Darren Conway* helps you decide which is the right mixer option for your receiver design.

High level rf mixers

The vast majority of radio receivers are based on the super heterodyne principle, where incoming rf signals are mixed with a local oscillator to produce an intermediate frequency In most cases a receiver uses two mixers to convert from rf to the desired base band signal.

One of the key design choices for a receiver is the selection of mixers – and in particular the first stage mixer The development of rf mixers over the past forty years has been a process of evolutionary development and refinement. Circuits have improved but the basic principles and techniques have remained largely unchanged.

The aim of this article is to review a representative sample of the current range of high level mixers and discuss the characteristics of each.

Discussion is limited to mixers used up to vhf and those that are readily available. You are encouraged to view the relevant data sheets and references in conjunction with this article as they contain a wealth of information that is not included here.

Although this discussion is limited to vhf, the basic principles and mixer characteristics are applicable at all frequencies. The purpose is to provide you with the information required to select the right mixer for the right application

Why have a mixer?

The primary application of a mixer is to add an input frequency and a local oscillator frequency to obtain a single intermediate frequency, or IF, output.

Ideally, a mixer output would only contain the desired output frequencies, $F_{RF}+F_{LO}$ and $F_{RF}-F_{LO}$, where F_{RF} is the received rf signal and F_{LO} is the local oscillator input But no such device exists.

In reality, mixers produce a whole range of frequency products

$$\pm mF_{rf} \pm nF_{lo} (n=0 \ldots \infty, \mathrm{n}=0 \ldots \infty)$$

at the IF output The unwanted harmonics are filtered out.

The balance of mixers

There are effectively three types of mixers which may all be implemented as passive or active. The basic passive circuits are shown in **Figs 1, 2** and **3**. For active mixers, the diodes are replaced with fets, mosfets or transistors.

An unbalanced mixer shown in Fig. 1 has no isolation between the two input ports and the output port. They are rarely used because lack of isolation between the local oscillator and the rf input results in unwanted transmissions from the antenna at the local oscillator frequency. These transmissions may be strong enough to contravene emc regulations, and even if they are within legal limits, they are still undesirable.

Detection of local oscillator transmissions has been successfully used in the past to locate clandestine or illegal receivers The main advantage with unbalanced mixers is that they can operate over a very wide frequency range spanning greater than five decades. In certain applications, this may justify their use.

Single-balanced mixers go some way to solving the problem of unwanted transmissions by providing isolation between the local oscillator and the rf input as shown in Fig. 2. In addition, the local oscillator signal is suppressed at the intermediate-frequency output.

However, like the unbalanced mixer, the rf input appears

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*Darren Conway,
Lieutenant
Commander,
ME(Elect), MIPENZ,
MIEE, C.Eng psc
RNZN

at the IF output port. If it is decided to fabricate a mixer from discrete components, then the single balanced mixer offers a reasonable compromise between the superior performance of the double balanced mixer, and the simplicity of the unbalanced mixer

Double-balanced mixers ideally offer infinite suppression of signals between the three ports. The only output should be the intermediate-frequency signals ($\pm mF_{RF} \pm nF_{LO}$) with the rf and local oscillator inputs fully suppressed.

In practice the local oscillator and the rf input are typically suppressed by about 50dB at the intermediate-frequency output. The ready availability of single package double balanced mixers often means that they are simpler to apply than either single balanced or unbalanced mixers. In most applications, the double balanced mixer shown in Fig. 3 will provide the best performance

What makes a good mixer?

Practical mixers are complex to analyse and their performance is defined by a number of characteristics. The following define the major specifications of a mixer in order of importance.

Frequency range Mixers are usually required for all receivers operating from very low frequency to tens of gigahertz. Typical mass-produced mixers operate to maximum frequencies in the range of 100MHz to 2.5GHz. The operating frequency range is a fundamental design characteristic that will in part determine the final selection of mixer type.

Dynamic range. This is one of the most important specifications for a mixer. The massive proliferation of rf transmitters and other interference sources means that the modern radio receiver is usually operating in the presence of significant rfi.

Even if the desired signal is always very weak – for example satellite transmissions – it is still important that a receiver has the ability to operate in the presence of strong signals so that the desired weak signal is not lost.

The lower limit of dynamic range is defined by the noise figure, while the upper limit is defined by the compression point, intermodulation products and burnout level.

Noise Typically, mixers have noise figures ranging from 6dB to 20dB. The noise figure for passive mixers is about equal to the insertion loss. The noise figure for active mixers depends on the selected devices and circuit topology. It is usual but not essential in receiver design to include a low-noise rf amplifier ahead of the first mixer in order to improve the noise figure of the receiver system.

Gain The ready availability of amplifiers that cover the radio-frequency spectrum means that the mixer is not generally required to have any gain. Excess mixer gain can reduce the dynamic range of the receiver.

In most cases, insertion loss through a mixer is also undesirable particularly in the case of passive mixers. Active mixers provide gain in the range of –1dB to +17dB while passive mixers have a typical insertion loss of between 5.5dB and 8.5dB.

Local-oscillator drive. The ideal mixer would be insensitive to both local oscillator level and harmonic content but in reality, the local oscillator specifications need to match the requirements of the mixer.

Passive double-balanced diode mixers require local oscillator levels from +7dBm up to +23dBm. Active mixers require local oscillator output levels ranging from –20dBm to +30dBm depending on the selected type. The design of the local oscillator is intimately related to the selected mixer type

Isolation Isolation is a measure of the mixer's ability to prevent a signal applied to a port, appearing at either of the other two ports. The only output should be the mixer products at the intermediate-frequency port. The degree of isolation depends on whether the mixer is unbalanced, single balanced or double balanced. Unbalanced mixers exhibit no isolation between ports. Double balanced mixers provide the best isolation between the three ports

Impedance matching. The three ports of a mixer should be matched at each port. Mismatch in active mixers usually results in reduced mixer gain

Passive mixers are particularly sensitive to mismatch at the intermediate-frequency output port which causes greater insertion loss and unwanted mixer products. Regardless of whether an active or passive mixer is used, due care should always be taken to implement proper matching to maximise mixer performance.

Simplicity. An important characteristic of any circuit is the ease of design and implementation. Complex designs are often complex to build and difficult to set up. A lower parts

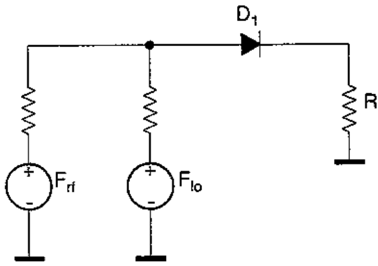
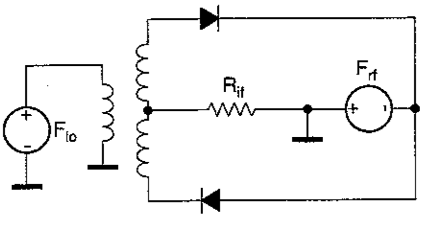


Fig. 1. With the unbalanced passive mixer, there is no isolation between the two input ports and the output port. This results in unwanted local-oscillator elements at the antenna.

Fig. 2. Below: single-balanced passive mixer solves the problem of local-oscillator feed through, but allows rf to pass to the output.



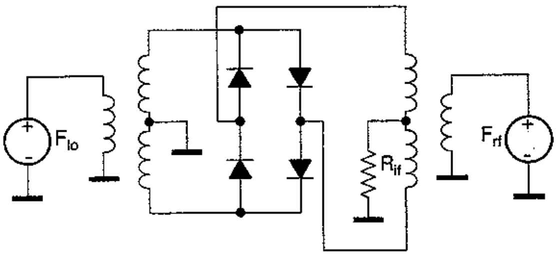


Fig. 3. The double-balanced passive mixer allows no local oscillator or rf components through to the output – in theory.

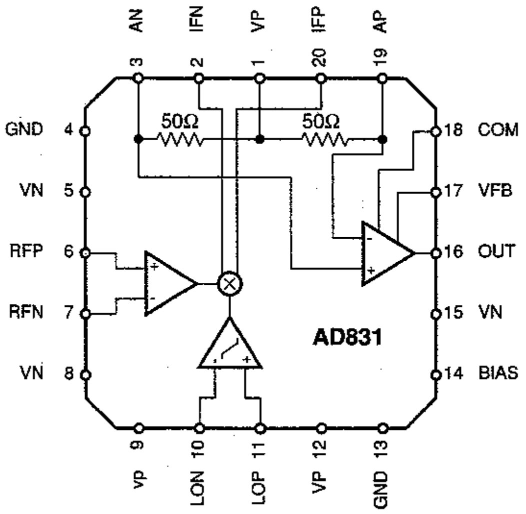


Fig. 4. Example of a high-level active double-balanced mixer – the bipolar AD831.

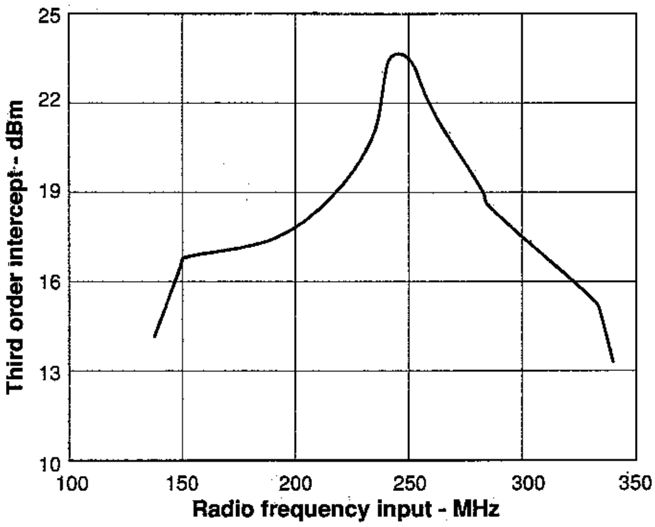


Fig. 5. Intermodulation versus frequency of the AD831 taken from its data sheet.

count has the added benefit of greater reliability, easier maintenance and a smaller spare parts inventory.

Overly complex design is a form of inefficiency that can have a significant effect on the through life cost of equipment. Good design concentrates on gaining the maximum performance from the minimum of components.

Integrated mixers

Given the superior performance of high level double balanced mixers and the availability of both passive and active devices in single packages, there is little incentive to use either an unbalanced or single balanced mixer. This assumes that the requirement for high level performance is one of the main design criteria. Applications demanding low power consumption or specialist functions may be more suited to mixers other than the high level double balanced mixers reviewed below.

AD831. The *AD831* is a modern example of a bipolar high-level active double balanced mixer. Housed in a PLCC package it includes a buffer amplifier with a 50Ω input and output, **Fig. 4**. The gain of the buffer amplifier can be set by appropriate feed back resistors. The buffer is configured as a balanced to unbalanced amplifier without the need for transformers.

The inclusion of the buffer amplifier with the mixer package makes this device particularly appealing as a first stage mixer. In most receiver designs, the first mixer is followed by a low-pass filter and then a buffer amplifier before the signal is applied to intermediate-frequency band-pass filters.

With the *AD831*, an additional two capacitors will implement a one-pole low-pass filter between the mixer outputs and the buffer inputs. The gain of the buffer amplifier can be set by two resistors to compensate for insertion loss in the following band-pass filters.

If a buffer gain of one is specified, then the feedback resistors are not required. Excessive gain reduces the gain bandwidth of the buffer amplifier and reflects noise back into the mixer.

When properly applied this single device and associated passive components can combine the mixer/filter/buffer functions into a very small space with no bulky tuneable components.

The *AD831* is specified for operation to 400MHz at the rf and local-oscillator inputs, but this needs qualifying. All performance curves are basically flat up to 100MHz. Above this frequency, some curves improve while others degrade.

Performance at about 200MHz is particularly ambiguous. If the application requires very good isolation between ports, then frequencies near 200MHz should be avoided. Local oscillator to rf isolation falls from 72dB at 100MHz, to a minimum of 45dB at 200MHz – which is still good by the way. However the high level performance peaks at 250MHz where the third order intercept reaches 23dBm and the –1dB compression point is 11dBm as shown in **Fig. 5**. It is an example how variable the important performance characteristics can be. This is not a particular fault of the *AD831* as all types of mixers both active and passive exhibit widely varying characteristics.

The *AD831* may be used with single or dual supplies. A programmable bias allows the user to define the power consumption. For the best third-order intercept performance, the *AD831* will typically draw 100mA quiescent current. The current may be reduced to 45mA for minimum power consumption.

The noise figure is specified at a high 20dB for a single ended voltage output. For receiver applications, this means that an rf amplifier ahead of the mixer is mandatory if a reasonable receiver noise figure is to be achieved.

In summary, the *AD831* is suitable for most mixer applications to at least 300MHz. Performance is very good up to 100MHz but performance varies at higher frequencies, particularly at 200MHz. The 20dB noise figure makes this device unsuitable for low noise applications.

The ability to combine a high performance mixer, low pass filter and buffer amplifier into a very small space with no tuneable components means that the AD831 would be a good choice for many applications.

SL6440. The *SL6440* is a bipolar double balanced mixer first produced by Plessey about 1980. In spite of its age, it is still a useful device with good performance.

The specified –3dB frequency range extends to 150MHz but I consider this to be a little optimistic for practical applications. The intermediate-frequency output level remains constant up to 50MHz after which the roll off is dependant on the supply voltages.

For a main dc supply voltage of 6V, the 1dB roll off occurs at 80MHz while for a supply of 12V dc, it occurs at just over 100MHz. I would conservatively rate this device as being suitable for applications up to 90MHz.

Mixer selection guide

For applications that require good performance, no tuned components, and a minimum of pcb real-estate, the *AD831* is an excellent choice The implications of the high noise figure need to be considered.

The *SL6440* is an old device but for applications that require an average noise figure with a low level local oscillator it remains a good choice.

If very high level performance and gain are the key criteria, then the jfet mixer should be selected Most applications will require the matching transformers to be hand crafted.

For those after the ultimate in high-level mixers, the mosfet mixer is supreme. But as with the jfet mixer, the effort required to implement the mixer and related circuitry makes this choice difficult to justify except for the most demanding applications.

When properly applied, the diode double balanced passive mixer combines the lowest noise figure with good high level performance. If low noise is important, and there is reasonable space and local oscillator power available, then a diode double balanced mixer is the right choice.

Almost all of the values shown in the **Table** are frequency dependent and can vary greatly depending on the exact operating conditions Mixers should be chosen based on performance at the intended operating conditions. Prototypes should then be constructed and tested because it is highly unlikely that the test circuits in the data sheets will match exactly the applied circuit

Table. Comparison between high-level mixers.

Characteristic	**Units**	**Active jfet** **SBL1***	**Diode** **RAY11***	**Diode**	**Mosfet** **AD831**	**Bipolar** **SL6440**	**Bipolar**
Frequency range	MHz	50-250	0.5-500	0.01-2500	0.2-500	0-400	0-90
Isolation rf local oscillator	dB	35	45	32	30	65	—
Isolation local oscillator – IF	dB	60	40	20	25	28	29
Overall noise figure (ssb)	dB	8	6	7	9	20	11
Local-oscillator drive level	dBm	+15	+7	+23	+16	–10	–5
Two-tone intercept point	dBm	+34	+16	+25	+44	+24	+30
Conversion gain	dB	+4	–5.6	–6.2	–7 to +18	0	–1
1dB compression	dBm	+13	+1	+15	+16	+10	+10

*MiniCircuits

The *6440* is contained in a 16-pin DIP package, **Fig. 6** It includes two input and two output pins for balanced signals but may also be configured for unbalanced signals. The *6440* also includes an input pin to program the supply current which can be useful for battery operation

It is possible to implement power load management by programming the supply current to a low value in the absence of a desired signal. When a signal is received, the supply current can be increased to improve the mixer performance. Such a feature would be relatively simple to include with the receiver squelch control.

Note that the supply current for most active mixers can be programmed by various means and this is not a unique feature of the *6440*. As a general guide for any mixer, either passive or active, intermodulation performance improves with increased supply current and voltage.

Like most active mixers, this device draws a significant current to achieve the best performance. The device requires two positive supply voltages. Rail V_{cc1} is for the mixer while the on chip oscillator buffer is supplied by V_{cc2}.

Typically the *SL6440* draws 30mA to 60mA, which may be increased with the use of a heat sink, or decreased to conserve power The quiescent current drawn by the mixer is determined by the value of V_{cc2}, and the programming current I_p into pin 3. The absolute maximum power dissipation is specified at 1200mW.

For maximum suppression of intermodulation products, the programming current Ip should be between 10mA and 12.5mA giving a total supply current of about 40mA The –1dB compression point is then about +7dBm but can be increased to +15dBm by increasing I_p to 30mA giving a total supply current of about 77mA. Reducing the programming current I_p below 5mA attenuates the wanted intermediate-frequency output signal.

Conversion gain or loss is determined by the input and output configuration and programmed current For resistive, unbalanced inputs and outputs a conversion loss of about 1dB would be expected. The use of tuned, balanced input and output transformers will provide a measured conversion gain of about 4dB.

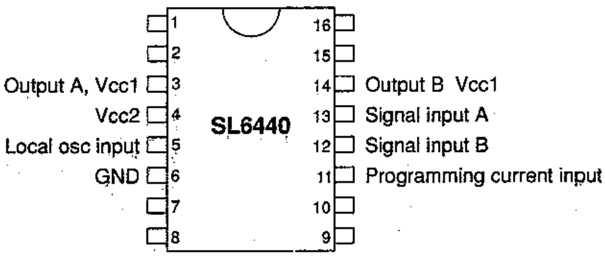


Fig. 6. Around since 1980, the SL6440 still has its uses. A drawback though is that it needs quite a few external components.

Using tuned transformers on the input and outputs offers the advantage of some gain and filtering without degrading performance. This is because balanced inputs and outputs evenly distribute current flow within the *SL6440* In either case conversion gain is dependant on both the programming current I_p and the load impedance. Excessive gain increases the risk of saturating the mixer output transistors and should be avoided.

While adequate, the information provided on the data sheet could not be described as comprehensive. There is a small selection of tables, text and graphs detailing overall performance and design procedure.

No information is given about the internal workings of the device nor are there any details of frequency dependent impedance characteristics. The design of matching circuits must therefore be accomplished by trial and measurement.

In summary, the *SL6440* may be old but its performance is still good up to about 90MHz. If you need optimum performance then tuned input and output circuits would typically be used. Even in a basic application, about a dozen passive components are required around the *SL6440* which means that this device occupies a reasonably large area of pcb real-estate. The 11dB noise figure is about as good as can be expected from this type of mixer.

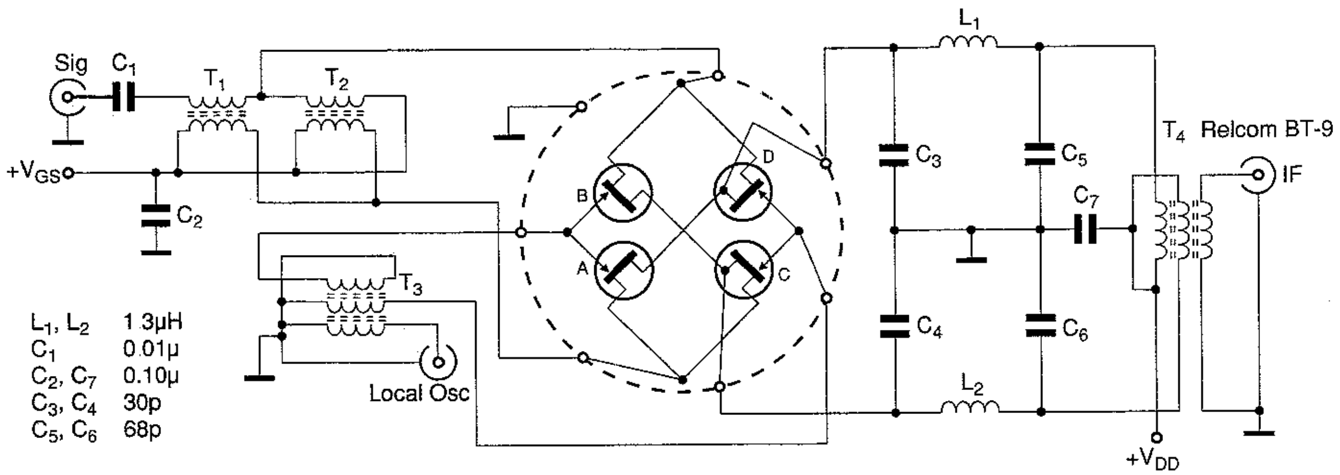


Fig. 7. Circuit for a double-balanced fet mixer by Ed Oxner.

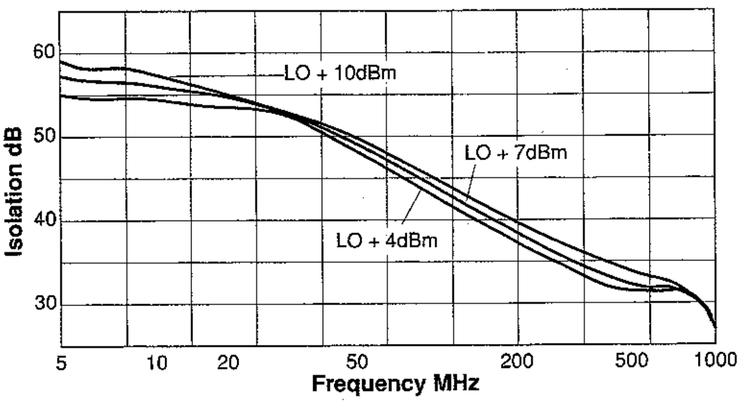


Fig. 8. Local oscillator to rf isolation performance for a diode mixer based on the Mini Circuits SBL-1.

Using junction and mos fets

Jfet mixer. The junction-fet mixer appears to offer the potential for very good performance. Conversion gain and intermodulation distortion characteristics are superior to typical passive mixers. Junction fets have an inherent square law response which reduces third order intermodulation distortion. And, like passive mixers, jfet mixers have a high burn-out level.

The main disadvantage is that there is no known source of ready-made units incorporating the jfets and transformers. Also a high local-oscillator drive is required.

Unlike double-balanced diode mixers, the jfet mixer has to be built up from individual components. Even commercially produced receivers such as the *ICOM R9000* uses a single balanced jfet mixer made from individual components.

The inability to obtain a single-package double-balanced mixer is a major disadvantage of the jfet mixer. Suitable transformers are difficult to obtain and for prototype work, hand made coils are usually necessary.

If optimum performance is to be achieved then the transformers need to be physically matched to high tolerances. It is possible to obtain good results with a combination of good construction techniques and a suitable balance adjustment.

Optimum power gain and noise do not occur at the operating point. The bias currents, local oscillator drive level and matching transformers must be properly selected to ensure that the fets operate in the square law region and that distortion is minimised. The lowest achievable noise figure is 8dB.

For optimum performance of a double balanced fet mixer, the fets should be perfectly matched which is very difficult to achieve using discrete fets due to the difficulties in precisely controlling characteristics between batches.

In practice matched characteristics can only be achieved if the fets are mounted within the same package and are made from the same silicon wafer. Such devices are available from Siliconix which manufactures dual (*U430*) and quad fets (*U350*) in single packages specifically for mixer applications.

For single-balanced mixers, the requirement for matched components is less stringent allowing the use of fets matched to within 10%.

Despite the problems of construction, the jfet mixer offers good performance. Their specifications are similar to that of a high-level diode mixer with the advantage of positive gain.

The major disadvantage is the high local-oscillator power requirement and the significant construction effort. For those of you wanting to experiment with jfet mixers, references 3 and 4 provide excellent details on the performance and practical construction of the mixer shown in **Fig. 7**.

Mosfet mixers. If there is a need for very high-level performance, then the jfets can be substituted for either monolithic dmos fet quads or a combination of rf power mosfets. Suitable monolithic devices include Calogic *SD8901* and the Siliconix *SD5000* from which very good results have been obtained. Double balanced mixers may operate the mosfets as switches with no drain voltage applied resulting in an insertion loss of about −7dB. Alternatively, drain voltage supplied to the mosfets may be used to give a mixer gain of up to +17dB.

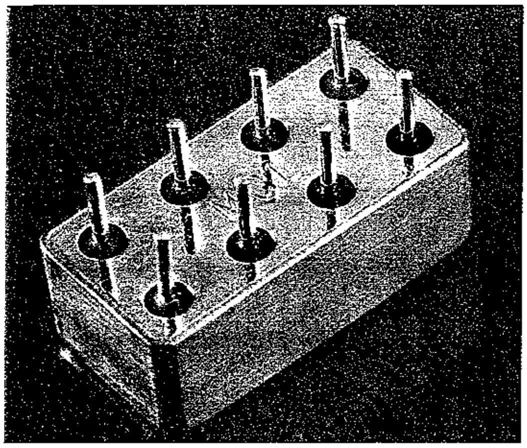
One of the features of mosfets is that the gate drive voltages are roughly the same for for all mosfet types. This means that the local oscillator power needed for a very high level mosfet mixer is less than the power required for an equivalent diode mixer. A mosfet mixer giving very high level performance does not require an excessively high local oscillator drive.

While mosfet mixers provide excellent very high level performance, they suffer from the same problem as jfet mixers in that the transformers and surrounding circuitry result in a high parts count and the use of a significant area of circuit board. Such a mixer would only be required where the receiver was physically located near a high powered transmitter. Typically, mosfet mixers would be found in very high performance hf and mf receivers.

Double-balanced-diode mixer

The double balanced diode mixer is a design that is positively archaic but still has application in modern receiver design. Its ability to withstand high level input signals, low cost and the ready availability of small mass produced mixers has ensured its continued use.

If the insertion loss is tolerable, the characteristics compare favourably with other high level mixers. Perhaps the most widely used mixer type is the *SBL-1* from Mini-



SBL-1 diode mixer from Mini-Circuits. Although not an active device, this mixer produces good results in a wide range of receiver applications.

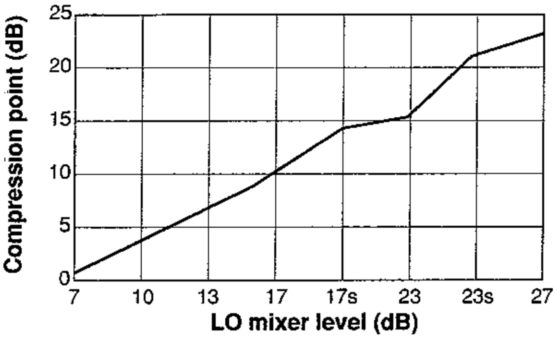


Fig. 9. Diode mixer 1dB compression point versus local oscillator level for various Mini-Circuits parts.

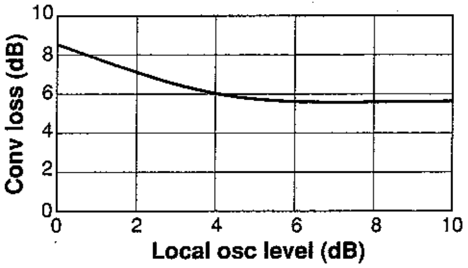


Fig. 10. Typical diode-mixer conversion loss versus local-oscillator level.

Circuits. It is cheap, compact and available. Mini-Circuits and other companies produce a wide range of passive mixers suitable for most mixer applications.

Like the other mixers described, the performance of the diode double balanced mixer is dependant on a variety of factors including but not limited to frequency, local-oscillator power, matching and temperature. The graph of local-oscillator to rf isolation shown in **Fig. 8** is typical of the variations seen in performance.

Proper matching of the intermediate-frequency output is essential to gain optimum performance from a diode double balanced mixer. The intermediate-frequency filter should feature a 50Ω resistive impedance across the rf spectrum. Failure to ensure proper matching will result in higher conversion losses and the generation of unwanted harmonics. In addition to impedance matching, the intermediate-frequency filter should attenuate all mixer products except the desired intermediate-frequency. Detail of the design of an intermediate-frequency filter for a passive diode mixer is the subject of a future article.

Diode mixers require a high-level local oscillator with at least +7dBm output. Some very high level passive mixers require up to +23dBm local oscillator drive. The relationship between local oscillator power and the 1dB compression point is shown in **Fig. 9** for a selection of diode mixers from Mini-Circuits.

The local-oscillator level also effects conversion gain as shown in **Fig. 10**. It is important that harmonics from the local oscillator are adequately suppressed. Harmonics from the local oscillator mix with the rf input and produce unwanted mixer products.

It can be difficult to design and build oscillators at the required output level combined with the desired spectral purity. This is particularly true for battery operated equipment where available power and voltage are relatively low.

Some mixers are available that include a built-in amplifier on either the local oscillator input, or at the intermediate-frequency output. These may ease the design problem in some situations. Local-oscillator power and purity has a major effect on the design and performance of the mixer stage and therefore the whole receiver system.

One of the main advantages with the diode double-balanced mixer is that being a passive device, it draws no quiescent current. This is somewhat offset by the high local-oscillator drive requirements and the need to compensate for the conversion loss.

Although diode mixers are available in very compact packages, the high level local oscillator and intermediate-frequency matching filter will normally require a significant circuit-board area. If high level and low noise are the prime requirements then the double balanced diode mixer remains the best choice.

In summary

The selection of a mixer for any receiver application depends on many variables. The information in the Table has been obtained from a number of sources. The values are representative of actual devices operating under typical conditions and in most instances these values will be different to those specified in data sheets.

As with most design choices, the selection of the right mixer for the right application is based on compromise. There is no single mixer that is suitable for all tasks and it is up to the design engineer to determine which characteristics should dominate the selection process. Selecting the right mixer is a matter of determining the most important characteristics and matching these to the appropriate mixer type. ■

References

1. 'Get the most from mixers,' Mini-Circuits
2. Yousif, AM and Gardiner, JG, 'Distortion effects in a switching-diode modulator with tuned terminations,' *Proc IEE* Vol. 119, No 2, Feb. 1972.
3. Oxner, E 'FETs work well in active balanced mixers' Siliconix Inc, *EDN*, 5 Jan. 1973.
4. Oxner, E, 'Active double-balanced mixers made easy with junction FETs,' Siliconix, Inc, *EDN* 5 July 1995.
5. Kanazawa, K, *et al*, 'A GaAs Double-Balanced Dual-Gate FET Mixer IC for UHF Receiver Front-End Applications,' *IEE Trans on Microwave Theory and Techniques*, Vol. MTT-33, No 12, Dec. 1985.
6. Hikita, M, and Akagi, T 'Single Balanced Mixer for SAW Front-End Module used in 800MHz Cellular Radio.' *Electronics Letters*, 22 Oct. 1992, Vol. 28, No 22.
7. DeMaw, D and Collins, G, 'Modern Receiver Mixers for High Dynamic Range,' *QST*, Jan 1981.
8. 'Introduction to Radar Systems' Skolnik Merrill Ivan, pub McGraw-Hill 1981
9. 'The ARRL Handbook' 1995