Theory of Intermodulation and Reciprocal Mixing: Practice, Definitions and Measurements in Devices and Systems, Part 2

A expert shows us how to achieve better IMD and IP measurements.

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Part two of this paper will deal with many practical aspects. We are going to look at the measurements done directly on mixers and analyze the possible pitfalls of such measurements and receiver systems. I will propose a novel interlaced dual-loop AGC system, which drastically improves intermodulation-distortion (IMD) performance in actual use. This is because the receiver system will initially maintain a 40-dB signal-to-noise ratio, and after reaching this, will increase at a reduced rate based on the shared AGC distribution.

Measurement of Mixers

Three elements determine the dynamic range of a receiver: the preamplifier (mostly used at frequencies above 30 MHz, unless electrically small antennas or active antennas are used), mixers and amplifiers. While the measurement principle is the same as for the mixers, we will concentrate on amplifiers for the moment.

For determination of the intercept point (IP) of an (ideal) receiver or a single component (for example, a low-noise amplifier, mixer), an assumption is made that at low-impact levels, the IMD products behave according to a square law (IP_2) or to a cube law (IP_3). They are typically selected to be approximately 1-5 µV or its equivalent in dBm (5 µV = –93 dBm; 1 µV = –107 dBm for 50 Ω). Interfering signals are applied to the device under test at power levels that lead to measurable IMD products. The input *IP* is then calculated according to Eq 19:

$$IP_{n,\mathrm{IN}} = \frac{(P_{\mathrm{OUT}} - P_{\mathrm{IM}n})}{n-1} + P_{\mathrm{IN}} \qquad \text{(Eq 19)}$$

where,

P_{OUT} = power of output signal (dBm)

$P_{\mathrm{IM}n}$ = power of intermodulation product (dBm)

P_{IN} = power of input signal (dBm)

n = order of intermodulation product

The output IP results in

$$IP_{n,\mathrm{OUT}} = IP_{n,\mathrm{IN}} + G \qquad \text{(Eq 20)}$$

where

G = gain of the receiver or device (negative for loss, in dB)

This means that for a passive device, such as a mixer, the output intercept point is reduced. The inverse is also true, meaning that the input intercept point of a passive device is always higher than that of the output.

When measuring receivers, the input signals are converted to an IF or to the audio band and a comparison method is used for determination of the IM products. An in-band test signal is applied to the receiver and the power level of this signal is increased until the signal appears in the audio band so that the signal plus noise is 3 dB above the noise floor. This power level is called P_{NF}. Next, an off-channel two-tone signal is applied, and the power levels of the two tones are ad-

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justed in tandem until the IMD product plus noise produce a level 3 dB above the noise floor. From these measurements, the input intercept point of order *n* can be calculated as:

$$IP_{n,\mathrm{IN}} = \frac{(nP_{\mathrm{D}} - P_{\mathrm{NF}})}{n-1} \qquad \text{(Eq 21)}$$

where

P_{D} = power of input signal producing IM products (in dBm)

P_{NF} = power of input signal reaching noise floor (in dBm)

n = order of the intermodulation product

The IMD dynamic range (*IMDR*) is the ratio of the level of the two off-channel signals producing an in-channel IMD product to that of a single in-band signal producing the same power. This statement may be confusing because IMDR is the ratio of two powers expressed in decibels, while the rest of the equation is a difference (in dBm).

$$IMDR = P_{\mathrm{D}} - P_{\mathrm{NF}} \qquad \text{(Eq 22)}$$

The *IMDR* is related to the input intercept point by:

$$IMDR_n = \frac{\left(IP_{n,\mathrm{IN}} - P_{\mathrm{NF}}\right)\left(n-1\right)}{n} \qquad \text{(Eq 23)}$$

In modern receivers, very high *IP*s are common. Good receivers have a third-order input-intercept point (IIP_3) of +35 dBm and a second-order input intercept point (IIP_2) of +80 dBm. Assuming the noise floor of a receiver is –130 dBm, then the IMDR_3 calculates to 110 dB.

For accurate calculation of the IP_3, we must ensure that the cubical behavior of the IP_3 curve is still valid. The applied power levels must be well below the 1-dB compression point of the receiver. Normally, the 1-dB compression point is 10-15 dB below the IP_3. Using the above example, the power for measuring the *IM* product is –20 dBm, and this is well below the 1-dB compression point of +20 dBm.

The above statements are only correct for single devices such as one mixer or one amplifier. The 3-dB-per-dB law applies only for those single devices. In the case of an RF front end of a receiver, this is not necessarily true. I am not addressing the influence of reciprocal mixing now but just the causes of intermodulation. In the case of receiver front-end switching diodes, as well as IMD products of the first crystal filter, all can occur at the same time. Inside the filter, the ferrite cores will also add to distortion. From a purely scientific view, we will not be able to distinguish what contributes what, but the sum of all products will show up.

Especially when testing a receiver, one never knows exactly where the IMD products occur. Most test setups require a dynamic range of up to 100 dB, spurious free, because (for reasons that will be explained) they have some internal IMD products and level differences for low-level IMD products. Thus, when measuring at a very low level, IMD products do not behave according to 3-dB-per-dB, but by some other funny numbers. ARRL testing has been subject to some comments, as their results do not always follow the 3-dB-per-dB rule. Likewise, the relationship between minimum discernable signal (MDS) and the third-order intercept point to be used for calculation of dynamic range does not provide reasonable answers. Complete receiver systems are just not inherently linear; based on the gain distribution, not all numbers are meaningful. More comments on this will follow.

I am getting ahead of myself, though. As I have stated here, for those measurements required to be at sufficiently high levels for receivers whose IP_3 is between 20 and 30 dBm, I recommend doing the measurements at 2 × –10 dBm at the receiver input. In this case, the dominant source in the chain for IMD products will be active and the 3-dB-per-dB law will work properly. The –10 dBm level may not be valid for all systems, but at least it generates a traceable standard.

Another issue is the use of a spectrum analyzer. Since the year 2000, spectrum analyzers have had a state-of-the-art on-screen resolution of between 100 and 120 dB. The lower level is determined by the noise figure of the spectrum analyzer, typically 20 dB, and the upper level is given by IMD products generated at the first mixer in the spectrum analyzer. Spectrum-analyzer measurements will use single devices and will terminate the device under test with its internal 50-Ω termination. A typical modern spectrum analyzer has an input intercept point of +20 dBm. By adding 30 dB attenuation, the resulting intercept point is 50 dBm and, therefore, all the spurious products will come from the test object or the device under test and not from the analyzer. In addition, reciprocal mixing does not apply here. It would be nice if all receivers had an IF monitoring output after the first IF, in which case the true front-end performance could be measured.

As to the accuracy of measurements, the use of a spectrum analyzer—with a built-in tracking generator for calculation—provides better than 1-dB accuracy. On the other hand, a practical receiver has a noncalibrated S-meter that needs to be calibrated for such tests. Many receivers nowadays don't have analog meters or high-resolution digital outputs with three digits of resolution, but have a bar-graph display. Unless the setting can be selected so a bar just starts, there can be a 6-dB inaccuracy problem, as these bars typically only jump in 6-dB steps. The AGC resolution on those bars makes setting a level for the two interfering tones difficult. One may need to vary those tones by up to 6 dB to get reproducible calculated values.

Measuring IP_3 in Mixers

The quality of a mixer has a great impact on the performance of a receiver overall. In addition to conversion loss and isolation, IP_3 is the key factor in the specification of a mixer. Measuring the IP_3 of a mixer is a task that needs very good measuring equipment and a lot of experience. If it is done without precaution, the results may be inaccurate and differ by tens of decibels from the correct values.

The standard procedure of measuring conversion loss and LO/IF isolation of mixers is to provide an RF signal and an LO signal with two independent signal generators having the required impedance, typically 50 Ω, and high internal isolation. The procedure investigates the power level of the converted output and LO signal at the IF frequency with a spectrum analyzer. For IP_3 measurement, two RF signals are used at adjacent frequencies. The frequency offset between the generators is typically 100 kHz to 1 MHz. Smaller offsets should not be used because the RF stages are limited in processing RF signals and thus IP_3 increases at very low offsets. The signals of the two generators are added via a hybrid coupler or combiner and injected into the RF port of the mixer. Fig 29 shows the spectrum of the input signal to the mixer and the intermodulation products (IM_3) at the frequencies ($2f1$–$f2$) and ($2f2$–$f1$), which are generated in the nonlinear mixer and then down-converted by the LO into the IF band. These signals represent the unwanted and interfering signals that limit the dynamic range of the mixer.

According to Eq 19, the input IP_3 of the mixer is given by:

$$IP_{3,\,\mathrm{IN}} = \frac{(P_{\mathrm{IF}} - P_{\mathrm{IM3}})}{2} + P_{\mathrm{IN}} \qquad \text{(Eq 24)}$$

where

P_{IF} = power of down-converted IF signal (dBm)

PIM_3 = power of intermodulation product (dBm)

P_{IN} = power of input signals *f1*, *f2* (dBm)

A standard test setup for IP_3 measurements is shown in Fig 30. The signals of two generators are added in a hybrid combiner and fed into the RF port of the mixer. Since most generators have only 15-17 dBm output, the LO signal is amplified to provide the necessary power level, that is, +20 dBm. The ARRL also measures with 20-kHz spacing.

Examination of a Simple Test Setup that Handles Only Medium Values for IP_3

Both generators provide their signals *f1* and *f2* to the hybrid combiner. The isolation between the generators is given by the isolation of the combiner itself plus the output attenuators of the generators, which are used for power-level control. Due to the finite isolation and reflection from poor termination, some energy from each generator appears at the other and nonlinearities in the generator output stages generate IMD in the test signal. The interference contribution of the two generators can be measured at point A in Fig 30: IM_3 products at the frequencies *2f1–f2* or *2f2–f1*. These IM_3 products will be injected into the mixer and degrade the measurement accuracy. This is an ideal case, since it assumes a perfect termination for the IF load, if a load such as a spectrum analyzer is used. The spectrum analyzer is typically operated at 30-40 dB attenuation with a useful dynamic range of 100 dB using 10-Hz resolution bandwidth. In this case, the spectrum analyzer will not show any IMD products.

Example: Assuming a Mixer with 10-dB Conversion Loss and an infinite IP_3

P_{IN} at *f1* and *f2* = 0 dBm; measured IM_3 at point A = –50 dBm; measured down-converted IM_3 product in the IF band = –60 dBm; measured IF output power = –10dBm. Using Eq 24, an input IP_3 of 25 dBm is calculated. Therefore, the test setup itself has an IP_3 of 25 dBm!

If any mixer is now connected at test point A, the injected IM_3 products of the test setup and the IM_3 products generated within the mixer will interfere. What will be the measured result?

If the mixer itself has an IP_3 of about 30 dBm, it cannot be measured with this test setup. Mixers with an IP_3 much lower than 25 dBm can be measured using this test setup with barely sufficient accuracy.

The frequencies of the IM_3 products are *2f1–f2* and *2f2–f1*. The two terms *2f1* and *2f2* will be also provided by the generators as harmonics. In the test setup, at point A, the harmonics *2f1* and *2f2* can be measured. Normally, harmonics of generators are about 30-40 dB below the fundamental frequency; the higher the output power of the generator, the lower is the suppression of the harmonics. A broadband mixer, such as DUT, converts these harmonics into the IF, which interferes with the desired down-converted signal.

In practice, at least six frequencies: *f1*, *f2*, *2f1*, *2f2*, *2f1–f2* and *2f2–f1*—are injected into the mixer instead of only two (*f1* and *f2*). See Fig 31.

Optimizing the Test Setup

The optimized test setup is shown in Fig 32. Interference produced by both generators because of insufficient isolation, and further generating unwanted IM_3 products, can be reduced by inserting attenuators in each signal path. The attenuators also improve the load matching of the combiner, which results in better isolation in the combiner itself, because the combiner achieves certain isolation levels only if the load impedance is correct. Additional isolators can be used to achieve greater isolation. The drawback of the isolators is a reduced bandwidth compared to that available with attenuators. Alternatively, high-linearity

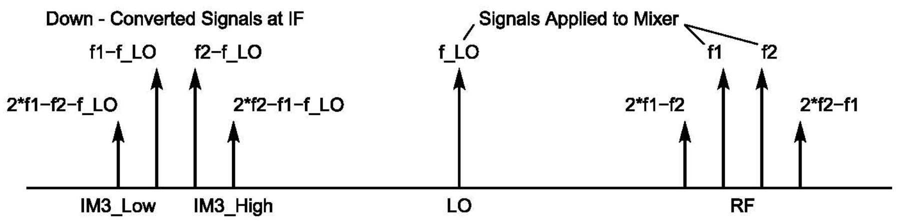


Fig 29—RF signals *f1*, *f2* and f_{LO} are applied to the mixer and are down-converted to the IF together with intermodulation products, IM_3.

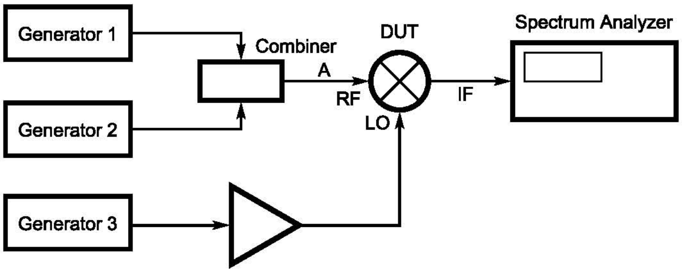


Fig 30—A minimum test setup for IP_3 measurements. (The concept and validation of the mixer test bed was supplied by Guido Baumann, Detlev Hollmann, and Roland Heilig, of the German firm HBH under contract to the author.)

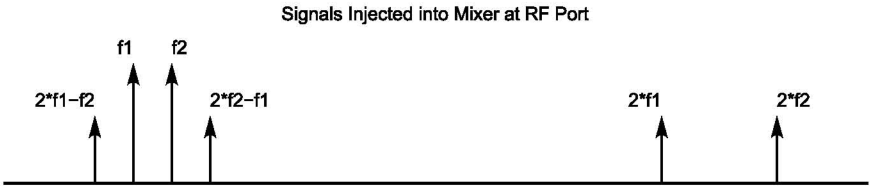


Fig 31—Signals injected into the RF port of the mixer in an IP_3 test setup.

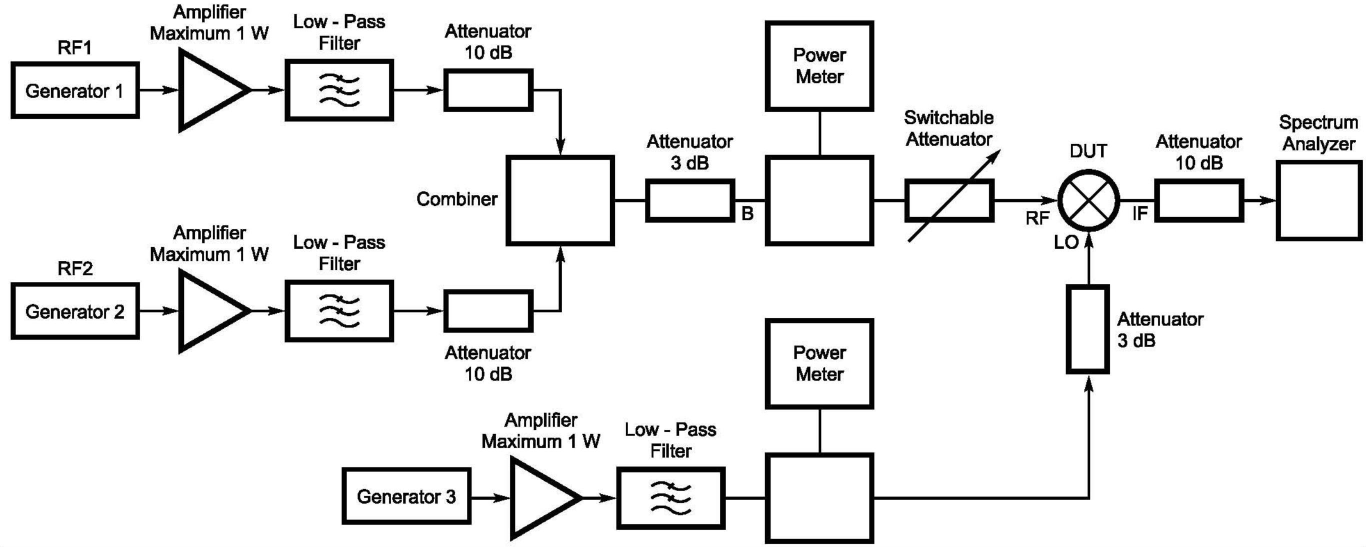


Fig 32—Test setup for high-IP_3 measurements.

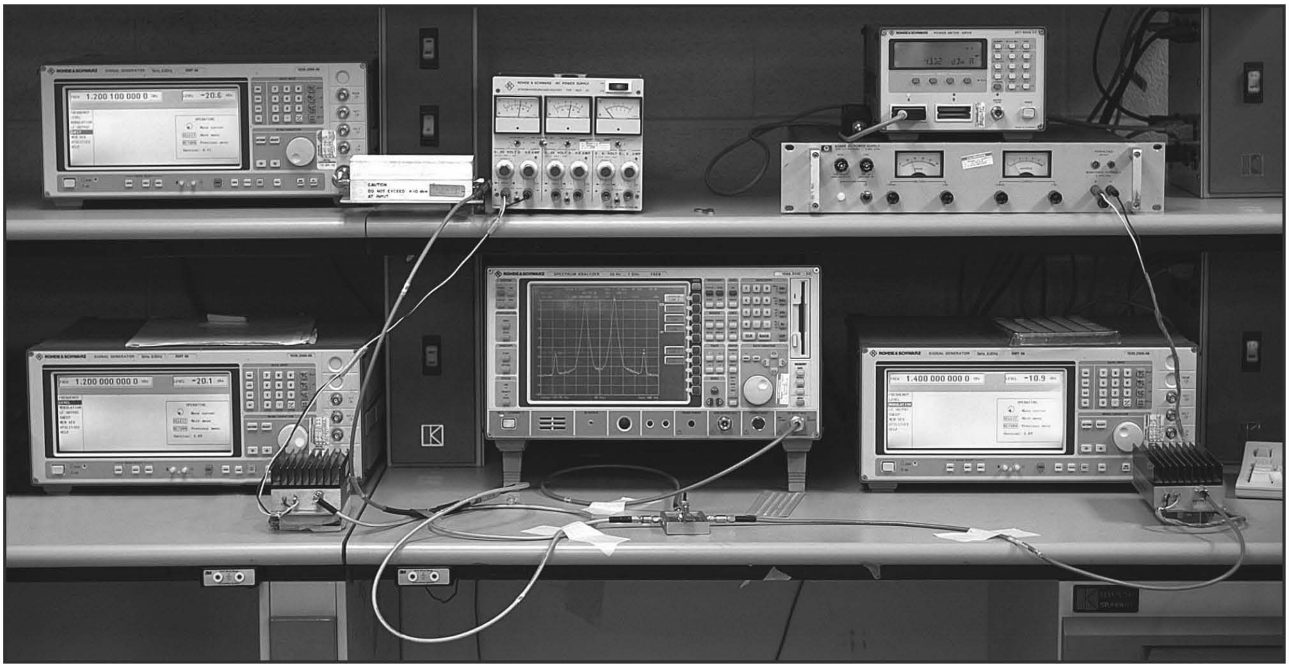
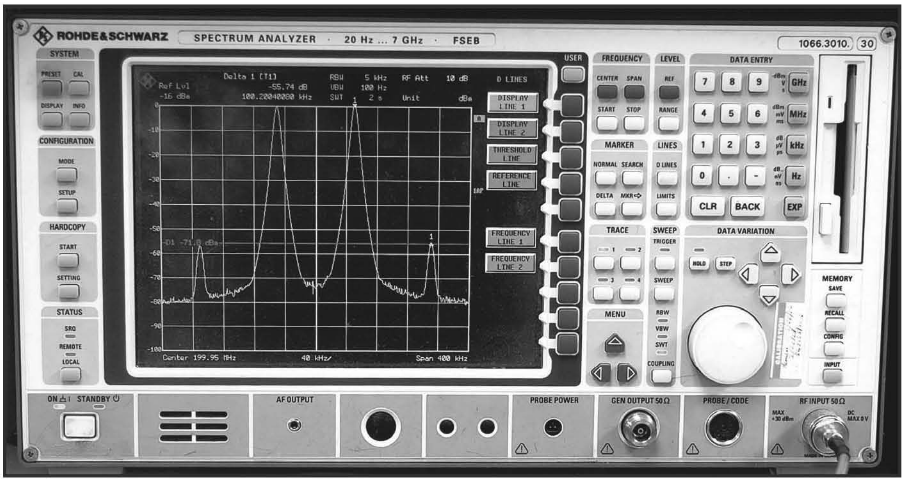


Fig 33—A photo of the setup without harmonic filters.

Fig 34—Measurements on the spectrum analyzer.



Delta 1 [T1] -55.74 dB 100.20040080 kHz
Ref Lvl -16 dBm
RBW 5 kHz
VBW 100 Hz
SWT 2 s
RF Att 10 dB
Unit dBm
D1 -71.8 dBm
Center 199.95 MHz
40 kHz/
Span 400 kHz

class-A amplifiers can be used as isolators. They have the advantage of providing the required power levels at the DUT. The isolation between both generators must be as great as possible for an expected IP_3. The IM_3 product at test point B must be at least 10 dB lower than the expected IP_3 product generated by the mixer. For example, to measure a mixer with an IP_3 of 35 dBm, the IM_3 product at point B must be lower than –90 dB for 0 dBm output. Such amplifiers have 20-dB gain, 1-W output power capability and 50-dB reverse isolation.

Fig 33 is a picture of a universal IMD-test setup. The picture shows two signal generators on the left (one on top of the other). They are connected to 1-W power amplifiers via a 10-dB attenuator to increase the isolation. These amplifiers have 20-dB gain and are capable of 1 W output. The device under test is shown at the bottom-center of the picture and is clamped down in a test fixture. The signal generator on the right feeds the input for the LO drive. The spectrum analyzer in the middle is a high performance Rohde & Schwartz FSEB spectrum analyzer operating from 20 Hz to 7 GHz. Its IF stages are DSP-based.

Fig 34 shows a close-in picture of the spectrum analyzer. The two input signals shown are at 0 dBm based on the attenuator setting. The symmetrical sidebands are roughly 56 dB down relative to 0-dB input. This calculates to IP_3 of +28 dBm.

We can reduce the harmonics of each generator by adding a low-pass filter after it. A better solution is to have two narrow band-pass filters shifted in frequency. In this case, both filters provide an additional isolation for the two generators. Practical measurements have shown that a 60-dB reduction of the harmonics has an influence on the IP_3 of about 4 dBm. To cover the complete RF range of the mixer, several low-pass filters with different corner frequencies are necessary.

To reduce the influence of the harmonics resulting from the LO amplifier, an additional low-pass filter after the LO amplifier is necessary. This can be demonstrated from an IP_3 measurement of a FET mixer with and without an additional low-pass filter. Differences up to 4 dB have been measured. For more details, see Fig 35.

For higher isolation, a special hybrid combiner can be used instead of a standard combiner. Some hybrids have a typical isolation of 35 dB. They

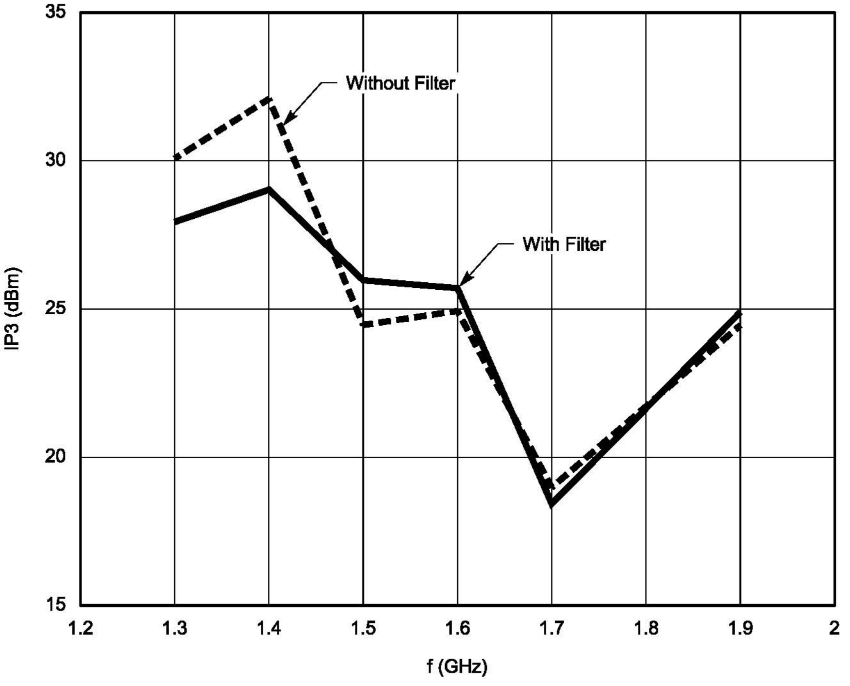


Fig 35—IP_3 measurements with and without a filter following the LO amplifier.

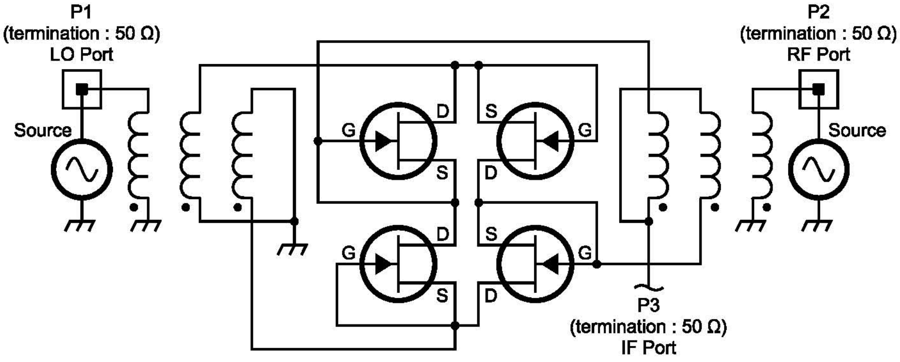


Fig 36—A doubly balanced mixer using GaAs FETs as mixer diodes, gate and source are connected (see References 1 and 2).

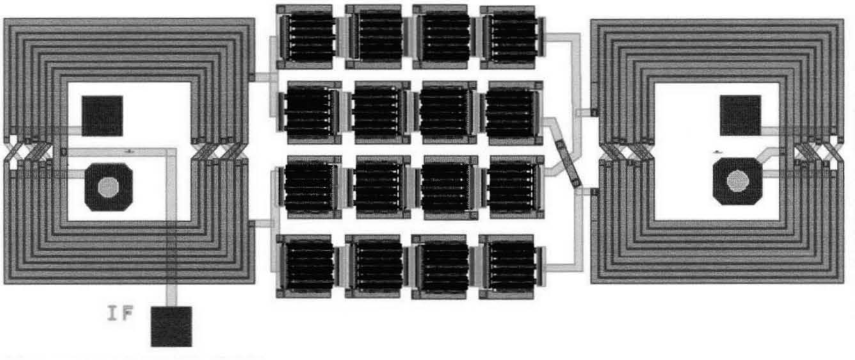


Fig 37—A view of the die for the circuit in Fig 36.

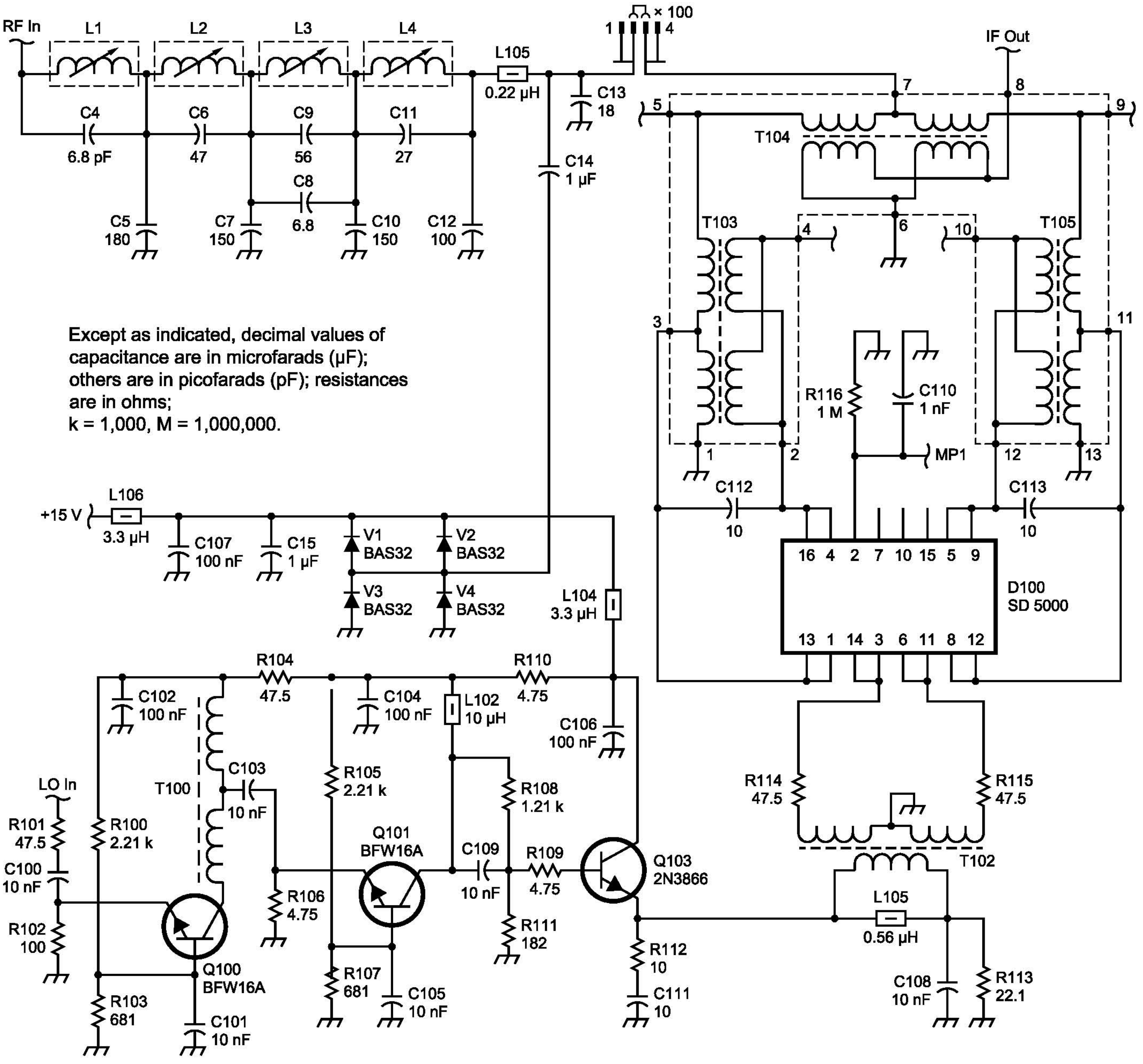
may be built with isolations up to 65 dB. A hybrid is recommended for narrow-band applications. The combiner or hybrid also needs a good load-impedance match at the common port. Therefore, an attenuator must be inserted between the combiner and RF port of the mixer.

Checking the Measured Result

To check the measured result of IP_3, a switchable attenuator is inserted at the input RF port of the mixer (see

Table 3—Comparison of IP_3 Measurements of a Diode Mixer and a FET Mixer

	IP_3 *measured at another facility*	IP_3 *measured by the Author*
Diode Mixer	31.5 dBm (w/o LO filter)	30 dBm (w/o LO filter) 33 dBm (with LO filter)
FET Mixer	34.5 dBm (w/o LO filter)	35.5 dBm (w/o LO filter) 34.5 dBm (with LO filter)



Except as indicated, decimal values of capacitance are in microfarads (µF); others are in picofarads (pF); resistances are in ohms;
k = 1,000, M = 1,000,000.

Fig 38—Circuit diagram of a high-performance receiver front end (EK890/895/896). It consists of a low-pass filter at around 33 MHz and a 40-dBm IP_3 switching-type mixer using the SD5000 quad switches. The three-stage amplifier underneath generates the high-voltage swing required for the mixer. To obtain high isolation, the first two amplifiers use a common-base configuration. This prevents any feedback from the mixer into the oscillator itself.

Fig 32). When the attenuation after the combiner is increased by 3 dB, the measured IM_3 product should decrease by 9 dB and the calculated IP_3 should be constant. If the IM_3 product falls less or more than 9 dB, optimize the test setup. Greater decoupling of both generators or greater harmonic suppression is necessary.

When you shift both frequencies $f1$ and $f2$, IP_3 must be constant and symmetrical. If not, the diodes are not matched, or signal generators 1 and 2 do not have equal output levels.

With shifts of the frequency difference between $f1$ and $f2$, IP_3 must be constant. Example: start with $f1 = 14.0$ and $f2 = 14.1$ MHz. The IMD products must remain at 14.2 and 13.9 MHz.

When changing the cable length, IP_3 must remain constant. It may happen that nonlinearity is present (cancellation of harmonics) within the test setup, which can result in much greater measured IP_3 than there really is.

To compare IP_3 test setups and measurements, the IP_3 of the diode mixer, as well as an FET mixer, were measured at another facility (see Table 3). Measurements were done at 1.8 GHz. Different high-level mixers available on the market were measured according to the above-described method.

As an example, a diode mixer was intended to have an IP_3 of 30 dBm; but the correct measurement resulted in an IP_3 of only 25 dBm. Another example was a FET mixer with an IP_3 of 38 dBm according to the datasheet. It was measured to have only 31 dBm in my test setup. The question arises: What kind of test setup did those companies use to evaluate their devices?

The mixer internally generates a large number of spurious products. This happens despite the mixer being doubly balanced. Manufacturers typically generate a table of such spurious products. Table 4 shows such a harmonic-spurious table of a doubly balanced mixer.

State-of-the-art mixers for high frequencies have used multiple diodes for high performance. A better or more modern way to use a GaAs FET-based diode ring is shown in Fig 36. Because the diode threshold level is now 1 V, as compared to 0.3 V for hot-carrier diodes, the local oscillator power required is 20 dB higher, and the intercept point is 20 dB higher than a conventional diode mixer ring. Such an array is shown in Fig 37. In low-frequency receivers, the use of silicon-based switching mixers has driven the IP_3 up to typically 36 dBm, and for well-matched cases, up to 42 dBm. A front end based on this doubly balanced mixer, such as the Rohde & Schwartz EK895, is shown in Fig 38. The circuit also gives information about the LO amplifier. An HF/Microwave version of this, called the Star Mixer, is shown in Fig 39. Fig 40 shows a picture of a production version. Because of the high LO drive required, a version with a preamplifier was built and is shown in Fig 41.

Impact of the Receiver Concept on IP_3 Performance

Recent publications, originating from England, have elaborated on dynamic-range requirements. It is true

Table 4—Harmonic Spurious of a Doubly Balanced Mixer

Harmonics		f_{LO}	$2f_{LO}$	$3f_{LO}$	$4f_{LO}$	$5f_{LO}$	$6f_{LO}$	$7f_{LO}$	$8f_{LO}$
$8f_{RF}$	100	100	100	100	100	100	100	100	100
$7f_{RF}$	100	97	102	95	100	100	100	90	100
$6f_{RF}$	100	92	97	95	100	100	95	100	100
$5f_{RF}$	90	84	86	72	92	70	95	70	92
$4f_{RF}$	90	84	97	86	97	90	100	90	92
$3f_{RF}$	75	63	66	72	72	58	86	58	80
$2f_{RF}$	70	72	72	70	82	62	75	75	100
f_{RF}	60	0	35	15	37	37	45	40	50
		60	60	70	72	72	62	70	70

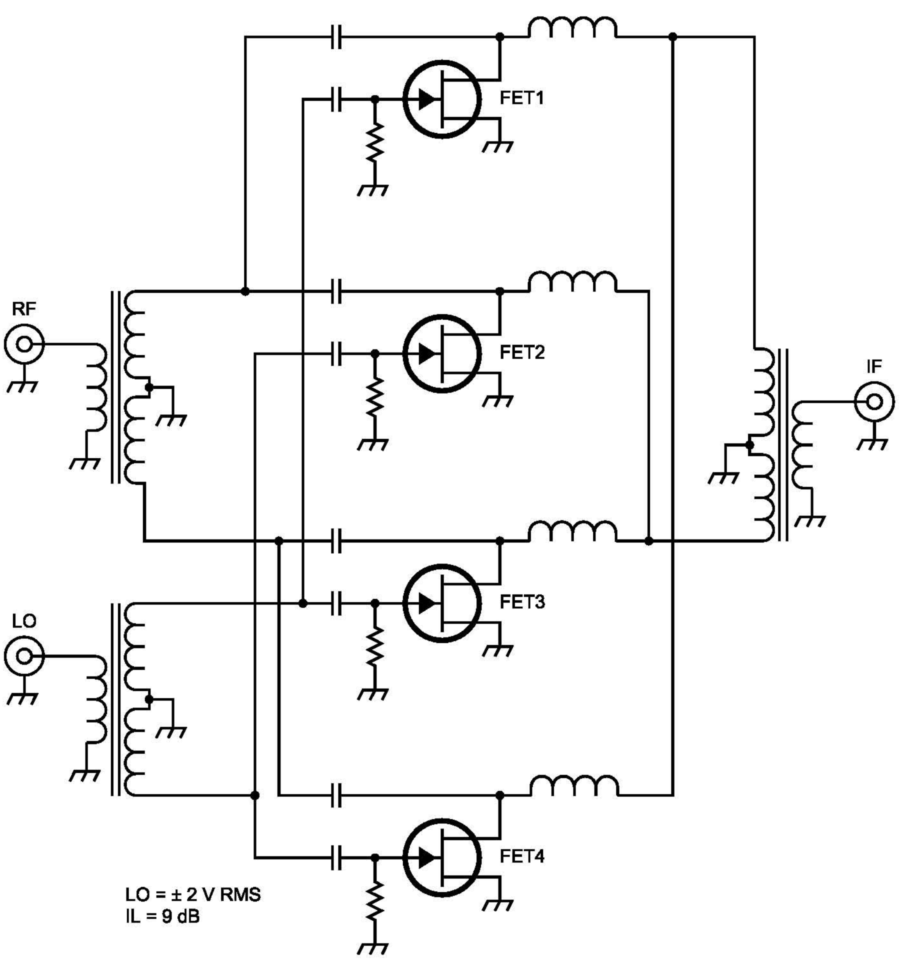


Fig 39—Star configuration, high-performance mixer having a 40-dBm intercept point. It uses GaAs FETs as switches. Depending on the input transformer, the frequency range can be adjusted. The particular one shown operates from 800-6000 MHz.

that about 10 years ago, the propaganda stations worldwide were congesting the airwaves; but things have changed. The real villains are the broadcast stations at 7.2 MHz, 9.6 MHz, 15.2 MHz, 17 MHz and 21.5 MHz. Precise measurements on a Rohde &Schwartz active antenna with constant electrical height show that the 20-, 17- and 15-meter broadcast stations adjacent to the ham bands can generate strong IMD products—specifically third-order. The second-order IMD products, such as 6 + 8 = 14 MHz, are more likely to be suppressed by input selectivity; however, the passband filter for the ham bands generally allows passing of the broadcast stations adjacent to ham bands quite well.

The traditional way around this problem is to build receivers with reasonable input selectivity, no preamplifier, but with high-level mixers. In any case, the preamplifier is an optional item and is switched in by diode switches; in most cases, they are neither PIN diodes nor relays. The best way to switch RF signals in the HF band is to use a common-gate FET switch, as shown in Fig 42.

Fig 43 shows a schematic of a modern receiver. The signal coming from the antenna is fed to a digitally controlled binary-coded attenuator with 60 dB of total range. The IP_3 of this attenuator exceeds 40 dBm and the IP_2 exceeds 80 dBm. It is followed by a low-pass filter set at 10% above the frequency of the highest frequency of reception and then followed by a band-pass filter; in this case, a 6.4-8 MHz filter. If the IP_3 of the low-pass and band-pass filters is above 40 dBm or 80 dBm for second-order products, it makes sense to put an RF attenuator after the second filter because the binary-coded GaAs switches produce some IMD products. An alternative, but much more expensive solution, is the use of a mechanical attenuator that does not add any IMD products. Such an attenuator has an IP_2 and IP_3 of infinity (>80 dBm for IP_3 and >120 dBm for IP_2), but is more expensive than its solid-state replacement.

Following the filters, there is an optional preamplifier with an intercept point of 20 dBm and 10 dB gain. Assuming the first mixer has an IP_3 of 30 dBm, this would reduce the IP_3 of the system down to 20 dBm; this is the same as the preamplifier. If it can be afforded, there is merit in designing a 30-dBm-intercept-point amplifier. This would reduce the practical intercept point from 40 dBm down to 30 dBm. This requires the previously shown high-level switching mixer.

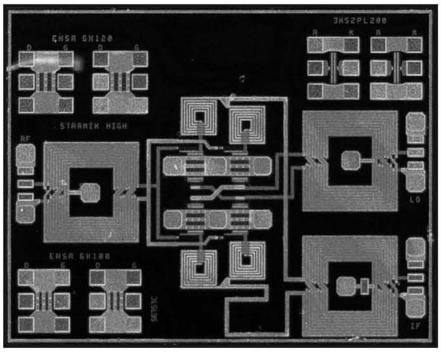


Fig 40— A view of the die for the Star Mixer shown in Fig 39. Notice the three printed inductors.

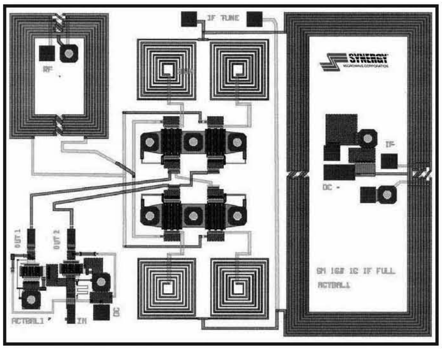


Fig 41—Layout of a proposed Star Mixer die with an LO driver amplifier at the lower left.

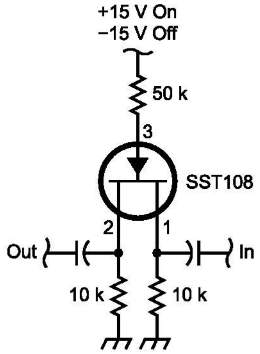


Fig 42—A single-FET switch with 0.1-dB insertion loss and an IP_3 of better than 40 dBm.

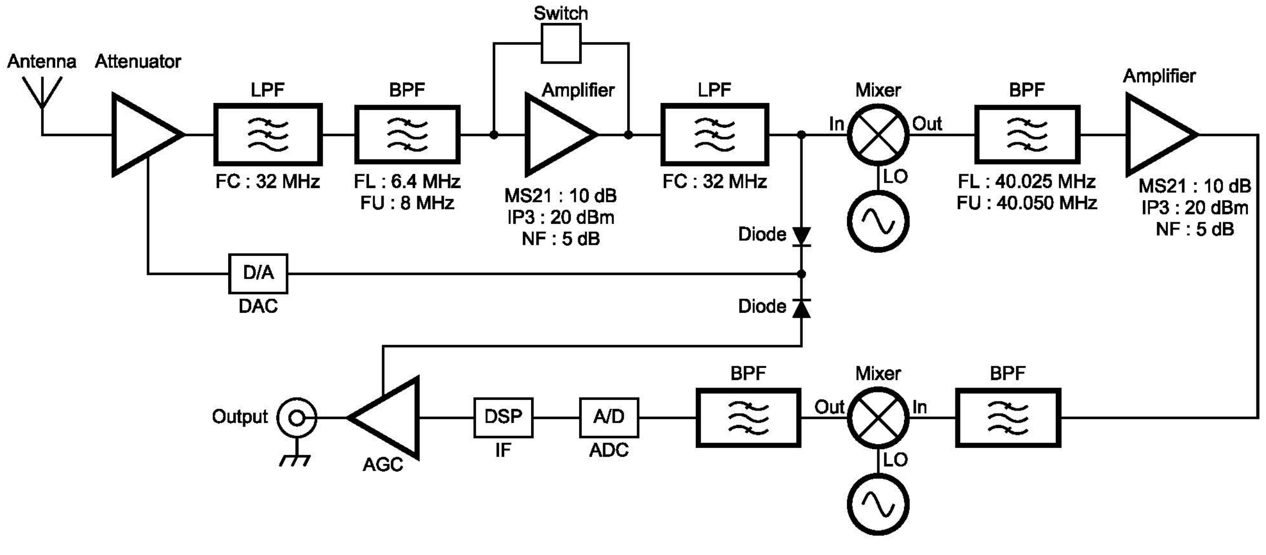


Fig 43—Block diagram of a high-dynamic-range receiver with two independent, interlaced AGC systems.

Dual-Loop AGC

The rest of the chain is conventional until we look at the AGC system. The receiver has two independent, yet connected, AGC loops. For signal levels up to 3 µV, the AGC system of the IF handles the first 30 dB of attenuation. The next 60 dB is a combination of IF and RF AGC; at approximately 1 mV and above, the contribution of the RF gain dominates. This can be seen in Fig 44. Because the AGC now makes heavy use of a pre-attenuator, which operates quasi-continuously, the intercept point now depends on the amount of pre-attenuation.

In the case of a DSP system, the in-band IMD is much less than the first- and second-mixer contributions. Given an intercept point of 20 dBm for the receiver, this is the case with the preamplifier on and listening to a signal of 100 µV based on the AGC in the RF loop. We already operate with 10 dB of RF attenuation. The trick of this method is to maintain a reasonable signal-to-noise ratio of 40 dB and

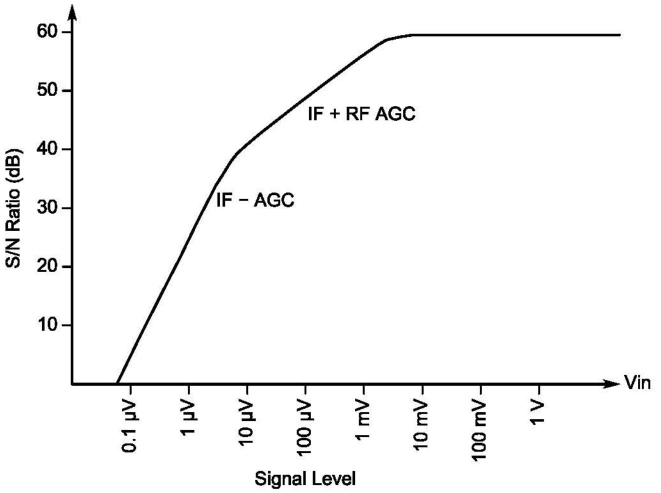


Fig 44—Signal-to-noise ratio (as a function of input voltage) plot for the receiver shown in Fig 43.

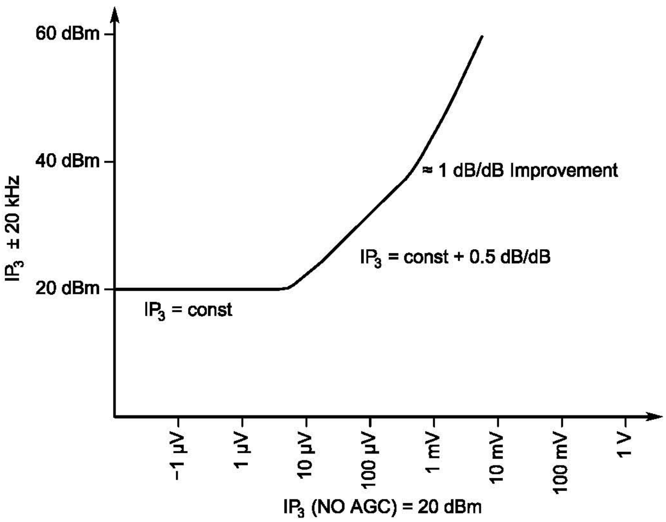


Fig 45—A plot of intercept-point behavior for the receiver system shown in Fig 43. The RF attenuation activated by the AGC voltage improves the third-order intercept point.

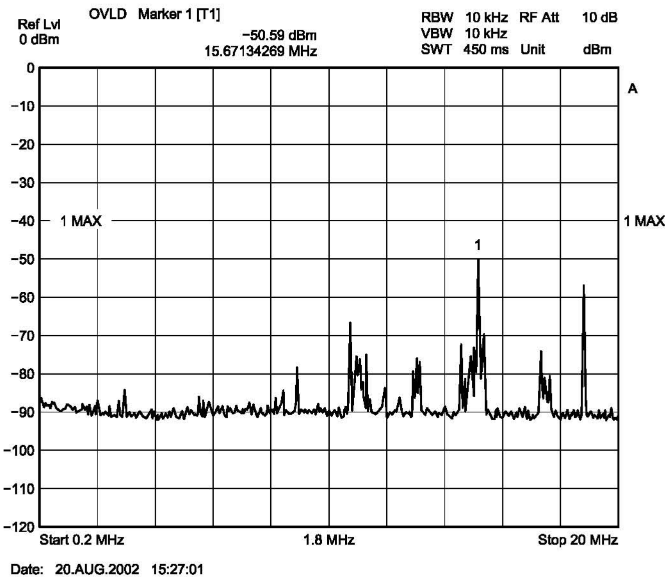


Fig 46—A spectrum-analyzer plot of signals from a calibrated Rohde & Schwartz active antenna covering 100 kHz to 100 MHz. The displayed frequency band is shown with a resolution bandwidth of 10 kHz. By reducing the resolution bandwidth to 1 kHz, 10 dB of more dynamic range can be obtained. The noise figure of the spectrum analyzer is roughly –100 dBm relative to a 1-kHz bandwidth.

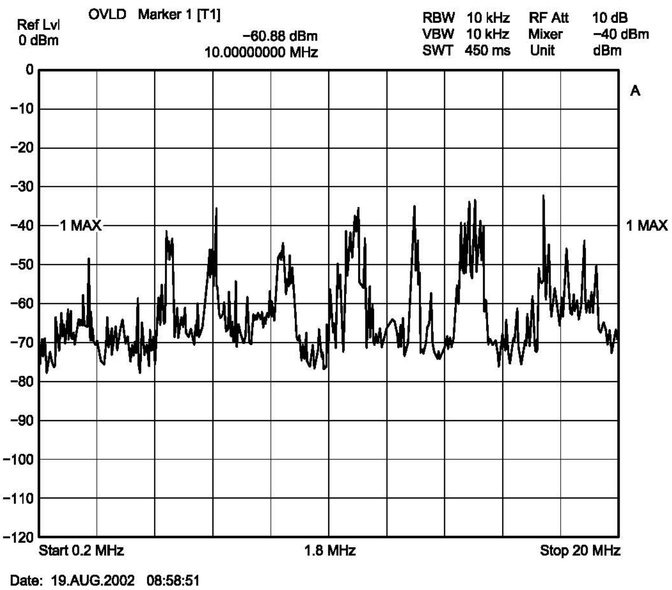


Fig 47—A 24-hour spectrum measurement covering the frequency range from 2 to 20 MHz. It is interesting to see that from 6 MHz to roughly 18 MHz we find a lot of busy bands. By reducing the resolution bandwidth to 1 kHz, the noise floor would drop down about 90 dBm and the actual shortwave dynamic range, meaning peak signal divided by noise floor, is 90 dBm – 35 dBm = 55 dBm. In this level range, a signal-to-noise ratio of the receiver of more than 55 dBm would be useless. This is why it was decided to limit the AGC signal-to-noise ratio to 60 dB, resulting in a sufficient safety margin.

use as much RF attenuation as possible. If an input signal would be about 1 mV, or 60 dB µV, equivalent to S9 + 26 dB, the intercept point of the receiver would increase over 40 dBm. Alternatively, the dual AGC system monitors the input to the first mixer. If the input at this point increases to 1 mV for any given interference outside the IF bandwidth, the pre-attenuator will become active. These conditions can occur at night on 40 meters. In this case, the noise level on 40 meters is equivalent to 10 µV into 50 Ω. Since the receiver sensitivity is 0.3 µV for a 10-dB signal-to-noise ratio (as seen in Fig 45) the receiver can afford at least 20 dB preattenuation, in which case the intercept point with the amplifier will increase to 40 dBm. Without the preamplifier on, it will increase to 60 dBm. At those levels, the input filters are likely to be the dominant source of intermodulation, unless good precautions have been taken.

In the past, many authors—including myself—have done signal evaluation on the shortwave bands, including ham bands. Previous spectrum analyzers, such as the HP-141, did not have low-phase-noise oscillators to really evaluate the spectrum. In addition, the shape factor of IF filters also was not sufficient to provide the necessary resolution. Only the modern (year 2000) spectrum analyzers built in extremely low-phase-noise, fractional-N synthesizers and DSP-based IF stages that provided enough resolution. The useful dynamic range of the spectrum analyzer needs to be more than 100 dB with a safety margin of 120 dB. Figs 46 and 47 show peak average measurements done with an active antenna and an appropriate spectrum analyzer. It is amazing how many holes are found between the stations, which the average receiver would not indicate.

Example: There have been discussions about measurements in general and the League's measurements in particular. For a point of reference, I have decided to do a set of measurements, in parallel with the League, and revisit one of my modified ham transceivers, the FT-890 by Yaesu. The test setup is the same as shown previously, and the first test object was the Rohde & Schwartz XK2100L and the EK895. Both receivers have the same front end but different IF combinations. The transceiver XK2100 is a dual-conversion system from a 45-MHz first IF to a 25-kHz second IF. The EK895 has three IFs; the middle one being 1.44 MHz. The reason for this is that the IF was once analog and was replaced by a DSP system. The Yaesu FT-890, one of my favorite inexpensive radios, was modified by replacing all the input filter switching diodes with MI204 PIN diodes. First, the system is calibrated for linearity.

The XK/EK system was measured with two tones set at 0 dBm (1 mW) at the antenna terminal and the two-tone IMD products at 82 dB down, or at –82 dBm, using the formula

$$IP_3 = P_{\mathrm{IN}} + \frac{P_{OUT} - IM_3\ \mathrm{products}}{2} = 41 \qquad \text{(Eq 25)}$$

where, IM_3 products is in decibels and P_{IN}, P_{OUT} and IP_3 are in dBm.

Both the XK and the EK systems were measured this way to have an intercept point of 41 dBm. The intercept point remains constant over the HF band (1.5-30 MHz) with a tolerance of ±1 dB. The actual specification for this was better than 36 dBm. These values are about the best on the market. When measuring at significantly lower levels, the IMD products of the test system appear to have an intercept point of +26 dBm. It is, therefore, essential to use an appropriate high level signal for the test.

The FT-890 uses a push/pull junction-FET mixer, and such a high intercept point cannot be expected. With the preamplifier on, two tones of –20 dBm, exactly, were provided to the receiver. The output from the hybrid coupler was set at 0 dBm followed by a 20-dB switchable attenuator. Two sets of measure-

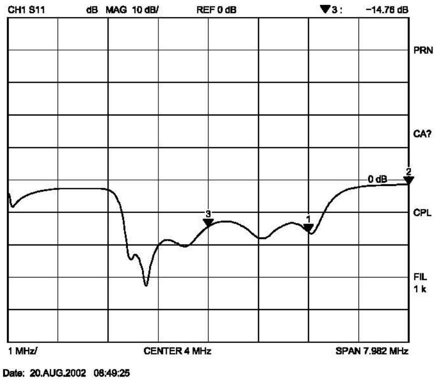


Fig 48—Input return loss of the Yaesu FT-890 for the 80-meter band.

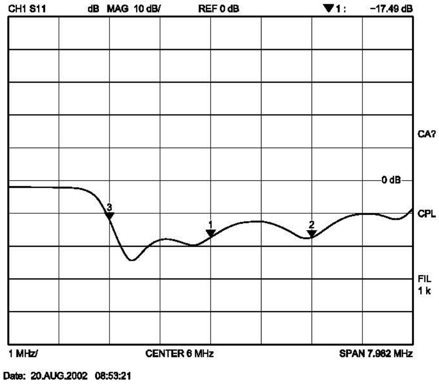


Fig 49—Input return loss of the Yaesu FT-890 for the 40-meter band.

Fig 50—The test setup for the Yaesu FT-890. The S-meter indicates such spurious products as described.

ments were done: one at 7.15 MHz/7.05 MHz and one at 14.15 MHz/14.05 MHz. With the preamplifier on, the spurious product—100 kHz higher or 7.25 MHz or 14.25 MHz—appears at a level of –84 dBm or approximately 14 µV. Using the above-stated equation, we obtained ((84 – 20) ÷ 2) – 20 = 32 – 20 = 12 dBm. This with the amplifier on! The corresponding values, without a preamplifier, were 2 × –6 dBm and the products at –70 dBm or 71 µV. The resulting number is ((70 – 6) ÷ 2) – 6 = 32 – 6 = 26 dBm. For comparison, here is data for the IC-746 at 25-kHz and 100-kHz spacing. The IP_3 with preamplifier on is ((70 – 22) ÷ 2) – 22 = 24 – 22 = 2 dBm. IP_3 with the preamplifier off is ((70 – 10) ÷ 2) – 10 = 60/2 – 10 = 30 – 10 = 20 dBm. IP_3 products were –70 dB down. Input power was –22 dBm and –10 dBm for the two cases.

Most companies in the ham business during recent years have followed my recommendation and incorporated PIN diodes prior to the mixer. The values for the input level at –6 dBm and –20 dBm are levels that Amateur Radio transceivers should be able to accept.

Having a step attenuator in front of the system allows us to reduce the level by some decibels, like 3 dB, in which case the IMD products need to go down by 9 dB. This is a necessary test to make sure that the measurements are in the linear region of the receiver.

To actually do those measurements, the S-meter reading was calibrated after seeing the IMD products at slightly more than S9. The limitation of the test setup can be dependent on the return losses of the receiver input. Fig 48 shows the input return losses at 4 MHz to be about 14.76 dB and Fig 49 shows the return loss at 6 MHz to be +17.49 dB. By definition, the maximum isolation for the hybrid coupler is insertion loss minus return loss. In our case at 40 meters, that is 6 + 17.45 dB = 23.45 dB. Fig 50 shows the actual test setup with the Yaesu FT-890.

The measured 10-dB signal-to-noise ratio with a 2.4 kHz bandwidth was –130 dBm with preamplifier on and –115 dBm with preamplifier off. The conventional definition of dynamic range would not be –30 dBm + 115 or 85 dB in 2.4 MHz bandwidth, while with the preamplifier on it is –22 dBm + 130 or 108 dB in 2.4 MHz bandwidth.

In my opinion, however, the conventional definitions are incorrect. One really should take a three-way power divider and add a third channel that is 3 kHz away from the IMD products. Such strong carriers generate some blocking problems from reciprocal mixing and the noise floor will now be 3 dB or higher. (In accordance with international conventions, the blocking and reciprocal mixing are the same effect only different expressions are used in different countries.) The 10-dB signal-to-noise ratio should be measured again 3 kHz away from the IMD products, and the actual large-signal 10-dB signal-to-noise ratio is found. This is the correct number when listening to stations that are strong enough to cause reciprocal-mixing noise. The current literature does not consider this effect.

Conclusion

In this paper, I have tried to give a comprehensive overview of the theory of nonlinearities—specifically, IMD products—and show practical requirements for a high-performance test setup. Several examples for mixers were given and IMD measurements were done on a set of military high-performance radios, as well as a popular Amateur Radio transceiver.

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