receiver performance.

Dynamic range is generally degraded by the addition of a preamplifier in front of a receiver. Although the low inherent circuit noise of a preamplifier may significantly improve minimum discernible signal sensitivity, degradation occurs because any additional gain in a system increases the amplitude of the desired signal, but increases the amplitude of the distortion products at an even greater rate, diminishing the maximum spurious-free input signal level. Thus, at least with respect to preamplifier gain, the old axiom, "If a little is good, a lot is better" can get us into trouble. Preamplifiers should be used only when actually necessary to improve weak-signal performance, and then only with as much gain as is actually necessary to establish the required system noise performance.

Even so, preamplifiers can result in a net degradation in system sensitivity. Some preamps are worse than others in this respect; as far as dynamic range is concerned, not all preamps are created equal. We need to measure and quantify their dynamic range, as well as their noise figure, in order to accurately predict their impact on system performance.

```
10 '---------> IMD.BAS <-------------------------
20 '            Rev. A, 24 May '84
30 '            by N6TX
40 '  COPYRIGHT (C) 1984 MICROCOMM
50 '
60 '  Determines Spurious-Free Dynamic Range from
70 '  Spectrum Analyzer Two-Tone IMD Measurements
80 '
90 '---------------------------------------------
100 CLR$ = CHR$(26) ' Defines Clear-Screen String
110 PRINT CLR$
120 PRINT "DO YOU WISH OUTPUT ROUTED TO:"
130 PRINT
140 PRINT "                    PRINTER (P)"
150 INPUT "           or       SCREEN  (S)";PR$
160 IF PR$="P" OR PR$="p" OR PR$="S" OR PR$="s" GOTO 200
170 PRINT CLR$
180 PRINT "YOU MUST RESPOND WITH 'P' OR 'S'" : PRINT
190 GOTO 120
200 '---------------------------------------------
210 PRINT CLR$
220 PRINT "TONES -->            |  |"
230 PRINT "                     |  |"
240 PRINT "                     |  |"
250 PRINT "                     |  |"
260 PRINT " IMD  -->         |  |  |  |"
270 PRINT "                  |  |  |  |"
280 PRINT "              ----------------" : PRINT
290 PRINT "FOR TWO-TONE OUTPUT SPECTRUM AS INDICATED ABOVE,"
300 PRINT
310 INPUT "ENTER Two-Tone Output Amplitude, in dBm ",TONES
320 INPUT "ENTER Third-Order IMD Amplitude, in dBm ",IMD
330 INPUT "ENTER System Gain,               in dB  ",GAIN
340 INPUT "ENTER System Noise Figure,       in dB  ",NF
350 INPUT "ENTER System Bandwidth,          in kHz ",BW
360 I3=TONES + ((TONES - IMD) / 2)
370 MDS = NF - 144 + 10*(LOG(BW)/LOG(10))
380 INMAX = ((2/3)*(I3-GAIN))+(MDS/3)
390 RANGE = INMAX - MDS
400 '---------------------------------------------
410 PRINT CLR$
420 PRINT "INTERMODULATION ANALYSIS BY MICROCOMM"
430 PRINT : PRINT
440 PRINT USING "####.# dBm -->          |  |    ";TONES
450 PRINT       "                        |  |    "
460 PRINT       "                        |  |    "
470 PRINT       "                        |  |    "
480 PRINT USING "####.# dBm -->       |  |  |  |";IMD
490 PRINT       "                     |  |  |  |"
500 PRINT       "                 ----------------"
510 PRINT : PRINT
520 PRINT USING "SYSTEM GAIN          = ####.# dB";GAIN
530 PRINT USING "SYSTEM NOISE FIGURE  = ####.# dB";NF
540 PRINT USING "SYSTEM BANDWIDTH     = ####.# kHz";BW
550 PRINT
560 PRINT USING "OUTPUT THIRD ORDER INTERCEPT POINT = ####.# dBm";I3
570 PRINT USING "MINIMUM DISCERNIBLE INPUT SIGNAL   = ####.# dBm";MDS
580 PRINT USING "MAXIMUM SPURIOUS-FREE INPUT SIGNAL = ####.# dBm";INMAX
590 PRINT USING "SPURIOUS-FREE DYNAMIC RANGE        = ####.# dB";RANGE
600 '---------------------------------------------
610 IF PR$="S" OR PR$="s" THEN GOTO 800
620 LPRINT "INTERMODULATION ANALYSIS BY MICROCOMM"
630 LPRINT : LPRINT
640 LPRINT USING "####.# dBm -->         |  |    "; TONES
650 LPRINT       "                       |  |    "
660 LPRINT       "                       |  |    "
670 LPRINT       "                       |  |    "
680 LPRINT USING "####.# dBm -->      |  |  |  |"; IMD
690 LPRINT       "                    |  |  |  |"
700 LPRINT       "                ----------------"
710 LPRINT : LPRINT
720 LPRINT USING "SYSTEM GAIN          = ####.# dB";GAIN
730 LPRINT USING "SYSTEM NOISE FIGURE  = ####.# dB";NF
740 LPRINT USING "SYSTEM BANDWIDTH     = ####.# kHz";BW
750 LPRINT
760 LPRINT USING "      OUTPUT THIRD ORDER INTERCEPT POINT = ####.# dBm"; I3
770 LPRINT USING "      MINIMUM DISCERNIBLE INPUT SIGNAL   = ####.# dBm";MDS
780 LPRINT USING "      MAXIMUM SPURIOUS-FREE INPUT SIGNAL = ####.# dBm";INMAX
790 LPRINT USING "      SPURIOUS-FREE DYNAMIC RANGE        = ####.# dB";RANGE
792 LPRINT
794 LPRINT
796 LPRINT
798 LPRINT
800 '---------------------------------------------
810 PRINT : PRINT
820 INPUT "TYPE <return> TO CONTINUE, 'Q' TO QUIT ",D$
830 IF D$ = "Q" OR D$ = "q" THEN GOTO 850
840 GOTO 100
850 '
860 '-----------------------------------------------------------------------
870 '
880 '        EQUATIONS EXECUTED
890 '
900 'MINIMUM DISCERNIBLE SIGNAL  =  -174 dBm/Hz  + NF (dB)  + 10 * LOG BW (Hz)
910 '
920 'OUTPUT INTERCEPT POINT      =  P (tones)  +  [ P (tones) - P (imd) ] /  2
930 '
940 'MAXIMUM INPUT SIGNAL LEVEL  =  (2/3) * (INTERCEPT - GAIN) + (M. D. S. /3)
950 '
960 'SPURIOUS FREE DYNAMIC RANGE =  MAXIMUM INPUT - MINIMUM DISCERNIBLE SIGNAL
970 '
980 '
990 '-----------------------------------------------------------------------
1000 END
```

fig. 3. CP/M BASIC language program listing to determine spurious-free dynamic range from spectrum analyzer two-tone IMD measurements.

gain compression

Inferences about an amplifier's dynamic range can be drawn by applying to its input a single signal of varying amplitude and observing the amplitude present at the output. In its linear region, the amplifier will produce a 1-dB change in output signal amplitude for every 1-dB change in the applied signal. That is, the gain of the amplifier is independent of applied signal level. But as the upper limit of dynamic range is approached, output signal changes will be unable to keep pace with the input. That is, the gain of the amplifier compresses at the upper end of its dynamic range. The output level at which the amplifier is exhibiting 1 dB less gain that it was under weak-signal conditions is referred to as its *output 1-dB compression point*, and is an indicator of the amplifier's immunity to intermodulation and cross-modulation distortion.

For a given noise figure, the preamplifier with the highest compression point will offer the greatest spurious-free dynamic range. But correlating the two parameters directly is difficult because the relationship between compression and distortion varies between active devices, and between circuit configurations.

Another indicator of dynamic range relates to the fact that if you continue to increase the drive level to an amplifier beyond the compression point, the gain further decreases. Eventually, the amplification of the desired signal is degraded to a point at which its amplitude at the output of the amplifier, and those of the intermodulation distortion products, would be the same. The output level at which this should occur is called the *output intercept point*.* Intercept point is more readily correlated to dynamic range than is compression point, but is difficult to measure directly. To best quantify dynamic range limitations, it is necessary to test the preamplifier in its actual operating environment — that is, under multiple-signal conditions.

```
INTERMODULATION ANALYSIS BY MICROCOMM

  -6.0 dBm -->         |  |
                       |  |
                       |  |
                       |  |
 -26.0 dBm -->      |  |  |  |
                    |  |  |  |
                ----------------

SYSTEM GAIN          =   -6.0 dB
SYSTEM NOISE FIGURE  =    7.0 dB
SYSTEM BANDWIDTH     =    2.4 kHz

      OUTPUT THIRD ORDER INTERCEPT POINT =    4.0 dBm
      MINIMUM DISCERNIBLE INPUT SIGNAL   = -133.2 dBm
      MAXIMUM SPURIOUS-FREE INPUT SIGNAL =  -37.7 dBm
      SPURIOUS-FREE DYNAMIC RANGE        =   95.5 dB
```

fig. 4. IMD analysis of a double-balanced mixer with a +7 dBm injected LO level.

two-tone testing

In the method of dynamic range testing prevalent in industry, two sinusoidal signals of equal amplitude are applied to the input of the device under test, and the resulting output spectrum monitored in the frequency domain. The two input signals, or tones, may be generated by summing the outputs of the two signal generators in a power combiner, or by applying a single RF source to the LO input of a balanced mix-

*For many amplifier circuits, this is a *theoretical*, rather than an *attainable*, level, because the active device may burn out before this output level is reached.

```
INTERMODULATION ANALYSIS BY MICROCOMM

 -7.0 dBm -->            | |
                         | |
                         | |
                         | |
 -65.0 dBm -->         | | | |
                       | | | |
                    ----------------

SYSTEM GAIN           =   -7.0 dB
SYSTEM NOISE FIGURE   =    8.0 dB
SYSTEM BANDWIDTH      =    2.4 kHz

    OUTPUT THIRD ORDER INTERCEPT POINT =    22.0 dBm
    MINIMUM DISCERNIBLE INPUT SIGNAL   =  -132.2 dBm
    MAXIMUM SPURIOUS-FREE INPUT SIGNAL =   -24.7 dBm
    SPURIOUS-FREE DYNAMIC RANGE        =   107.5 dB
```

fig. 5. IMD analysis of a double-balanced mixer with a +17 dBm injected LO level.

```
INTERMODULATION ANALYSIS BY MICROCOMM

 -14.0 dBm -->           | |
                         | |
                         | |
                         | |
 -25.0 dBm -->         | | | |
                       | | | |
                    ----------------

SYSTEM GAIN           =   12.0 dB
SYSTEM NOISE FIGURE   =    2.0 dB
SYSTEM BANDWIDTH      =    2.4 kHz

    OUTPUT THIRD ORDER INTERCEPT POINT =    -8.5 dBm
    MINIMUM DISCERNIBLE INPUT SIGNAL   =  -138.2 dBm
    MAXIMUM SPURIOUS-FREE INPUT SIGNAL =   -59.7 dBm
    SPURIOUS-FREE DYNAMIC RANGE        =    78.5 dB
```

fig. 6. IMD analysis of a bipolar junction transistor preamplifier.

er, a suitable audio signal generator to the mixer's IF input, and applying to the device under test the double-sideband (two-tone) signal appearing at the mixer's RF port. In either case, the two tones must be separated in frequency sufficiently to be individually resolved on the spectrum analyzer's display, yet sufficiently close in frequency to both fall within the response bandwidth of the device under test.

A typical interconnection of instruments for two-tone dynamic range analysis is shown in **fig. 1**, and a typical resulting spectrum is displayed in **fig. 2.** Note that the distortion products of greatest amplitude (in this case, the pair of signals immediately adjacent to the two applied tones) are roughly two divisions, or 20 dB, below the amplitude of the desired output tones. The intermodulation distortion level of this particular amplifier, measured at this particular signal level, is thus -20 dB.

If the vertical axis of the spectrum analyzer is calibrated in absolute amplitude (typically in dBm), the output power per tone, the PEP output power (6 dB above the level of each individual tone), and power of the individual distortion products can be readily determined. And from these values, with minimal number crunching, we can determine the dynamic range of the preamplifier.

data analysis

The mathematical relationships applied next are, as is said in college texts, "beyond the scope of this course." However, I have included in **fig. 3** a listing of a Micro-soft™ BASIC program that performs the complete analysis. Although written to run under the CP/M™ operating system, the program can likely be modified to run on any of the popular home computers using their version of BASIC. **Figures 4** through **8** are sample executions of the IMD program for various receiver configurations. Comparing these printouts will enable us to draw some significant conclusions with regard to the utility of preamplifiers in VHF and UHF communications systems.

mixer design considerations

As a rule, balanced mixers offer excellent dynamic range and intermodulation distortion performance, although their weak-signal sensitivity leaves something to be desired. Mixers are designed to operate at different levels of local oscillator injection, and generally, the higher the LO level employed, the higher will be the mixer's compression level. However, raising the LO injection above perhaps 5 milliwatts tends to degrade mixer conversion efficiency and noise figure. Nonetheless, as **figs. 3** and **4** indicate, so-called high level mixers offer sufficiently improved dynamic range to override the considerations of slightly degraded sensitivity, in most applications.

Not shown in the computer runs, but worthy of consideration, are the so-called "starved LO" mixers. These devices use an extremely low LO injection level with external DC bias of their mixer diodes, and excel in low-noise performance. Their dynamic range, however, is severely degraded, typically 12 to 15 dB below that of even the "low-level" balanced mixer shown in **fig. 3**. Thus, except in those applications in which it is impractical to generate 5 milliwatts or more of LO injection, starved LO operation should be avoided.

The same is true for harmonic mixers. These devices are extremely popular in microwave TV receive converters, and employ LO injection at half the normal frequency, with the mixer diodes serving double duty as frequency multipliers. Obviously, the more frequencies we generate within a mixer, the more spurs will be available to bite us later. I recommend multiplying in a stage separate from that doing the heterodyne conversion.

preamp design considerations

Most receive preamplifiers operate with their active devices drawing relatively low quiescent current. This is done because high device current generates high thermal activity, which degrades noise performance significantly. Unfortunately, biasing any active device

```
INTERMODULATION ANALYSIS BY MICROCOMM

 -9.0 dBm -->            | |
                         | |
                         | |
                         | |
-22.0 dBm -->          | | | |
                       | | | |
                     -----------------

SYSTEM GAIN            =    17.0 dB
SYSTEM NOISE FIGURE    =     3.0 dB
SYSTEM BANDWIDTH       =     2.4 kHz

     OUTPUT THIRD ORDER INTERCEPT POINT =     -2.5 dBm
     MINIMUM DISCERNIBLE INPUT SIGNAL   =   -137.2 dBm
     MAXIMUM SPURIOUS-FREE INPUT SIGNAL =    -58.7 dBm
     SPURIOUS-FREE DYNAMIC RANGE        =     78.5 dB
```

fig. 7. IMD analysis of a MOSFET preamplifier.

```
INTERMODULATION ANALYSIS BY MICROCOMM

 -2.0 dBm -->            | |
                         | |
                         | |
                         | |
-28.0 dBm -->          | | | |
                       | | | |
                     -----------------

SYSTEM GAIN            =    24.0 dB
SYSTEM NOISE FIGURE    =     1.0 dB
SYSTEM BANDWIDTH       =     2.4 kHz

     OUTPUT THIRD ORDER INTERCEPT POINT =     11.0 dBm
     MINIMUM DISCERNIBLE INPUT SIGNAL   =   -139.2 dBm
     MAXIMUM SPURIOUS-FREE INPUT SIGNAL =    -55.1 dBm
     SPURIOUS-FREE DYNAMIC RANGE        =     84.1 dB
```

fig. 8. IMD analysis of a GaAs FET preamplifier.

near cutoff tends to limit its dynamic range, such that the "optimum" bias point from a noise figure standpoint often coincides with the "worst" bias point as far as dynamic range and actual system sensitivity are concerned. Remember, although we talk about desiring high "signal to noise ratio," what we really need for maximum sensitivity is a signal level that is high relative to the sum of noise and distortion. If we can considerably reduce IMD interference by giving up some slight amount of noise performance, the overall system sensitivity has to improve!

Joe Reisert, W1JR — probably the most prominent UHF DXer of our time — has long advocated designing bias circuits for preamplifiers so that device quiescent current can be readily and remotely varied.[3] This way the user can optimize noise figure when operating conditions call for it, and readily improve dynamic range, at a sacrifice in noise performance, should interference conditions dictate. Since all RF design is a series of compromises, Joe's approach seems to offer the best of all possible worlds.

There has long been controversy in Amateur circles over the relative merits of bipolar junction transistors and MOS field effect devices as VHF preamplifiers. Bipolar advocates boast the excellent low-noise performance of these devices, while those preferring the MOS devices cite their higher gain and stable operation, which eliminates the need for neutralization. **Figures 6** and **7** seem to indicate that neither device holds a clear advantage as far as overall system performance is concerned. The two representative amplifiers I tested in preparing this manuscript exhibited identical dynamic range.

N6TX TABLE 1
RECEIVER DYNAMIC RANGE COMPARISON

	STANDARD LEVEL DBM	HIGH LEVEL DBM	BIPOLAR JUNCTION TRANS	MOS FIELD EFFECT	GaAs FIELD EFFECT
Conversion Gain (dB)	-6	-7	12	17	24
Noise Figure (dB)	7	8	2	3	1
IMD Intercept (dBm)	+4	+22	-8	-2	+11
SSB Sensitivity (dBm)	-133	-132	-138	-137	-139
Maximum Input (dBm)	-38	-25	-60	-59	-55
Dynamic Range (dB)	95	107	78	78	84

NOTE: Measurements were performed at 144 MHz, with representative devices. Results at other frequencies will vary, but comparisons will be similar.

Gallium-Arsenide Field Effect Transistors, on the other hand, are the undisputed winner in all areas of VHF and UHF performance. As indicated in **fig. 8**, the GaAs FET offers exceptional high gain, low noise, and wide dynamic range performance. If only they weren't so expensive!

summary

In evaluating receiver performance, it is necessary to consider dynamic range limitations, as well as noise figure, to select the combination of devices and circuits that will yield the best overall sensitivity. **Table 1** summarizes the results of testing various competing mixer and preamplifier technologies. Although the tests were performed at 2 meters, we can generalize the results to other VHF and UHF bands as well.

It appears that best receiver performance will be achieved by cascading a GaAs FET preamplifier with a high-level doubly-balanced mixer. Two-tone analysis confirms that such a combination has considerable immunity to intermodulation and cross-modulation interference, while maintaining an impressively low-noise figure.

references

1. H.W. Bode, *Network Analysis and Feedback Amplifier Design*, D. Van Nostrand Co., Inc., New York, New York, 1945.
2. H.T. Friis, *"Noise Figures of Radio Receivers," Proceedings of the IRE*, July, 1944, page 419.
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ham radio