Homebrew

We start looking at high performance HF receivers.

HOMEBREW CAN WORK WELL! The fact that you use home made equipment should never be used as an excuse for poor performance. There is no reason why home made equipment should not perform at least as well as the best commercially made equipment. The home constructor has a number of advantages that are not available to the commercial manufacturer. Amateurs can choose to focus their greatest effort or expenditure on a single aspect of the design. You might choose to use a £10 low noise transistor or a £50 mixer, even if it only makes a small difference to the quality of the equipment. Amateurs can afford to spend an unlimited amount of time and effort on a project, happily spending a week or two tweaking a home made IF filter to achieve the perfect response.

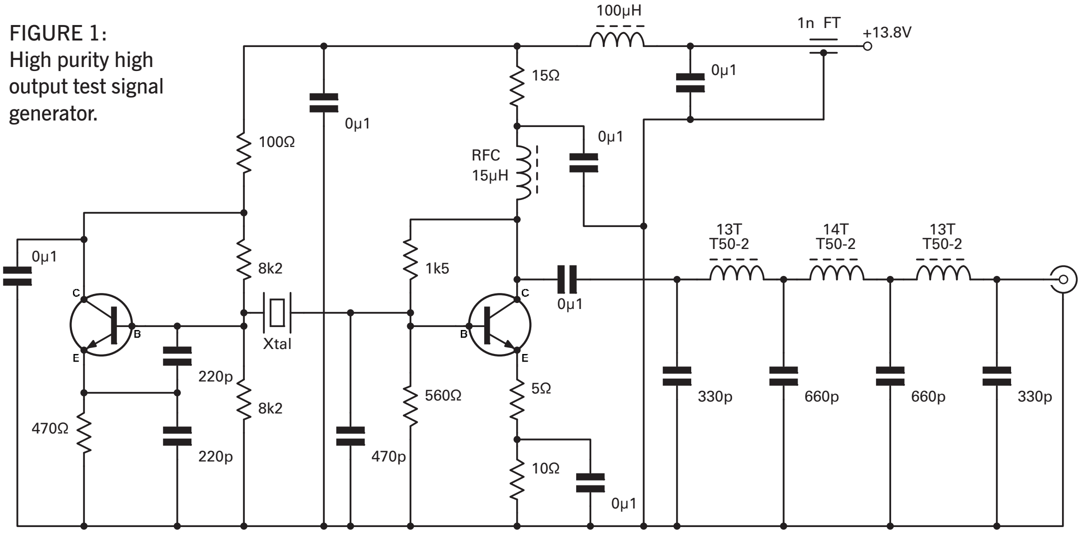
Most home made receivers and transceivers are built from a collection of separate modules. If you are unhappy with the performance of any individual stage, it is relatively easy to modify it or even replace it with a completely different circuit. The amateur constructor can always try to build a better mousetrap. There are no warranty issues to worry about when you modify a brand new homebrew rig!

PERFORMANCE DIFFERENCES. This month, we will look at high performance receiver front ends. Before we begin, we should try to define 'high performance'. Apart from the weight, the most significant difference between an average rig and a top of the range transceiver is the receiver. Adverts for the flagship transceivers from commercial manufacturers are often adorned with lots of TLAs (three letter acronyms) like MDS, IMD, IP3 and DSP. So what are all these strange letters about and do they really mean anything?

One of the most important parameters in a receiver specification is dynamic range. To add to the confusion, there are several different ways of specifying dynamic range. In the most commonly used definition, dynamic rage is a ratio that is expressed in decibels. The MDS (minimum discernible signal) is the weakest signal that can be heard above the receiver noise floor. At the other end of the range is the maximum level of multiple received signals that a receiver can tolerate without generating any measurable distortion products. The ratio between these two levels is the dynamic range. The MDS is reasonably easy to establish. All that is needed is a single signal generator with a known output level and an accurate attenuator. The receiver audio output is monitored with a millivolt meter or other sensitive measuring instrument. The signal generator is connected to the receiver input and its output level is increased until the received signal is just detectable above the receiver noise floor. The MDS is sometimes defined as a signal that is 3dB above the noise floor. The ability of the receiver to cope with strong signals can be measured by applying two very strong signals to the receiver input and then measuring the level of the spurious signals that are generated in the receiver. Odd order intermodulation products tend to be the most troublesome because they produce in-band spurious signals that cannot be eliminated by improved front-end band pass filtering. Here, in Western Europe, the 40m band presents a worst case scenario where there are several very strong broadcast stations on frequencies that are inside or very close to the amateur band. We will consider a hypothetical situation where there is a very strong broadcast station on 7.2MHz and another equally strong station on 7.3MHz. Third order intermodulation distortion within the receiver will produce unwanted signals at 2f1 ± f2 and 2f2 ± f1. The 2x7.2 – 7.3 intermodulation distortion (IMD) product will produce a signal at 7.1MHz, which is likely to swamp a weak DX signal within the amateur band. It is important to note that, at least in this case, the interfering signal is not transmitted by either of the broadcast stations. This phantom signal is generated entirely within your receiver.

The ratio between the MDS and the signal level where spurious signals caused by a pair of strong off-channel signals begins to cause spurious signals due to IMD is known as the two-tone dynamic range. So how good does a HF band receiver need to be? A receiver with a two-tone dynamic range of 100dB or more would be considered to be excellent. 80 – 90dB is reasonably good and anything below 70dB would be a poor performer. Sometimes dynamic range isn't everything. For a VHF EME (moonbounce) station in a remote location, extreme sensitivity might be more important than strong signal handling. Similarly, an LF band operator in a noisy location would not see any benefit from having a sensitive receiver with high gain and a low noise figure. Most of the better quality HF receivers try to cater for every situation by having a good strong front end mixer and a switchable pre-amp that is not usually needed on the lower frequency bands. To cope with the most extreme conditions, many receivers have a switchable attenuator at the front end. Using the attenuator will dramatically reduce IMD products. Every 10dB of attenuation will reduce 3rd order IMD products by 30dB. This improvement comes at the expense of reduced sensitivity. Using the attenuator will probably eliminate

FIGURE 1: High purity high output test signal generator.



the IMD products, but it might also eliminate that elusive DX signal.

MDS is easily measured with a calibrated signal generator. Even if such a generator is not available, it is easy to evaluate the sensitivity of a receiver by simply removing the aerial and replacing it with a 50Ω load. If there is a significant increase in receiver noise when you switch from the room temperature resistor to the aerial, you know that the receiver is good enough to hear anything above your local noise level. This test should be performed on a quiet frequency. This is generally during daylight hours on the LF bands and after midnight on the HF bands.

Testing two-tone dynamic range is a little bit more difficult. You will need two signal generators that are capable of producing a strong signal (about +10dBm is ideal). The signals from the generators must have extremely good spectral purity. **Figure 1** shows the schematic of one of my test generators. The crystal oscillator is a standard common-collector Colpitts type. The most significant difference between this oscillator and similar oscillators used in some of our previous projects is that the output is taken via the crystal rather than from across the emitter resistor. The series resonant crystal acts as a BPF, which cleans up the output signal. Observing the output signal at this point with an oscilloscope shows that the output is a very nice sinewave, quite unlike the distorted signal at the transistor emitter. The oscillator signal is amplified by a transistor amplifier and then fed to the BNC output connector via a 7-element low pass filter. The measured output level is 5V peak (3.535V RMS) into 50Ω. This is 250mW or +24dBm. The crystal frequency is 10.245MHz. I have built several of these oscillators. As this particular one produces more output than any of the others, it will be used as the local oscillator for the high level mixer tests described later.

If we are to use a pair of these signal generators to provide a receiver test signal, we will need to find a way of combining the two test signals without generating any IMD products in the process. Then we will need to use an attenuator to bring the two signals to a suitable level for feeding them into the receiver input. A signal of around 0dBm (1mW) is about right for testing a good HF receiver. This is strong enough to generate clearly measurable IMD products but not strong enough to damage anything in the receiver.

If the output of the two signal generators are simply connected together at a common point, the high level signals from each generator will tend to modulate the output of the other generator. This is a highly undesirable situation as we will have no way of determining whether any IMD products that appear in the test receiver are due to non-linearity in the receiver or if they are caused by unwanted mixing of the generator outputs. The answer to this problem is to use a splitter/combiner to combine the two signals while maintaining good isolation between the two generators. A Wilkinson splitter/combiner **[1]** as described in previous Homebrew projects is one possible solution to this problem. The 6dB hybrid combiner as shown in **Figure 2** also makes an excellent broadband signal combiner. This circuit is also known as a return loss bridge. This is a simple Wheatstone bridge as used in previous projects **[2]**. A 1:1 balun is used between the centre of the bridge and the detector port so that the bridge can be used with an unbalanced 50Ω detector without unbalancing the bridge. The detector is usually a sensitive power meter, an oscilloscope with a 50Ω input or the input of a spectrum analyser.

RETURN LOSS AND SWR

Return loss just is essentially another way of looking at VSWR. Technically, it's the proportion of the signal power which is reflected, expressed in decibels. Compare with VSWR, which is the ratio of the maximum voltage to the minimum voltage on the line, expressed as a simple ratio. It is relatively easy to convert between (V)SWR and return loss, particularly using online tools. The following table gives some useful conversion points.

SWR	RL	SWR	RL
10:1	-1.7dB	1.5:1	-14dB
5:1	-3.5dB	1.2:1	-20.8dB
3:1	-6dB	1.1:1	-26.4dB
2:1	-9.5dB	1.05:1	-32.2dB

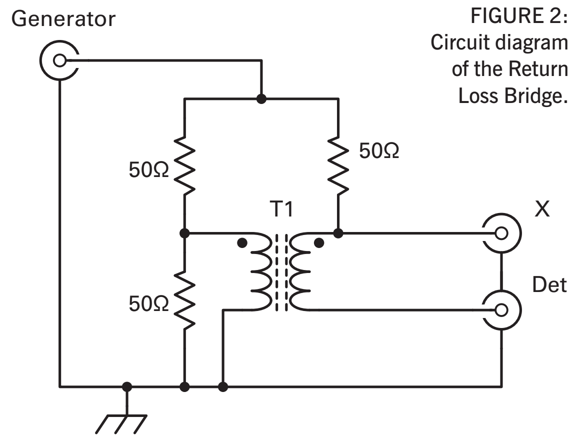


FIGURE 2: Circuit diagram of the Return Loss Bridge.

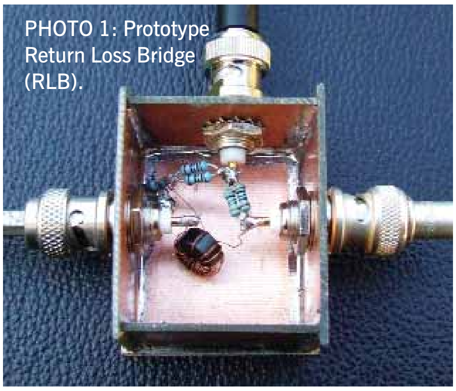


PHOTO 1: Prototype Return Loss Bridge (RLB).

RETURN LOSS BRIDGE. The first of this month's construction projects is a simple return loss bridge (RLB). The RLB is a useful measuring impedance indicating device. It can be used to check cables, antennas, tuning stubs, filters and a whole lot more, just by feeding it with a signal and seeing how much comes out of the Detector port. Although it might look a bit scary, in reality it's not really more complex than a Wheatstone bridge for DC. The RLB here is built in a small box made from double sided PCB laminate. The box is seam soldered inside and out (except for the lid). BNC sockets are used for the Generator, unknown (X) and Detector ports. T1 is 15 turns, of enamelled copper wire bifilar wound on a FT37-43 ferrite toroid. Each of the three resistors is made from a parallel pair of 100Ω 1% tolerance metal film resistors (Maplin M100R or similar). The finished project is shown in **Photo 1**.

TESTING THE RLB. The generator port should be connected to the 50Ω output of a signal generator. The detector port should be connected to the 50Ω input of a sensitive power meter. Check the output at the detector port when the unknown port is both open circuit and short circuited. The detector output should be exactly the same for both conditions. This is the 0dB return loss (SWR = infinity) reference level.

When the port is terminated by a 50Ω resistive termination, there should be no output at the detector port (SWR = 1:1). I use a good quality 1W 50Ω BNC terminator for this purpose. In practice, even the best RLB won't have infinite directivity. My RLB shows more than 40dB of return loss from 1.5MHz to 100MHz and better than 30dB up to 200MHz. The RLB makes an ideal companion for a spectrum analyser and tracking generator. I use this bridge with a SM5006 (HM5006) analyser. This combination makes it very easy to plot return loss over a wide frequency range. Despite its apparent simplicity and negligible cost, the RLB is one of the most useful items in the homebrewers toolkit.

As well as its great utility as a measuring instrument, the RLB makes a superb power combiner. If one generator is fed to the generator port and a second generator is fed into the detector port. The two signals will appear at the unknown (X) port. There is a 6dB loss for each signal. As we have already seen when the circuit was used to measure return loss, any signal applied to the generator port will not appear at the detector port. When a signal generator is connected to the detector port, equal voltages of opposite phase will be applied across the centre of the bridge. These signals are effectively cancelled out at the generator port. This isolation between the two generators means that there is little possibility of one generator modulating the output of the other.

HIGH LEVEL MIXERS. One of the most important stages in a radio receiver is the first mixer. The mixer must be able to respond to all input signals in a linear manner over a huge dynamic range. Just to put this in perspective, 100dB is a power ratio of 10000000000:1. Ordinary low-level mixers are not quite up to this level of performance. Simple single FET or bipolar transistor mixers will often offer a reasonable compromise between sensitivity and dynamic range. Such mixers have very low power consumption, low noise figure and extremely low cost. However, if we want to build a high performance HF receiver, we will need to use a high level mixer. Several options are available. There are a few high level active mixer ICs. The now-obsolete Plessey SL6440 mixer was a popular way to achieve good performance. These devices are still available on the surplus market, but they are probably not a good choice for a new design. Newer ICs like the Analog Devices AD831 offer a 3rd order intercept point (IP3) **[3]** of +24dBm for only -10dBm of local oscillator drive.

The diode ring mixer makes an excellent high-level mixer. It is quite easy to make a diode balanced or double balanced mixer. All you will need is a few diodes and a couple of ferrite toroid cores. If this seems too much like hard work, you can buy a ready made DBM in a convenient package. The most popular types of diode mixers are made by Mini-Circuits **[4]**. There are several different ranges of pre-packaged mixers available, which operate at every frequency from DC to several GHz. The most popular device is the SBL-1 that is designated as a level-7 mixer because it requires +7dBm of local oscillator power. Other available ranges are level-10, -17, -23 and -27. As with the lower power types, the number indicates the LO drive requirement in dBm.

Figure 3a shows the classic diode DBM configuration. This type of mixer has very predictable characteristics. It will work over a wide bandwidth. The third order output intercept point will be approximately the same as or slightly higher than the LO injection level. Passive diode mixers have conversion loss rather than gain. The loss for a double balanced mixer is typically about 6dB and slightly less for a single balanced mixer. The conversion loss means that the input IP3 will be greater than the output IP3. Passive diode mixers cannot achieve a very low noise figure. However, as they contain no active devices, they are inherently quiet. If the local oscillator is clean and relatively free of phase noise, the noise figure of a diode mixer is essentially the same as the conversion loss.

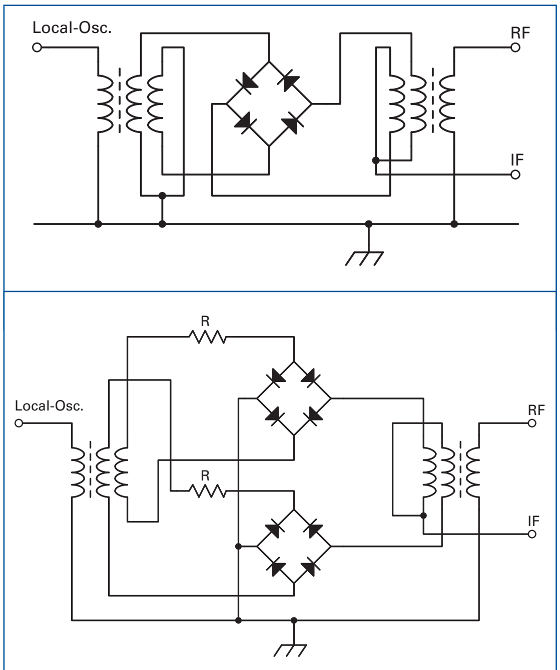


FIGURE 3: Two configurations diode mixer. (a) Classic double balanced mixer. (b) Dual bridge type.

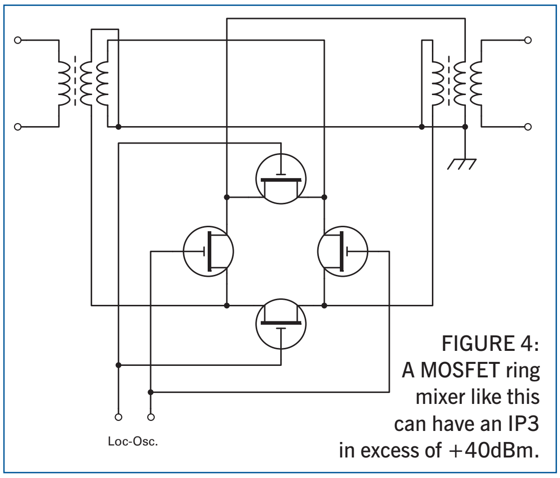


FIGURE 4: A MOSFET ring mixer like this can have an IP3 in excess of +40dBm.

Another type of diode mixer is shown in **Figure 3b**. This is a dual-bridge diode mixer as described in SSD **[5]**. The eight diodes are not connected in a ring configuration, but as a pair of bridges. I used this mixer in the front end of my main HF transceiver (built in 1992). After 16 years of abuse, it continues to provide excellent service. I did some dynamic range measurements at the time the receiver was built. The testbed version of this mixer used +27dBm (500mW) of local oscillator injection and had an input IP3 of +33dBm. This level of mixer performance was not really required because the input IP3 of the post mixer amplifier was somewhat lower than this value. The local oscillator was later reduced to a slightly more reasonable level of +23dBm. This still results in an input IP3 in the high 20s. Receiver sensitivity is good enough to hear sub-microvolt signals with the preamp turned off. It is a bit deaf on the higher bands above 15m where the preamp is required for comfortable copy of weak signals.

It is also possible to make a ring mixer using MOSFET switches in place of the diodes. **Figure 4** shows a double balanced mixer using high-speed switching MOSFETS. This is the configuration used in the now famous N6NWP MF/HF front end **[6]**. This mixer can have an input IP3 in excess of +40dBm!

Even this extraordinary level of performance has been surpassed by the H-mode mixer **[7]** developed by Colin Horrabin, G3SBI. The H-mode mixer moves the MOSFETs to a different point in the signal path so that the source terminal of all four FET switches can be grounded. The N6NWP mixer and the G3SBI H-mode mixer are usually used with a square wave local oscillator signal that is supplied by high speed digital logic ICs. Some of the more recent implementations of the H-mode mixer are based on low cost, high speed bus switch ICs like the FST3125. Some constructors have reported input IP3 levels as high as 40-50dBm from this type of mixer.

The purpose of my recent experiments with high level mixers has been to select a suitable mixer for my next HF transceiver. I haven't yet decided which type of mixer to use. I will probably end up using a modular system with a plug-in first mixer unit so that I can try them all.

NOISE & SENSITIVITY. I haven't said much about sensitivity and noise figure so far. The reason for this is quite simple. Lack of sensitivity is rarely a problem at HF. My relatively deaf HF rig can easily hear a 0.225μV CW signal in an SSB bandwidth, even when the RF preamplifier is switched off. The thermal noise generated by a resistor at room temperature (290K) is -174dBm in a 1Hz bandwidth. The sensitivity of a receiver is approximately -174dBm + NF + 10logB, where NF is the receiver noise figure and B is the bandwidth in Hz. This suggests that a receiver noise figure of about 20dB should be quite adequate for the lower HF bands.

I did a few two-tone tests on a few passive diode mixers. A pair of homebrew signal generators was used to generate the two test signals at 14.318MHz and 14.745MHz. The two signals were combined in a 6dB hybrid combiner as described earlier and a precision attenuator was used to bring the level of the

FIGURE 5: Combined mixer and diplexer.

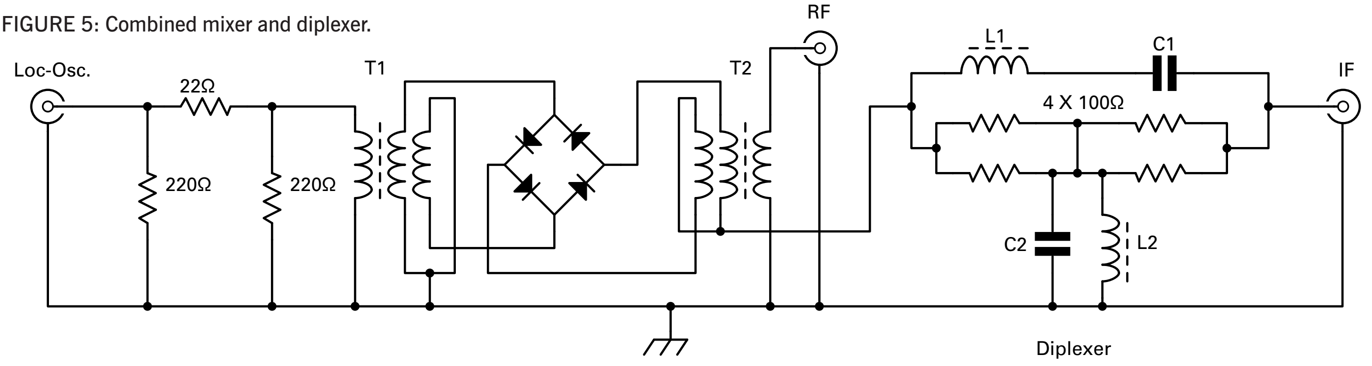
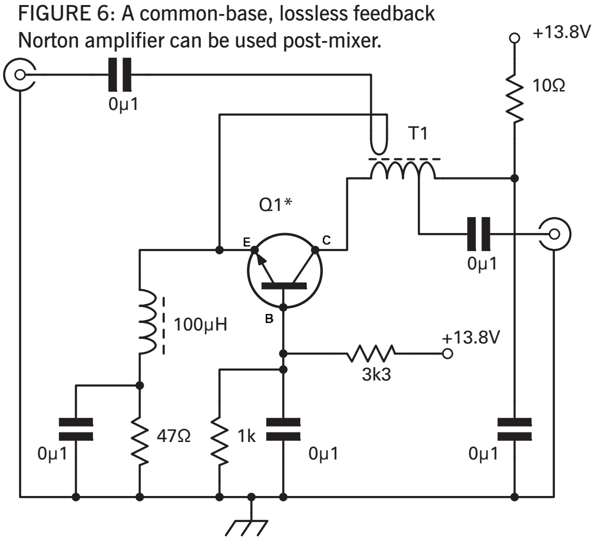


FIGURE 6: A common-base, lossless feedback Norton amplifier can be used post-mixer.



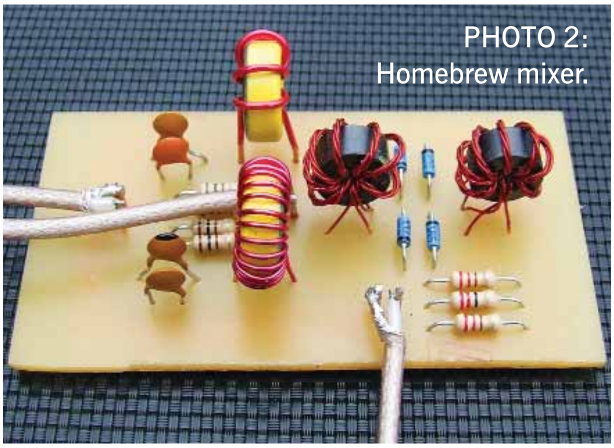


PHOTO 2: Homebrew mixer.

two signals down to 0dBm (1mW). The first mixer tested was a dead-bug style dual-bridge diode mixer. The 10.245MHz local oscillator injection level was set to +17dBm and the f_sig – f_LO signals at just over 4MHz were observed on a spectrum analyser. The 3rd order IMD products were measured at -51 to -52dBm which indicates an input IP3 of over +25dBm. Not bad for a few pennies worth of diodes and a couple of FT37-43 toroids. The next mixer tested was a Mini-Circuits SRA-2H which is a level-17 device. Tested under the same conditions, the SRA-2H showed an output intercept of +27dBm, which was a bit better than expected. The final tests were on a home made diode ring mixer as shown in **Photo 2**.

At +24dBm the input IP3 of this mixer was almost as good as the dual-bridge mixer. Increasing the local oscillator drive to +24dBm resulted in an input IP3 of just over +30dBm. The obvious conclusion from these experiments is that it really is possible to make homebrew diode mixers that are as good as the pre-packaged high-level mixers. This is good news for the home constructor because level-27 mixers are rather expensive.

These tests were performed under ideal conditions for a diode mixer. The IF port of the mixer was terminated by the 50Ω input attenuator of the spectrum analyser. The RF port was terminated by the signal generator attenuator and there was a 7dB attenuator connected to the LO port for the +17dBm tests. In a real-world application, the mixer is unlikely to live in such a benign environment. It is particularly desirable that the IF port should see a good 50Ω termination over a wide bandwidth. It is common practice to use a 6dB attenuator at the IF port. Unfortunately, this will increase the receiver noise figure by a similar amount. The mixer in **Photo 2** has a diplexer between the mixer IF port and the input of the post mixer amplifier. The diplexer is a Bridge-Tee type with a Q of 5. This provides a good 50Ω termination at the IF image and LO frequencies and at other frequencies that are well removed from the IF frequency. The values of C1 and L1 are chosen for a reactance of 250Ω at the IF frequency. C2 and L2 should have a reactance of 10Ω. Most constructors would use variable capacitors or inductors in the diplexer. I took the more difficult option of using fixed inductors and hand-picked pairs of fixed capacitors for C1/C2. Tuning the diplexer in this fashion took about one hour, but the end result justified the effort. For my 10.7MHz IF, I used 30t on a T50-6 for L1 and 5t on a T50-6 for L2. C1 is 57pF (47pF + 10pF) and C2 is 1470pF (1nF + 470pF). Insertion loss is just 1dB. The schematic of the mixer and diplexer is shown in **Figure 5**. 1N5711 Schottky diodes are used in both of the home made mixers. The broadband transformers are 8 turns trifilar wound on FT37-43 cores.

The amplifier in **Figure 6** can be used as a post-mixer amplifier and/or as an RF amplifier. This type of common-base lossless feedback amplifier is commonly known as a Norton amplifier (after one of its inventors). I used 8 turns, tapped at three turns from the DC supply end for the transformer winding and a single turn for the negative feedback winding. I got the best input and output return loss figures when I used a two-hole binocular balun core with unknown properties. Replacing this core with a single FT37-43 gave unsatisfactory results. In an effort to replicate the size and configuration of the balun core, I use two pairs of FT37-43 toroids (4 toroids) side by side for the core of T1. This gave identical performance to the junk box balun core. The transistor is an NEC 2SC1426 with f_T = 2.5GHz and P_{tot} of 3.5W. A 2N5109 would make a reasonably good substitute. The measured gain is 10dB ±1 dB from 1MHz to well over 100MHz. When the output is terminated with 50Ω, the input return loss is better than 20dB (SWR 1.2:1) up to 17MHz, 14dB (SWR 1.5:1) up to 36MHz and 9.5dB (SWR 2:1) up to 129MHz. Measured input IP3 is above +30dBm, output IP3 is greater than 40dBm!

Next month: band pass filters.

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