Extended Dynamic Range Mixers

Low noise amplifiers (LNAs) often are used to increase receiver sensitivity, but their additional gain may drive the mixer into saturation earlier, reducing dynamic range. The author shows how MESFET image rejection mixers improve this situation.

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Low noise RF amplifiers (LNAs) are commonly used to improve the minimum detectable signal level of any receiver front end, not limited by antenna noise. However, their increased RF gain often causes most existing second stage mixers to overload at high input signal levels, thus reducing dynamic range. Recently we have found that MESFET image rejection mixers operate at the same local oscillator power as Schottky diode mixers, but provide typically 6 dB higher input RF 1 dB compression powers. Furthermore, these passive mixers have low phase noise and third harmonic intermodulation products which are ideal qualities for receivers that must detect signals near noise while in the presence of multiple high level signals.

LNA-Mixer Front Ends

One of the most common design challenges in radar, communication and spectral analysis receivers is to design the receiver to search for low level RF signals in the presence of other, much higher power level signals. The radar receiver must withstand large reflections from nearby objects yet be sensitive to the reception of desired signals from distant targets 80 to 100 dB lower. The intermodulation between two local closely spaced wireless communication signals must not interfere with the distant, much lower power user. The molecular resonant spectral lines of a radiated organic or material specimen must not be masked by the large excitation signal.

Most of these applications employ narrow bandwidth and, therefore, the principal undesired mixing product of the LNA or mixer is the multi-tone third order (i.e. $2RF_1 - RF_2$ or $RF_1 - 2RF_2$). It is not possible to eliminate this interference by filtering because the causal and resulting spur frequencies converge upon each other in narrow bandwidth receivers.

A common receiver front end is illustrated in Figure 1. Definitions of frequently used terms are given in *Appendix A*. Our block diagram is more simplified than that of most actual systems so that certain basic design principles can be reviewed. We first notice that the input signal to noise ratio has been degraded by the appearance of IP3 spurs from the amplifier and mixer. The concept SFDR (spur free dynamic range) is commonly understood to mean the power difference (in dB) between the largest input signal and largest corresponding spur product above the noise.

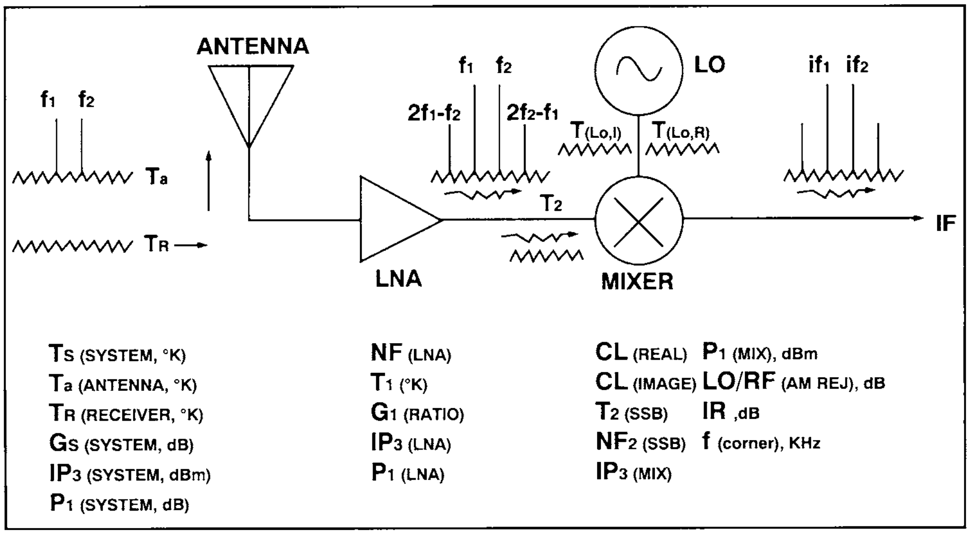


Figure 1. Receiver front-end components.

Noise levels in receiver components, including the antenna, are generally expressed as the equivalent temperature that an input resistive termination must be elevated (in°K) to produce the same output noise as the component of interest[1]. Thus, an antenna facing the horizon (or ground) usually has a 290°K (25°C) noise temperature, whereas the space directed antenna may experience less than 10°K, particularly at C and X band. This is an important consideration when choosing a LNA to upgrade the sensitivity of a receiver, because the overall system noise temperature is the sum of the antenna and receiver contributions.

Thus, the system improvement between a 35°K (0.5 dB noise figure) LNA versus a 75°K (1 dB noise figure) LNA would be marginal if 300°K antenna noise dominated the system. Conversely, for a very low antenna noise space receiving system, the distance improvement would be proportional to the square root of the old and new system noise temperatures (75/35) or 40 percent more range. LO source noise occurring at the RF and image frequencies is also included in the front-end model of Figure 1. Three other important basic aspects of LNA usage are:

- When the amplifier has gain at the image frequency response of the following mixer (2LO-RF), then additional noise will be converted to the output IF frequency. Thus, a 0.5 dB noise figure LNA would result in a 3.5 dB overall system noise figure. This problem is commonly avoided by using an image rejection mixer or image rejection filter at the output of the amplifier.

- High LNA gain will insure best system noise figure, but dynamic range will be reduced, because at high input signal levels the output of the amplifier and/or mixer input will saturate. Likewise, two-tone IP3 spur products will increase. The advantages of the high level MESFET mixers will be discussed relative to this problem.

- Another alternative design strategy for higher dynamic range is to use a lower noise figure mixer rather, than a LNA. For this application, the high level Schottky diode image rejection and recovery mixers described may offer the best solution, particularly when the antenna noise is high.

New Image Recovery Mixer Circuits

The dynamic range of any mixer is determined by the difference between its conversion loss (or noise figure), at low signal levels and its input intercept power IP3 (or 1 dB compression) at high signal levels. For wide RF/IF bandwidth applications, the maximum signal level, also may be limited by other single tone (M x N) intermodulation products. For our discussion, however, only narrow bandwidth usage is considered, for which the two or multi-tone IP3 is the dominate contributor. The maximum input RF signal is also limited by the available LO power.

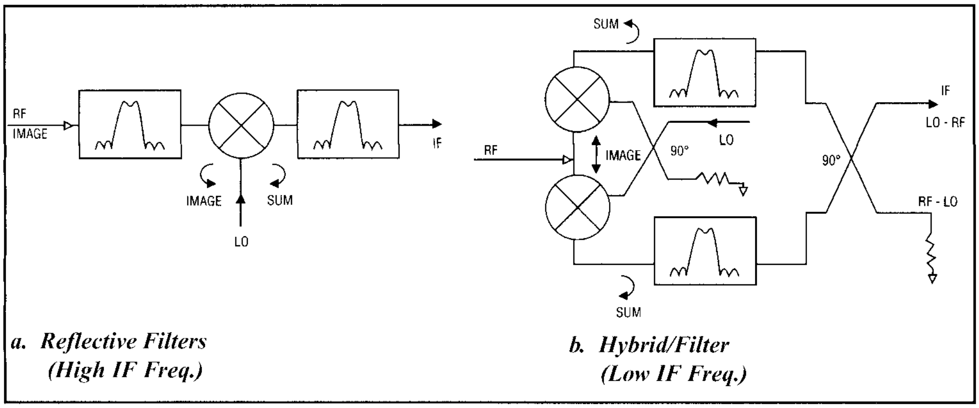


Figure 2. Image recovery (and rejection) mixer circuit.

Thus, the mixer designer seeks to achieve lowest conversion loss and highest IP3 with the least LO power. In general, the lowest conversion loss mixers currently use Schottky diodes to switch or multiply the LO and RF, while the highest IP3 mixers use MESFET semiconductors. We will now briefly review recent test results achieved with each type of mixer.

3.5 dB Conversion loss Schottky Diode Mixer

Image recovery mixers can be made using filter structures or hybrid circuits dependent upon the IF frequency (Figure 2). In each case, the internal mixer image energy is reflected or directed back into the mixer and converted to the IF frequency. External image signals, however, are reflected or absorbed in resistive terminations.

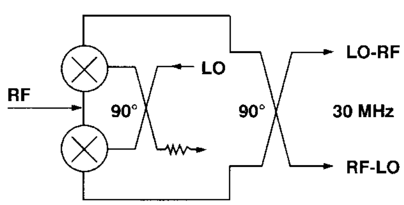
The performance of a 4.5 dB conversion loss hybrid, 5.4 GHz image recovery circuit with a 30 MHz IF[2] is shown in Figure 3. The RF 1 dB compression point of this mixer is 0 dBm. More recently we have made a filter type image recovery mixer circuit for a narrow band receiver at 3.25 GHz with a 500 MHz IF. The unusual feature of this design is that the RF balun also acts as a low-loss two pole reflective image filter. Figure 4 shows the conversion loss of this mixer and the RF input response. High level diodes were used in this design which required +16 dBm LO power in order to maintain a +13 dBm RF 1 dB compression power. Two further advantages of this design are unusually high LO to RF isolation for AM noise rejection and the use of low 1/f noise diodes for low phase noise.

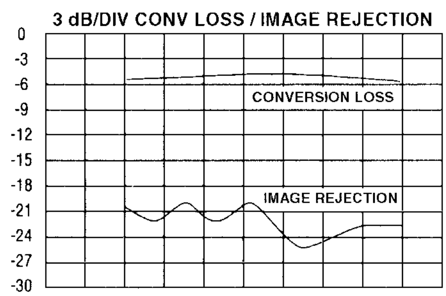
High Compression (1/2 Watt) MESFET Mixers

MESFET mixers evolved from the higher power characteristics of these semiconductors when used in switch applications. A very small amount of gate power controls a much larger power transfer between source and drain. Mass[3] recognized that the odd symmetry of the drain/source E/I characteristics yields low third order distortion. Other workers[4] utilized these characteristics to realize wide band +30 dBm (IP3) mixers up to 8 GHz using +20 dBm LO power. In general, greater LO (or gate) powers are needed for MESFETS in the mixer mode relative to the switch mode, because of the faster rates of charging and discharging the gate to source capacitance.

Figure 3. Hybrid image recovery Schottky diode mixer.

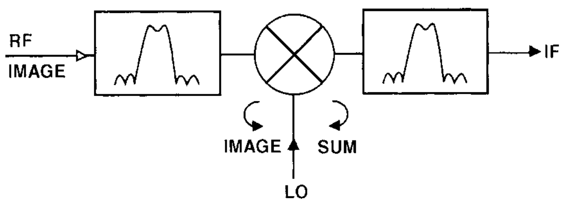
- **IF .... 20 to 40 MHz**
- **RF/LO .... 5.4 to 5.9 GHz**
- **Conversion Loss .... 4.5 dB**
- **Input IP3 .... +8 dBm**
- **LO VSWR 1.5:1**
- **LO Power .... +7 dBm**





Recently we have extended the RF input 1 dB compression of X-Band MESFET mixers to +26 dBm respectively using +25 dBm LO power. Double balanced MESFET image rejection mixers were also built in the 1.8 GHz PCN band with +40 dBm (1 Watt) IP3 and an input RF compression level of +30 dBm (*that is, ±10 volts peak across 50 ohms*!). Most important is the fact that MESFET mixers are not necessarily restricted to high LO powers but rather exhibit (with bias), high ratios of IP3 to LO power in the same LO power range as Schottky mixers, thus making dynamic range retrofits feasible without changing LO power.

- **Conversion Loss .... 3.5 dB**
- **RF (10% BW) .... 3.0 to 3.3 GHz**
- **IF .... 500 ±100 MHz**
- **Input IP^3 .... +23 dBm**
- **LO Power .... +17 dBm**
- **LO to RF Isolation .... 40 dB**
- **Phase Noise at 10 KHz .... -165 dBc/Hz**



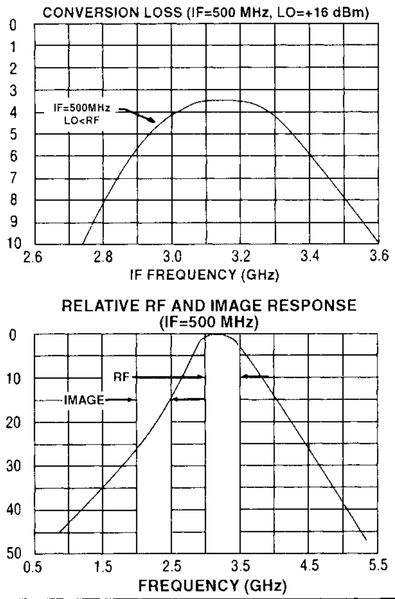


Figure 4. Filter/balun type image recovery Schottky mixer.

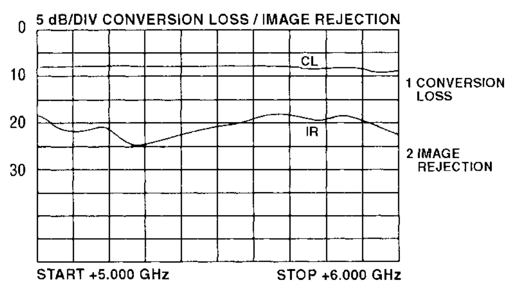
The performance of a 5.5 GHz image rejection mixer at various LO powers is illustrated in Figure 5. Note, that a similar LO power Schottky mixer would compress at +7 dBm RF, whereas this unit handles +13 dBm RF, making it an ideal substitute when a LNA is used in front of the mixer. The following design problems and solution options illustrate both the former system design theory and the newly designed mixer circuits in practical applications.

Low Cost Upgrade of a Communication Receiver.

An existing ground communication receiver with an 8 dB single side band (SSB) noise figure is to be modified for a new application requiring 1.4:1 greater distance coverage. What modification options are possible, assuming that the same transmitter power, antennas and local oscillator are used? The receiving antenna has approximately 300°K of background noise (Figure 6).

Option 1: Replace the existing mixer with a 3.5 dB conversion loss Schottky diode image recovery version of the filter or hybrid type as discussed previously. This approach maintains the same maximum input signal level but improves minimum detectable signal without the expense of a LNA.

- **RF/LO .... 5.4 to 5.9 GHz**
- **IF .... 20 to 40 MHz**
- **Conversion Loss .... 7.5 dB**
- **Input IP^3 .... +23 dBm**
- **LO Power .... +10 dBm**
- **RF 1 dB Comp. .... +13 dBm**



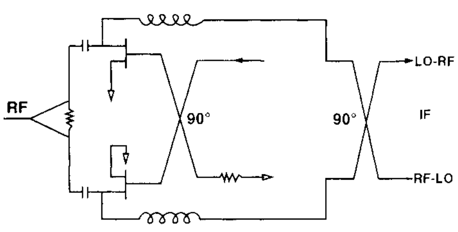


Figure 5. C-Band, high power, MESFET image rejection mixer.

Option 2: A 2 dB noise figure low noise amplifier also will achieve the required additional system sensitivity, but the full noise benefit of this amplifier is not realized because the existing receiving mixer has no image rejection. The increased system gain will, of course, restrict the maximum signal input by the same amount.

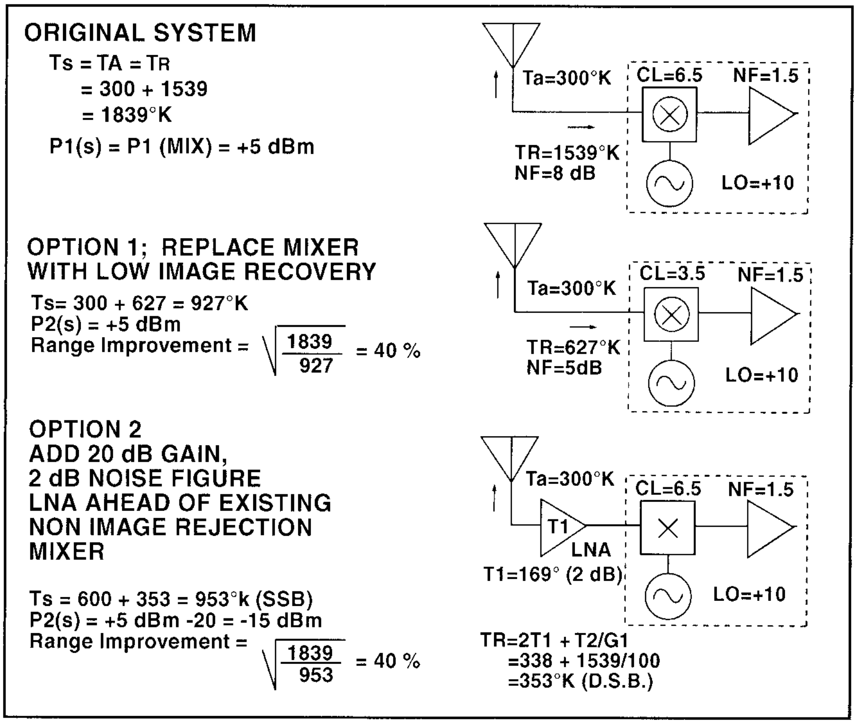


Figure 6. Front-end upgrade.

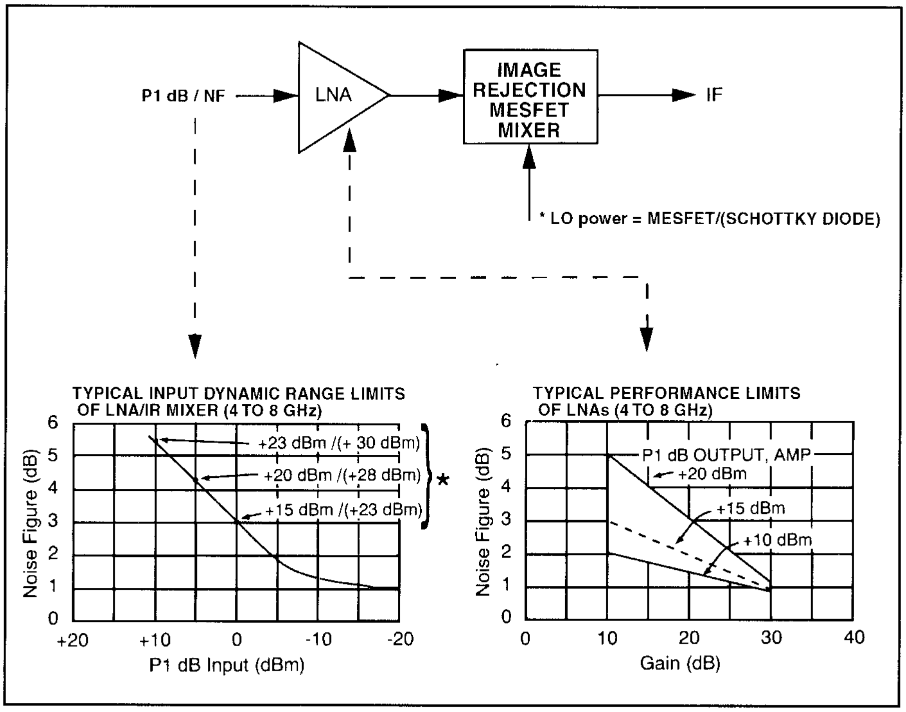
Most important, in order to maintain the assumed mixer input and amplifier output compression relation, we must supply adequate LO power. As already noted, herein lies the advantage of MESFET mixers. The required MESFET LO power is shown at several points on the curve of dynamic range (Figure 7), with the greater required Schottky diode mixer power also shown (in parenthesis). It can be seen from the curve that in order to maintain the desired 0 dBm input compression level, a +15 dBm LO would be required.

The best compression (-2 dBm) obtainable with the existing LO and choice of LNA is shown in Figure 8.

Radar Range Upgrade with Existing LO

Upgrade the dynamic range and sensitivity of a C-Band radar receiver by utilizing a LNA and new higher power image rejection mixer, with the existing LO source. It is desired to handle a 0dBm maximum RF input signal level.

Figure 7. LO power required to achieve various front input noise figures and compression levels, MESFET or Schottky diode image rejection mixers.



Solution: The performance limits of a 4 to 8 GHz LNA and the resulting front-end noise figure/1 dB compression limits when this LNA is combined with a MESFET or Schottky second stage image rejection mixer having 6 dB conversion loss[5] are shown in Figure 7. We first notice that the LNA noise figure, gain and output compression power are constrained to fall within a performance region defined by the circuit design and semiconductors used. Furthermore, if the image rejection mixer input power is set equal to the output power of the LNA, the overall system dynamic range can be approximated by the difference in 1 dB compression power and noise figure shown.

Mixer Performance with a Noisy LO source.

What local oscillator characteristics are desirable to avoid degrading the noise Figure of a wide dynamic range MESFET mixer, particularly when low video IF information is processed?

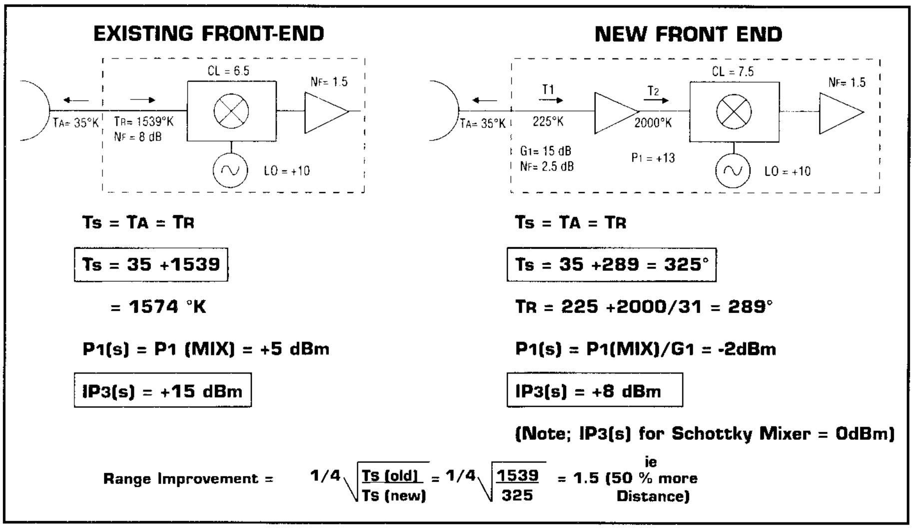


Figure 8. Radar upgrade using LNA/MESFET mixer and existing LO.

In general, one must first be mindful of the type of modulation used for the received information (i.e. AM or PM). Amplitude and phase time variations of the local oscillator are commonly represented in the frequency domain as a pure tone with pairs of sidebands spaced by the rate of unwanted LO modulation, including noise.

AM noise sidebands that are spaced by the system IF frequency above and below the local oscillator are particularly troublesome, because they cause additive input noise that will enter the mixer via the LO port and self mix with the LO in the mixer and appear at the IF frequency. Fortunately, most balanced mixers reject additive AM noise applied at the LO port. The rejection of this noise is dependent upon the decoupling or LO to RF isolation of the mixer used and can vary from -20 to -45 dB. Ideally, one would want to choose a local oscillator source with mixer rejected spectral noise density sidebands at the RF and image frequencies that are lower than that of the mixer's own thermal AM noise. Double balanced mixers having high LO to RF isolation are particularly desirable for highest AM noise rejection. Additive LO AM noise sidebands at the RF and image frequencies also can be reduced with a bandpass filter provided that the IF frequency is 10 percent or more of the LO frequency.

The higher level (1/f) closely spaced AM noise sidebands of the local oscillator usually represent low frequency amplitude (product) modulation of the LO which will also modulate the IF output frequency of the mixer, but the level is proportionally very low. The 1/f noise is far more deleterious when the mixer IF frequency is also low, such as for Doppler applications.

In this case, the sidebands are equal to the RF and image and will act as additive signals as described previously. Most direct LO oscillator sources without an amplifier have considerably less AM noise than PM, because the active feedback device usually operates in a compressed or amplitude limited state. However, the mixer isolation should continue to reject AM 1/f noise when the intermediate frequency is also low.

PM noise of the local oscillator, however, will be translated directly, by the mixer, to the IF frequency. LO power amplifiers can add low frequency (product) modulation or signal level independent phase noise as well as (additive) level dependent higher frequency RF and image phase noise when the noise figure and gain are high. The intersection of the rapidly decreasing lower frequency product noise and the flatter spectrum additive noise is known as the *corner frequency*. Additive PM (and AM) noise from the flat thermal spectrum of the amplifier can be minimized by filtering or using a larger input signal power with a lower gain and noise figure amplifier. This conclusion arises from Parker's[6] PM and AM noise model for amplifiers:

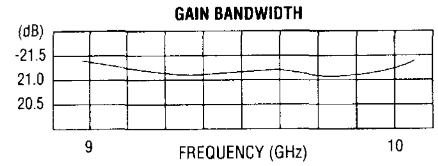
$$S_{\phi}(f) = S_{A}(f) = \alpha_{E}\ 1/f + 2KTFG(f)/P_{O}$$

The 1/f product noise is, however, unaffected by the signal level. Figure 9 shows the PM noise of a high power (+27 dBm) amplifier that we built which is usable with very high level MESFET mixers in phase noise sensitive applications.

In general, a good system design principle is to have all components stressed to the same degree both in terms of their cost and performance contribution to the overall task. This usually results in greatest economies (*the Henry Ford design rule*)[7]. In the case of receiver design, we have reviewed how high antenna noise can spoil the advantages of an expensive low noise amplifier and make a low conversion loss Schottky mixer more practical. In addition, an improperly chosen mixer following a high gain LNA can limit the overall system dynamic range.

Furthermore, the extra cost of a higher power LO needed to raise the IP3 of a Schottky diode mixer may be wasted relative to the choice of newer more power efficient MESFET mixers. Finally, for many crowded communication receivers, the lower limit of dynamic range is not thermal LNA amplifier noise, but rather the single or multitone spur products of the second stage mixer. Thus, for many receiver designs, the choice of mixer semiconductors (Schottky or MESFET) is highly dependent on the cost and power levels of the surrounding components.

- **RF .... 9 to 10 GHz**
- **Gain................................ 20 dB**
- **Noise Figure..................... 5 dB**
- **P1 dB Output .... +27 dBm**
- **Phase Noise (Δ = 1 KHz).... -150 dBc**



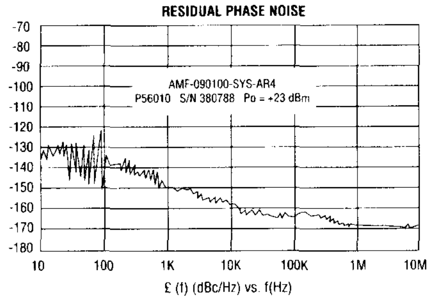


Figure 9. High output power, ultra low phase noise LO amplifier.

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Appendix A - Definition of Mixer Terms:

TS = system equivalent noise temperature (°K) = (TA + TR).

TA = Equivalent antenna ground or sky noise (°K) include image when not rejected.

TR = Overall SSB receiver equivalent noise (°K) = (T1 + T2/G1) with image rejection, = 2T1 + T2/G1) *without image rejection DsB.*

T1 = Equivalent LNA input noise temperature (°K) = (NF-1) To, where NF is power ratio.

T2 = Equivalent mixer SSB input noise temperature (°K) (CL-1) To + LO/RF (Rej.){T (LO, I) + T (LO, R)}.

T (LO,I) = Equivalent noise temperature (°K) of additive local oscillator noise spectral density (dBm/Hz) at image frequency. For example, when an LO amplifier is used after an ideal noiseless oscillator then, T (LO, I) = {To + T (Amp)}G.

T (LO,R) = Equivalent noise temperature (°K) of additive local oscillator noise at RF frequency. In theory, the AM portion of this noise and T(LO,I) will both be suppressed by the mixer small signal or common mode LO to RF isolation LO/RF (Rej).

G1 = LNA Gain (Ratio = 10 exp (Gain dB/10)).

CL = Mixer loss (power ratio) between desired RF and IF signals, (ie: 6dB=4).

P1(S) = Input system 1 dB gain compression power (dBm) (i.e. use the minimum quantity P1 (LNA) / G1 or P1 (mix) / G1.

P1 (Mix) = Mixer input RF power that causes 1 dB decrease in IF output. This is highly dependent on LO power used and whether Schottky diode or MESFET semiconductors are used.

IP3 (LNA) = Amplifier output power (each f1 or f2 tone) that will cause interfering product (2f1-f2) or (f1-2F2) to be equal in power to f1 or f2 tone (i.e. intercept output power of linear gain and nonlinear third order product lines). In general, the third order output products decrease by 3 dB for every 1 dB reduction of input signal power. Therefore, the relative difference (in dB) or dynamic range between the signal and spur powers is 2 (IP3 - P(IN)G).

IP3 (MIX) = IP3 (Mix input) + CL = Mixer IP3 is traditionally specified at the input since this is the larger power due to conversion loss but, most system IP3 calculations are based upon the output contribution of each component.

IP3 (S) = System output third order power 1/{(1/IP3(LNA)+G(LNA)/ IP3(MIX)}. Assuming worst case phase coherency between each tone (Ref. P. 395, Microwave Receivers, Etc., NTIS PB84-108711).